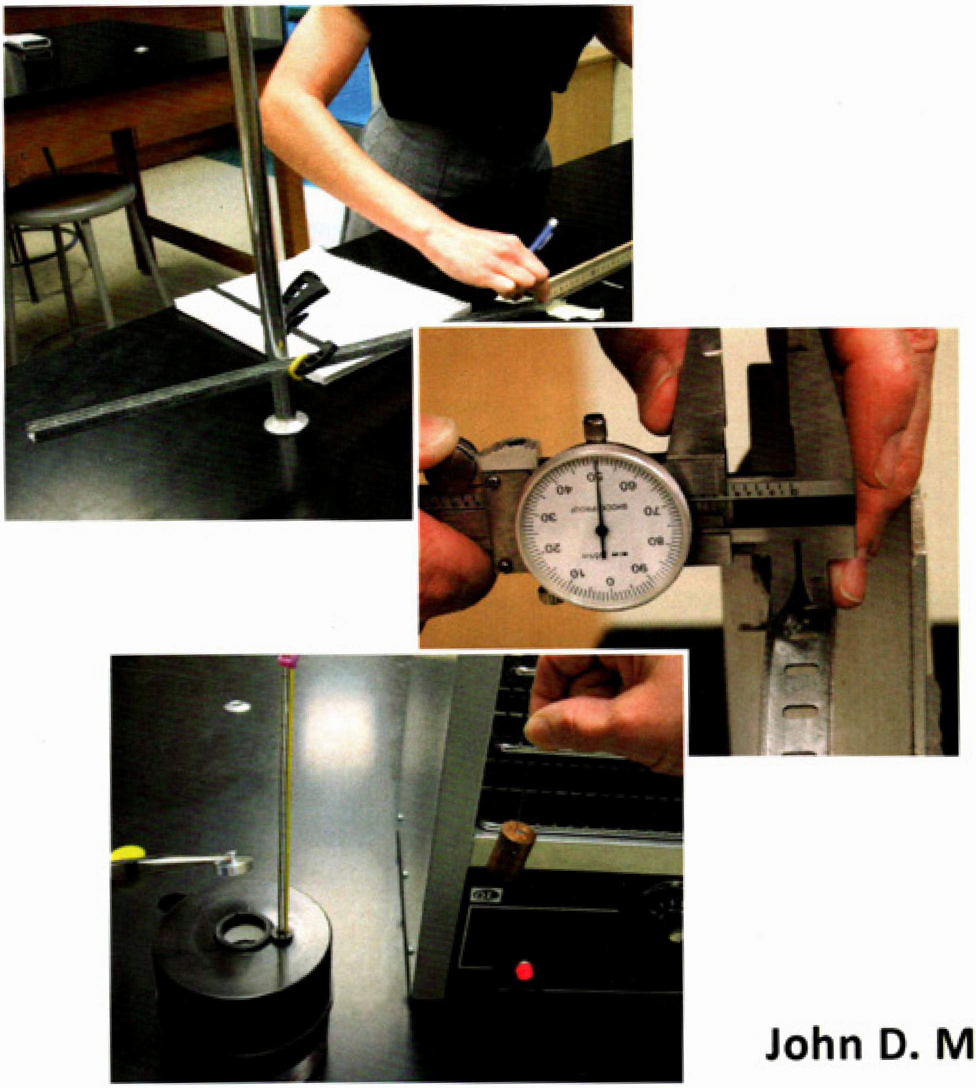
Experiments
for
Physics: Modeling Nature



John D. Mays

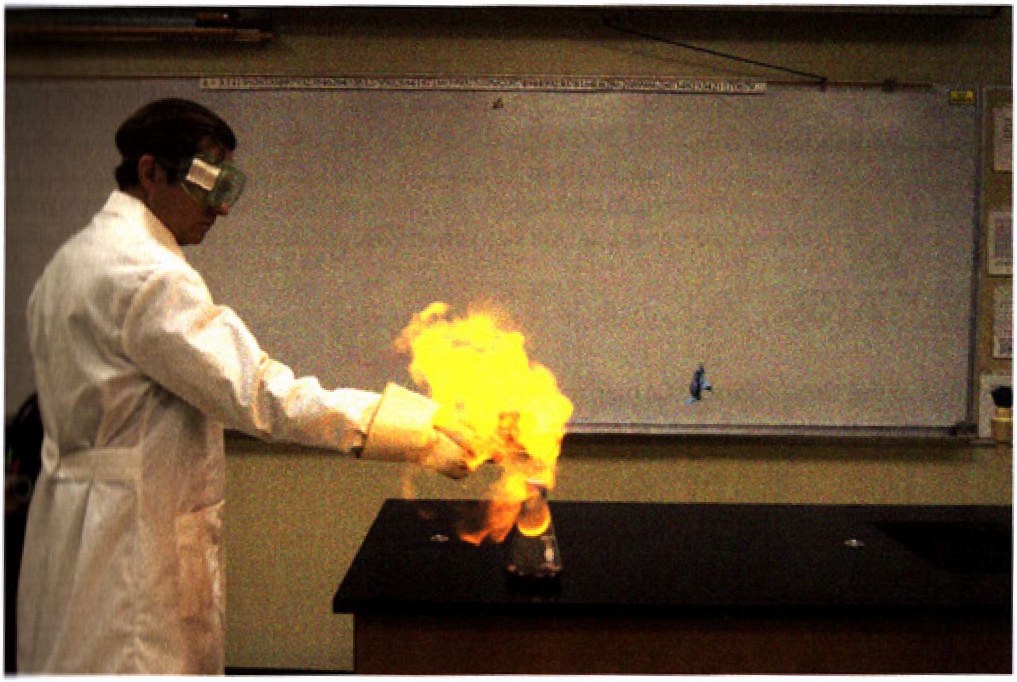
Experiments for *PHYSICS: MODELING NATURE*

Important Notes

The contents of this book are adapted from our book *Favorite Experiments for Physics* and Physical Science. There are some uncorrected page number references, and some references in this book to pages or sections in *Favorite Experiments* that are not included in the present volume.

