Outline of a Lab Report

Your name

Your partner’s name

Title of the experiment

Introduction

Briefly (in a short paragraph) explain why we are doing this experiment and what we are supposed to learn from it. Also provide a short description of the experimental setup; a graphical sketch might also help to outline the basic idea behind the experiment.

A journal and the data

Write down what you did in the lab, if you encountered any difficulties, etc.; you must also have your data (the results of your experimental measurements) here. Note: the idea is not to recount the procedure but to point out things that came up during the experiment.

Calculations and data manipulation

Here you use your data to determine the quantities of interest leading to your final results. You need to show every detail of your calculations. If asked to compare your experimental results with theoretical expectations or “world averages”, you will have to calculate the percentage of error in your results; and, most importantly, to explain the dominant sources of error (see next page). Note: simply saying “human error” or “equipment error” is not sufficient; you need to comment in detail about all the experimental and theoretical factors that could have affected your results.

Conclusions

Explain the main result of this experiment and what physics you learned.
“Errors”: limitations on the accuracy of measurements

Measurement “errors”, or accuracy limitations, may arise from various sources. For example,

- accuracy of the measurement device: if you measure the diameter of a CD with a ruler with minor tics of 1 mm apart then you can not determine the radius with a precision much better than ±1 mm (think about it); you would quote your result in the form \( d = 12 \text{ cm} \pm 1 \text{ mm} \).

- systematic errors, i.e. limitations due to the setup or measurement procedure: say you would like to actually determine the surface area of the CD but you only have a ruler; you need to actually measure the radius or diameter and then assume that the CD is a circle so that you can use the relation \( A = \pi R^2 \). Since your CD will not truly be a perfect circle, by using this relation you are going to introduce an error.

- measurement errors due to external influences: if the temperature in your lab is higher in summer than in winter, the CD will have a slightly different radius in summer as compared to winter; this is because objects expand as they are heated. If you mean to provide a “universal” value of the radius which is valid both in summer and in winter you should quote a sufficiently large \( \pm \Delta R \) which covers the variation with the seasons.

- human error: read-off errors, forgotten or neglected calibration etc.; such kind of sources of error should obviously be avoided whenever possible.

In your lab report you should at least mention what you consider to be the most important source of error (or limitation on the precision of the measurement).
Measurements and Conversion of Units

Goals: the goal of this experiment is to gain experience in converting from one set of units to another.

Experimental procedure:
1) Measure the mass of a penny in grams and convert it to kg. Use the conversion factor 1 kg = 1000 g.

2) Measure the length, width and height of your textbook (or notebook) in cm. Calculate the volume of the textbook in cm$^3$ and then convert it to m$^3$ using 1 m = 100 cm.

3) Measure the diameter ($d$) of a CD in cm. Calculate the radius ($r$) of the CD ($r = \frac{d}{2})$. Calculate the area ($A$) of the CD in cm$^2$ using $A = \pi r^2$ (this is the area of a circle) where $\pi \simeq 3.1416$. Convert the area to m$^2$.

Conclusions: Discuss the possible sources of error in your results in detail. Be specific and precise; saying "human error" or "equipment error" is not enough. Think of possible errors that could be involved when you make your measurements.
Gravitational Acceleration $g$

Goals: the goal of this experiment is to measure $g$, the gravitational acceleration near the surface of the Earth and to compare it with the known value $g = 9.81 \, \text{m/s}^2$.

Experimental procedure: Cut a paper tape, about 1.5 m long. Attach the weight to one end of the tape using an alligator clip. Pass the other end of the tape underneath the black carbon paper of the spark machine and hold it steady. Turn on the sparker and release the weight. Turn off the sparker after the weight hits the floor. Make sure the tape leaves the sparker before it hits the floor. If you set the sparker frequency to 40 Hz then the time difference between two adjacent points is $1/40 \, \text{s}$. For example, let the time at $y_0$ be $t = 0 \, \text{s}$. Then the time at $y_1$ is $\frac{1}{40} \, \text{s}$, the time at $y_2$ is $\frac{2}{40} \, \text{s}$, ···, the time at $y_{14}$ is $\frac{14}{40} \, \text{s}$ and so on.

