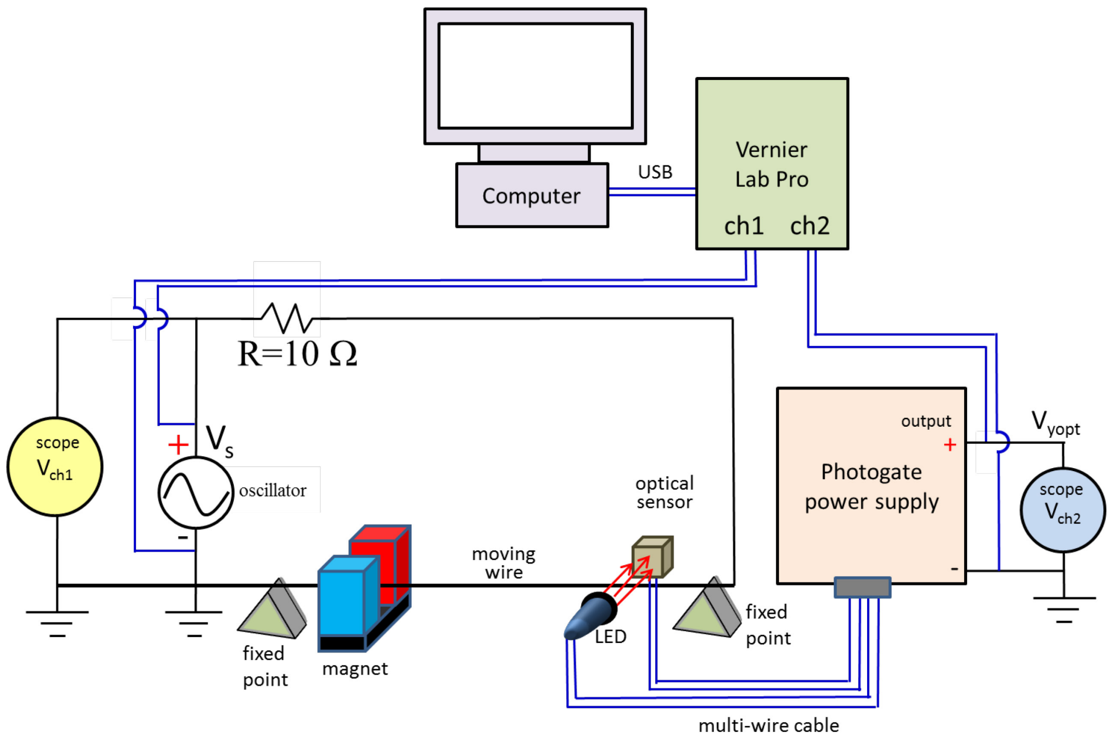
Laboratory Manual
for
Experimental Physics I: Mechanics



Ninth Edition - Revised June 2021

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Introduction to the Lab

Official Course Description

Methods and rationale of experimental physics. Intended for physics majors and science and engineering students who desire a more rigorous approach. Experiments chosen from the areas of mechanics (from PHYS171), gas laws, and heats. Theory and applications of error analysis.

Course Web Site: **http://www.physics.umd.edu/courses/Phys275**

What do you need to bring to the Lab?

1. Bring a printed paper copy or PDF of the lab write-up for the week's experiment, or you can access the manual by logging in to your Expert TA account using the lab computers.
2. Bring a flash-memory stick to save your spreadsheet report and data.
3. Bring a lab notebook. Most of your results will be recorded in a spreadsheet, but a notebook is handy for making sketches, jotting down ideas, and doing algebra, geometry, calculus, and propagation of errors.
4. Bring a pencil or pen.

