

An Undergraduate Guide into Experimental Physics:  
Rigid Body Mechanics and Oscillations

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A special thanks to the editors of this book who performed each experiment and submitted corrections.

Editors: Roy Cooper, Grace Green, Gwen Hamilton, Qiana Hunt , William Shankles, Deana Smith, and  
Randy Smith.

# Chapter 1

## The Simple Harmonic Pendulum

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### 1.1 A Brief History

In 1584, a young scientist at the age of 20 observed simple harmonic motion using a pendulum. While at first glance the motion of a pendulum may appear to be trivial, the motion of the pendulum is quite the opposite, as you will discover in this experiment today. This young scientist, also known as Galileo, observed the regular periodic motion of a swinging pendulum while using his heart beat as a watch. Keep in mind that at the time, reliable time measuring devices had not been invented. During today's exercise you will alter the motion of a pendulum using different parameters to observe what Galileo observed.

### 1.2 Notes

1. Always read the lab manual before coming to class. Daily quizzes will be given at the beginning of each class covering material in this manual.
2. Questions that are boxed in are required to be in your lab reports typed and turned in the following week. See the example lab report that accompanies this manual.
3. It is always a good idea to bring a flash drive to class in case you may want to save images or data gathered during the experiment. I would recommend that each group member bring their own flash drive; relying on a single group member to email relevant data is never a good idea. This manual and your TA will remind you one class in advance if a flash drive is absolutely necessary.
4. Throughout the semester you will find that the necessary theory to solve some of the problems in the labs will be developed within the procedure. Read ahead!
5. Today you may want to familiarize yourself with **Datastudio**. Make notes of how the interface works and that each member of the group knows how to use the software. It is important that each individual member can perform each experiment that requires **Datastudio**, because the Midterm and Final Exam will require such knowledge.
6. Items outlined in boxes are questions that you may try to answer during class; however it is more of an individual task to answer those questions outside of class time. They should be addressed in the results section of your lab report.
7. If you are in the Honors section, be sure to review all of the Honors questions before leaving class. Sometimes steps will be required in the class to answer those questions. It is also a good idea to work on those problems with your group mates so as to not pull an all-nighter trying to figure out if something is a 2 or a 3.

8. Expect typos in this manual. This is the first semester it is in use and there are bound to be errors. Send an email to mws0002@alumni.uah.edu to report any typos. Your TA may or may not give extra credit for this.

### 1.3 Definitions

1. *Simple Harmonic Motion*-Motion that repeats itself at regular intervals is considered to be harmonic motion.
2. *Amplitude*-The maximum absolute value of a periodically varying quantity<sup>1</sup>.
3. *Period*-The time interval between two successive occurrences of a recurrent event or phases of an event; a cycle<sup>1</sup>.
4. *Pivot Axis*-The Pivot Axis is the point at which the pendulum swings about.

<sup>1</sup>Definitions were provided by *The American Heritage Science Dictionary*.

### 1.4 Laboratory Objectives

By the end of today's exercise you will understand how intricate and complicated a "simple" harmonic pendulum is. The three factors that you will be comparing are:

1. The **mass** of the pendulum bob.
2. The **length** of the string connecting the bob to the pivot axis.
3. The **amplitude** of the swing, or rather how high the bob is lifted initially.

Of course there are some questions that you should already be asking yourself (unless you are in the 8 a.m. section, in which case I understand if you are not asking any questions yet).

1. "If I increase the mass of the bob, while keeping length and amplitude constant, what will happen to the period of the swing?"
2. "If I increase the length of the pendulum, while keeping mass and amplitude constant, what will happen to the period of the swing?"
3. "If I increase the amplitude of the bob, while keeping mass and length constant, what will happen to the period of the swing?"

What do all of these questions have in common? If your answer is "The Period" then you are correct.

### 1.5 Equipment

Pendulum, Meter Stick, Lab Stand, Motion Sensor, and Datastudio

### 1.6 In Class Lecture

1. The TA will introduce the concepts that will be covered in this lab as well as go over the syllabus.
2. The TA will give a brief introduction of how pendulums operate and an overview of the software required for the experiment.

## 1.7 Procedure

1. Measure the mass of your pendulum bob.

$m_b$ : \_\_\_\_\_ s

2. Find a suitable *and* reasonable length to use for your pendulum. I recommend **100 cm**. Hang the bob from the stand provided. Record the length of your pendulum.

Length of Pendulum: \_\_\_\_\_ cm

3. Attach and adjust your **Motion Sensor** such that the sensor is parallel to the motion of the pendulum's swing.
4. Open **Datastudio**, then find and select the **Motion Sensor**. Click the *Setup* button and set the Sample rate to **20 Hz** and then click on the Motion Sensor tab and set a standard distance of **0.5 m**.
5. I recommend that the **Motion Sensor** be placed approximately **20 cm** away from the pendulum bob.
6. Do one practice run to make sure the pendulum bob passes the **Motion Sensor** properly.
7. Raise the **Amplitude** of the bob to a suitable *and* reasonable height from the base height so that the bob is displaced **10 cm** from its rest position. Hold it at that position until the next two steps are complete. Note: Do not exceed an angle of 1 radian from the rest angle. Do not know how to convert between degrees and radians? Multiply by  $180/\pi$ .
8. You will be measuring **10** periods once you release the pendulum.
9. Click the start button in **Datastudio** and then release the pendulum. Visually count **10** periods and then stop the bob. Stop **Datastudio**.
10. If the process was completed correctly then **Run 1** should appear in a window on the left. Drag **Run 1** to the graph window located in the bottom left window.
11. Double check to see that the graph that is now displayed as position vs time.
12. Use the *Scale-to-Fit* button if the graph appears to be too small or too large.
13. Use the *Smart Tool*, located to the left of the *Fit* button, to record the times for each period.

	Time (s)		Time (s)
1		6	
2		7	
3		8	
4		9	
5		10	

14. Calculate the average (*also called the arithmetic mean*) time of the ten measurements. Recall that the equation for calculating averages is the sum of all the individual data points divided by the number of data points collected. Equation 1.1 shows the equation for the average time with  $t_k$  being the  $k^{th}$  time recorded. For instance,  $t_1$  will be equivalent to time 1, and  $n = 10$  for our case.

Average Time Calculated  $t_i$ : \_\_\_\_\_ s

$$\frac{1}{n} \sum_{k=0}^n t_k = \frac{t_1 + t_2 + t_3 + \dots + t_n}{n} \quad (1.1)$$

15. Lets try a more reliable and accurate method of calculating the average time by including accurate *and* precise measurements. (The previous method was only precise and not necessarily accurate) Do the same process you did before with the same pendulum settings. (e.g. **10 cm** displacement, **100 cm** length, same mass as before). This time, measure the time it takes to complete **10** periods. Do this for **3** runs. Note: Do not forget to divide by 10.

$$t_1: \text{_____ s} \quad t_2: \text{_____ s} \quad t_3: \text{_____ s}$$

Using equation (1.1) find the Average Time

Average Time Calculated  $t_f$ : \_\_\_\_\_ s

16. Now lets take the two times you found for the different runs. The first average time you found we will label  $t_i$  and the second time you found we will label  $t_f$ . Find the absolute value of the difference of these two numbers and then divide by the average of the two numbers. This is known as **Percent Difference** and is shown below in equation (1.2).

$$\frac{|t_f - t_i|}{t_{avg}} \times 100 \quad (1.2)$$

Calculate the **Percent Difference** \_\_\_\_\_

Is the value you calculated above large or small. Which result would be ideal?

17. Now lets continue to keep the **Mass** and **Length** the same, but instead adjust the **Amplitude** of the swing twice by increasing the displacement with **5 cm** increments. So if you initially chose to begin with a **10 cm** displacement, the next displacement should be **15 cm**, and then **20 cm** respectively. Record the Average Time for **10** periods for each amplitude displacement.

$$t_1: \text{_____ s} \quad t_2: \text{_____ s}$$

**Question 1:** Does the **Amplitude** of the swing alter the **Period** of the pendulum according to your results? Discuss this in the results section of your lab report.

18. Now alter the **Mass** of the bob by either adding another block or some other appropriate and reasonable method. Keep the **Amplitude** and the **Length** constant. I recommend you let **Amplitude** have a **10 cm** displacement, and continue letting the **Length** be **100 cm**. Record the time for **10 Periods**.

$$t_1: \text{_____ s}$$

**Question 2:** Does the **Mass** of the bob alter the **Period** of the pendulum according to your result? Discuss this in the results section of your lab report.

19. Now it is time to alter the **Length** of the pendulum. Keep the **Amplitude** and **Mass** constant throughout this step. For three runs (10 periods each), record the values for lengths of **100 cm**, **75 cm**, and **50 cm** respectively. It is important to measure the length of the string as the distance from the knot at the top of the string to the center of the bob. Note: Do not forget to divide by **10** for each case.

Length (cm)	Period 1 (s)	Period 2 (s)	Period 3 (s)
100			
75			
50			

Average Period Calculated  $t_{avg}$  100 cm: \_\_\_\_\_ s

Average Period Calculated  $t_{avg}$  75 cm: \_\_\_\_\_ s

Average Period Calculated  $t_{avg}$  50 cm: \_\_\_\_\_ s

20. Now make a graph using a graphing program of your choice, I would recommend using Excel as it is user friendly and the job can be done in about five minutes. **Plot Period vs Length**. When you are asked to plot Something A vs Something B, it is easiest to remember this trick, Something A (y-axis) = Something B (x-axis). So for all values of x, y will have an associated value. Plot your 3 data points. You may also use the space below to make a rough sketch of this graph.

**Question 3:** You can do a quick sketch ↑ of the graph on this manual since it is only three data points. Is the graph linear or exponential? That is to say, is the graph that of  $y = x^2$ ,  $y = x$ , or  $y = \sqrt{x}$ ? Discuss this in the results section of your lab report.

**Question 4:** Does the **Length** of the pendulum alter the **Period** of the pendulum according to your results?

★**Honors Question A:** Calculate the **Theoretical Value** of the period for the lengths of **100 cm**, **75 cm**, and **50 cm**. (Show all work and steps in your lab report)

$$T \approx 2\pi\sqrt{\frac{L}{g}} \tag{1.3}$$

Length (cm)	Theoretical Period (s)
100	
75	
50	

★**Honors Question B:** Calculate the **Percent Difference** between the theoretical values you calculated and the average values you calculated of the period for the lengths of **100 cm**, **75 cm**, and **50 cm**. If the values were vastly different, explain why. (Show all work and steps in your lab report)

Length (cm)	Percent Difference (%)
100	
75	
50	

\*\*\* **Theory — Honors Question C:** From equation (1.3) you can see the  $\approx$  sign. This means it is an approximation. Earlier in the lab you may have noticed that I mentioned that the **Amplitude** of the swing of the pendulum is accurate as long as the angle it makes from its rest position is never greater than 1 radian. Raise your pendulum to an amplitude that exceeds an angle of 1 radian from its rest position and record the period for **10** swings. Is it the same for when you measured it before? In equation (1.3)  $T \approx 2\pi\sqrt{\frac{L}{g}}$  there is no mention of angles. Would it be unreasonable to simply multiply by some factor of an angle to this equation? What are the units of radians?

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QUIZ 1 - Simple Harmonic Pendulum

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## Chapter 2

# Inclined Planes

### 2.1 A Brief History

Inclined planes are planes that are tilted with respect to (w.r.t.) a horizontal surface. During the Renaissance, scientists added the inclined plane to the category of “simple machines”. It was used to lessen the force required to elevate objects. It is theorized by some historians that the Great Pyramids of Giza were built using inclined planes. Today you will observe the effects of placing an object on an inclined plane while the angle  $\theta$  is adjusted.

### 2.2 Definitions

1. *Force Vector*-A component of force that has both direction and magnitude.
2. *Sum of Forces*-Since Forces are vectors they can be represented graphically. The sum of vectors is a vector sum, or resultant vector. In our case we will be looking for a resultant force vector.
3. *Free Body Diagram*-A diagram depicting forces on an object of interest using vector notation.
4. *Normal Force*-Force that is perpendicular to the plane of “action”.
5. *Newton*-Unit of Force.

