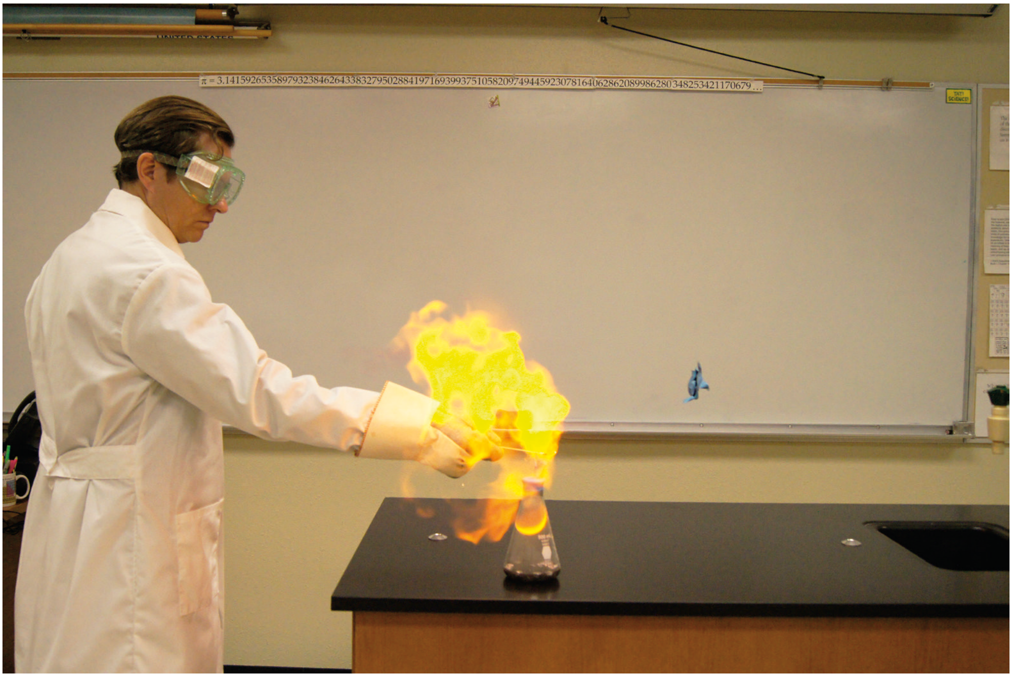
Experiments for *PHYSICS: MODELING NATURE*



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A Guide to Content, Style and Formatting for Effective Science Lab Reports

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Regents Physics
Bull's-Eye Lab
CHAMPIONS

Experiment 1 The Bull's-Eye Lab

Learning Objectives

Features in this experiment support the following learning objectives:

1. General objectives for laboratory experiments (see page 4).
2. Use vector-based equations for two-dimensional projectile motion to make predictions.

This is our first experiment of the year in physics. The experiment is both simple and fascinating for the students. I make it doubly fun by having the teams compete with one another for a team prize. The team that gets the lowest prediction-result difference ratio wins a Bull's-Eye Lab Champions T-shirt for each team member. Moreover, I obtained permission from the school administration for the champions to wear their T-shirts to school on Physics exam days for the rest of the school year. (This is viewed as an especially valuable prize since students at our school are ordinarily required to wear school uniforms every day!) Thus, Bull's-Eye Lab day each September is full of anticipation, tension, and the glory of victory.

Materials Required (per team)

1. steel ball, 1 inch diameter, such as No. AP5626 available from Flinn Scientific (flinnsci.com)
2. laboratory support rod or ring stand
3. clamp (small)
4. shelving support rail, 5/8 in wide x 3/8 inch deep (available at hardware stores)
5. stop watch
6. masking tape
7. plumb bob (available from hardware store or construction supply store)
8. nylon string
9. meter stick
10. carpenter's level
11. target (photocopied)
12. carbon paper (one sheet for the class)

Experimental Purpose

Use the principles of projectile motion to predict where a rolling steel ball will land when it rolls off a table and hits the floor, and compare the prediction to the actual landing spot.

Overview

Students assemble a makeshift ramp/track on a horizontal table. Then they release a 1-inch diameter steel ball so it will roll down the ramp and off the table. Between the ramp and the edge of the table students mark off a timing zone 80 cm or so long. By timing the ball several times while it is rolling on the table through the timing zone they determine the velocity the ball has when it leaves the table. Using this velocity and the height of the table, they predict where the ball will land when it hits the floor. They work out this prediction during the lab time, and then tape down a target on the floor with the center at the predicted landing location. When they are ready for the moment of truth, the instructor brings a sheet of carbon paper and places it carbon-side down on the target. Then the team releases the ball. When the ball hits the carbon paper it leaves a distinct black dot on the target where it landed.

