Optical Bench

Refraction, Critical Angle, Total Internal Reflection, and Chromatic Aberration

Isn’t that a mouthful! Sounds pretty tough, doesn’t it? Don’t worry, that’s just a fancy way of saying that we’re going to examine what happens when light passes from one transparent material to another, such as from glass to air.

Equipment:
- Optics bench
- Light source
- Slit Plate
- Slit Mask
- Cylindrical Lens
- Ray Table
- Ray table base
- Viewing Screen
- Component Holder
- Ray Table Component Holder

Cautions:
Handle lenses and mirrors by the edges only. It’s a lot easier to keep these clean than it is to clean them!

First, you’re going to do a basic setup. Remember, the more careful your setup, the better your data!

Procedure to set up the optics bench (usually done by teacher):
1. Place the optics bench in the middle of the lab table, with the 0cm mark to your left. Don’t put the bench too close to the edge of the table!
2. Place the light source on the left end of the bench with the light opening pointing to the right. Align the end of the light source with the end of the bench.
3. Set the ray table base on the right end of the bench, slanted toward the light source.
4. Place the ray table on the ray table base. The round protrusion fits into the hole in the table. Make sure that the “Degree Scale” side is up, not the “mm Scale” side. The ray table provides a convenient way to see and measure rays of light.
5. On one of the component holders (flat bottom) place the slit mask on one side and the slit plate on the other. Align them so that the slits are vertical and so that only one slit is open. We only want one ray of light, so all the other slits are blocked by the slit mask.
6. Place the assembled component holder on the optics bench at the 25cm mark. Point the “foot” of the holder toward the light source. You want the holder close to the light for maximum intensity, but far enough away to create a sharp ray.
7. Move the ray table base as close to the component holder as possible.
8. Plug the line cord into the transformer, and the transformer into the light source.
9. Make sure that the light source is turned off. (rocker switch flipped toward “O”)
10. Plug the line cord into an outlet.
11. Turn the light source on.
12. You should see a single ray across the ray table. If you don’t, figure out what isn’t right.
13. Use the knob on top of the light source to align the ray with the center hole of the ray table.
14. On the ray table, you will see a line labeled “NORMAL”. Align this line with the ray. You can readjust the knob on the light source to get the alignment *just* right.

Your first investigation will be the determination of the index of refraction of the material in the plastic of the cylindrical lens. The cylindrical lens is great for this task because a single
ray (aimed at the center point) entering or leaving the curved side is always normal to the lens and therefore won’t be refracted. That way, you only have to worry about a single refraction, the one on the flat side.

Procedure to determine the index of refraction:
1. Make sure that the beam is still aligned with the normal line
2. Place (touching it only on its edges) the cylindrical lens on the ray table. Align the flat side of the lens with the line marked “COMPONENT”. The round side of the lens points away from the light source.
3. Make sure that the ray still points along the NORMAL line. You may have to move the lens back and forth along the “COMPONENT” line to get it aligned.

At this point, you must be very careful not to disturb the position of the lens on the ray table. If it is disturbed, you have to go back to this step and start over!

4. Rotate the ray table about its center pivot until the incoming ray is on the 10° mark, measured from the zero point on the side of the ray table toward the light source. This gives an angle of incidence of 10°. You may turn the ray table either direction.
5. Read the angle of the outgoing ray. Read this angle from the zero point on the side of the ray table opposite the light source. This gives the angle of refraction. Hint: The angle of refraction will be about 7°.

6. Use the data to fill in the following table:

<table>
<thead>
<tr>
<th>Angle of Incidence(θ₁)</th>
<th>Angle of Refraction(θ₂)</th>
<th>Calculated index of refraction(n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40°</td>
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<tr>
<td>50°</td>
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<tr>
<td>60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7. Using the same technique, collect data for 20° to 80° and fill in the appropriate spaces in the table.

