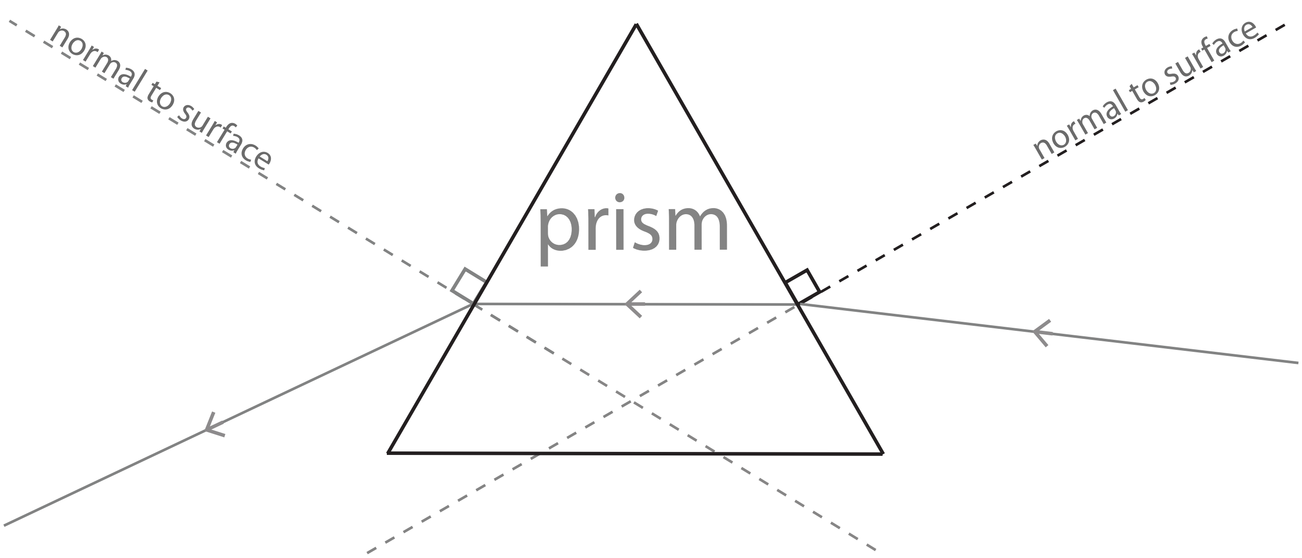
Laboratory 3 Pre-Lab (value: *2 marks*)

Submit to your lab instructor ***by 4pm the day BEFORE*** your scheduled lab period.

1. Refering to Equation 1 in the Theory section, how would the *spacing* y_m between *bright fringes change* if the other variables in the equation were held constant but (a) *incident wavelength* λ was *increased* (b) *slit-to-screen spacing* L was *increased* (c) *slit separation* d was *increased*?

2. What is *specular reflection*? How do light rays behave during this kind of reflection?

3. The figure below shows the path (marked with arrows) a ray takes as it passes into and then out of a *prism*. *Identify and label* the *angle of incidence* & *angle of refraction* at BOTH the *air-prism* AND *prism-air* interfaces; *use a protractor to measure all of the angles to the nearest degree*, recording your values on the diagram next to your labels.



Laboratory 3: Wave and Geometric Optics

Experiments are to be completed on the provided laboratory sheets below; any supporting material (eg. graphs) should be attached. Make sure your name and your partners name(s) are clearly indicated on the front page of your lab. **Neatness and clarity count!** Explain your answers clearly and concisely. If an equation is to be used in a calculation, *write the equation down* and then insert numbers and solve. Report your final answer to the appropriate significant figures.

The lab write-up is due by the end of the lab. Late labs will not be accepted.

APPARATUS

White light ray box w/ slotted screen, 500g mass (used as a *paperweight*), small rectangular mirror w/ stand, prism, laser refraction tank, red & green lasers with holders, power supply and C clamp, CAL multi-pattern diffraction grating, spring-loaded lens holder and desk clamp.

