

Development of Inexpensive Hands-On Mechanics Laboratory Exercises for the  
Web and Around the World

by

Rachel C Reed

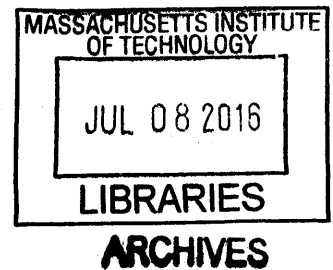
Submitted to the Department of Mechanical Engineering  
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

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## ABSTRACT

Online education has rapidly expanded in recent years, but offering a true laboratory component to online curricula has been limited by the ability to replicate lab experiments at a low cost. Some online courses offer videos or simulations of lab experiments that can be completed on learner's laptops with little to no physical experimentation. The development and implementation of three hands-on suites of laboratory activities designed for independent learners or for AP physics high school MOOCs on the topics of pendulums, inclined planes, and rubber bands is described, with a focus on the design process of creating low cost labs suitable for a variety of student learners, including single learners, multiple learners, and students with instructor supervision. The goal of these labs is to develop observational, measurement, analysis, and modeling skills that connect to students' experiences in the real world. The aim is to advance experimental insight and develop intuition that connects learners to how physical objects will act in their everyday lives. The experiments have been designed to teach multiple concepts via coordinated sets of hands-on activities, including reducing uncertainty, graphing techniques for clear representation of the functional form of the data, experimental design to minimize systematic errors and comparing different ways of measuring the same physical properties.

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I would like to thank Dr. Paul Belony from the MIT Haiti initiative for generously distributing our Pendulum Laboratory exercises to university professors in Haiti to use in their undergraduate classrooms. We are so excited to start testing these labs with their intended audiences.

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## **1. Introduction**

The development of three hands-on suites of laboratory activities for AP mechanics high school MOOCs using pendulums, inclined planes, and rubber bands as the main experimental vehicles is described with a focus on the design process and implementation of low cost labs that students can run as part of AP physics courses. These activities and modules were developed to be able to be performed by students all over the world, regardless of students' financial resources or ability to access high-tech or expensive equipment. Keeping this in mind, the labs are designed to be completed using nothing more complex than a stopwatch and a ruler as the measurement tools.

Early on, it became evident that these labs had the potential to be useful for a wide range of learners and could be decoupled from AP courses. They could represent an inexpensive and accessible resource for laboratory experiences in a wide variety of learning environments. Three basic learner situations were considered when developing the lab modules:

1. Single learner with no instructor supervision
2. Multiple learners with no instructor supervision
3. Learners with instructor supervision

The most challenging situation to accommodate is a single learner with no instructor supervision. For this case, lab exercises must require no more than two hands at any given time. This proved difficult when designing labs for the pendulum and inclined plane suites.

Section 1 covers background information on the need for hands-on laboratory experiment exercises. Section 2 presents the pedagogical goals of this work, followed by the details and challenges faced when designing the labs in Section 3. Student feedback and initial observations are analyzed in Section 4. Finally, conclusions and future work are discussed in Section 5.

### **1.1 Importance of MOOCs**

Massive Open Online Courses, or MOOCs, are courses offered by universities and other institutions via the internet to users all over the globe, sometimes free of charge. Teaching materials for MOOCs can include video, reading, problems, quizzes, and even student forums. In 2015, there were over 35 million students enrolled in 4,200 distinct MOOCs [1]. The importance



of MOOCs is their ability to allow thousands of students all over the world to access courses and opportunities that were previously unavailable to them. MOOCs are not typically for students who are seeking full-time educational credentials, but rather for students who want to supplement traditional courses.

## 1.2 Limitations of MOOCs

Despite successfully opening access to courseware, MOOCs still have many limitations. Not only is it difficult to teach complex science topics to students online, it is a significant challenge to include experimental laboratory experiences in these online courses. Unlike their counterpart classes in universities and high schools, very few MOOCs include hands-on laboratory components. Online Advance Placement (AP) physics classes do not currently support a laboratory component, even though the governing body, College Board, requires that all AP science classes devote 25% of course time to “hands-on laboratory work with an emphasis on inquiry-based investigations” [2].

The few courses that do include labs do nothing more than provide videos of others performing experiments, and may include short interactive animations that students are required to watch. These lab videos do not include any of the steps involved with setting up or calibrating the lab equipment [3]. While informative, watching videos or performing labs on the computer do little to introduce hands-on learning and teach critical thinking.

The closest a MOOC has come to providing real hands-on activities is *Introductory Physics I with Laboratory* by the Georgia Institute of Technology. The class is held in high enough regard to give participants who satisfactorily complete the course six (6) Continuing Education Units from the American Association of Physics Teachers. All students are asked to complete five labs as part of the course, each of which requires the students to do the following [4]:

- Record a moving object (using any device that records video)
- Analyze the video using the free video analysis package, Tracker
- Create models of motion using computer programs written in Python/VPython
- Compare the observations to the models

- Create a five-minute video lab report
- Upload the video to YouTube
- Evaluate video labs submitted by peers

While this course has made strides in providing digital laboratory exercises, it has many shortcomings that need to be addressed. Currently MOOCs require an internet connection and web browser, which means that all students must have access to a computer upon which they can install and use software. Many schools do not allow students to download software on school-owned computers, preventing students who are using library or school-owned computers from participating in labs. Students are also required to have access to digital cameras or smart phones with good cameras -- expensive tools. A number of students living in countries with poor or restricted access to the web reported difficulties engaging in the course, partially due to limited access to YouTube because it has been banned by their governments [4]. Finally, this particular class exhibits a dramatic drop off in the number of students that complete the course. In 2013 it was reported that out of the 18,829 students registered for the class, in the first week an average of only 26% of students watched all twelve required videos. By the fifth week, only 4% of students were watching lecture videos. Even fewer students submitted laboratories than watched lecture videos. Only 2% of students completed lab 1, while just 1% of students completed lab 2 [4]. This is significantly below the average completion rate of 15% for MOOCs [5].

Well-designed, hands-on laboratory experiences are extremely important in developing problem-solving and critical-thinking skills. While computer-simulated labs and video-based activities can increase student exposure to a variety of topics in physics, they cannot be considered as a substitute for actual hands-on lab experience.

### **1.3 Hands-on Learning**

Hands-on learning has been proven many times to have a variety of benefits for numerous students [6]. Not only does hands-on experimentation reinforce material and improve retention, but students also learn better when physically manipulating objects and creating experimental set-ups; a combination of activities that requires moving, listening, and talking uses multiple areas of the brain which increases the student's chance of retaining the information [7]. Not only do hands-on

projects engage tactical and kinesthetic learners as one would expect, they also engage visual learners who have the opportunity to see what they are building. Non-auditory learners often struggle with traditional lecture based classrooms, while hands-on projects engage learners of many different types [8].

The most effective hands-on activities are those that enable students to make connections between what they can see and touch, and scientific ideas that come from observations. Making these connections effectively through traditional lecture-based classrooms is difficult, but hands-on activities often make these links more explicit. For example, a study conducted by researchers at Purdue University found that 8<sup>th</sup> graders who were taught about the human impact on water quality through a hands-on project, instead of the traditional textbook and lecture method, showed significantly greater understanding of the concepts. In every area the researchers tested, the students who participated in the hands-on project learned more and demonstrated a more thorough understanding of the material than did the control group [9].

Scientific concepts can be abstract and complex. Manipulating and examining physical objects can make these abstract concepts more concrete. Through such hands-on experiences, students are able to see physical examples of ideas and observe outcomes produced by changing variables in experiments. Experimental learning is critical to developmental growth in all years and areas of study. Continued engagement in hands-on experiences inspires students and teaches important skills often sought by potential employers.

## **1.4 Teaching Critical Thinking**

One of the central goals of education is arguably to make students begin to think critically about models and data [10]. The ability for students to make decisions based on data and facts is an important skill in today's society. Critical thinking is an analytical and reflective style of thinking, with roots in logic that require learners to ask questions such as:

- What caused this to happen?
- What evidence is there to support your claim?
- How reliable is our evidence?

- Is this a plausible cause?
- Are our results biased or can we back up our claims?
- What else could cause this result?

Critical thinking is what enables scientists to make discoveries and generate new solutions. It forces students to go beyond describing a situation and think about how it happened. Critical thinking is a skill that must be learned but unlike other subjects cannot be explained to students; for learners to truly be able to understand and apply critical thinking skills, they must practice them first-hand. Experts recommend that scientific reasoning be taught in the context of other subject matter because neither teaching content nor engaging in investigative experience alone will lead to a proficiency in science [10]. By making the critical thinking process explicit to students and having them apply the process through targeted activities with feedback, educators can help students adopt new, more analytical ways of thinking.

It is possible for students to study a subject in depth and yet finish their studies with misconceptions about basic concepts. Critical thinking helps students understand potential gaps between theory and practice, dispelling common misconceptions. Students in lab classes may assume that data they acquire are low quality because experiments are not performed in a “true lab”; alternatively, they might not question the quality because the apparatus is set up by an instructor. These assumptions can lead students to make incorrect conclusions about the quality and value of their data. Scientists avoid such pitfalls by engaging in critical thinking by repeatedly comparing data to models and deciding on valid conclusions based on analytical testing.

## **2. Pedagogical Goals**

These labs were designed to do more than simply demonstrate theory learned in the classroom. They were created to motivate, encourage, and empower learners to begin making their own observations, measurements, and even designing their own investigations and devices. This is why each of the core sets of exercises is linked to real world examples and applications that the learners can connect to their own experiences.

In this vein, a primary goal of these lab activities is to help students develop observational, analytical, and modeling skills in a way that connects their experiences to the real world. We aim to promote experimental insight in students and develop intuition that connects them to the physical objects and phenomena they will encounter in their everyday lives. An important aspect of these labs is that they have clear and explicit goals beyond simply demonstrating the validity of theoretical physical models. To accomplish this, experiments were designed to teach multiple concepts via coordinated sets of hands-on activities, such as reducing uncertainty in measurements, graphing techniques for clear representation and analysis of data, and comparing different ways of measuring the same physical properties.

The original plan was to design two sets of experiments; a “low tech” version using nothing more complex than a stopwatch and a ruler as measuring devices, and a “high tech” version using smartphones and free apps. Over time, it became evident that the greater and more valuable challenge would be to design learning activities using extremely limited resources while still emphasizing experimental insight and students’ cleverness. There are many additional possibilities within the “high tech” area and they will be included as options for future iterations of this project.

We aim to make the benefits associated with hands-on laboratory experiences available to the masses through a suite of low-cost experiments. Critics often condemn the monetary costs associated with hands-on science, saying the results do not always justify the expensive purchases needed to perform the experiments. Each experiment described here costs between 0 to 75 cents per student, depending on the number of household items they have already on hand. By making the entire set of experimental supplies cost under \$10 including the basic measuring devices needed (i.e. a stopwatch and a ruler) the cost barrier to entry is dramatically lowered, opening up opportunities for learners in disadvantaged economic situations to perform science experiments all over the globe.