### 2.3 Laboratory Objectives

By the end of today’s exercise it is in the hopes of this Author that you will understand how useful a free body diagram can be in terms of resolving force vectors. Let us begin by stating Newtons Basic Laws of Motion in a basic form:

1. “Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it.”
2. “The relationship between an object’s mass  $m$ , its acceleration  $\vec{a}$ , and the applied force  $\vec{F}$  is  $\vec{F} = m\vec{a}$ . Acceleration and force are vectors (as indicated by their symbols being displayed in slant bold font); in this law the direction of the force vector is the same as the direction of the acceleration vector.”
3. “For every action there is an equal and opposite reaction.”

The first law is the **Law of Inertia**, which will be covered in Chapter 9. The second law is called, trivially I might add, **Newton's 2<sup>nd</sup> Law**. The third law is the **Law of Equal and Opposite Reaction**, which will also be covered later in the semester. The law we shall investigate today is  $\vec{F} = m\vec{a}$ . See below for a **Free Body Diagram**.

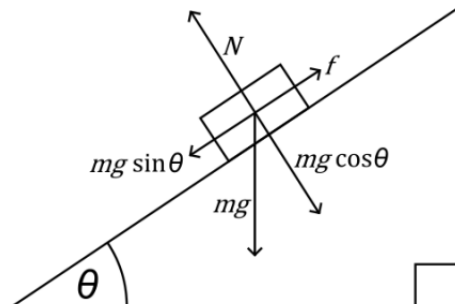


Figure 2.1: Freebody Force Diagram

$\vec{N}$  denotes the **Normal Force** vector that is perpendicular to the plane of the incline.  $m\vec{g}$  denotes the **Force** caused by gravity acting on the mass of the block.  $m\vec{g}\cos\theta$  denotes the equal and opposite **Force** caused by the **Normal Force**; also perpendicular to the incline.  $m\vec{g}\sin\theta$  denotes the **Force** parallel to the incline and also dictates which direction the block will move (without outside Forces that is).  $f$  denotes the frictional force that is equal and opposite of  $m\vec{g}\sin\theta$ .

## 2.4 Equipment

Carts, Track, Lab Stand, Masses, Meter Stick, Balance, Force Sensor, and DataStudio

## 2.5 In Class Lecture

1. The TA will give a go over force vectors and the angles they make with respect to an incline plane. It might be a good idea to review this concept prior to class.

## 2.6 Procedure

1. Attach and adjust your **Force Sensor** such that the sensor is hanging from the lab stand. The hook at one end of the **Force Sensor** will allow you to hang a mass to calibrate the system.
2. Open **Datastudio**, and click the *Setup* button. Deselect Force and select *User Calibrated Force*. Set the *Sample Rate* to 20 Hz. Click *Calibrate Sensor* at the top of the window.
3. All forces that the **Force Sensor** will be “negative” forces when items hang from the hook. Verify that “Calibrate all similar measurements simultaneously” is not checked. Verify that the “2 point” Force option is checked.
4. With no weight hanging from the **Force Sensor**, press the *Zero* button which is physically located on the force sensor device. Press the *Read* button to take a value. It should be near **0**. Recall that measurements in the  $10^{-4}$  region are close to **0**. Hang **1 kg** of weight on the Force Sensor and type **-9.8** into the second field of the 2 point calibration box. Press the *Read* button. Calibration is complete and data may be taken now.

- Try recording data by clicking the *Start* button. Wait a few moments then click *Stop*. In the upper left hand corner drag the “Run” down to the “Table Display”. This will display your data in sets of numbers.
- In the Table Display, select the *Show Selected Statistics* button and *Mean* should be displayed. If *Mean* is not displayed, click on the drop-down arrow beside *Show Selected Statistics* and select *Mean*. This will display the mean value of the force that acted on the force sensor. Record this value.

$F_{mean}^{0.0kg}$ : \_\_\_\_\_ N

Note that the superscript denotes the mass and the subscript denotes the mean.

- Now apply **0.1 kg** to the **Force Sensor** and find the mean. Do the same for **0.2 kg**, **0.5 kg**, and **1 kg**. Record all of the mean values.

$F_{mean}^{0.1kg}$ : \_\_\_\_\_ N     $F_{mean}^{0.2kg}$ : \_\_\_\_\_ N     $F_{mean}^{0.5kg}$ : \_\_\_\_\_ N     $F_{mean}^{1.0kg}$ : \_\_\_\_\_ N

- Calculate the theoretical forces for each of the masses you measured.

$F_{Theoretical}^{0.1kg}$ : \_\_\_\_\_ N     $F_{Theoretical}^{0.2kg}$ : \_\_\_\_\_ N     $F_{Theoretical}^{0.5kg}$ : \_\_\_\_\_ N     $F_{Theoretical}^{1.0kg}$ : \_\_\_\_\_ N

- Find the percent differences between your measured values and the theoretical values you calculated.

$$\frac{|F_T - F_m|}{F_m} \times 100 \quad (2.1)$$

Percent Difference(0.1kg): \_\_\_\_\_    Percent Difference(0.2kg): \_\_\_\_\_

Percent Difference(0.5kg): \_\_\_\_\_    Percent Difference(1.0kg): \_\_\_\_\_

- Using a graphing program of your choice, plot the absolute value of the force you measured vs the theoretical force you calculated. You may also draw a rough sketch below ↓.

**Question 1:** What is the slope of the line you found in the previous step? Discuss this in the results section of your lab report.

- Take the **Force Sensor** off of the stand now and place it at the bottom of the track with the hook facing the length of the track such that the cart will be able to rest on the hook of the **Force Sensor**.

12. Take your cart to the balance and measure its mass.

Mass of the cart: \_\_\_\_\_kg

13. Lets dust off those trigonometry skills and discover how high the track must be raised on one side to give an angle  $\theta$  of approximately **10** degrees. Recall that you know the length of the track  $x$  and the target angle therefore you can calculate the height  $y$  in which the track should be raised.

$$\tan \theta = \frac{y}{x} \quad (2.2)$$

14. Physically located on the **Force Sensor** device is a *Zero* button. Click it.

15. Place the cart on the track such that it is in contact with the hook, thus applying a force on the sensor.

16. Record the Mean value of the force on the sensor.

$F_{mean}^{\theta=10}$ : \_\_\_\_\_N

17. Raise the incline to approximately **15** degrees, and then approximately **20** degrees, and record the Mean force for each  $\theta$  respectively.

$F_{mean}^{\theta=15}$ : \_\_\_\_\_N     $F_{mean}^{\theta=20}$ : \_\_\_\_\_N

18. Calculate the theoretical values associated with the cart and the different inclinations. You will need to use **Free Body Diagrams** to find these values. Here is some space to work in:

$F_{Theoretical}^{\theta=10}$ : \_\_\_\_\_N     $F_{Theoretical}^{\theta=15}$ : \_\_\_\_\_N     $F_{Theoretical}^{\theta=20}$ : \_\_\_\_\_N

19. Find the percent differences between your measured values and the theoretical values you calculated.

Percent Difference( $\theta = 10$ ): \_\_\_\_\_ Percent Difference( $\theta = 15$ ): \_\_\_\_\_

Percent Difference( $\theta = 20$ ): \_\_\_\_\_

Using a graphing program of your choice, plot the force you measured vs the theoretical force you calculated. Make a rough sketch below to get the general idea of the structure of the graph.

**Question 2:** What is the slope of the line you found in the previous step? Discuss this in the results section of your lab report.

★**Honors Question A:** The force on an object given by  $m\vec{g}$  may be resolved into two components:  $m\vec{g}\sin\theta$  and  $m\vec{g}\cos\theta$ . The former force is parallel to the inclined plane and may cause the cart to begin rolling down along the inclined plane. The latter is perpendicular to the inclined plane, why does the cart not move perpendicular to the inclined plane? Which of Newton('s) Law(s) described above best describes this?

★★**Honors Question B:** Instead of measuring the height and base of the apparatus to find the inclined plane's angle, describe briefly how can you determine the inclined plane's angle using what you know about the force of an object on the plane?

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QUIZ 2 - Inclined Plane

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## Chapter 3

# Projectile Motion

### 3.1 A Brief History

Projectile motion is a phenomenon in which an object which has some initial velocity  $v_0$  which moves along a curved path to an end point. When speaking about an object near the Earth's surface, projectile motion is achieved when an object is launched with initial velocity  $v_0$  and moves in a curved parabolic path until it reaches its final position at some time later. Today you will be observing the effects of a projectile launched from a horizontal position at some height  $y$  above the tabletop.

### 3.2 Definitions

1. *Initial Velocity*-The velocity that was measured at a start time, usually at  $t = 0$ .
2. *Final Velocity*-The velocity that was measured at the final time of interest, usually when the object interacts with some outside force.
3. *Velocity Vector*-A vector which has velocity components in the x and y directions. Also note that it may have higher dimensions, namely a z component as well. For today, only x and y are considered.
4. *Projectile*-An object that has been launched from some initial height that travels a distance x.
5. *Trajectory*-The path a projectile follows.
6. *Free Fall*-The motion of an object that travels without interference from an outside source. Under normal circumstances when an object falls in Earth's gravitational field it is considered in free fall.

### 3.3 Laboratory Objectives

By the end of today's exercise it is in the hopes of this Author that you will understand how projectile motion works. You should be able to:

1. Separate **Velocity Vectors** into their **x** and **y** components.
2. Understand what is meant by saying an object has an **Initial Velocity** and a **Final Velocity**.
3. Understand the relationship between an object in vertical **Free Fall** and an object in **Free Fall** that has a horizontal velocity component also.

Of course there are some questions that you should already be asking yourself.

1. “If an object is dropped from a certain height  $h$  with a zero initial velocity, how long will it take the object to hit the ground?”
2. “If I throw an object at a certain height  $h$ , the same height in (1), with a non-zero initial velocity whose direction is directly downward, how long will it take the object to hit the ground?”

Let us take these questions and proceed to observe and learn why these relationships are important.

### 3.4 Equipment

PVC pipe, Marble, Nail, Carbon Paper, Notebook Paper, Wooden blocks, Meter stick, Rulers

### 3.5 Procedure

1. The lab apparatus should be set up by the TA prior to the groups arrival. If it is not set up, position the PVC pipe on the lab stand such that the marble may roll down the tube to be projected to land on the notebook paper which should be positioned below the carbon paper.

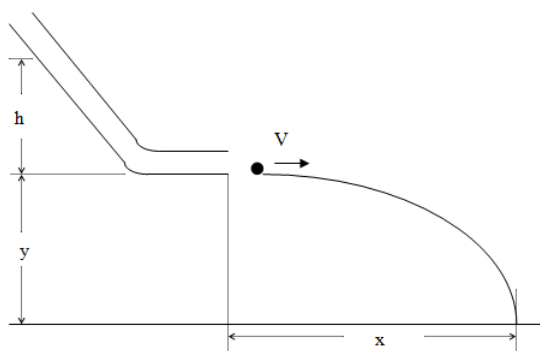


Figure 3.1: Projectile Motion Diagram

2. On the PVC pipe there are five holes located near the top of the apparatus. By placing a nail into a hole you can fix the marble to a fixed height. The height  $h$  corresponds to the distance from the bottom of the PVC pipe to the nail. Pick a reasonable point to start, preferably the hole closest to the base of the apparatus, then place the nail into the hole. You may now place the marble into the slot. Record three values of  $h$ , these distances will be the heights you will use in the next few steps. The height  $h$  corresponds to the distance from the bottom of the PVC pipe to one of the three chosen nail slots. Record the value of  $y$ .