1) You should have about $10 - 15$ points (black dots) on your tape. Choose one of the first points to be the origin $y_0$; it should be a point close to the beginning of the tape but should be clearly visible with no other points too close to it.

2) Label and measure the position of all the points on the tape, starting with the origin labeled $y_0$ and the rest as $y_1$, $y_2$, ···. These are your data points. Measure the distances $y_1$, $y_2$, ··· from the origin $y_0$.

3) Calculate the average velocity $v$ at each data point using $v_1 \equiv \frac{y_2 - y_0}{\Delta t}$, $v_2 \equiv \frac{y_3 - y_1}{\Delta t}$, ···, $v_{14} \equiv \frac{y_{15} - y_{13}}{\Delta t}$ so that $v_1$ is the average velocity of the weight at the point labeled 1, $v_2$ is the average velocity of the weight at the point labeled 2, and so on. Determine the velocities for at least $7 - 8$ data points using $\Delta t = \frac{2}{40} \, \text{s}$.

4) Plot the average velocities you obtained vs. time on a graph. Velocities should be on the vertical axis and time is on the horizontal axis. Make sure to utilize the full page in order to make your figure as big as possible. Draw the best straight line through your velocity points. The best fit is the one where your drawn line comes as close to as many data points as possible.

5) Calculate the slope of the line using two points which are on the line. Note: these two points don’t have to be actual data points, they just need to be on the line. For the best accuracy choose them as far apart as possible. The slope of a line is defined as the rise over the run, in this case it is $\frac{\Delta y}{\Delta x}$. Compare the value of the slope with the known value for $g$ and find your percentage of error using

$$\left| \frac{g_{\text{measured}} - g_{\text{known}}}{g_{\text{known}}} \right| \times 100.$$  

Conclusions: Discuss what you learned about the gravitational acceleration, and the sources of error in your experimental determination of $g$. What is the meaning of the intercept (the point where the line crosses the vertical axis) ? Remember the relation between velocity and acceleration $\vec{v}_f = \vec{v}_i + \vec{a} \, t$. 
Adding vectors in 2-D, Force Table

**Goals:** the goal of this experiment is to gain experience in adding vectors (in this case, forces) in 2 dimensions and to reconstruct a vector from its components. Use $g \simeq 10 \frac{m}{s^2}$.

**Experimental procedure:** Using the provided force table, define a $x-y$ coordinate system; the $x$ coordinate should point along the $\theta_1 = 0^\circ$ angle and the $y$ coordinate along the $\theta_2 = 90^\circ$ angle. You should attach three hangers to three strings which are connected to a white loop which is centered around the pin in the middle of the force table.

1) Put a mass of $m_1 = 100$ g on the hanger along the $x$ ($\theta_1 = 0$) direction and another mass $m_2 = 100$ g on the hanger pointing along the $y$ ($\theta_2 = 90^\circ$) axis. Find out how much mass $m_3$ is needed on the third hanger, and at what angle $\theta_3$ it needs to be placed so that the white loop is centered perfectly around the pin.

2) Calculate the force of gravity acting on the three masses, i.e. their weights $|\vec{F}_1| = m_1 g$, $|\vec{F}_2| = m_2 g$, $|\vec{F}_3| = m_3 g$.

**Theory:** From the laws of vector algebra one can show that (you should be able to derive this on your own)

$$|F_{3x}| = |\vec{F}_1|, \quad |F_{3y}| = |\vec{F}_2|$$

and

$$|\vec{F}_3| = \sqrt{F_1^2 + F_2^2}, \quad \theta_3 = 180^\circ + \tan^{-1} \frac{|\vec{F}_2|}{|\vec{F}_1|}.$$  

Here, $\tan^{-1}$ denotes the inverse function of the tangent (on some calculators, this is written as “atan”); make sure that your calculator is in the mode where angles are given in degrees, not radians.

This is the prediction of theory for $\vec{F}_3$. Compare the measured values for $\theta_3$ and $|\vec{F}_3| = m_3 g$ with the values expected from theory, compute the percentage of error for both $|\vec{F}_3|$ and $\theta_3$.