The experiments will work well as independent lab exercises that teachers can implement in their high school AP classrooms, as laboratory components for MOOCs and as supplements to university physics courses as part of blended learning and more active versions of a flipped classroom. This means that they need to be simple to set up and implementable in spaces as small as a dorm room or in the home. Additionally, the ability of the experiments can be detached from MOOC’s and work as standalone experiments is extremely beneficial for educators in poorer

communities in this country, as well as in poorer areas throughout the world, where learners often cannot afford or do not have access to traditional science classroom supplies.

### **3. Design of Labs**

Three suites of hands-on laboratory activities were developed. Each suite is built around a specific physical system and has a core set of activities and goals.

1. Pendulums
2. Inclined Planes
3. Rubber Bands

Each suite consists of four primary components. The first is to directly measure a physical property, which allows students to apply measurement skills and learn how to set up labs to minimize errors. Second, the students record data, perform calculations, and extract physical meaning from their data. The third component of the labs is to make observations and predictions throughout the experiment. Finally, students make connections to real world artifacts and phenomena related to their laboratory measurements.

The cost of supplies for performing all three suites of labs is less than \$10. This includes all materials needed to run the labs and the measuring tools, a ruler and stopwatch. This is significantly less than the cheapest physics lab sensor on the market, a lab module produced by the University of Illinois that costs \$100 [11]. The list of materials needed to run all three suites of lab exercises is given in *Table 1*.

**Table 1:** Laboratory materials needed for lab exercises

General Materials	Lab 1: Pendulum Lab	Lab 2: Inclined Plane	Lab 3: Rubber Bands
Tape Ruler Stopwatch	Plumbob or other weight Pencil String	Large flat movable surface like a textbook or piece of wood Small block of wood Materials from Lab 1 Cardboard box	Weights or other small objects like large screws or pieces of candy 12 Rubber bands of the same kind 4 Pencils Plastic Cup Paper clips or string from Lab 1

The following subsections outline the three suites of lab exercises designed.

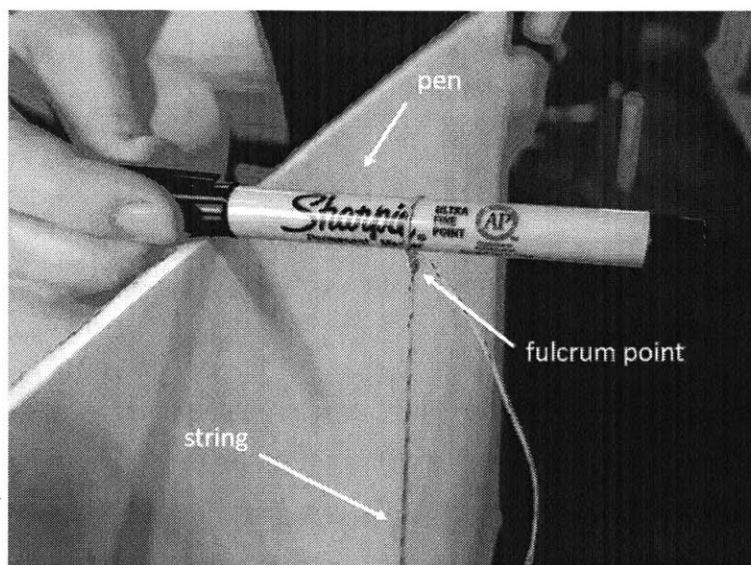
### 3.1 Pendulum

The first suite of labs uses a simple pendulum and connects it to everyday phenomena from wrecking balls on cranes, musical instruments and harmonic oscillators in general. One set of objectives is to determine if and how mass, length and acceleration of gravity affect the period of a simple pendulum. During this section, students also develop better experimental procedures, graphing skills, learn how to extract information from graphs and begin connecting simple pendulums to other more complex systems like physical pendulums.

One goal in designing this initial lab was to make sure that simple systems could be developed that would permit the learners to collect accurate enough data that could be analyzed to extract good values of the period of a simple pendulum. In order to run the experiment, the learner needs to have enough room to be able to set up a system that can swing with as much as 1 meter length of string and a place from which to hang the pendulum. After setting up the experiment, the learner measures the time it takes the pendulum to swing through 10 cycles for different lengths and analyzes that data to extract the relationship between period and pendulum length.

### 3.1.1 Set-up

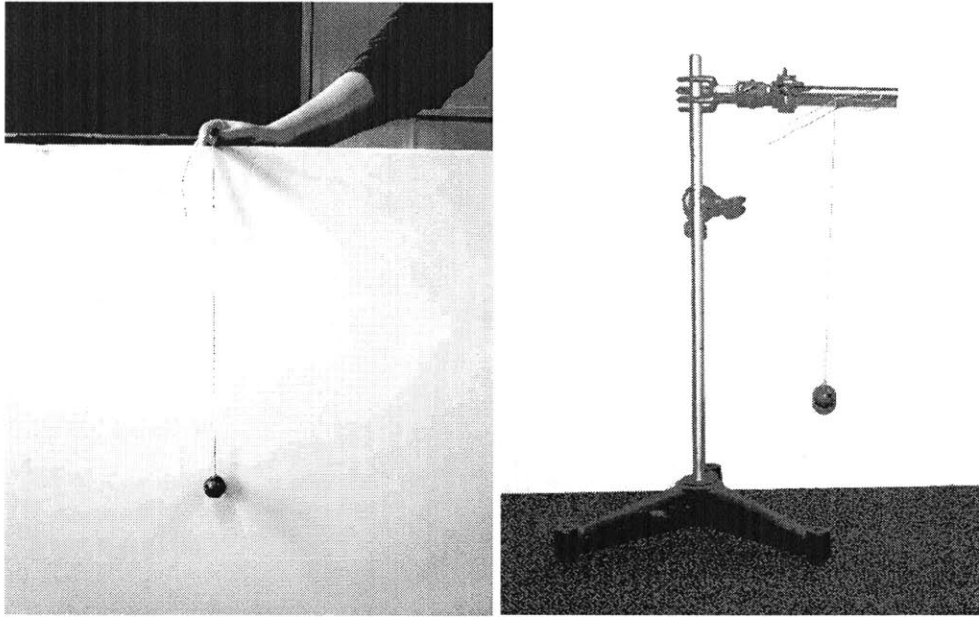
One of the largest challenges associated with setting up this experiment in a non-laboratory setting was finding a suitable location from which to hang the pendulum. Finding enough space from which to hang a 1 meter object maybe difficult in a confined space such as a dorm room. A pen was used to provide a proper fulcrum point for the pendulum, as shown in *Figure 1*. This is minimizes any effects from the string wrapping around the fulcrum.



**Figure 1:** Fulcrum attachment point for pendulum

In order to measure the data variability for experiments run on a student made set-up vs. a laboratory set-up, two stands were built, one representing what students might build in their home (*Figure 2a*), and the other using traditional lab equipment (*Figure 2b*).

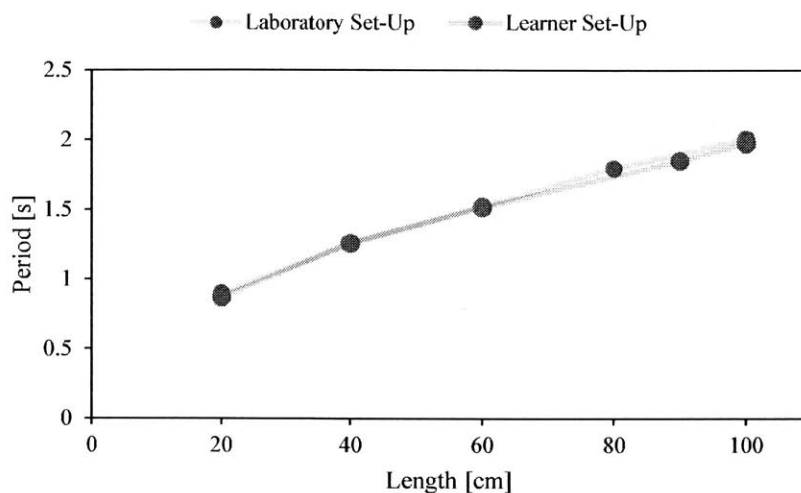




**Figure 2:** (a) Learner's set-up for pendulum experiment. (b) Laboratory set-up for pendulum experiment.

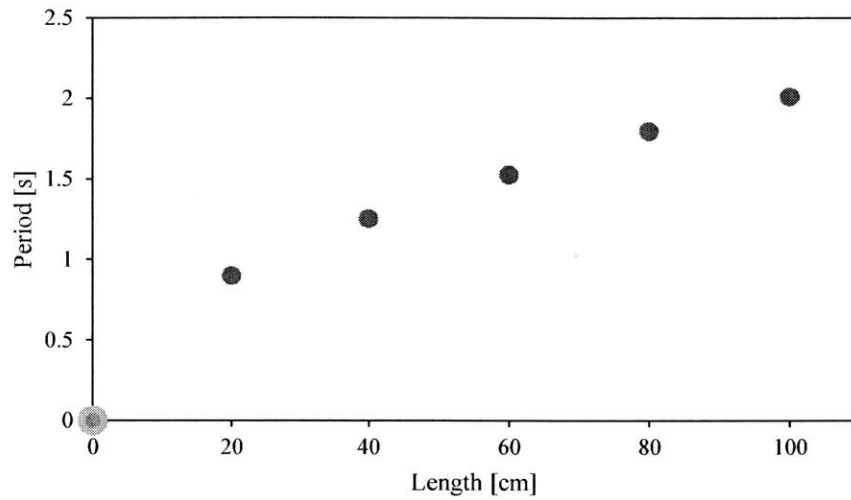
### 3.1.2 Analysis

Data taken on both a typical learner's set-up and a traditional laboratory set-up are presented in *Figure 3*. The accuracy of the data collected was not dependent on the set-up. The learner's set-up and laboratory set-up yielded an average measured value for the acceleration due to gravity of  $9.93 \pm 0.30 \frac{m}{s^2}$  and  $9.92 \pm 0.17 \frac{m}{s^2}$ , respectively. This shows that low-cost labs can produce comparable results to those of higher quality systems, so that students will be capable of producing data that are good enough to extract meaningful values and trends.



**Figure 3:** Period vs length for a simple pendulum on two different quality set-ups. The typical learner's set-up and laboratory set-up yielded a value of the acceleration due to gravity of  $10.20 \frac{m}{s^2}$  and  $9.74 \frac{m}{s^2}$ , respectively.