Height  $y$ : \_\_\_\_\_ cm

$h_1$ : \_\_\_\_\_ cm    $h_2$ : \_\_\_\_\_ cm    $h_3$ : \_\_\_\_\_ cm

3. Test what sort of distance the marble is going to travel by releasing the highly sophisticated nail. After you have roughly judged where the marble will land, strategically place the piece of notebook paper and carbon paper onto the battlefield such that when the marble hits the blue side of the carbon paper it will leave a mark on the notebook paper placed under it.



4. Place the marble back into its cosy starting position using the nail. Drop the marble five times through the tube and record five measurements of  $x$  according to the figure above. S stands for slot, therefore S1 means Slot 1, S2 = Slot 2, etc....

$$x_1^{S1}: \text{_____ cm} \quad x_2^{S1}: \text{_____ cm} \quad x_3^{S1}: \text{_____ cm} \quad x_4^{S1}: \text{_____ cm} \quad x_5^{S1}: \text{_____ cm}$$

5. Place the marble into the next highest slot available. Drop the marble five times through the tube and record five measurements of  $x$  according to the figure above.

$$x_1^{S2}: \text{_____ cm} \quad x_2^{S2}: \text{_____ cm} \quad x_3^{S2}: \text{_____ cm} \quad x_4^{S2}: \text{_____ cm} \quad x_5^{S2}: \text{_____ cm}$$

6. Place the marble into the next highest slot available. Drop the marble five times through the tube and record five measurements of  $x$  according to the figure above.

$$x_1^{S3}: \text{_____ cm} \quad x_2^{S3}: \text{_____ cm} \quad x_3^{S3}: \text{_____ cm} \quad x_4^{S3}: \text{_____ cm} \quad x_5^{S3}: \text{_____ cm}$$

7. Now calculate the average  $x$  value for each slot.

$$x_{avg}^{S1}: \text{_____ cm} \quad x_{avg}^{S2}: \text{_____ cm} \quad x_{avg}^{S3}: \text{_____ cm}$$

8. Let us digress briefly and review some equations which best describe projectile motion relating distance to time. We know that distance travelled in some time is related by this equation:

$$x = vt \tag{3.1}$$

$x$  is the distance travelled in the  $x$  direction, and  $v$  is the velocity in the  $x$  direction. Therefore, for the  $x$  direction I will define  $v \equiv v_{x0}$  where the  $x$  represents velocity in the  $x$  direction and the 0 represents that it is the **Initial Velocity**.

In Earth's gravitational field the distance covered in the vertical direction takes on a slightly different form.

$$y = v_{y0}t - \frac{1}{2}at^2 \tag{3.2}$$

For this experiment, the marble leaves the PVC pipe with *no* initial vertical velocity. The marble ideally exits the PVC pipe completely horizontally and then tends downwards until it hits the tabletop. Thus setting  $v_{y0} = 0$  and equating  $a = -g$  we get the equation:

$$y = \frac{1}{2}gt^2 \tag{3.3}$$

Let us take one more step and solve for time  $t$  in equation (3.1), then substitute that result into equation (3.3). The result is:

$$y = \frac{1}{2}g \left( \frac{x}{v_{x0}} \right)^2 \tag{3.4}$$

Solving for  $v_{x0}$  yields the result:

$$v_{x0} = x \sqrt{\frac{g}{2y}} \tag{3.5}$$

Note that because we solved for time to substitute one equation into another, it yielded an astounding result that connects both position  $x$  and position  $y$  by just the **Initial Velocity** in the  $x$  direction. No information about time is necessary, this is truly intriguing!

9. Calculate  $v_{x0}$  for each average value of  $x$  you calculated in part 7 above. Record these values because they will yield an interesting result relating  $\sqrt{h}$  and  $v_{x0}$ ! Take note of the units, they are in meters per second now. As a general rule of thumb, for quantities of interest in the experiments we will be doing throughout the semester it is usually a good thing to leave your units in terms of meters, seconds, and kilograms. *For some calculations however, it may be reasonable to leave results in different units.*

$$v_{x0}^1: \text{_____ m/s} \quad v_{x0}^2: \text{_____ m/s} \quad v_{x0}^3: \text{_____ m/s}$$

10. Digressing yet again, let us look at the motion of the marble as it traverses *the inside* of the PVC pipe. Later in the semester you will be introduced to the idea of a rolling object having an acceleration associated with its inertia which is *completely independent* of the objects mass. This is true as long as the marble does not “slip” as it slides down the incline, that is to say that the marble *never loses contact* with the PVC pipe. You will have to trust me when I say this leads to the inevitability that

$$v \propto \sqrt{h} \tag{3.6}$$

for some calculated velocity  $v$ , and some measured height  $h$ .

The symbol  $\propto$  means proportional to. That means that there exists some constant in which  $\sqrt{h}$  is multiplied by to make  $\propto \Rightarrow =$ . More explicitly,

$$v = A\sqrt{h} \tag{3.7}$$

where  $A$  is some constant.

11. Calculate  $\sqrt{h_i}$  for  $i = 1,2,3$  respectively from part 2.  $i$  is the index, so for  $i = 1$  you would calculate  $\sqrt{h_1}$ , it is simple once you realize how the notation works. *If you are a Physics student, Aerospace Engineer, or a Chemistry Student, learn to love this notation.:*

$$\sqrt{h_1}: \text{_____ cm} \quad \sqrt{h_2}: \text{_____ cm} \quad \sqrt{h_3}: \text{_____ cm}$$

You may notice as the semester continues the notation used in this lab manual will become more “*advanced*”, however, whenever new notation is invoked I will try to elaborate when I feel I “jumped the gun” from your coursework a bit. This will allow the steps to become shorter via the use of shorthand notation. Almost all of the notation should take less than 30 seconds of your time to understand the first time, and then you may use it to impress your teachers later on! Also, your instructor is well versed in all mathematical shorthand relevant to this course if you have questions. If your instructor is not well versed in such notation, feel free to glare menacingly at them from a safe distance.

12. Make a simple plot of  $v_{x0}^i$  vs  $\sqrt{h_i}$  below for  $i = 1,2,3$ . Also make a plot using a graphing program of your choice for your lab report due next week. Discuss the results of this plot in the results section of your lab report.

**Question 1:** Is the graph in the previous step linear or exponential? What is the slope of the graph? Is it a fair assumption that assuming the slope you found is correct, is it in fact the constant A described above? Discuss this in the results section of your lab report.

13. Let us delve deeper into the abyss of experimentation and undergo an analysis of constant height  $h$ , but varying the parameter  $y$ . Choose a slot for your  $h$ , it might be useful to pick one that you have used before.

Height  $h$ : \_\_\_\_\_ cm

14. Using the technologically innovative raising and lowering blocks for your apparatus, pick an arbitrary  $y$ .

$y_1$ : \_\_\_\_\_ cm

15. Place the marble inside the PVC pipe at the desired pre-chosen  $h$  and record 5  $x$  positions upon release of the marble.

$x_1^{y_1}$ : \_\_\_\_\_ cm    $x_2^{y_1}$ : \_\_\_\_\_ cm    $x_3^{y_1}$ : \_\_\_\_\_ cm    $x_4^{y_1}$ : \_\_\_\_\_ cm    $x_5^{y_1}$ : \_\_\_\_\_ cm

16. Raise the height  $y$  and place the marble inside the PVC pipe at the pre-chosen  $h$  and record 5  $x$  positions upon release of the marble.

$y_2$ : \_\_\_\_\_ cm

17. Record 5 measurements of  $x$ .

$x_1^{y_2}$ : \_\_\_\_\_ cm    $x_2^{y_2}$ : \_\_\_\_\_ cm    $x_3^{y_2}$ : \_\_\_\_\_ cm    $x_4^{y_2}$ : \_\_\_\_\_ cm    $x_5^{y_2}$ : \_\_\_\_\_ cm

18. Raise the height  $y$  and place the marble inside the PVC pipe at the pre-chosen  $h$  and record 5  $x$  positions.

$y_3$ : \_\_\_\_\_ cm

19. One last time, raise the height  $y$  and place the marble inside the PVC pipe at the desired pre-chosen  $h$  and record 5  $x$  positions upon release of the marble.

$x_1^{y_3}$ : \_\_\_\_\_ cm    $x_2^{y_3}$ : \_\_\_\_\_ cm    $x_3^{y_3}$ : \_\_\_\_\_ cm    $x_4^{y_3}$ : \_\_\_\_\_ cm    $x_5^{y_3}$ : \_\_\_\_\_ cm

20. Now calculate the average  $x$  value for each height  $y$ .

$x_{avg}^{y_1}$ : \_\_\_\_\_ cm    $x_{avg}^{y_2}$ : \_\_\_\_\_ cm    $x_{avg}^{y_3}$ : \_\_\_\_\_ cm

21. Make a simple plot of  $x_{avg}^{y_i}$  vs  $y_i$  for  $i = 1, 2, 3$ , (remember that  $x$  and  $y$  are distances, for this you will be plotting  $x_{avg}^{y_i}$  on the y-axis and  $y_i$  on the x-axis. Confused yet?) below. Also make a plot using a graphing program of your choice for your lab report due next week.

**Question 2:** Is the graph in the previous step linear or exponential? Using equations 3.1 and 3.3, what can you say about the relationship between  $y$  and  $x$ ? Write out the equation in your lab report and relate it to your graph. Discuss this in the results section of your lab report.

★**Honors Question A:** If you were on the moon and preformed the same experiment where

$$g_{moon} = \frac{1}{6}g_{earth},$$

and your  $x$  measurement was  $x_{avg}^{S1}$  and your  $y$  measurement was the first  $y$  height measured in this experiment, what would  $v_{x0}$  be on the moon? Calculate the percent difference between the initial velocity on the Moon and the Earth.

$$v_{x0}: \text{_____ m/s} \quad \frac{|v_M - v_E|}{v_E}: \text{_____}$$

★**Honors Question B:** Are the  $x$  values measured on the Moon the same as on Earth? Why or why not?

★★ **Theory — Honors Question C:** Suppose that you are on the Moon with the same experiment apparatus. If the apparatus were tilted slightly upwards such that the marble *does* have an initial vertical velocity what can you say about the  $x$  values that you would measure? Are they the same as on Earth? If they are not, what mathematical correction would you make to equation 3.3? Hint: You may have to use the quadratic formula.

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QUIZ 3 - Projectile Motion

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## Chapter 4

# Newton's Three Laws

### 4.1 A Brief History

Isaac Newton was born on Christmas Day in 1642. It very well may be impossible to take any physics courses without ever mentioning his name in some context. In 1687, Newton published his three laws that describe rigid body motion. The title of the publication was called *The Principia* and it would be more than two hundred years before the equations would undergo any sort of “corrections”, or more precisely a “generalization”. Newton’s Three Laws of Motion are applied to objects that are considered to be one entity. That is to say: a planet may be considered a single entity, a cardboard box may be considered a single entity, and even your cat may be considered a single entity. The point I am trying to convey is that Newton’s Three Laws, as they stand, consider all objects to be point-like objects. In today’s experiment you will observe the motion that Newton’s Three Laws describe.

For any students that are Physics Majors or are just genuinely curious, it might be interesting to know that the generalization of Newton’s Laws involves Special Relativity and the Euler-Lagrange formalism of classical mechanics. That is to say, Newton’s Laws are fantastic approximations for objects travelling with small velocities relative to the speed of light.

### 4.2 Definitions

1. *Force*-The quantity used to describe the relationship between an objects mass and acceleration.  $\vec{F} = m\vec{a}$
2. *Acceleration*-The rate at which an objects velocity changes.  $\vec{a} = \frac{d\vec{v}}{dt}$
3. *Mass*-Intrinsic property of matter which provides resistance to movement.
4. *Newton's First Law*-Also called the Law of Inertia. A body remains at rest or in uniform motion in a straight line unless acted upon by a force. See Chapter 9 for more information.
5. *Newton's Second Law*-The force a body exhibits is equal to its mass times acceleration. Quite simply  $\vec{F} = m\vec{a}$ .
6. *Newton's Third Law*-A force that acts on a body due to another body exhibits an equal and opposite force simultaneously on that body.  $F_1 + F_2 = 0$  or in perhaps a more familiar form  $F_1 = -F_2$ .
7. *Equilibrium*-When the sum of the forces on an object is equal to zero that object is said to be in equilibrium.