4) Repeat the experiments with $m_1 = 100$ g and $m_2 = 150$ g. Keep track of which mass is attached to which string: eq. (2) for $\theta_3$ assumes that $\vec{F}_1$ and $\vec{F}_2$ point at $0^\circ$ and $90^\circ$, respectively.

**Conclusions:** In your own words, state Newton’s 2nd law and explain how it was used in this experiment. Think of all the forces acting on the white loop and draw a diagram showing these forces and the angle $\theta_3$. Discuss the sources of error in determination of $\vec{F}_3$. 

Newton’s second law

**Goals:** the goal of this experiment is to test Newton’s 2nd law and to gain experience using it.

**Experimental procedure:** Put a cart with mass $m_1$ on the track on the table and attach a light string to it. Pass the string over the pulley at the end of the track and down toward the floor. Attach a hanger to the free end of the string and hold on to the cart so that it does not move. Put a small mass $m_2$ on the hanger and make sure it is not swinging.

Release the cart but make sure **not** to give it a push. With a timer in your hand, watch the cart travel some distance $d$ and measure the time it took to cover this distance. Make sure to stop the timer before the mass on the hanger hits the floor or the cart hits the block at the end of the track. Use $a_{\text{exp}} = \frac{2d}{t^2}$ (note: for this relation to be valid, the initial velocity of the cart must be zero so make sure not to give the cart a push when you release it) and the measured values of distance $d$ and time $t$ to find the acceleration of the cart as it moves on the track and then find the net force acting on the cart using $F_{\text{net}}^{\text{cart}} = m_1 a_{\text{exp}}$.

**Theory:** According to Newton’s 2nd law the acceleration of the cart is (you should know how to derive this on your own)

$$a = \frac{m_2}{m_1 + m_2} g$$

Compare this theoretical expectation to your measurement and calculate the percentage of error.

**Conclusions:** Does the cart accelerate during the time it is moving? If so, where does the net force causing the acceleration come from? What are the sources of error in this experiment?
Simple Pendulum

Goals: the goal of this experiment is to study a pendulum, to measure its period of oscillation and the frequency, and to discuss the concept of conservation of mechanical energy.

Experimental procedure: Take a pendulum and a ruler from the instructor’s desk. Measure the length \( \ell \) of the pendulum from where it is attached to the horizontal bar to the center of the bob. Raise the pendulum bob slightly such that the pendulum string makes a 10 – 15\(^\circ\) angle with the vertical. Release the bob from rest and watch it as it swings to the other end and comes back to where it was released from. The time it takes to complete one full oscillation is the period of oscillation \( T \). The frequency \( f \) tells you how many oscillations have been performed per unit time, so that \( f \equiv \frac{1}{T} \).

To measure the period of oscillation \( T \), raise the pendulum (10 – 15\(^\circ\)) and release it from rest. Let is oscillate about 10 times and measure the time it took with the stop watch. To obtain the period, divide by the number of oscillations.

Next, remeasure the period for a significantly longer and shorter length \( \ell \); you should have a total of 3 measurements. Then repeat the measurement with a lighter (or heavier) bob.

Theory: According to theory, the period of oscillation of a simple pendulum is given by

\[
T = 2\pi \sqrt{\frac{\ell}{g}}
\]

(This expression is valid for small angle oscillations). Compare your measured values of the period to the theoretical expectation. Can you confirm, within measurement errors, that the period is proportional to the square root of the length \( \ell \) of pendulum, and that it is independent of the mass \( m \) of the bob?

Conclusions: What are the possible sources of error and how do they affect your measured values of the period? Also, think about conservation of mechanical energy during the oscillation: when is the kinetic energy maximal, when is it zero? Explain how “conservation of mechanical energy” is manifest in the oscillation of simple pendulum.
Momentum Conservation

Goals: the goal of this experiment is to indirectly test the law of conservation of momentum when there is no net external force.