There are frequent references to Flinn Scientific as an equipment supplier. While Flinn Scientific is a fine supplier for schools, they do not serve home schoolers. For alternate materials sources, see the Materials List beginning on pg. 71.

Experiments for *PHYSICS: MODELING NATURE*



John D. Mays

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Teaching Science so that Students Learn Science
A Paradigm for Christian Schools

The Student Lab Report Handbook
A Guide to Content, Style and Formatting for Effective Science Lab Reports

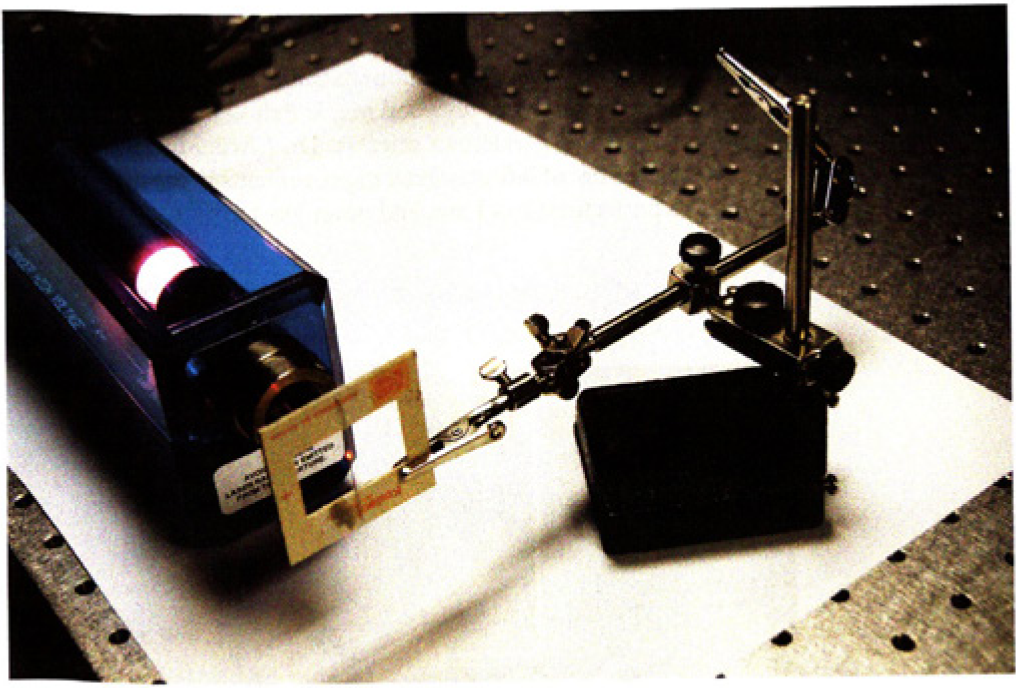
Appreciations and Acknowledgements

As with my previous books, this book would not have been possible without the support, encouragement and collegial collaboration of the faculty at Regents School of Austin. Thanks especially to Chris Corley and Cathy Waldo, who continue faithfully to teach there.

Thanks to Caleb Kyle, who as a 15-year-old student introduced me to blowing up coffee creamer and taught me every single detail of performing that demonstration. Thanks to my old supervising teacher from the 1980s, Sam Saenz, who taught me the art of hunting monkeys.

Thanks to all my family for their continuous encouragement. Special thanks to Jeffrey and Rebekah for their direct support of and contributions to this project. And thanks to my brother-in-law Ray Arneson, who gave me the plywood Magic Belt hook.

Finally, thanks to good friend and gentleman scientist Dr. Chris Mack. To produce good science books one must never tire of infinitessimal improvements in the details. In this regard, Chris is just as much a perfectionist as I am, and never lets me off the hook.



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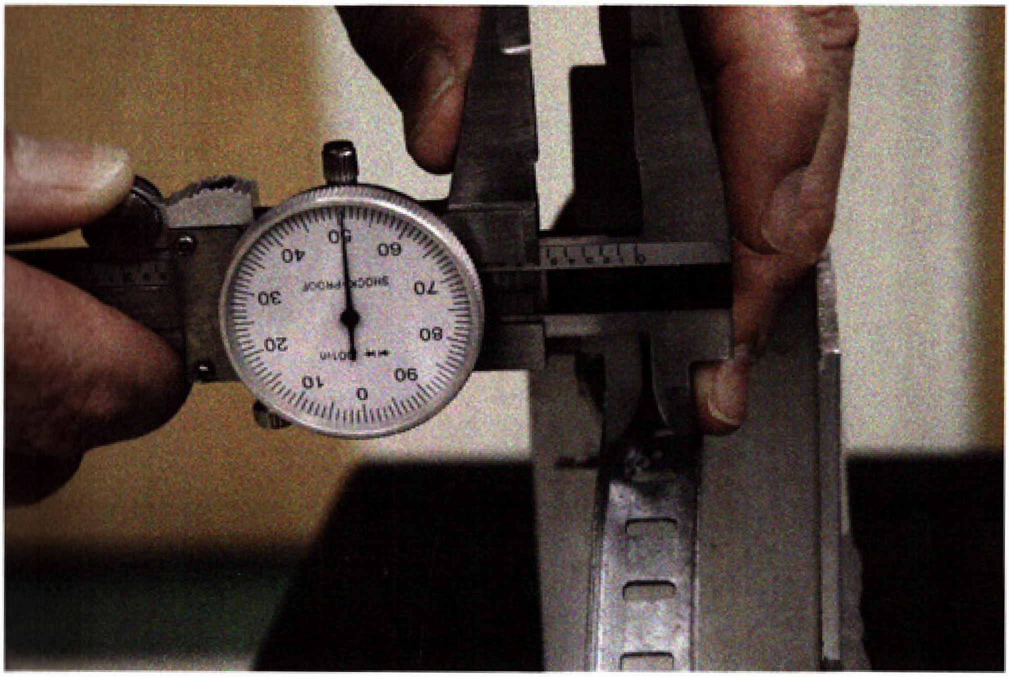