Policies for Working in the Lab

1. DO NOT BRING FOOD or DRINKS into the lab.
2. Proper attire is required for working in the labs. Tie back long hair.
3. Do not leave backpacks or other personal items on the floor where people can trip over them. Slide them under the bench, out of the way.
4. Do NOT use a calculator in the lab. Instead, use EXCEL for calculations. The spreadsheet is better than a calculator and you can use it to save all of your work in one place, including data, plots and photographs.
5. Turn off your cell phone. You should not be on your phone, talking, texting, browsing, answering e-mail, watching videos or otherwise distracting yourself and others.
6. Use the lab computer and NOT your own laptop in the lab. The lab computer is often needed for taking data and accessing custom software used in the labs. Also it is difficult for your instructor or TA to view a small dim laptop screen. Instead use the computer at your lab station, which has all necessary software and a wide-screen high-resolution monitor.
7. The lab computers are only to be used for working on the labs.
8. Follow all safety warnings given by your instructor or in the lab write-ups.
9. Let your instructor and TA know immediately of broken or damaged equipment, or if you find something unsafe in the lab.
10. When you are done, turn off all of the equipment except for the computers. Be especially careful to turn off equipment that uses batteries.
11. Do not turn off the computers - just close all documents and leave the computer on - the computers will automatically shut down when the day is over.
12. If your computer locks-up, check with your instructor. No password is required to restart the computer. If the computer demands a password, shut it down and restart.
13. You must leave the lab at the end of your scheduled lab period.

How To Get a Good Grade in the Lab?

1. If you want a good grade, prepare before going to the lab. Read through the lab write-up and think about it before you go to the lab. Do not skip the introduction because this gives an overview of what the experiment is about. If you skip this section, you will not understand what you are doing or why you are doing it. While you can walk in cold and get through the simple experiments, the most challenging experiments require preparation to complete.

2. **Do the Pre-lab assignments and Homework and turn them in on time.** They help to prepare you for the lab and count significantly towards your grade.

3. **Don't miss classes.** You will need to complete all of the labs to pass the course. The experiments are typically only set up for a week, so if you do miss a lab, check with your instructor that week to see if there are any open seats in other sections. If there are no other open stations available during the week, you will need to arrange with your instructor to make up the lab during the make-up week.

4. **Don't be late for class.** Class starts right at 2 PM. During the first ten minutes, your instructor will discuss the experiment, give helpful suggestions, and tell you about any changes in procedure. If you are too late, your instructor may require you to make up the lab at some other time.

5. **Do NOT use a calculator in the lab** because it is too easy to make mistakes, too hard to correct errors, and impossible for your instructor to check what you did. Instead, you should **always use EXCEL** on the lab computer to save data, do calculations and make plots.

6. When you make a plot in EXCEL, always use an **xy-scatter chart** because it is the only type of Excel chart that actually plots points at their Cartesian coordinates.
   - On all your charts, always **label the axes**, include proper units and include a title.
   - Check that you have included **units** for quantities you record in your spreadsheet and always use standard SI units (meters, kilograms, seconds, ...).
   - Use the correct number of **significant figures** when recording measurements and reporting results. Learn how to use EXCEL to set the number of digits displayed.
   - Don't forget to include your name, the date, your data, analysis, plots and brief answers to the Final Questions.

7. Save your work on the computer at least once every 15 minutes. The only place that you can save documents is to the "My Documents" folder.

8. If there is something that is puzzling you about an experiment or a concept, ask your instructor or the TA. They are there to answer your questions and try to explain things to you. If there are not things that puzzle you about an experiment, then you are probably not thinking enough about what you are doing and what is going on.

9. Stay focused. Don't waste time and don't skip questions or steps in the procedure.

10. Always include uncertainties in your measured quantities.

11. **Learn how to propagate errors and how to correctly fit to data**.

12. **Before you walk out of the lab, you must submit a copy of your spreadsheet to ELMS Canvas.** Do this even if you haven't finished everything. That way your instructor has a record that you did the lab and there is a saved copy of your work that you can access later.

