RICE UNIVERSITY

PHYSICS 101
Laboratory Manual

Fall 2008

Contents

Physics 101

I. Schedule of Experiments - Fall 2008

WEEK OF		EXPERIMENT
Aug.	25	None; First week of classes
Sep.	1	None; Labor Day
Sep.	8	1. Kinematics in 1-D
Sep.	15	2. Projectile Motion
Sep.	22	3. Forces
Sep.	29	None
Oct.	6	4. Uniform Circular Motion
Oct.	13	None; Fall break
Oct.	20	5. Energy Conversions
Oct.	27	None
Nov.	3	6. Collisions in Two Dimensions
Nov.	10	None
Nov.	17	7. Angular Dynamics
Nov.	24	None; Thanksgiving break
Dec.	1	8. Simple Harmonic Motion; Last week of classes
Dec.	8	Make-up period Dec. 8 - 9 only (special sign-up)

II. General Information

"The truth is, the science of Nature has been too long made only a work of the brain and the fancy. It is now high time that it should return to the plainness and soundness of observations on material and obvious things."

R. Hooke

LABORATORY OBJECTIVES

The laboratory work associated with Physics 101 has two principal goals: To give you hands-on experience with the phenomena and models you will study in class; To develop basic experimental and analytic skills that will be used throughout your career in the sciences or engineering.

The laboratory exercises that you will do here are not "experiments", in the sense of forays into the unknown designed and executed by an intrepid young scientist (you). Rather, they were chosen to illustrate physical phenomena, ingenious techniques or useful methods. They were not intended to be extremely precise, and your results will be far from exact. You will be evaluated on your understanding of the material and your approach to problems, not merely the precision of your results, and you should allocate your effort accordingly.

As one of the earliest laboratory courses in your career at Rice, PHYS 101 will emphasize very basic skills. You should develop the ability to carry out common laboratory procedures correctly and safely; To make measurements and report your results in physically meaningful form, including estimates of uncertainties where appropriate; To recognize when equipment or procedures are not working, and undertake logical corrective action. You will also have the opportunity to communicate your results in the form of short reports on each experiment. To see how these goals fit into the overall laboratory program at Rice, you can consult the overview of laboratory objectives at http://www.owlnet.rice.edu/~labgroup/.

LABORATORY ORGANIZATION

Your laboratory group will meet for three hours each week that an experiment is scheduled. Each session will begin with a ten minute quiz, discussed below. You and your partner should use the remainder of the time to collect and analyze the data for the experiment, and to each prepare a brief report of your results.

Attendance at the laboratory session is mandatory. If you must miss your regular meeting for any reason there are two options:

a) You may attend another session during the week, with permission from the instructor in charge of the "host" section. Permission will not be granted if the section is full.
b) You may attend the make-up sessions after the last week of labs. Note, though, that you will not be allowed to make up more than one experiment this way. A sign-up sheet will be provided during the last week of labs for you to schedule your attendance.

DATA TAKING

It will be difficult to complete a lab if you have not read over the experiment before class. As you read, try to "think through" the experiment in order to decide what quantities you will vary, how the data should be plotted, and what you think the results should be. You may also want to lay out the data tables you think you will need, and make note of useful formulae. Remember to bring a calculator to class.

Once the apparatus is set up, you can start taking data. You and your partner will often need to work together to get the data and record it efficiently. In any case, you should both try all phases of the experiment, rather than becoming specialists. If at all possible, make a plot of the data as you go along. Your graph will very quickly tell you if the data are reasonable, if the parameters are being varied enough, and if the apparatus is working.

The apparatus you are using, although relatively simple, is remarkably expensive. Please be gentle so that neither you nor the apparatus is damaged. Particularly delicate or hazardous operations are noted in the lab manual as they occur. Please heed the warnings. If a piece of equipment does malfunction, please tell the instructor so it can be tagged for repair. We usually have a spare with which you can finish the lab.

REPORTS

The bulk of your lab grade will be based on a written report, produced during the lab session. The report should include:

a) One or two sentences stating what you measured and why.
b) A description of the procedures that you used, *if* they are not adequately described in this manual. Otherwise, a statement to the effect that you followed the standard procedure will be sufficient.
c) Your data and analysis, including appropriate graphs. Be sure your data include units, and that graphs are clearly labeled. Particularly important items to include here will be noted at the end of each experiment description.
d) Answers to the questions asked in the experiment descriptions. These may be integrated into the body of your report at appropriate points.
e) Conclusions or comments which you choose to add.