OBJECTIVE

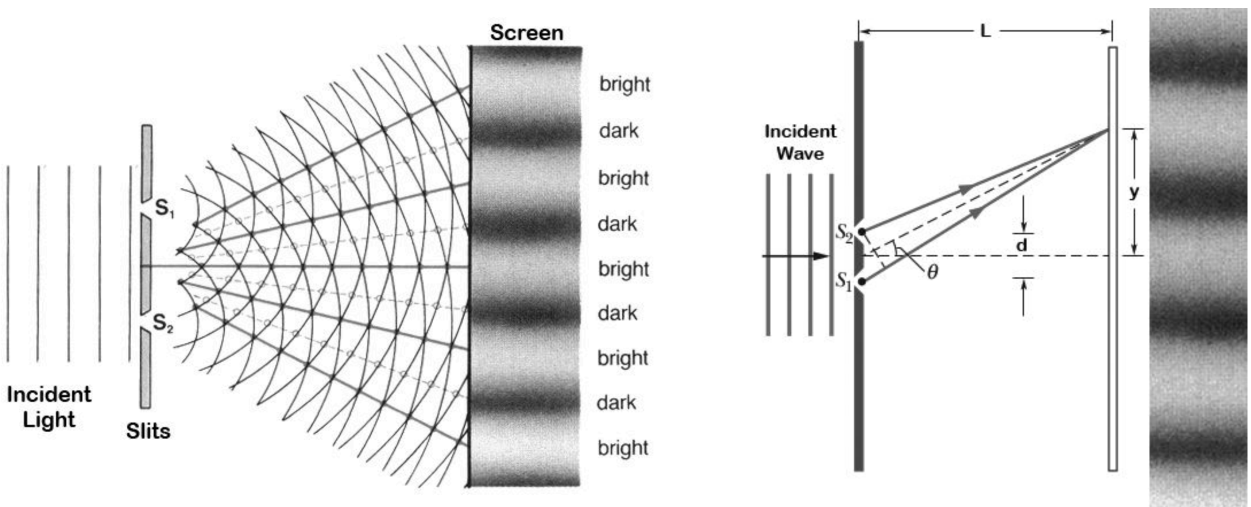
1. To qualitatively confirm interference pattern dependence on wavelength & slit separation.
2. To investigate specular reflection using a mirror.
3. To investigate refraction and confirm Snell's Law using a prism.
4. To investigate refraction & total internal reflection using a laser refraction tank.
5. To determine the refractive index of different materials.

THEORY

Diffraction and interference of light

Diffraction is the *spreading out or bending of light waves as they pass through (narrow) openings or around the edges of obstacles.* If a *well-collimated monochromatic source of light*, e.g. a LASER, is incident on *fine, closely spaced parallel slits* cut into an opaque surface, *diffraction of the incident light* causes *each* slit to act as a new, independent *light source.* The resulting light waves propagate and interact beyond the slits, striking a (distant) screen to create *a series of alternating light and dark bands* (or ***fringes***) known collectively as an ***interference pattern***.

An example is shown in Figure 1(a). Light is incident from the left onto (two) slits; diffraction of light due to the thin slits creates two new and independent point sources of light which propagate toward a screen on the far right. The light waves from these new sources are indicated by curved wavefronts which represent the ***peaks*** of the propagating light waves; halfway between the peaks are the low points or ***troughs***. ***Where wavefronts (peaks) from the two sources meet they add together yielding a more intense (brighter) signal***; the paths from the slits to the screen along which these brighter signals occur are denoted by the solid straight lines and ***result in bright fringes*** on the screen. ***Where a wavefront (peak) from one source meets a trough from the other source the signals cancel out***; the paths from the slits to the screen along which this occurs are denoted by the dashed straight lines and ***result in dark fringes*** on the screen.



(a) The *interference pattern* resulting from a laser beam incident on two slits.

(b) Geometry to locate the *bright fringes* in the *interference pattern* for two slits.

Figure 1: Details of the *interference pattern* arising from two slits.