This experiment can be performed very inexpensively. For the ramps you can purchase one or two sections of the support rail used in adjustable-shelf bookcases and cabinets. These sections of rail come in six-foot lengths. Cut the rail so that each team has a piece about 22 to 24 inches long. Use a grinder to grind off one end of the rail at a steep angle so the upper edge of the track where the ball will be rolling comes down close to the table top when the track is angled at about 10 degrees (see photos). After completing the rough grinding, be sure to smooth off all sharp points and edges with a file.

Pre-Lab Discussion

Perform this experiment after students have spent several days solving projectile motion problems. You will not then need to spend any time explaining how to calculate where to place the target. On the day of the experiment I briefly review how to obtain the initial (horizontal) velocity of the ball by timing it as it rolls through the timing zone on the table. I advise students to time it several times, with different students operating the stop watch, and to use the mean time to estimate the ball's initial velocity.

I generally assume my students are honorable, but I also wish to avoid any team gaining an unfair advantage by "accidentally" allowing their ball to hit the floor during the time trials, perhaps noticing approximately where it landed. Thus, I have an important rule for this experiment that I enforce with uncompromising rigor: Any team that allows their ball to hit the floor for any reason prior to the official run for the target forfeits 25 points from each of the team members' lab reports. This rule has been effective in motivating each team to keep their ball on the table until they are ready for their official run for the target.

The rest of the pre-lab discussion needs only to focus on a few practical details.

1. Caution the students to make the angle of the ramp fairly low, as indicated in the accompanying illustrations. This is the only way to keep the speed of the ball low enough so that it can be accurately timed in the timing zone with a stop watch.
2. There needs to be a convenient way to consistently position the ball on the ramp. The little clamp used to attach the ramp to the support stand (see photos) will meet

this need if it is positioned so that the metal arm of the clamp can act as a stop for the ball at the top of the ramp.

3. Students need to use a carpenter's level to check the table to assure that it is level in both horizontal directions. This is critical, since even a slight tilt to the surface of the table can have a significant effect on the velocity of the ball.
4. The bottom of the ramp should be secured with masking tape so it doesn't shift around.
5. Students need to project the edge of the table down to the floor for measuring out to where the target needs to be placed. A plumb bob on a string is the easiest way to accomplish this.
6. Students may need to be reminded that the variable they are predicting in this experiment is the horizontal displacement of the ball past the edge of the table. Accordingly, when calculating the prediction-result difference ratio the distance from the landing spot to the center of the target, which is the measurement everyone is immediately interested in, is not the value to use. Instead, the actual total horizontal travel is compared to the predicted value. The horizontal displacement depends on the initial velocity of the ball and the height of the table, and in my lab the predictions are typically in the range of 30-35 cm. Thus, missing the target by 1.5 cm long or short represents a prediction-result difference ratio of about 5%.
7. For reasons explained below, I ignore any deflection of the ball to the right or left of the target and consider only the difference ratio in the direction of motion. Even though my reasons for this approach are due to the design of my lab tables, I think I would do it even if my tables were different. This is because the prediction the students are making is in the direction of motion, so that is where the difference ratio calculation is relevant. Of course, in the real world the details of mechanical design also play a major role in how well engineered systems perform, so you would be justified in taking left-right deflection into consideration in determining the winner of the prize.

Additional Experimental Details

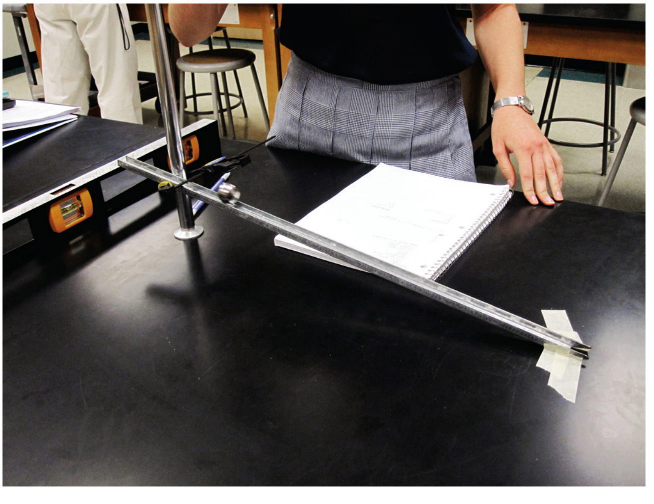
1. The ramps are made of the metal railing used inside of bookcases to support the shelves. This material is very inexpensive and makes a perfect track for a 1-inch steel ball. As mentioned above, angle the ends of the rails for a smoother transition for the ball as it moves from the rail to the table top. The ball will still bounce a bit when it hits the table, but not enough to cause a problem. Make sure to go over all of the edges of the metal with a file to remove burs and sharp corners.
2. As you can see in the illustrations, the tables in my lab have sockets into which support rods may be inserted. I like this feature because the support rods can't get knocked over like a ring stand can, and storing the rods is easier than storing ring stands. However, this design does present a limitation for this experiment: There is a hole for another support socket right in the runway for the rolling ball! We get around this by placing the ramp at a very slight angle so the ball misses the hole.