Key Concepts in Physics 275

Experiment	Key Experimental Concepts	Key Physics Concepts
1. Introduction to Excel and Uncertainty	Average, standard deviation, the 1/3 rule for estimating the intrinsic precision of an instrument, Using Excel for calculation and plotting.	Every measurement of a physical quantity has an uncertainty
2. Propagation of errors + χ^2	Error propagation, using χ^2 to test a theory, interpreting χ^2	Physics is science - experiments determine if a theory is correct
3. Dice and Distributions	Probability, statistical uncertainty, frequency distribution (histogram), using χ^2 to test a theory, interpreting χ^2	probability distributions, binomial distribution
4. Statistics of Random Decay	Probability, statistical uncertainty in counting experiments, using χ^2 to test a theory, uncertainty in the average	Radioactive decay, Poisson distribution and $\sqrt{n}$ statistics
5. Position, Velocity and Acceleration	Estimating precision in a measurement, using χ^2 to test a theory, determining whether disagreement is random or systematic, interpreting χ^2	Motion of an object with constant acceleration
6&7. Review and Exam	You need to learn and retain key concepts in experimental physics!	
8. Free Fall	Estimating precision in a measurement, error propagation, reducing systematic errors by using a better technique and theory, using χ^2 to obtain a best fit value	Motion of an object with constant acceleration
9. Mass and Spring Oscillator	Using χ^2 for non-linear fit to extract parameters, decay time τ, analyzing relatively large data sets, error propagation	Simple harmonic motion, $\omega_o = \sqrt{k/m}$, decay time τ, the resonance frequency is independent of amplitude
10. Forced Harmonic Motion	Resonance, resonance frequency, phase and amplitude, quality factor Q, automatic data collection and using macros in Excel	Simple harmonic motion, resonance, $\omega_o = \sqrt{k/m}$, decay time τ, and Q
11. Standing Waves on a String	Experiment on a complex physical system, Weighted average, error propagation, non-linear fit	Behavior of waves on a string, $v=\lambda_n f_n$, $\lambda_n=2L/n$
12. Designing an Experiment to Measure g to 0.01%	Using error analysis to design an experiment to high precision and accuracy, correcting for systematic errors by calibration, cross-checking with a second measurement	Motion of a pendulum
13. Anharmonic Oscillator	Qualitative difference between harmonic and anharmonic motion, analyzing relatively large data sets, error propagation	anharmonic oscillator, the resonance frequency depends on amplitude
14&15. Review and Exam	You need to learn and retain key concepts in experimental physics!	

Philosophy of the Course

The main purpose of a traditional physics laboratory class is to demonstrate physical effects that have been described in a lecture course. In contrast, the main goal of this lab is to provide an introduction to experimental physics. This goes far beyond just demonstrating physical effects. You will begin to learn how experimentalists do research, how to design experiments to study the way the world works, and how to test whether a given theory is an adequate description of observed phenomena.

In laying out the course, we have chosen experiments for the first half that introduce and emphasize basic topics, including uncertainty, error propagation and understanding χ^2 fitting, as well as how to use Excel for analyzing and plotting data. The experiments in the second half of the course are meant to be noticeably more challenging. In particular, these experiments not only explore physical systems that can display quite complex behavior, but the setups can be rather complex for an introductory physics lab, the techniques can require more care or sophistication, and the results can be remarkably precise or accurate. Students can learn a lot from any of the experiments, but the experiments in the second half are really intended to raise the bar.

There are a few key experimental concepts that this course will emphasize:

(1) ***Reality:*** In the lab, you will acquire real data on real physical systems and then analyze the data to extract meaningful physical quantities. To get the data, you must manipulate the apparatus yourself. In most student physics labs, if you do this well, then you should expect to get "good" results that agree with theory. However, for many students, the most difficult concept to grasp is that not every experiment agrees with theory. You should not expect to always get the "right answer". In these labs, you may occasionally find results that do not conform to your expectations. We could, for example, load your dice in Experiment 2 and see whether you notice. In the real world, in a real experiment, you will never know with certainty what "the right answer" is. Nature sometimes does the unexpected and when something "goes wrong" it can be an indication of a new phenomenon or that you have overlooked some essential physics.

(2) ***Error Analysis:*** We want you to understand the limitations of your measurements*: i.e.* how to estimate the experimental uncertainties and understand how they affect your final results. In Physics 174, you learned how to fit theoretical formulas to your data. Here you will review these concepts and start to master the propagation of errors. You will also see some examples of systematic errors and the way in which they can be minimized by calibrating your equipment.

(3) ***Distributions:*** All measurements you make have errors. Knowing how the errors are distributed in size can be useful for understanding the limitations of your measurement. It is also a good way to diagnose problems, reveal some types of systematic errors, and check that your estimated errors are reasonable.

(4) ***Creativity and Experimental Design:*** Most lab experiments that students do are "cookbook". If you can follow a set of instructions, you can get the lab to work and get reasonable data. On the other hand, many real experiments don't come with a nicely written set of instructions. Instead you have to figure out how to do the measurement, figure out a good measurement procedure, apply for a grant, and then design, build and assemble the apparatus. For some experiments, this requires a truly extraordinary combination of creativity, analysis and hard work. For the experiments in Physics 275, we don't expect you to build everything up from scratch, and for the most part the labs will have clearly written instructions. While some of the labs have a part that requires judgement and creativity to complete, all of the labs require that you understand what you are doing and why - it will be painfully obvious to your instructor and other students when you are lost or not paying attention to what you are doing.