From the geometry in Figure 1(b) the *position y_m of the bright fringes* for small angles θ is

$$y_m = \pm\frac{m\lambda L}{d} \qquad m = 1, 2, 3 \ldots \tag{1}$$

where λ is the *wavelength of the incident light*, d is the *slit spacing*, L is the *distance from the slits to the screen*, and m are integers representing the fringe number (or *order*) on either side of the (zero-order) *central fringe*. Since m are integers and L is typically chosen, the ***fringe spacing*** y_m is *proportional to the wavelength of light* used and *inversely proportional to the slit spacing.*

Reflection of light rays from a surface

Light rays striking the *surface of a material* may be ***reflected*** in a predictable manner or they may be *scattered* unpredictably, depending on the nature of the material and the type of surface. *Smooth, mirror-like surfaces* result in the predictable (or *specular*) reflection of the incident light such that ***the angle of incidence equals the angle of reflection***, where these angles are measured relative to the direction ***normal*** (or perpendicular) *to the surface* as shown in Figure 2.

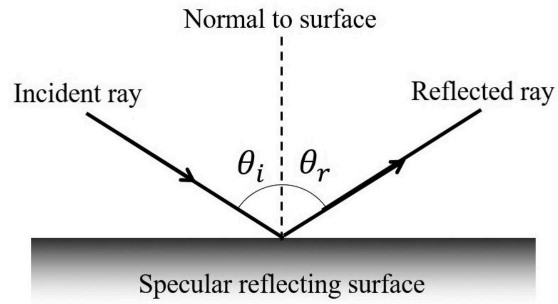


Figure 2: Reflection from a specular surface.

Refraction of light rays crossing a boundary between two materials

Light rays crossing the boundary between two transparent materials will *change direction* or ***refract*** if the speed of light within the materials is *different.* Light travelling from a material in which it has a *higher speed* (such as *air*) into a material in which it has a *lower speed* (such as *glass*) will result in ***refraction toward the normal*** *(perpendicular) to the boundary* as in Figure 3(a); conversely, light travelling from from a material in which it has a *lower speed* into a material in which it has a *higher speed* will result in ***refraction away from the normal***, as in Figure 3(b).

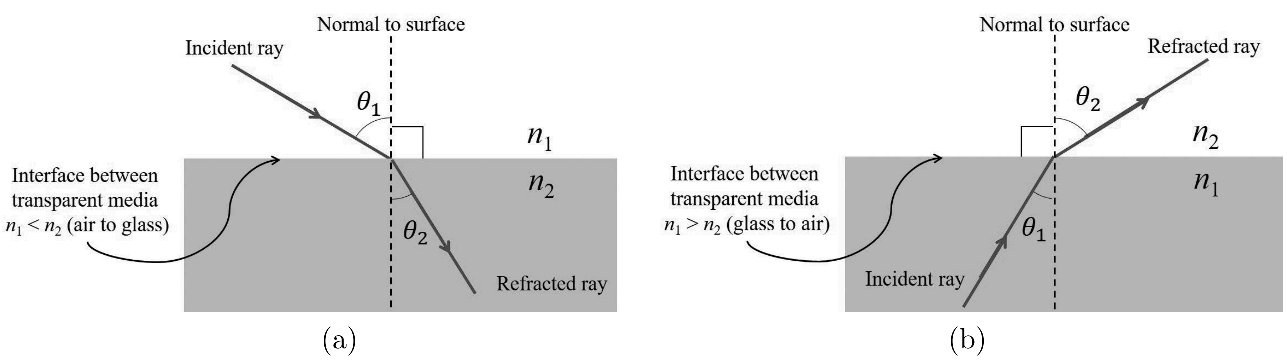


Figure 3: Refraction of light traveling from (a) *air-to-glass* ($\theta_2 < \theta_1$) (b) *glass-to-air* ($\theta_2 > \theta_1$).

The amount of *refraction* the light experiences depends on the *angle at which the light is incident upon the boundary* and the ***index of refraction*** of each of the materials. The relationship relating these quantities is known as ***Snell's Law***, given by

$$n_1 \sin\theta_1 \quad = \quad n_2 \sin\theta_2 \tag{2}$$

where n_1 & n_2 are the ***indices of refraction*** of the *incident* and *refracted* materials and θ_1 & θ_2 are the ***angles relative to the normal*** for the *incident* and *refracted* rays, respectively.