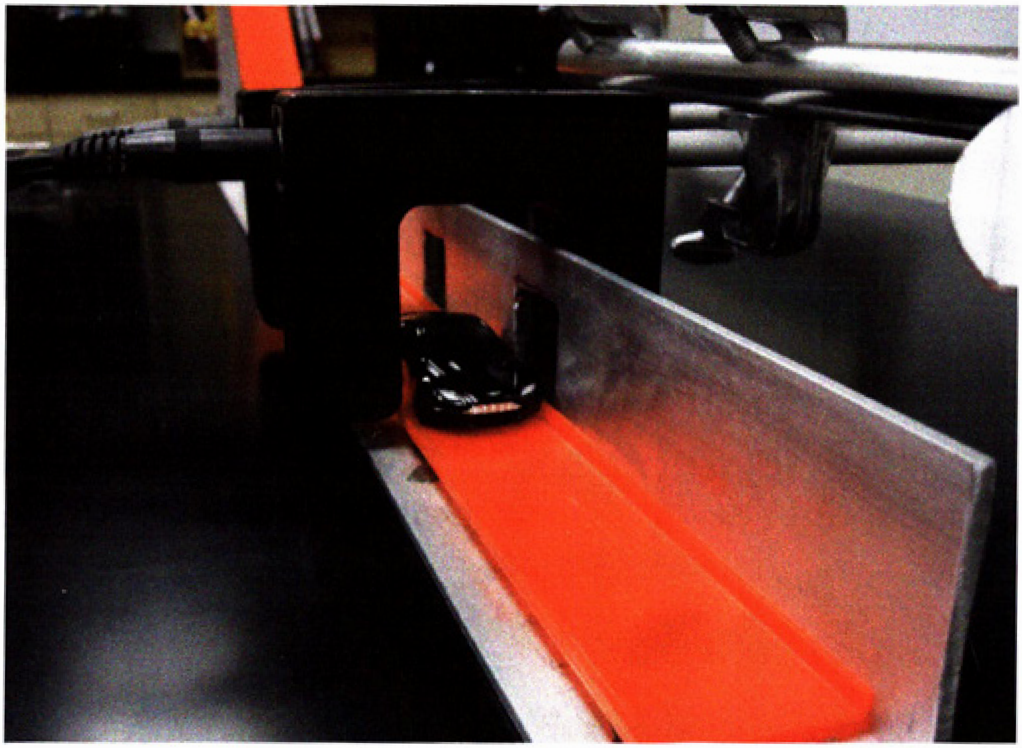

Introduction

Why I Wrote This Book

Back in the 1980s when I began teaching ninth grade Physical Science and Senior Physics, I was at a public high school that had not invested much in apparatus for physics labs. So as I began planning my lessons for that year I did what anyone else would do. I got the "Lab Manuals" for our texts, studied them to learn what equipment was required for all the experiments, wrote up a big purchase order and bought all of it. You probably know what kind of equipment I am talking about—little carts; mass sets; ticker-tape timers; ramps and little wooden boxes for fooling with friction; spring scales; a balance beam for demonstrating torque; DC circuit kits; etc., etc.

I studied the teacher's guides, wrote up lesson plans, and enthusiastically led the students in their lab activities like I was Delacroix's *Liberty Leading the People*. My doubts about the whole process began when I tried to explain how to use the space between the dots on the timer tape to determine the speed of the cart at different times. What a cumbersome way to measure velocities, I thought. In a decade when everything was going digital and many students already had computers at home, the technology seemed crude and the unwieldy strips of paper were a pain. Moreover, it was often the case (and still is) that the apparatus either didn't work or the accuracy was low. The torque balance beam demo with a meter stick is so finicky it is frustrating to the teacher and unconvincing to the students. The wheels tend to come off of the little carts. The DC circuit kits look like they belong in an elementary school classroom.

The mathematical connection between the spacing of the dots and what we were studying was there, of course, but even after careful review with the students many of them were clearly thinking, "We do what? With what? Okay, whatever you say." Not a good way to build interest in what I felt should be everyone's favorite subject.

An effective classroom is not a place where students mindlessly go through the motions of tasks they do not understand in order to perform an "experiment" that does not interest them.

So I began using my imagination to dream up better ways to engage students in lab activities that would provide them with a more meaningful encounter with the basic principles of physics. My motivation was to develop experiments and demonstrations that would be academically solid, inexpensive and interesting.

The activities in this book are the results of those years trying things out and improving my home-made apparatus to increase the reliability and accuracy of the results. These experiments and teacher demonstrations are the ones I presently do in my own classes, the little carts and friction boxes now gathering dust in a closet.