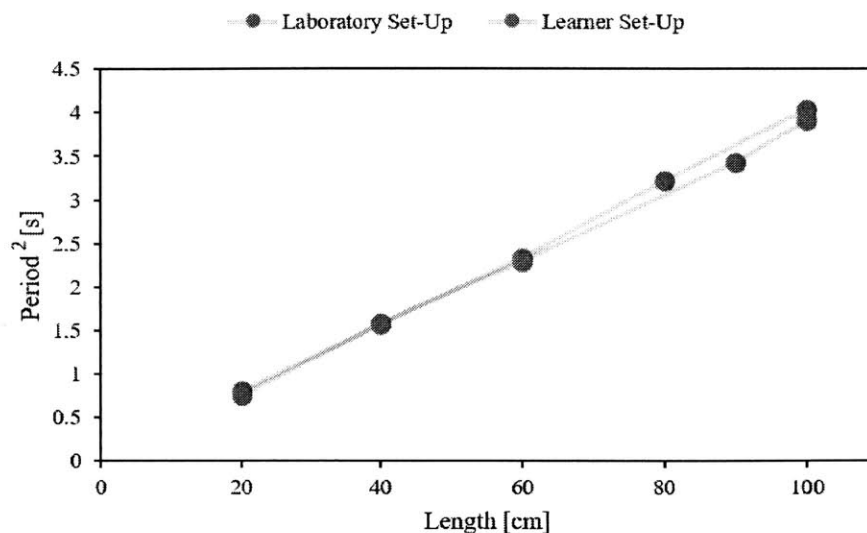
From the limited number of data points it is difficult to see that the graph for period vs. length is not in fact linear. Because of this, the origin (0, 0) was included on the graph in order to make the non-linear functional dependence more clear. While including (0,0) along with the actually measured data is not technically correct since the system is non-ideal, it is valuable for emphasizing the visible non-linear trend of this data. When including this in future lab discussions, students will be informed of the appropriate caution they should use when including (0, 0) on their graphs. To remind them that (0, 0) is a unique data point, students will circle it on their graph. The effect of adding a data point at (0, 0) is shown in *Figure 4*, where it is now apparent that the trend is non-linear.



**Figure 4:** Period vs length for a simple pendulum with included data point of (0, 0).

If instead the learners are directed to the graph of period<sup>2</sup> vs length, as shown in *Figure 5*, it becomes readily apparent that a linear fit could be applied. This supports the equation students will derive for a simple pendulum where  $T$  is the period,  $L$  is the length of the pendulum, and  $g$  is the acceleration due to gravity,

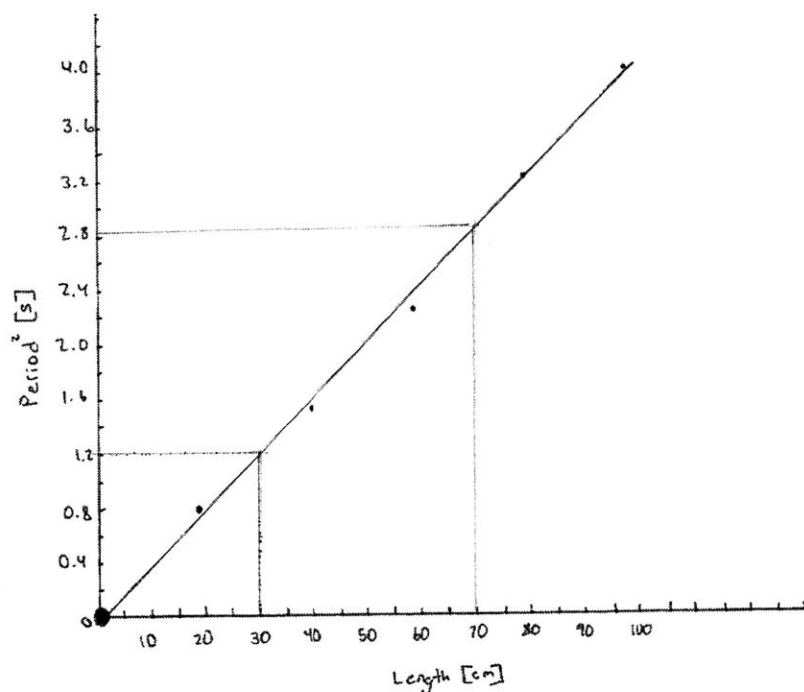
$$T = 2\pi \sqrt{\frac{L}{g}} \quad (1)$$



**Figure 5:** Period<sup>2</sup> vs length for a simple pendulum on two different quality set-ups. Both values for gravity extracted from the slopes are within 2% of  $9.81 \frac{m}{s^2}$ .

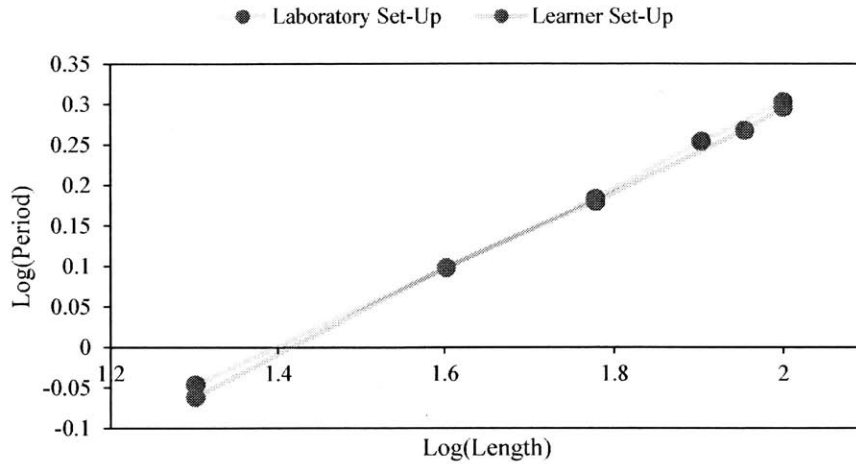
The results obtained when determining the slope from a hand drawn graph are comparable to those from the computer graphing program shown in *Figure 5*.

This technique of choosing the axes so as to linearize the graph is an important feature of this and subsequent labs. Not all students will have access to graphing and fitting programs such as Excel, but students do quite well in determining a good fit for a straight line by eye. Plotting a linear fit and extracting “g” from the slope of the graph of provides a value of  $9.75 \frac{m}{s^2}$  for the graphing program. This is comparable to the “g” of  $9.75 \frac{m}{s^2}$  extracted from the slope of a hand drawn linear fit and graph as seen in *Figure 6*. Both extracted values are within 1% of the true value of  $9.81 \frac{m}{s^2}$ .



**Figure 6:** Hand drawn graph period<sup>2</sup> vs length for a simple pendulum with a value for the acceleration due to gravity of  $9.75 \frac{m}{s^2}$  extracted from the measured slope of this curve.

As an optional extension for students with the appropriate math background, this lab can be used to demonstrate the power of log-log plots in determining the relationship between two variables when the exact equation is unknown. Using a log-log plot, one can extract the power of the relationship between period and length for a simple pendulum from the slope of the graph. Shown in *Figure 7*, one can see that the slope of the typical learner's set-up and laboratory set-up were both 0.49, a value very close to the 0.5 power given in Eq. (1).



**Figure 7:** Log-log plot of period vs length of a simple pendulum with slopes of 0.49.

The simple pendulum described above is an ideal system and many pendulums found in the real world, referred to as “physical pendulums”, differ significantly from the simple pendulum in their mass distribution. To examine the differences between an ideal pendulum and a physical pendulum learners measured the period of a physical pendulum and compared it to the oscillation period of a simple pendulum of the same length. In order to use a simple object that all users would have access to, a ruler (or meter stick) was selected as the physical pendulum. Users will already be required to have a ruler or meter stick in order to complete the earlier portions of the lab. The period for physical pendulum is:

$$T = 2\pi \left[ \frac{I_{piv}}{mgd} \right]^{\frac{1}{2}} \quad (2)$$

Where  $m$  is the mass of the pendulum,  $g$  is  $9.81 \frac{m}{s^2}$ ,  $d$  is the distance between the center of the mass of the object and the pivot point, and  $I_{piv}$  is the moment of inertia about the pivot point and can be found from the parallel axis theorem to be  $I_{piv} = I_{cm} + md^2$ , where  $I_{cm}$  is the moment of inertia about the center of mass. Measurements with a traditional meter stick yielded a period of  $1.638 \frac{1}{s}$ . By rearranging Eq. (2) and using the measured period, a “ $g$ ” of  $9.809 \frac{m}{s^2}$  can be extracted, a value very close to the true value of “ $g$ ”.

Statistical analysis of numerous tests of set-ups of differing design found no significant difference in the measured value of the acceleration due to gravity. This means that students will be able to build a pendulum lab set-up at home using typical house hold items that will allow them to make good measurements.

### **3.1.3 Other Branches**

There are various other branches of study using more sophisticated technology that students could pursue at home if they have the available resources. Using smartphones to collect data is one such branch. Currently, there are over 2.1 billion cell phone users globally [12]. This number is expected to grow to 6.1 billion by the year 2020, with 78% of them using Google's open source Android platform [13]. Android based phones are the most common in developing nations due to their lower price. It can be expected then, that the most commonly used smartphone platform by learners would be Android.

One experiment that was explored utilizing smartphone technology was measuring the period of a person using a playground swing modeled as a simple pendulum. Upon investigating this branch, it was discovered that there are not currently any low-cost android phone applications that will allow users to take a video on their phones and analyze data in the app. While users could take video with their cellphones or cameras and then analyze it using free third party software, these applications often have very steep learning curves and it cannot be expected that all learners will have access to computers to which they can download external software. The greater number of steps needed for such measurements can present a barrier to the learners' completing the assignment. This could have been one of the factors in the dramatic drop-off of the completion of *Introductory Physics I with Laboratory* by the Georgia Institute of Technology [4].

Another option to collect data for determining the period of a person swinging would be to use a smartphone app that tracks your acceleration since virtually all modern smartphones contain accelerometers. Currently, there are numerous free apps for smartphones that allow users to save and export data on acceleration. This could be used in conjunction with free online software such as Google sheets to analyze the data and in turn extract the period.