Total internal reflection (TIR) and the critical angle

When light travels from a material with a *higher refractive index* to a material with a *lower refractive index* the ***light is refracted away from the normal***, such as when moving from *glass to air* as in Figure 3(b). In such circumstances, if the *angle of incidence* θ_1 is ***increased*** it will eventually reach a value known as the ***critical angle*** θ_c where the *resulting angle of refraction* θ_2 *is equal to 90°*, as illustrated in Figure 4(a). *Angles of incidence* greater than the ***critical angle*** θ_c result in ***total internal reflection (TIR)***, where all of the incident light is *reflected back into the incident material*; an example of this is shown in Figure 4(b).

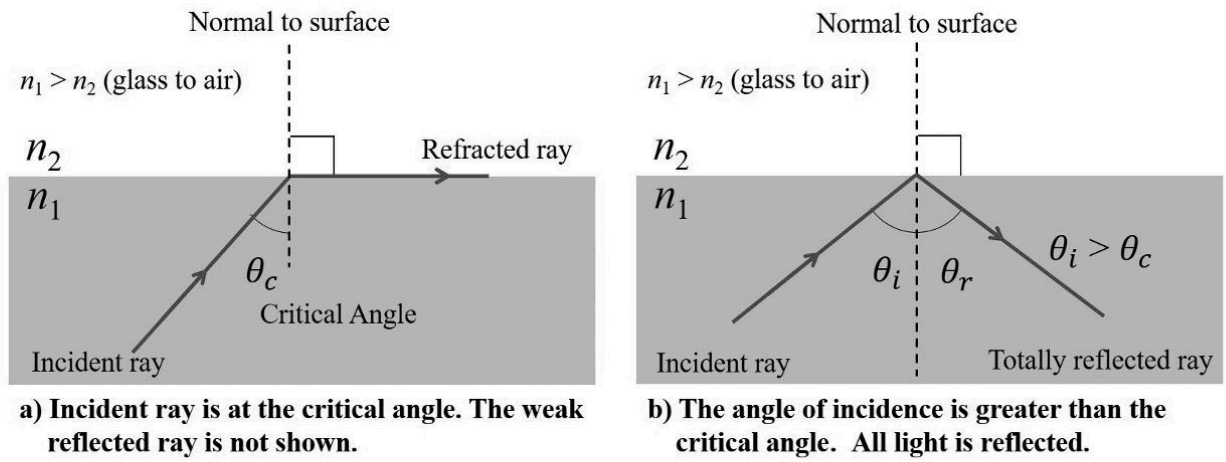


Figure 4: The *critical angle* θ_c and *total internal reflection (TIR).*

Laboratory 3: Wave and Geometric Optics

Part A: Diffraction and interference of light using red & green lasers

1. Obtain two small pieces of blank rectangular paper each. Laser stations are setup at the ends of the lab benches in *pairs*, with one RED and one GREEN laser. **Using *either*, power on the laser and adjust the beam horizontally & vertically so that it passes through the CAL *diffraction plate* and strikes the target board**. With the CAL logo *top right and facing toward the laser*, aim for the center of a pair of slits located in the *rightmost column, 2nd from the top*.

Adjust the beam position to get as sharp & bright an interference pattern as possible. Tape one of your blank papers to the target board so that *the interference pattern falls on the paper's upper half* and with a sharp pencil **trace the outline of FIVE (5) sequential bright fringes centered on the BRIGHTEST one** (i.e. two fringes to either side of the brightest). **Reposition the beam** to pass through the slits in the *rightmost column, 3rd from the top* & repeat the above *on the paper's lower half*. **LABEL the paper with the laser colour & slit positions.** Using the *other* laser **REPEAT the entire process on your second piece of blank paper.**

Each partner does their OWN *interference fringe tracings*; tape yours below. [***1 mark***]

(a) Bright fringes for **GREEN** laser

(b) Bright fringes for **RED** laser

2. [***2 marks***] For BOTH lasers, **comment on the change in *fringe spacing*** when *moving from the second pair of vertical slits to the third pair of vertical slits*, i.e. increasing *slit spacing* d. **Are your results consistent with the theoretical prediction**, e.g. Equation 1? **Discuss briefly**.