Experimental procedure: Take two carts, one with a plunger and one without, and place them on the track (back to back). Make sure they are at rest. Gently hit the cart with the plunger on the pin, this will release the plunger and the carts will move apart. The idea is to make sure that the carts hit the opposite ends of the track at the same time. Measure the distance travelled by each cart before it hits the end of the track. Ignoring friction, the speed of either cart is constant and is given by $|\vec{v}| = \frac{d}{t}$.

Theory: According to the law of conservation of momentum, the final momentum of the entire system must be equal to its initial momentum. In our experiment, initially both carts are at rest ($\vec{v}_1^i = \vec{v}_2^i = 0$) and the total momentum is zero

$$\vec{P}^i = \vec{p}_1^i + \vec{p}_2^i = m_1 \vec{v}_1^i + m_2 \vec{v}_2^i = 0.$$

Hence, if total momentum of the system is conserved, the final momentum must also be zero,

$$\vec{P}^f = \vec{p}_1^f + \vec{p}_2^f = m_1 \vec{v}_1^f + m_2 \vec{v}_2^f = 0.$$

Replacing $\vec{v}_1^f$ and $\vec{v}_2^f$ in eq. (3) by $\frac{d_1}{t}$ and $-\frac{d_2}{t}$, respectively (note that the velocities point in opposite directions), and then multiplying both sides of the equation by $t$, we get

$$m_1 d_1 - m_2 d_2 = 0.$$ (4)

The relation (4) follows from the law of momentum conservation and we will check to see if it is true. First, try this with the two carts and no other masses on them. In this case, $m_1 \approx m_2$. Using the measured values of $d_1$, $d_2$ check to see how accurately eq. (4) holds; a useful measure for the discrepancy is obtained by dividing both sides of that equation by the average momentum (times time) of the carts,

$$\frac{m_1 d_1 + m_2 d_2}{2}.$$ (5)

To calculate a percentage of error, multiply by 100%.

In a second run, choose two different masses by adding an iron block to one of the carts so that $m_1 > m_2$. Repeat the experiment and calculate the percentage of error. Explain the various factors that could lead to discrepancies between your measurements and the theoretical expectations.

Conclusions: Did we actually test conservation of momentum or a consequence of it? How would you actually test the conservation of momentum in this experiment? How would the theoretical relations given by (3) and (4) change if the carts were initially moving toward each other rather than being at rest?
Torque and Angular Acceleration

Goals: With this experiment we test the idea that if there is no net torque on an extended object, it will not undergo angular acceleration. That is, if it is initially at rest, it will remain at rest and will not rotate.

Experimental procedure: Take a ruler, measure its mass \( m_{\text{ruler}} \) and balance it on the balance beam. Measure the location of the pivot point. If the density of the ruler is uniform then the pivot point should coincide with the geometric center of the ruler (also called center of gravity of the ruler since one can assume that the force of gravity of the Earth on the ruler acts in that point).

In the first part of the lab, place a mass of \( m_1 = 100 \, \text{g} \) at the right end of the ruler. Shift the pivot point to restore balance and measure its distance from the location of mass \( m_1 \); this distance is the lever arm \( \ell_1 \).

In part two, place another mass \( m_2 \) at the left end of the ruler, keeping \( m_1 \) where it was before. Move the pivot point again to restore balance. Measure the two lever arms \( \ell_1 \) (note: this will differ from \( \ell_1 \) from above !) and \( \ell_2 \).

Theory: In analogy with Newton’s 2\textsuperscript{nd} law there is a law for rotation which states that the angular acceleration of an object is proportional to the net torque acting on it. For our experiment this implies that when the ruler is balanced, the net torque should be zero.

The torque acting on an object is defined as
\[
\vec{\tau} = \vec{F} \times \vec{\ell} , \quad |\vec{\tau}| = F \ell \sin \theta . \tag{6}
\]

\( F \) is the force applied to the object and \( \ell \) is the lever arm while \( \theta \) denotes the angle between them (in this experiment \( \theta = 90^\circ \) so that \( \sin \theta = 1 \)).