## 3.2 Inclined Plane

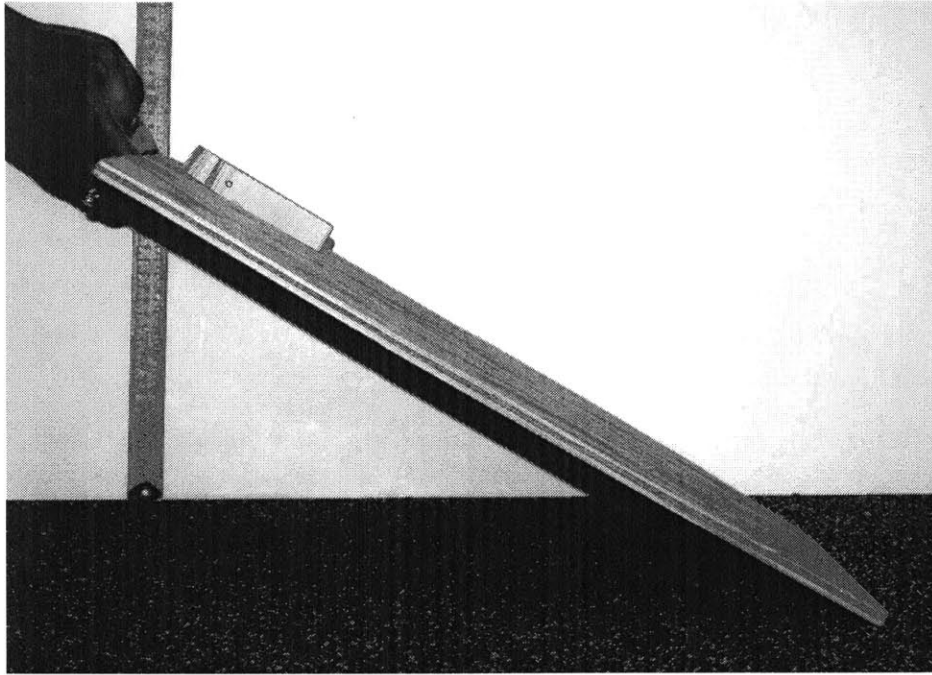
The second suite of labs is based on inclined planes. The first experiment builds on the cleverness of Galileo's experiment in using an inclined plane to reduce the effective acceleration due to gravity and make it easier to measure with a stopwatch the resulting accelerated motion of objects rolling down a plane. Other experiments included (i) determining how the angle of incline affects the acceleration of objects and (ii) determining the angle at which a block tips rather than slides. Students will also develop better experimental procedures when measuring systems in non-laboratory conditions, such as determining why data may vary or ways to adjust experimental conditions for more accurate measurements.

After setting up the simple laboratory apparatus, the learner would measure the angle at which an object they placed on their inclined plane slipped. They would then place a block on the plane in an orientation that would cause it to tip before slipping. Slowly raising the slope of the ramp, they would measure the angle at which a block tips. This is a way to determine the coefficient of static friction without having to know the mass of the object. Lastly, they would go out into their surroundings and measure the slope of an actual ramp such as a loading dock or handicap ramp.

### 3.2.1 Sliding and Tipping Angles

In order to simplify the experimental set-up so that measurements varying the angle can be made by a single learner with no supervision, it is recommended that the learner tape a ruler to the wall and lift their plane up along this ruler seen in *Figure 8*. That way, only one hand is required to lift the surface and the other hand is free for other uses. For the "Galilean" measurements of acceleration of a rolling object, the plane can be fixed at a small angle by propping up the elevated end with books or other objects and marking start positions on the board. By placing a hard surface at the end of the ramp, learners will easily be able to determine when their object has reached the end of the slope from the sound of the impact. All of this makes it easier for a single learner to run the experiment determining the time it takes for the object to roll known distances.





**Figure 8:** Set-up configuration for the inclined plane that requires only one hand to operate.

One of the greatest challenges that came with designing the inclined plane suite was finding everyday objects that would be suitable for sliding or rolling down the inclined plane. Many objects either had too large coefficients of static friction to easily slide down the inclined plane or were not symmetrical and would not slide evenly down the plane. For the demonstrative set-up a small block of wood was used, but any material could be used as long as it has a flat surface and slides down the plane.

Once the set-up has been built, determining the sliding and tipping angles of the block is simple. Using the length of the inclined plane and the height of the plane when the object begins slipping or tipping, one could easily determine the critical angle. Multiple materials were tested in order to determine an optimal material that would most easily demonstrate the desired physical behaviors. Using the measurements in *Table 2* and observations noted during the trials, it was decided that one pair of good materials for these observation of slipping were acrylic objects on cardboard. Not only will cardboard be one of the most readily available materials, many household objects such as CD covers are made out of acrylic or other plastics.

**Table 2:** Critical angle for slipping block on various mediums

Medium	Angle (deg)
Wooden block on cardboard	33
Aluminum block on cardboard	22.5
Acrylic block on cardboard	25
Wood block on wood	32

The linear acceleration of an object rolling on an inclined plane is a function of the shape, but is independent of mass and radius. The linear acceleration for a round object rolling down a plane without slipping is

$$a = \frac{g \sin(\theta)}{1 + \frac{I}{mr^2}} \quad (3)$$

Where  $m$  is the mass of the object,  $r$  is the radius,  $g$  is  $9.81 \frac{m}{s^2}$ ,  $\theta$  is the angle of the ramp, and  $I$  is the moment of inertia of the object. The moment of inertia is dependent on the shape of the object, for a solid sphere it is

$$I = \frac{2}{5} mr^2 \quad (4)$$

and for a hollow cylinder it is

$$I = mr^2 \quad (5)$$

By combining Eq. (3) & Eq. (4) and rearranging, one can see that the linear acceleration for a solid sphere rolling down an inclined plane is greater than that of a hollow cylinder, determined using Eq. (3) & Eq. (5). If you roll a solid sphere and a hollow cylinder down an incline plane, the sphere will always finish first, regardless of the relative radius or mass of either object. The solid sphere wins the downhill race because less of the gravitational potential energy is converted to rotational kinetic energy.

A cylindrical shell should lose a rolling race against any other rigid object with a circular cross section because it has essentially all of its mass a full radius away from the axis of rotation. In

many cases the other objects might have more mass than the chosen hollow cylinder. One pedagogical concern was that learners might interpret the observation that the other shapes would win the races was due to the fact that they had greater mass – even though the acceleration is independent of the mass and only due to the shape. One way to address this concern was to use the hollow cylinders that were clearly more massive than the other objects. This meant that when these hollow cylinders would lose the race, it could not be the mass that determined the acceleration of the objects.

This task proved to be surprisingly difficult. Multiple items like rolls of duct tape and toilet paper rolls were tried, but they did not roll reliably down the ramp. It was found that sections of hollow metal cylinders worked well, but they are not always easy to obtain. For these reasons it was decided to include a video of a sphere and a hollow cylinder rolling down an inclined plane so that learners can observe the effect of moment of inertia on the acceleration. In the video, the weight of the objects will be shown and multiple cases will be demonstrated where (i) the cylinder is heavier than the sphere and (ii) the sphere is heavier than the cylinder. If the learners have access to the needed materials and wish to run the experiment at home they will have the option to do so, but it will not be a required component of the suite.

### **3.2.2 Inclinator**

We want students to connect their experiences in measurement, analytical, and modeling skills with the real world. Hands-on experiences are key to developing these connections as learners are able to see real life examples of ideas and observe the result of changing variables' values. As a possible branch for the inclined plane suite of exercises, various ways to find examples of inclined planes used in everyday life were explored. One common example of this is handicap ramps. Due to many countries' laws guaranteeing equal access to spaces, regardless of disability, handicap ramps are becoming increasingly common. Originally, physically measuring the length and height of wheelchair ramps was attempted, but discovered that it was often difficult to measure height as the sides of the ramps were located where it was not possible to make a measurement of the height. As shown in *Figure 9*, many ramps are built in a manner that makes it impossible for students to accurately measure the height. Even if students were easily able to measure the height of the

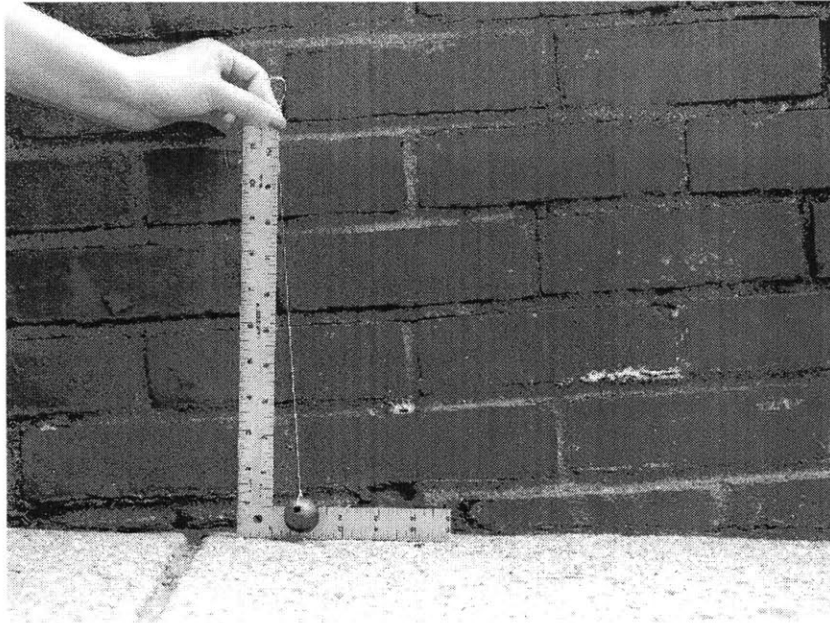
handicap ramps, it does not mean that the ground itself is level. The important angle of incline is with respect to the true horizontal – not the ground.



**Figure 9:** Example of a handicap ramp of which the students are unable to measure the slope because the change in height is essentially impossible to measure.

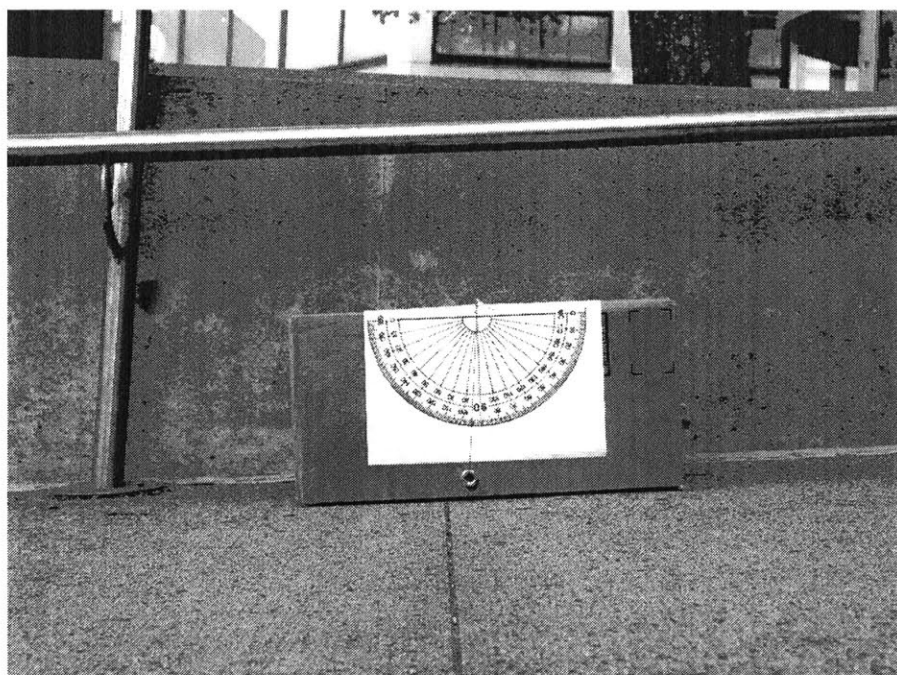
Because of the difficulty of measuring of handicap ramp heights, students instead will be asked to build a home-made inclinometer. They will use it to measure the construction angle of local handicap ramps, and see if they meet standard ADA requirements of a maximum slope of 1:12 [14]. Students who live in areas where handicap ramps are not available could instead do this experiment using other forms of ramps such as those used for trucks or at loading docks.