Laser colour	average fringe spacing (mm) (2nd from top slits)	average fringe spacing (mm) (3rd from top slits)
GREEN		
RED		

Table 1: *Average* measured spacing of *bright interference fringes*.

3. [***2 marks***] Make a *vertical* pencil mark through the *center* of the leftmost AND rightmost bright fringes of each of your *interference fringe tracings* (e.g. for ALL four cases). **Measure the distance *in millimeters (mm)* with a ruler between these marks and divide this by *four* to yield the *average center-to-center bright fringe spacing* for EACH pattern. Record these values in Table 1 showing ONE full sample measurement/calculation below.**

From your results in Table 1, **comment on the change in *fringe spacing*** when *moving FROM the green laser TO the red laser* for a given slit, i.e. increasing *wavelength* λ. **Are your results consistent with the theoretical prediction**, e.g. Equation 1? **Discuss briefly**.

Part B: Reflection of light using a mirror

1. **Fold your lab manual** so that this single page lies as flat as possible on the bench; you may use the 500g mass to help keep it flat/in place. **Align the small rectangular mirror with the line marked *'mirror'*** in the space provided in Figure 6, with the reflective side facing toward the dashed line marked *'normal to surface'*. **Plug in the white light ray box** and *add the single-slot screen to the front to create a single, well collimated light ray.* Position the light box a few inches away from the mirror such that the light ray is incident on the mirror & strikes it where the dashed *'normal to surface'* line meets the mirror. **Orient the white light ray box** such that the *angle of incidence* is *roughly* 30° and the *reflection is centered* about the *normal to surface* (you may need to adjust the distance of the ray box from the mirror to ensure that BOTH the *incident* and *reflected* rays are *clearly* visible). Your setup should look similar to what is shown in Figure 5.

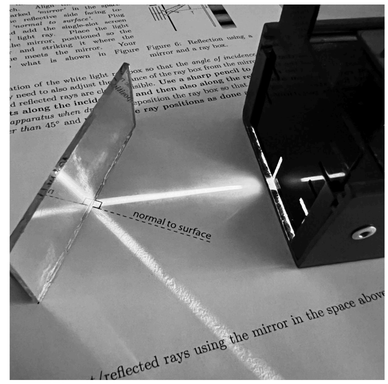


Figure 5: Reflection from a mirror.

2. [*2 marks*] **Use a sharp pencil to draw two small, widely spaced dots centered along both the incident & reflected rays**. *Do NOT move the mirror!* **Reposition the ray box** so the *angle of incidence* is *roughly* 60° and **mark the ray positions as above**.

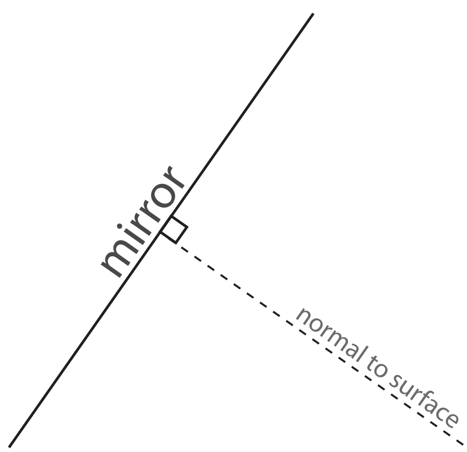


Figure 6: Draw labeled incident/reflected rays using the mirror in the space above.

Unplug the light box after both partners finish, leaving the single slit in place for use in Part C.

Remove the mirror and **use a ruler to connect the dots to form the incident and reflected rays, adding arrows to indicate the direction of the light and labeling the incident and reflected angles for each case**, resulting in something similar to what is shown in Figure 2.

3. [***2 marks***] **Measure the *angle of incidence* θ_i & *angle of reflection* θ_r relative to the *normal to the mirror surface* for each case and enter your values in Table 2**. **Compare** θ_i to its corresponding θ_r for each case **using *percent difference* and comment** on whether your results are consistent with the predicted behaviour for *specular reflection.* **Show a full sample calculation** for ONE of the cases in the space below the table.

