



A Compact Device for Inductive Instruction in General Physics

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Research from the past three decades has found that an interactive engagement approach to teaching the sciences which involves physical interaction with systems helps students build effective mental models. Our team of engineering students has developed a novel tabletop teaching device called the Touchstone Model 1 (TM1) designed to help incoming students solidify and retain knowledge of first-term General Physics in an iterative manner. The device is a combination of classic physics models: a pendulum of adjustable length, a rail system including an incline plane, a rolling ball/weight, and a ball launcher. An integrated microcontroller combines these conceptual models, and allows the difficulty of the problem to be adjusted by including or excluding new physics concepts in tandem with the lecture curriculum. The design is informed by a pedagogical model based on giving students open-ended problems that require a network of conceptual knowledge. This hybrid hands-on and inductive model could increase student motivation to more deeply understand concepts that have often been difficult to learn. A prototype device has been partially integrated into Portland State University's existing Physics with Calculus Workshop curriculum, being used in three of nine weekly sessions. At the end of the term, anonymous questionnaires were used to gauge student interest in the device as a learning and motivation tool in the workshop environment, informing future research and development of the device. The data from the student surveys was also used to create a more formal assessment of student knowledge gains. Positive results were seen in both categories, with unanimous student approval and a small median increase in test scores. A second prototype is under development, and could be more fully integrated into the workshop model in the future. Precision machining and an integrated microcontroller could build on the initial prototype and can be thought of as a modular, highly-predictable Rube Goldberg machine. A novel aspect of this work is that the device was conceived, developed, fabricated and tested entirely by undergraduate engineering students. Another distinctive feature is that an Arduino microcontroller provides the data collection and control of the apparatus, allowing for great curriculum mobility.

I. Introduction

Traditional lecture-based general physics classes have been shown to be ineffective in instilling Newtonian physics intuitions in students^{1,2}. Although the lecture model remains the dominant paradigm for physics education in practice, a variety of other approaches have been examined. These alternative approaches often incorporate the findings of Physics Education Research (PER), a body of work that has led to the conclusion that students “need to participate in the process of constructing qualitative models and applying these models to predict and explain real-world phenomena.”²

At Portland State University in 2011, an updated Physics with Calculus Workshop curriculum was developed to present general physics students with difficult, involved physics problems that demand a high degree of critical thinking and problem-solving skill. These workshops are each made up of three long-form problems with some prompts and hints to help students form mental models, matching the “Guided Inquiry” category of Inductive Teaching³. A single peer workshop leader is present for each workshop to keep students on-course, but lecturing is rarely a part of the class and is expressly discouraged during workshop leader training. Students pool knowledge and approach the problem from a variety of angles before finding a solution. The workshops are organized and run by students in conjunction with faculty from the physics department.

A research-driven device and corresponding curriculum elements were developed to help students make connections between mental models and physical mechanisms. The device was incorporated into an existing Physics with Calculus workshop model for a representative set of Workshop students, whose polled responses were used to categorize student response. The

device was developed by a team of engineering students working under the moniker “Physics in Motion” (PIM). Two of these students also led physics workshops, and incorporated the device into their workshops to examine student interaction with the prototype.

II. Methods

a. Design Considerations

A project was undertaken by Mechanical Engineering students starting in the spring of 2013. The goal of the project was to identify a need in student education and to apply engineering skills to move towards a solution to the chosen problem. The problem isolated was informed in part by the findings of Halloun and Hestenes, who demonstrated⁴ that students’ misconceptions followed them through their study of physics—a problem barely addressed in the classroom nearly three decades later. Initial interviews with advising faculty revealed a dissonant set of beliefs regarding the root of this problem: during an interview with a physics professor, the team was told that students learn to apply mathematical models to physics problems, but that they never develop a real intuitive knowledge. Conversely, during an interview with a mechanical engineering professor, the team was told that students all have an intuitive knowledge of physics, but are not taught to effectively apply mathematics. These interviews, while somewhat conflicting, demonstrated in both cases the belief that a fundamental problem in teaching physics lay in the translation between intuitive senses and analytical models.

