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# Survey and Analysis of 1st Year Physics Labs for Selected Colleges

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# Survey and Analysis of 1st Year Physics Labs for Selected Colleges

by

Wesley Belleman

A Major Qualifying Project

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

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March 2017

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Professor Frank A. Dick, Advisor

## Abstract

The project seeks to analyze how thirteen selected schools cover the basic laboratory topics of introductory mechanics. A chart is presented which depicts the collection of topics within the realm of introductory mechanics. This chart is then used to discuss the coverage of each topic across all of the schools. The coverage of the topics by school is then discussed in further detail. Focus is paid to Worcester Polytechnic Institute for the strengths and weaknesses of its laboratory collection.

# Contents

# Section 1: The Status of the Topics Covered across All Schools

## Section 1.1 Introduction

It is commonplace in the majority, if not all, of universities in the United States for students to take a course on mechanics as their introduction to physics. In this section, laboratories from thirteen universities are discussed. Universities considered comparable to Worcester Polytechnic Institute were researched for this study. Those which had available or were willing to provide information about their basic physics laboratories are the ones that are discussed here.

These laboratories are considered by topic. The chart below outlines the classification of topics in mechanics.

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | $\vec{r}, \vec{v}, \vec{a}$ | $\vec{F} = m\vec{a}$ | $\Delta\vec{p} = \vec{F}\Delta t$, $\vec{p}_f = \vec{p}_i$ | $W = \vec{F} \cdot \vec{r}$ | $\vec{F} = 0$ |
| Rotational | $\theta, \vec{\omega}, \vec{\alpha}$ | $\vec{\tau} = m\vec{\alpha}$ | $\Delta\vec{L} = \vec{\tau}\Delta t$, $\vec{L}_f = \vec{L}_i$ | $W = \tau\theta$ | $\vec{\tau} = 0$ |
| Statics | n/a | n/a | n/a | n/a | $\vec{F} = 0, \ \vec{\tau} = 0$ |

This section contains summaries and descriptions of trends in the laboratories across the schools which are used for this study. These schools are:

Worcester Polytechnic Institute,
Rice University,
Massachusetts Institute of Technology,
Boston University,
Northeastern University,
Wentworth Institute of Technology,
Illinois Institute of Technology,
University of Massachusetts-Boston,
University of Virginia,
Dartmouth College,
University of California-Los Angeles,

University of Texas-San Antonio,
University of Minnesota,
University of Notre Dame.

Topics include how well the topic is covered in the various universities, what methods are generally used, and setups which are common. Following this summary is an outline of the laboratory which the author considers to be the most exceptionalin the collection of labs. The laboratory is explained in detail and the author explains why this laboratory is exceptional and gives a few recommendations pulled from the other laboratories in this study about how the laboratory could be improved.

## Section 1.2 Translational Kinematics

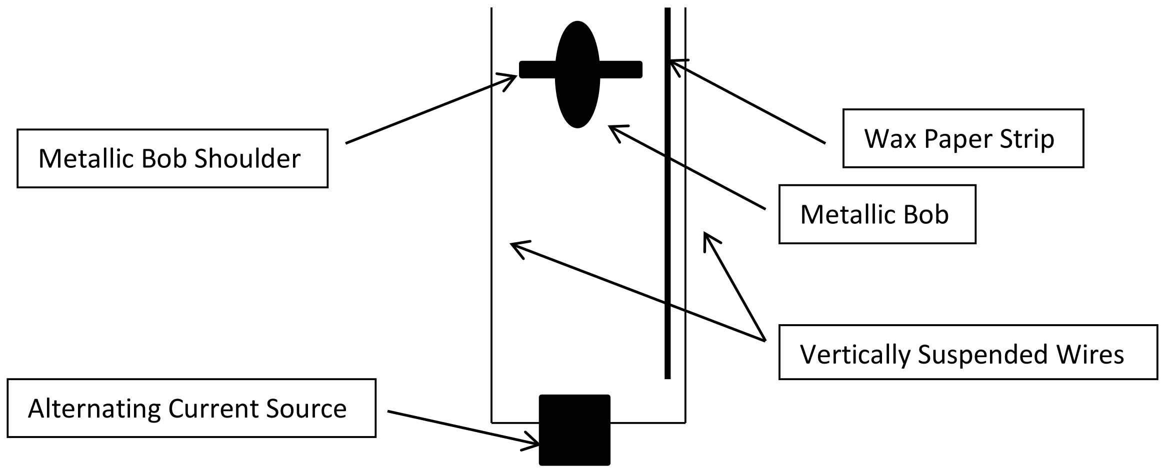
### Summary

The study of kinematics provides students with a set of algebraic relations for motion in the cases of constant velocity and constant acceleration. A kinematics lab should therefore explore the relations of these motions without consideration of forces acting on the objects. This is a relatively difficult task as forces are a part of life, and a constantly accelerating body requires a force to accelerate it. Additionally, any setup is subject to friction and air resistance which are complex forces that could prevent constant acceleration.

Every school in this study has a kinematics laboratory. This is a well-covered topic across the schools. Setups tend to use tracks with carts or air tracks with a glider. Both of these provide for low friction motion of an object which is to be measured. Another common set up is an object in free fall. Schools use a variety of measurement techniques including motion sensors, spark timers, video recording, and a simple stopwatch with measuring stick. Video recording probably provides the best form of measurement. The motion sensor and spark timer are almost like black boxes in that they perform a function that the student does not really understand. With the video recorder, students can actually see the location of the object in question at a certain time. The videos can be difficult to analyze as students have to determine the location of the cart for several different time stamps. The motion sensors provide the simplest way to determine motion as the computer automatically builds the motion graphs. Additionally, most of the software will also automatically build velocity and acceleration graphs as well.

The schools vary in the way of dealing with the forces at hand. Some address the forces, including friction directly. Some even introduce students to the theoretical calculation for the acceleration of this force. This introduces students to a topic which they will soon be covering and ties things together. A downside of this method is that it may confuse students and take away from the kinematics calculations which are on hand at the time.

Standout Lab: University of Massachusetts, Boston - Kinematics of Free Fall




A metallic bob is placed between two wires, not touching them, being held in place by an electromagnet. The bob has a metallic shoulder which is close enough to the wires such that it will make sparks with the wires when an alternating current is run through the wires. A piece of wax paper is placed in the path of these sparks so that it will burn at the location of the sparks. Students then turn on an alternating current source with a frequency of sixty cycles per second. Students release the bob by turning the electromagnet. Students then are able to see the height of the bob for every 1/60 seconds. Students measure the heights and use the data to determine the acceleration of gravity.

This laboratory provides a way for students to see the constant-accelerating motion of the metallic bob on the sheet of wax paper itself. After the bob falls, the students will be able to look at the wax paper and see exactly where the wax paper was at each time interval. Students then measure the distances in order to determine the acceleration of gravity which was the acceleration of the bob during its motion. This measurement is crucial because students themselves determine the motion plots instead of having a computer do it for them. This allows students to have a more hands-on grasp of the constantly accelerating body.

## Section 1.3 Rotational Kinematics

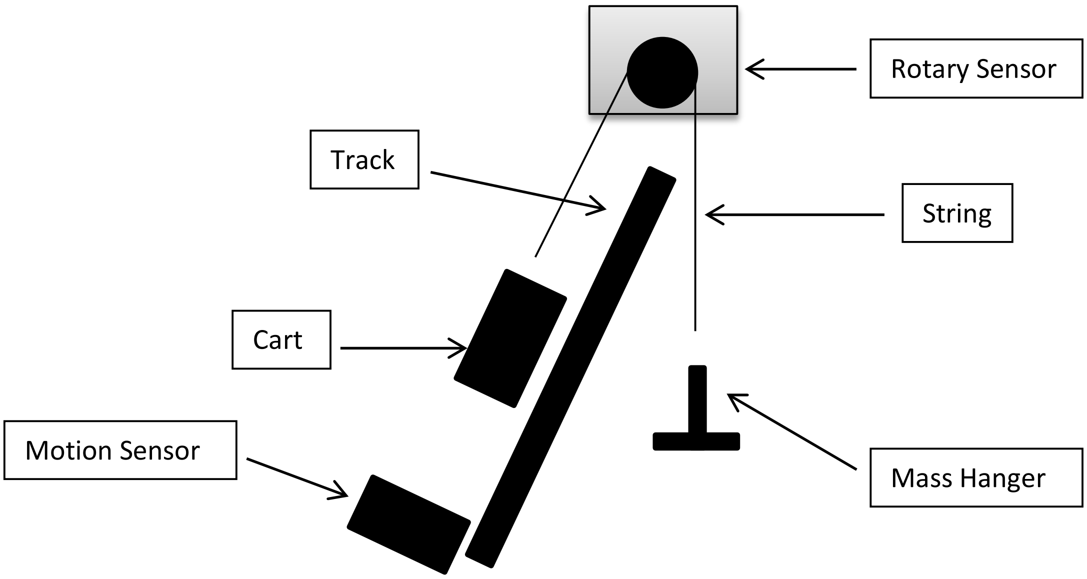
### Summary

Kinematics equations can also be represented in polar coordinates. Students will find an understanding of the relationships between position, velocity, and acceleration in these coordinates extremely useful for understanding the motion of rigid bodies. While this is just a mathematical result of the corresponding translational physics, it is extremely important that students see these results in the laboratories so that their understanding of the ideas is solid and founded in experience.

This is, however, not a well-covered topic across the schools. Only four of the schools have such a laboratory in this section. It could be argued, that those laboratories which cover the ideas of rotational energy and rotational dynamics include a constant accelerating rotational body and therefore present the ideas of rotational kinematics along with the other ideas. The main deficiency in those labs which display rotational kinematics both in and out of this category is that they tend to use a translational force to power the spinning. The spinning recorded is usually the result of a string pulling along a pulley or rotor causing the object to rotate. This type of apparatus is extremely useful in drawing the connection between translational and rotational dynamics. It is also helpful in showing the student how to perform the calculations of the two systems together. Unfortunately, of the one hundred and fifty laboratories in this study, not a single one has a rotating system powered by a rotating force. A rotating force might be an untwisting rope or a torsion spring. Such a laboratory would be useful in isolating the rotational motion of an object for students to consider that topic on its own.

There are several sensors used to measure rotations in the rotation experiments. Some use a rotor pulley which automatically reports the rotational motion of the pulley to the computer. Others use a photo sensor which measures the time which stripes on a rotating body switch between white and black. When friction is low enough for slow, sustained rotational motion, students can measure periods of revolution in order to determine the angular speed of a rotating body.

Standout Lab: Worcester Polytechnic Institute - Translational and Rotational Dynamics




Students are presented with an inclined track, a motion sensor at the bottom of this track, rotary sensor pulleys at the top of the track, and a cart tied to a mass which is heavier than the cart run over these pulleys. The cart is on the track and is slid down the track, towards the motion sensor. The mass on the other end decelerates the cart so that it eventually comes to a halt and goes back up the track. Students record the translational motion of the cart and the rotational motion of the rotary sensor, assuming a no slip condition and knowing the radius of the rotary sensor pulley. Students run the string over the other radii of the rotary sensor pulley and repeat the procedure. Students compare the angular accelerations of the pulley for the different trials.

This laboratory provides a way for the pulley to experience constant acceleration without moving constantly in the same direction. Students are therefore able to see how a torque can both slow down and speed up the angular speed of the pulley. The combination of the motion sensor and the rotary pulley allows the students to directly compare the motions of the cart and the rotary sensor over time. Students are able to adjust the value of the acceleration by adjusting the mass hanging from the mass hanger. Students can also change the pulley they are using on the rotary sensor in order to see the effect that having the same force run over a different radius affects the motion as well.

## Section 1.4 Translational Newton's Laws

### Summary

Once students learn Newton's laws, they are able to be introduced to forces. This makes the range of labs which can be developed to explain this topic extremely wide. Forces available include spring forces, gravity, hand pushing, and friction, among others. Students review their understanding of kinematics as they explore the effect of constant forces on an object.

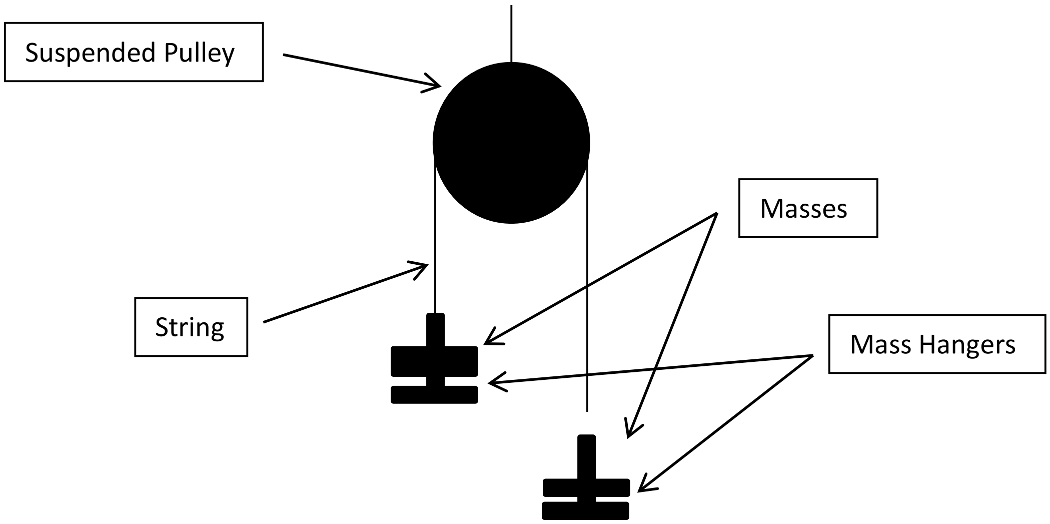
One of the most common setups across the schools in the study is Atwood's machine. Additionally, many schools have a cart on a track powered by a mass falling off of the side of the track. In all of these cases, students are able to adjust the mass and the force separately, although not quite independently.

This topic is well covered throughout the schools in this study. Each school has its own way of studying it but all cause the students to verify Newton's laws in one way or another. Some schools rely on a student to determine the force on an object by calculating it, while others use a force sensor. It seems that it is best to use a direct sensor whenever possible as this removes any chance of abstraction of an idea when possible. Most schools require the students to calculate what motion they expect based on Newton's laws beforehand and then compare this to the experiment's result.

Some schools use the friction force to further the study of Newton's laws as a force in its own. Others try to ignore friction whenever possible and use setups which have little to no friction. There is some danger in both cases as one does not allow students to make simple calculations from the ideal case, seeing a straightforward and easy to interpret result, while the other ignores reality. It is probably best to show students both cases when possible.

Several sensors are used in these labs. Sensors include motion sensors, spark timers, photogates, force meters, video recording, and some just a stopwatch. Assuming that students have a strong understanding of kinematics at this point, it is probably fitting to use a motion sensor. This makes performing mathematical calculations much easier as the motion sensors usually report the motion graph directly to software which is able to analyze it. Motion sensors are less effective for two dimensional motion, so video recording is a good choice for two dimensional motion. A laboratory that can combine a force sensor and a motion sensor is likely to be very successful at most directly displaying Newton's laws as students will be able to directly compare acceleration to the force of the object.

Standout Lab: University of Texas, San Antonio - Atwood's Machine




Students have two mass hangers connected by a string which is run over a pulley. Students place several five gram masses on each hanger so that one is heavier than the other. Students allow the heavier one to drop and record the time it takes for the mass to drop a certain distance. Students move one of the masses from one hanger to the other so that the total mass is the same but the net force changes. Students repeat this procedure for several net forces. Students then start removing one mass from both hangers so that the net force remains the same but the total mass changes. Students record the motion for several total masses but a constant net force.

While there are several versions of Atwood's machine at the universities looked at in this study, only the one from University of Texas, San Antonio specifically looked at the cases in which the net force and the total weight remain constant. These cases allow the students to directly see the effect of changing the mass and changing the force have on the acceleration while keeping the other of the two constant.

The one drawback to this lab is the lack of a motion sensor. Recording the time of drop the old fashioned way does not allow students to see the constant acceleration of the drop which they could see on a plot from a motion sensor.