## 4.3 Laboratory Objectives

By the end of today's exercise it is in the hopes of this Author that you will have observed the following:

1. The **1<sup>st</sup> Law of Motion**: Law of Inertia
2. The **2<sup>nd</sup> Law of Motion**:  $\vec{F} = m\vec{a}$
3. The **3<sup>rd</sup> Law of Motion**: Law of Action and Reaction

## 4.4 Equipment

Cart Track, Two Carts, Plastic Picket Fence, Meter Stick, Two Photogates, Balance, Various Weights, Datastudio

## 4.5 Procedure

1. **Newton's First Law**: Place a cart on the level track with the picket fence attached to the dorsal area of the cart. The part of the **Picket Fence** with **7** black bands should be the part that passes through the photogate sensor. It will turn red for each band if the photogate is at the correct height.
2. The first photogate that the cart will pass through we shall call **Photogate 1**, the second photogate that the cart passes through shall be called **Photogate 2**. Allocate the cords from **Photogate 1** to Channel 1, and likewise for **Photogate 2** to Channel 2.
3. On the Datastudio program select the *Photogate and Picket Fence* icon. Under measurements, deselect position and acceleration. Under the Constant tab type in **0.01 m**. This represents the spacing for the **Picket Fence**. Repeat for the second photogate.
4. Let us now observe Newton's First Law - The Law of Inertia. Place the cart at one end of the track such that it will pass through **Photogate 1** first, and then **Photogate 2** second. The following figure may be useful.

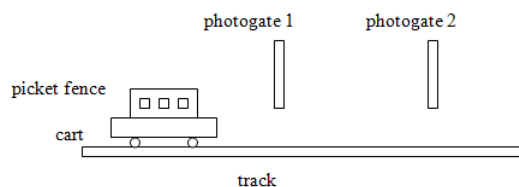


Figure 4.1: Photogate Setup

5. Begin recording data by clicking *Start*. Now push the cart forward with a *reasonable* push. If the cart somehow managed to leave the track and hit the group across from your group, you did it wrong and you should feel bad.
6. After both **Photogate 1** and **Photogate 2** have been cleared by the slowly rolling cart you may click the *Stop* button to stop recording new data.

7. The *Table Display* should show the velocity of the cart as it passed **Photogate 1** and **Photogate 2** separately once you drag your data to that icon. Drag the *Velocity* run data and place it in the *Table Display* icon. Once the table is displayed with data from the Velocity, drag the data from Channel 2 to the *Table Display* icon. Using the *Statistics* button choose “Mean” and then record the two values of interest below where  $m = \text{mean}$ .

$$v_1^m: \text{_____ m/s} \quad v_2^m: \text{_____ m/s}$$

8. Perform this experiment two more times recording the mean values.

$$v_3^m: \text{_____ m/s} \quad v_4^m: \text{_____ m/s} \quad v_5^m: \text{_____ m/s} \quad v_6^m: \text{_____ m/s}$$

**Question 1:** What have you noticed about the change in velocity between the gates?

9. **Newton’s Second Law:** Incline the track slightly, perhaps around **10** degrees by eye. **Photogate 1** and **Photogate 2** should be readjusted such that they measure the same section of the **Picket Fence** that you measured previously. With the track inclined, you now have a triangle with the table being the base. Measure the distance of the base and the height of the inclined track.

$$x(\text{base}): \text{_____ cm} \quad y(\text{height}): \text{_____ cm} \quad \theta(\text{angle}): \text{_____ deg} \quad R = (\sqrt{x^2 + y^2}): \text{_____ cm}$$

10. Measure the mass of the cart with the picket fence attached.

$$m_1: \text{_____ kg}$$

11. Invoke a “buddy” system in your group such that you do not let go of the cart until the next step. One person should place the cart at one end such that it passes through **Photogate 1** first and **Photogate 2** second. Your “buddy” should be located at the opposite end of the track such that the cart may be caught upon arriving at its final destination.
12. In Datastudio, click the *Start* button to begin recording. At your leisure, allow the cart to pass through both gates. You may click the *Stop* button upon the cart’s successful descent into your buddy’s hands.
13. Drag the relevant Run data to the Table Display for **Photogate 1** and **Photogate 2**. As before, find the Mean velocity for the run.

$$v_1^m: \text{_____ m/s} \quad v_2^m: \text{_____ m/s}$$

From class you derived many equations that involve velocity and acceleration. One of these equations that was derived is

$$v_2^2 = v_1^2 - 2aR \tag{4.1}$$

where  $v_2$  and  $v_1$  are the Mean velocities you measured for **Photogates 2** and **1** respectively. Keep in mind that  $v_2$  and  $v_1$  are squared.  $a$  is the acceleration of the object in question and  $R$  is the distance travelled on that path. In our case  $R$  is the track length, do not forget to convert units if necessary. Solving for the acceleration of the object yields

$$a = -\frac{(v_2^2 - v_1^2)}{2R} \tag{4.2}$$



Find the acceleration from the recent data you collected.

$$a_1: \text{ \_\_\_\_\_\_ m/s}^2$$

Using Newton's Second Law, find the force associated with that acceleration.

$$F_1: \text{ \_\_\_\_\_\_ N}$$

14. Add a **0.5 kg** bar to the cart and find the Mean velocities for another Run.

$$m_2: \text{ \_\_\_\_\_\_ kg}$$

$$v_3^m: \text{ \_\_\_\_\_\_ m/s} \quad v_4^m: \text{ \_\_\_\_\_\_ m/s} \quad a_2: \text{ \_\_\_\_\_\_ m/s}^2 \quad F_2: \text{ \_\_\_\_\_\_ N}$$

15. Add another **0.5 kg** bar to the cart and find the Mean velocities for another run.

$$m_3: \text{ \_\_\_\_\_\_ kg}$$

$$v_5^m: \text{ \_\_\_\_\_\_ m/s} \quad v_6^m: \text{ \_\_\_\_\_\_ m/s} \quad a_3: \text{ \_\_\_\_\_\_ m/s}^2 \quad F_3: \text{ \_\_\_\_\_\_ N}$$

**Question 2:** Make a rough plot sketch of  $F$  vs  $M$  below for your own convenience. Is the relationship between them linear? Find the slope. What is the significance of the slope? Would Newton's Second Law hold if the plot was linear or non-linear? Describe. If you were to trace the line back to  $F = 0$ , what point on the mass axis would it go through? Make a plot in a graphing program of your choice for your lab report due next week.

16. **Newton's Third Law:** Lower the track back to the level position. Remove the masses from the cart and readjust the two photogates such that they measure the **Picket Fence** black bands you have been measuring throughout this experiment.

17. Measure the masses of the two carts and picket fences

$m_1$ : \_\_\_\_\_kg    $m_2$ : \_\_\_\_\_kg

18. One of the carts that you have has a metal plunger. It is spring loaded and can be locked into position by firmly pushing it in while pushing up simultaneously. Lock the plunger.

19. Place the two carts together such that the two cart system is located between **Photogate 1** and **Photogate 2**. The idea is that once the plunger is released the two carts will separate and we will then be able to measure the velocities as cart 1 passes **Photogate 1** and as cart 2 passes **Photogate 2**. Obviously the plunger should be facing one of the carts or your group will look quite silly when nothing happens once the plunger is released. It is an ideal setup in which both of the photogates are located at the edges of the two cart system such that each cart will pass completely through their respective photogate.

20. In **Datastudio** click the *Start* button after reading the next step.

21. Using a nifty trick that I personally developed, grab the black **0.5 kg** bar used to add mass to the cart. By using the bar to tap the metal rod that releases the plunger you may almost completely remove the element of quick reflexes from this part of the experiment. On a side note, if you ever mention "human error" in a lab report, you are doing it wrong. "Human Error", in a submitted college paper, means that you did not want to go through the effort of telling the reader what actually happened in detail, *because knowing is half the battle*.

22. Using the "buddy" system developed previously, catch the two carts before they bounce back into the range of the two photogates. Click the *Stop* button in **Datastudio**.

23. Display the two velocities the same way you have been using the *Table Display* icon and record their mean velocities.

$v_1^m$ : \_\_\_\_\_m/s    $v_2^m$ : \_\_\_\_\_m/s

24. Multiply  $v_1^m$  by  $m_1$  to get the momentum  $p_1$ .

$p_1$ : \_\_\_\_\_kg m/s

25. Multiply  $v_2^m$  by  $m_2$  to get the momentum  $p_2$ .

$p_2$ : \_\_\_\_\_kg m/s

**Question 3:** Are the momenta approximately equal? Calculate the percent difference between the two momenta. Discuss this in the Results section of your lab report.

26. Repeat this part of the experiment two more times.

$v_3^m$ : \_\_\_\_\_m/s    $v_4^m$ : \_\_\_\_\_m/s    $v_5^m$ : \_\_\_\_\_m/s    $v_6^m$ : \_\_\_\_\_m/s

$p_3$ : \_\_\_\_\_kg m/s    $p_4$ : \_\_\_\_\_kg m/s    $p_5$ : \_\_\_\_\_kg m/s    $p_6$ : \_\_\_\_\_kg m/s

★**Honors Question A:** Derive Newtons Second Law from momentum. You may attach this derivation to your lab report. It may be hand written.

★★ **Theory — Honors Question B:** In physics there are quantities called conserved quantities. A quantity is considered conserved if its derivative is equal to 0. If the net force on a system is 0 N and the system is in constant motion what can you say about the momentum? Is momentum conserved?

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QUIZ 4 - Newton's Three Laws

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## Chapter 5

# Centripetal Forces

### 5.1 A Brief History

Centripetal Force is a force that acts perpendicular to the velocity of an object that is following a curved path. A good example of Centripetal Force is that of a Merry-Go-Round from our cherished childhoods. As a child you may have decided to sit on the edge of the Merry-Go-Round while your “friends” spun you around. As your so-called-friends spun you faster and faster telling you that it would be fun you felt the urge to hold on tighter as a “force” pushed you out of the ride. That “force” pushing you out of the Merry-Go-Round turned out to be a Centrifugal Force. To be clear, Centrifugal Force  $\neq$  Centripetal Force; see (XKCD-123) for some light details. The force you “feel” pushing you out is merely the change in velocity as your body turns with the ride; there is no outward force. Recall that velocity is a vector quantity and even if the Speed of motion is constant, the direction may not be constant; hence a change in velocity. There is an inward force however, this is the Centripetal Force. Why then do you not fly into the middle if the outward force is not real? Quite simply, you are attached to the Merry-Go-Round. The force that is *fighting* your grip on the Merry-Go-Round is the Centripetal Force. In today’s experiment you will observe the force caused by uniform circular motion.

### 5.2 Definitions

1. *Centripetal Force*-The force that is created upon an object moving in a curved path where the force points perpendicular to the movement of the object.
2. *Radius*-The length between two points of interest conventionally in polar coordinates, usually taken from the origin to a point of interest.
3. *Uniform Circular Motion*-Motion an object undergoes that traces a circle with constant speed.

### 5.3 Laboratory Objectives

By the end of today’s exercise it is in the hopes of this Author that you will understand how:

1. The **angular acceleration** is related to the velocity squared.
2. The **force** acting on an object is related to the angular acceleration.
3. The **inverse** relationship that angular acceleration and force have with the radius of an object in circular motion work.

Of course there are some questions that you should already be asking yourself:

1. “If I increase the velocity of the object, what happens to the force while the radius is constant?”
2. “If I decrease the velocity of the object, what happens to the force while the radius is constant?”
3. “If I increase the radius of circular motion of an object, what happens to the force and acceleration?”
4. “If I decrease the radius of circular motion of an object, what happens to the force and acceleration?”