The team worked to develop a device which could help students to bridge the gap between the abstract world of mathematics and the tangible world of machines. The design and development of the Touchstone Model 1 device (TM1) was informed by PER, and especially influenced by an idea expressed by Redish⁵: “Touchstone problems and examples are very important...Touchstone problems become the analogs on which [students] will build the more sophisticated elements of their mental models.” Touchstone problems, as defined by Redish, are problems which “...the student will come back to over and over again in later training.” Redish lays out a set of principles that relate cognitive science research to the practice of teaching physics effectively. One way to take advantage of these principles and the research behind them is to encourage the growth of a basic touchstone model in students’ minds, then to expand on this model by adding small sets of conceptual elements iteratively. This is a principle Redish addresses: “It is reasonably easy to learn something that matches or extends an existing mental model.” The project described in this paper is based on the principle of asking students to build a mental touchstone model, then asking them to add layers to this existing model, all the while reminding students to examine the network of relationships between new elements and those that were previously part of the model.

The TM1 device, shown in Figure 1, is a parallel construction made up of a set of classic physics machines: the pendulum (energy), the ramp (forces), and the ball launcher (kinematics).

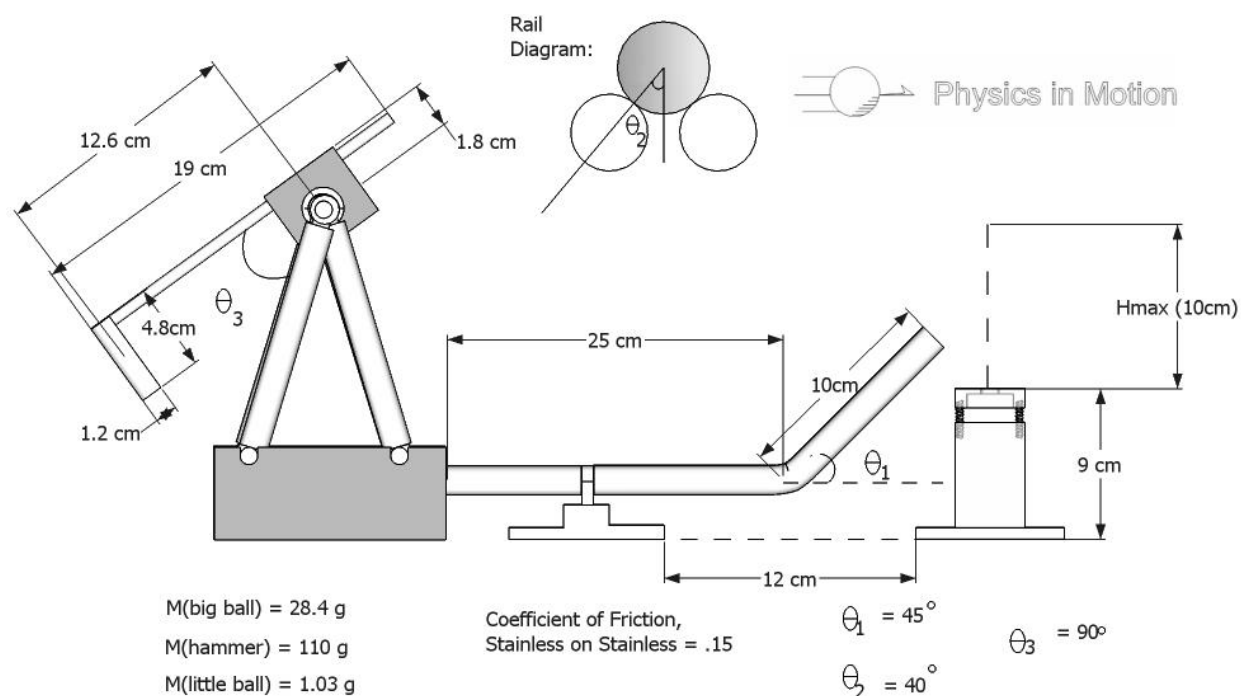


Figure 1: Schematic for the TM1 Device

The engineering aspect of the device involved both the physical design – a construction that can repeat a series of mechanical movements consistently, with a high degree of precision – and the incorporation of a unique Arduino microcontroller difficulty-scaling mechanism which allowed the curriculum to cover a robust set of topics in a sequential order. The microcontroller increases the modular nature of the device, as a physics instructor could quickly learn to develop new code for the Arduino, changing the problem in whatever respect he or she desired.