## Section 1.5 Rotational Newton's Laws

Summary

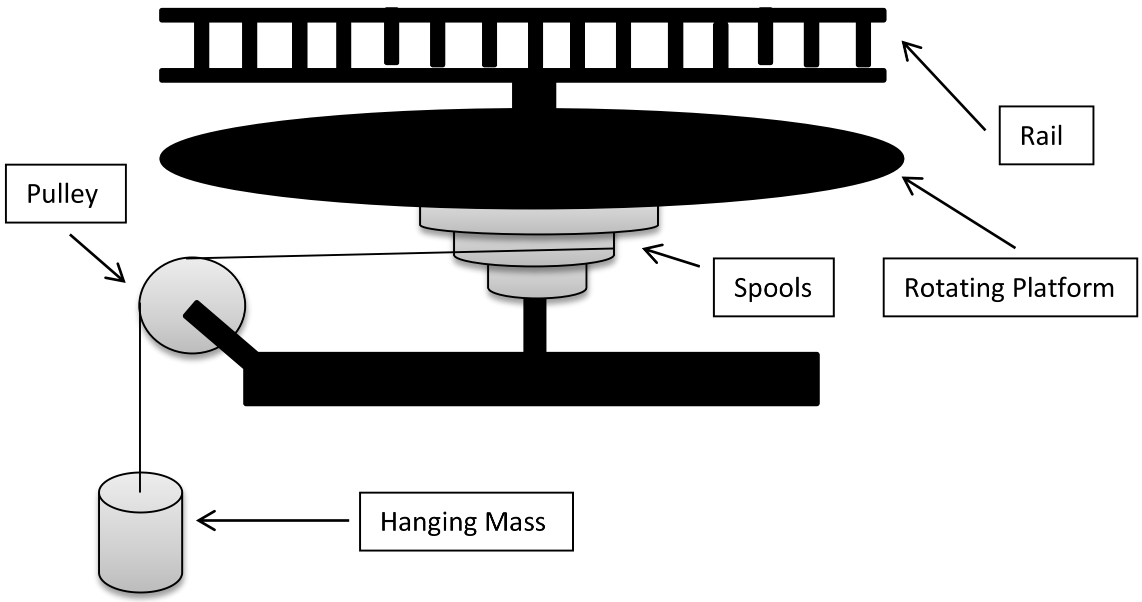
As with kinematics, Newton's laws can be written in polar form to provide a useful set of results for the rotational frame. Students will find these results immensely useful for the motion of rigid bodies. Students, however, are presented with a somewhat abstract idea. This is the idea of the moment of inertia. Students learn that an object of a certain shape and mass will resist a torque more than an object of a different shape and mass. In some cases, this may not be entirely intuitive to the student. Thus the labs in this section seek to build some intuition and experience in this idea for the student.

This section is the best covered in the area of rotational motion for the schools in the study. Eight of the fourteen schools have a laboratory in this section, and those that do not cover this topic along with their laboratory that focuses on rotational energy.

The common setups that cover this section are a rotating table, a physical pendulum, and a gyroscope. The physical pendulum is nice for sliding the masses further away from the center of rotation and seeing how changing the moment of inertia in this way affects the motion. The actual motion of the pendulum is somewhat complicated, however, when seen from a rotational perspective. As the force on the pendulum is gravity, which is constantly pointing downward, the direction of the force is changing from the rotational perspective. Additionally, the physical pendulum requires on periodic motion which is not a straightforward way to see how changing torques and moments of inertia change the rotation of a body. A gyroscope is a great way to cap off a student's understanding of rotational Newton's laws, but may be a bit complicated for a first look.

Several sensors are used in these setups. At this point it is a good idea for a rotational motion sensor to be introduced. Some of the setups have a rotor which automatically outputs the rotational motion to the computer. Others have a photo sensor which can measure the times that lines change between black and white on part of the rotating object. Another way is to have a photogate around a rotating object with spokes. All of these allow for the quick collection of a lot of rotation points so that students may see the motion of the object in the highest time resolution.

Standout Lab: Illinois Institute of Technology - Torque




Students have a rotating platform with an attachment called a rail. On the rail, students can hang masses in order to change the moment of inertia of the system. On the rotating platform there are three different spools. Students wrap a string around one spool and run it over a pulley which is off of the platform and then tie the string to a mass. Students release the mass to get the rotating system rotating. The platform is connected to a rotational measurement sensor that allows students to measure the rotational motion of the platform. Students devise an experiment to determine the moment of inertia of a certain setting of the rail by changing which spool setting is used, but keeping the applied force constant. Students then develop an experiment to verify Newton's second law for rotational motion.

While many schools have a similar setup as this one, the rail makes this laboratory exceptional. With the rail students are able to hang masses as certain locations and therefore get a much better sense of how the moment of inertia is affected by placement of different sized masses. This gives the students a very strong intuition for moment of inertia. Additionally, students are able to change which horizontal pulley is used on the bottom and the value of the mass in order to change the torque on the system.

## Section 1.6 Translational Work-Energy

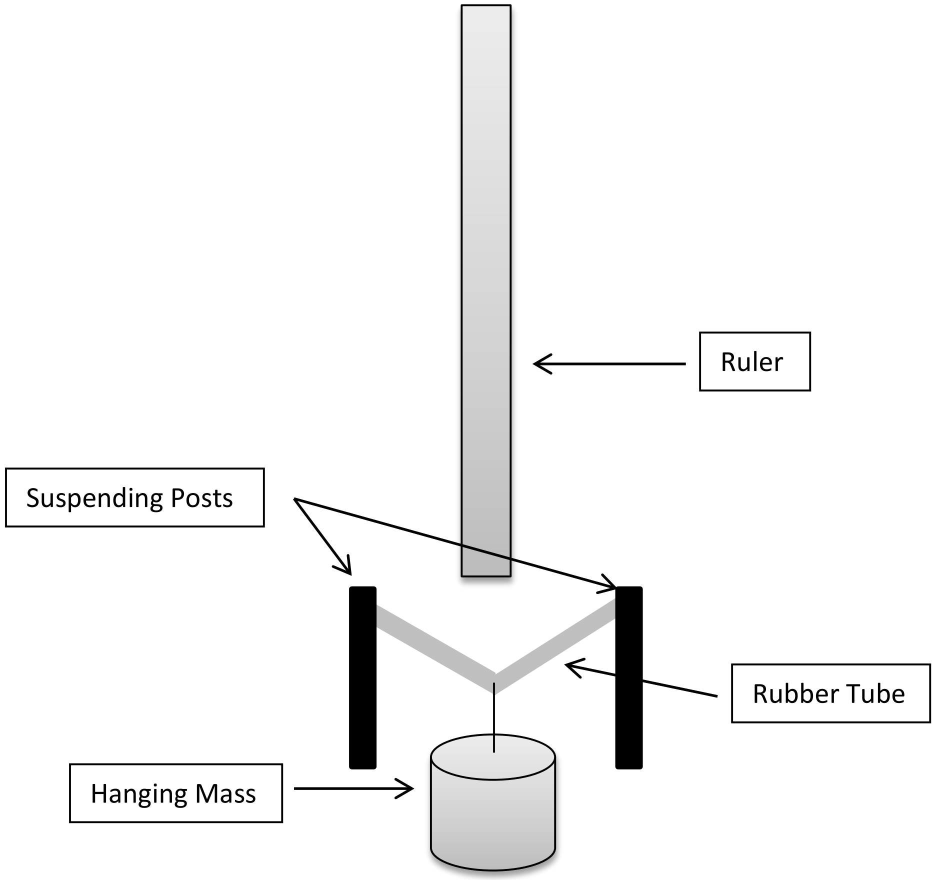
Summary

After learning the basic math and laws behind dynamics, students are able to begin studying the idea of work and energy. This study has two important effects. First it gives students the tools to solve complex problems. Students know that regardless of the path of an object, the energy of a system is conserved. The other effect is that students begin relating mechanics to their everyday life. Students are familiar with many of the quantities of work and energy as they relate to electric power. Furthermore, students often use these terms in everyday speech to describe things very similar to the idea of mechanical energy.

There are two setups extremely common to explaining the work-energy concepts. One is a simple pendulum and the other an inclined track. Some schools also use the energy of a spring to explore this idea. The pendulum has the advantage of taking a complicated path between the peak of height and the peak of motion. This makes it so that performing calculations using Newton's laws are rather difficult for this situation. Students instead therefore must actually rely on the results of the work-energy theorem. The pendulum's strange motion also makes it difficult to track. Linear motion can be easily tracked by a force sensor, and therefore the mechanical energy of an object can be determined at several time intervals. Introducing spring motion is another alternative as the changing force of the spring makes it difficult to use Newton's laws to calculate the resulting motion of the object on the spring. Additionally linear spring motion can be measured with a motion sensor.

Many of the same sensors are used here as before. Motion sensors are good for gathering a lot of points and therefore being able to determine several different energies. A pendulum lab can be made much better using a pulley which records its angular motion over time. This can easily be converted into linear motion so that the student may determine the mechanical energy at several time intervals.

Standout Lab: Dartmouth College - Elasticity and Energy




Students have a rubber tube which is suspended horizontally. Students determine the spring constant of this tube. Then students use the tube to launch several masses into the air. They pull the mass downward some distance and determine the potential energy of the pull. They then release the mass and record the maximum height. Students verify that the mechanical energy just before launch is equal to the mechanical energy at the top of the mass's motion.

This laboratory allows the students to see how one form of energy can be converted into another. The energy from the rubber tube "slingshot" is shot into the air to be converted into gravitational energy. This lab only uses potential energies, however it seems that it would be relatively straightforward to place a motion sensor above the mass so that the objects mechanical energy could be determined at several points in time.

The main reason that this lab is a standout is that the slingshot is unique and relates to a device that many students may be familiar with. The setup is also simple and requires no technology.

## Section 1.7 Rotational Work-Energy

### Summary

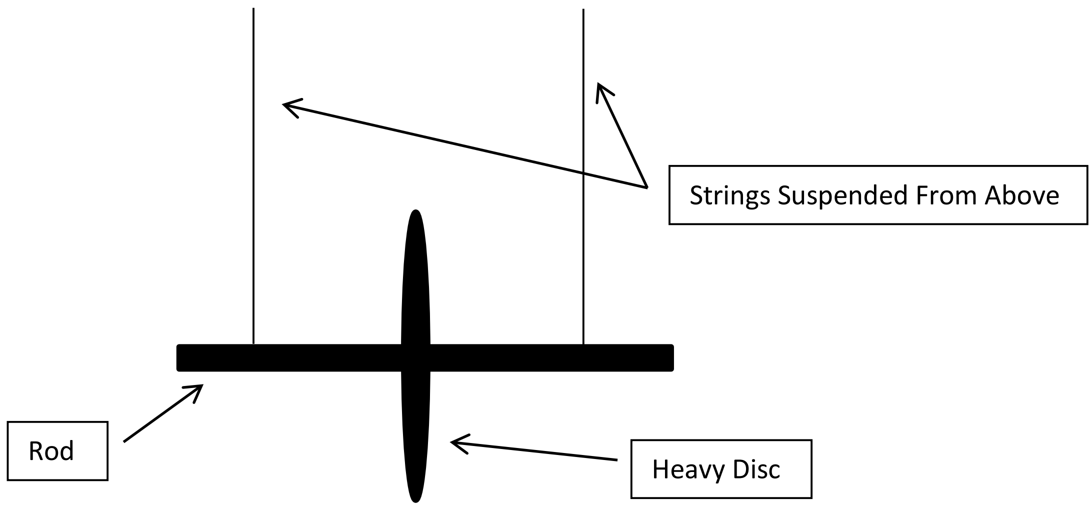
Rotational energy is the energy which students are likely most familiar with because it is the energy of a motor. When learning this topic, students are introduced to the energy of a rotating object and how it relates to the energy of a moving object. Students then consider the energy of an object that both moves and rotates. Students learn that these energies add. The also learn strange effects of this idea, such that a ring and disc of the same mass and radius will roll down a ramp with different accelerations!

This is not a very well-covered topic across the schools used in this study. Only three schools have laboratories which display the topic directly and not coupled into another primary topic. This is likely to have students miss the opportunity to understand the importance of rotational energy.

All of the setups in this section have an object that rolls. For two of the setups the object rolls down a moving track. In this way the objects gravitational energy is converted into linear and rotational kinetic energy. When students do this with several objects, it is likely to cement the importance of rotational energy in performing physics calculations.

The sensors used in these experiments measure the linear motion of the object and assume the circular motion using a no slip condition. While this is effective, it does remove direct calculations of the rotational energy which will be simpler for the student so that he or she can comprehend how the rotational energy is separate from the translational energy. One way to record rotational motion is to draw a line along a diameter of the rotating object and record its motion in a video.

Standout Lab: Northeastern University - Maxwell's Wheel




Students have a disc in the center of a rod which is suspended by two strings from above. The strings wind around the rod when it rotates with the disc. Students measure the dimensions and mass of the disc and the rods in order to determine its moment of inertia. Students then spin the disc and record the falling times and distances of the rods for several falls. Students use this data to determine the moment of inertia and compare it to the calculated value. Students then add brass weight attachments in order to change the moment of inertia of the system and repeat the procedure.

This is a simple setup with the advantage that its rotational energy should be far greater than its translational energy so that the effect of rotational energy absolutely cannot be ignored. This setup is also unique as it is not the typical cylinder rolling down a track.

The current measurement process of taking falling times and distances is not as effective as recording the rotation with a video recorder and/or having a motion sensor measure the motion of the falls and rises. Another modification could have this suspended from both sides in such a way that it is stationary but free to rotate. Students could then pull up on the strings with a force meter and determine the work done and the resulting rotational energy of the object.

## Section 1.8 Translational Impulse - Momentum

### Summary

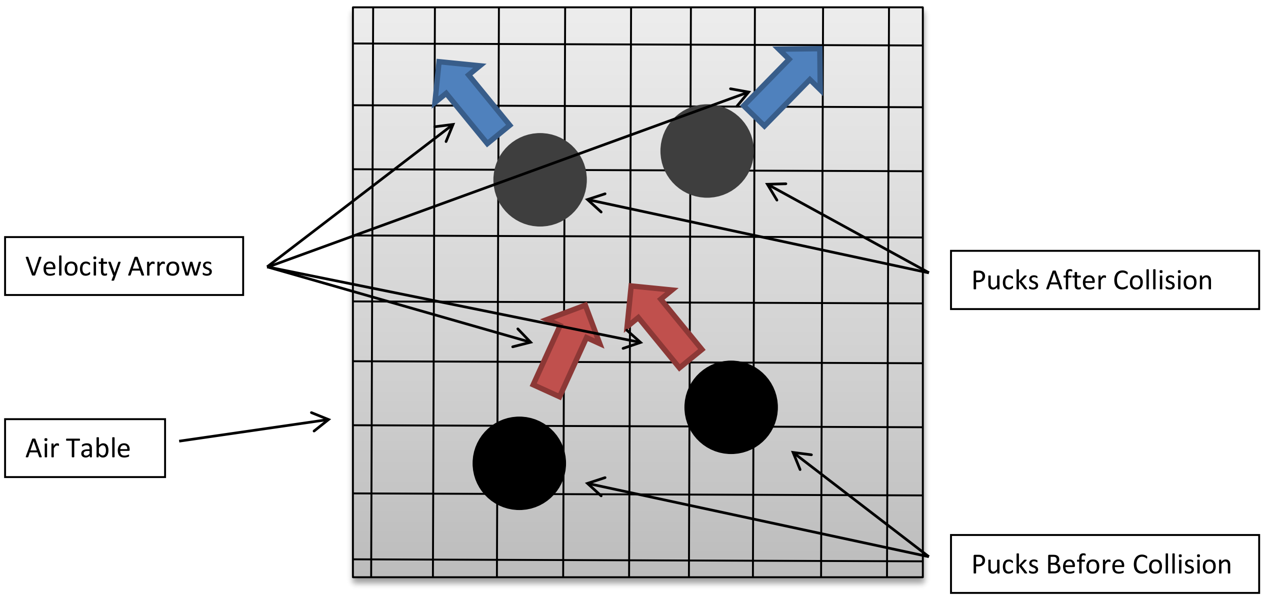
After learning about work and energy, students learn another result of Newton’s laws. Some say that the impulse-momentum theorem is the most important result of Newton’s laws for making predictions in classical mechanics. This is likely said because in any collision momentum is conserved. Meanwhile energy is only conserved in elastic collisions, and no real-life collision is completely elastic.