(5) ***Above and Beyond*** - There are many places in these labs where you can explore higher-level topics or observe phenomena that are ordinarily not covered in an introductory lab. This is particularly true of the experiments in the second half of the course. Some examples can be found in the "Hotshot problems" in the Homework assignments. The Hotshot problems are optional and only intended for students who like thinking about more challenging questions.

(6) ***Reporting Results:*** You need to learn how to report your results in a complete, clear and concise manner. Each experiment includes questions that require you to write one or two paragraphs in clear English using complete sentences. For example, we may ask you to describe a plot, explain how you are going to make a measurement or how you are going to decide whether your results agree with a theory. Your explanation should never exceed one page. These questions are meant to prepare you for the task of writing a complete lab report, which will be required in later lab courses. Along with your data and analysis, the questions need to be answered in the Excel spreadsheet that you turn in for the lab.

(7) ***Test for Key Skills:*** Two exams will be given in which you must demonstrate that you have mastered key skills and understand each experiment. Before each exam, you will have a review lab in which you can go back over the apparatus and refresh your understanding of the main concepts. Since everyone needs to master these experimental concepts, the experiments are typically designed to be completed by an individual student, with the exception of a few places where you may require a partner's assistance for making a measurement or where you analyze data from the class or compare your results to others in the class.

Course Textbooks

The required textbook for the course is a current electronic copy of this lab manual and ***"A Practical Guide to Data Analysis for Physics Science Students"***, by Louis Lyons (Cambridge University Press). Lyons' book provides a good brief introduction to error analysis. We also highly recommend ***"An Introduction to Error Analysis"*** by John R. Taylor (2nd edition, University Science Books). Taylor's book is longer and has more detail than Lyons' book, so you may want to look at it if you are having difficulty with a topic.

Appendix A in this manual also provides a summary of the main concepts of error analysis, propagation of errors and χ^2.

You may find yourself wondering: what's the point of error analysis? In many experiments, the idea is to determine whether a given result is correct or if a particular law of physics is actually obeyed. This is not so easy to do. Measurement of a physical quantity, such as position, can only be made to within a certain precision or uncertainty. Because of this, it turns out that one cannot prove with mathematical rigor that a physical law is true by doing experiments. The best you can do is show that your measurements agree, or do not agree, with theory to within the uncertainty. Thus, it is essential to understand measurement uncertainty before you can decide whether your results agree with theory. The subject can be quite complicated and we have found that some students can have difficulty "getting it". In Physics 275, we will assume that you have mastered the basics; here you will see how things work out in real experiments. Let your instructor know when something isn't clear or doesn't make sense.

About the Equipment

Although most of the equipment used in the Phys 275 lab is fairly simple and durable, treat all equipment with care. Not only will the students who follow you be grateful, but you'll also get better data. If something is broken, immediately inform your instructor or one of the lab technicians. Hundreds of students have used the equipment and it won't be the first time something broke. If you have a problem, let your instructor or TA know immediately.

Safety First!

Always be aware of any potential dangers when using a piece of equipment. Where we know of possible hazards, clear and prominent warnings are given in the laboratory manual.

Going Paperless and Using the Graphics Pad

One of the biggest changes in the last few years is that the lab manual is now only available as a PDF distributed via Expert TA. Of course you can always print out a paper copy. There are some significant advantages to the electronic form: you can get updated or corrected versions, we can include high resolution color photographs, you can access the manual anywhere you have access to the web, and we can add links to other web-based content. There are also some potential disadvantages. Going completely paperless in the lab is a big deal. Of course students have been using EXCEL and electronic data collection in the labs for many years, but some things have always seemed easier to do with paper and pencil. Making a sketch of an apparatus or propagating errors are much more easily done with a pencil than a keyboard, for example.

To let you work electronically with pen-based inputs, starting in Fall 2015 we have added simple graphics pen pads to the labs (see Figure 1). Using the electronic pen and pad, you can write, sketch, or make notes directly in EXCEL or your electronic copy of the lab manual. The look and feel of the electronic pad and pen is similar to a regular pen, except that the writing appears on the screen, rather than the pad surface (don't use a regular pen or pencil on the graphics pad). You can also copy, erase, stretch, shrink, highlight or change the color of anything you draw with the pen.