The Arduino module functions as an input device, for which timers are set for the dropping pendulum and for the small ball launcher. This is the full extent of the input, and once these variables have been entered, the TM1 elements are triggered at times corresponding to those entered by students. This simple interface – an LCD screen and two input buttons – allows the student to select a difficulty level by choosing whether certain elements of physical interaction are turned “on” or “off”. Timers can then be set with a precision of 1.00 seconds. Figure 2 below shows a typical sequence of inputs corresponding to a “Level 4” difficulty.

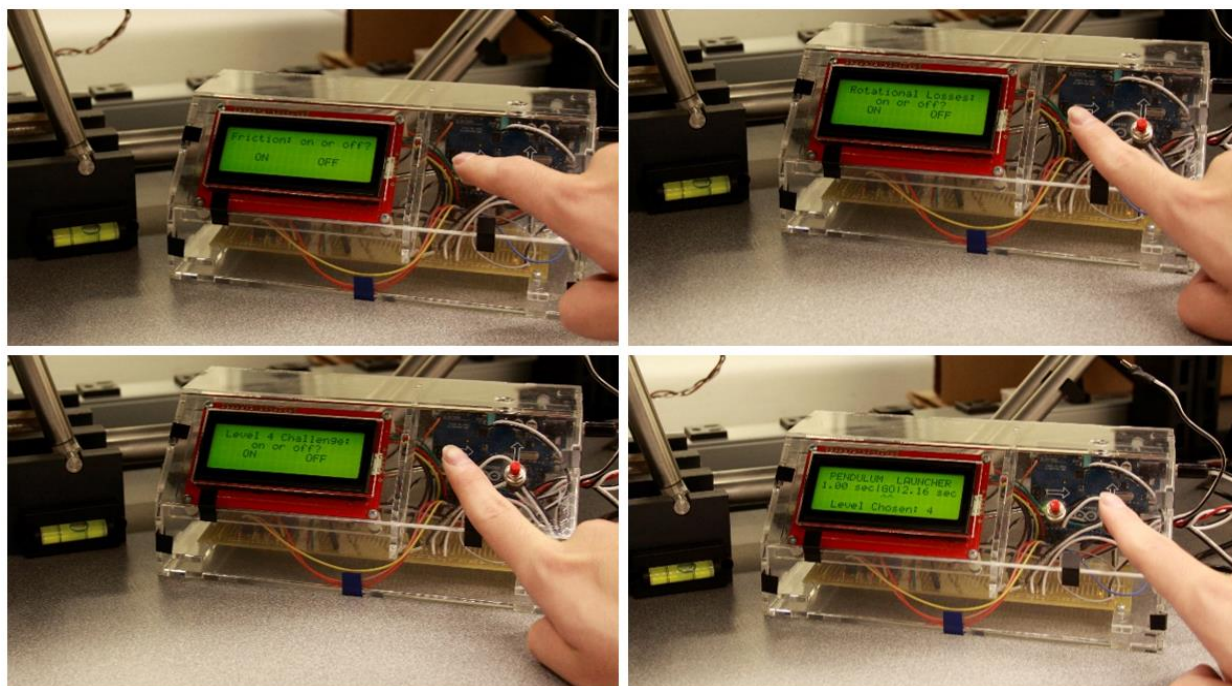


Figure 2: Inputs Corresponding to a Level 4 Attempt

One could say that the TM1 is a collection of classic physics touchstone problems. Together, this initial configuration of the device includes most of the topics covered in the Mechanics term of a college-level general physics class. Table 1 is a broad summary of the concepts traditionally covered in the class, and their application to the machine overall and to the curriculum developed and tested in classrooms. The same table describes the elements which can be turned on or off at varying difficulty levels.