Most of these experiments can be performed very inexpensively. In my descriptions I indicate how to do the experiment with little investment, making the experiments accessible to schools and homes with limited funds. Over the years I have enhanced some of these experiments with digital electronics for data collection. This makes the experiment more interesting to the students, who are surrounded with digital electronics and tend to find anything else uninteresting. The electronics also increase accuracy significantly, improving results and making the analysis more satisfying. But my experience has shown that the simple act of doing an experiment outside with a pickup truck is so exciting for the students that they will love it whether you collect force data with fancy digital equipment or with lowly bathroom scales purchased from a discount store, as I did for many years. If budgetary constraints are an issue for you, start doing the experiments without the fancy digital equipment. You can modify the experiment and add the electronics over time as funds become available.

I know there are a lot of books out there with ideas for science experiments. But the emphasis in this book is on experiments that are captivating, are low cost (at least initially), provide solid opportunities to do physics (and a little chemistry), and use equipment that is either already familiar or worth knowing about. I hope some of these experiments will enhance your own classes.

How Many Labs to Do

As a public school teacher in Texas in the 1980s I was required to make 40% of my class time laboratory-based. Even as a young man just beginning a teaching career I knew this was an insane standard. For starters, once students are in high school their science studies need to be academically rigorous. If a student finishes a course in physics, he or she ought to know the basic principles of physics and be able to solve problems. But three days per week to study the theory is not adequate time for students to master the basic calculations of high school physics.

Reinforcing this problem is the fact that typical "lab manuals" include 25 or 30 different experiments, implying that teachers need to spend a day or two every week running labs and that students need to be filling out report sheets every week. Such an environment, requiring students to race through lab activities and crank out weekly fill-in-the-blank reports will almost certainly be superficial, feeding what I call the *Cram-Pass-Forget cycle*. Students cram for tests, pass them, and then forget most of what the teacher wanted them to learn. I am opposed to superficiality in principle and deeply concerned about this deplorable trend in science education in particular. Students should learn fewer topics but learn them deeply through extended class discussion, in-depth problem assignments, and report writing that is engaging. The result will be deeper comprehension and retention of fundamentals. This in turn will allow students more easily to grasp and master more advanced topics in future studies.

These considerations suggest we should be looking at more like five to six full experiments with lab reports each year for high school science classes.

The Importance of Real Lab Reports

Writing lab reports is a crucial element of the science laboratory experience. To equip your students with the information they need to prepare high quality reports, I commend to you my resource for students, *The Student Lab Report Handbook*.[1] This volume contains all the information students need to use lab journals and prepare excellent lab reports, and can be considered a companion volume to this book. In the preface to *The Student Lab Report Handbook* I make the case for requiring students to produce their own typed lab reports

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[1] *The Student Lab Report Handbook*, by John D. Mays (2009). Available from Novare Science and Math at novarescienceandmath.com.

from scratch, rather than using pre-printed forms in a lab manual. Writing such a report is a significant undertaking and requires a lot more time than students can afford to give every week. Thus, it is important to select lab activities very carefully so that they support the goal of deep engagement. Experiments have to hit on key topics, they have to be spaced out so there is adequate time for report writing, and they have to have enough complexity to support deeper analysis. In physics this deeper analysis usually involves predicting results from theory, and comparing experimental results to predictions with properly designed graphs.

In the Student Instructions for most of the experiments in this book there are remarks addressing specific issues pertaining to the lab report for the experiment. These comments are based on the assumption that students are asked to prepare reports in accordance with the requirements presented in *The Student Lab Report Handbook*.

Do We Need This Much Detail?

After reading some of my experiment descriptions, you may be tempted to accuse me of being pedantic to a fault. So much detail! How can anyone remember all of these little details?! This guy is nuts! Well, this is what the real world of science is like—excruciating, fastidious, mind-numbing attention to detail, and to the elimination of every conceivable source of error. In every lab activity you perform, impress upon your students the paramount importance of attending to detail and employing painstaking care. In so doing you are teaching them part of the ethos of good experimental science.

Teacher Background

In this book the theoretical background for the experiments is quite abbreviated. Teachers who are new to teaching physics or who would like to read the theory behind the experiments in full detail should refer to a good text on the subject.

Accuracy, Precision, Significant Digits, Units of Measure, etc.

I assume many of my readers already know the difference between accuracy and precision, and how to deal with units of measure. However, it is also the case that teachers without a strong background in physics are sometimes recruited to teach it. Most of the experiments in this book involve predicting a physical quantity, measuring the quantity in the experiment, and comparing the predicted value to the experimental value. This process always involves measurements and computations, and these in turn always involve units of measure and everything else that goes with making measurements.

For those readers who may not be familiar with the details of these issues, who would appreciate some advice on what to cover in class, or who would like a short tutorial on the units involved in the experiments in this book, I have included an Appendix that contains a primer on measurement.

Learning Objectives for a Secondary Science Laboratory Program

There are many learning objectives to consider when organizing a lab program for middle and high school students. Most of these objectives are realized over a period of several years, as students go through several different science courses and engage in a number of experiments in each course.

The general objectives I have identified and seek to address in the experiments in this book are listed in the table below. The goal is that after having completed the secondary course of study at a school, students will be competent in each of the objectives listed. The objectives listed in the table are addressed by nearly every experiment in this book.