If you have used a graphics pad before, you should have no problem with the simple system used in the lab. If you have not used a pen-based system, you will need to practice some. After a while you should find you are naturally switching between the pen, the mouse and the keyboard, depending on the type of input.

To get started, using the graphics pad, open EXCEL, click on the **Review** tab and then go the right side of the menu and click on **Start Inking** (see Figure 2). Note that the Start Inking tab will only appear if you have a graphics pad plugged in or are using a tablet. The **Ink Tools** menu will then come up (see Figure 3). You can then click on one of the pens or highlighter buttons, pick up the electronic pen and start drawing on the pad. Notice also there is an eraser and some buttons for changing the pen color and width.

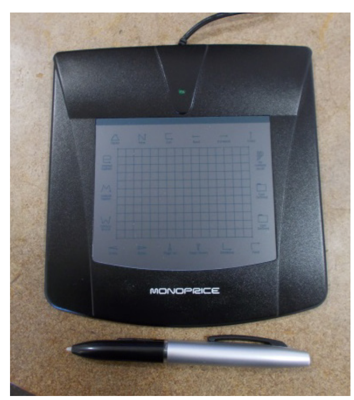

Figure 1. Graphics pad and electronic pen.

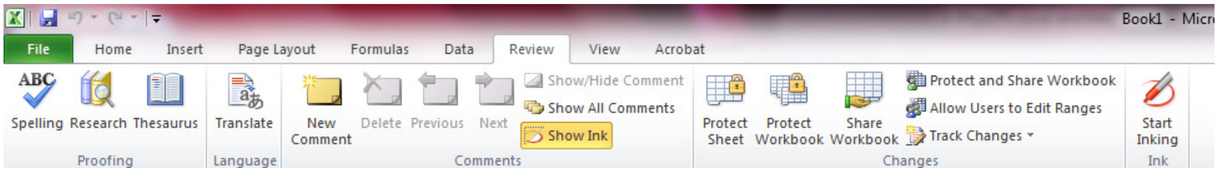

Figure 2. **Review** menu - notice the **Start Inking** button on the right.

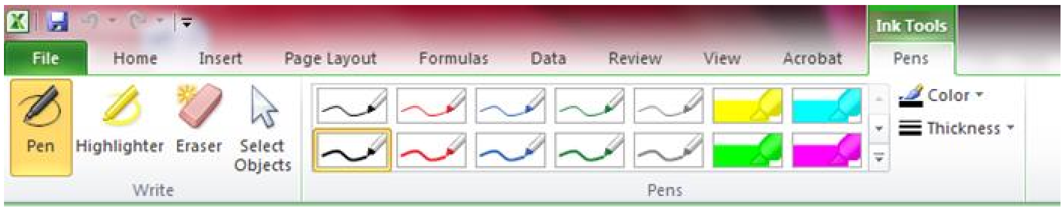

Figure 3. The **Ink Tools** menu shows buttons for choosing pens, highlighters, *etc.*

You can also use the graphics pad to write in a PDF, such as this lab manual. To do this open up the PDF, go to the right hand side of the menu bar, and click on **Comments**. Click on the button showing a small red pen and you can now use the pad and electronic pen to draw on your PDF. There are also buttons for an eraser and for drawing a few simple geometrical objects such as circles, rectangles and straight lines. To change the color of the pen, right click on something you have drawn, select **properties** and then click on the little red square next to the word color. A palette will then be displayed that you can select colors from. You can also change the thickness and the opacity of the line. After you are done, you can click on your drawing again and choose **make current properties default** and the pen will be set to this color. As in EXCEL, you can cut, copy, paste, delete, stretch and shrink anything you have drawn in a PDF.

Software

Some of the experiments use custom Excel templates to help students collect, organize and analyze their data. The use of templates represents a judgement call on how much time students should be spending on collecting data, organizing their work and analyzing their results. The templates allow many tasks can be fully or partially automated, which makes them particularly useful when we ask students to collect multiple large data sets and when the analysis is complex or repetitive. The templates can also provide a common layout for data and analysis, which facilitates in-class discussions and grading. In addition, some experiments use customized LoggerPro templates to run automated data collection routines. In most cases these are simple data collection routines, but in other cases, such as Experiment 11- Waves, the LoggerPro panel provides additional plots and fitting information. Table 1 summarizes the labs that currently use Excel or LoggerPro templates, including Excel template for Experiments 4 and 8, which are new to this version and Experiment 11 - Waves, which uses one Excel template to record data and two other general-purpose Excel templates for fitting.