The report should not be a big production. The objective is to write down the *significant* details of the experiment, the analysis and the conclusions. Two or three neatly written pages, including tables, will suffice for most of the experiments. The emphasis should be on the data and conclusions, not a polished exposition. An example of a properly prepared report can be found on the course web page.

The laboratory assistants have been instructed to collect all reports at the end of the lab session. The report will be returned to you, graded, at the next regular meeting.

QUIZZES

At the beginning of each lab meeting you will be given a ten minute quiz on the lab you are about to start. The questions will concern items which you should have noticed in reading over the experiment prior to the lab meeting. You may use the lab manual in answering the questions, but if you have thoughtfully read the experiment in advance you will not need the manual.

GRADES

The lab grade is based on quiz scores, performance during lab sessions and quality of the lab reports. The resulting score will be reported to the lecturer as your grade for the laboratory portion of PHYS 101.

Grading is a necessary evil but you should be aware that most students do reasonable work and get good scores. A good grade is not, therefore, the most valuable thing you can get from this course.

III. Uncertainty and Significant Figures

"Errors using inadequate data are much less than those using no data at all."

C. Babbage

The results of any physical measurement process will be inaccurate to a greater or lesser degree. We will frequently want to know if two measured quantities are the same or different, or if a set of data is adequately described by some mathematical model. Because our measured numbers cannot be exact, this comparison is not as simple as asking if two or more numbers are equal. Rather, one must investigate the uncertainties in the measured quantities and then ask if the deviations are within the range of those uncertainties. If the deviations are smaller than the uncertainties we say that there is agreement, otherwise there is a significant difference. This section will introduce you to the rudiments of that comparison process for some simple situations. Later in your career you will learn more sophisticated statistical treatments for more difficult problems.

ESTIMATING UNCERTAINTIES

There are many possible sources of error and uncertainty in measurement, but they can be roughly classified into three groups. The most obvious is the mistake. Measuring the wrong quantity, writing down the wrong number or misreading a dial all lead to wrong answers. The cure is to be careful, and to check that all results are reasonable. Systematic errors form another group. Here the apparatus or operating procedure gives a result which always differs from the correct value in a predictable way. For example, a wood meter stick might have expanded due to high humidity, causing lengths to be read as shorter than they are. This type of error is usually discovered by comparing different measurement methods, or sometimes by a detailed study of the instruments and procedures. Even without mistakes or systematic errors, one finds that measurements are not exactly repeatable. This residual uncertainty is essentially random, so it is often called "random error" even though it is inherent in the measuring process and not a mistake of some sort. The rest of this section describes how to estimate and deal with this type of uncertainty.

The idea of repeating a measurement several times to check for variation is probably familiar. The arithmetic mean of the measured values is usually taken as the best estimate of the actual value, and the range or standard deviation is an estimate of uncertainty. For example, we might wish to know the weight of a rodent for a biological study. If we put the animal on a scale with a digital indicator, the readings will fluctuate as it wiggles. Reading the figures several times and averaging should then give us a better estimate of the weight than a single reading. We could also use the range of readings we get to estimate the uncertainty in our average value. In other situations we might have to repeat an entire measurement process to get several values to average, but the principle is the same.

The resolution of the measuring instrument may also limit the precision of a measurement. For example, if we use a digital scale to weigh an inanimate object the reading will probably be very steady, and we will probably get very nearly the same reading if we reweigh the object later. Even so, we cannot determine the weight more closely than the value of the lowest digit on the indicator, whether or not we average many readings. With an analog instrument, like a meter stick, it might be possible to interpolate between the smallest scale divisions, but that will not give infinite precision either. In these cases we can take the uncertainty to be the smallest increment that can be read from the scale.

SIGNIFICANT FIGURES

Having made a measurement and estimated the uncertainty, we also need to know how to record and report the result. The usual procedure is to write down the value ± the uncertainty, using only the appropriate number of digits for each. For example, in weighing the rodent we might find an average for 5 readings of 74.54 gm, with a variation of 1.3 gm. From these numbers we deduce that the "true" weight lies somewhere in the range 73.89 gm to 75.19 gm. Given this range, it is clearly overstates our precision to give the weight as 74.54 gm. Rather, one should use 74.5 gm ± 1.3 gm, or even 74 gm ± 1 gm when reporting the result. The exact number of digits to keep is not rigidly fixed, but the basic principle is to give only significant digits, those that represent a value larger than the uncertainty in the quantity. Writing down more digits just because they are on the calculator display is both misleading and a waste of effort.