The first inclinometer, seen in *Figure 10*, was a T-square that used the change in distance of a plumb-bob attached to a string in order to determine the angle of the ramp. This proved to be very prone to errors, partially due to the difficulty associated with interpreting small changes in length, and also from the variability in the surface angle of the concrete ramp.



**Figure 10:** The first iteration of a homemade inclinometer that used a T-square, plumb-bob, and string.

To address the errors due to inconsistencies in the concrete surface angle, an inclinometer was created that used a simple cardboard box, a protractor printed from the internet, and the string and plumb-bob used from the pendulum suite experiments. As seen in *Figure 11*, the large size of the base of the box allows for a more global measurement of the average slope since the box isn't as easily effected by small defects in the concrete. The large printed protractor allows learners to easily distinguish small changes in angle, diminishing the error found when using the T-square. It is important to note that the thinner the string being used to attach the plumb-bob to the inclinometer, the easier it is to discern the angle of the slope.



**Figure 11:** Home-made inclinometer used to measure the slope of handicap ramps.

Data taken of ramps on the MIT campus using the inclinometer in *Figure 11* is given in *Table 3*. The ratios were calculated using the box height of 4.4 inches. The maximum allowable angle of an ADA approved handicap ramp is 4.78 degrees. All values measured meet this requirement for ADA approval.

**Table 3:** Handicap ramp slopes measured using a homemade inclinometer

Ramp	Angle (degree)	ADA Compliant?
1	4	Yes
2	3	Yes
3	1.5	Yes
4	3.5	Yes
5	2.5	Yes

Constructing an inclinometer and using it to measure the slope of a handicap ramp is a viable application of basic physics to everyday objects. It is especially valuable in that it connects the two lab suites of the pendulum, here used as a plumb-bob to determine an angle, and the inclined plane. Students often believe that the data they collect are unusable or not good enough because it wasn't

collected in a “real lab”. This project shows students that they’re capable of developing very simple tools that can measure real world objects accurately in a non-laboratory setting.

### 3.3 Rubber Bands

The third suite of labs uses rubber bands to allow students to explore the nature of elastic systems. The primary reason for choosing rubber bands is that they are more accessible than suitable springs to learners outside of a school environment. While rubber bands exhibit the relevant behavior only in tension (rather than in both tension and compression as do springs), the key relevant properties can be explored with rubber bands – making their accessibility a decisive factor in their selection.

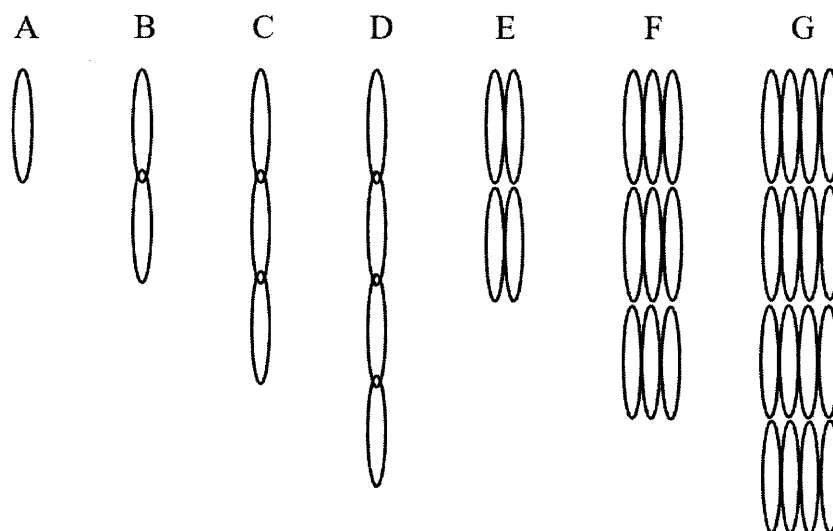
The basic measurements deal with force vs. extension curves to explore the region of linear relationship (Hooke’s Law) and to discover that this represents only a portion of the overall behavior as a wider range of extensions is characterized. In addition to seeing the non-linear part of the force vs. extension curve, the learners can explore the phenomenon of hysteresis: the difference in the curves one can obtain by progressively increasing or decreasing the load on the rubber band.

The objective is to follow a procedure that allows students to investigate the elastic properties of rubber bands. These procedures are similar to those used to determine the elastic constants of springs. Investigating the effective spring constants of rubber bands in parallel and in series provides a nice vehicle for exploring some basics of Newton’s laws as well as elastic systems.

Once the learners have set up the laboratory experiment, they will measure the stretch of the rubber bands in different configurations for varying loads. The learner will measure the stretch of a rubber band for the following cases, as shown in *Figure 12* below:

- (A) Single Rubber band
- (B) Two rubber bands in series
- (C) Three rubber bands in series
- (D) Four rubber bands in series
- (E) Doubled rubber bands in series
- (F) Tripled rubber bands in series

(G) Quadrupled rubber bands in series



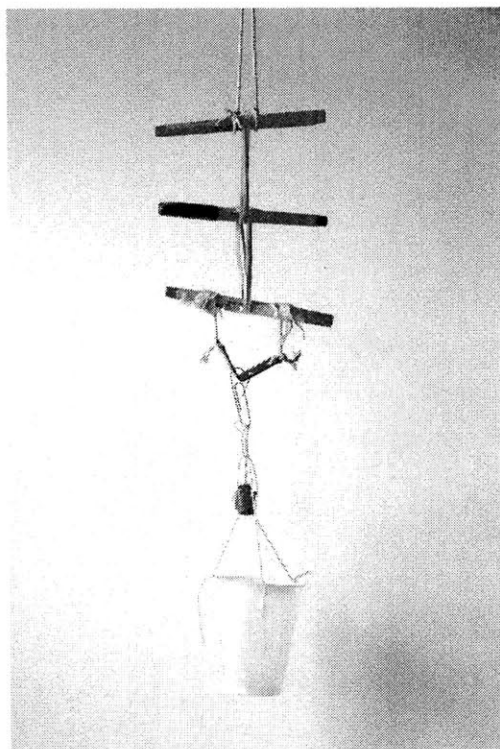
**Figure 12:** Different configurations of rubber bands that lab students will test

After measuring the stretch of the rubber bands for 10 points, students will plot their data and extract an effective spring constants for each of the various test cases.

### 3.3.1 Set-up

To ensure that the force was evenly distributed across the rubber bands, a set-up using pens was devised. Placing the rubber bands around the pens as shown in *Figure 13* ensures that the weight is evenly distributed across the bands. Any small cylindrical objects such as pencils, pens, markers, or dowels would accomplish the goal. It is critical that students use a set of identical rubber bands so that when they add rubber bands in series or parallel they are able to collect consistent data.





**Figure 13:** Rubber band set-up with pens used to evenly distribute force and a plastic cup to place weights in.

To keep the weight receptacle (cup) from tipping when weights were added to the system, a string was strung through four holes in the plastic cup and attached to the bottom marker using a paper clip.

To make sure that the rubber band is stretched enough for there to be a measurable change in length, it is recommended that students use objects that produce a change of length of at least 0.5 cm per additional mass. Aluminum angle brackets were used as the experimental weights in *Figures 14-17*, but any item of substantial weight would work as a unit. Note that the learner should have a number of identical items of the same weight available. An alternative option for varying the load on the rubber band is to use a measured amount of water because learners can easily determine the weight of their water from simple volume measurements using readily accessible containers of known volume such as water bottles and tablespoons.

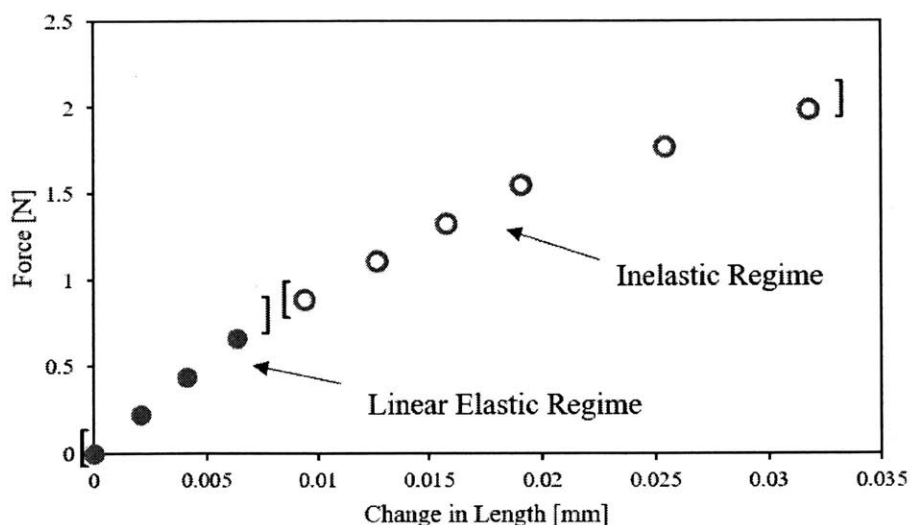
### 3.3.2 Analysis

In the linear region, the force applied to a rubber band removes it from the equilibrium, or unstretched point, this relationship between force and extension can be expressed by Hooke's Law:

$$F = kx \quad (6)$$

Where  $F$  is force,  $k$  is the spring constant, and  $x$  is the distance from equilibrium. As more force is applied, the more the rubber band is stretched, and the greater the force exerted by the rubber band towards its equilibrium length. Rubber bands and springs have an elastic limit. If you pull the rubber band past a certain point, the physical properties of the rubber band change and the spring constant decreases, at which point the function is no longer linear. A rubber band has reached its elastic limit when it has been stretched past the point from which it can return back to its original shape.

To ensure that students would be able to repeatedly produce data that is good enough to extract meaningful values and trends, data for a single rubber band was collected. You can see the linear and elastic regime for this trial in *Figure 14*. Eq. (6) was used to measure the spring constant of  $80.4 \frac{\text{N}}{\text{m}}$  in the linear regime.



