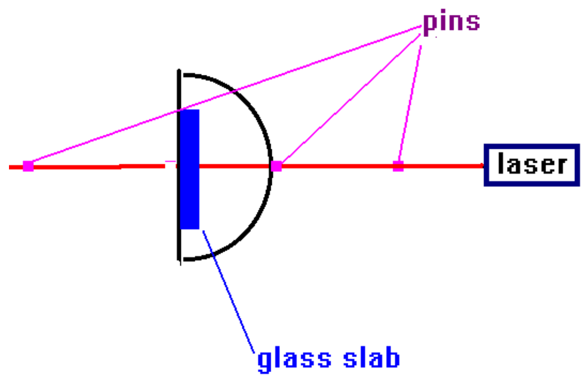
Angle of reflection, index of refraction, Brewster's angle, total internal reflection
revised 2017

Part I: The law of reflection

As you know from class, the law of reflection states that the angle of incidence is equal to the angle of reflection, or

$$\theta_i = \theta_r \quad .$$

One of the easiest things that you will test in today's lab is this law of reflection. In order to do this, I have provided you with a rudimentary optical bench. You will need to place the cork board on top of a larger flat board. In order to elevate the cork board I have placed weights under the boards. I have also placed a sheet of chart paper on top of the cork board in order to provide rulings for a surface.



You should now have your optical table constructed. The next thing that you will need to do is to align a laser with the nail through the protractor. You may want to raise the rear end of the laser slightly over the front end with your weights in order to provide some possibility of skimming light along the cork board (this, it turns out, does not work all that well). Now place a pin in front of the protractor's 90 degree mark, and then place a second one also in front of the 90 degree mark about 1 inch or so in front of the first pin. If these pins are placed on opposite sides of the printed line on your chart paper, the idea will be that the laser light will pass through them. You will want to consider placing a third pin directly behind your protractor (but not close enough so that the thing can't rotate) in order to confirm optical alignment. If everything is right, then you ought to see laser light reflected off of all three pins. But don't spend a lot of time looking at the laser light with your remaining good eye after you have already ruined your bad eye .... **in other words, avoid looking directly at the laser light**! What is really important for the optical alignment is that the laser light pass right over the center of the protractor.

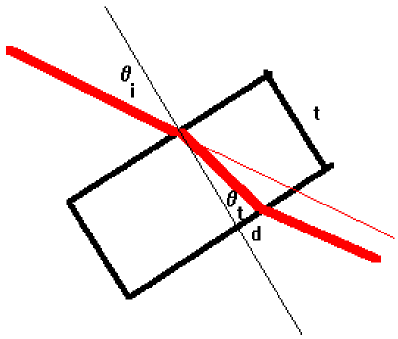
Now, take a thick glass slab and place it so that the laser light is initially normally incident (remember this term from class?) What should (but won't) happen is that the laser light will be reflected back into the laser. What you will need to do is to adjust your glass slab until this is the case. **It is necessary that your glass slab is situated so that the front surface of the slab is over the pin that holds the protractor to the cork board** ... (why? because when you rotate the slab, you want the position that the laser light strikes at to remain as close to stationary as possible in the translational sense). You might want to use a small piece of double sided tape here to hold the glass slab on the glass stage.

Now if you have everything constructed correctly, it is time to verify the law of reflection. Here is how to do this: rotate your protractor about 10. Notice that the angle measurement is subtracted from 90 degrees (for example, 90-80=10) to give the angle of incidence. The spreadsheet will automatically do this subtraction for you, provided you align your protractor initially at the 90 degree mark. Take a pin and move it around the protractor until the reflected laser light strikes the pin. You will probably notice that two dots are actually seen, but one is dimmer than the other. This is because the light from the glass slab is reflected off of both the front surface and also the back surface. The fact that the light is refracted in the glass provides a displacement between the two dots but this does not provide an acceptable method for measurement of the index of refraction for the glass. I'll show you how that is done later.