PROPAGATION OF UNCERTAINTIES

In many instances we will want to calculate other quantities from measured numbers. As you might expect, the uncertainties in the measurements result in uncertainties in those calculated values. This is sometimes called "error analysis", and can be done rigorously, but a simple approximation is more useful here. Roughly speaking, if a quantity can be measured only to 10%, then any calculation involving that quantity can give results known only to about 10% also. That is, your calculated results are never going to be better than the data that went into them.

Two approximate rules will cover most of the computations that arise in this lab. For multiplication and division, the relative error in the result is the sum of the relative errors in the inputs. For addition or subtraction, the absolute error in the result is the sum of the absolute errors in the inputs. (This is why it is usually bad when your answer is the difference of two large numbers.) These rules can be summarized in a set of formulae:

$$z = xy \quad \text{or} \quad z = x / y \qquad \frac{\Delta z}{z} = \frac{\Delta x}{x} + \frac{\Delta y}{y} \qquad \text{(III-1)}$$

$$z = x \pm y \qquad \Delta z = \Delta x + \Delta y \qquad \text{(III-2)}$$

where Δx, Δy are the uncertainties in the inputs and Δz is the uncertainty in the calculated quantity.

An example of this whole process may be useful. Suppose we wish to measure the average speed of a ball rolling down an inclined plane by measuring the travel time between two marks on the plane. Using a meter stick, we measure the distance between the marks to be 10.0 ± 0.1 cm. The ± 0.1 cm means the true distance could be anywhere in the range 9.9 cm to 10.1 cm. Given the width of the marks and the smallest divisions on the ruler we can't do any better. Next, using a stopwatch, we measure the time interval. The watch reads to 0.01 s, but in several trials we get values varying by 0.18 s, so we estimate the time interval as 1.5 ± 0.1 s. Note that the error estimates were arrived at by studying the apparatus in one case, and by observing variations in results in the other. We calculate the average speed to be 10.0 cm/1.5s = 6.7 cm/s, using the best estimates of distance and time. Computing the percent uncertainties we find that the distance is known to about ± 1%, while the time is known only to ± 6%. The calculated result must then be uncertain by about ± 7%. We would then claim the speed is known to be 6.7 ± 0.5 cm/s.

You will have many opportunities to estimate errors in the course of your work this semester. You should not become tangled in details, but simply apply some common sense along the lines indicated to estimate the reliability of your results. Since all measurements are inaccurate to some degree, an ability to realistically estimate one's state of knowledge is essential to the scientific enterprise.

IV. Graphing

"One must learn by doing the thing; though you think you know it, you have no certainty until you try."

Sophocles

GENERAL PRINCIPLES

Graphs are frequently used to present and analyze data in science, engineering and business. Regardless of the purpose of a given graph, there exist several "rules" of plotting that lead to clear, useful graphs. Some of them are summarized here, and more detail can be found under the appropriate headings at http://www.owlnet.rice.edu/~labgroup/.

1. A graph should be labeled so that its meaning is clear. The quantity plotted along each axis should be indicated, along with the units in which the plotted data are expressed. An appropriate title should also be on the page.
2. Scales should be chosen for ease of use. This is best accomplished by choosing one division equal to a multiple of 1, 2, 5, or 10. The scales used on the two axes need not be the same, but should be chosen so that the data fill the page. It is not essential to have the point (0,0) on the graph.
3. Experimental points should be plotted with a small dot, cross, etc. A circle can then be drawn around the point to better show its position.
4. The data are fitted by drawing a smooth curve through the experimental points. Because the world is not perfect, the curve may not pass through all the points, but it should be close.

Figure IV-1 is a simple graph which illustrates these rules.