**Figure 14:** Change in length vs applied force for a single rubber band with spring constant of  $80.4 \text{ N/m}$ .

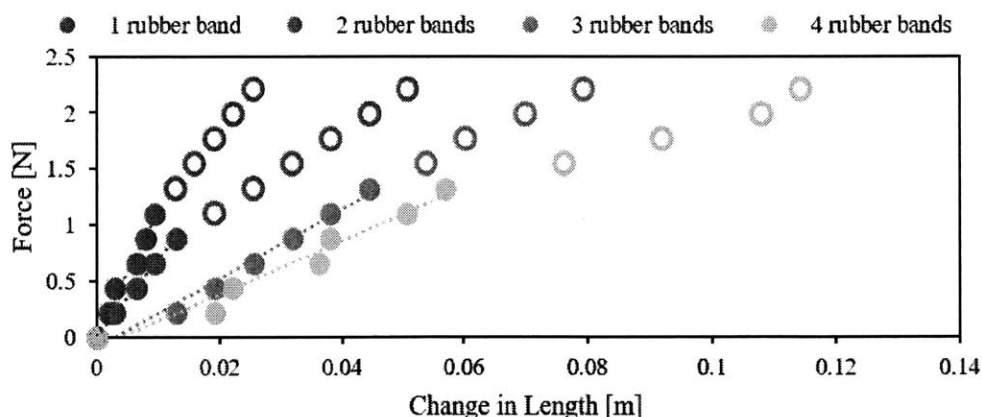
Rubber bands placed in parallel or in series can be used to determine the effective spring constant for the multi-band system. For identical rubber bands in series, the effective spring constant is

$$k_{eff} = \frac{k}{n} \quad (7)$$

Where  $k_{eff}$  is the effective spring constant,  $k$  is the spring constant for a single rubber band, and  $n$  is the number of rubber bands in series. For identical rubber bands in parallel, the effective spring constant becomes:

$$k_{eff} = kn \quad (8)$$

In order to cement their understanding of springs, learners must examine the effect on the spring constant of connecting rubber bands in series. Data were collected for a single rubber band, two rubber bands in series, three rubber bands in series, and four rubber bands in series, as shown in *Figure 15*.



**Figure 15:** Change in length vs applied force for 1 to 4 rubber bands in series with measured spring constants of 85.7 N/m, 41.5 N/m, 29.5 N/m, and 19.2 N/m, respectively. Filled circles indicate the elastic region for each experiment.

Since the vertical axis is Force and the horizontal is Length, then Eq. (7) and Eq. (8) can be used to see that the slope of data is simply the spring constant. For the data collected the effective spring constants of the configurations given in *Table 4* were found and compared to the expected effective spring constant.

**Table 4:** Measured and expected  $k_{eff}$  for rubber bands in series

# of Rubber Bands in Series	Measure K [N/m]	Expected K [N/m]	% Discrepancy
1	85.7	-	-
2	41.5	42.8	- 3.0
3	29.5	28.6	+ 3.2
4	19.2	21.4	- 10

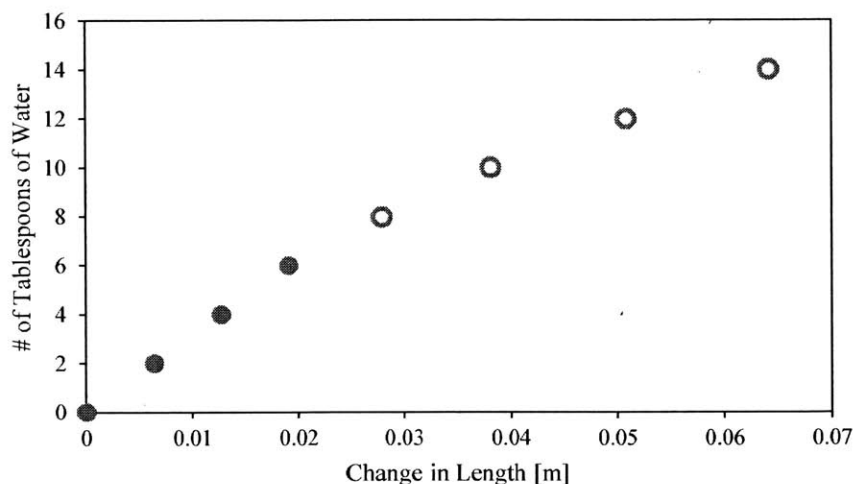
As seen in Table 4, the measured values of the effective spring constant and the expected spring constant are close enough to demonstrate the effects on spring constants from placing rubber bands in series. Average discrepancy of -3.3% indicates good agreement with the expected value of  $k$  for the multiple-band configurations tested.

It was found that attempting to measure the change in length for rubber bands in parallel using the same weighting system resulted in displacement results that were too small for learners to easily measure, because the high spring constant from adding rubber bands in parallel as shown in Eq. (8). In order to make the rubber bands “stretchier”, sets of parallel rubber bands were added in series to create a comparable displacement. The configuration for these sets of parallel rubber bands in series can be seen in *Figure 12 E - G*. By combining Eq. (8) and Eq. (7), one will find that configurations E – G in *Figure 12* have a  $k_{eff}$  that is equal to that of the spring constant for a single rubber band. This gives learners the ability to measure the springs in parallel while still having measureable difference in the change in length. This has the added benefit of giving the learners experience in combining rubber bands in configurations that involve combinations of series and parallel arrangements.

Discovering the relationship between rubber bands in series and in parallel not only teaches students many properties about springs, but also prepares them for other topics like electronics: springs in parallel combine like capacitors in parallel and springs in series combine like capacitors in series.

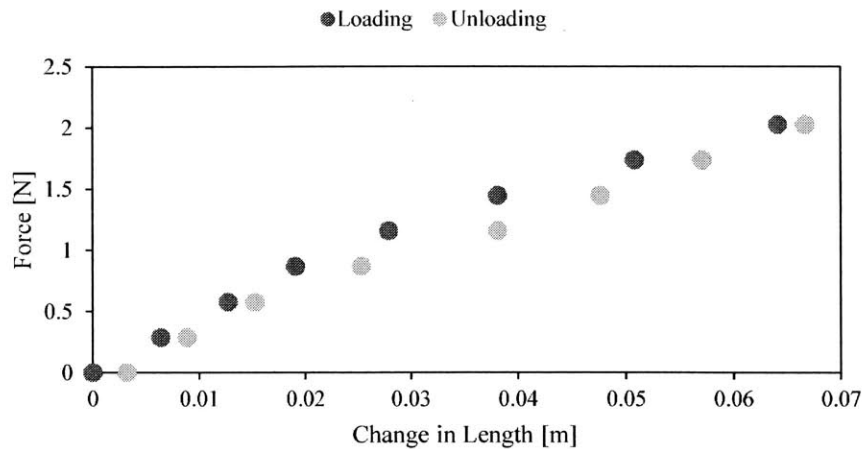
As mentioned in section 3.3.1, a valid option for weights is to use a measured amount of water because learners can easily determine the weight of their water from simple volume measurements using readily accessible containers of known volume. To test this, a system of two rubber bands

in series was tested using water as the weight with measurements taken in increments of two tablespoons. From *Figure 16*, it is possible to extract data from a system using water.



**Figure 16:** Change in length vs applied force for two rubber bands in series using water as a weighting system. The spring constant of the water based system is 45.4 N/m, this is 8.5% different from the spring constant of 41.5 N/m found for the non-water based system in *Figure 15*. Filled circles indicate the elastic region.

The final topic introduced to learners is the concept of hysteresis. Shown in *Figure 17*, the behavior of rubber bands when a load is removed is not the same as that when the load is being increased. This is called “hysteresis”. If one repeatedly stretches and un-stretches a rubber band the stiffness gradually decreases and it becomes easier to stretch. As it is repeatedly stretched, the heat produced from the transfer of energy from the rubber bands to its molecules can be felt. This loss of energy through heat causes the observed hysteresis. This is a valuable concept to begin to introduce to students as it helps them connect seemingly disjointed occurrences like stretching and heat to hysteresis loops [15].



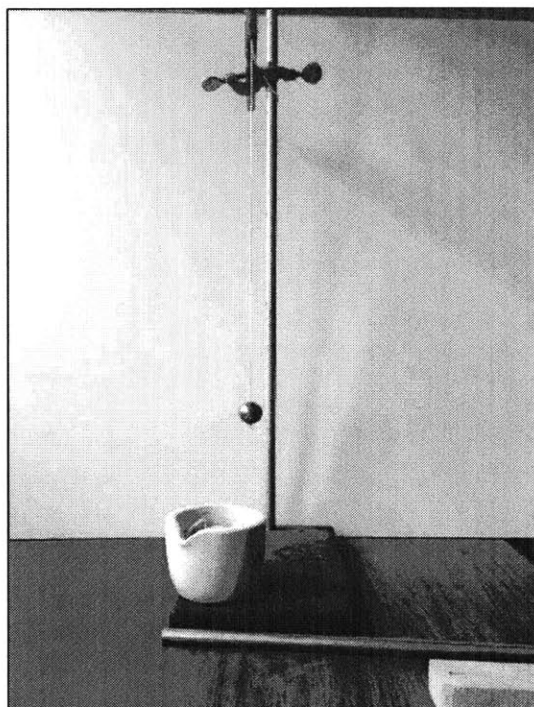
**Figure 17:** Change in length vs applied force for two rubber bands showing hysteresis. The red points indicate the loading curve and the pink indicate the unloading curve.

#### 4. Implementation of Pendulum Lab

In order to receive initial feedback on the functionality of the Pendulum Lab, 12 students in their first semester at MIT ran the experiment as part of a requirement for their Classical Mechanics class, known as 8.01. All students who participated by performing the Pendulum Lab were students in a special program at MIT known as Experimental Study Group (ESG). While MIT students are not the ultimate target of the designed lab experiments, valuable insights were gained from this initial round of implementation. The following section outlines some comments and assessment results from these students regarding the lab as well as some observations made after reading their lab reports.

The Pendulum Lab Handout given to the students to complete (see Section 6. Appendix) was actually a combined set of individual shorter labs that would normally be performed over a series of weeks, as described in the Appendix. Students were given 2 weeks to complete the experiments with partners of their choosing during their own time. Their hands-on work was not supervised by an instructor, so in that regard this provided a test of the efficacy of the instructions for learners who do not have expert supervision. Due to the late roll out in the semester of the pendulum lab, to keep from burdening students with needing to develop their own set-up, a testing apparatus

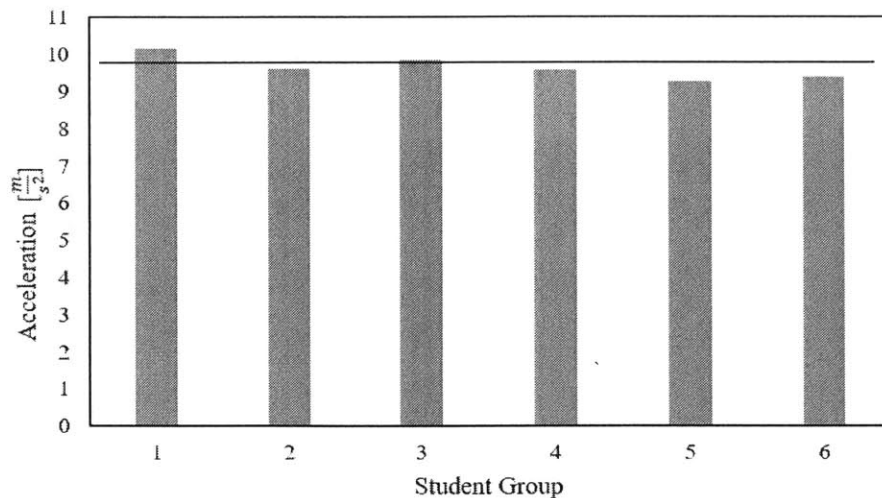
shown in *Figure 18*, was set-up in a room that students could freely access to complete their experiment.