In any event, you should observe that the angle of reflection is about at the 70 degree mark which means that the real angle of reflection is 10 degrees and the angle of incidence is also 10 degrees. I want for you to make measurements on the angle of reflection vs. the angle of incidence for angles ranging from 10 to 100 degrees for every 10 degrees minimum. In your analysis, you should plot a graph with angle of incidence on the x-axis and angle of reflection on the y-axis. By fitting a linear fit to your data, you should obtain (theoretically) a slope of 1. You should compare your measured slope with the theoretical slope by using the % error.

Part II: Measurement of the index of refraction

You are now going to measure the index of refraction for at least two glass slabs in a nice straight-forward manner. You will want to make about 5 measurements of each of the two glass slabs that I have provided since I had problems with reproducibility in this part of the lab. Also, if the results of your work produce an index of refraction which is less than one, then you know 100% for sure that you're wrong and you need to be a bit more careful.



You will want to refer to this figure. What you will recognize is a problem similar to one that we have had in class. Here, however, you want to find the actual displacement of the beam of light through the glass. Snell's law gives us the angle of transmission:

$$n_1 \sin(\theta_i) = n_2 \sin(\theta_t) \Rightarrow \sin(\theta_t) = \frac{n_1}{n_2}\sin(\theta_i) = \frac{\sin(\theta_i)}{n} \Rightarrow n = \frac{\sin(\theta_i)}{\sin(\theta_t)}$$

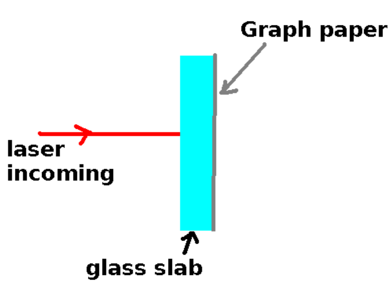
By trigonometry, however, we have:

$$\tan(\theta_t) = \frac{d}{t}$$

So

$$n = \frac{\sin(\theta_i)}{\sin(\theta_t)} = \frac{\sin(\theta_i)}{\sin\left(\tan^{-1}\left(\frac{d}{t}\right)\right)}$$

where n is the index of refraction. You should be able to obtain the index of refraction by measurements of θ_i , d and t. The procedure is this: cut a piece of millimeter graph paper and clamp it to the back of a slab of glass which you have measured the thickness (t) of in mm (the lines should not be against the glass). Align the laser beam so that the light initially travels through the glass (normal incidence) and produces a spot of light on the paper. The front of your glass slab should be over the protractor pin at this point. Now rotate the protractor and you will notice that the spot moves by a small distance. Rotate the glass slab until the dot moves from the initial small division line to the next small division line. This is your measurement of the deviation (d) in mm. You will want to repeat this measurement about 5 times to get an average index of refraction. Now repeat this for the sides of the triangular shaped glass slab in order to obtain the index of refraction for this material.



Part III: The Brewster Angle

The Brewster Angle is one of my favorite quantities in physics. There is a tremendous amount of physics contained in a very simple measurement. As part of your lab today, you will make measurements of the Brewster Angle.

One of the properties of the Brewster Angle is that light which reflects off of a surface which is incident at the Brewster Angle **will be completely polarized**. It follows that if you remove the component of polarization which would be reflected, then what will happen is that if you will shine light on a surface no reflection will occur. You might think about invisibility here and you would be correct to do so. The other property of the Brewster Angle is that light which is refracted at the Brewster Angle has an angle of 90^0 between the reflected ray and the refracted ray. This property turns out to be significantly harder to measure than the first property. Thus, we won't be verifying the 90 degree angle today. In connecting these two properties, we find that the index of refraction is given then in a very simple manner:

$$n=\tan(\theta_B)$$

I would like you to repeat this measurement about 5 times (on the same piece of glass) to get a good set of values that can be averaged. The spreadsheet will also calculate the standard deviation of the results for you. Additionally, if you wish, you can repeat these measurements for the triangular piece of glass provided.