Trial	θ_i (degrees)	θ_r (degrees)	% difference
1			
2			

Table 2: Data and θ_i vs θ_r comparison for reflection from a mirror [***2 marks***].

Part C: Refraction of light using a prism

1. Fold your lab manual so that this single page lies as flat as possible on the bench. Place one point of the prism at the apex ('V') of the outline marked 'prism' in Figure 7 below. Maintaining the alignment of the tip of the prism and the 'V', adjust the prism to best align the sides with the provided outline. Plug the ray box back in and position it so that the ray is incident on the prism such that it strikes the prism *centered* on where the dashed 'normal to surface' line meets the prism.

2. Adjust the orientation of the white light ray box so that the *incident ray* is *BELOW* and makes a *roughly* 45° with the dashed *'normal to surface'* line. **Use a sharp pencil to draw two small, widely spaced dots centered along the ray incident on the prism and also along the ray exiting the opposite side of the prism**. *Take care not to shift the apparatus when drawing!* **Unplug the light box** after both partners are finished marking the ray positions.

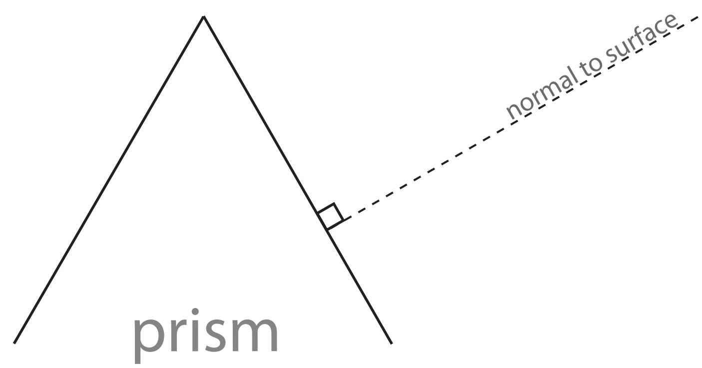


Figure 7: Draw labelled refracted rays using the prism in space above.

3. [***2 marks***] Remove the prism and **use a ruler to carefully connect the dots to form the incoming and outgoing rays, adding arrows to indicate the direction of the rays.** Make sure to extend the ray lines out to the page margins. **Extend the provided 'normal to surface' dashed line all the way through the prism and then, using a protractor and ruler, create the corresponding 'normal to surface' line passing through the point where the exiting ray leaves the prism on the opposite face.** Using a ruler, **complete the path of the ray through the prism by connecting the points where the ray enters and leaves the prism. Finally, label the incident and refracted angles on the diagram**, using θ_1 & θ_2 when entering the prism and θ_3 & θ_4 when exiting the prism. The result should look similar to Figure 8.

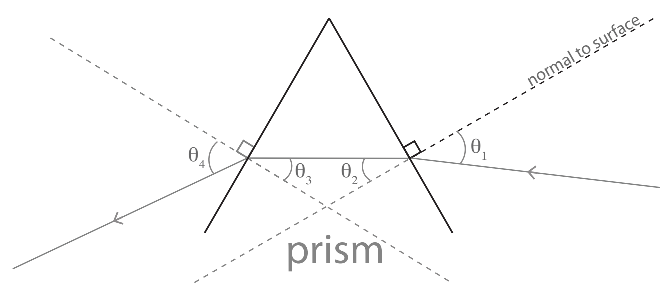


Figure 8: Sample prism diagram.

	θ_i (degrees)	θ_r (degrees)	index of refraction, n_{prism}
entering prism			
exiting prism			

Table 3: Data and *index of refraction* for the *prism* [***2 marks***].