Experiment #	Templates
1 - Excel	Excel
2 - χ^2	Excel
4 - Radiation	Excel+LoggerPro
5 - XVA	LoggerPro

Experiment #	Templates
8 - Free-fall	Excel+LoggerPro
10 - Forced Harmonic Motion	Excel+LoggerPro
11 - Waves	Excel+LoggerPro
12 - Pendulum	LoggerPro

Comments on this Edition

This is the ninth edition of the lab manual for Phys 275. This version is based on the eighth edition and was prepared in spring/summer 2021 at what we hope is the end of the Covid-19 pandemic. While the last year brought many changes to our operations, including capacity restrictions and occasionally the need to resort to on-line activities, we have prepared this version in the hope and expectation that things will return to normal and students and instructors will again be allowed into the labs without extraordinary restrictions.

Although the numbering of this "new Phys 275" edition sequence started in 1999, the course began long before that. Despite the many times that Phys 275 has been revised over the last two decades, and the difficulties of the last year, this version of the lab manual brings some significant improvements. We have also taken the opportunity to fix small errors found in the previous version. I thank Wendell Hill in particular for spotting problems, for making suggestions and for his insight into teaching the labs over the last year. The largest changes were in Experiments 4, 8, 11 and 12. Although the magnitude of the changes only become apparent by comparing the old and new versions, nevertheless we expect that students and instructors will appreciate being able to get better results with less "mucking about".

Part of the intended design of Phys 275 was that the experiments in the first half of the course would emphasize elementary topics. This is essential because our students enter the course with a wide range of backgrounds, including some who have never previously taken a physics lab. In contrast, experiments in the second half of the course are designed to be noticeably more challenging, complex, and engaging. The changes to Experiments 8, 11 and 12, in particular, have not only made these challenging experiments more fun, but should allow students to obtain much better results and better appreciate the phenomena.

In **Experiment 4 - Statistics of Radom Decay**, we have introduced new Cs-137 gamma ray sources to replace a mixture of older and newer Co-60 gamma ray sources. Most of the Co-60 sources were old and getting to be quite weak (about 5 to 10 times background) while two newer Co-60 sources were much stronger (about 100 times background). This led to different students getting quite different looking distributions of counts and most students only seeing distributions that had an average of 2 counts or less. The new Cs-137 sources produce about 20 counts per second in the apparatus, which is quite close to that of the newer Co-60 sources. With a consistently higher count rate, we changed the data taking procedure so that students can now see how the Poisson distribution changes shape as the average number of counts goes from much more than 1 to much less than 1. As Wendell Hill suggested, the new procedure also explores the similarity between the normal distribution and Poisson distribution when the average number of counts is large compared to 1. This let us reinforce some key concepts with the normal distribution, such as the relation between the FWHM and standard deviation. The new procedure involves more data collection and analysis than the previous version and we now provide a spreadsheet template to help keep the data and analysis organized.

In **Experiment 8 - Free Fall**, we have modified the apparatus so that each set-up now uses 3 photogates instead of the 2 used in the old apparatus. The new photogates were custom designed in the Physics Department by Allen Monroe and Bruce Rowley, fabricated by commercial 3D printing, trimmed and squared-up by Bruce, wired up by Jack Touart, and mounted into the setups by Greg Wolters. Compared with the old gates, the new gate design allows much simpler and much more accurate measurements to be made of the gate location. In addition, by using three gates on each apparatus, students should now be able to measure values for the acceleration due to gravity that are accurate to better than 0.1% with a single ball drop. A test on the prototype 3-gate apparatus yielded average g values from four drops that were within 0.01% of the known value. This is far superior to the old 2-gate setup, which typically could get g accurate to within about 1% by fitting to data from 5 ball drops. The greatly improved accuracy is only partly due to the improved ability to accurately locate the gate positions. Another important factor, is a new procedure that uses the data from 3 gates to eliminate systematic errors caused by variations in the time at which the ball starts to fall and variations in the speed at which the ball is arriving at the first gate. The speed variations at the first gate were a bit of a surprise, not least because the old 2-gate procedure relied on the ball arriving with the same speed at the first gate, which was not moved. With the first gate at the same location, the speed variations appear to be caused by changes in the force exerted on the ball as it leaves the magnetic mount, which changes the initial acceleration depending on the balls magnetization. The procedure has been modified to focus on the importance of having a good measurement technique and testing assumptions, with the students exploring why the 3 gate technique works so much better than similar one or two gate techniques. Given the amount of data that students acquire (4 drops) and the number of techniques (3) that they use to analyze the results, we also put together a spreadsheet template to help keep things organized and do some of the heavy lifting in the analysis. This includes a new graphical tool and technique for accurately determining the timing of the pulses (another important factor in obtaining highly accurate values for g) and automatic calculations of the uncertainty in g for the 2 and 3 gate analysis.