Table 1: TM1 Difficulty Levels and Topics Included

Difficulty Level	Set Up	General Physics Topic	Demonstration	Workshop
Level 1	Given the initial speed of a stainless steel ball traveling on a straight track, time the launch correctly in order to cause a collision with a small ball from a ball launcher.	Measurement	<i>The device requires students to measure most of the device's dimensions manually.</i>	Workshop 3
		Motion along a straight line	<i>Students calculate the motion of the ball on the track as well as after leaving the track, requiring linear motion analysis and two dimensional projectile motion analysis (kinematics).</i>	
		Vector analysis		
		Motion in two dimensions		
Level 2	Solve the problem above with friction of the track added.	Friction & Free-body diagrams	<i>Students calculate and include the effect of a frictional force between the track and the ball, assuming a sliding object without rotation on a flat surface and on an incline plane.</i>	Workshop 6
		Forces and Acceleration		
Level 3	Consider the rotation of the steel ball on the track, and calculate the linear and rotational energy distribution during the motion.	Kinetic energy and work	<i>Students must analyse the traveling speed of the stainless steel ball by considering both linear and rotational motion, as well as energy storage/transfer between kinetic energy, potential energy, and rotational energy.</i>	Workshop 9
		Potential energy		
		Conservation of energy		
		Linear momentum		
		Rolling		
Level 4	No initial speed is given; solve the problem purely by measurement and analysis, including the motion of the pendulum.	Angular momentum	<i>Calculating the actual initial speed of the steel ball requires analysis of the motion of the pendulum using the parallel axis theorem and requires students to find a relationship between conservation of energy and conservation of momentum.</i>	Workshop 9
		Center of mass & Parallel axis theorem		
		Conservation of momentum & Collisions		
Advanced	Calculate the true drop time of the pendulum, and include all other effects listed above.	Applied Differential Equations	<i>Calculating the pendulum drop time requires a second-order partial differential equation, solvable by numerical integration or Taylor Series approximation.</i>	Not Incorporated
		Taylor Series Expansion		

The time at which the pendulum and launcher are triggered is offset by the Arduino, which has stored constants that correspond to correct solutions for each difficulty level. Therefore when a student selects the first difficulty level—which treats surfaces as frictionless and ball's motion as linear—a constant is applied after the students input their calculated trigger times. This ensures that the balls do indeed collide assuming a correct theoretical input.

It is worth mentioning that this touchstone problem has more curriculum potential than has been fully demonstrated to date; for example, further levels of complexity could require students to construct and solve a differential equation to describe the drop of the pendulum and the ensuing motion. Furthermore, the device is highly modular, with each element being adjustable: the pendulum's height, mass, and arm length are designed to be variable; likewise, the length of the track can be adjusted by swapping out track pieces; and the height and speed of the ball launcher could be easily modified through a voltage controller or by exchanging solenoids.

Another design criterion hinged on student motivation: the device was designed with a variety of exposed electronic systems, shining stainless steel rails and trusses, and an overall aesthetic designed to catch a student's eye and promote interest in the system as a whole. The interface is also designed for ease of use. Upon powering on, the LCD screen displays a series of factors which can be turned on or off by the user, leading to an interactive selection of one of the difficulty levels shown in Table 1.

Figure 3 shows the prototype TM1 device, along with component annotations.