4. [***4 marks***] **Measure the *angle of incidence* θ_i & *angle of refraction* θ_r relative to the *normal to the bounday* when entering & when exiting the prism and record your values in Table 3**. *Be careful identifying which angle is which as the light enters and exits the prism!* **Use Snell's Law to calculate the *index of refraction* of the prism,** n_{prism}, for BOTH cases, i.e. from when the ray enters the prism AND from when it exits. Assume the *index of refraction for air* is $n = 1.000$. **Show a full sample calculation** for ONE of the cases in the space below but **enter both of your calculated values of n_{prism} into Table 3**. ***NOTE:** retain & record an 'extra' digit for n_{prism} but clearly underline the least significant digit!*

Calculate the *average* index of refraction of the prism from your unrounded values and ***compare* to the expected value $n = 1.495$ using *percent deviation.* Comment.**

Part D: Refraction & total internal reflection using a laser refraction tank

1. Place the *refraction tank* on the lab bench; if not already done, *add water as precisely as possible until the air-water interface is even with the midpoint line of the tank*, as shown in Figure 9.

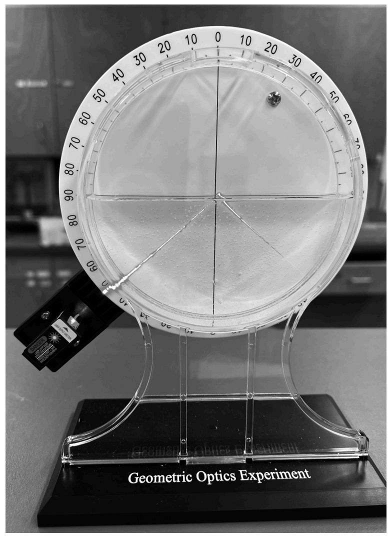


Figure 9: *Refraction tank* with laser; the bottom half is filled with water.

2. *Turn on the laser*; the laser housing may be pushed to rotate the laser to allow for different incidence angles at the interface. *Orient the laser so that it is in the* ***upper-left quadrant*** *and the ray travels in air to the interface.* **Set the *angles of incidence* θ_i** as specified for **Trials 1-3** in Table 4 and **estimate the resulting *angles of refraction* θ_r to the nearest degree**; the width of the laser beam is $\sim 1°$. *Reposition* the laser to the ***lower-left quadrant*** **so the ray travels in water to the interface** & repeat for the values specified for **Trials 4-5**. *Turn off the laser.*

Air-to-water			
Trial	θ_i (degrees)	θ_r (degrees)	n_{water}
1	20.°		
2	45°		
3	60.°		
Water-to-air			
4	30.°		
5	40.°		

Table 4: Measuring θ_r & determining the *index of refraction* n_{water} [***2 marks***].

3. [*2 marks*] **Use Snell's Law to calculate the *index of refraction for water*** (n_{water}) **for EACH of the Trials 1-5.** Assume that the *index of refraction for air is* $n_{air} = 1.000$ and **make sure to match** the *correct* n with the *correct* θ when determining n_{water} using *Snell's Law*; refering to Figure 3 may be helpful. **Show full sample calculations for Trial 1** AND **Trial 5 in the space below** but **enter all your calculated values for** n_{water} **into Table 4**. ***NOTE:** retain & record an 'extra' digit for* n_{water} *but clearly underline the least significant digit!*

4. [*2 marks*] **Calculate the *average index of refraction of water*** using your unrounded values from Trials 1-5 and ***compare* to the expected value** $n_{water} = 1.333$ **using *percent deviation.*** **Show all work. Comment on your result.**

5. [***2 marks***] With the laser starting in the position used for Trial 5, **increase the *angle of incidence* θ_i until the *refracted beam ends up exactly parallel with the surface of the water*** and record the value of θ_i (*to the nearest degree*): ________°

Hint: increase the angle of incidence θ_i one degree at a time until the refracted beam has JUST 'vanished'; it may help to gently tap the refraction tank to slosh the water a little to see how close the beam is to being parallel to the surface of the water.

This angle is known as the ***critical angle*** (θ_c). **Calculate the theoretical value of θ_c using *Snell's Law*** with $\theta_r = 90°$, $n_{air} = 1.000$ and your *average* value for n_{water}. **Compare this calculated result to your measured value for θ_c using *percent difference* and comment.**

6. [***1 mark***] **What is it *called* when $\theta_i > \theta_c$? What happens in this case?** (*see Figure 4*)