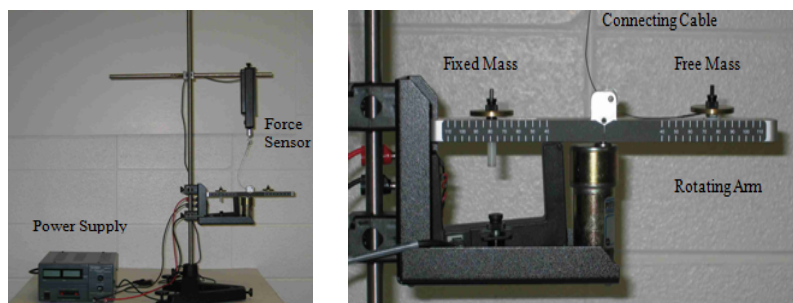
If you read through the introduction then perhaps some of these questions have already been answered to some depth, but lets delve deeper into the rabbit hole in order to observe what I have described above.

## 5.4 Equipment

Centripetal Force Apparatus, Various Disk Weights, Datastudio

## 5.5 Procedure

1. See the following figures for labels that I will be referring to for the remainder of this chapter.



2. Begin by adding a small amount of weight to the **Free Mass Holder**, **0.02 kg** is reasonable. The **Free Mass Holder** weighs approx. **0.004 kg**. Add the same amount of weight to the opposite side on the Fixed Mass Holder. Use the screw that is attached to the device to firmly secure the weights. The **Free Mass Holder** should be able to move linearly in *one direction*. If you have a hard time moving it, loosen the **Free Mass Holder** slightly until it may move unhindered by such a petty thing as friction.

Mass Added: \_\_\_\_\_kg Free Mass Holder: \_\_\_\_\_kg

3. The **Force Sensor**, which is the same **Force Sensor** used in Chapter 2, is located above the apparatus and is connected by a string. Position the **Force Sensor** such that the **Free Mass Holder** is located at the **8 cm** position and the string is taut between the two. Adjust the **Fixed Mass Holder** to be at the same position. This is merely to balance the unit such that it does not break, thus sending your instructor to the hospital for six months.
4. On the Desktop for your computer should be a file named “Force Vel Linear SW 2”. Click on that file. **Datastudio** should have been opened. On the *Calculate* box, enter the value for your radius in meters. For our case this is **0.08 m**. Click the *Accept* button once that is done.
5. Turn on the **Power Supply** connected to the **Centripetal Force** apparatus. *Slowly* increase the voltage, which will cause the rotary arm to spin. When the speed of the rotary arm reaches a constant value and the voltage is **1 or 2 volts**, click the *Start* button in **Datastudio** to begin recording data.

6. *Slowly* increase the voltage to a maximum of **8 volts**. This will cause the rotary arm to speed up and also give you relevant data on the relationship between increased velocity and force. Once you reach **8 volts** click the *Stop* button in **Datastudio** to stop recording new data. You may now *reduce* the voltage to **0 volts** on the **Power Supply**.
7. **Datastudio** automatically graphs the data for this run. Using the Graph Display icon display the data. Select the *Fit* button on the graph toolbar and select the option “Quadratic Fit”.

**Question 1:** Are the two curves sketched out approx. the same? Discuss this in the results section in your lab report.

8. Click the *Smart Tool* button on the graph toolbar. This will allow you to view the x-axis coordinates and the y-axis coordinates. Find three points that interest you and record them. Make a note of whether Force is the x-axis or the y-axis, and the same for velocity. It is important! Recall that in the equation of a line, namely  $y = mx + b$ , the value b is where  $x = 0$ . Similarly we shall use the letter C such that in our case C is the value of force where the velocity is 0 (not position). Find where the velocity is 0 and record its value of force. Note: A lot of your measurements may be negative, why?

C: \_\_\_\_\_N

$x_1$ : \_\_\_\_\_ m/s    $y_1$ : \_\_\_\_\_ N    $x_2$ : \_\_\_\_\_ m/s    $y_2$ : \_\_\_\_\_ N    $x_3$ : \_\_\_\_\_ m/s    $y_3$ : \_\_\_\_\_ N

For each of your y-axis values that you recorded, subtract C from your  $y_i$  for  $i=1,2,3$  to find what  $F_r^i$  is.  $F_r^i$  stands for the recorded Force for each  $y_i - C$ .

$F_r^1$ : \_\_\_\_\_ N    $F_r^2$ : \_\_\_\_\_ N    $F_r^3$ : \_\_\_\_\_ N

9. Now instead of reading the Force values from the graph, let us find the Force  $F_c$  predicted for each velocity  $x_i$  found above. More to the point, instead of subtracting C from the  $y_i$  values above, we will directly calculate the force using

$$a = \frac{v^2}{r} \tag{5.1}$$

and

$$F = ma. \tag{5.2}$$

When 5.1 is plugged into 5.2, we get

$$F = \frac{mv^2}{r}. \tag{5.3}$$

Take the three values you have for velocity, namely  $x_i$  (for  $i=1,2,3$ ). Using the total mass, which is the Mass Added + Mass of the Free Holder, plug them into (5.3) to discover what  $F_c^i$  is.

$F_c^1$ : \_\_\_\_\_ N    $F_c^2$ : \_\_\_\_\_ N    $F_c^3$ : \_\_\_\_\_ N

**Question 2:** Find the percent difference between the Force you calculated ( $F_c^i$ ) and the Force recorded by the apparatus ( $F_r^i$  for  $i=1,2,3$ ). Discuss this in the results section of your lab report.

- Close the current session in Datastudio by completely exiting the program. On the Desktop there is a file called "Force Mass SW2"
- Your goal is now to find the relationship between the Centripetal Force and Mass. Set the **Power Supply** to **7 volts** and let it spin for a few seconds. Click the *Start* button and let it spin for a few more seconds such that you may record enough relevant data. Click the *Stop* button.
- Turn the **Power Supply** to **0 volts** for the time being.
- Display the data gathered using the **Table Display** icon. The table will show up with the relevant data gathered. Find the Mean value of the Force.

$F_1^m$ : \_\_\_\_\_N     $m_1$ : \_\_\_\_\_kg

- Drag the Force vs Mass data to the *Table Display* icon. Type in the values for the total mass and the mean value of the force in the correct slots. Keep this table for the next few steps.
- Add **0.005 kg** to both sides of the Centripetal Force Apparatus. Repeat the same process that you did for  $F_1^m$ . Record all of the Mean Force Values and Total Masses. Repeat two more times.

$F_2^m$ : \_\_\_\_\_N     $m_2$ : \_\_\_\_\_kg

$F_3^m$ : \_\_\_\_\_N     $m_3$ : \_\_\_\_\_kg

$F_4^m$ : \_\_\_\_\_N     $m_4$ : \_\_\_\_\_kg

(Note: Add the new data collected to the table). There should be a graph that automatically displays the data for you. By now you should have easily been able to figure out that the graph is linear due to Newton's Second Law.

**Question 3:** Using a graphing program of your choice plot a graph of  $F_i^m$  vs  $m_i$  for ( $i = 1,2,3$ ). Make a linear fit and find the slope of the line. What is the significance of the slope? Include this graph and discuss this question in the results section of your lab report.

**Question 4:** Discuss the relationships of Centripetal Force, Velocity, Acceleration, and Mass in the results section of your lab report.

★**Honors Question A:** In what direction does the acceleration in (5.1) point?

★**Honors Question B:** What is the difference between Centrifugal Force and Centripetal Force? Judging by your difference is centrifugal force real or is it a virtual force?

★★★ **Theory — Honors Question C:** Can centripetal acceleration be used on the international space station (ISS) to create a sense of “artificial gravity”? If so, how would you go about this? Hint: Read the book 2001: A Space Odyssey, or watch the movie.

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QUIZ 5 - Centripetal Force

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## Chapter 6

# Energy Conservation

### 6.1 A Brief History

Conservation Laws are to Physicists as Violins are to Violinists. Conservation means that something can not be created or destroyed without leaving something equal to its former existence behind. This “something” may be thermal heat, an act of force, or even a change of momentum. In today’s experiment you will observe how energy transfers from Kinetic Energy to Potential Energy and from Potential Energy to Kinetic Energy.

### 6.2 Notes

1. Bring a flash drive for the next lab: Conservation of Momentum.

### 6.3 Definitions

1. *Kinetic Energy*-The energy that is conventionally associated with the velocity squared of an object.
2. *Potential Energy*-The energy that is conventionally associated with the stationary initial location of an object.

### 6.4 Laboratory Objectives

By the end of today’s exercise it is in the hopes of this Author that you will understand how:

1. The **kinetic energy** may become potential energy.
2. The **potential energy** may become kinetic energy.
3. The **conservation** of energy holds for a closed system.

### 6.5 Equipment

Cart Track, One Cart, String, Various Hangable Masses, One Photogate, Datastudio.

## 6.6 Procedure

1. Open **Datastudio** as usual and select the all-too-familiar “Photogate and Picket Fence” option from the sensor list. Select the *Setup* button, and click on the tab labelled *Constant* and set the Picket Fence band gaps at 0.02 m.
2. Measure the mass of your cart and picket fence combined:

$m$ : \_\_\_\_\_ kg

The following figure should give you an idea on how this experiment is going to work.

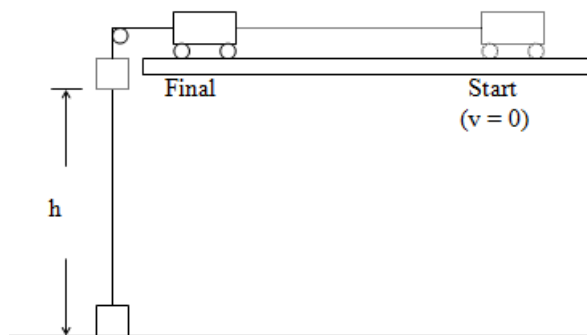


Figure 6.1: Cart-Track Setup

3. Using the **String** provided, attach the **Cart** to the **Hanging Mass** via the pulley system. The ideal length of **String** is when the **Cart** is in its *Final Position* as seen above in the figure and the **Hanging Mass** is barely touching the ground.
4. While the **Cart** is in its *Final Position*, place the Photogate such that it is directly behind the **Cart**. That is to say that the **Cart** should fully pass the Photogate and then come to a stop such that the *Final Velocity* is measured.
5. Retract the **Cart** to the start position and then measure the distance  $h$  as shown in the figure above.

$h$ : \_\_\_\_\_ m

6. Place something in the way of the **Cart** so that you do not need to hold it while you read the following few tidbits about Kinetic Energy and Potential Energy.

Any object that is in motion with respect to some reference point, say the origin of a coordinate system, is defined to have a Kinetic Energy ( $K$ ) associated with its velocity  $v$ :

$$K = \frac{1}{2}mv^2, \quad (6.1)$$

where  $m$  is the mass of the object, and  $v$  is the velocity of the object. That same object also has a Potential Energy associated with its mass and position in a gravitational field. Such energy is called the gravitational Potential Energy ( $U$ ):

$$U = mgh, \quad (6.2)$$

where  $m$  is the mass of the object,  $g$  is the acceleration of gravity, and  $h$  is the height from a reference point of interest. In today's experiment the ground will be the reference point of interest.

Let us put these two quantities in terms of today's experiment. When the Hanging Mass starts out initially, it has zero velocity relative, to the ground therefore it has zero Kinetic Energy. Its Potential Energy, however, is not zero. In fact it is  $mgh$ . When the cart is released from its stationary position the hanging mass will begin to fall. As the Hanging Mass falls, the distance  $h$  begins to shorten as it approaches the ground. As  $h$  decreases, so does the Potential Energy  $U$ . Simultaneously, the Hanging Mass has a non-zero velocity once the cart is released. This means that the Kinetic Energy is increasing as the Potential Energy is decreasing. As previously stated, the total energy of a closed system is conserved. This leads to the conclusion that the total energy is

$$E_{tot} = K + U. \quad (6.3)$$

**Question 1:** What is the initial Kinetic Energy of the Cart? What is the initial Kinetic Energy of the Hanging Mass? What is the initial Potential Energy of the Cart? What is the initial Potential Energy of the Hanging Mass? Discuss this in the results section in your lab report.