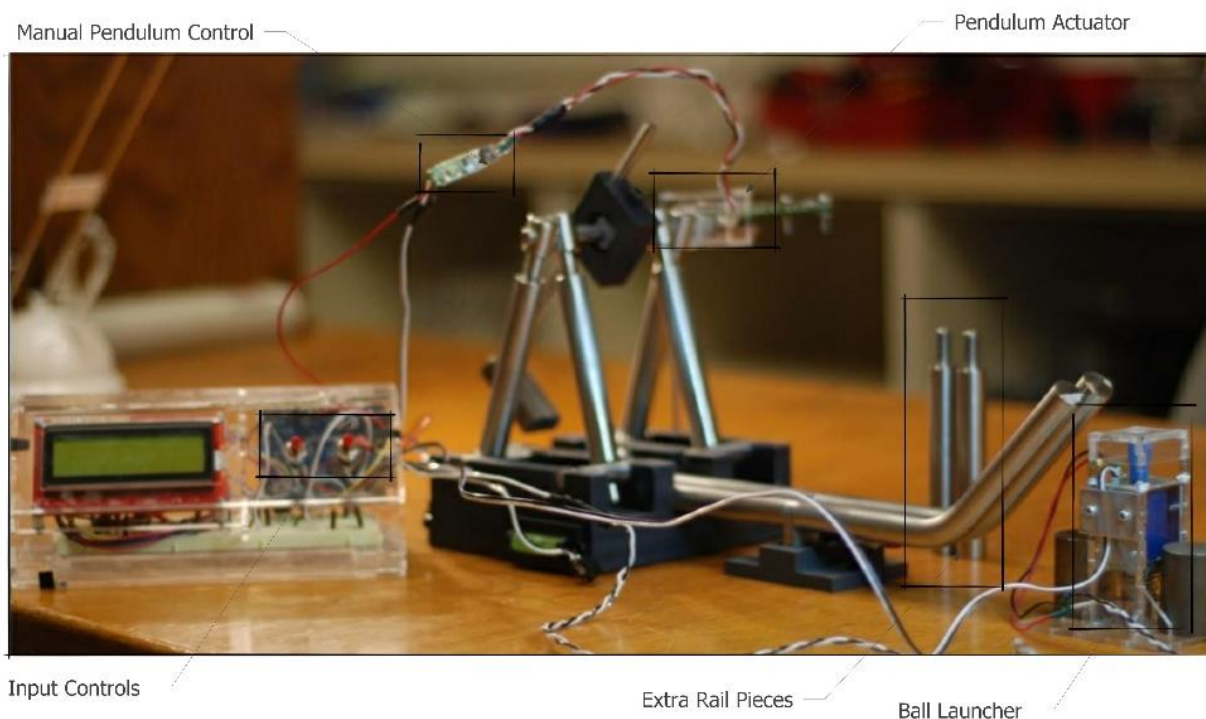


Figure 3: Annotated photo of the TM1 Device

b. Curriculum Development and Execution

A total of 58 students attended the Physics with Calculus workshops; of these, 20 students attended special PIM workshop sections, broken into two groups that met weekly. Students who were in the special PIM workshop sections followed exactly the same workshop model as their peers for six of the nine total workshops, but their 3rd, 6th, and 9th workshops were replaced by the repeating TM1 problem. For PIM workshop students, difficulty was increased gradually by including factors that had not been considered in the previous workshop and which were synchronized with the syllabus of the General Physics class to reinforce new concepts. A single workshop leader was present in each workshop, and had been trained to be minimally involved in student problem-solving. The workshop leader's task was to help turn students back towards the central elements of the problem if the line of reasoning strayed from the principles applicable to the problem.

For these three PIM sessions, the curriculum closely followed the existing workshop model, with a few key differences. First, the set of three problems was replaced with a single problem and one goal: to make the two balls collide in mid-air by inputting the proper timer settings for the pendulum drop and ball launch. Second, the degree of help offered by the written workshop was intentionally decreased, while an extra element was added to each with the goal of forcing students to create hypotheses about the result of their analysis before undertaking the mathematics involved.

A primary goal for this initial curriculum was to help students develop an intuitive sense of the relative influence of friction, kinetic and potential energy, rotational energy, and mass

Students were provided with a schematic of the mechanism, and were required to isolate the variables that would matter for their analysis at each difficulty level. After breaking the problem down into isolated events, students were able to reassemble these segments of motion into a cohesive whole, finding a time difference between the pendulum drop and the ball launch that would theoretically cause a collision. After solving the problem, students were able to test their solution by physically preparing the device, entering the solution and observing the result as a group. Copies of each special PIM workshop are shown in Appendix A.

[illegible]

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Students were told that the device was a prototype developed for a set of experimental workshops, in collaboration with the Portland State Mechanical Engineering Department. Students were not made aware that their workshop leaders had any connection to the curriculum.

III. Results

a. Student Response

Following the device's deployment, a short supplemental questionnaire was added to the existing Physics with Calculus Workshop evaluation sheet. It was comprised of two questions: "Did working with the device change your experience in the workshop? Please explain." and "Did the device help you understand where the physics formulas come from? Did the device help you understand how physics formulas interact together?" The survey is available in Appendix B.

Because the workshop allows students to be absent during one of the nine meeting times, and because the final meeting during which the evaluation sheet was administered occurred during the week before final exams, attendance in both PIM workshop sessions was significantly diminished at the time of the survey. A total of (7/20) PIM workshop students were present to complete the questionnaire. The questionnaire was administered by the workshop leader, who then left the classroom to allow students to comment on the workshop anonymously.

Of these 7 responses, all were positive, with each student expressing the sentiment that the device was a useful addition to the workshop model. Many students responded that the device helped them understand how physics functions in the "real world". Multiple students responded that the device helped demonstrate how mathematical models and physical systems are connected through some act of translation. Table 2 is an attempt to qualify the responses through the use of keywords.