In part one, there are two torques acting on the ruler: one is caused by the weight of the ruler itself, the other is due to the weight of \( m_1 \). When they balance,
\[
\tau_{\text{net}} = \tau_{\text{ruler}} - \tau_1 = m_{\text{ruler}} g \ell_{\text{ruler}} - m_1 g \ell_1 = 0 . \tag{7}
\]

Note that the torques have opposite directions: the torque due to the weight of the ruler acts counter clockwise while the torque due to mass \( m_1 \) acts clockwise. This is the reason for the relative minus sign between the two terms in eq. (7). Now calculate the net torque using the measured lever arms and masses and compute the percentage of error; a useful measure for discrepancies is constructed by dividing both sides of eq. (7) by the average of the absolute values of the two torques,
\[
\frac{m_{\text{ruler}} g \ell_{\text{ruler}} + m_1 g \ell_1}{2} . \tag{8}
\]

In part two, three torques act on the ruler. When balanced, the net torque on the ruler must be zero. Repeat the calculation of \( \tau_{\text{net}} \) for this case and compute a percentage of error for your measurement.

Conclusions: In your own words, explain what you learned by doing this experiment. Is there a net torque acting on the ruler before we added \( m_1 \) and \( m_2 \)? Why or why not? Explain the sources of error in your measurements.
Speed of Sound in Air

Goals: the goal of this experiment is to measure the speed of sound in air and to compare it to the “world average” of \( v_{\text{sound}} \simeq 340 \text{ m/s} \).

Experimental procedure: Fill up the water container that is attached by a small rubber tube to the big glass cylinder containing some water. Make sure it does not overflow. You can lower and raise the water level in the big glass cylinder by lowering and raising the water container. Practice this a few times so that you feel comfortable with it. When you are ready, raise the water level in the glass cylinder to the highest level without spilling. Hit the tuning fork on the table so that it vibrates. Hold it above the glass cylinder, very close to its opening but without touching it. Make sure to hold the tuning fork such that the two arms are vertical rather than horizontal; also, the tip of the tuning fork should be at the center of the opening of the glass cylinder.

With the tuning fork vibrating, lower the water level in the glass cylinder slowly and listen for a loud sound (a so-called resonance). Try to fine-tune the water level to determine the loudest sound as accurately as possible. Note the location of the water level, \( \ell_1 \).

Now lower the water level in the glass cylinder further and again hit the tuning fork against the table to keep it vibrating. The resonance should disappear but eventually reappear at a lower water level. Write down the location \( \ell_2 \) of the second loud sound as well.

Theory: Sound waves need a medium to propagate in, such as air. In this experiment a sound wave is generated by the vibrating tuning fork which then travels down the glass cylinder and bounces off of the water. As the sound waves travel up and down the glass cylinder they interfere and can produce a standing wave (think of what a \( \sin \) or \( \cos \) function looks like). The distance between two successive maxima or two successive minima is called the wavelength of the standing wave. In our experiment, the location of the two successive loud sounds in fact correspond to an adjacent maximum and minimum of the standing wave so that the distance between two resonant sounds is half of the wavelength of the sound wave.

There is a relation between the wavelength (\( \lambda \)) of the sound wave, its frequency (\( f \)) and speed \( v \). It is given by

\[
v = f \lambda \tag{9}
\]

The frequency of the sound wave is set by the frequency of the tuning fork that generates the sound wave. It is written on the tuning fork (remember 1 Hz \( \equiv 1 \frac{1}{s} \)). Using the measured value of the wavelength and the given frequency, calculate the speed of sound \( v \) in air. Compare this value with the world average of \( v_{\text{sound}} \simeq 340 \text{ m/s} \). Compute the percentage of error in your measurement.

Conclusions: Would you get a different result for the speed of sound if you used a tuning fork with a different frequency? What would need to change in order to get the same speed? If in doubt, repeat the experiment using a tuning fork with a different frequency or compare your measurements for \( \ell_1 \) and \( \ell_2 \) to those of another team who used a different tuning fork.

Describe possible sources of error in your measurements.
Specific Heat of Metals

**Goals:** the goal of this experiment is to use conservation of heat energy in order to determine the specific heat capacity of some metals.