This results in a small deflection to the left or right, but the effect on the horizontal displacement in the direction of travel (the main variable) is negligible.

3. The small angular deflection in the path of the rolling ball necessitated by the extra socket holes in my lab tables is one of the reasons why I have allowed students to base the prediction-result difference ratio only on the distance in the intended direction of travel (call it x) from the landing spot to the center line of the target. The other reason is that the experimental variable the students calculate is the *horizontal displacement* (x displacement) while the ball is airborne. So it is only the difference between this predicted horizontal displacement and the actual horizontal displacement that has meaning in the difference ratio calculation. (The predicted value of the y displacement, that is, the displacement perpendicular to the intended direction of travel, is zero.) Of course, displacement in the y direction will be captured by increased error in the x direction, which is incorporated into the prediction-result difference ratio calculation.
4. Team members should all agree on the calculations, and the horizontal displacement prediction, before their official trial is performed. Any discrepancies should be resolved in advance. This will help avoid a large prediction-result difference ratio due to error in the calculations. If a team's difference ratio is larger than just a few percent there is a reason for it, and team members should strive to identify it and discuss it in their lab reports.
5. Since carbon paper is a vanishing commodity, you may have trouble finding it at the local office supply store. There are still plenty of places that have it online, but you may have to buy a packet of 100 sheets or so. (One or two sheets is probably enough to last your entire teaching career!)

Student Instructions

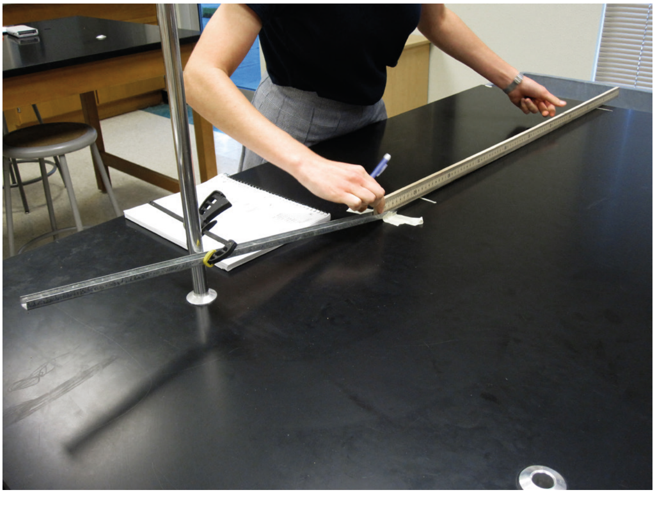
A set of instructions you may reproduce and give to students begins after the following illustrations.



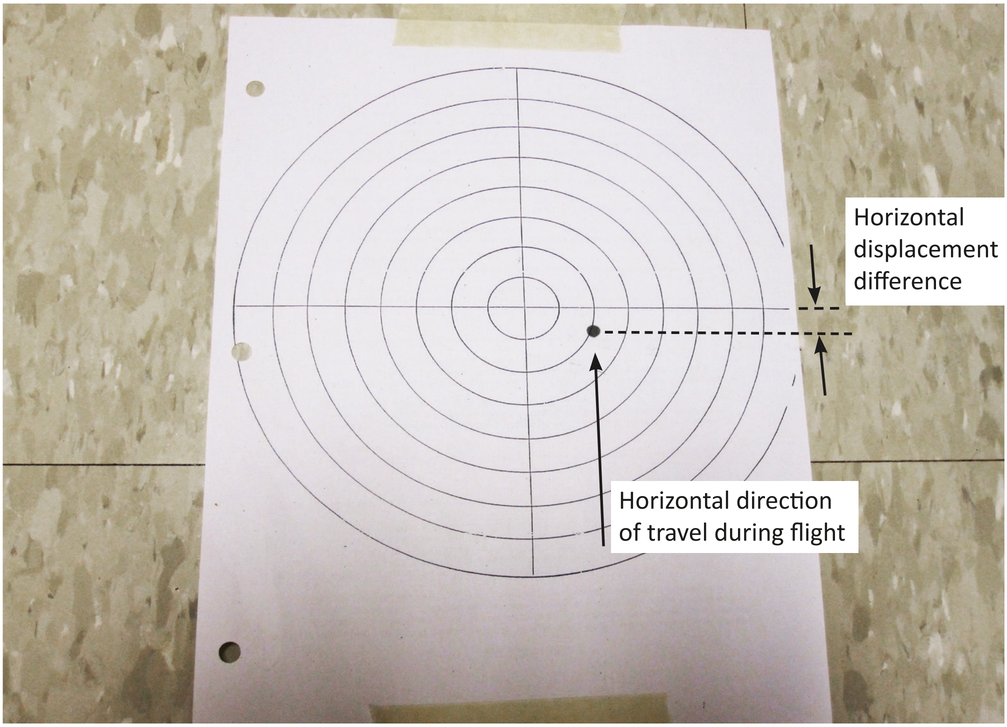
The basic setup, with the steel ball on its way for a time trial.