This is a well-covered topic amongst the schools in this study probably due to its importance in making predictions and calculations. Twelve of the schools have a lab in this section that primarily focuses on the impulse-momentum theorem in Cartesian coordinates. Some schools have multiple labs on this topic and one has a lab in both one and two dimensions.

The setups all use some sort of collision. Some have objects collide with each other while others have objects collide with a force bumper. Many have collisions that are nearly elastic and inelastic in order to show the student how energy is also conserved in elastic collisions. This is very useful for students to see. The one dimensional collisions usually involve a cart or glider on a track while the two dimensional collisions usually involve pucks on an air table. Carts or gliders have springs or magnets in order to make the collisions elastic. They also have velcro in order to make moving objects stick together and have a perfectly inelastic collision.

The normal motion sensing methods are used in these experiments. For the two dimensional collisions a video camera must be used as it was in the projectile motion laboratories. The unique sensor to this set of labs is the force sensor bumper. This sensor is attached to the edge of a track and measures the force of an object that hits it. This is extremely useful for considering impulses. When combined with a motion sensor, this makes a powerful setup for considering the impulse-momentum theorem.

Standout Lab: Air Table




Rice University, Northeastern University, and University of Massachusetts, Boston, all have a similar laboratory in which students cause collisions between pucks on an air table. The air table should have a grid as in the diagram because this allows for the most accurate measuring of positions of the pucks at different times. Students record the motion of the pucks before and after the collisions in order to determine that momentum is conserved in both directions. Students are able to change the axes of consideration and still achieve the conservation result. Additionally students can determine the path of the center of mass between the pucks and note that the momentum and energy is conserved for this two mass system.

While other schools do their momentum labs in one dimension, these three perform it in two dimensions. This gives the students a much better understanding of the conservation of momentum and why it is important.

This laboratory could be modified to also analyze the conservation of angular momentum. Students could simply draw a line along the diameter of the pucks and analyze video to determine the rotational speed of the pucks before and after collisions. Additionally, if bumper force sensors are introduced, students can consider the effect of impulse on the momentum of the pucks for a host of different cases.

## Section 1.9 Rotational Impulse-Momentum

### Summary

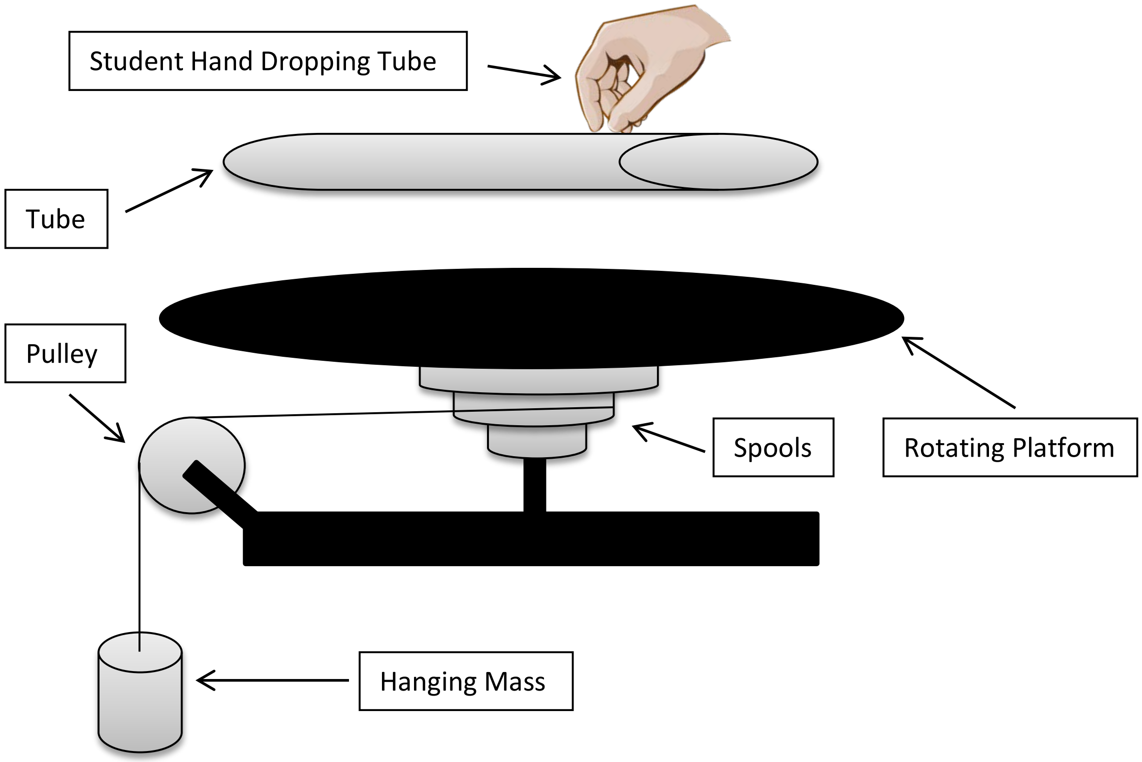
Students are able to make further mechanical predictions with an understanding of impulse and momentum in polar coordinates. This study furthers their understanding of the mechanics of rigid bodies. Students can predict the motion of a collision between a linearly moving object and an object which rotates and the motion of two rotating objects.

This is not a very well-covered topic across the schools used in this study. Only three schools have laboratories which display the topic directly and really at all. It seems that many courses either gloss or jump over this topic and do not have a way to directly show students collisions from a rotational frame. This deprives students of the opportunity to gain experience and intuition about the result of a rotational collision.

Two of the setups in this set have an object which is dropped onto a spinning object. The two objects eventually start spinning together which is a perfectly inelastic collision. The third setup has a linearly moving object come into contact with a rotating object. This has the advantage of showing students that rotational mechanics are really no different from linear mechanics while still isolating the conservation of rotational momentum.

The sensors used in these experiments measure the rotation of the rotating bodies in various ways. It is important for these labs to display a high time resolution of rotational motion so that students are able to see the angular velocities immediately before and after the collision. This can be done with a photosensor or a rotary sensor that is connected to a computer.

Standout Lab: Illinois Institute of Technology - Angular Momentum




Students have a rotating disk with a groove and a tube which fits right into that groove. Using masses, a pulley, and a string, students develop an experiment to determine the moments of inertia of the two items. Students can measure the rotational motion of the disc with a rotational measurement sensor. Students then use this data to observe the conservation of angular momentum. Students rotate the disc and then drop the tube into the groove gently. Students determine the angular momentum before and after this collision.

This laboratory is effective because the dropped tube automatically starts to spin with the platform. In this way the students can determine the speed immediately before and after collision without having to worry about time for friction to do its work and have the dropped object start moving with the lower object. While students may have the hanging mass drive the motion and then do math to figure out how adding the tube affected the motion, it is hoped that the students will use the mass just as a way to off balance the kinetic friction force. An instructor using this lab may want to write that specifically in the instructions.

## Author-made Laboratory: Angular Momentum

### Introduction

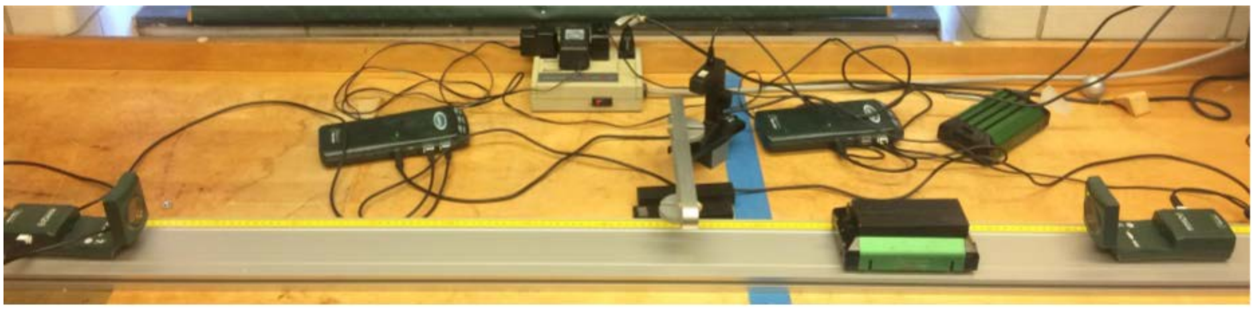
This section will outline a laboratory which covers the topic of angular momentum. Students will cause a collision between a linearly moving cart and a rotating system and determine the angular momentum of the system before and after the collision. Students will display the conservation of angular momentum in the collision.

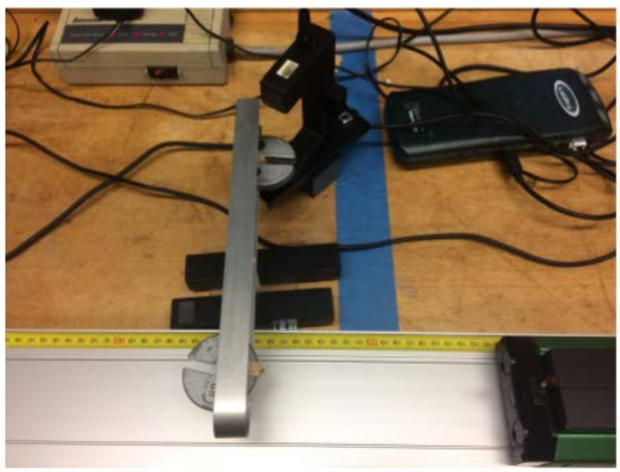
### Instructor's Guide

### Putting Together the Setup

This experiment requires a track (a), a cart with small bolt in front (b), a rotator (c), two LoggerPro sonic motion sensors (d), one LoggerPro photogate (e), one photogate stand (f), two rubber bands (g), one set of mass discs (these discs should be 50 grams or more in order for the conservation of angular momentum to be truly observed) (h), and four heavy bars (i). Each of the materials used is pictured below with the corresponding letter label. Students will also require a scale and a ruler to determine the mass of the cart and the discs and both the mass and dimensions of the rotator.

Set the track on the table so that it is level. Place the cart on the track and the rotator immediately next to the track on the side further from the edge of the table. Place two of the heavy bars onto the base of the rotator. Place the cart onto the track and note the height of the cart as compared to the rotator. The small bolt of the cart must collide with the rotating piece of the rotator, so adjust the height of the rotator using supports underneath to ensure these two pieces are at the same height. Then place the photogate in such a way that when the rotator is perpendicular to the track, the rotator is not within the photogate, but it will immediately enter the photogate after being struck with the car. A picture of the entire setup is below.





## Setting Up LoggerPro

The Vernier LabPro device will only fit two sensors with the type of plug that the motion sensors and the photogate have. For this reason, two LabPro devices must be hooked up to the computer. Ensure that the two motion sensors are on one LabPro device and the photogate is on its own LabPro device. The plugs for these devices will go into the top right-hand side DIG/SONIC outlets on the device. The photogate may not work if a motion sensor is hooked up to the same LabPro device as the photogate.

Once the sensors are connected, create three graphs in the LoggerPro window, Position 1 over Time, Position 2 over Time, and GateState over Time. Adjust the scale of the position graphs so that they range from zero to a little beyond the distance to the rotator. Adjust the scale of the GateState so that it varies between zero and one.

## Student Guide

## Introduction

The conservation of momentum and angular momentum are powerful tools for predicting the outcome of collisions. While some collisions are elastic and conserve energy, most are not; and yet momentum and angular momentum are still conserved in such collisions. In this laboratory, students will explore a collision in which the angular momentum of a linearly moving object is conserved after a collision with a rotating object.

## Pre-lab Questions

This lab will require students to find the moment of inertia of a plate around its center. Students should therefore either find or calculate (depending on the mathematical intensity of the course) the moment of inertia of a plate or a block around its center given its length and width. Additionally, this lab will require students to consider the angular momentum of a cart as it moves in a straight line. It may be a good idea to have students consider this idea ahead of time. One way to do this is to have students calculate the angular momentum of a particle of mass m located at $\mathbf{r}_0$ moving at a velocity v towards a point $\mathbf{r}_1$.

## Experiment Procedure

At the lab station, there should be a cart on a track and a rotating system which we will call a rotator. You will cause the cart to collide with the rotator and determine the angular momentum before and after each collision. First make the necessary measurements. The mass of the cart and rotator must be determined, in addition to the dimensions of the rotator. Determine the mass of each disc, the rubber bands, and the two bars provided. Release the plunger from the cart (press the wide button on the front) and slide the cart near the rotator. Turn the rotator so that it is perpendicular to the track and have the small bolt which is on the cart come as close as possible without touching the rotator. Measure the distance from the center at which the plunger will come into contact with the rotator.

Begin with a practice collision between the cart and the rotator. Ensure that the rotator is always perpendicular to the track before collision. One student should slide the cart at the rotator and the other should catch the cart so that it does not hit the motion sensor on the other side. If the rotator hits the rear of the cart after the initial collision, a trial must be repeated. To avoid this, slide the car a little faster. While performing practice collisions, hit “Collect” on the LoggerPro program and look at the bottom left of the LoggerPro screen. Determine which distance is associated with which sensor on the track. You must also determine the distance at which the cart collides with the rotator. To do this, hit “Collect” on the LoggerPro program and push the cart so that it just barely touches the rotator when it is perpendicular to the track. Record the position associated with the sensor that the cart moves away from before collision.

Once you have mastered sliding the cart, hit the “Collect” button on the LoggerPro program and perform the same collision again. There should be three graphs on the LoggerPro screen. Find the graph associated with the sensor which the cart was moving away from. This sensor should have a straight, smooth line of positive slope up to the point where the collision occurs. Highlight part of this smooth line and hit the button on the top which says “R=” and has a curve above it. A box should appear on the graph on which you highlighted and the slope is indicated in this box. Record this slope. The graph of the sensor which the cart was moving towards, should have a smooth, straight line with negative slope after the collision time. Find and record the slope of this line. The third graph is associated with the photogate. This graph should display a series of peaks. Each peak indicates the time when one end of the rotator enters the photogate. Record the time value at each peak. Finally, go into the table on the top left of the LoggerPro program and find the column with the position associated with the sensor that the cart moves away from. Find the time at which the cart collided with the rotator by finding the time at which the cart was at the distance which you determined was the collision distance. This will be called the collision time.

Repeat this procedure for various masses of the cart and various moments of inertia of the rotator. Add one or two bars to the cart in order to change its mass. Use rubber bands to strap the mass discs onto the rotator. Ensure that you measure the distance of the mass discs from the center of rotation. For larger masses, you may have to slide the cart faster in order to get enough spins of the rotator to determine the angular speed.

## Report

Students will calculate the angular speed of the rotator at the collision time for each collision. Students will use this date and other data to calculate the total angular momentum of the system about the axis of the rotator immediately before and immediately after the collisions.

In order to determine the angular speed of the rotator at the collision time, students will use the date recorded from the photogate. This data will be a series of timepoints at which the rotator went through the photogate. Thus students should plot this data with the angle associated with the amount of rotation. The first time should thus be associated with the angle 0, the second associated with pi radians, the third associated with 2 pi radians, and so on. Students should find the line of best fit (a quadratic) for this set of data and then differentiate this function in order to achieve the rotational speed over time equation. Students finally will plug in the collision time in order to determine the angular speed at that collision time.

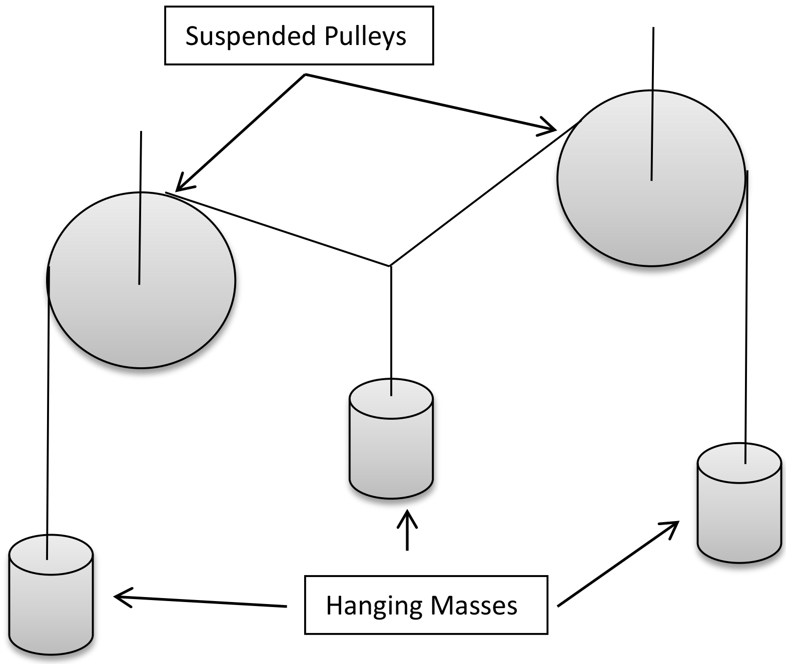
## Section 1.10 Translational Equilibrium

Summary

After learning about dynamics, students are taught to consider the special case when the sum of the forces and/or the sum of the torques are equal to zero. In this case there will be no acceleration or rotation of the object in question. This allows students to learn how different forces at different angles cancel out given certain conditions. This prepares engineering students for their studies of statics down the road.