General Learning Objectives for a Secondary Science Laboratory Program	
After completing the program of laboratory exercises in the secondary program, students will be able to demonstrate competence in each of the following tasks:	
1	State and follow standard laboratory safety practices.
2	Correctly identify and use standard laboratory apparatus.
3	Use proper care in setting up apparatus and handling materials to maintain a safe environment, protect equipment and maximize accuracy in results.
4	Describe and follow the proper methods for making measurements with common instruments. This includes identifying the types of errors that can introduce inaccuracies in measurements and describing how to avoid them.
5	State the role of precision in taking measurements, and relate this to the significant digits in a measurement.
6	Apply the scientific method to conducting experiments and to writing reports.
7	Apply appropriate logic to conducting experiments and to writing reports.
8	Maintain a proper lab journal.
9	Clearly explain the theoretical background behind an experiment using quantitative analysis where appropriate.
10	Use quantitative predictions from scientific theory to form testable hypotheses.
11	Clearly and efficiently describe a scientific procedure and the results and discoveries that followed.
12	Use appropriate care in experimental procedures and data collection.
13	Present calculations and data in a clear, organized fashion such that others can verify calculations or check results. This includes development of tables and graphs using standard scientific units and formatting.
14	Apply quantitative analysis to experimental data as appropriate.
15	Apply qualitative analysis to experimental results as appropriate.
16	Estimate uncertainty in measurements.
17	Apply cogent reasoning to analysis and discussion of experimental results. This includes reasonable identification of the factors that contributed to the difference between predicted and measured results (aka, "experimental error").
18	Use computer tools to take data, graph data, manipulate data and develop reports.
19	Use clear, concise, and accurate language in a technical style in scientific reports.
20	Explore the uses and limitations of unfamiliar scientific equipment.
21	Cooperate with team members successfully to accomplish each of the above objectives.

In addition to these general objectives, each experiment has one or more unique features that suggest specific objectives that apply to that experiment. These specific objectives are listed at the beginning of each experiment.

Student Instructions for Experiments

Student instructions are included at the end of each of the 11 experiments. These instructions may be reproduced and distributed to students. Alternatively, PDF files of the student instructions are available as free downloads from our website, novarescienceandmath.com. These may be downloaded, reproduced and distributed to students. Simply go to the Free Resources tab on the website and enter the pass code "**novarefavexp.**"

A Note About Experimental Error

One of the conventional calculations in high school science labs is the so-called "experimental error." This experimental error is typically defined as the difference between the predicted value and the experimental value, expressed as a percentage of the predicted value, or

$$\text{experimental error} = \frac{|\text{predicted value} - \text{experimental value}|}{\text{predicted value}} \times 100\%$$

From the perspective of the average high school student, this use of "experimental error" makes perfect sense. After all, student are studying well-established theories and the goal of the experiment is to learn about the theory, not to validate or refute it. In the world of science, however, experiments are the golden standard by which theories are judged. When there is a mismatch between theory and experiment, it is often the theory that is found wanting. That is how science advances.

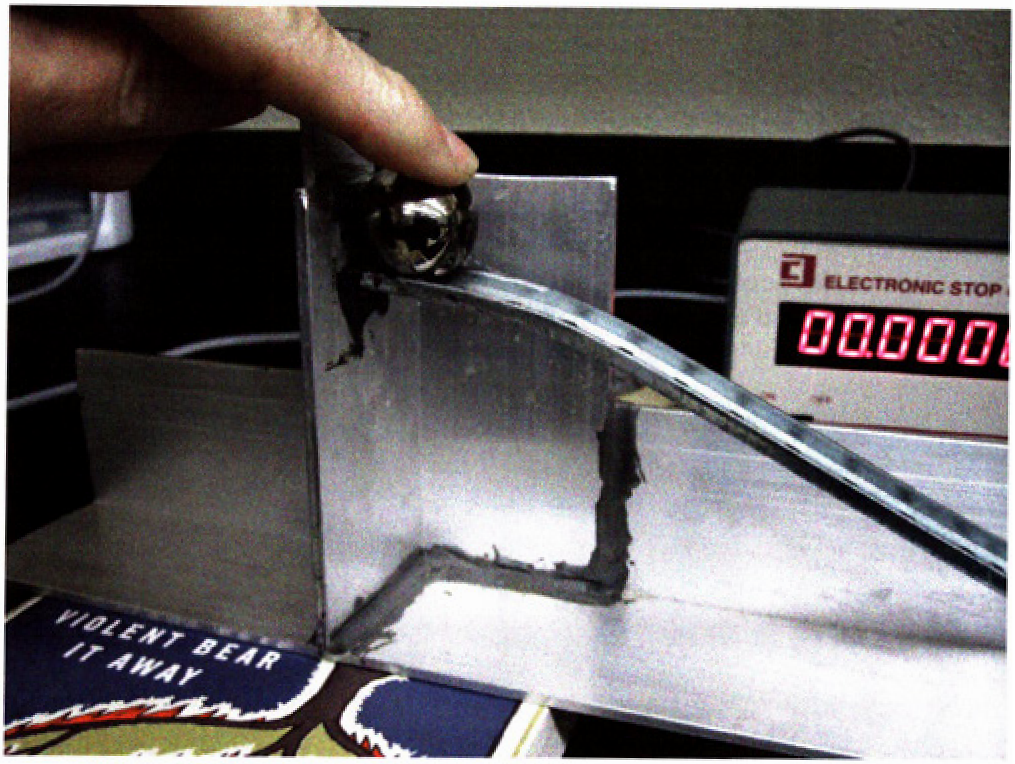
In my early books, such as *The Student Lab Report Handbook*, I used this same terminology ("experimental error") to express the difference between prediction and result. Over the years, however, research and discussions with practicing scientists have led me to the conclusion that this terminology is misguided. Used in this way the term *error* implies that the theory is *correct* and that the error in the experiment may be summarized by this difference equation. However, the difference between prediction and experimental result may not be caused by deficiencies in the experiment. In more general scientific practice the theory may *not* be correct. Thus, in secondary classrooms it is better to reserve the term *error* for discussions about lack of accuracy in specific measurements, when the measurement is known to contain or is suspected of containing error (that is, differing from the true value, see Appendix). Referring to the overall difference between prediction and experimental result as "experimental error" is a bad habit to get into.