The end of the rail is ground at an angle to help smooth the ball's transition from ramp to table top.

A plum bob hanging off the end of the table is used as an aid in projecting the edge of the table down to the floor. The ball's horizontal displacement while in flight is measured from this mark.



Laying out the timing zone.



The target taped in position, with the black spot showing where the ball landed. In this case, the horizontal displacement of the ball was about 1 cm short of the prediction. For a prediction of 30 cm, this would result in a prediction-result difference ratio of 3.3%.

Front and rear views of the coveted prize for the winners—Bull's-Eye Lab Champions T-shirts!

Student Instructions

The Bull's-Eye Lab
Projectile Motion

Your task is to make an accurate prediction of where a steel ball will land when it rolls off a table top. You will do this by setting up a ramp for the ball to roll down, and then timing the ball as it passes through a marked timing zone on the table top. You will use the time data to determine the horizontal velocity of the ball on the table top. This velocity, combined with the height of the table top, will enable you to calculate where the ball will land. After you have calculated and marked where the ball will land, you will tape a target onto the floor with its center placed precisely at the predicted landing spot. When you are ready, your instructor will place a sheet of carbon paper face down on your target. You will then let your ball roll down the ramp and off the table, and the carbon paper will mark where it lands. Your grade will be based on (a) how close you got to the bull's eye, and (b) your report, including your analysis of your results and errors.

SPECIAL WARNING

You will only get one chance to hit the bull's eye. Do not let your ball roll off the table onto the floor until you are ready for your "official trial" which must be witnessed by your instructor. If any group lets their ball roll off the table and onto the floor, even if by accident, the members of that group will each incur a penalty of 25 points on their lab reports.