Only one school in the study had a laboratory specifically dedicated to translational equilibrium. Other schools cover the topic with a static equilibrium lab or while learning about forces. Since this is a special case of prior topics, it is logical that many schools would choose to focus on the prior topics more. The one advantage to equilibrium labs is that everything can be measured by the student without special equipment because the objects of interest do not need to be moving.

Standout Lab: Wentworth Institute of Technology - Translational Equilibrium




Students have a system of two pulleys set in place in the same plane but with different heights and separated by a significant horizontal distance. A string is run over both pulleys with a mass hanger tied to the ends of the string on the left and right and a third mass hanger tied to the string in between the pulleys. Students are told to consider the three values of the masses, and the two angles the string in the middle makes to the horizontal. Students are given three of these five values and told to solve for the other ones using equilibrium assumptions. Students place the appropriate masses on the appropriate hangers according to their calculations and measure the angles. Students compare the measurements to the prediction.

This is a useful laboratory for showing how forces in the same direction need to add up to zero in order for a body to be in translational equilibrium. The ability to change all three masses makes it for a very adjustable lab and therefore communicates the concept very well.

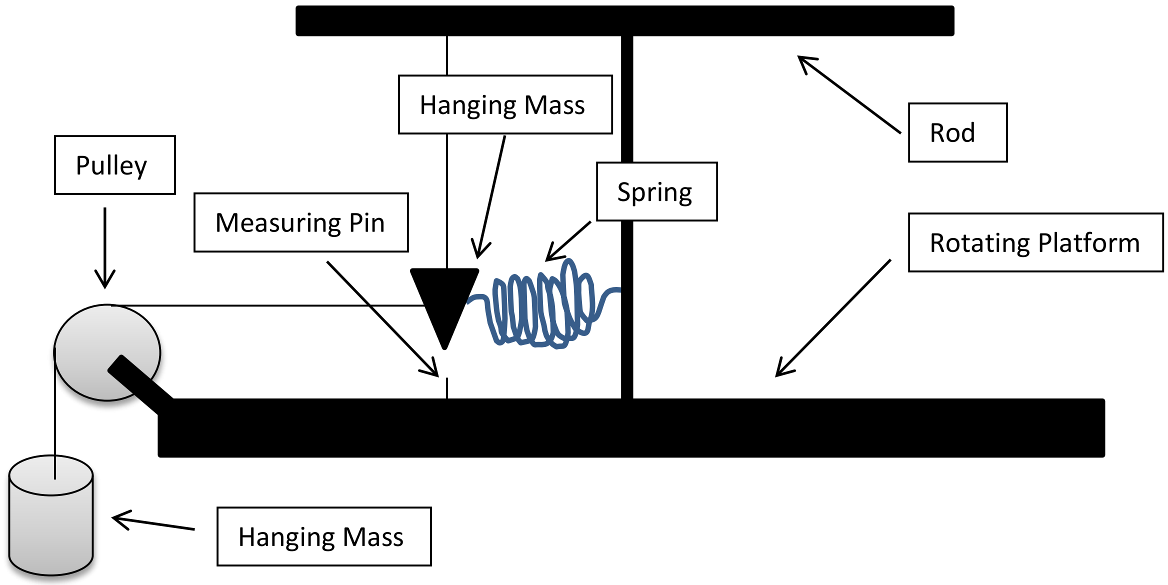
## Section 1.11 Rotational Equilibrium

Summary

After learning about dynamics, students are taught to consider the special case when the sum of the forces and/or the sum of the torques are equal to zero. In this case there will be no acceleration or rotation of the object in question. This allows students to learn how different forces at different angles cancel out given certain conditions. This prepares engineering students for their studies of statics down the road.

Six schools had a lab on rotational equilibrium. This is generally because this was an easy way for the schools to teach the idea of the centripetal force. The schools have the centripetal force cancel out with another force, usually the spring force. This allows the students to learn how the centripetal force works and also get their first introduction to the idea of equilibrium.

Standout Lab: Rice University - Uniform Circular Motion




This lab has students see the effect of centripetal force. A mass with a pointy bottom and spring are attached to a rod on a platform which can be rotated. The student measures the force on the spring required to bring the mass just above a pin using a pulley-mass system. The student then removes the pulley mass system and uses his or her finger to rotate the rod with a constant angular velocity so that the spring extends outward away from the center of rotation until it is just over the pin. A photogate measures the period of rotation which students record when they are sure that the mass is in the right place. Extension length is kept constant; however springs of varying strengths are used.

This is a complicated lab that illustrates quite a few concepts. Powered rotation would help the setup be more dependable. If the motion was controlled by a motor, it could be ensured that the rotation was actually constant. Having the hanging mass come out right over the measuring pin makes the setup pretty accurate though as students can literally see that they are spinning the apparatus with constant angular velocity.

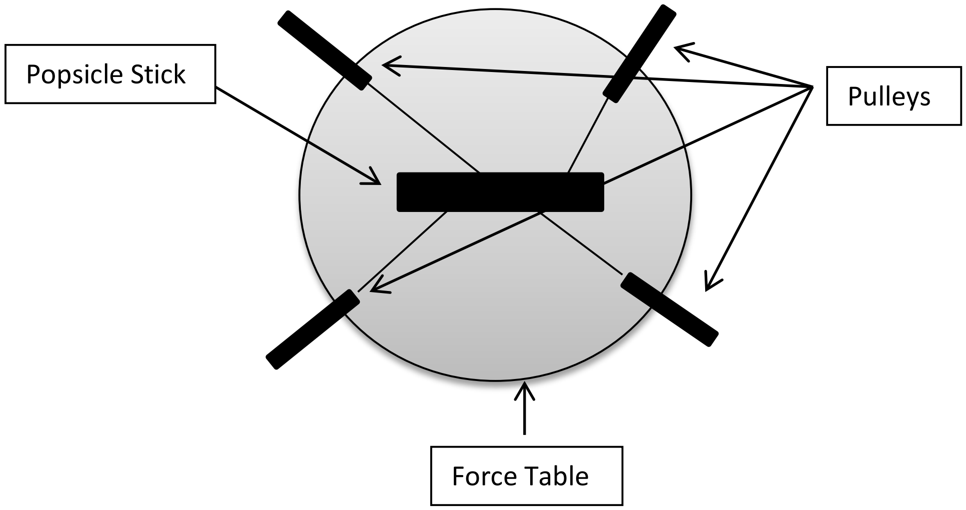
## Section 1.12 Static Equilibrium

Summary

After learning about dynamics, students are taught to consider the special case of statics. In this case there will be no motion either translational or rotational of the object in question. This allows students to learn how different forces at different angles cancel out given certain conditions. This prepares engineering students for their studies of statics down the road.

Six schools have a laboratory specifically dedicated to static equilibrium. Most of these setups involve something fixed or not fixed on an axis and several forces pulling on it at different angles. Students are asked to consider the values of the forces and the angles they make with each other. Students determine that all of the forces cancel out.

Standout Lab: Worcester Polytechnic Institute - Static Equilibrium




This experiment utilizes a “force table” which is an elevated disk with a hole in the center and several angle markings around the edges. There are four pulleys around this force table (top view in diagram above). Four strings are tied to a popsicle stick (two on each side), run over the pulleys, and connected to mass hangers. The popsicle stick has a hole in it, which a pin may be placed in so that the popsicle stick can be fixed at the center. Students add masses to the various hangers in order to determine conditions for rotational equilibrium and translational equilibrium. Students add masses with the pin both holding the popsicle stick in place and not.

This is the most comprehensive of the statics labs because it considers when the popsicle stick is fixed to an axis and when it is not. Although the setup is a little complicated and the force tables are used especially for this lab, it definitely displays the topic in the most comprehensive manner.

# Section 2: The Status of the Topics Covered across Each School

### Introduction

In addition to the discussion of the laboratory topics and their coverage across the schools, we shall discuss the coverage of the topics across each school. In this section, the table presented in section 1 will be presented again for each school. The boxes indicate which laboratories cover many topics. The indicated numbers allow the author to determine which labs cover the topic in the appendix. If a laboratory is deemed to sufficiently cover multiple topics, it will cover multiple boxes. Additionally if multiple laboratories are deemed to sufficiently cover a single topic, there will be multiple laboratories in a single box.

Beneath a table, the section will discuss the completeness of each laboratory collection. In some cases, a laboratory may cover many topics. That may cause it to weakly address any of the topics in particular, which can keep students from understanding that the purpose of completing that laboratory is to learn the indicated topic. In some cases, it might seem that addressing some of the missing topics was never the instructor's intention. Possible suggestions for the schools to address its deficiencies are suggested.

In all, it is clear that most schools' deficiencies lie in the section of rotational mechanics. Eleven of the thirteen schools have a complete translational mechanics collection, and those that do are only missing one laboratory in that row. Meanwhile no schools have a complete rotational mechanics column and only five are only missing a single laboratory in that row. Schools may want to consider whether or not rigid body motion is as important to their mechanics curriculum as is linear motion and if so, update their laboratory set to reflect that.

**Worcester Polytechnic Institute**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 2, 3 | 4, 5 | 6, 8, 11 | 7, 8 | 9 |
| Rotational | 10 | 12 | 12 | | 9 |
| Statics | N/A | N/A | N/A | N/A | 9 |

Worcester Polytechnic Institute lacks a lab for rotational momentum, as indicated by the empty box on this chart. In reality, however, the only section in which Worcester Polytechnic Institute's rotational laboratories do not need work is in equilibrium. The laboratories indicated as covering kinematics, Newton's laws, and work-energy in the rotational row are the physical pendulum and a laboratory which analyzes the motion of a pulley as a cart moves.

The physical pendulum allows the student to adjust the moment of inertia and see the effect, but students only measure the period, and the actual computation is relatively complicated. This is because the torque on the pendulum is constantly changing as the pendulum moves. The pendulum moves under the force of gravity which acts in a linear direction. For this reason, the physical pendulum is not a great way to display rotational dynamics.

The other laboratory can almost be hardly classified as rotational dynamics at all. The pulley's moment of inertia is almost negligible to the masses of the hanging mass and the cart in the motion of the system. While students may see a constant rotational acceleration, the focus is not on that rotation within the setup's system.

Worcester Polytechnic Institute does have the best static equilibrium laboratory amongst all of the schools indicated. The laboratory allows for the student to "play" with translational and rotational equilibrium. Other schools should consider adopting such a laboratory as many do not cover all three sections of equilibrium as Worcester Polytechnic Institute does.

It is recommended that Worcester Polytechnic Institute consider adopting some of the rotational dynamics laboratories listed in the previous section in order to complete its collection of laboratories.

**Rice University**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 1, 2, 10 | 3, 4, 9, 10 | 5, 10, 11, 12 | 6 | 3, 9, 11 |
| Rotational | 4 | 7, 14 | 7, 8, 13 | | 4 |
| Statics | N/A | N/A | N/A | N/A | |

Rice University has just two gaps in its collection of laboratories. One gap is in the static equilibrium section. As this is just a special case of the topics in Newton's laws and equilibrium, students do not lose a significant amount of fundamental physics in the process. The lack of an angular momentum lab, however does leave a significant gap. Many consider the conservation of momentum to be the most important law for making predictions in mechanics.

Rice University already employs a fantastic impulse-momentum lab which could easily be adjusted to be an angular momentum laboratory. In this setup, several pucks collide with each other on an air table. Video is used as a method of determining that momentum is conserved between collisions. Students could simply draw lines along the diameter of the pucks and determine how the collisions affect the angular momentum of each. This is a confusing setup, however, and a simpler angular momentum lab would be more suitable.

**Massachusetts Institute of Technology**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 1, 2, 12 | 3, 6 | 7, 8, 14 | 8 | 5, 6 |
| Rotational | 4 | | 9, 11 | 10 | 4, 13, 14 |
| Statics | N/A | N/A | N/A | N/A | 5, 6 |

Massachusetts Institute of Technology only as a single gap in the rotational Newton's laws box. None of the laboratories really directly address torque at all. This also causes the rotational work-energy laboratories to be similarly uncommunicative of the intended concepts. The laboratories used here are a physical pendulum and a pot-scrubber experiment.

The physical pendulum allows the student to adjust the moment of inertia and see the effect, but students only measure the period, and the actual computation is relatively complicated. This is because the torque on the pendulum is constantly changing as the pendulum moves. The pendulum moves under the force of gravity which acts in a linear direction. For this reason, the physical pendulum is not a great way to display rotational dynamics.

The other laboratory can hardly be described as rotational mechanics at all. The pot scrubber experiment is intended to show how energy from a falling mass can be turned into heat energy. The falling mass turns a pot scrubber, but the whole system is complicated enough that the rotation of the scrubber is a very small part of the entire set up. In fact, students just see the mass falling and the changing temperature. The scrubber itself is hidden from view. A more straightforward rotational energy laboratory would be more suitable.

**Boston University**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 1, 2, 3, 4 | 4, 5, 8 | 7, 9, 10 | 9, 11 | 6 |
| Rotational | | 13 | 14 | 12 | |
| Statics | N/A | N/A | N/A | N/A | 6 |

Boston University has gaps in the rotational kinematics and rotational equilibrium cells. Many other schools fill both of these cells with a laboratory which observes the centripetal force with the help of a spring. Boston University also uses a physical pendulum as its rotational work-energy laboratory. Boston University does, however make the adjustment that the pendulum will only oscillate about its center and it masses will slide in and out from the center. This does cement an understanding of the moment of inertia. The problem that the physical pendulum moves under a linear force however, is still sufficient enough that another rotational energy laboratory would better suffice the topic.

**Northeastern University**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 1, 2 | 3 | 6, 10, 11 | 5 | 7 |
| Rotational | 4 | | 8, 9 | | 4, 7 |
| Statics | N/A | N/A | N/A | N/A | 7 |

Northeastern University has gaps in the rotational Newton's laws and rotational momentum cells. The rotational laboratories of this collection are a statics laboratory, Maxwell's wheel, and rolling on a track. Maxwell's wheel and rolling down a track are both outstanding ways to convey the idea of rotational energy, but the rolling motion itself is a linear motion. It is abstracted in such a way that the student cannot see the torques occurring on their own.

Many schools have a static equilibrium laboratory as their main instruction in torques as Northeastern University. While the results from static equilibrium do display an important result in rigid body mechanics, they are not enough to show the students the importance of angular dynamics. This is because torques cause a rigid body to accelerate their rotation. Students should therefore see the results of this acceleration in addition to the results when there is no motion.

**Wentworth Institute of Technology**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 1, 2, 3, 4, 5 | 3, 6, 7 | 8, 9, 10, 11 | | 12 |
| Rotational | 14 | 15 | | | 13 |
| Statics | N/A | N/A | N/A | N/A | 12, 13 |

Wentworth Institute of Technology has gaps in the both momentum cells and the rotational energy cell. In fact, although the school has four translational energy laboratories, two of them just measure the distance pulleys move in relation to each other and another has students calculate their power output in a run up a flight of stairs. The other just has students measure a fall time for Atwood's machine. This is a calculation which really only uses kinematics and Newton's laws and the conservation of energy is just another way to calculate it. A pendulum might be a better way to perform a calculation which actually relies on the results from the conservation of energy.

Wentworth Institute of Technology has some great setups with the rotating platform from experiment 14 to the several pulley systems across the experiments. These experiments give students a very unique sense of physics if they are used effectively. Unfortunately, these experiments only demand that the student measure the distance one block moves in relation to another. A dynamic use of these tools could provide students with a very strong understanding of the results of the Work-Energy Theorem.