Consider this case: an experimental measurement of velocity produces a value that is consistently less than the predicted value. Most likely this is because the predictions did not take air resistance into account. Is this an experimental error? It is more correct to say that the theory is inaccurate because we made the unrealistic assumption that there would be no air resistance. Such causes of differences between predictions and measurements are quite common, and it is great if the future scientists in your class can understand that this is not an error in the experiment.

As a result of these considerations, beginning with this book I am adopting a different convention. Henceforth I will use the phrase "prediction-result difference ratio" to describe the value computed by the above equation. When quantitative results can be compared to quantitative predictions, students should compute the difference ratio as

$$\text{prediction-result difference ratio } = \frac{|\text{predicted value } - \text{ experimental value}|}{\text{predicted value}} \times 100\%$$

In the Discussion section of their lab reports, students should state the value(s) of the prediction-result difference ratio for their experiment. After doing so, much of their subsequent analysis of the experimental result will consist in attempting to identify the reasons for this difference. Students may use the possibility of *errors* in different measurements, along with other factors such as lurking variables or insufficiently elegant experimental methods, in their attempts to account for the prediction-result difference. Being able to explain the prediction-result difference for an experiment is one of the most important jobs of the scientist—and the science student.


ELECTRONIC STOP
00.000
VIOLENT BEAR
IT AWAY

Experiments

The five experiments in this section were developed for upper-level high school physics students (typically seniors, but sometimes juniors). If you teach senior physics you may have turned straight to this section. I encourage you to read the Introduction for the background on why I developed these experiments and what I was trying to accomplish by departing from the standard sorts of experiments high school students usually perform.

I also encourage you to read through the six experiments in Part 1 of this book, which I use with ninth grade students. When I teach senior physics I assume these six experiments were all performed by the students in their freshman year, thus providing background experience and context for our experiments in senior physics. For example, Experiment 2 (Newton's Second Law) is an excellent investigation which I have done with older students. Over the years I decided that it was accessible for younger students, so I moved it to the ninth grade in our curriculum. But if your students have not performed it in a prior science class I recommend you include it in the program of experiments you do with your senior class. The same thing goes for Experiments 3 (Conservation of Energy) and 4 (DC Circuits). These experiments treat standard topics in physics all students should experience.

As I wrote in the Introduction, the ability to write a solid lab report from scratch is one of the important tools students use to engage in science studies. While writing the material for the experiments in this section my operating assumption is that students engaging in these experiments will be writing full reports, and I have written the student instructions with this in mind.

Finally, please see the Introduction (page 6-7) or the Appendix (page 249) for information about my use of the phrase, "prediction-result difference ratio."


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

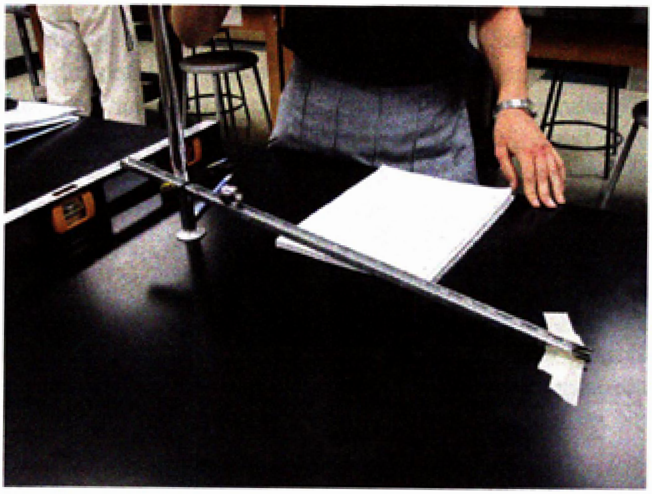
1. The ramps are made of the metal railing used inside of bookcases to support the shelves. This material is very inexpensive and makes a perfect track for a 1-inch steel ball. As mentioned above, angle the ends of the rails for a smoother transition for the ball as it moves from the rail to the table 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.

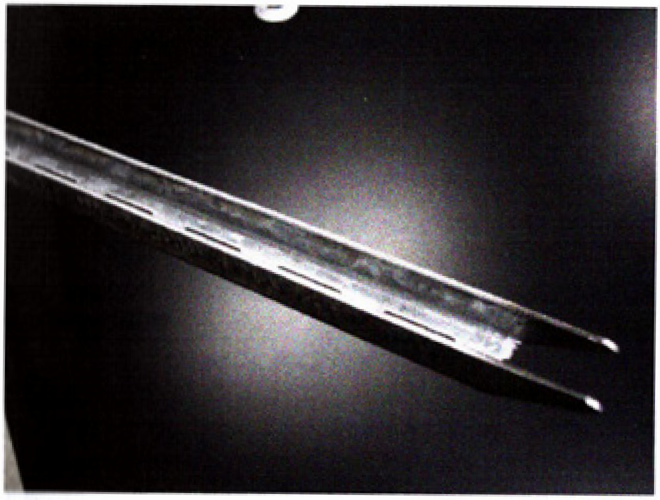
3. The small angular deflection in the path of the rolling ball necessitated by the extra socket holes in my lab tables is one of the reasons why I have allowed students to base the prediction-result difference ratio only on the distance in the intended direction of travel (call it *x*) from the landing 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.