In **Experiment 11 - Standing Waves**, we have introduced a new optical gate setup that allows fine adjustments of the photogate position. These photogate were recycled from the old photogates that were used in the previous 2-gate version of Experiment 8, which we replaced with new 3-D printed photogates. Greg Wolters machined bolt holes into the old gates and attached them to fine-control z-stages. This should improve the stability of the setup and greatly simplify the alignment of the photogate with the wire, which must be done quite precisely. Better alignment will improve the fidelity of the optical gate response to changes in the wires position. Testing on the prototype suggests that the photogates can resolve wire motion down to a minimum amplitude of about 1 μm at the gate, with some averaging on the scope, and up to a maximum amplitude of about 0.8 mm. One of the goals of this experiment was that it would be the most sophisticated and complex of the experiments in Physics 275. Although there were no changes in the procedure, this hardware change resulted in a most satisfying upgrade to the look, the feel, and the actual performance of the apparatus.

In **Experiment 12 - Designing an Experiment to Measure g to 0.1%**, we designed a new holder that greatly simplifies the accurate measurement of the pendulum length by an individual student. In the old apparatus, the accurate measurement of the pendulum length was by far the most challenging task. The measurement is cross-checked by a second student and it could take upwards of an hour to get agreement within the required accuracy between two different measurements of the length of the same apparatus. The old apparatus had two pointers on a 2-m wooden ruler. The most accurate procedure involved very precisely placing one of the pointers at a known location on the ruler, then having the instructor hold the ruler so that this pointer was just under the support bar holding the pendulum string, while the student then tried to adjust the location of the second pointer so that it just scraped the bottom of the pendulum bob. This was slow and clumsy and of course students often tried using simpler techniques, which generally gave poor results. To simplify the procedure, the apparatus has been modified to include a top-plate that allows the 2-m wooden ruler to be hung from a stop-block that is at a precisely chosen mark on the ruler. An individual student can then adjust the pointer at the other end of the ruler, setting it to just scrape the bottom of the pendulum bob. The next step is to accurately determine the distance between the stop block and the pointer. Since the rulers can stretch and warp on the 0.1% scale, they do not have enough intrinsic accuracy. In the previous set-up, this required a time consuming and difficult to check calibration of the wooden ruler against the 1-m lab standard ruler. To simplify this part of the experiment, Allen Monroe found new 2m long metal rulers with NIST traceable calibrations that greatly simplify the accurate measurement of the pendulum length. The new procedure should allow students to quickly make a (nearly) fool-proof and accurate measurement of the length that can easily be checked. In test measurements on the prototype that Greg and Allen assembled, we were able to easily measure the length and get g to an accuracy of better than 0.1%. We hope that the ease, speed and accuracy of the new setup will enhance student satisfaction with this particular experiment.

Finally, I would like to thank Allen Monroe, Bruce Rowley, Greg Wolters, Jack Touart, and Wendell Hill for their many thoughtful suggestions, insights, patience and hard work over the last year, without which these upgrades would not have been possible.

Comments on the Previous Editions

The eighth edition included two new experiments (Experiments 1 and 2) and many other changes from the previous edition. These developments were mainly driven by changes in the Physics program at Maryland. The removal of our introductory lab course Phys 174, which was a pre-requisite for Phys 275, means that new students will be entering Phys 275 with much less preparation than has been the case for more than 20 years. In the past, students had a strong enough background from Phys 174 that they could walk in cold and still be able to work through a Phys 275 lab. Unfortunately this is no longer the case and forced us to add basic introductory labs on Excel, uncertainty, error propagation and χ^2. It also drove the creation of pre-lab assignments for each experiment. In this edition, we also took the opportunity to modify some of our most interesting labs. For example, in Experiments 10 and 11 we have changed the procedure, added new measurements and now include use of an oscilloscope. This has not only made the experiments better, but provides students with the chance to get some experience with an oscilloscope, which they will need in later lab courses. Special thanks to Allen Monroe and Greg Wolter for helping out with the lab upgrades, testing some of the modified setups, and getting everything together in time for the fall. I also thank Chris Lobb and Min Ouyang for taking a look at the new setups and making helpful suggestions. Finally, I thank Jordan Goodman for his skill and effort in making videos on key topics on Excel and errors for this lab (see links in Experiment 1).