Snell’s Law states that: \( n_1 \sin \theta_1 = n_2 \sin \theta_2 \)
\( n_1 \) is the index of refraction of air, which is very close to 1.0.
We can rearrange the formula to: \( n_2 = \frac{\sin \theta_1}{\sin \theta_2} \)

8. Using your calculator and the above formula, determine the index of refraction for each angle measured. Place your answers in the table.
9. Answer the following questions:

Did the index of refraction vary with the angle? If so, what do you think caused this variance.

Do you think that the index values determined for large angles of incidence are more or less accurate than those for small angles? Why?

The index of refraction is defined as the ratio between the speed of light in a vacuum and the speed of light in a particular substance. Stated in a formula, it is

\[ n = \frac{c}{v} \]

Where \( n \) is the index of refraction, \( c \) is the speed of light (300,000,000 m/s) and \( v \) is the speed of light in the substance in question.

Rearranging this formula to solve for velocity, we get:

\[ v = \frac{c}{n} \]

Determine the speed of light in the plastic. Show your work here:
Now that you’ve determined the index of refraction, now you’re going to determine the critical angle. This is the angle at which light no longer passes through the surface separating two transparent materials, but instead is reflected back from the surface. This reflection at large incident angles is called “Total Internal Reflection” because that sounds really impressive. You will use exactly the same setup as the previous experiment, except that the cylindrical lens will reversed. You can only get Total Internal Reflection when the beam passes from a material in which the light is slower (plastic) to one in which it is faster (air)

**Procedure to determine the critical angle:**

*Note: if you have just completed the index of refraction exercise and you haven’t disturbed your setup, you may simply rotate the ray table so the curved side of the lens points toward the light source and the incoming ray is on the NORMAL line. You may then skip to step 4*

1. Reset the ray table so that the ray is aligned with the NORMAL line. *If it’s out of alignment, use the knob on the light source to line it back up.*
2. Place the cylindrical lens on the ray table. Align the flat side of the lens with the line marked “COMPONENT”. The round side of the lens points toward the light source. *This is the opposite direction of the previous exercise.*
3. Make sure that the ray still points along the NORMAL line. You may have to move the lens back and forth along the “COMPONENT” line to get it aligned.

   At this point, you must be very careful not to disturb the position of the lens on the ray table. If it is disturbed, you have to go back to this step and start over!

4. Slowly rotate the ray table clockwise while observing the refracted (outgoing) ray. Note that the ray rotates in the opposite direction compared to that of the ray table! In the space below, explain why this occurs.

5. Continue rotating the ray table until the refracted ray becomes parallel to the flat face of the lens. You can rotate the ray table back and forth to find the exact position where this occurs. Read the angle of incidence under the incoming ray. This angle is called the “critical angle”. Write the angle here:
6. The critical angle may be found mathematically using the formula:

\[ \sin \theta_c = \frac{1}{n} \]

Where \( \theta_c \) is the critical angle and \( n \) is the index of refraction of the material.

Using the index of refraction determined in the previous activity, calculate the critical angle. Show your work here. Does this angle agree with the angle determined experimentally?

7. Continue turning the ray table. Note that the refracted ray disappears and is replaced by a strong reflected ray. Beyond this point, total internal reflection occurs. Note that the ray now rotates in the same direction as the ray table’s rotation. Why?

Next, you will investigate the phenomenon of Chromatic Aberration. This is a fancy word for light of different colors bending different amounts. You will use the same setup as you used to determine the critical angle, with a viewing screen added.

**Procedure to observe Chromatic Aberration:**

1. Attach the viewing screen to the ray table component holder (the one with two “hooks” on the bottom to attach to the ray table disc). It should face in the same direction as the “foot”.
2. Rotate the ray table until a refracted ray is visible.
3. Place the ray table component holder on the edge of the ray table so that the refracted ray strikes the viewing screen.
4. Rotate the ray table to a point just before the critical angle is reached. You may have to reposition the screen to keep the ray’s image on it. When you get close to the critical angle, the ray will spread out. Stop at that point! You should see a “rainbow” effect. This effect is called “Chromatic Aberration”
5. Answer the following questions:

Are all frequencies of light refracted at the same angle?

Which color is bent most?

Which color is bent least?

Why would this chromatic aberration concern a camera designer?