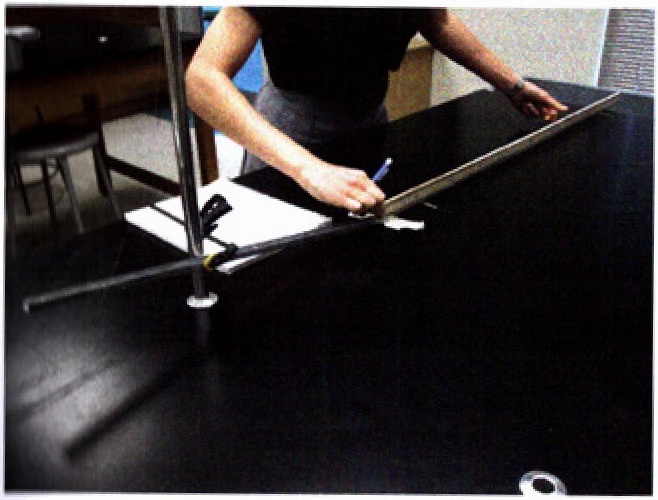


The basic setup, with the steel ball on its way for a time trial.

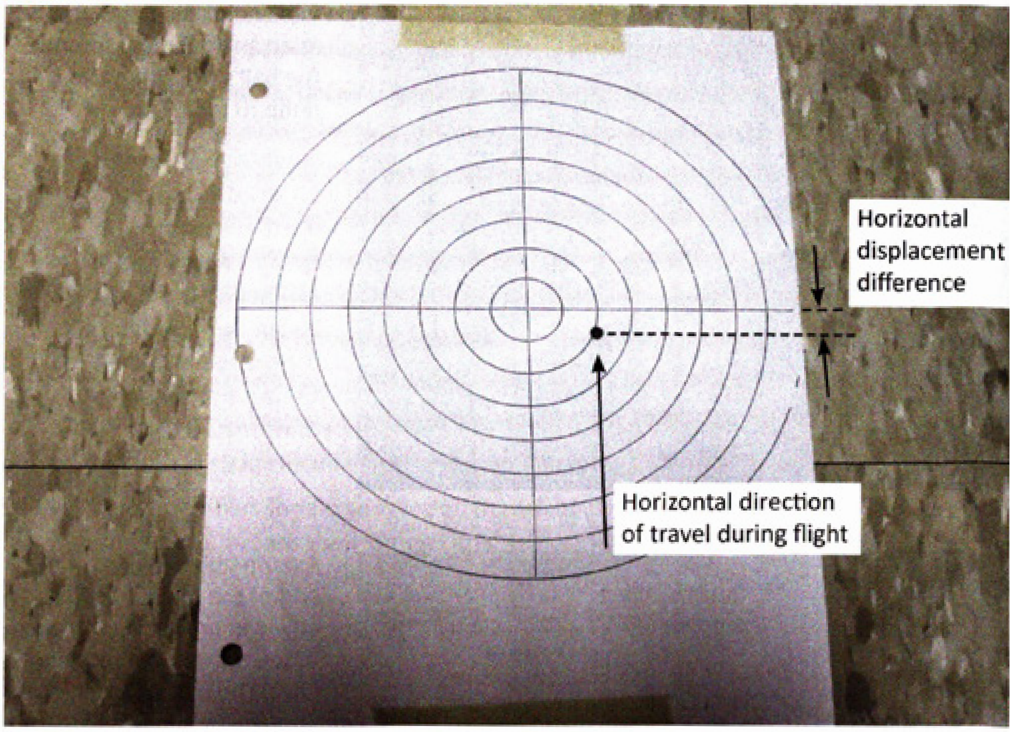


The end of the rail is ground at an angle to help smooth the ball's transition from ramp to table top.