Experimental Procedure

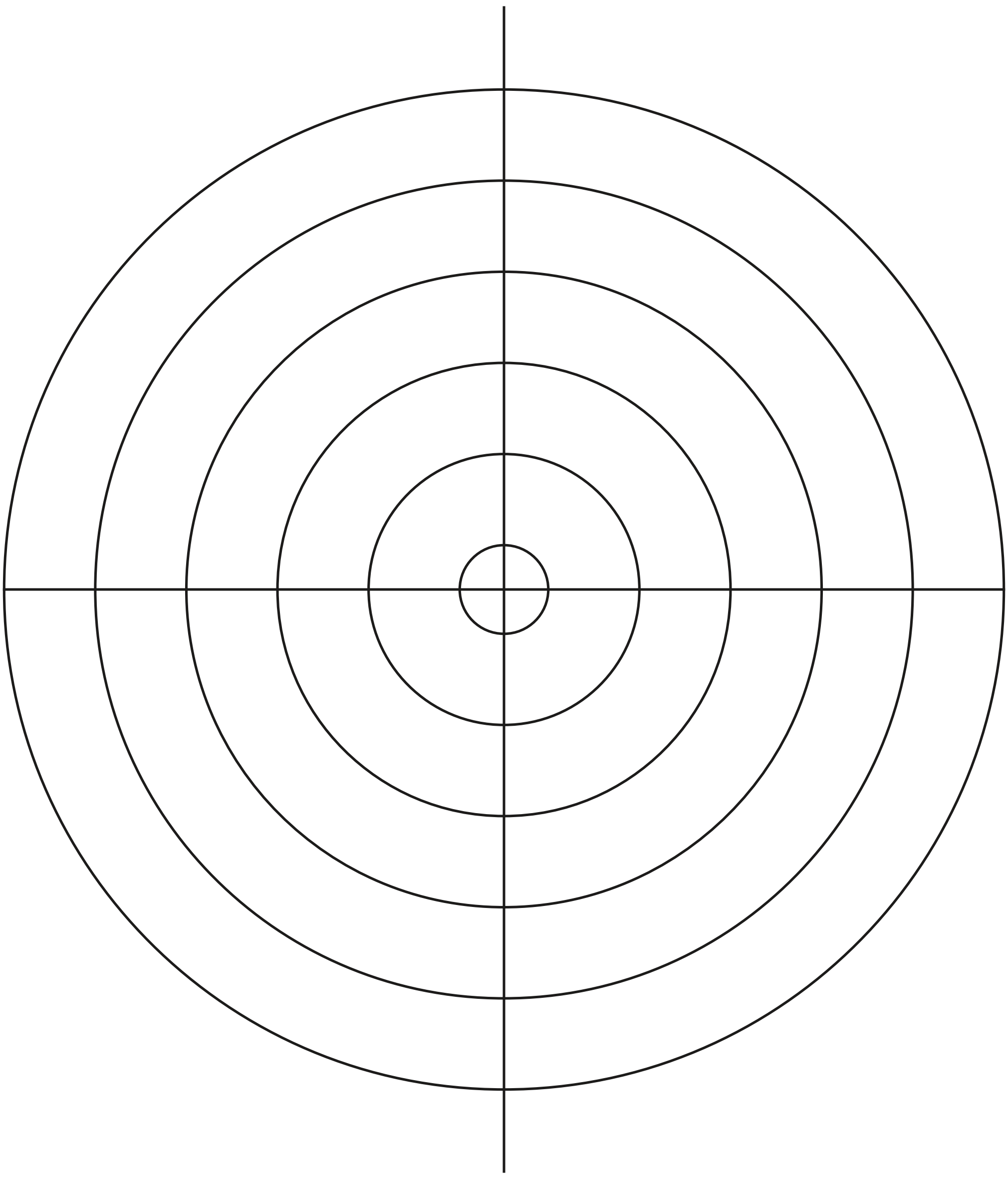
1. Using the stand, ramp and clamp, set up a ramp on your table. Roll your steel ball down the ramp several times to get an idea of what its velocity will be as it leaves the table. A small ramp angle will allow the ball to move slowly enough so that timing its motion on the table top may be done with reasonable accuracy.
2. Mark off a timing zone between the end of your ramp and the edge of the table. In this zone place two strips of masking tape. These strips will be used to time the ball as it goes through the timing zone so that you can calculate the velocity with which it will leave the table using $v = d/t$.
3. Use the ramp clamp as a stop at the top of the ramp for starting the ball consistently.
4. *Without letting the ball hit the floor*, use a stop watch to time the ball several times through the timing zone, after it has been released from the top of the ramp. Average these times and use this average along with the length of the timing zone to calculate the ball's velocity as it leaves the table. Be sure to record all data in your lab journal.
5. Measure the height of the table and use this with your calculated initial velocity to calculate where the ball will land when it hits the floor.