**Illinois Institute of Technology**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 2 | 1, 3, 4, 5, 6 | 7, 8 | 9 | 6 |
| Rotational | 10 | 11 | | 12 | 10 |
| Statics | N/A | N/A | N/A | N/A | |

Illinois Institute of Technology has gaps in rotational work energy and static equilibrium. It is nice for students to see static equilibrium in action. It is a way for them to see the results of Newton's laws for both rotational and translational systems in action. It is additionally useful for engineering students who will continue studies of statics in their engineering courses. Yet, the fact that Illinois Institute of Technology covers both translational and rotational equilibrium gives the impression that students will have a relatively strong grasp of the result of no net torques or forces.

The lack of a rotational work-energy laboratory does leave a significant gap in the instruction, however. It is important for students to see how a force can do work on an object to cause it to rotate. Some of the results from rotational work energy are non-intuitive, and it is therefore good for students to observe it during a laboratory.

**University of Massachusetts – Boston**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 2, 3, 4 | 4 | 1 | 5, 6 | 8 |
| Rotational | 7 | | | 5 | 7 |
| Statics | N/A | N/A | N/A | N/A | |

The University of Massachusetts – Boston has gaps in rotational Newton's laws, rotational work-energy, and static equilibrium. It is nice for students to see static equilibrium in action. It is a way for them to see the results of Newton's laws for both rotational and translational systems in action. It is additionally useful for engineering students who will continue studies of statics in their engineering courses. Yet, the fact that University of Massachusetts – Boston covers both translational and rotational equilibrium gives the impression that students will have a relatively strong grasp of the result of no net torques or forces.

As with many other schools, this school is lacking in its rotational laboratory collection. The ballistic pendulum does display conservation of angular momentum; but since the final speed of the object is calculated as a pendulum, the rotational momentum is somewhat abstracted in the experiment. The rotating spring which displays Hooke's law and centripetal motion is a good laboratory, but it does not really display a lot of the ideas of angular dynamics. Students are not able to observe the torque or see how work can cause a change in rotational energy.

A few schools, including University of Massachusetts – Boston show Archimedes principle to students. This laboratory is a good way to show equilibrium and an effect of Newton's laws with fluids.

**University of Virginia**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 1, 2, 3 | 4 | 5, 8 | 6 | 4 |
| Rotational | 7 | 7 | 7 | 7 | |
| Statics | N/A | N/A | N/A | N/A | |

The University of Virginia has gaps in rotational and static equilibrium. As these are special cases of mechanics, it is commendable that University of Virginia covers the rest of the topics. These topics are covered thoroughly as well. While it seems that laboratory 7 may be spread too thinly, it should be noted that the University of Virginia has large laboratories with several "activities" which are intended to be completed over a few laboratory sessions. The University of Virginia has a strong emphasis on laboratory physics for its students which provides them the necessary experience to develop an intuition in the topics in mechanics.

**Dartmouth College**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 1, 3 | 6, 7 | 5 | 2, 3 | 7 |
| Rotational | | | | | |
| Statics | N/A | N/A | N/A | N/A | |

Dartmouth College has a completely empty rotational mechanics row and no static equilibrium. It is likely that this is by design for the collection of laboratories provided for this study. The translational kinematics laboratories are effective and convey the ideas well. For a course which does not intend to add the complexity of rigid body motion to its discussion of mechanics, this collection of laboratories is complete and effective.

**University of California – Los Angeles**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 1, 8 | 2, 7 | 3 | 4 | |
| Rotational | 6 | 6 | | | 5 |
| Statics | N/A | N/A | N/A | N/A | 5 |

The University of California – Los Angeles has gaps in its collection for rotational work-energy, rotational impulse-momentum, and translational equilibrium. It seems that the laboratory section of the mechanics course at University of California – Los Angeles is secondary to its theoretical instruction as many of the laboratories seems to be exciting in nature rather than purely instructive. This can be seen in the biceps muscle model which is focused on showing students how torques relate to the motion of the arm. It is also shown in the use of a gyroscope which is a complicated topic that displays a strange effect of rigid body mechanics to students.

The University of California – Los Angeles uses the air track and glider system that many other schools use in order to display the translational mechanics concepts. This setup effectively displays these topics, but the other topics could be covered in a more straightforward, instructive manner for the laboratory setting. This allows students to see concepts in isolation and determine their importance.

**University of Texas – San Antonio**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 1, 2, 3 | 4, 10 | 3, 9 | 5 | 8 |
| Rotational | 7 | 7 | | | |
| Statics | N/A | N/A | N/A | N/A | |

The University of Texas – San Antonio has gaps in its rotational work-energy, rotational impulse-momentum, rotational equilibrium, and static equilibrium cells. It is nice for students to see static equilibrium in action. It is a way for them to see the results of Newton's laws for both rotational and translational systems in action. It is additionally useful for engineering students who will continue studies of statics in their engineering courses. Yet, the fact that University of Texas – San Antonio covers both translational equilibrium gives the impression that students will have a relatively strong grasp no net forces, but may require an understanding of how different torques can cancel each other out.

University of Texas – San Antonio only has a single rotational mechanics laboratory. This laboratory does effectively display the idea of rotational inertia as students see how the inertia of a disc and a ring vary. Students see how a torque causes rotational acceleration in real time with the use of a rotor pulley that reports its motion directly to the computer. It is however, still not enough to show the students the important results of conservation of angular energy and momentum. These concepts require additional coverage.

**University of Minnesota**

| | Kinematics | Newton's Laws | Work/Energy | Impulse/Momentum | Equilibrium |
|---|---|---|---|---|---|
| Translational | 1, 2 | 3 | 5, 7 | 6 | 3 |
| Rotational | 4 | | | | 4 |
| Statics | N/A | N/A | N/A | N/A | |

The University of Minnesota has gaps in its rotational Newton's laws, rotational work-energy, rotational impulse-momentum, and static equilibrium cells. It is nice for students to see static equilibrium in action. It is a way for them to see the results of Newton's laws for both rotational and translational systems in action. It is additionally useful for engineering students who will continue studies of statics in their engineering courses. Yet, the fact that the University of Minnesota covers both translational and rotational equilibrium gives the impression that students will have a relatively strong grasp of the result of no net torques or forces.

The University of Minnesota has only a single rotational mechanics laboratory. This may be by design as often times the centripetal force is the only part of rotational mechanics covered in elementary physics courses that focus on translational kinematics. In that case this is a complete set of laboratories and the topics are well covered.

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# Appendix A: Worcester Polytechnic Institute Laboratories

1 - Uncertainties of Experimental Data

Students write the means and standard deviations of various data sets in order to learn and practice the correct formatting for reporting data measurements.

2 - Understanding Graphs of Motion

Students move a cart along a track with a motion sensor. The motion of the chart is plotted in real time as the cart moves along the track. The students attempt to match motion curves in displacement over time and velocity over time charts. The students then create curves with follow rules about increasing, decreasing, or constant acceleration, velocity, and displacement.

3 - One-Dimensional Kinematics

Students use software to plot the motion of a cart over time. The cart is released up an inclined track and allowed back down. The plot contains displacement, velocity, and acceleration over time. Students use the software to integrate over a certain interval in the velocity and accelerations plots and see how that compares to the intervals in the displacement and velocity graphs respectively. The students also find the tangent lines of the displacement and velocity graphs at certain points and see how the slopes of these lines compare to the values of the velocity and acceleration graphs, respectively, at the same time value.

4 - Free Body Diagrams

Students stand on a force plate and plot the changes in force as they complete activities such as lifting books, dropping a book from one hand to another, and jumping off of the plate. Students create force diagrams for each of the scenarios.

5 - The Mass-Dependence of Friction

Students record the acceleration of a cart sliding down a gentle slope. Students add masses to the cart and see how the motion of the cart changes and use knowledge of friction to explain the change.

6 - Conservation of Energy

Students record the motion of a mass on a spring. For several points in time, students use the instantaneous velocity and position to calculate the mechanical energy of the spring mass system at any point in time. The students compare these values of mechanical energy to observe energy conservation.

7 - The Impulse-Momentum Theorem

Students drop a ball on a force plate from a fixed height. Students use the changing momentum on impact and the readings from the force plate to show that the impulse equals the change in momentum.

8 - Work-Energy and Momentum

Students place a cart in the center of a track and another cart at one end of a track. Motion sensors are on either side of the track, each measuring the motion of one cart. The cart on the end is slid towards the cart in the center, causing a collision. Such collisions are measured for varying masses of carts, for nearly elastic collisions (using a springy plunger on the cart), and collisions in which the carts stick together (using velcro). Students take note of the energies and momenta of the carts before and after the collisions.

9 - Static Equilibrium

This experiment utilises a “force table” which is an elevated disk with a hole in the center and several angle markings around the edges. There are four pulleys around this force table. Four strings are tied to a popsicle stick (two on each side), run over the pulleys, and connected to mass hangers. The popsicle stick has a hole in it, which a pin may be placed in so that the popsicle stick can be fixed at the center. Students add masses to the various hangers in order to determine conditions for rotational equilibrium and translational equilibrium.

10 - Translational and Rotational Dynamics

Students are presented with an inclined track, a motion sensor at the bottom of this track, rotary sensor pulleys at the top of the track, and a cart tied to a mass which is heavier than the cart run over these pulleys. The cart is on the track and is slid down the track, towards the motion sensor. The mass on the other end decelerates the cart so that it eventually comes to a halt and goes back up the track. Students record the translational motion of the cart and the rotational motion of the rotary sensor, assuming a no slip condition and knowing the radius of the rotary sensor pulley.

11 - Simple Pendulum

Students measure the period of a simple pendulum with varying lengths and masses of the weight on the end. Students then plot and compare the values.

12 - Physical Pendulum

Students hang a meter stick as a simple pendulum. Different masses are placed at different heights below the pivot point of the pendulum, and the pivot point is also varied. Students measure the period of each variant to determine its dependence on each factor. Students then use known theory to determine the acceleration of gravity.

# Appendix B: Rice University Laboratories

1 - Kinematics in 1D

This lab has students analyze the motion of a cart in one dimension. A camera records the motion of the cart and the student determines the velocity of the cart over time using software which pinpoints chart values of a picture given some sort of length scale.

2 - Projectile Motion

This lab has students analyze the motion of a dropping ball, a thrown ball, an asymmetrical object (such as a water bottle), a leaping human, and a falling styrofoam bowl. A camera records the motion of the cart and the student determines the velocity of the cart over time using software which pinpoints chart values of a picture given some sort of length scale.

3 - Forces

This lab has students analyze the motion of a cart with applied forces including hand pushing, friction, and a spring. A camera records the motion of the cart and the student determines the velocity of the cart over time using software which pinpoints chart values of a picture given some sort of length scale.

4 - Uniform Circular Motion

This lab has students see the effect of centripetal force. A mass and spring are attached to a rod which can be rotated. The student uses is or her finger to rotate the rod with a constant angular velocity so that the spring extends outward away from the center of rotation to a specified distance. A photogate measures the period of rotation. Extension length is kept constant, however springs of varying strengths are used.

5 - Energy Conversions

This experiment has students show the conservation of energy of a cart, pulley, and mass system in addition to a card and spring system. The experiment uses a photogate to measure the time it takes the cart to travel a certain distance and then mathematics is used to verify that energy is conserved over this travel.

6 - Collisions in Two Dimensions

In this experiment, students slide plastic pieces on an air table in order to observe and analyze several collisions between the pieces. A camera records the motion of the plastic pieces and the student determines the velocity (speed and direction) of the plastic peices before and after each collision using software which pinpoints chart values of a picture given some sort of length scale.

7 - Angular Dynamics

In this experiment, a falling mass drives the rotation of a two mass system. The falling mass is connected with a string to a rotor pulley which has three different radii. The student is to analyze how changing the radius of the rotor pulley and the falling mass affects the acceleration of the rotation. A photogate is used to measure the periods of rotation.

8 - Simple Harmonic Motion

A long flat piece of metal is hung from one of its many holes. For each of the holes, the student measures the distance from the hole to the center of mass of the bar. The student then lifts the bar about 20 degrees and allows it to swing. The periods of motion are measured over time.

9 - Friction

In this experiment, a sliding system is dragged along a surface. The student measures the motion of the sliding system with a sonic ranger and uses the results to determine the static and kinetic coefficients of friction.

10 - Falling in Air

A styrofoam cup is released in the air, and its motion is measured using a video camera. Analysis of the cup motion with the video camera allows its various positions over time to be measured. The student fills the cup with varying amounts of plastic discs, and records the weight of the cup with its contents each time. These pieces of data are used to analyze the nature of the force of drag on the cup.

11 - Work-Energy Relations

A sliding mass system is dragged with a spring. The motion of the system is measured using a sonic ranger. The student shows the work energy relation and the energy lost to friction.

12 - Oscillations

The student measures the motion of a simple mass spring system with a sonic ranger.

13 - Rolling Motion

A round object is placed on a tilted surface. The mass and radius of the object are measured and the tilt of the surface is as well. The student performs the calculation to determine the equation of motion of the object. The student then uses a video camera which can analyze the motion of the object over time to test his or her prediction.

14 - The Gyroscope

A sphere is placed into a sphere shaped hole, out from which air blows to keep the sphere afloat. A rod is attached to the sphere so that the center of mass is placed away from the center of the sphere and the sphere will exhibit gyroscopic motion. A strobe light is used to measure the frequency of rotations of the sphere and the period of precession of the rod is measured with a stopwatch.

# Appendix C: Massachusetts Institute of Technology Laboratories

1 - Introduction to DataStudio

Students are introduced to the DataStudio programs ability to measure several distances from a motion sensor over time. Students move their hand towards and away from the motion sensor in order to visualize what the program is plotting. Students oscillate their hands back and forth to create a wave pattern, and then fit the wave using the program. This allows the students to find instantaneous velocities and accelerations of their hands at different moments in time.

2 - Projectile Motion

In this experiment student have a tube with a ball inside. The ball can either be held in place with a pin and released, or it can be held against a spring and released. Students first angle the tube so that the end which the ball is released is below the end with the ball inside. Students then release the ball without being held against the spring. Students measure the distance the ball travels. Students repeat at different angles. Students then angle the tube upwards and have the spring launch the ball. Student again measure the distance that the ball travels.

3 - Modeling Forces

Students have two magnets sliding along a pole. The magnets are oriented such that they repel one another. Students stack pennies on top of the upper magnet and measure the distance between the two magnets for varying amount of pennies. Students use this information to determine the distance dependence of the force between the two magnets.

4 - Circular Motion

Students attach a spring-mass system to a rotating motor. The mass is a magnet which passes through a voltage sensor. Students turn on the motor and use DataStudio to record the times at which the mass passes through the voltage sensor. The apparatus has a viewer which allows easy measurement of the distance between the motor and the mass (radius of the circle of rotation). Students adjust the speed of rotation and compare the radius of rotation to different periods of rotation.

5 - Static Equilibrium

A mass is hung on a horizontal string which is connected to a force meter. Students compare the angle the string makes and the tension on the string with predictions made from static equilibrium calculations. Students lengthen the string such that it can make a larger angle with the horizontal and use different sized masses in order to perform the same calculation for different cases.

6 - Friction

A string is connected to a force meter and then a hanging mass. The string passes over a cylinder which is the source of friction for the string. Students wrap the string around the cylinder, each time comparing the value of the force on the force meter. Students repeat, wrapping the string around a smaller cylinder. Students determine the coefficient of static friction for each case.

7 - Conservation of Energy

A track is elevated with a motion sensor on the elevated end and a force sensor with attached springs on the lower end. Students allow a cart to slide along the track, recording its motion. Students analyze how the gravitational potential energy is converted to kinetic energy and then to potential energy in the springs.

8 - Collisions

A level track has a motion sensor on one end and a force sensor with attached springs on the other end. A cart is placed near the middle and another cart is slid from the end with the motion sensor towards the other cart to cause a collision. The carts have velcro so that they stick together after the collision. Students use the resulting data to determine the total momentum before and after the collision and the total energy before and after the collision. Students then determine how to calculate how much energy is lost in a “completely inelastic collision.”

9 - Physical Pendulum

Students hang a meter stick from its end and measure the period of its pendulum swing raising it to different heights. Students clip a brass weight onto the ruler in order to change its moment of inertia, repeat the swings, and record the new period of the pendulum.