**Figure 18:** Laboratory set-up used by students in ESG to complete their pendulum lab experiment

#### 4.1 Student Lab Reports

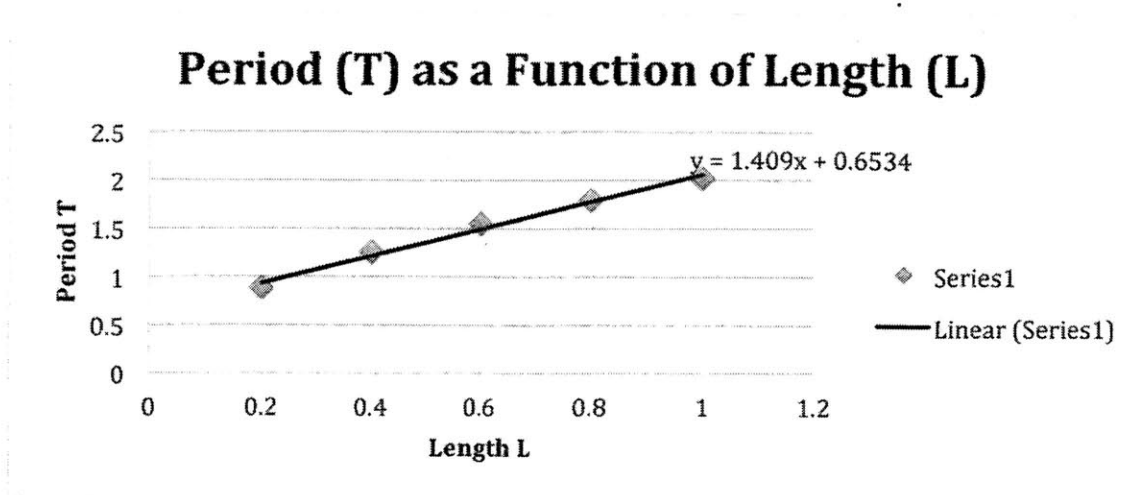
After reading the lab reports submitted by students, there are a few observations on their understanding of concepts that can be made. First of all, for students in their first semester of college, their lab reports were extremely well written and well organized. Students took great care in drawing their graphs by hand and some even went as far as to plot their graph using Excel. The care taken by students is evident from inspecting the slope of their graphs. When students drew a graph by hand and then extracted the value for gravity shown in *Figure 19*, it was found with a 95% confidence interval that their value for the acceleration of gravity were not statistically significant from the expected value of  $9.81 \frac{m}{s^2}$ .



**Figure 19:** Values for gravity calculated by ESG students. The average value with 95% confidence is  $9.65 \pm 0.31 \frac{m}{s^2}$ , which is statistically indistinguishable from the expected value of  $9.81 \frac{m}{s^2}$ .

As an additional part of the lab exercise, students used dimensional analysis to determine the relationships between length and the acceleration of gravity of a simple pendulum. For learners below the college level this might be considered an advanced feature of such a lab. However, this provided a good opportunity to explore a wide range of exercises connected to the basic hands-on lab experiences. As shown in Eq. (1), it is evident that the relationship between period vs. length is not linear. Even after they derived this equation, multiple students plotted a linear fit to the data taken for period vs length, shown in an example from a student lab report in *Figure 20*. Even though they may have mathematically understood that the relationship was not linear from the equation, the results appeared somewhat linear due to the small number of points, and therefore they went with their (incorrect) intuition rather than their recently acquired mathematical understanding.





**Figure 20:** Graph on the period vs length submitted by students showing an incorrect linear fit.

As a way to make the data trends more evident and avoid their reliance on faulty intuition, in future instructions it will be suggested that learners include  $(0, 0)$  as a point on their graphs. As pointed out in Section 3.1.2, including  $(0, 0)$  as a data point would be strictly speaking incorrect because it is not an actual measured result and using it can hide systematic errors in their data. However, including  $(0,0)$  on the graphs is so helpful in making evident the non-linear character of the  $T$  vs.  $L$  curve that it is important to be included. Students will be informed of the appropriate caution they should use when including  $(0, 0)$  on their graphs.

Another aspect that students had trouble with was internalizing that the period is independent of the mass. Even though they have determined that mass is not in the equation for period of a simple pendulum by deriving Eq. (1), many students made comments throughout their papers that lead us to believe that they have trouble believing this. One student wrote:

We attached a piece of string to a small rubber ball using a piece of tape with ideally negligible mass.

If there is no mass in the equation for the period of a simple pendulum, then it is not necessary for the tape to have a negligible mass. There will be an explicit branch of the basic measurement wherein they will vary the mass of the simple pendulum bob while keeping the length constant so

that they can observe that the oscillation period is independent of mass to within experimental error.

While most students correctly predicted that the period of the physical pendulum would be longer than that of the simple pendulum, one student predicted this was so because the physical pendulum has more mass rather than it being due to the distribution of the mass. To better address these misconceptions, in the future students will take measurements for the simple pendulum using a weight that is comparable to the weight of the ruler they measured for the physical pendulum. Doing this would allow for them to better see how it is not the mass that affects the period, but rather the distribution of the mass.

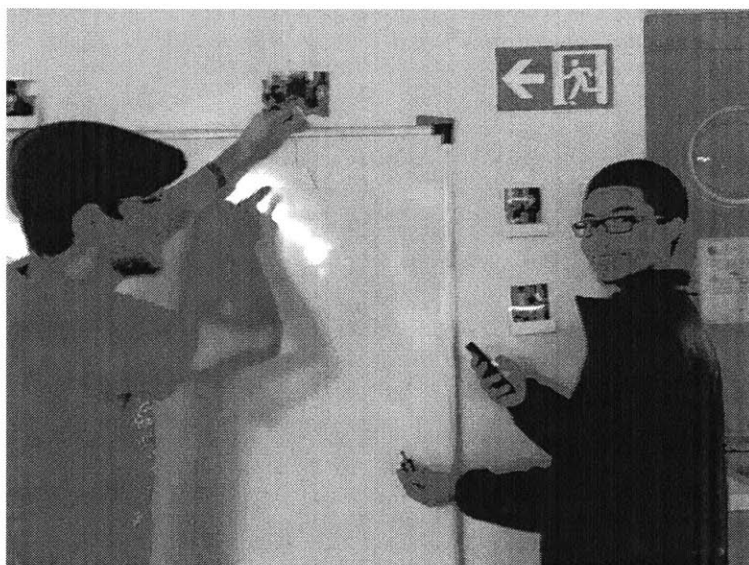
Despite having no formal training in error analysis or instruction on how to minimize errors in this class, all of the students provided great insight into the importance of measuring the period over a large number of cycles rather than measuring the period over just one cycle. Below is an excerpt from one of the lab reports submitted.

If you only measure the time for one cycle (short time) this experimental error is a big percentage of the short time (which means the error can change the measured time by larger value). When you stop the time for ten cycles the time is then times as long and the experimental error of starting and stopping is only a small percentage of this time. Now we can divide the time for ten cycles by ten and hence divide the measuring error by ten. The new time for one cycle only has a tenth of the measuring error.

Students also understood the significance of log-log plots and realized the value in using them if you need to determine the particular power relationship between two variables. All students successfully plotted the data using log-log plots and properly observed the slope of the line to determine the corresponding power of  $L$  in the expression for  $T$ .

A major hope for the project is to encourage learners to use material around them to design their own apparatus. This was not included as an explicit part of the instructions that were provided to the MIT students due to time constraints. However, it was delightful to find that one pair of students chose to create their own laboratory set-up using materials found around their room, rather than the set-up provided for them. With no instructions or supervision, they created an excellent

set-up shown in *Figure 21* where they used a small pocket light as the plumb-bob and a piece of string attached to a pen as the fulcrum. They even went a step further and used a whiteboard to mark a 20 degree angle from the perpendicular to be able to release the plumb-bob from the same position every time. The value for gravity that they extracted from their data had a value of  $9.84 \frac{m}{s^2}$ , which is a 0.3% discrepancy from the “true” value for gravity. This shows that students can build systems on their own and add features that improve the measurement.



**Figure 21:** Experimental set-up for the pendulum lab exercise designed by students without instruction.

Overall, the students were very successful in their lab reports and compiled excellent data on the period of simple and physical pendulums.

## 4.2 Survey Results

Written comments from all 6 pairs of students were solicited regarding the pendulum lab exercises they performed. Due to the size and uniqueness of the population tested it is not possible to draw statistically conclusive results, but the preliminary findings will be used to refine the labs and future assessments as they are developed.

Students were asked to indicate how much time they spent on the entire laboratory exercise. On average, students spent 30 minutes completing the data acquisition portion of the lab and 2 hours on the analysis and write up. Because the students were performing several components of a suite of laboratory exercises at once, rather than the intended format of “mini labs”, the actual time to complete any one lab should be significantly less than that reported.

Overall, the written comments from the students regarding the labs were positive and recommended including it next year as part of the curriculum. Many students stated that the labs were a success in that they illustrated the concepts being taught well and motivated them to learn more about the differences between simple and physical pendulums. One student stated, “...I did find it helpful; hands-on experience is always more valuable in my opinion, which is why I liked this lab.” Students also noted that the labs motivated them to learn more about new topics. One student wrote, “[This lab motivated me to learn more about] the differences between physical and simple pendulum.”

Not all comments were positive. Many students suggested making the lab instructions less confusing to read. They would have preferred seeing it as smaller blocks of text that didn’t seem as intimidating. It is not beneficial for students being exposed to physics for the first time to be scared of learning. In the future instructions will be modified to appear less daunting to the learners. One student stated that labs had too many questions, something that will be solved when the lab suite is broken up into “mini labs” as it was intended to be.

Some students stated that they would like to see labs centered on angular momentum and gyroscopic precession, as well as pulley labs that work on measuring acceleration and seeing forces in action. They also would like the labs to go more in depth and have allowed them to discover relationships rather than giving them an equation and asking them to collect data that supports this theory. These comments will help us shape current and future labs in ways that will be beneficial to the intended spectrum of learners.

As a fortunate occurrence, the pendulum lab will be incorporated into a Physics Workshop funded by the NSF to teach Haitian University professors how to include active learning in their classrooms during the summer of 2016. This will provide valuable feedback for the pendulum lab’s being used in an important type of environment for which it is intended.

Even though the work is at an early stage, the opportunity to have it used and feedback provided by groups as disparate as MIT freshmen and Haitian learners will give us the opportunity to adapt the work to a wide range of learners and learning environments.