Since the total energy in this system cannot increase or decrease we may set  $E_{tot}$  equal to some constant. Let us choose  $E_{tot} = 0$  such that  $K = -U$ . It is not uncommon to say that the initial state of a system has a net total energy of zero. In fact, we define the starting position of the system to have zero Potential, and zero velocity. Therefore, as the **Hanging Mass** changes position and velocity the Kinetic Energy and Potential Energy will cancel each other out ideally. This is known as the conservation of energy.

7. Add **0.025 kg** to the Hanging Mass. On **Datastudio**, click the *Start* button. Release the **Cart** to allow the **Hanging Mass** to fall downwards. Using the "buddy" system developed earlier, catch the **Cart** after it passes through the photogate completely. On **Datastudio**, click the *Stop* button.
8. Display your data using the *Table Display* icon. Find the mean of the velocity.

$v_1^m$ : \_\_\_\_\_ m/s     $m_1$ : \_\_\_\_\_ kg

9. Add **0.005 kg** to the **Hanging Mass**. Repeat part 8.
10. Display your data using the *Table Display* icon. Find the mean of the velocity.

$v_2^m$ : \_\_\_\_\_ m/s     $m_2$ : \_\_\_\_\_ kg

11. Add **0.005 kg** to the **Hanging Mass**. Repeat part 8.
12. Display your data using the *Table Display* icon. Find the mean of the velocity.

$v_3^m$ : \_\_\_\_\_ m/s     $m_3$ : \_\_\_\_\_ kg

**Question 2:** Just before the **Hanging Mass** touches the ground, is the Kinetic Energy larger or is the Potential Energy larger? Discuss this in the results section in your lab report.

13. Calculate the Kinetic energy for each case of the **Hanging Mass**.

$$K_1: \text{ \_\_\_\_\_\_J} \quad K_2: \text{ \_\_\_\_\_\_J} \quad K_3: \text{ \_\_\_\_\_\_J}$$

14. Calculate the Potential energy for each case of the **Hanging Mass**, remember this will be the Potential Energy at height  $h$ .

$$U_1: \text{ \_\_\_\_\_\_J} \quad U_2: \text{ \_\_\_\_\_\_J} \quad U_3: \text{ \_\_\_\_\_\_J}$$

15. Find the difference between the two.

$$K_1 - U_1: \text{ \_\_\_\_\_\_J} \quad K_2 - U_2: \text{ \_\_\_\_\_\_J} \quad K_3 - U_3: \text{ \_\_\_\_\_\_J}$$

**Question 3:** Was the difference between K and U almost 0? If not, explain why. Discuss this in the results section in your lab report.

★**Honors Question A:** Was the energy of the system conserved? Elaborate to the best of your ability.

★**Honors Question B:** In your opinion, do you think that mass or velocity controls Kinetic energy the most? Give your reasons.

\*\*\* **Theory — Honors Question C:**  $v^2$  is one of the most important quantities in physics. In the Euler-Lagrange formalism of classical mechanics it is the  $v^2$  term in the Euler Lagrange equation which allows physicists to generalize an action. Hypothesize why you might be inclined to believe that any action that happens in this Universe on the non-relativistic level may be described simply by  $v^2$ . What does this have to do with energy?

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QUIZ 6 - Conservation of Energy

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## Chapter 7

# Conservation of Momentum

### 7.1 A Brief History

In Chapter 6 you explored the Conservation of Energy. Let us now extend our growing index of Conservation Laws to include the Conservation of Momentum. For an isolated system, the total momentum  $\vec{p}$  will always be constant. Imagine that you are in space playing billiards with your best mates where the billiards tabletop is Euclidean flat-space. You see that the 8-ball is in an ideal position to make the corner pocket that has been placed at infinity. Aligning the cue-ball, you take the shot. The cue-ball travels at some initial velocity  $v_i$  until it hits the 8-ball, remarkably you notice that the cue-ball stopped moving upon impact with the 8-ball and that the 8-ball is now drifting with a velocity  $v_f$  towards the corner pocket placed at infinity. Assuming the two balls have the same mass you cleverly deduce that  $v_i = v_f$  and thus have observed that the transfer of momentum was total. In today's experiment you will observe the total and partial transmission of momentum from one object to another.

### 7.2 Definitions

1. *Momentum*-An object that has mass and a non-zero velocity is said to have a momentum  $\vec{p} = m\vec{v}$ .
2. *Elastic Collision*-A collision is considered **elastic** if the bodies collide and then separate.
3. *Inelastic Collision*-A collision is considered **inelastic** if the bodies collide and do not separate.

### 7.3 Laboratory Objectives

By the end of today's exercise you will understand how:

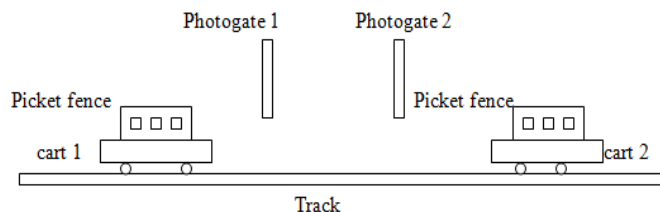
1. The **momentum** of an object may transfer to another object.
2. The type of **collision** affects the momentum of the system.

### 7.4 Equipment

Cart Track, Two Carts, Two Photogates, Balance, Various Weights, Datastudio.

## 7.5 Procedure

1. In the usual manner, open **Datastudio** and select the *Photogate and Picket Fence* icon and verify that your experiment setup looks similar to this:



2. Place the carts on the level track with the **Picket Fence** attached to the dorsal area of the cart. The part of the **Picket Fence** with 7 black bands should be placed such that when the cart passes through the photogates such that the sensor turns red for every band that passes through it.
3. In **Datastudio** select *Setup* to adjust some parameters for each photogate. Under the *Constants* tab type in **0.01 m**. This represents the spacing for your **Picket Fence**. Repeat this for **Photogate 2**.
4. Take your carts and picket fences to the balance and find the masses.

$m_1$ : \_\_\_\_\_kg    $m_2$ : \_\_\_\_\_kg

5. To calibrate the position of the photogates, place the two carts in the middle of the track such that they are touching end to end. **Photogate 1** and **Photogate 2** should be placed such that the two carts placed end to end easily fit inside the distance between them.
6. Adjust **Photogate 1** and **Photogate 2** such that the motion sensor only reads the .02 m black bands. Position the carts at opposite ends of the track as seen in the figure above.
7. **Elastic Collisions**: There is a magnet located at one end on both carts. Locate this magnet and adjust the orientation of the carts such that the magnets will repel when the carts are within a certain proximity to one another. This will ensure an Elastic Collision.

8. On **Datastudio**, click the *Start* button to begin recording data. Push the two carts towards one another such that the collision happens completely between the photogates. Allow the carts to repel one another and pass back through their respective photogates. Stop the two carts before they pass through the photogates a third time. On **Datastudio**, click the *Stop* button to stop recording data.
9. Drag the relevant data to the *Table Display* icon. You will now need to separate the data into the desired sections. The first six data points for each gate represent the velocities before the collision. Select the first six data points and find the mean value:

$v_1^m$ : \_\_\_\_\_m/s    $v_2^m$ : \_\_\_\_\_m/s

10. The seventh data point is irrelevant, therefore ignore it.
11. The data points eight through thirteen represent the velocities after the collision. Select the data set that consists of data points eight through thirteen and find the mean value:

$v_3^m$ : \_\_\_\_\_m/s    $v_4^m$ : \_\_\_\_\_m/s

12. Calculate the momentum for each cart before the collision.

$$p_1: \text{ \_\_\_\_\_\_ kg m/s} \quad p_2: \text{ \_\_\_\_\_\_ kg m/s}$$

13. Calculate the momentum for each cart after the collision.

$$p_3: \text{ \_\_\_\_\_\_ kg m/s} \quad p_4: \text{ \_\_\_\_\_\_ kg m/s}$$

14. Calculate the kinetic Energy for each cart before the collision.

$$K_1: \text{ \_\_\_\_\_\_ J} \quad K_2: \text{ \_\_\_\_\_\_ J}$$

15. Calculate the kinetic Energy for each cart after the collision.

$$K_3: \text{ \_\_\_\_\_\_ J} \quad K_4: \text{ \_\_\_\_\_\_ J}$$

**Question 1:** Find the total kinetic energy of the two cart system before and after the collision. What do your results mean? Discuss this in the results section in your lab report.

16. Place one cart between the two photogates and one car at one end of the track. On **Datastudio**, click the Start button to begin recording data.

17. Push the cart that has been placed at one of the ends of the track such that it collides Elastically with the cart that was placed in the center of the photogates.

18. Drag the velocities to the *Table Display* icon. You will now need to separate the data into the desired sections. The first **6** data points for each gate represent the velocities before the collision, *but what do you know about the initial velocity of the cart in between the two photogates?* Select the first **6** data points and find the mean value:

$$v_1^m: \text{ \_\_\_\_\_\_ m/s} \quad v_2^m: \text{ \_\_\_\_\_\_ m/s}$$

19. Select the rest of the data set and find the mean value:

$$v_3^m: \text{ \_\_\_\_\_\_ m/s} \quad v_4^m: \text{ \_\_\_\_\_\_ m/s}$$

20. Calculate the momentum for each cart before the collision.

$$p_1: \text{ \_\_\_\_\_\_ kg m/s} \quad p_2: \text{ \_\_\_\_\_\_ kg m/s}$$

21. Calculate the momentum for each cart after the collision.

$$p_3: \text{ \_\_\_\_\_\_ kg m/s} \quad p_4: \text{ \_\_\_\_\_\_ kg m/s}$$

22. Calculate the kinetic energy for each cart before the collision.

$$K_1: \text{ \_\_\_\_\_\_ J} \quad K_2: \text{ \_\_\_\_\_\_ J}$$

23. Calculate the kinetic energy for each cart after the collision.

$$K_3: \text{ \_\_\_\_\_\_ J} \quad K_4: \text{ \_\_\_\_\_\_ J}$$



**Question 2:** Find the total kinetic energy of the two cart system before and after the collision. What do your results mean? Discuss this in the results section in your lab report.

24. **Inelastic Collision:** Place the carts in a similar manner to the previous setup in which one cart is placed in between the two photogates and one cart is located at one of the end points.
25. Orient the carts such that the velcro on both sides of the carts will stick once the carts collide. You may need to move the position of the photogates so that both carts will pass through the second photogate. On **Datastudio**, press the *Start* button to begin recording data.
26. Push the cart that is located at one of end points and allow it to hit the cart that has been placed between the two photogates. Allow both carts to pass the final photogate. On **Datastudio** press the *Stop* button.
27. Drag the relevant data to the **Table Display** icon. You will now need to separate the data into the desired sections. *What do you know about the initial velocity of the cart in between the two photogates?* Select the first **6** data points and find the mean value:

$$v_1^m: \text{ \_\_\_\_\_\_ m/s} \quad v_2^m: \text{ \_\_\_\_\_\_ m/s}$$

28. The first six data points from the other photogate measured the final velocity of the cart starting from rest. The last six data points measured the final velocity of the other cart. Separately select each six points and find the mean value:

$$v_3^m: \text{ \_\_\_\_\_\_ m/s} \quad v_4^m: \text{ \_\_\_\_\_\_ m/s}$$

29. Calculate the momentum for each cart before the collision.

$$p_1: \text{ \_\_\_\_\_\_ kg m/s} \quad p_2: \text{ \_\_\_\_\_\_ kg m/s}$$

30. Calculate the momentum for the two-cart system after the collision.

$$p_3: \text{ \_\_\_\_\_\_ kg m/s}$$

31. Calculate the kinetic energy for each cart before the collision.

$$K_1: \text{ \_\_\_\_\_\_ J} \quad K_2: \text{ \_\_\_\_\_\_ J}$$

32. Calculate the kinetic energy for the two-cart system after the collision.

$$K_3: \text{ \_\_\_\_\_\_ J}$$

**Question 4:** Find the total kinetic energy of the two cart system before and after the collision. What do your results mean? How does this compare to the previous questions? Can you confidently state that the momentum in each was approximately conserved? Discuss this in the results section in your lab report.