**Experimental procedure:** Fill a styrofoam cup about half-way with tap water (not more than about 300-500 g of water). Weigh the styrofoam cup with and without its water content to determine the mass of the water. Place a thermometer in the water to monitor its temperature and wait until it is steady. This is the initial temperature $T_i^w$ of the water.

Now also weigh the metal object provided by the instructor and then immerse it in the boiling water on the counter. Once you place the metal in the boiling water, it will stop boiling. Wait a little until the water is boiling again and the metal has reached the same temperature as the water. The initial temperature of the metal is now $T_i^m = 100 ^\circ C$.

Remove the metal from the boiling water and quickly (and completely) immerse it in the water in the styrofoam cup. Monitor the temperature of the water in the styrofoam cup until it is steady. Write down the temperature, this is the final temperature $T_f$ of the water and the metal.

**Theory:** Assuming that no heat is emitted into the environment as you perform the experiment, conservation of heat energy implies that the heat $Q_m$ lost by the metal is equal in magnitude to the heat $Q_w$ gained by the water in the styrofoam cup. We define “emitted heat” to be negative while absorbed heat is positive. Hence,

$$-Q_m = Q_w$$
$$-m_m c_m (T_f - T_i^m) = m_w c_w (T_f - T_i^w) .$$

(10)

This equation can be used to calculate the specific heat capacity $c_m$ of the metal. Since every metal has a particular specific heat capacity, this tells us what the metal is.

$$c_m = c_w \frac{m_w}{m_m} \frac{T_f - T_i^w}{T_i^m - T_f} .$$

(11)

Using the measured masses of water and metal, the final and initial temperatures of the water and metal and the known value of the specific heat capacity of water, $c_w = 1 \text{ cal g}^{-1} ^\circ C$, calculate the specific heat capacity of the metal $c_m$. Compare this value to $c_{\text{steel}} = 0.110 \text{ cal g}^{-1} ^\circ C$, $c_{\text{alum}} = 0.215 \text{ cal g}^{-1} ^\circ C$, $c_{\text{lead}} = 0.030 \text{ cal g}^{-1} ^\circ C$, $c_{\text{copp}} = 0.093 \text{ cal g}^{-1} ^\circ C$ to decide what sort of metal you’ve been experimenting with. Calculate the percentage of error.

**Conclusions:** Based on your results, is heat conserved? What are the biggest sources of error in this experiment? Would your results depend on the altitude (height) where you perform the experiment? If so, what would be different?
**Ohm’s Law**

**Goals:** the goal of this lab is to build a simple electric circuit and to get familiar with the concepts of electric current $I$, resistance $R$ and potential difference $\Delta V$ (voltage) in a circuit. We shall also test Ohm’s law which relates the potential difference across a resistor to the current passing through it and to its resistance.

**Experimental procedure:** Obtain a multimeter, a “mother board”, a battery, a resistor and some electric wires. First, use the multimeter to measure the voltage of the battery and the resistances of the resistor. Confirm your measurements by comparing to the nominal voltage printed on the battery, and with the resistance deduced from the color code on the resistor (see [http://en.wikipedia.org/wiki/Electronic_color_code](http://en.wikipedia.org/wiki/Electronic_color_code)).

Then build a circuit on the mother board using the battery and the resistor. Measure the electric current $I$ passing through the resistor $R$ and the potential difference $\Delta V$ across the resistor $R$.

**Theory:** According to Ohm’s law, the potential difference across a resistor is related to the current passing through it and its resistance via

$$\Delta V = I R$$

(If the circuit is interrupted what resistance would that correspond to and what would be the electric current ?)

Using the measured resistance, current and electric potential difference check Ohm’s law.

**Conclusions:** A current can only flow through a circuit connecting the two poles of the battery. Can you confirm Ohm’s law ? What are some of the sources of errors in your measurements?
Oscillations of a weight attached to a spring

Goals: in this experiment we determine the spring constant \( k \) of a given spring and measure the oscillation frequency of a weight attached to it.

Experimental procedure: Obtain a tripod, spring, a timer and some weights from the instructor. Check the mass of the weights with a scale.