10 - Angular Momentum

A horizontal rotor is connected to a string and a mass along a pulley such that when the mass is released, it will pull downward and the rotor will spin. As the rotor is spinning, students drop a disc onto it and record how the angular velocity changes to account for conservation of angular momentum.

11 - Energy Transformations

A weight is tied to a string which is run over a vertical pulley and then wrapped around a horizontal pulley such that the horizontal pulley rotates when the weight is released. The pulley powers the spinning of a pot scrubber which is inside a pot. There is also water in the pot and a probe that measures the temperature of the water. The system is closed so that the heat energy from the spinning scrubber will stay in the pot. Students determine the energy lost to friction when the weight falls and compare that to the increase in thermal energy in the water.

12 - Falling Object

An electrical apparatus is set up such that the time that a wire nut is released from an alligator clip to the time that it hits the cup below is able to be recorded accurately. Students drop the wire nut from several different heights and compare to the predicted fall time for the different heights.

13 - Centripetal Force

A rubber band is tied to a motor which rotates in the horizontal plane. A 6-32 nut is attached to the other end of the rubber band. Students turn on the motor so that the nut is in orbit around the motor. Students turn off the lights and turn on a strobe light until they see the rubber band make a stationary plus sign. Students then know that the rotation frequency is one quarter of the strobe light's frequency. Students then measure the radius of rotation. After completing the experiment, students measure the spring constant of the rubber band. Students compare their results with the predicted results for the strength of the centripetal force.

## 14 - Vibrating Systems

Students connect a hanging rubber band to a paper cup, fill the cup with a few pennies, and pull the cup downwards slightly to begin oscillation. Students determine the period of oscillation. Students add pennies to the cup and determine the effect this changing mass has on the oscillation period. Students then set the pendulum into circular motion so that it sweeps out a cone. Students record the period of the conical pendulum and its dimensions. Students also determine the mass of the cup, the mass of one penny, and the spring constant of the rubber band in order to compare their observations to theory.

# Appendix D: Boston University Laboratories

1 - Graphical Analysis

A computer simulation simulates the dropping of an object in gravity. The simulation outputs the height of the object over time as it falls. Students then graph the height of the object over time and consider the relationship between the two variables.

2 - Position, Velocity, and Acceleration

Students use a motion sensor to record the motion of a cart on a track. Students slide the cart back and forth along the track and note the motion. Students then tilt the track and record the cart sliding down the track. Students finally record the motion of the cart sliding up the track, sliding it in that direction, and then back downwards.

3 - Projectile Motion

Students have a gun which launches a ball using a spring. Students may adjust the angle at which the gun is aiming and the force with which the ball is launched. Students fire the ball at a target paper several times in order to determine the range of a certain setting. Students then adjust the settings and analyze the effects of these adjustments.

4 - Constant Acceleration

A cart is on a track with a motion sensor on one side and a mass-pulley system, which is tied to the cart, on the other. The system is such that when the mass is released, the cart will begin moving away from the motion sensor. Students are able to add mass to the cart and change the mass in the mass-pulley system. Students compare the acceleration of the cart for varying masses of each.

5 - Forces between Carts

Students attach force sensors to carts in order to measure the force on a cart by another cart. Students one cart collide into another. They have the carts collide into each other. Students have one cart just push another along. Students add weights on top of the carts in order to change the mass of the carts and record how this affects the forces recorded in the different situations above.

6 - Friction

A wood block is placed on a wooden board. The block is tied to a string which runs over a pulley and then is tied to a mass hanger. Students add a little mass to the hanger at a time and then give the block a little push in the direction of the pulley. At first the block will just stop, but eventually it will continue to move after the push in the direction of the pulley at a nearly constant velocity. After observing this motion and determining the mass that causes it, students then put the block back where it started and add mass to the hanger, little by little, until the block begins to slide without any push. Students record the mass at which this occurred. Students use these mass values to determine the coefficients of static and kinetic friction between the block and the board.

7 - Energy Conservation

A cart and a force sensor have magnets placed on them such that the two repel each other and the repelling force is the force which the force sensor records. Students allow the cart to roll down a track towards the force sensor. A motion sensor is placed at the top of the track. Students analyze how the gravitational potential energy is converted into kinetic energy and then into magnetic potential energy.

8 - Magnetic Forces

Students have a cart on a track with a motion sensor one one side and a force sensor on the other side of the track. The cart and the force sensor have magnets attached to them such that the two repel and the force sensor records this repelling force. Students slide the cart towards the force sensor in order to determine the force for different distances between the magnets. Students then start the cart near the force sensor and release it such that it launches in the other direction. Students repeat this with the track tilted such that the force sensor launches the cart slightly upward. Students use this data to determine the potential energy of the magnets.

9 - Impulse and Work

Students have two carts on a track, placed between two motion sensors. There are force sensors on the carts as well. Students cause several collisions to occur between the carts, adding weight barts on top of the carts to vary their masses. Students determine the momenta of the carts before and after and the impulse on each cart during the collision. Students verify the impulse-momentum theorem for each cart and the conservation of momentum for the system as a whole.

10 - Energy and Work

Students start with a level track. There is a single cart on the track and a motion sensor on one side. Student slide the cart along the track and record the loss in velocity due to friction. Students compute the work done by friction. Students then tilt the track upwards and record the angle of tilt. Students allow the cart to roll down the track and compare the increasing kinetic energy with the work done by gravity on the cart. Students vary the mass of the cart to compare. Students also account for losses due to friction as determined in the first part of the experiment.

11 - Collisions

Students have two carts placed on a track, between two motion sensors. Students cause several collisions to occur and determine the before and after momenta of each cart and of the system. Students add weight bars on top of the carts in order to change their masses. The first collision is with magnetic bumpers. The bumpers cause the carts to repel one another. Students have one cart slide one cart towards another and record. They then slide the carts at each other and record. The students throw the carts softly enough such that they never fully collide. Students then perform these collisions with velcro bumpers so that the carts stick together. The students then place the carts next to each other and cause a spring powered plunger to be released between the carts while they are both stationary. Finally, students complete the collisions with one cart having an extended plunger during the collision so that the carts do not stick together.

12 - Angular Momentum

A metal bar is free to rotate about an axis with a cup on one end of the bar and a counter weight on the other. A spring gun shoots a ball into the cup so that the bar begins to rotate. Students fire the ball with the gun several times in an open space to determine the initial velocity of the ball. Students then aim the ball at the cup and record the angle, as compared to the axis of rotation with which the gun fires the ball. Students change this angle while still firing the ball into the cup. Students record the resulting rotation. They record the time of each revolution until the bar stops rotating. Students use this data to confirm that the angular momentum of the system before and after are the same.

13 - Torque and Moments of Inertia

A weight is tied to a string which runs over a vertical pulley and then is wrapped around a horizontal pulley. The horizontal pulley is a part of a system with two pulleys and a disc-shaped plate on top. The rotation of this system is measured by an optical reader that counts the number of alternating stripes that pass by it. Students measure the angular acceleration of the system when the weight is attached to both pulleys. Students use this to determine the moment of inertia of the system. Students then determine the moments of inertia of a bar and a disk by placing them on top of the plate and repeating the above procedure.

14 - Simple Harmonic Motion

Students connect a brass bar to a rotary motion sensor near its sensor. Students place a mass on each end of the bar, one closer to the end so that this end hangs down. Students then allow the bar to oscillate and record its motion. Students record the period of the rod's oscillations for various positions of these masses. Students then adjust the masses such that the pendulum can undergo large amplitude oscillations. This occurs when the masses are a similar distance from the center of oscillation. Students obtain the motion graphs for the different oscillations and compare.

# Appendix E: Northeastern University Laboratories

1 - Free Fall

A mass falls freely along a paper paper tape which is set up such that a mark will be made at the location of the mass every 25 milliseconds. Students measure the positions of the marks in order to determine the speed and acceleration of the object as functions of time. Students repeat the experiment with different weights and investigate the claim that the acceleration of a falling object does not vary with mass. Students also consider the drag of the paper tape on smaller masses.

2 - Motion in One and Two Dimensions

Students have an inclined plane which uses a system similar to an air hockey table such that a puck can slide along it with little friction. Students slide puck up and down an inclined plane several times. For each trial students determine the position of the puck at several constant time intervals. Students then plot the position, velocity, and acceleration in the the direction along the incline and perpendicular to it over time. Students compare the independence of these two components.

3 - Newton's Second Law

Students have a horizontal air table with a gliding mass block on top of it. The block is tied to a string which is run over a pulley and tied to a hanging mass. Students determine the motion of the system for varying masses in order to test Newton's second law.

4 - Uniform Circular Motion

A rotating platform has a post between the center and edge of the platform. From the post a bob is hanging as a mass. The bob is tied to a spring which pulls the bob inwards towards the center of rotation. Students rotate the platform until the bob is hanging vertically and record the angular speed at which this is required. Students then stop the rotation and tie the bob to a string which is run over a pulley and hung to a mass hanger. Students determine what mass is required to make the bob hang vertically while the rotating platform is at rest. Students use these values to compare the measured centripetal force to the theoretical.

5 - Conservation of Momentum in Collisions

Students have an air table which pucks can slide on with very little friction. Students slide the pucks up and down the table in such a way that they will collide with each other. Students determine the position of the pucks over constant time intervals before and after the collision in order to determine the momentum of the pucks before and after the collision. Students then attach velcro to the edges of the pucks so that they stick together upon collision. Students determine the momentum of the pucks before and after these collisions. Students also determine the motion of the center of mass of the two puck system for both types of collisions in order to analyze the motion of the center of mass of a two mass system.

6 - Work and Energy on an Air Track

Students have an air track on which a glider can move with little friction. First students tilt the track and allow the glider to slide down it. Students have a motion sensor which can measure the motion of the glider over time. Students measure the tilt angle and analyze how the gravitational potential energy is converted into kinetic energy. Students then level the track and tie the glider to a string which is run over a pulley and tied to a hanging mass. Students measure the motion of the hanger again considering how the gravitational energy of the mass is converted to kinetic energy of the mass glider system.

7 - Forces and Torques in Equilibrium

Students mount one end of a meter stick onto an axle such that it can swing in a vertical plane. Students then tie a string to the other end of the meter stick. This end of the string is attached to a spring scale which reports the force on the string. Students adjust the angle of the meter stick and the string in several ways and record the force on the spring scale. Students use this to determine the torque on the stick for each case and compare it to the results from the static condition.

8 - Maxwell’s Wheel

Students have a disc in the center of a rod which is suspended by two strings from above. The strings wind around the rod when it rotates with the disc. Students measure the dimensions and mass of the disc and the rods in order to determine its moment of inertia. Students then spin the disc and record the falling times and distances of the rods for several falls. Students use this data to determine the moment of inertia and compare it to the calculated value. Students then add brass weight attachments in order to change the moment of inertia of the system and repeat the procedure.

9 - Rolling Motion on an Inclined Track

Students record the motion of a hollow cylinder rolling down a track with an adjustable ramp. Students have a sonic motion sensor which can record this motion. They fill the cylinder with fluids of different viscosities and compare the viscosities with the acceleration of the cylinder. Students explain the differences in acceleration.

10 - The Simple Pendulum

Students have a simple pendulum, a mass suspended on a string. Students determine the period of the pendulum for several lengths of string. Then students plot the period squared against the length in order to calculate the gravitational acceleration. Students repeat the experiment with different masses on the end of the simple pendulum. Students verify that the period of the pendulum is independent of the mass.

11 - Simple Harmonic Motion

Students have an air track which a glider can move on with little friction. The glider is attached to two springs on either end of the track. The motion of the glider is measured by a sonic motion sensor. Students slide the glider away from equilibrium and allow it to oscillate. Students determine the period and amplitude of the oscillation. Students displace the glider several times different amounts in order to achieve different amplitudes of oscillation. Students confirm that the period of oscillation is independent of the amplitude.

# Appendix F: Wentworth Institute of Technology Laboratories

1 - Acceleration

Students have a titled air track and a glider that can slide down the air track with little friction. Students place a photogate near the lower end of the track. Students measure the distance between the top of the track and the photogate. Students release the glider from the top and simultaneously start a stopwatch. Once the glider enters the photogate, students stop the stopwatch. Students can determine the final velocity of the glider using the enter and exit times of the photogate and the length of the glider. Students use these data to determine the acceleration of the glider down the track.

2 - Free Fall

Students have a photogate-impact pad system which can determine the time that something takes to travel between the gate until it hits the impact pad. Students drop various masses at various heights through this system. Students determine the acceleration of gravity and verify that it is independent of the mass of the falling object.

3 - Measuring Acceleration Due to Gravity: Galileo’s Method

Students have a titled air track and a glider that can slide down the air track with little friction. Students place a photogate near the lower end of the track. Students measure the distance between the top of the track and the photogate. Students release the glider from the top and simultaneously start a stopwatch. Once the glider enters the photogate, students stop the stopwatch. Students can determine the final velocity of the glider using the enter and exit times of the photogate and the length of the glider. Students repeat this procedure for several angles of the track incline and then use this data to determine the acceleration of gravity.

4 - Projectile Motion

Students have a launcher which can launch a metal ball bearing at a piece of carbon paper. Students launch the ball horizontally from a certain height five times. Students then determine the centroid at the center point of the five marks. Students use this with the height to calculate the horizontal velocity of launch. Students then repeat the procedure at a different height and compare values of the horizontal velocity.

5 - Trajectory of a Projectile

Students have a launcher which launches a metal ball bearing at a piece of carbon paper. Students launch the ball horizontally from a certain height five times simultaneously timing the time of flight from launch to landing each time. Students then determine the centroid of the five marks on the carbon paper. Students repeat this procedure for fifteen different heights. Students then determine the initial velocity using the flight times and heights and the distances and heights and compare the differences.

6 - Atwood’s Machine

Students have two mass hangers tied to each other with a string and run over a pulley. Students add weights to the mass hangers so that the masses on each are close but slightly different. Students record the time that it takes for the heavier mass to fall a certain distance. Students then add small masses to the heavier mass and record the time for the fall for two more trials. Students compare the fall time to the theoretical time.

7 - Dynamics of Atwood’s Machine

Students have two mass hangers tied to each other with a string and run over a pulley. Students add weights to the mass hangers so that the masses on each are different. Students record the time that it takes for the heavier mass to fall a certain distance. Students use this time to determine the acceleration of the drop. Students determine the ratio of the acceleration to the acceleration of gravity and plot this against the ratio of the masses in the system. Students record several such ratios for several different mass combinations.

8 - Work and Efficiency I

Students have a triple pulley system which is set up such that a mass hung on a moving pulley will move half the distance as a mass hanging off the end of the string. Students hang a mass on the moving pulley and a mass on the string. Students slide the mass on the end of the string down a certain distance and measure the distance that the other mass moves. Students use this information to calculate the work done by both masses. Students then calculate the efficiency of the pulley system.

9 - Work and Efficiency II

Students have a five pulley system with a mass hanging on one of the pulleys and a mass hanging at the end of the string. Students determine what the ideal mechanical advantage of this system is and then compare it to the actual mechanical advantage. Students let the mass hanging at the end of the string move a certain distance and measure the distance that the other mass moves. Students use this information to determine the efficiency of the system.

10 - Conservation of Energy

Students have two mass hangers tied to each other with a string and run over a pulley. Students add weights to the mass hangers so that the masses on each are different. Students record the time that it takes for the heavier mass to fall a certain distance. Students use this time to determine the mechanical energy of the system at the end of the drop and compare it to the mechanical energy at the beginning of the drop. Students calculate the percent difference between these values.

11 - Your Useless Power Output

One student runs up a flight of stairs as fast as possible while another records the time that the student takes to run. Students determine the total height that they ran upwards and also weigh themselves. Students use this to determine the work they did against gravity and the average amount of power of their run.

12 - Translational Equilibrium

Students have a system of two pulleys set in place in the same plane but with different heights and separated by a significant horizontal distance. A string is run over both pulleys with a mass hanger tied to the ends of the string on the left and right and a third mass hanger tied to the string in between the pulleys. Students are told to consider the three values of the masses, and the two angles the string in the middle makes to the horizontal. Students are given three of these five values and told to solve for the other ones using equilibrium assumptions. Students place the appropriate masses on the appropriate hangers according to their calculations and measure the angles. Students compare the measurements to the prediction.