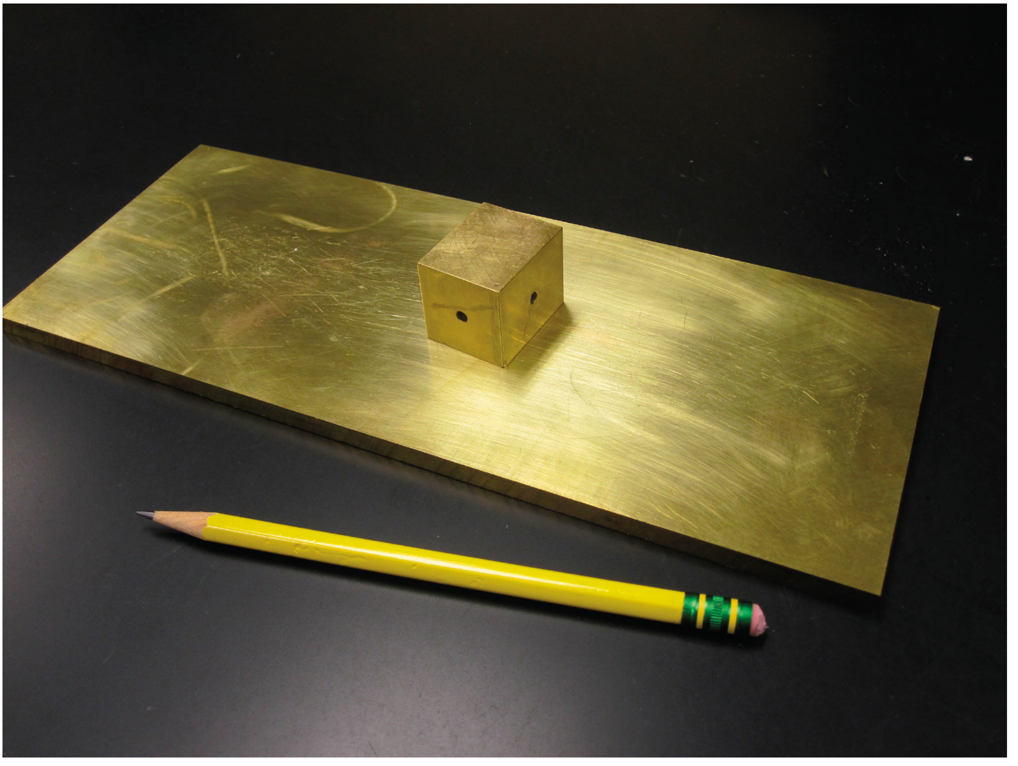
6. Use a plumb bob to project the edge of the table down to the floor. Make a small mark with a pencil on the floor locating the edge of the table. From this mark, measure the predicted horizontal displacement for the ball's flight. Mark the spot on the floor where the ball will land. Tape your target down, centered on that spot.
7. You need to devise a way to assure that the center lines of the target are parallel/perpendicular to the ball's direction of travel. If the floor surface is commercial tile, the lines in the tile can be used to square up the target. Otherwise, you may need to project the table edge down to the floor in two places and measure out from each of them to locate the center line of the target.
8. Notify the instructor that you are ready for your official trial. The instructor will place a piece of carbon paper face down on the target. Then your team will let the ball roll freely down the ramp and hit the target.

Notes on calculating the prediction-result difference ratio for this experiment:

1. As always when comparing theoretical predictions to experimental results, you must calculate your prediction-result difference ratio. Your predicted value is the horizontal distance the ball will travel while it is in the air. Thus, your experimental value is the actual horizontal distance it traveled while in the air. This is a different number from the distance your ball was away from the center line of the target.
2. Your horizontal distance is the distance to the target or the landing spot from the line of the edge of the table projected onto the floor. Do not try to account for angular error in the trajectory, which might have made the ball land to one side or the other of the target. Discuss only the straight-line distance error to the line of the edge of the table.

Reproducible Target





Experiment 2 The Friction Challenge

Learning Objectives

Features in this experiment support the following learning objectives:

1. General objectives for laboratory experiments (see page 4).
2. Develop a reliable, original experimental approach that will allow accurate and precise determination of four separate variables.
3. Explore and learn to use unfamiliar scientific equipment.
4. Use correct polishing techniques to prepare metal surfaces.
5. Work within a project budget.
6. Accomplish interim experimental tasks and present results in interim reports according to a project schedule.
7. Work with an experimental team to brainstorm, plan and execute a multi-phase experimental project.
8. Use computer tools to calculate the standard deviation as an estimate of uncertainty.

This project requires student teams to develop their own experimental design to measure the static and kinetic friction coefficients, μ_s and μ_k, for metal-on-metal contact, with and without lubrication (four separate coefficient values). Students develop and execute their experimental plan just as they would if they were involved in an engineering project in industry, with deadlines, a budget, access to a finite variety of laboratory resources, and freedom to use their ingenuity and creativity to solve the problem any way they can. If students can procure equipment and materials at no cost, then they don't count against the budget. A set of the two brass parts (a section of plate and a piece of flat bar) is furnished to each team, along with a supply of metal polish, and the cost for all of these items is charged against each team's budget. Other stock laboratory materials may made available to teams, depending on what equipment the lab has on hand.

The beauty of this project is that students are given no advice on how to go about determining the values of the coefficients. So their thinking will begin with the basic definitions of the friction coefficients. But soon they will be thinking in terms of vector force analysis and kinematics, and asking themselves a chain of questions about how measurement of one thing can lead to the determination of another thing, and so on, until they finally have a way of getting at the coefficient itself. When this happens, this simple experiment about friction will transform into a nice workout in the computations associated with kinematics and dynamics.