## **5. Conclusion**

The initial purpose of this project was to create a set of low-cost hands-on mechanics experiments to complement online courseware. However, it was soon realized that the experiments could also be decoupled from this particular application and offered separately as a coordinated set of hands-on experiences for a wide range of learners across the world. By building devices like the inclinometer, these labs show that students are capable of developing tools that can connect multiple suites of labs using primitive devices. The challenges of developing these lab exercises included choosing widely obtainable materials, minimizing the lab costs, and designing experiments that could produce the necessary results to see the desired trends, even when built non-ideally. The feasibility of a core set of exercises using very limited and accessible resources has been demonstrated. Furthermore, it has been shown that learners can be connected to the basic underlying physics in such a way that it develops expert skills in observation and experimentation. The basic suites are each linked to real world applications that the learners can experience, observe and measure for themselves.

In the future, more branches to the labs will be added that will provide the opportunity to make more advanced measurements and connect the work to even more applications. Furthermore, the original basic work will be supplemented with measurements that make use of the video and accelerometer capabilities of smart phones that are becoming more and more broadly available across the world. As noted earlier, this was part of the original plan, but priority was given to the development of the basic simple labs not only for its wider accessibility, but for important pedagogical reasons. Smart phones sensors and interface systems such as those provided by Vernier software, all have often subtle mediating devices and technologies between the learners and the physical phenomena—essentially “black boxes”. These can not only hide the nature of the phenomena, but can inject artifacts into the measurements and analysis that are not readily

recognized. So, even as we contemplate adding such options for the learners, we will build them on the foundations of simpler and more direct experiences.

Overall, the laboratory exercises developed for this project were quite successful and have provided an insightful stepping stone to continue the development of additional branches and laboratory exercises.

## 6. Appendix

### Experimental Pendulum Lab for ESG

#### I. Introduction - Why you might care about a pendulum.

Pendula are all around us from swings in the playground to wrecking balls on cranes to human limbs to metronomes. In addition, a pendulum is a simple example of a harmonic oscillator – and harmonic oscillators are everywhere from masses on springs to the crystals in electronic watches to vibrating molecules to musical instruments.

In this lab, you'll work primarily with a simple pendulum which ideally is a point mass suspended from a frictionless pivot by a massless string of length  $L$ .

#### II. Let's consider the period "T" of a simple pendulum

A. Working out how the period depends on the length ( $L$ ) and the acceleration of gravity ("g") using dimensional analysis.

If we take as given that the two parameters that govern the period "T" of a simple pendulum are the length of the pendulum " $L$ " and the acceleration of gravity " $g$ ". We also assume that it depends on these parameters raised to particular powers.

→ Please see the accompanying sheet that describes a technique for performing dimensional analysis.

**Exercise #1: Use dimensional analysis to find out what the powers of  $L$  and  $g$  are that determine the period of a simple pendulum. Write down your work and your result. Compare your result to the exact expression given below.**

B. As stated above, a simple pendulum consists of a point mass suspended by a massless string of length " $L$ ".

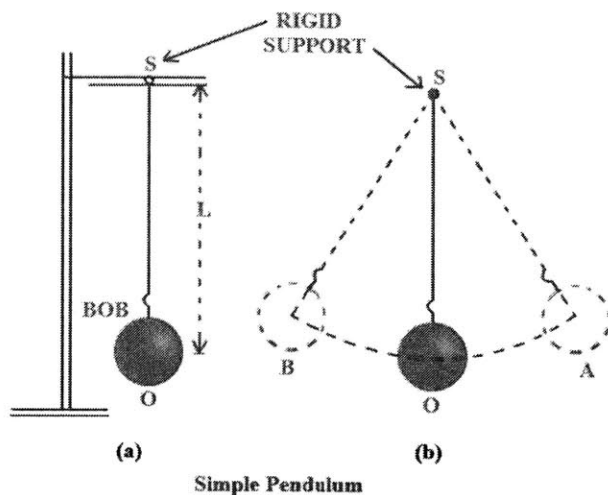
The complete expression for the period of a simple pendulum from the differential equation is:

$$T = 2\pi \left[ \frac{L_{piv}}{gd} \right]^{\frac{1}{2}}$$

This expression is derived using the small angle approximation that says for  $q$  small,  $\sin q \approx q$ . For all your measurements please observe oscillations with a maximum angle of  $20^\circ$  or less so you are in the regime where this approximation is valid.

#### III. The Basic Measurement

In your foundation measurement for this lab you will measure the period” (time for one complete cycle) of a pendulum as a function of its length.



(a) Bob at rest in mean position O.  
(b) Bob in swinging motion between extreme positions A and B.

### Procedure:

1. Adjust the string length so that the distance between the pivot and the center of the metal sphere is 20 cm.

[Because the spheres is not a point mass, it is a good approximation to consider all of its mass located at its center.]

Start the pendulum swinging by pulling it back so the angle is small ( $20^\circ$  or less). You can met this criterion if its lateral distance displaced is one third of its length or less.

- Measure the total time it takes for 10 complete cycles.

Note: One complete cycle consists of a swing “there and back”, so when you release the pendulum to start, that is at time  $t = 0$  and you count the first cycle when the pendulum returns to its original position.

2. Repeat this procedure for pendulum lengths of 40, 60, 80 and 100 cm.

3. Make a table for the length of the pendulum and the time you recorded for ten cycles and also the calculated time or one cycle.



Length (m)	Time 10 cycles (s)	Time 1 cycle (s)
0.2		
0.4		
0.6		
0.8		
1.0		

### Exercise #2

Why is measuring the total time for ten cycles a better experimental procedure than measuring the period one cycle at a time?

Explain your reasoning.

### IV. Graphing your results

What you have done so far is to make careful measurements of the period versus the length of the pendulum. Now you will be concerned with representing that data in helpful ways that will allow you to observe patterns and to extract useful information from your measurements.

You will make graphs by hand using graph paper.

Later, you will have the bonus option of creating the graphs in Excel or other graphing programs. For this lab, a major goal is for you to get a sense of how to work with graphs without too much help from computers. This is not only for your own learning, but to help us to develop material for learners who do not have access to computer graphing or fitting software.

A. Graph the period  $T$  in seconds (y axis) as a function of  $L$  in meters (x axis). Please express  $L$  in meters as indicated in the table above. This will require a unit conversion from centimeters and will be allow you to extract appropriate values of slopes and “ $g$ ” from your graphs.

B. Make a table of  $\log T$  and  $\log L$ .

Graph  $\log T$  as a function of  $\log L$

C. Make a table of  $T^2$  and  $L$ .

Graph  $T^2$  as a function of  $L$

## V. Extracting information from your graphs by analyzing them.

A. Describe the shape of the T vs. L graph. Can you tell from looking at it that T is proportional to  $L^{1/2}$ ? Why might that be difficult?

B. Look at the Log T vs. Log L graph. Theoretically, it should be a straight line with slope =  $1/2$ , where  $1/2$  is just the power of L in the expression for T.

(Extra challenge: can you show why this graph should have a slope of  $1/2$ ?)

Draw a straight line that best fits your data point and measure its slope.

Compare your value to the theoretical value of  $1/2$ .

You can get a good sense of your uncertainty in the slope measurement, by drawing two more lines: one that has a higher slope than does your best fit line— but comes pretty close to all the data points and another that has a lower slope than does your best fit line but comes pretty close to all the data points. The slope of those two additional lines give you a good idea of the range coming out of your data.

You might get something like: 0.45, 0.48, 0.51 and you would express your results as  $0.48 \pm 0.03$ . Is your value consistent with  $1/2$ ?

Note: There are no units to worry about here – why not?

### Exercise #3

Can you see the value of such a log-log plot?

If you did not know the power dependence of T on L – if all you knew that it was something like  $T = aL^n$ , what would a log T vs. Log L plot look like and what information would it give you?

C. Extracting a value of “g” from your graph of  $T^2$  vs. L.

Draw a straight line that best fits your data point and measure its slope.

Compare your value to the theoretical slope value from the expression for  $T^2$ .

Find a value for “g” from your slope measurement.

Compare your value for “g” with the accepted value of  $9.81 \text{ m/s}^2$ .

[You can again get a sense of your measurement uncertainty by doing the same higher and lower slope measurements you did above. We won't ask you to do that again here – unless you want to.]

Extra: We ask all of you to make the graphs and extract the information as described above.

If you are familiar with Excel or another graphing program, you can in addition generate the graphs, best fit lines and values for the slopes with that software.

You can compare these results with those you got with the basic techniques described above.

## VI. Another kind of Pendulum -- the Physical Pendulum

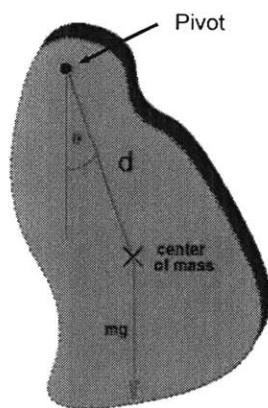
### Introduction:

The simple pendulum is an ideal form and many real pendula differ significantly from the simple pendulum in their mass distribution. However, such “physical pendula” still display harmonic motion about a pivot with a well-defined period.

This period now depends upon the relevant parameters according to the following expression:

$$T = 2\pi \left[ \frac{I_{piv}}{mgd} \right]^{\frac{1}{2}}$$

Here  $I_{piv}$  is the moment of inertia about the pivot point and “d” is the distance between the center of mass of the object and the pivot point. [From the parallel axis theorem  $I_{piv} = I_{cm} + Md^2$ , where  $I_{cm}$  is the moment of inertia about the center of mass.] See the figure below:



A Physical Pendulum

In this experiment, you will use the provided wooden meter stick as your physical pendulum.

Suspend the meter stick by the attached ribbon. [Note: in this case the pivot point is outside the meter stick.]

**A. Make a prediction:**

You will measure the period of the physical pendulum and compare it to the oscillation period of a simple pendulum of the same length.

In this case, consider the  $L$  of the physical pendulum to be the distance from the pivot to the end of the ruler. [Note that this distance is greater than 1 meter.]

**Exercise #4**

Before you make any measurement on the physical pendulum, predict whether its period will be the same, longer or shorter than that of the simple pendulum of the same length. Write down your prediction and state why you think it should be the case. There is no penalty for an incorrect prediction. We want to know how you are thinking about this problem, so you be credited for the clarity of your explanation.

**B. Make the Measurements**

Procedure:

1. Measure the length  $L$  of the meter stick pendulum and also note the location of the center of mass of the meter stick (that will be easy).

Start the meter stick pendulum swinging by pulling it back so the angle is small:  $20^\circ$  or less. You can meet this criterion if its lateral distance displaced is one third of its length or less.)

- Measure the total time it takes for 10 complete cycles and find  $T$ , the period.

2. Now put up the simple pendulum and adjust the string so the length of this pendulum (from the pivot to the center of the mass) is the same as the  $L$  for the meter stick pendulum.

- Measure the total time it takes for 10 complete cycles and find  $T$ , the period.

3. Compare your results from parts 1 and 2 – do they agree with your prediction?

Discuss your observations.

**Extra:**

Compare your results for the period of the meter stick pendulum with the theoretical expression using the expression for  $I_{cm}$  for a ruler and the parallel axis theorem. Comment on the comparison. [Note, you do not need to measure the mass of the meter stick – why not?]

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