13 - Rotational Equilibrium

Students have a two meter stick. Students clip the stick to a fulcrum which it can rotate freely around. Students move the fulcrum until the stick is balanced horizontally. Students are then told to hang a certain mass at a certain location on the stick. Then students prepare a second mass which they place on the stick wherever necessary to keep the stick balanced horizontally. Students compare this to their theoretical calculations. Students finally move the fulcrum so that it is off-center and repeat the procedure.

14 - Rotation and Angular Measure

Students have a rotating platform with three rotor pulleys underneath. Students wrap a string around one of the pulleys and then run it over a pulley and tie it to a mass hanging off the edge. Students pull the mass down a certain length and record the amount that the platform rotates. Students compare the rotation to what would be predicted for the no slip condition. Students repeat for two different such distances.

15 - Moment of Inertia

Students have a rotating platform with three rotor pulleys underneath. Students wrap a string around one of the pulleys and run it over a pulley at the edge of the table and tie it to a mass which is hanging off the edge of the table. Students let the mass fall a certain distance and time the fall. Students use this data to determine the moment of inertia of the platform. Students then measure the dimensions and mass of a disc in order to determine its moment of inertia. Students add the disc onto the rotating platform in order to measure its moment of inertia experimentally. Students compare the two values.

# Appendix G: Illinois Institute of Technology Laboratories

1 - Introductory Experiments

Students determine the density of several sets of materials. They use vernier calipers to determine their volumes and a mass balance to determine their masses. Students then calculate the densities of the materials. Students then attempt to test Hooke’s Law for several springs. Students use a force meter to determine the force a spring exerts for different extension lengths. Students also hang the spring and place different masses on a hanger. Students compare their results to Hooke’s law.

2 - Projectile Motion

Students have a launcher which can fire metal balls at three different initial velocities. Students can also adjust the angle which the launcher launches the ball. The launcher is set up with a photogate such that the ball will pass through the photogate immediately after launching. There is also carbon paper on the ground below the launcher which can detect the impact of the ball. The photogate and the carbon paper are hooked up to a oscilloscope which displays a peak when the carbon paper enters the photogate and another peak when the ball hits the carbon paper. Students use this to determine the time of flight. Students determine the initial velocity of the three velocity settings using kinematics calculations of projectile motions. Students also determine the relationship between launch angle and range.

3 - Newton’s 2nd Law

Students have a glider that can slide on an inclined air track with very little friction. Students allow the glider to slide down the track through a photogate to determine the acceleration of the glider. Students use this to confirm Newton’s second law. Students then add masses to the glider in order to confirm that the acceleration is constant for different masses. Students are asked to explain why this is the case and if it conflicts with Newton’s second law.

4 - Newton’s 2nd Law, Incline Plane and Pulley

Students have a glider that can slide on an inclined air track with very little friction. The glider is tied to a mass which is run over a pulley at the elevated end of the glider. Students determine the theoretical acceleration of this system for different masses of the glider and the hanging mass. Students add weights to the glider and change out the hanging mass in order to determine the experimental acceleration. Students have a photogate with which they can determine the speed of an object. Students then use the setup to devise an experiment to show that mass and acceleration are inversely proportional for a constant net force.

5 - Atwood's Machine

Students have two masses connected by a string and run over a pulley. The pulley has spokes and is connected to a photogate in such a way that the photogate can record the time each spoke enters and leaves it. The software is able to convert this information into the position of something running along the pulley. Students determine the acceleration of the two mass system for several different variations of the masses. Students then use this experiment to determine the acceleration of gravity.

6 - Friction

Students have a block on a surface tied to a string which runs over a pulley at the end of the surface and then is hanging off of the end. The pulley has spokes and is connected to a photogate. The software automatically converts this data to kinematic data for the block-string-mass system moving along the pulley. Students must develop an experiment to determine the coefficient of kinetic friction of different mass blocks on different surfaces. Students then determine the coefficient of static friction for the same masses and surfaces. Finally, students use a force meter to confirm their measurements of the coefficients of friction.

7 - Conservation of Energy

Students have an air track with a glider that can move along the top of it with little friction. The motion of the glider can be measured with a photogate. Students develop a method to observe the transfer of potential energy in the spring to kinetic energy of the glider, sliding along the track. Students determine whether or not friction is negligible in this experiment. Students then develop a method to observe the transfer of potential energy in the spring to gravitational potential energy. Students are able to add mass to the glider and add wooden blocks to the base of either side of the track in order to elevate it.

8 - Mechanical Energy

Students have a horizontal air track and a glider that can move along the top of it with little friction. Students have a photogate that can measure the motion of the glider and a force sensor that can measure the force acting on the glider. Students tie the glider to a string that runs over a pulley at the end of the track and then is connected to a hanging mass. Students are asked to use this setup to develop an experiment which will determine that the work the falling mass does converts to kinetic energy in the glider. Students are asked to show that the work done by the mass is independent of the path taken. Students then connect the glider to a spring on the end of the track opposing the pulley. The spring is connected to a force sensor. Students are asked to develop an experiment to determine the total mechanical energy of this system and whether or not the mechanical energy is conserved over time.

9 - Momentum

Students have a horizontal air track and two gliders which can slide across the air track with little friction. Students can measure the motion of the gliders with two photogates. Students can add velcro to the end of the gliders so that they will stick together on a collision or rubber bands so that a collision between them will be nearly elastic. Students are asked to confirm conservation of energy and momentum for the nearly elastic collisions. Students repeat this experiment with masses added to the gliders. Students then are asked to perform several collisions in which the gliders stick together. Students confirm that momentum is conserved in these collisions.

10 - Circular Motion

Students have a rotating platform which has a small post placed about halfway between the center of the platform and the edge. Hanging from the top of this post is a brass bob. The bob is tied to a string which runs under a pulley and up to a spring which is hanging at the center of the rotating platform. The bob is tied to another string which runs over a pulley and then is tied to a mass. The mass balances the force of the spring such that the bob is initially hanging vertically. The platform is connected to a rotational measurement sensor that allows students to measure the rotational motion of the platform. Students develop an experiment with this setup to determine that the centripetal force is proportional to the square of the angular velocity of rotation for constant radii. Students then develop an experiment to determine that the force on the bob is proportional to the radius of the motion for constant angular velocities.

11 - Torque

Students have a rotating platform with an attachment called a rail. On the rail, students can hang masses in order to change the moment of inertia of the system. On the rotating platform there are three different spools. Students wrap a string around one spool and run it over a pulley which is off of the platform and then tie the string to a mass. Students release the mass to get the rotating system rotating. The platform is connected to a rotational measurement sensor that allows students to measure the rotational motion of the platform. Students devise an experiment to determine the the moment of inertia of a certain setting of the rail by changing which spool setting is used, but keeping the applied force constant. Students then develop an experiment to verify Newton’s second law for rotational motion.

12 - Angular Momentum

Students have a rotating disk with a groove and a tube which fits right into that groove. Using masses, a pulley, and a string, students develop an experiment to determine the moments of inertia of the two items. Students can measure the rotational motion of the disc with a rotational measurement sensor. Students then use this data to observe the conservation of angular momentum. Students rotate the disc and then drop the tube into the groove gently. Students determine the angular momentum before and after this collision.

# Appendix H: University of Massachusetts - Boston Laboratories

## 1 - The Simple Pendulum

Students have a pendulum consisting of a metal bob attached to the end of a string which is fastened to the ceiling. Student measure the length of the pendulum and then determine the pendulum's period. Students do this two ways, first they measure the time of a single oscillation one hundred times. Then they measure the time of fifty oscillations twice. Students use their determined period and length to calculate the acceleration of gravity. Students compare this to the known value of the acceleration of gravity.

## 2 - Speed of Sound

An oscilloscope is set up with two speakers in such a way that the oscilloscope will determine the amount of time that a sound pulse travels between the speakers. Students move the speakers until the travel time is 0.5 milliseconds, and then 1 millisecond, and then 1.5, all of the way up to 3 milliseconds. Students measure each of these distances and then plot the slope of distance versus time to calculate the speed of sound. Students compare this value to the known value for the speed of sound in air.

## 3 - Kinematics of Free Fall

A metallic bob is placed between two wires, not touching them, being held in place by an electromagnet. The bob has a metallic shoulder which is close enough to the wires such that it will make sparks with the wires when an alternating current is run through the wires. A piece of wax paper is placed in the path of these sparks so that it will burn at the location of the sparks. Students then turn on an alternating current source with a frequency of sixty cycles per second. Students release the bob by turning the electromagnet. Students then are able to see the height of the bob for every 1/60 seconds. Students measure the heights and use the data to determine the acceleration of gravity.

## 4 - The Kinematics of Not So Free Fall

Five photogates are positioned along an inclined plane. Students measure the position of each photogate. The inclined plane is similar to an air table and a "glider" is allowed to slide down it with little to no friction. Students release the glider down the inclined plane. A bumper is placed at the bottom of the inclined plane which causes the puck to recoil and travel back up the track, and then back down again. Students record the different photogate times in order to determine the acceleration of the glider down the track. Students then estimate the acceleration of gravity using the angle of the inclined plane.

5 - Ballistic Pendulum

Students have a gun which launches a ball. Students measure the mass of the ball and measure the distance of its launch into an open space in order to determine the speed with which the ball is launched. Students then launch the ball into a cup which is hanging at the bottom of a string to make a pendulum. Students record the final height of the pendulum. Students use this height to determine the initial speed of the cup and pendulum and then determine the momentum of the system and compare it to the initial momentum of the ball.

6 - Two-Dimensional Momentum

Two pucks are on an air table. Students launch the pucks from different sides of the air table such that they collide. Students record several such collisions with an iPhone using the Video Physics app. Students use metrics on the table to set scales on the video. Then students mark the location of the puck on the app for several different times. The app will automatically turn this into a plot. Students analyze the plot to determine the momentum of the two pucks before and after the collision.

7 - Hooke's Law and Centripetal Motion

Students hang various masses on various springs and record the extension lengths. Students push the limits of the spring, adding mass to them until the spring is stretched to sixteen centimeters. Students determine the validity of Hooke's Law. Students then attach the same springs to a Lucite machine which is a motor that rotates in the horizontal plane. Students attach the spring-mass system such that the mass goes into orbit around the motor. Students speed up the motor until the extension is about fifteen centimeters. Students flash a strobe light onto the spinning system until the spring seems stationary in order to determine its frequency of rotation. Students compare this to the centripetal acceleration calculation and their determinations of the force of the spring.

## 8- Archimedes Principle

Students have a pan balance and two cylinders of the same size. One cylinder is hollow and the other is solid. The solid cylinder is hung over the left pan and held just over the bottom of a beaker. The hollow cylinder is placed on the left pan. Students add weight to the right pan until the system is balanced. Students then fill the beaker with water until it is completely submerged. Students record the result in the balance of the pan. Students then fill the hollow cylinder until the pan is rebalanced. Students compare the result to Archimedes principle. Students then record the mass of a pycnometer with and without water in order to determine the density of water. Students then hang the hollow cylinder off of one pan and into a beaker. Students measure the mass required in the other pan in order to balance the pans. Students then fill the beaker so that it submerges the cylinder and remove the mass on the other side required to rebalance the scale. Students use this to determine the density of water.

# Appendix I: University of Virginia Laboratories

## 1 - One Dimensional Motion

Students have a motion sensor which determines their walking motion. Students walk towards and away from the motion sensor and plot the motion. Students then try to walk in such a way as to match a predetermined graph. Students also alter their speeds and plot their velocity over time. Finally students measure the motion of a cart which they allow to roll at a constant velocity along a track using the motion sensor.

## 2 - Velocity and Acceleration

Students have a cart that rolls along a level track with a fan attached to it. The number of batteries powering the fan can be changed so that the fan has more power. A motion sensor is connected to the track that records the motion of the cart and outputs it on the computer. Students record the motion of the cart when the fan has two batteries and plot the velocity over time. Students predict how this chart will change if the fan has four batteries. Students then add the extra batteries and test this prediction. Finally students turn the cart so that the fan is pushing it towards the motion sensor. Students give the cart a push away from the motion sensor and record the motion as it rolls away, slowing down, and then speeds up back towards the motion sensor.

## 3 - Projectile Motion

Students have a launcher which can launch a steel ball at various angles and at three different initial speeds. Students launch the ball horizontally through two photogates and use the travel time and distance between the photogates to determine the ball's initial speed. Students do this several times for all three launch settings and determine the average initial speed for each. Students then launch the ball at 45 degrees several times for each setting onto a table covered in carbon paper. Students use the marks on the paper to determine the range of the launcher for each setting. Students compare the range value to the initial speed value. Students then change the angle of launch. For several angles students determine the range and compare the range to the angle of launch.

4 - Force

Students have a cart on a track. The cart has a force probe on top of it, and the track as a motion sensor on the end which measures the motion of the cart. Students grab the hook of the force sensor and move the cart back and forth, recording the motion. Students then determine the relationship between the acceleration and the force. Students then tie a string to the hook of the force sensor and run it over a pulley and tie it to a mass hanging off the end of the track. Students allow the mass to drop, dragging the cart away from the motion sensor. Students compare the theoretical and measured forces and the acceleration. Students then predict the velocity and acceleration of a ball as it is tossed into the air and then falls. Students use a motion detector to measure the motion of a ball and compare their prediction to the resulting data produced. Students then measure the motion of a falling coffee filter and compare the motion of this object to the motion of the falling ball. Third, the students use the motion detector to track the motion of a cart which moves up an inclined track and then rolls back down. For each situation students measure the acceleration of the object and compare. For the second part of the experiment, students measure the motion of a block sliding on the table. Students mount a force sensor on the block and pull a string attached to the block so that the block starts to move away from the motion sensor. Students determine the forces of static and kinetic friction on this block. Then students change the mass of the block and see how this changes the forces of friction on the block.

5 - Work and Energy

Students have an elevated track and a cart that can roll on it. Students pull the cart up a ramp with a force sensor, pulling parallel to the ramp. Students try to ensure that the cart is being pulled at a constant velocity. Students determine what average force is used to perform this task. Students then predict what force would be required to pull the cart at an angle of 45 degrees off of the track. Students pull with the force sensor again so that it is 45 degrees off of the track and compare the measured force to the predicted. Students then lay a motion detector on a surface and hold a mass just above the motion detector with a force sensor. Students pull the mass upward and use the data from the motion sensor and the force sensor to determine how much work was performed on the mass. Students then have a level track with a motion sensor on one end and a mounted force sensor connected to a spring which is connected to the cart on the other end. Students measure the motion of the cart as they pull it towards the motion sensor, stretching the string. Students determine the work done. Students then record the motion of the cart after releasing the cart from the stretched position. Students confirm that the work done on the cart by the string is equal to the final energy of the cart. Students then have a tilted track with only a motion sensor measuring the motion of the cart. Students allow the cart to roll down the track and determine the total mechanical energy before and after. Students then roll the car up the track and allow it to roll back down and determine the mechanical energy at the beginning, middle, and end of the path. Finally students add a friction pad on the bottom of the cart and allow the cart to roll down the track. Students determine the work done by friction and mechanical energy lost to friction. Students then hang a spring from a force sensor above a motion sensor. Students stretch the spring to different lengths and record the force in order to determine the spring constant. Students then attach a mass with an index card on the bottom to the spring and allow it to oscillate. Students record the mechanical energy over time and determine the work done by air resistance.

6 - Collisions and Momentum

Students have strings attached to force sensors which are hooked together. Students pull on the strings so that the force sensors pull on each other. Students play a gentle game of tug of war and compare the pulls of each person. Students then have two carts on a track which have velcro bumpers so that they will stick together when they collide. Students have the carts collide several times and qualitatively determine which sets of speeds result in the carts being at rest after the collision. Students then add motion sensors to the track and force sensors to the carts. One of the force sensors has an extended spring on it so that the collision will be nearly elastic. Students cause several collisions and determine the impulse of each cart on the other and the momenta of the carts before and after the collisions. They also determine the work done by one cart on the other and the energy of the carts before and after. Students repeat this procedure without the spring on the force sensor so that the collisions are inelastic.