★**Honors Question A:** Was momentum conserved in this experiment? If yes, in what way?

★**Honors Question B:** Was energy conserved in this experiment? If yes, in what way?

\*\*\* **Theory — Honors Question C:** On a separate piece of paper, prove A and B mathematically. Approximations are ok considering friction.

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QUIZ 7 - Conservation of Momentum

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# Chapter 8

## Torque

### 8.1 A Brief History

Torque( $\tau$ ) is a term in physics that is best used to describe what happens when a force is applied on a object that causes a rotation. Torque is often confused as being a force, however a quick delving into dimensional analysis yields that  $[\tau] = \text{Newton-Meter}$ . Being more concise we state that a Torque is a force applied over a distance. For example, when you left your dwelling to come to campus today you applied a force over a distance to a door to open it and then close it; a Torque. In the previous chapters we discovered that Force is in fact a vector. Since [Torque] is defined to have units of Force  $\times$  Distance, it is a safe assumption to make that Torque is indeed a vector. In today's experiment, you will observe how Torques applied to a Meter Stick can cause a rotation about a center of rotation.

### 8.2 Definitions

1. *Torque*-The measure of a force's tendency to produce torsion or rotation about an axis, equal to the product of the force vector and the radius vector from the axis of rotation to the point of application of the force; the moment of a force<sup>1</sup>.
2. *Fulcrum*-The point or support on which an object pivots.

<sup>1</sup>Definitions were provided by *The American Heritage Science Dictionary*.

### 8.3 Laboratory Objectives

By the end of today's exercise it is in the hopes of this Author that you will understand:

1. **Torque** is defined on an object that is not considered to be "point-like".
2. The **relationship** between Force and Distance with respect to an applied Torque.
3. How to **determine the mass** of an object without using a balance.

### 8.4 Equipment

Knife Edge Meter Stick Clamp, Meter Stick Support Stand, Meter Stick, Various Hanging Masses, Balance, Hanging Strings.

## 8.5 Procedure

1. The experiment apparatus should already be ready to go with the **Meter Stick** located on the **Meter Stick Support Stand** at about the **50 cm** point. This will allow the **Meter Stick** to balance itself.
2. Next, place a **0.01 kg** mass ( $m_1$ ) on one side of the **Meter Stick**, and place a **0.02 kg** mass ( $m_2$ ) on the other side of the **Meter Stick**. Find a position for  $m_1$  such that it balances the **Meter stick** with  $m_2$  on the other side. *You may need to adjust  $m_2$  also.* Record these two positions:

$d_1$ : \_\_\_\_\_ cm     $d_2$ : \_\_\_\_\_ cm

3. Let us digress and find how one might approach finding the Torques for the distances  $d_1$  and  $d_2$  you measured. It was not *clearly* stated before, but Torque is defined as Force crossed into Distance, or rather

$$\tau = \vec{F} \times \vec{d}. \quad (8.1)$$

Notice that the Torque is perpendicular to both the Force and the Distance Vector. You may think of the Distance Vector as being the radius with a direction associated with it. For the case you are dealing with I made use the definition of the cross product

$$\tau = \vec{F} \times \vec{d} = Fd \sin \theta$$

with

$$\sin \theta \approx 1$$

because the angle  $\theta$  between the force and the distance vector will be approximately  $\pi/2$ . I will also ask you to ignore the direction of the torque...*unless you are in the Honor's section, since one of the Honor's questions deals with answering this particular problem.* Therefore,

$$\tau = Fd. \quad (8.2)$$

4. Using equation (8.2) find the torque at the point  $d_1$  and the point  $d_2$ . *Do not forget to change your distance into meters.*

$\tau_1$ : \_\_\_\_\_ N m     $\tau_2$ : \_\_\_\_\_ N m

Find the Percent Difference of Torque between the two sides: \_\_\_\_\_

**Question 1:** Do the torques on the left side of the Meter Stick cancel out the Torques on the right side of the Meter Stick? Would you expect the net Torque on the Meter Stick to be 0? Discuss this in the results section in your lab report.

5. Next, place a **0.01 kg** mass ( $m_1$ ) on one side of the **Meter Stick**, and place a **0.02 kg** mass ( $m_2$ ) on the other side of the **Meter Stick**. Now add a third mass of **0.05 kg** to the side of your choosing, ( $m_3$ ). Find a position for  $m_1$ ,  $m_2$ , and  $m_3$  such that the **Meter Stick** returns to equilibrium.

$d_1$ : \_\_\_\_\_ cm     $d_2$ : \_\_\_\_\_ cm     $d_3$ : \_\_\_\_\_ cm

6. Find the associated torques:

$\tau_1$ : \_\_\_\_\_Nm    $\tau_2$ : \_\_\_\_\_Nm    $\tau_3$ : \_\_\_\_\_Nm

Find the Percent Difference of the torque between the two sides: \_\_\_\_\_

- Using the remainder of the class time, devise a means to measure the weight of the **Meter Stick** using torques. Measure the weight of the **Meter Stick** using a balance to compare your result. Write a step by step procedure on how to do this in your lab report due next week. Here is some room to work:

$m_{ms}$ : \_\_\_\_\_ kg

★**Honors Question A:** What is the direction of the Torque in step 3?

★**Honors Question B:** The  $\sin \theta$  oscillates between -1 and 1. What does this tell you about the maximum and minimum torque on an object? When is the torque on an object 0? What direction is the Force when the torque is 0?

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QUIZ 8 - Torque

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## Chapter 9

# Inertia

### 9.1 A Brief History

Inertia( $I$ ) is perhaps one of the most challenging and interesting subjects that future young physicists such as yourselves will deal with. Quite simply stated, Inertia is the tendency to resist movement. More generally, Inertia is the tendency to resist any *change* in motion. In a way, anything that has mass is quite lazy in that it does not want to move unless there is some sort of outside involvement. Inertia is related to Torque in that if you divide the Torque( $\tau$ ) applied to a system by the angular acceleration( $\alpha$ ) you will find the Inertia  $I$  of that system. More concisely,  $I = \frac{\tau}{\alpha}$ . In today's experiment you will observe the Inertia of a disk.

### 9.2 Definitions

1. *Inertia*-An object that exhibits a tendency to resist changes in velocity is said to have inertia.

### 9.3 Laboratory Objectives

By the end of today's exercise it is in the hopes of this Author that you will understand how:

1. The **inertia** of a system can change by adding objects.
2. The **moment of inertia** depends strictly on the distribution of mass an object has.
3. Different **shapes** that have mass have different Inertia.

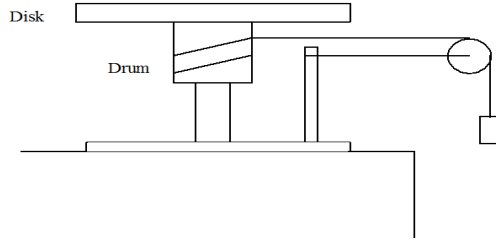
### 9.4 Equipment

Rotary Apparatus, Disk, Ring Disk, Calipers, Meter Stick, Various Weights, Balance, Pulley with string, Datastudio, Standard Ruler.

### 9.5 Procedure

1. The apparatus should have been setup by the instructor such that it has the following arrangement:





2. Measure the radius  $r_{dr}$  of the Drum. Choose and measure the weight of a **Hanging Mass**  $m_1$ .

$r_{dr}$ : \_\_\_\_\_ cm     $m_1$ : \_\_\_\_\_ kg

3. After securing the **Hanging Mass** to the string and passing the string through the **Pulley**, *rotate* the **Disk** such that the **Hanging Mass** is approximately at the *same* height as the table. Hold the **Disk** such that it does not move while you complete the next step.
4. We would like to find the acceleration of the **Hanging Mass** as it falls. Open **Datastudio** and allocate the *Smart Pulley* icon to Channel 1. On **Datastudio**, click the *Start* button. Keep in mind that after the next step you will want to press the *Stop* button the moment before the **Hanging Mass** hits the ground. This may take a few practice rounds.
5. Release the **Disk** such that it allows the **Hanging Mass** to fall to the ground and press the *Stop* button before the **Hanging Mass** is able to touch the ground.
6. Take the data recorded from the run and display it using the *Graph Display* icon. Make a note to yourself whether or not the graph is plotted as velocity vs time.
7. Select the *Fit* button and apply a *Linear Fit* to the graph that has been plotted by **Datastudio**.

Slope: \_\_\_\_\_ m/s<sup>2</sup>

**Question 1:** What does the slope of the line represent? For a hint, see the units listed above. Discuss this in the results section in your lab report.

8. Now it is necessary to calculate the Moment of Inertia of the **Disk**. Using Newton's Second Law and the "Sum of Forces" we get that the Drum-Hanging Mass system has this relationship:

$$mg - T = ma.$$

Rearranging and solving for the Tension  $T$  in the string gives

$$T = mg - ma. \tag{9.1}$$

We want to relate this equation to the equation for a Moment of Inertia. We know a Torque( $\tau$ ) acting on a body that may freely rotate about a central axis has an angular acceleration( $\alpha$ ) denoted by

$$\alpha = \frac{\tau}{I} \tag{9.2}$$

where  $I$  is the Moment of Inertia of the object in question. Rearranging to solve for  $\tau$  we get that

$$\tau = I\alpha. \quad (9.3)$$

Now using the relationship between linear and angular acceleration

$$\alpha = \frac{a}{r} \quad (9.4)$$

where  $r$  is the radius of the **Drum** and  $a$  is the linear acceleration. Substituting (9.4) into equation (9.3) gives

$$\tau = \frac{Ia}{r}. \quad (9.5)$$

We also know that  $\tau$  is also force times distance. In this case the force in question is the tension  $T$  in the string that connects the **Drum** and the **Hanging Mass**. The distance is  $r$  which is the radius of the **Drum** such that

$$\tau = rT. \quad (9.6)$$

Substituting (9.1) and (9.5) into (9.6) and solving for  $I$  gives

$$I = \frac{mr^2(g - a)}{a}. \quad (9.7)$$

9. Find the Moment of Inertia of the **Disk** using (9.7)

$$I_{disk}: \text{_____ kg } m^2$$

10. Place the **Metal Ring** on top of the **Disk**, and perform the following steps with the **Metal Ring** on top of the **Disk**.
11. We would like to find the acceleration of the **Hanging Mass** as it falls in this new system. On **Datastudio**, click the *Start* button. Keep in mind that after the next step you will want to press the *Stop* button the moment before the **Hanging Mass** hits the ground.
12. Release the Disk-Ring system such that it allows the **Hanging Mass** to fall to the ground and press the *Stop* button before the **Hanging Mass** is able to touch the ground.
13. Take the data recorded from the run and display it using the *Graph Display* icon. Make a note to yourself whether or not the graph is plotted as velocity vs time.
14. Select the *Fit* button and apply a *Linear Fit* to the graph that has been plotted by **Datastudio**.

$$\text{Slope 2: _____ m/s}^2$$

15. Find the Moment of Inertia of the Disk-Ring( $dr$ ) system using (9.7)

$$I_{dr}: \text{_____ kg } m^2$$

16. It is important to note that inertia follows an additive identity. That is to say that if we know the Moment of Inertia of all of the individual objects in a system, we know the total Moment of Inertia of a system. For the **Disk** we know that it has a Moment of Inertia of

$$I_{disk} = \frac{1}{2}MR^2 \quad (9.8)$$

where  $M$  is the mass of the **Disk** and  $R$  is the radius of the **Disk**. See your textbook for derivation of this result. Similarly for the **Metal Ring** with an inner radius  $R_1$  and an outer radius  $R_2$  we have

$$I_{ring} = \frac{1}{2}M(R_1^2 + R_2^2). \quad (9.9)$$

Notice that this is the same result if we had added the Moments of Inertia of two separate Disks with radius  $R_1$  and  $R_2$  respectively. Now measure the mass of the **Disk** and the **Ring**.