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

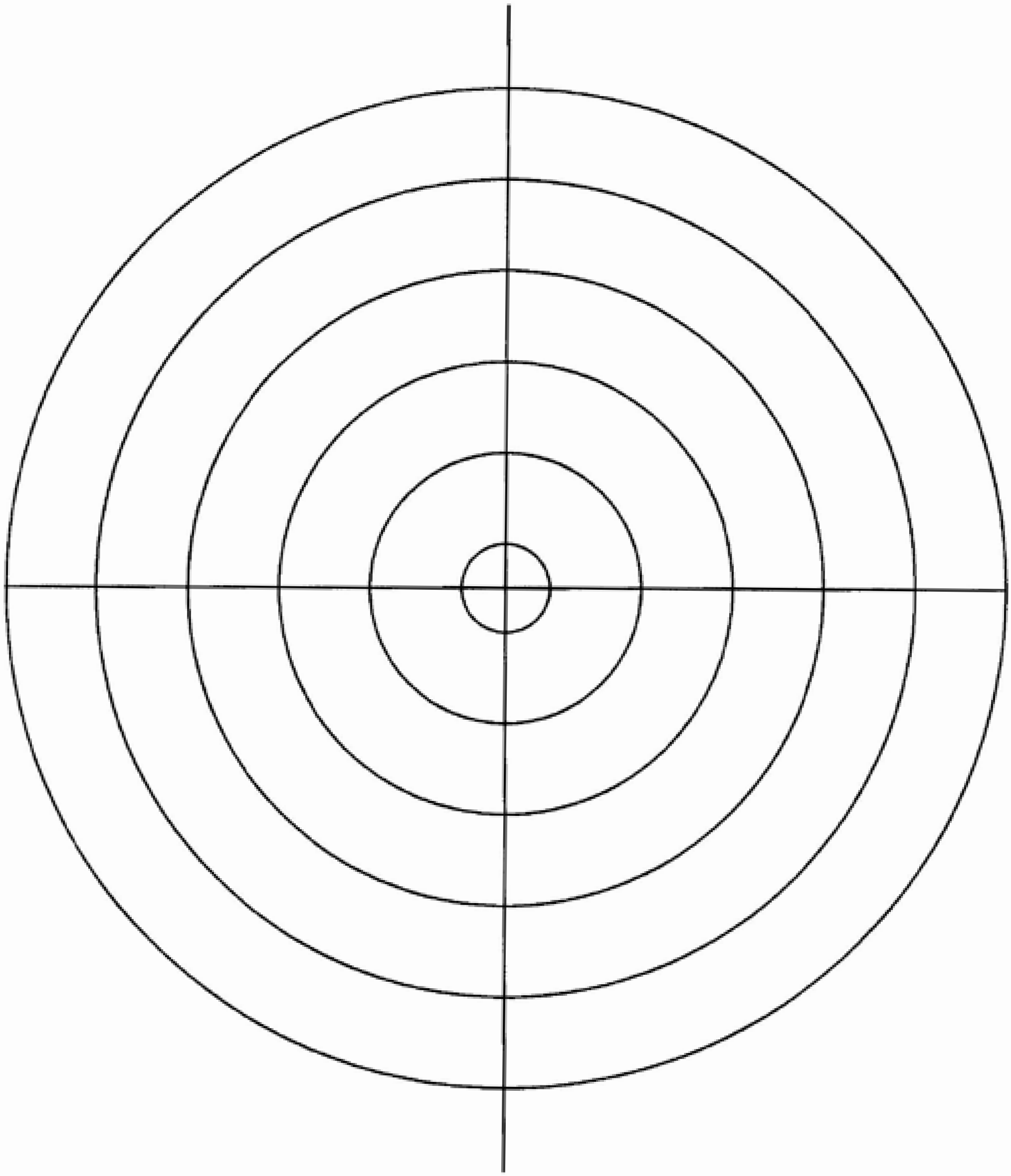
1. Using the stand, ramp and clamp, set up a ramp on your table. Roll your steel ball down the ramp several times to get an idea of what its velocity will be as it leaves the table. A small ramp angle will allow the ball to move slowly enough so that timing its motion on the table top may be done with 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.

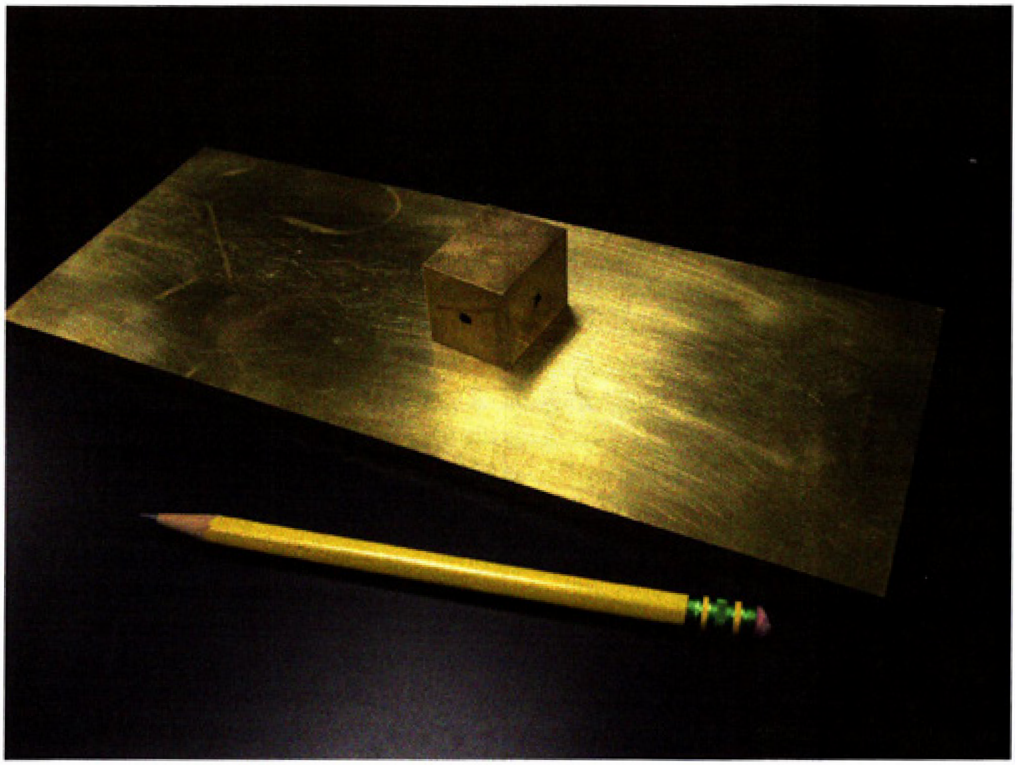
6. Use a plumb bob to project the edge of the table down to the floor. Make a small mark with a pencil on the floor locating the edge of the table. From this mark, measure the predicted horizontal displacement for the ball's flight. Mark the spot on the floor where the ball will land. Tape your target 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

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