7 - Rotational Dynamics

Students have a rotating platform on a table which has a string wrapped around part of it. The string is run over a pulley and connected to a mass hanging off the end of the table. In this way if the mass is released the platform will start rotating. Students determine the moments of inertia for the platform experimentally. To do this they allow the mass to fall and record the time that it takes to fall. Students then measure the mass and dimensions of a disc to determine its theoretical moment of inertia. They place it on the platform and compare. Students then measure the rotational speed of the platform using a photosensor. Students allow the mass to fall and determine the kinetic energy of the system after the fall. Students determine if the work done by the mass is equal to the kinetic energy of the system. Finally students perform a series of inelastic collisions between the disc and the platform. Students spin the disc and drop it or they spin the platform and drop the stationary disc. Students also drop the disc when both are rotating together or in opposite directions. For each case students confirm that angular momentum is the same before and after the collision.

8 - Harmonic Motion and the Pendulum

Students have a simple pendulum consisting of a string hanging from above with a bob on the bottom. Students have an aluminum and brass bob which have clearly different masses. Students measure the period of the pendulum with each bob on it but with the the pendulum set at the same length. Students then change the length for one of the bobs and measure the period of the pendulum with it set at several different lengths. Students determine how a changing pendulum length affects its period. Then students measure the motion of the bob with a motion sensor at a particular length. Students lift the bob to a certain height and release it. Students determine the speed of the bob at the bottom of the oscillation and verify that energy was conserved as the bob swung.

# Appendix J: Dartmouth College Laboratories

1 - Changes in Motion

A cart is placed on a track with a motion sensor on one side and a fan on the other. The students measure the motion of the cart as the fan accelerates it towards the motion sensor. Students then gently slide the cart towards the fan and measure the motion of the cart decelerating away from the motion sensor and then accelerating towards it.

2 - Collisions; Conservation of Momentum

Two carts are placed on a track. A motion sensor is on one end of the track and a force sensor bumper on the other. A force sensor is also on one cart. Students slide one cart into the other to cause a collision. Students determine the impulse of one cart on another and the impulse required to stop the two carts at the end. These are compared to the momenta before and after the collision.

3 - Collisions and Trajectories

Students have a track which a ball rolls down. At the bottom of the track a student places another ball either inline or not with the rolling ball. The track is elevated so that the second ball will fall a foot and a half down onto a sheet of carbon paper. Students calculate the speed of the ball rolling down the track and then calculate the initial speed of the ball that was knocked off the bottom of the track. Students show that momentum was conserved in the collision.

4 - Conservation of Energy

Students drop a ball onto a motion sensor and measure its motion. Students determine the mechanical energy of the ball at several points in the drop and show that it is the same. Students then record the motion of a cart moving down an inclined track. They record the angle of the track and determine the mechanical energy of the cart along its path and show that it is constant. Students then hang a spring from a force sensor and with a motion sensor below and a mass hanging on the spring. Students allow the spring-mass system to oscillate after measuring its spring constant and determine its mechanical energy throughout the oscillation. Students then add an index card to the bottom of the mass to provide air resistance. Students allow the spring to oscillate again and show how energy dissipates over time due to air resistance.

5 - Elasticity and Energy

Students have a rubber tube which is suspended horizontally. Students determine the spring constant of this tube. Then students use the tube to launch several masses into the air. They pull the mass downward some distance and determine the potential energy of the pull. They then release the mass and record the maximum height. Students verify that the mechanical energy just before launch is equal to the mechanical energy at the top of the mass's motion.

6 - Forces and Motion

Students pull a rubber band on a force sensor a certain distance. Students then pull two rubber bands the same distance. Students repeat for up to five rubber bands, recording the force on the force sensor for each number of rubber bands. Students then have a track with a motion sensor and a cart with a force sensor on it. Students pull the hook on the force sensor to get the track moving and simultaneously record the motion with the motion sensor. Students consider the relationship between the acceleration and the force. Students finally tie the hook of the force sensor to a string which is run over a pulley and then tied to a mass hanging off the edge of the track. Students allow the mass to fall and record the motion. Students change the mass and repeat, noting any changes in acceleration.

7 - Friction

Students have a container which has a string attached to it. Students drag this container with a force probe at a constant velocity and record the value of the average force. Students then use a motion sensor to measure the motion of the container. Students use the motion sensor to ensure that their pulling is actually at a constant velocity. Students then add weight to the container and determine the relationship between the friction force and the normal force.

# Appendix K: University of California - Los Angeles Laboratories

## 1 - Kinematics

Students have an air track and a glider which slides along the track with little friction. A motion sensor measures the motion of the glider. Students tilt the track up slightly and gently slide the glider up the track and allow it to come back down. Students record the motion of the glider and experimentally determine its acceleration. Students calculate the angle of the track and calculate the theoretical acceleration. Students compare these values.

## 2 - Newton’s Second Law

Students have a horizontal air track and a glider which slides along the tack with little friction. The glider is tied to a string which runs over a pulley and to a mass hanger. The pulley is connected to a photogate and the computer automatically converts rotation of the pulley to motion of something running along the pulley, assuming the no-slip condition. Students measure the motion of the glider for various masses of the glider and the hanger. Students determine the acceleration for each case and compare to Newton’s second law.

## 3 - Conservation of Energy

Students have a horizontal air track with a glider which can move along the air track with little friction. The glider is tied to a string which is connected to a spring on the left which is fixed to the left end of the air track. Two strings are tied to the right. One string simply goes over a pulley to a mass hanger. The other string goes to a pulley and wraps around 180 degrees and is connected to another spring which is also fixed to the left end of the track. The second pulley is connected to a photogate and the computer automatically reports the motion of the items moving along the pulley. Students add mass to the mass hanger in order to determine the spring constant of the spring system. Students then remove the mass hanger and pull the glider away from equilibrium so that it starts to oscillate. Students record the oscillations and determine the mechanical energy at different points of the oscillation. Students determine whether energy is conserved in this motion.

4 - Momentum and Impulse

Students have a horizontal air track with a glider which can move along the air track with little friction. The glider has rectangular piece on top of it which is positioned so that it will pass through a photogate near the end of the track. The glider also has a bumper on the end. A force sensor is placed at the very end of the track on the same side as the photogate. Students slide the glider at the force sensor. The glider bounces off and slides back towards the student who catches it. The student is able to see the time that the rectangular piece enters and leaves the photogate, and therefore he or she can determine the speed of the glider given the length of the rectangular piece. Thus students can determine the momentum before and after the glider hits the force sensor. Students show that the change in momentum of the glider is equal to the impulse of the force sensor.

5 - Biceps Muscle Model

A compression meter is placed vertically with an axle attached to its bottom. A strip of metal is connected to the axle such that it can swing freely. The strip has several holes in it. A second compression meter is connected at the top to the first, but is then is connected to a hook which is slid through one of the holes near the end of the strip closer to the meters. This causes the strip to be suspended horizontally. Students place different masses at the other end of the strip and record the readings on the compression meter for different masses and when the hole that the second compression meter is hooked to is changed.

6 - Rotation and Gyroscopic Precession

Students have a rotor pulley the rotational position of which the computer can measure. The pulley is attached to a rod in such a way that the rod is perpendicular to the rotation axis of the pulley. A pulley mass system is connected to the rotor pulley and then released in order to cause the rod to rotate. Students change the rod’s position and add masses to its ends in order to change its moment of inertia and repeat the dropping of the mass. Students record how these changes affect the acceleration of rotation. Students then move to a different apparatus, a gyroscope. The exact apparatus is a on an axle such that it can tilt. A disc, free to spin, is on one side, and weights on the other side. Students can determine the mass and location of the disc and weights on each side in order to figure out what the torque would be for a certain angle the rod makes with the horizontal. The disc is spun and one student uses a strobe light to determine the rotation rate of the disk. The other student times the amount of time for a full rotation of the entire gyroscope. After determining the moment of inertia of the disc, students can compare the measured angular speed of the gyroscope to the “gyroscope equation.”

7 - Uniform Acceleration

Students have a horizontal air track and a glider which slides along the tack with little friction. The glider is tied to a string which runs over a pulley and to a mass hanger. The pulley is connected to a photogate and the computer automatically converts rotation of the pulley to motion of something running along the pulley, assuming the no-slip condition. Students measure the motion of the glider for various masses the hanger. Students determine the acceleration of the system for each mass.

8 - Measurement of *g*

Students have an apparatus consisting of two photogates and a single impact sensor. This is hooked up to the computer in order to determine the time that a dropped ball passes through each photogate and strikes the ground. Using the height of each, students show that the acceleration of the ball is constant and determine what that acceleration is. Students then drop a comb-like object through a photogate. This object has lots of gaps like a comb such that the photogate will flash on and off as the comb passes through it. Students use the times the photogate reports for the comb and the distance between spokes of the comb to determine the acceleration of gravity a different way. Students compare results to each other and to the known value.

# Appendix L: University of Texas – San Antonio Laboratories

1 - Position, Velocity, and Acceleration

Students have a track on which a cart can travel with little friction. The cart has a fan accessory on it that provides an acceleration force. On the track is a motion sensor which records the motion of the cart. Students turn on the fan and release the cart from rest. Students record and plot the motion and determine the acceleration of the cart.

2 - Acceleration of a Cart

Students have an inclined track on which a cart can travel with little friction. On elevated end of the cart is a motion sensor which records the motion of the cart. Students slide the cart up the track and record the motion. Students compare the acceleration of the cart with the theoretical acceleration given for that angle of inclination.

3 - Projectile Motion and Conservation of Energy

Students have a launcher which launches a metal ball. The surface is covered with carbon paper, so the impact point is marked upon landing of the metal ball. The launcher has three settings. Students fire the ball five times at each launch setting and determine the average range. Students then launch the ball several times from a certain setting at several different angles both level with the surface and above it. Students compare the angles to the distances the ball travels. Finally students place the launcher so that it launches the ball vertically. Students measure the height that the ball launches to by placing a meter stick next to it five times. Students repeat for all three settings. Students then confirm that the mechanical energy is the same at the peak as at the launch using the initial velocities determined from the first part of the experiment.

4 - Atwood's Machine

Students have two mass hangers connected by a string which is run over a pulley. Students place several five gram masses on each hanger so that one is heavier than the other. Students allow the heavier one to drop and record the motion. Students move one of the masses from one hanger to the other so that the total mass is the same but the net force changes. Students repeat this procedure for several net forces. Students then start removing one mass from both hangers so that the net force remains the same but the total mass changes. Students record the motion for several total masses but a constant net force.

5 - Collision - Impulse and Momentum

Students have an elevated track with a motion sensor on the elevated end and a rubber bumper-force sensor on the lower end. Students allow a cart to roll down the track and hit the rubber bumper. Students use the recorded data to determine the change in momentum and the impulse and verify the impulse-momentum theorem.

7 - Rotational Inertia

Students have a step pulley that rotates horizontally and has a string wrapped around it. This string is run over a vertically rotating pulley which is then connected to a hanging mass. Students are able to place a disc on the pulley. Students allow the mass to fall as the computer records the motion of the step pulley. Students use this information to determine the experimental moment of inertia of the disc and compare it to the theoretical moment of inertia given the disc's dimensions and mass. Students then add a ring to the disc and repeat.

8 - Archimedes Principle

Students have a metal cylinder and a container of water. Students measure the size of the metal cylinder and place it in the water and determine the volume of water displaced, confirming that it is the same as the volume of the cylinder. Students then hang the cylinder from a force meter via a string and determine its weight. Students then place the metal cylinder into the water again and determine its weight in the water. Students compare the weights and confirm that the difference is the weight of the volume of water displaced.

9 - Simple Harmonic Motion

Students have a string hanging from a force sensor. Students hang several different masses from the spring and record the length to which the spring extends and the force on the force sensor for that extension. Students use this information to determine the spring constant of the spring. Students then place a motion sensor underneath the mass and pull the mass down slightly so that it starts oscillating. Students determine the frequency of oscillation and verify that it is what is predicted for that spring constant.

10 - Newton’s Second Law - Constant Force

Students have a horizontal track with a motion sensor on one side and a pulley on the other. A cart is on the track with a force sensor attached to the top. A string is tied to the hook on the force sensor, run over the pulley, and then tied to a mass hanger. Students allow the mass to fall, dragging the cart away from the motion sensor, for several different masses. Students determine the acceleration for each mass and compare it to the predicted acceleration given the mass of the cart-force sensor system.

# Appendix M: University of Minnesota Laboratories

## 1 - Description of Motion in One Dimension

Students have a self powered electric car. Students turn on the car and measure the time it takes to move across the length of a dowel. Students then line the dowels and to end and record the time the car passes a single dowel. Students then video the buggy moving along a meter stick and analyze the video to determine the position of the buggy at several times. Students plot the motion of the buggy over time and compare it to their prediction for the motion. Students then have a cart which can roll down an inclined track. Students video the cart rolling down the track and determine the average acceleration. Students repeat this procedure giving the cart a little toss at the beginning so that it has an initial velocity. Students then video several balls falling along a meter stick. Students plot the motion of each ball and determine their accelerations.

## 2 - Description of Motion in Two Dimensions

Students have an inclined track on which a cart can travel. Students slide the cart up the track so that it decelerates and slides back down. Students video this motion and plot it. Students then allow the cart to roll down the track several times, adding mass to the cart each time. Students record the motion in order to determine the acceleration each time and compare the accelerations to the masses. Students then record a video of the tossing of a ball ensuring that the ball is within the frame from launch to landing, Students record the distance the ball travels and the time it travelled in order to determine the axes of the video. Students plot the motion of the ball over time in each axis. Students repeat this procedure for balls of different masses and compare.

## 3 - Forces

Students have a block tied to a string which is run over a pulley and tied to a mass hanger. Students put enough mass on the mass hanger so that the block accelerates towards the pulley. Students record this acceleration and use it to determine the friction between the block and the surface. The block has a felt side and a wooden side, so students determine the friction force for both sides with the aluminum surface. Students then have a three mass two pulley system. Students hang different masses on the ends and center of the string running along the two pulleys and measure the height of the center mass as compared to the pulleys. Students measure the forces in each direction and compare. Students then allow the same block used in the first part to slide down a steep track, recording its motion to determine its acceleration. Students change the mass of the block by adding weights on top and change the angle of the track and record the motion again. Students use this to determine the effect of the normal force on the friction force.

4 - Circular Motion

Students have an apparatus that causes a platform to spin. They record a video of the platform spinning and plot the rotational motion of a specific point on the platform. Students then have an apparatus consisting of a tube that has a string through it. The string has masses on each end. Students make the tube vertical and rotate it in the horizontal plane in such a way that the top mass goes into orbit around the tube. Students measure the period of the orbit and the radius of orbit. Students change the bottom mass and repeat. Then students have a meter stick which they lay on the table. Students place several masses on the meter stick and then determine the balance point, the place where they can put the fulcrum and the stick will remain horizontal. Students put some masses underneath the meter stick and shift it until they find the balance point. They consider the difference between the actual point and their predicted point.

5 - Mechanical Oscillations

Students have extension and compression springs. Students determine how to measure the spring constants of the springs with a mass set, a metal rod, a track, a wood block, and a meter stick. Then students determine the spring constants. Students then hang two springs in line and parallel with a mass connected to the lower spring and to both springs, respectively. Students predict the effective spring constant of the two springs in both cases and then measure the spring constant with a mass set and compare.

6 - Impulse and Momentum

Students have a cart with a compression spring attached. The students know the spring constant of the compression spring. Students slide the cart into a fixed block and record a video of the motion. Students use the video to determine the impulse of the spring on the cart and the momentum of the cart before and after the collision. Students then have two carts which have velcro bumpers such that they will stick together upon collision. Students slide one cart into the other and record the motion. Students determine the motion of the carts before and after the collision and compare to the prediction for perfectly inelastic collisions. Finally students remove the velcro pumpers and place the carts next to each other. Each cart has a removable plastic arm which releases with the press of a button on top. Students release the arm so that it pushes the carts apart and record the motion on video. Students determine the motion of the carts after the explosion.

7 - Energy

Students have an inclined track and a cart which can roll down the track. Students record the angle of the track and release it from several points on the track. Students record the motion of the cart and record the time of travel before the cart hits the stopper at the end. Students determine the final velocity and verify that the work done by gravity is equal to the kinetic energy of the cart at the end of its descent for each trial. Students then video a simple spring mass oscillator. Students determine the energy of the oscillator at different points in time and confirm that the mechanical energy of the oscillator is conserved. Students then are given a track with two carts. The carts have magnetic bumpers so that the carts repel one another. Students slide one cart at another and record the motion. Students assume that both energy and momentum are conserved in the process and calculate what will happen and compare predictions to the actual motion of the carts.