$M_{disk}$ : \_\_\_\_\_ kg     $M_{ring}$ : \_\_\_\_\_ kg

17. Measure the radius of the **Disk** and measure the radii of the **Metal Ring**.

$R_{disk}$ : \_\_\_\_\_ m     $R_1$ : \_\_\_\_\_ m     $R_2$ : \_\_\_\_\_ m

**Question 2:** Is it a safe assumption that  $I_{dr} = I_{disk} + I_{ring}$ ? Discuss this in the results section in your lab report.

18. Find the moment of inertia of the **Ring** using your results from Question 2 and earlier recorded values.

$I_{ring}$ : \_\_\_\_\_ kg  $m^2$

19. Find the Theoretical Values for  $I_{disk}$  and  $I_{ring}$

$I_{disk}$ : \_\_\_\_\_ kg  $m^2$      $I_{ring}$ : \_\_\_\_\_ kg  $m^2$

20. Percent difference between what you measured and what you theoretically calculated

Percent Difference for the **Disk**: \_\_\_\_\_    Percent Difference for the **Ring**: \_\_\_\_\_

**Question 3:** Were your percent difference values high or low? If they were high, explain why. If the percent differences were low, explain what could cause high differences. Discuss this in the results section in your lab report.

**Honors Question A:** Since  $\tau = I\alpha$  where  $\tau$  is a vector, does this mean that  $I$  is also a vector? Explain the role of inertia in terms of torque.

**\*Honors Question B:** What are the units of Inertia? Using dimensional analysis, (also known as unit analysis), and (9.7), show what the units of inertia are on a separate piece of paper. Handwritten work is acceptable.

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QUIZ 9 - Moment of Inertia

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# Chapter 10

## Oscillations

### 10.1 A Brief History

In Chapter 1 you quantitatively analysed the periodic motion of a simple harmonic pendulum. We will now come full circle and try to add some generality to simple harmonic motion by looking at the periodic motion of a spring. In the late 1600's, there were two physicists competing with each another in various aspects of physics. One of those two physicists was Isaac Newton, and the other was Robert Hooke. If Isaac Newton had not been born, it is possible that we would be using Hooke's Three Laws of Motion. Digressing specifically to Hooke's contributions, Hooke's work with springs led to the Law of Elasticity. Quite essentially, this describes the restoring force of a material after it has been compressed or stretched. A spring that has been displaced from equilibrium by a distance  $x$  and then released will try to return to the state of equilibrium. However, if you have ever owned a Slinky, you know that it won't immediately go back to the equilibrium state. The Slinky will pass the point of equilibrium and begin oscillating until it loses enough energy to come to rest. In today's experiment, you will observe the periodic motion of the oscillations of a spring.

### 10.2 Definitions

1. *Simple Harmonic Motion*-Motion that repeats itself at regular intervals is considered to be harmonic motion.
2. *Period*-The period of a oscillation is the time to complete one full cycle of motion.

### 10.3 Laboratory Objectives

By the end of today's exercise it is in the hopes of this Author that you will understand how

1. The **mass** affects the displacement of a spring.
2. The **displacement** of the spring affects its motion.
3. The **periodic motion** of the spring is considered Simple Harmonic Motion, the same as the pendulum in Chapter 1.

### 10.4 Notes

1. This chapter will be the final chapter in the classical mechanics section of this laboratory manual. As a reminder, if you would like to submit any final corrections, typos, or small quirks that don't float

your boat, email Mark Sterrett at mws0002@uah.edu. Next semester will be Electromagnetism and Thermodynamics.

## 10.5 Equipment

Spring, Force Sensor, Various Weights, Meter Stick, Motion Sensor, Datastudio.

## 10.6 Procedure

1. **Spring Force:** Attach and adjust your **Force Sensor** such that the sensor is hanging from the lab stand. The hook at one end of the **Force Sensor** will allow you to hang a mass to calibrate the system.
2. Open **Datastudio** and click the *Setup* button. Set the sample rate to **20 Hz**. Click the *Calibrate Sensor* button.
3. Physically located on the **Force Sensor** is a *Zero* button, press it. For calibration point 1 the standard value should be set at **0**. Click *Read From Sensor*. Hang **1 kg** mass on the **Force Sensor**. For calibration point 2 set the value to **-9.8**. Click *Read From Sensor*.
4. Confirm selection and proceed to the *Sampling Options* tab. We will want to enter some data manually so chose the “keep data values only when commanded” option and type “Stretch” for Name and “m” for the units.
5. Attach one end of the Spring to the Force Sensor such that it hangs freely. Measure the distance from the tabletop to the bottom of the Spring. This is the equilibrium state.

$x_1$ : \_\_\_\_\_m

6. Physically located on the **Force Sensor** is a *Tare* button; press it. On **Datastudio**, press the *Start* button.
7. To record the first data point press the *Keep* button in **Datastudio**. It will prompt you for a value, enter **0** as it is your starting value at equilibrium position. Note: For these next steps keep in mind that all you are doing is measuring the continued displacement of the spring as more mass is added, that is it. Read the notation carefully and follow it step by step.
8. Add **0.02 kg** to the end of the Spring and measure the position of displacement.

$x_2$ : \_\_\_\_\_m

9. Find what  $x_2 - x_1$  is and label this  $\Delta x_2$ .

$\Delta x_2$ : \_\_\_\_\_m

10. Record the second data point by pressing the *Keep* button, enter  $\Delta x_2$  as the value.

11. Add **0.01 kg** to the end of the Spring which already has **0.02 kg** and measure the position of displacement.

$x_3$ : \_\_\_\_\_m

12. Find what  $x_3 - x_1$  is and label this  $\Delta x_3$ .

$\Delta x_3$ : \_\_\_\_\_m

13. Record the third data point by pressing the *Keep* button, enter  $\Delta x_3$  as the value.
14. Add **0.01 kg** to the end of the Spring which already has **0.03 kg** and measure the position of displacement.

$x_4$ : \_\_\_\_\_m

15. Find what  $x_4 - x_1$  is and label this  $\Delta x_4$ .

$\Delta x_4$ : \_\_\_\_\_m

16. Record the fourth data point by pressing the *Keep* button, enter  $\Delta x_4$  as the value.
17. Add **0.01 kg** to the end of the Spring which already has **0.04 kg** and measure the position of displacement.

$x_5$ : \_\_\_\_\_m

18. Find what  $x_5 - x_1$  is and label this  $\Delta x_5$ .

$\Delta x_5$ : \_\_\_\_\_m

19. Record the fifth data point by pressing the *Keep* button, enter  $\Delta x_5$  as the value.
20. Add **0.01 kg** to the end of the Spring which already has **0.05 kg** and measure the position of displacement.

$x_6$ : \_\_\_\_\_m

21. Find what  $x_6 - x_1$  is and label this  $\Delta x_6$ .

$\Delta x_6$ : \_\_\_\_\_m

22. Record the sixth data point by pressing the *Keep* button, enter  $\Delta x_6$  as the value.
23. Add **0.01 kg** to the end of the Spring which already has **0.06 kg** and measure the position of displacement.

$x_7$ : \_\_\_\_\_m

24. Find what  $x_7 - x_1$  is and label this  $\Delta x_7$ .

$\Delta x_7$ : \_\_\_\_\_m

25. Record the seventh data point by pressing the *Keep* button, enter  $\Delta x_7$  as the value.
26. On **Datastudio**, click the *Stop* button. You should have a full set of data points. Drag your force data to the **Graph Display** icon. Verify that the graph is force vs time. This is not correct, by default **Datastudio** displays this. Drag your data list labelled “Stretch” to the *Horizontal Time axis* to replace the data. Verify that the graph is now Force vs Stretch.
27. From your coursework you are aware that

$$F = -k\Delta x \tag{10.1}$$

which is Hooke’s law. Hooke’s Law describes the relationship between the displacement caused by a Force on a Spring. Consequently, you have a lot of data for the force the spring experienced and the corresponding displacements. Notice that  $F$  is linearly related to  $\Delta x$ , meaning that  $k$  must also be represented somewhere on your graph...question 1 probably gives the answer away.

28. Apply a linear fit using the methods that you have used all semester.

**Question 1:** What does the slope represent? What is the value of  $k$ ? Discuss this in the results section in your lab report.

**Question 2:** Find the Force for each displacement,  $\Delta x_i$  for  $(i=2,3,4,5)$ , above using the value of  $k$  found in Question 1. Record these in your lab report. Do they make sense? Discuss this in the results section in your lab report.

29. **Simple Harmonic Motion of a Spring:** Simply exit out of **Datastudio** and reopen it to perform the next experiment. You may also remove the weights from the Spring but leave the spring attached to the **Force Sensor**.
30. Select the *Motion Sensor* icon. In **Setup** select the *Motion Sensor* tab and set the *Sample Rate* to **40 Hz**. Confirm to close the tab.
31. Place the **Motion Sensor** directly under the Spring such that it may measure the period of oscillation. There should be approximately **0.4 m** distance between the end of the Spring and the **Motion Sensor**. Do your best to avoid dropping the weights onto the **Motion Sensor**. If you are unable to avoid damaging the **Motion Sensor** it will result in a sad Instructor and a 9001% increase in tuition for you and your mates next year.
32. Add **0.05 kg** to the end of the Spring and let the Spring reach equilibrium. Using the “buddy” system, have someone ready to hit the *Start* button in **Datastudio** upon extension and release of the Spring-Mass system. You will be counting *10 periods* of oscillation.
33. From its equilibrium position with the mass attached, extend the Spring by **0.05 m** more and on **Datastudio** click the *Start* button. Release the Spring and allow it to oscillate. If the system is behaving ideally the Spring will have minimal horizontal displacement and almost complete vertical displacement during oscillation.
34. On **Datastudio**, click the *Stop* button once 10 periods have been reached. Drag the data recorded to the **Graph Display** icon. Verify that it is Position vs Time. For each peak, record the corresponding time value.

$t_1$ : \_\_\_\_\_ s    $t_2$ : \_\_\_\_\_ s    $t_3$ : \_\_\_\_\_ s    $t_4$ : \_\_\_\_\_ s    $t_5$ : \_\_\_\_\_ s

$t_6$ : \_\_\_\_\_ s    $t_7$ : \_\_\_\_\_ s    $t_8$ : \_\_\_\_\_ s    $t_9$ : \_\_\_\_\_ s    $t_{10}$ : \_\_\_\_\_ s

35. Calculate the corresponding periods for each time segment, that is to say calculate for  $t_2 - t_1 = T_1$ ,  $t_3 - t_2 = T_2$ , ect...



$T_1$ : \_\_\_\_\_ s    $T_2$ : \_\_\_\_\_ s    $T_3$ : \_\_\_\_\_ s    $T_4$ : \_\_\_\_\_ s    $T_5$ : \_\_\_\_\_ s

$T_6$ : \_\_\_\_\_ s    $T_7$ : \_\_\_\_\_ s    $T_8$ : \_\_\_\_\_ s    $T_9$ : \_\_\_\_\_ s

36. Find the average period.

$T_{avg}$ : \_\_\_\_\_ s

37. From your coursework you know that the period of a **Spring** may be calculated with

$$T = 2\pi\sqrt{\frac{m}{k}} \quad (10.2)$$

38. Find the Theoretical Period.

$T_{theo}$ : \_\_\_\_\_ s

39. Find the Percent Difference.

Percent Difference: \_\_\_\_\_

**Question 3:** Was the percent difference high or low? If it was high, what do you think went wrong? If it was low...high five! Discuss this in the results section in your lab report.

**Question 4:** What are the units of the Spring Constant?

★★ **Theory — Honors Question A:** Compare the oscillating spring to the oscillating pendulum. Write approximately a half page single space comparing the two. Pay particular attention to the variables that both depend on and the motion they trace out.

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QUIZ 10 - Oscillations

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