Optical Alignment Procedure for obtaining Brewster's Angle measurements

In order to set up your system, you will need to use a polarizer which is mounted on a holder. Set up your cork board as in a previous lab. You will use the laser to optically align your system. The steps are these: (a) pin your protractor to the central end of your board (I have already done this for you). Leave enough room so that the protractor can rotate through 360 degrees without hindrance. (b) rotate your protractor so that the 90^0 line points toward the laser. Place a pin directly in front of this mark. (c) Change the position of your board until the laser is shining on the dissecting pin in front of the 90 degree mark. (d) place a pin directly behind the protractor 90 degree mark (outside the interior of the protractor) and far enough away so that the protractor can rotate. (e) change the system position until the laser light is striking both pins. At this point, you have the laser light correctly aligned. (f) Place the large glass slab on the protractor edge with the center over the pin holding the protractor to the cork board. (g) Rotate the glass slab until the laser light is reflected back onto the center opening of the laser, or as near the center opening as possible. (h) Place the polarizer on the cork next to the laser edge of the board. Reorient the polarizer until the laser light is reflected back onto the center opening of the laser.

You should now have good optical alignment of your system. Do not move your laser. Now, move in your white light source and place it next to the polarizer so the light is shining through the polarizer. You can place your large fender washers between the polarizer and glass slab to concentrate the light beam. Slowly and gently rotate the glass slab ***and*** the polarizer until you reach an angle where the reflected light (from the front surface) is extinguished. This is Brewster's angle. Place a pin at the 90 degree mark on the protractor to mark the normal angle. The angle between 90 degrees and the first pin you placed is the angle of incidence which is Brewster's angle. It is best at this point to gently remove your white light source and realign your polarizer with the laser light. Then replace your light and make fine adjustments to the protractor and the polarizer until the light is most completely extinguished. Record your value for Brewster's angle.

You can now find your index of refraction. Do this for a total of 2 different glass slabs (these slabs are all supposed to be made of the same material).

Part IV: Observation of the critical angle and the minimum angle of deviation

As the final part of this lab, you should make observations of the critical angle for total internal reflection for your prism, and you should also observe that at one angle, the beam which is deviated through the prism is at a minimum. You can do this by placing your prism on the protractor with a flat side facing the laser beam. Rotate your prism until you can clearly see the beam which passes through the prism. Now if you rotate the prism so that the internal angle of incidence is large, you will eventually reach one angle where the beam is seen to completely extinguish. This is related by geometry to the critical angle. You can also rotate the prism in the opposite direction and notice that at one orientation, the beam passing through the prism is at a minimum deviation. This is called the angle of minimum deviation. As you can imagine, both of these angles are related to the index of refraction. In this lab, however, I only want you to observe these phenomena. Ultimately I will, however, demonstrate this for you. It is useful to know what the minimum angle of deviation is because in older spectroscopic literature, you will occasionally see this mentioned when the literature talks about experimental procedures. In more modern times, spectroscopy is more easily accomplished with diffraction gratings.

You should ask me to demonstrate the minimum angle of deviation.

The analysis of the critical angle should allow a measurement of the index of refraction also. The analysis is this: for light emerging from a medium 1 towards air, the critical angle for total internal reflection is given by:

$$\sin(\theta_c) = \frac{1}{n} \quad .$$

If you measure the critical angle it is relatively easy to invert this to obtain the index of refraction.

Sample calculations

(1) Choose a (physically valid) index of refraction. Calculate the angle at which the transmitted ray will be at right angles to the reflected ray.

(2) Choose a focal length for a concave mirror. Choose a real object position. Characterize the resulting image giving the image position and the magnification.

(3) Choose a focal length for convex mirror. Choose a real object position. Characterize the resulting image giving the image position and the magnification.