Special thanks to Don Schmadel and Min Ouyang for identifying numerous issues in the seventh edition. The sixth edition corrected a few errors and included a new version of Experiment VIII on waves. Special thanks go to Min Ouyang for keeping track of problems in the previous edition and Tommy Baldwin for sorting through numerous hardware issues associated with creating a new version of Experiment 8. Without them, this version would not have been possible.

The fifth edition was updated from the fourth edition in June 2015 with input and corrections from Ki-Yong Kim, Min Ouyang, Steve Cowen and others who have taught the course recently. The main changes were to:

(i) Fix typos and minor errors (in the pendulum experiment for example),

(ii) Clean up some of the formatting and the procedures,

(iii) Update to EXCEL 2010,

(iv) Update the instructions to include the use of a graphics pad so the lab can be done on either a paper or PDF version of the manual,
(v) Update to allow electronically graded Homework exercises via Expert TA.
(vi) Renumber the experiments to include the reviews, exams, and a new experiment.
(vii) Add a new experiment: *Experiment 10 - Forced Harmonic Motion.* This experiment was adapted from Physics 261 and uses a fairly sophisticated EXCEL template to extract amplitude and phase information from the LoggerPro data. This gives it a somewhat different look and feel from the other experiments. It was intended to replace *Experiment 9 - Mass and Spring Oscillator*, which are both about simple harmonic motion. Your instructor may choose to do Experiment 9 instead of 10, or do both 9 and 10 and drop *Experiment 11 - Anharmonic Oscillator*.

The fourth edition of the new Physics 275 lab manual was updated from the previous edition in June 2010 by Chris Lobb and Fred Wellstood. The main change was in Experiment 3, where we have revised the radioactive decay experiment and introduced digital Geiger counters that allow the data to be taken much more quickly. The third edition was updated in May 2008 by Profs. Richard Greene, Lobb, and Wellstood. The most significant changes were in Experiment 5, in which g is found by dropping a ball. The new version corrects an error pointed out to us by Prof. Jean-Paul Richard - we need to use the leading of the ball (new version) and not the center of the ball (old version) when we do the timing. We also took the opportunity to simplify some of the position measurements as well as fix typos and make other minor changes in the rest of the manual. The previous version (fifth version, second edition) was updated in May 2007 by Greene and Wellstood. The fourth version was updated in summer 2004 by Greene and Wellstood. The main changes were to correct typos and update sections where the apparatus has changed. Sometime between the first and the third version, Prof. Derek Boyd created the LinFit and LnLnFit macros for Excel, and these have been a welcome additions to the course ever since. In fact, it was these macros were used by Dr. Steve Cowen in 2014 to spawn a large and diverse collection of fairly sophisticated macros that now appear in the Phys 261/271 labs and the new Experiment 10 on Forced Harmonic Motion. The original version of this manual was put together in Fall 1999 by Profs. Boyd and Wellstood. Whenever possible, we borrowed shamelessly from the Physics 262a/263a lab sequence and the previous version of the Physics 275 lab manual that was largely constructed by Prof. Emeritus Jean-Paul Richard.

We especially thank Sarah Mitchell and Chris Van Breen for their help in selecting and trying experiments during the summer of 1999. We also thank Bill Parsons who did a very thorough job of proofreading the first version while he was a Physics 275 student. We most gratefully acknowledge the invaluable work of Tom Baldwin and Allen Monroe in getting all the equipment together, keeping it running, and being willing to try endless variations on how to do things. Finally, we would like to thank Bill Norwood for finding and obtaining a few more pointers for the 2-meter sticks. Tom thinks these pointers were probably last made and sold in about 1947, which says a lot about how ancient and tough some of the equipment is, and even more about the dedication and resourcefulness of the lab staff at Maryland. Finally, we thank Tom for hunting down graphics pads and finding a model that work well with our computers.

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