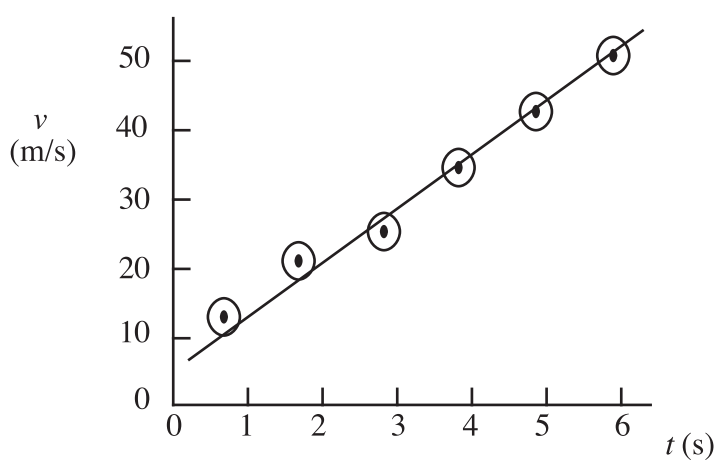

Fig. IV-1. Example of a properly drawn graph showing velocity vs time for an object in free fall. The solid line is the best fit to the data.

ANALYSIS WITH GRAPHS

For many purposes a graph is used only to provide a compact display of data. We will usually want to take an additional step, and use the graph to quantitatively analyze the data. In the example, the data seem to lie on a straight line. If we had a theory which predicted a linear relation, we could conclude that these data are consistent with the theory. Even without a theory, we could conclude that $v = v_o + at$, and that $v = v_o + bt^2$ is probably not correct.

The equation of a straight line can be written as $v = v_o + at$ when v is plotted vertically and t horizontally. The constant a is the slope of the line, and v_o is the value of v when $t = 0$ (the "intercept"). The values of slope and intercept are easily found from the plot by drawing in the straight line that seems to pass closest to the data points, and then finding the parameters of that line. Alternatively, the graphing software on the lab computers will do the same thing if you invoke the linear curve fit. With either method, you are using all the available information to deduce the slope and intercept, which is far preferable to using two arbitrarily chosen data points for the computation.

Be aware that when plotting data with units, both the slope and the intercept have units also. Since the slope is a ratio of the quantity plotted vertically to the quantity plotted horizontally, it has the units of that ratio. The intercept has the same units as the quantity plotted vertically. In the example of Fig. IV-1, the slope is measured in m/sec^2 and the intercept in m/sec.

You can estimate the uncertainty in the slope and intercept by drawing other lines that are plausible but at the outer limits of the scatter in the data, and computing their slopes and intercepts. If you use the graphing software it will automatically display uncertainties, but tends to underestimate them.

When the measurements are not expected to follow a linear relationship, the analysis can follow one of two possible approaches. The simplest is to linearize the relationship by a clever change of variable. Alternatively, one can use specialized software to find the parameters of an assumed function that gives the best description of the observations.

As an example of the linearization approach, suppose we measure two quantities, y and x, which are actually related by $y = a + bx^2$. A plot of y vs x will be a curve, and it might be hard to decide by examination whether or not the data actually follow the quadratic. However, a plot of y vs x^2 will be a straight line with slope b and intercept a, and it is quite easy to see how closely the data follow the presumed line. A more complicated example is a measurement of position, s, as a function of time for uniform acceleration. Theory predicts the relation $s = v_o t + 1/2\, at^2$. If we divide both sides by t we obtain $s/t = v_o + 1/2\, at$. A plot of s/t vs t should be a straight line, and we can quickly decide if the theory is correct.

The graphing software available on the lab computers will allow you to choose a function that you think describes your data and find the values of the adjustable parameters that lead to the best approximation. In the second example above, we could plot s vs t, and then ask the program to find the values of a and b in the expression $s = at + bt^2$ that give the closest agreement with the data. The numerical values of a and b would then be converted to physically meaningful parameters by comparison with the original equation.

It should be obvious at this point that graphical data analysis is something of an art. Intuition, theory and experience all provide useful guides, but each situation must be examined carefully. You will have considerable opportunity to study this art during the weeks ahead.

V. Using LoggerPro

"Nothing is more terrible than to see ignorance in action."

J. W. Goethe (1749-1832)

LoggerPro is a general-purpose program for acquiring, graphing and analyzing data. It can accept input from a video camera, read a video file or, through the LabPro interface device, acquire data from a variety of other sensors. Pictorial data can be reduced to x-y coordinates of selected objects, while sensor data is presented in tabular form as a function of time. The program will prepare plots of the data, compute statistics like the mean, fit specified curves to a data series, and calculate derived quantities. Basic operations will be described here. Additional information can be found in the internal help system and in the *LoggerPro 3 Quick Reference* guide available in the lab room.

To start LoggerPro you can click on the caliper icon in the main toolbar, or double-click on one of the startup files with a .cmbl extension on the desktop. The startup file can configure graphs, sensors and other features for a particular experiment, so this is the preferred method.