First, you need to determine the spring constant \( k \). To do so, attach an object (mass about 200 g) to the spring and measure by how much it stretches. If the object is at rest in the stretched configuration then the net force is zero and so its weight \( W \) must equal the force \( F \) exerted by the spring (in magnitude). With \( W = mg \) and \( F = -kx \) you find that \( k = mg/|x| \).

Next, we let the object perform an oscillation: pull the object a little further down and start the timer while you let go. Let it perform about 5 - 8 full oscillations and then determine the period \( T \) for a single oscillation.

Repeat the oscillation with a heavier object (say, this time \( m = 300 \text{ g} \))

Theory: according to Newton’s theory, the oscillation frequency turns out to be related to the spring constant and the mass of the object via

\[
\omega = \sqrt{\frac{k}{m + \frac{1}{3}M_s}}
\]  

(13)

where \( M_s \) is the spring mass. Confirm that the frequency carries units of inverse seconds (or Hertz). It measures how many radians are covered within a time of 1 s; as one full oscillation corresponds to \( 2\pi \) rad, it follows that the frequency \( \omega \) is related to the period \( T \) as follows:

\[
\omega = \frac{2\pi}{T} \quad , \quad T = \frac{2\pi}{\omega}.
\]

(14)

Compare this theoretical result to the measured oscillation frequency (or period) and determine the percentage of error. Discuss possible sources of error.
Reflection and Refraction of Light

Goals: with this experiment we study reflection and refraction of light and measure the index of refraction in a medium different from air; we use it to calculate the speed of light in that medium.

Experimental procedure: When light crosses from one medium to another one, its speed changes. The speed of light in vacuum is commonly denoted by $c$ and is equal to $c = 3 \cdot 10^8 \text{ m/s}$. Its magnitude relative to the speed of light in a medium ($v_{\text{med}}$) is defined to be the index of refraction of that medium $n_{\text{med}}$. Note that the speed of light in any medium is always smaller than the speed of light in vacuum so that the index of refraction is always larger than 1. In this experiment, we will assume that the speed of light in air (a very dilute medium) is the same as the speed of light in vacuum.

Take a plastic container and fill it with tap water. Place the container on a blank white sheet of paper and mark its location by drawing lines corresponding to the front and back side of it. Take a source of light and use it to shine light on the container at an angle. Make sure that the beam of light coming out of the light source is well collimated, i.e. that it has a narrow width. This is the incident beam. Note that the beam gets reflected from the front surface of the water container. This is the reflected beam. Draw a line marking the incident beam and another line marking the reflected beam. Mark the point where the beam of light exits the water container and then remove the container. Draw a line from the point where the beam exited the container to the point where the incident beam hit the front face of the container. The angle of incidence ($\theta_{\text{inc}}$) is defined to be the angle between the incident beam and the line normal (perpendicular) to the front side of the container. The angle of reflection ($\theta_{\text{refl}}$) is defined to be the angle between the reflected beam and the normal line. The angle of refraction ($\theta_{\text{refr}}$) is defined to be the angle between the normal line and the refracted beam. Measure these angles and write them down.

Theory: According to theory, the angle of incidence is equal to the angle of reflection

$$\theta_{\text{inc}} = \theta_{\text{refl}} \, . \quad (15)$$

The refraction angle, on the other hand, follows from Snell’s equation

$$n_1 \sin \theta_{\text{inc}} = n_2 \sin \theta_{\text{refr}} \, . \quad (16)$$

In our experiment, $n_1 = 1$ because air is a very dilute medium and nearly the same as vacuum. Using the measured values of the angles, first check to see if eq. (15) holds and calculate the percentage of error. Then use eq. (16) to calculate $n_2$, the index of refraction for water. Use $v_\text{water} = \frac{c}{n_\text{water}}$ to calculate the speed of light in water. Compare your result to the “world average” value of $v_\text{water} = 225563909 \text{ m/s}$ and calculate the percentage of error for your measurement.

Conclusions: Why does light slows down in a medium as compared to vacuum? Think of light as a circular waves crossing into the water from air, what happens to the shape of the waves as they enter a denser medium?