Table 2: Student Response Keywords

	"Yes"	"Real"	"Challenging" <i>n=7</i>
Question 1	6	4	-
Question 2	7	-	2

b. Knowledge Gains

After the completion of the class, midterm, final, and overall scores were compared for three groups of students. Students who did not complete the workshop or who did not pass the class were removed from the dataset. Group 1 ($n=20$) is the group of students in the special PIM workshops. Group 2 ($n=30$) is the group of students in the normal Physics with Calculus workshops. Group 3 ($n=132$) is the group of students who did not attend a physics workshop. Figure 5 shows median scores from each group, while Figure 6 gives a box plot representation of scores from each group.

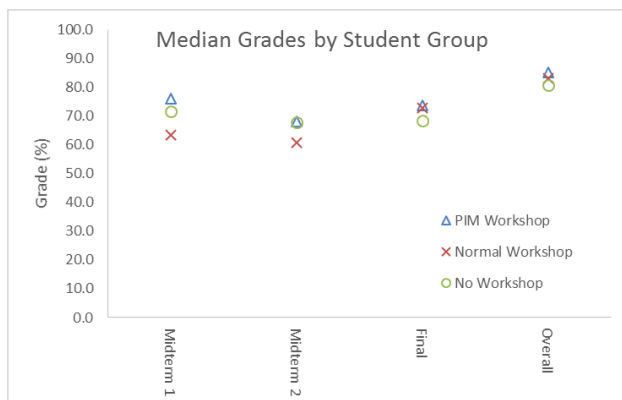


Figure 5: Median Scores by Group

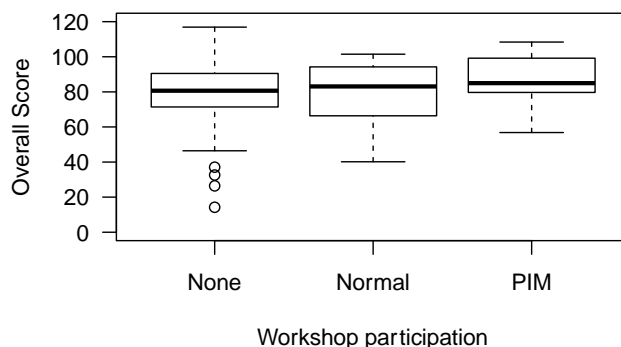


Figure 6: Overall Scores by Group

Tables 3 and 4 show comparisons of the mean and median scores (respectively) for the three exams (midterm 1, midterm 2, and final) given by the instructor in the Physics course. The mean scores are susceptible to outliers, so it is prudent to use the median score differences for comparison. In all four assessments, the students who attended the PIM workshop showed the highest median scores.

Table 3: Mean Student Grades by Group

	Midterm 1	Midterm 2	Final	Overall
PIM	69.1	68.3	80.7	85.9
Workshop	62.7	59.2	68.7	79.1
No Workshop	71.9	67.5	71.2	80.6

Table 4: Median Student Grades by Group

	Midterm 1	Midterm 2	Final	Overall
PIM	75.9	68.1	73.7	85.0
Workshop	63.5	60.8	72.8	83.1
No Workshop	71.5	67.7	68.4	80.7

The data in Tables 3 and 4 give some degree of confidence that the PIM workshop may be helping students learn the course material or helping them approach complex problem solving. However, we have not controlled for incoming student characteristics. Motivation for taking workshops as a supplementary course range from a desire to improve main-section test scores, to a desire to understand physics more completely, to incentives instilled by extra-credit opportunities. Furthermore, as each workshop is led by a different leader, student scores may be affected by this factor as well.

The statistics above do not make a conclusive case regarding the efficacy of the TM1 device in the workshop model. Further research would be required to gain formal knowledge of the device's effects on student learning. Specifically, experiments designed to test student knowledge gain in specific skillsets or subjects could help to inform further development of TM devices and their accompanying curriculum.

IV. Conclusion

A prototype touchstone model device was designed and deployed to augment the existing Physics with Calculus Workshop at Portland State University. A curriculum was also developed to help students form a conceptual model which would increase in complexity as the main section of the general physics class advanced. This single device allowed students to explore nearly every concept in first-term general physics, with the exception of static equilibrium and gravitation.