Materials Required (per team)

1. brass plate, 10 in x 4 in x 5/16 in (approx.), may be sourced from Industrial Metal Supply, (industrialmetalsupply.com)

2. brass flat bar, 1 in x 1 in x 1.25 in (approx.), may be sourced from Industrial Metal Supply, (industrialmetalsupply.com)
3. waterproof polishing paper in four grades: 120-C, 220-A, 320-A, and 400-A. These are available from Abrasive Sales.com (abrasivesales.com) as part nos. 19823, 19808, 19798, and 19795, respectively.
4. cleaning cloths
5. nylon cord
6. WD-40 spray silicon lubricant
7. laboratory balance
8. other standard laboratory materials as available in the laboratory, such as low-friction pulleys, table clamps, mass sets, adjustable ramps with angle gauge, timing equipment, and measurement tools.
9. other materials furnished by team members

Experimental Purpose

Design methods to produce precise, accurate measurements of static and kinetic coefficients of friction (μ_s and μ_k), and implement these methods to measure the values of μ_s and μ_k for brass-on-brass contact under dry and lubricated conditions.

Overview

I developed this experimental project around using two brass parts so that students would investigate coefficients associated with metal-on-metal contact. Clearly, the same idea could be applied using two pieces of wood or other materials. In fact, using wood or other materials would cost a lot less and entail less hassle. However, it seems to me that the use of metals is really crucial for making this investigation a success for the students. Simply put, using common pieces of wood seems immediately to be *boring*, while working with brass parts seems *intriguing*. Thinking about this difference has persuaded me that there is an opportunity here to enhance student interest and provide them with an experience that will prove especially valuable if they enter careers in science or engineering. Using metals brings in such considerations as these:

1. Many students have never worked with solid brass materials before. There is added interest simply in the novelty of working with unfamiliar materials. When presented with the brass pieces the students' first impulse is to pick them up and handle them, feeling the density, etc.
2. By handling these materials they will learn first hand about the density of this alloy and its susceptibility to scratching due to its softness relative to steel.
3. As they polish the parts to remove scratches and oxides, students will be fascinated by the colors and the change in appearance of the brass.
4. Wood is seldom used in mechanical or machine design, whereas metals are universally used. Thus, measuring friction coefficients for metal-on-metal contact is

a more realistic scenario for application of the physics involved, and students are subconsciously aware of this.

5. The coefficient of static friction for dry metal-on-metal contact can be quite high, and, counterintuitively, the more polished the materials the higher it gets due to the Coulomb attraction between planes of atoms. This phenomenon should generate a good deal of classroom discussion about the nature of friction, its cause, and the consequences for mechanical design.

Students will acquire four sets of data in this project, static and kinetic friction coefficients of brass-on-brass, both with and without lubricant. Each data set will consist of at least six separate measurements, providing an opportunity for teams to determine and report the uncertainty (s) values in their data. Low values of uncertainty will contribute favorably to the students' "performance reviews," that is, the grades on their reports. High precision in the measurement techniques will allow variation in the measurements to be measurable, while high accuracy will reduce uncertainty. The description of the experimental method in the report and comparisons between the teams' reports should allow the instructor to judge how accurate the results are.

From the perspective of educational value, three major elements are present in this project. First, the students must develop their own experimental design. This immediately takes the experiment out of the realm of the canned physics experiment and places it in the more exciting realm of industrial research. In today's technology-driven culture just about anyone can imagine participating on a design team of this nature.

Second, students will need a thorough understanding of how friction works in a mechanical system (at the macro level, as opposed to the microscopic level), including the coefficients and equations for both static and kinetic (sliding) friction. They will also need to be comfortable with the basic calculations of kinematics and dynamics, including vector force analysis for blocks sliding on inclined planes with friction, Newton's Second Law, and so on.

Third, students will use a simple spreadsheet to facilitate data analysis. Familiarity with spreadsheets is a significant advantage for students entering science or engineering programs in college.

Measuring the coefficient of static friction, μ_s, is not difficult. The team merely needs to devise a way of applying a measurable force to the brass block parallel to the surface of the plate (with the plate fixed horizontally). Then the amount of this force must be incrementally increased until the block breaks free and moves. The weight of the block and the force required to make it move can be used immediately to calculate the value of μ_s.

Measuring the coefficient of kinetic friction, μ_k, is much trickier. Essentially, the measurement requires students to find a way to make the block move at a constant speed, and to measure the force necessary to do this, which would be equal in magnitude to the force due to friction. If the setup depends on the block moving at a constant speed, then students must devise a means of verifying that the block is in fact moving at a constant speed, which is not a simple task. Alternatively, and perhaps more easily, students can devise a setup that results in a uniform, measurable acceleration. Once the acceleration has been determined the friction force may be calculated using standard dynamics calculations.