If the program is already running, you can get a clean copy with File > New on the taskbar, or load a new startup file with File > Open... When doing so, or when quitting the program, you will be prompted to save your previous work. This is usually not necessary but if you do wish to save, use File > Save As... and follow the dialog to create a new file so that the original is available for other students.

DATA COLLECTION - SENSORS

Be sure that the power supply for the LabPro is plugged in, and that it is connected to the computer by a USB cable. The sensors needed for a particular exercise will usually already be connected to the LabPro interface, but the program needs to know what sensors are connected to each port, and how they should be calibrated or actuated. Loading the startup file specified for each exercise will provide the proper configuration, a data table with useful columns, and graphs as needed. In the unlikely event that the startup file settings are not adequate, modifications can be made with the menu entries under Experiment and Data. If you do make changes, *do not save them* under the original file name.

Once the program and sensors are configured, you start data collection by clicking the Collect button. After a brief pause, the sensors will be read at regular intervals until the Stop button is clicked or the time limit is reached. Data will appear in the table and on the graph, if present, as it is obtained. When data collection is complete, you can use the graphing and data analysis functions as needed.

DATA COLLECTION - VIDEO

Video is used to measure and analyze the motion of objects, usually in two dimensions. Two steps are required: A movie of the desired motion is captured in a LoggerPro window, and then the movie is analyzed in a separate window.

Recording. Be sure the camera is plugged in, turned on, and connected to the computer. Start LoggerPro and open a recording window by going to Insert > Video Capture.... Check that the image is what you want, and then click on the Start Capture button to begin recording. Carry out the desired action and then click the Stop Capture button to stop recording. Close the recording window by clicking on the dot at the upper left corner.

Measuring. The analysis window should now contain your new movie. Movie player controls are on the bottom at the left, or you can move along the movie series with the blue slider control. Click on the icon with three dots and a triangle at the bottom right to open the analysis toolbar. The actual measurement process consists of marking the desired point in each movie frame and then marking a known length in one frame to convert picture positions to physical dimensions.

To mark points, click on the second icon in the vertical row, the one with a dot in crossed lines. Position the crosshair cursor at the desired place in the picture and click. The program will record the coordinates, put a colored dot at that location, and advance to the next frame. Repeat until you have marked all the positions of interest for the motion you are studying.

To calibrate the scale, move to a frame that shows something of known length which is at the same distance from the camera as the object of interest. (The object itself is frequently a good choice.) Click on the ruler icon, which is fourth from the top in the analysis toolbar. Put the arrow cursor at one end of the known length, then click and drag to the other end. Enter the length in the pop-up window. The computer will convert pixel coordinates to real distances and place the values in the data table and onto the graph.

If you need to mark a second set of positions in the movie, click on the icon with two dots and lines to pull down the menu. Select Add point series and mark the new points as needed. The same pull-down menu lets you add more series, or choose among the series you have already created.

GRAPHING

Data from sensors or a movie is usually graphed automatically when appropriate. To change the graph scales, click at either end of the x or y axis. Enter the maximum or minimum scale value desired and push return. To change the quantity being graphed on either axis, click on the axis label and select the desired variable from the menu.

You can add additional columns for manual data entry using Data > New Manual Column. To calculate a new column from data in previous columns, use Data > New Calculated Column... and follow the dialog that pops up. The pull-down menus in the box allow you to pick from the available variables and functions to calculate the new column entries.

To use LoggerPro as a manual graphing tool, load the startup file Graph.cmbl. This will produce a data table with two columns for manual data entry. Type data into the cells of the table, and it will be plotted on the adjacent graph. Adjustments can be made as before.

ANALYSIS OF GRAPHED DATA

A number of analytic tools can be activated by menu items under Analyze or by clicking on icons in the task bar. The analysis will use all the data in the selected graph, unless a subset has been selected by clicking and dragging on the graph or data table. The tools most useful for this course are

Statistics or Stat icon: Computes mean, standard deviation and some other statistics for the selected data.

Integral or curve and area icon: Calculates area under the selected portion of the curve.

Linear Fit or R = icon: Fits a straight line to the data and displays slope, intercept and correlation coefficient. To obtain error estimates for the fit parameters, double click on the display box and check the option in the dialog.

Curve Fit or f(x) = icon: Fits any of several functions to the data. Choose the desired function and follow instructions in the dialog box.