Student response to the use of the device in the classroom was positive, although formal analysis of student knowledge gain was inconclusive. A larger study would allow for a more complete examination of the application of a modular and increasingly-difficult touchstone model device; furthermore, specific knowledge gain goals should be assessed in order to analyze the effect of the TM1's use on persistent physics misconceptions. With proper design, these experiments could be used to inform further curriculum development if the results are shown to be promising.

A second prototype is under development, which aims to include a wider variety of possible physical arrangements to help maintain student interest. This second iteration is also designed to allow for more hands-on student interaction beyond dimension measurement, further bridging the gap between mathematical models and physical mechanisms. The design is intended to function similarly to a modular, highly-precise Rube Goldberg machine, containing classic physics devices which can be recombined into new Touchstone problems. Ideally, future curriculum will incorporate conceptual problems which will be analyzed through student experiments, followed by analytical problems which will be analyzed through mathematics and then confirmed by experiment.

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Workshop 3

➤ Problem 1: *Position; projectiles; insight hunting*

Set-Up:

See the schematic attached to this workshop.

Your goal is to make a large steel ball collide in mid-air with a small steel ball. This is accomplished by setting two timers – one defines when the pendulum will drop, and the other defines when the small ball will be launched from the launcher.

Things to Think about:

Some information in the schematic will be helpful to you. Some will not be. Part of dealing with real situations in science and engineering is deciding which factors need to be included in your model.

At this point in your physics education, there are many real-world factors that you do not yet have the tools to insert into this model. For the purposes of this workshop, you may ignore:

- Friction
- Air Resistance (Drag)
- Energy or Speed changes due to Elevation or Rotation

Objective (I):

1. Sensors at the beginning of the ball's path and at the start of the ramp are set of at times $t_1 = 0s$ and $t_2 = 0.162s$. The pendulum takes 0.11s to drop before it hits the ball. If you set the pendulum's timer to go off at $t = 1.00$ seconds, what time should you set the ball launcher to go off to make the balls collide in mid-air? *Neglect the velocity change on the ramp.*

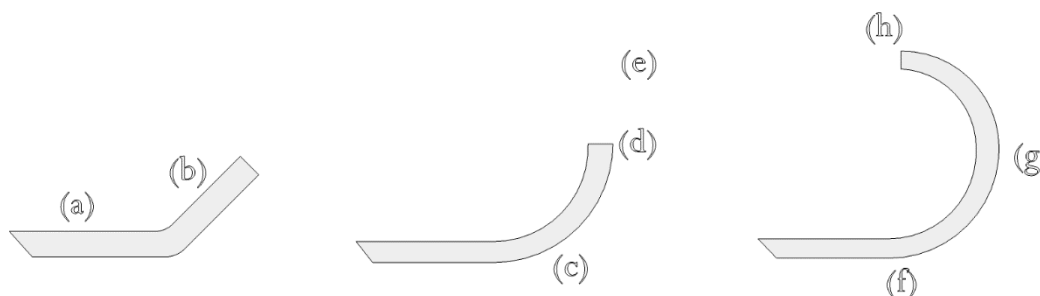
Discussion:

1. Do you think that the physics tools you used to solve this problem would work for this situation in the real world? What factors have not been taken into account?
2. How does the machine work, if you have not taken real factors into account?
3. How many solutions did you find to the problem?

Objective (II):

Above, we have taken an idealized ramp in which the ball smoothly moves from horizontal motion to some angle theta. We are now interested in how that curve affects the ball's acceleration.

1. For each figure shown, sketch the ball at each point (a), (b), etc. Add vectors to describe the ball's velocity, and vectors to describe the ball's acceleration. Be sure to show these vectors differently so that they could not be confused.



Workshop 6

➤ Problem 1: *Forces and Energy*

Set-Up:

See the schematic attached to this workshop. Your goal is to make a large steel ball collide in mid-air with a small steel ball. This is accomplished by setting two timers – one defines when the pendulum will drop, and the other defines when the small ball will be launched from the launcher.

Things to Think about:

Some information in the schematic will be helpful to you. Some will not be. Part of dealing with real situations in science and engineering is deciding which factors need to be included in your model.