If electronic timing equipment is available (infrared sensors and digital timers, such as described in the Hot Wheels Lab in Part 1, Experiment 3) additional possibilities open up; if not, the teams will need to do without it. It may or may not occur to students that a movie taken with an iPhone can be imported into iMovie and analyzed to extract time data. Since many students now have access to these tools, there is no real obligation for the science lab to purchase expensive timing equipment just to make this project tractable.

The availability of electronic force measurement equipment would seem to make the kinetic problem easier, but even then students will have to determine a way of creating a constant force that will pull a system at either a verifiably constant speed or with a known acceleration. If they decide to judge by eye that the system is moving at a constant speed, that is up to them, but the crude method of pulling an object by hand at a constant speed with a spring scale should be disallowed as not being nearly accurate or precise enough.

The process of thinking though the possibilities of an experimental design will have students buzzing about not only the definition of the coefficient of friction, but also about various combinations of ramps, pulleys, masses and timing apparatus. Teams will probably need to try out several different ideas for measuring the coefficients until they arrive at a solution. Because of this, it will be good if each team has a dedicated work space available at specific times where they can test ideas. If teams are held accountable for producing their own original ideas, privacy and security will also be a concern.

Depending on the school's resources, equipment available to students for this project could be extensive or sparse. If the inventory is sparse students will have to locate their own apparatus, which can make the project both more challenging and more interesting. If the lab is equipped with a supply of standard apparatus, these items can be made available to students. If the lab has the funds for such equipment, I recommend making the following items available to each team:

1. Inclined plane with an angle gauge capable of indicating the angle to at least three significant digits.
2. Low-friction pulleys with mounting clamps that will fit the raised end of the inclined plane.
3. Mounting clamps for attaching the low-friction pulleys to the edge of a table top.
4. Mass set.

Project Schedule

Experienced teachers know that when students are given a project assignment that stretches out over several weeks they are strongly tempted to procrastinate. Students are quite often driven by the closest deadline and tend to ignore everything else. In a project of this kind students do not really know how much time the project will take, and are highly likely to underestimate the time required for trial and error. Thus, procrastination will almost certainly result in poor work hastily performed at the last minute, or even failure to complete the project. To avoid such disasters, give your students a set of interim project milestones with due dates. This will force them to keep moving. I also recommend that you allocate several class days during the term for teamwork on the projects. Much of their work will need to be performed outside of regular class time, but a few class days devoted to working on this project will really help (as long as they are not allowed to use that time studying for tests, etc., which they are likely to attempt).

The table below shows a sample schedule I used in the fall of 2011. The schedule is based on presentation of friction in class in late September, with project assignments distributed a few days later and final lab reports due from each student prior to end-of-term exam preparations.

Project Milestones and Critical Dates	
Date	Activity and/or Submittal Due
Wednesday, Oct. 5, 2011	First in-class lab session. Teams begin working on experimental plan and identifying needed materials.
Friday, Oct. 21, 2011	Second in-class lab session. Teams continue planning and begin experimenting with possibilities for actual setup.
Friday, Oct. 28, 2011	Experimental plan due (typed).
Thursday, Nov. 3, 2011	Third in-class lab session. Teams complete setting up and begin taking data.
Friday, Nov. 18, 2011	Data summary due (typed).
Tuesday, Dec. 6, 2011	Final reports due.

Notes on Metal Materials

The small brass pieces required for this project will be cut from larger stock by the metal supplier. The term *plate* refers to metals originally fabricated in large sheets. *Flat bar* is the term used to described materials manufactured in long bars around 20 feet in length. The 10 in x 4 in x 0.25 in piece may be cut from either plate or flat bar, whichever is most readily available and thus least expensive. The 1 in x 1 in x 1.25 in block will be most economical if you specify a piece of 1 in x 1 in flat bar 1.25 inches in length. When I first ordered these parts I ordered several sets so that I could have several separate student teams working simultaneously. (In a class of four students or fewer I would have them work together as a single team.) When the parts arrived I took them down to a local machine shop and had 1/8-inch holes drilled through the centers of the blocks in two directions (see photo on page 178). This provides students with a convenient way of attaching a cord to the block for testing. During the testing the block is oriented so that one of the 1 in x 1.25 in surfaces without a hole is in contact with the plate underneath.

Wet-polishing the brass.

The brass metal parts specified in the materials list will come from the metal supplier with sharp edges. Go over all the edges and corners with a flat file so that there are no sharp edges on which students can potentially cut themselves. Be careful not to touch the steel file to the working surface of the brass, because the lower hardness of the brass means it will be easily scratched or gouged by contact with steel.