In a previous workshop, we looked at the same situation while ignoring real influences that had not yet been covered in class. Now, our goal is to look at the contributions of these factors:

- Friction
- Energy changes due to Elevation

Discussion 1:

1. What do you think will affect the ball's energy more: friction, or the change in potential energy up the ramp?
2. When friction removes kinetic energy from a moving body, that energy goes mostly into the form of heat. Where does the kinetic energy go during the ball's movement up the ramp?
3. Which do you think really has the greatest effect on the ball's energy?
 - a. Energy that dissipates as heat due to friction
 - b. Energy that leaves as the ball's elevation changes
 - c. Energy that goes into making the ball rotate
4. Which do you think would give the ball more initial kinetic energy?
 - a. Doubling the weight of the pendulum hammer
 - b. Doubling the length of the pendulum hammer
 - c. Halving the density of the ball

Objective:

2. The pendulum hammer has a mass of 110 grams. The pendulum takes 0.11s to drop before it hits the ball. The initial value of θ_3 is 90 degrees.
3. The big ball has a mass of 28.4 grams. The little ball has a mass of 1.03 grams. We will assume that the ball is sliding, not rolling. The coefficient of kinetic friction between the ball and the track is $\mu_k = 0.15$.
4. If you set the pendulum's timer to go off at $t = 1.00$ seconds, what time should you set the ball launcher to go off to make the balls collide in mid-air?

Discussion 2:

Looking at your solution, which factor turned out to be the greatest contributor to energy changes for the large ball? How do you think this will compare to the case where we introduce rolling?

Workshop 9

➤ Problem 1: *Inertia, Rolling, Problem Solving*

Set-Up:

See the schematic attached to this workshop. Your goal is to make a large steel ball collide in mid-air with a small steel ball. This is accomplished by setting two timers – one defines when the pendulum will drop, and the other defines when the small ball will be launched from the launcher.

Things to Think about:

Some information in the schematic will be helpful to you. Some will not be. Part of dealing with real situations in science and engineering is deciding which factors need to be included in your model.

In a previous workshop, we looked at the same situation while ignoring some influences that had not yet been covered in class. Now, our goal is to look at the contributions of these factors:

- Moment of Inertia of the Pendulum
- Energy changes due to rotation

Discussion 1:

1. Which do you think really has the greatest effect on the ball's energy?
 - a. Energy that dissipates as heat due to friction
 - b. Energy that leaves as the ball's elevation changes
 - c. Energy that goes into making the ball rotate
2. The device has been designed so that the center of mass of the system is directly below the axel. Why?

Objective:

1. The pendulum hammer has a mass of 110 grams. The rod has a mass of 47 grams. Find the moment of inertia of the hammer-rod system about the axel.
2. The big ball has a mass of 28.4 grams. At first, assume that the ball doesn't roll when the hammer hits it, and find the initial velocity of the ball.
3. Now, assume the ball actually begins rolling instantly when it is hit by the hammer. How much of its energy goes into rotation? How much goes into translation?
Remember, the ball is on two tracks, and does not rotate about its very bottom point...
4. The little ball has a mass of 1.03 grams. If you set the pendulum's timer to go off at $t = 1.00$ seconds, what time should you set the ball launcher to go off to make the balls collide in mid-air?

Discussion 2:

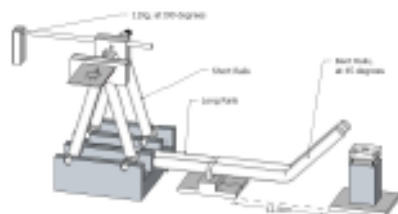
Looking at your solutions from these three pendulum workshops, which factor turned out to be the greatest contributor to energy changes for the large ball?

Consider the case where the ball begins rolling when it is hit by the pendulum, instead of sliding along the whole track. By the time it leaves the ramp, will it have...

- a. ...a greater speed than if it were sliding?
- b. ...a smaller speed?
- c. ...the same speed?
- d. ...impossible to say?

Appendix B: PIM End-of-Term Survey Addition

Some workshops were part of an experimental project which put a physical device in the workshop and then asking students to analyze it. **Please answer these questions if you were in one of these experimental sections.**



1. Did working with the device change your experience in the workshop? Please explain.
2. Did the device help you understand where physics formulas come from? Did the device help you understand how physics formulas interact together?