Contents

You can find another list of the labs inside the back cover.

Introduction

These are labs for introductory physics courses. They're aimed roughly at the algebra-based course, but there is a lot in here that would be useful in a "physics first" class or in conceptual physics. And there's plenty that's suitable for students taking calculus.

We assume that students have computers available for data analysis. You will find pages about how to use Logger *Pro* and Fathom, though the lab instructions themselves are mostly software-independent, and the principles are universal.

In this volume—which is the first of three—the labs *do not require probes*. There's not too much data to enter by hand, and without probes, setup is a little easier.

And here is the really important part, the two beliefs that permeate these labs:

- First, we believe that deeper data analysis—especially through making and interpreting models—leads to better and more effective labs.
- Second, we believe that the right approach to data analysis can improve labs by helping students be more thoughtful and independent.

We will discuss each of these in turn, using the pendulum lab (pages 67–76) as an example. In this lab—which is probably familiar to you—students discover that the period of a pendulum depends on its length, not on its mass. With the data, they can get a value for *g*, the acceleration of gravity.

Along the way, we'll put other important ideas in gray boxes, like the one at right.

About Lab Manuals

When we were preparing this book, we worked with experienced physics teachers. We discovered a remarkable thing: although they all had a slew of lab manuals on their shelves, they rarely used those labs as written. They designed their own labs and made their own handouts.

Why? Because labs are detailed, idiosyncratic activities. The labs you do, and how you do them, depend on the specific equipment you have, your own personal history and comfort, the particular needs of your syllabus, and which students are enrolled. After a few years on the job, there is no way an author outside your building can design a pendulum lab for your class as well as you can.

So what's the point of having a book like this? First, it may give you new ideas for labs; second, you might get new perspectives to make your labs better; and finally, if you've never done a particular lab before, sometimes it's nice to have procedures and handouts all laid out, even if you're going to completely revamp it next year—or next period.

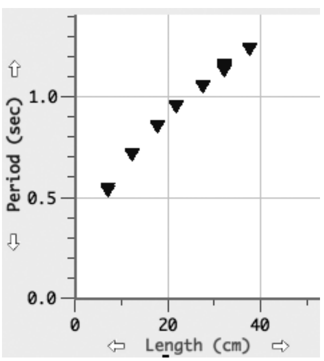
In this book, you may indeed get a few new ideas, and you may occasionally want to use the handouts—or modify them; there are files with the text for student handouts on the CD so you can edit them.

Data Analysis, Modeling, and All That

When you took physics, unless you were really lucky, it took almost the whole period to wrestle with the equipment and take your data. Then, in the last five minutes, you had to put everything away, and the instructor would say, "we don't have time for the data analysis, just do that for homework." That analysis consisted of filling in the blanks on the handout, or copying the steps into your lab manual. At the end, you compared your value (9.6 m/s^2) with the orthodox value, computed your percent error, and you were done. If you were really advanced, you might have to do something as elaborate as computing a standard deviation or standard error (whatever that was), and writing it down, too.

These days, we can do better.

In these labs, we ask students to compare data to mathematical functions, or *models*. This involves one big principle and a number of consequences.



Sample data from a pendulum experiment showing measurements of period for various lengths of string. Mass is constant.

The Big Principle: Relationships, Not Numbers

Whatever we emphasize in data analysis should help students understand the physics concepts we're trying to teach. And the physics is in the *relationships*.

For example, when you do the pendulum lab, the point is not the value of *g*, but rather the *relationship* between the length and the period. The curved pattern on the period-length graph comes from the physics of the situation; the value of *g* is just an accident of our location.

We often represent these relationships using *scatter plots*. Ideally, these plots have functions on them, *models* that mirror the patterns in the data. Even if your students don't do fancy functions such as square roots, they can still use quantitative data, analyze it conceptually, and sketch the function. Students can see where the data fall, and reason about the relationship.

Does this mean that we think determining the acceleration of gravity is unimportant? Not at all. But if we approach the lab as if that's the goal, the students will remember "981" instead of "the period depends on the length, not on the mass."

So where does finding *g* fit in?

Form and Parameters

When you look for a function to fit the data, you need to figure out two things: the *form* of the function, and the values of the relevant *parameters*.

We usually figure out the form by looking at the underlying physics of the situation (though sometimes we can understand the underlying physics by looking at the form). Then, given a reasonable form, we adjust the specific function to fit the data by changing the values of parameters. In the case of our pendulum, *g* is a parameter in the period-length function, $T = 2\pi\sqrt{(L/g)}$.

Suppose you know the form of the function. How do you get the best values for the parameters? Here we have a strong opinion: don't try for *best* values. Instead, try for *pretty good* values. This means fitting by eye instead of using automatic fitting routines.

Why not do automatic fits? Machinery built into most graphing calculators will do nonlinear best-fit regressions. But for most students, these things are black boxes. They tend to give the parameters names of their own, not names students choose. Students may not know how to make a fit less general in an appropriate way (for example, to peg the zero-order term at zero), or to insert a constant (such as the ½ in $\frac{1}{2} mv^2$). And students tend to shop for the best value of that coefficient of determination, r^2, regardless of the physics of the situation. Never mind that the formula for period has a square root; a cubic polynomial works fine! There are other problems, but those are plenty.

Until recently, the alternatives weren't too good. Now, however, students can put functions on graphs with variable parameters that they control with "sliders" or similar screen widgets. The students slide the parameter values, and the functions change on the screen immediately to reflect the new values. We cannot overstate how important this is; with this technology, students get a visceral feel for how parameter values affect the functions. They essentially get to do continual, dynamic, what-if experiments. "What if *g* were 800 cm/s²? What would the curve look like? Whoa, not like the data. No way *g* is that low." (See the illustration in the margin.)

Students adjust these sliders to get parameter values that, while not exactly equal to the least-squares value, are pretty close.

This is cool looking and fun. It gets students looking at the data *longer*. And it is fundamentally the way empirical science works: We collect data about phenomena. We invent models to explain the data. We evaluate the models depending on how closely they match the data under various circumstances. If we can't adjust the parameters to fit, well, either the form of the function is wrong—perhaps we misunderstood the physics—or maybe it applies only over a certain range.

One more advantage to "pretty good" fits is this: Because each group will get a different value for a parameter—even when they use the same data—it helps students realize that the parameter value itself is uncertain. Too often, given a best-fit value, students think that it is not only best but also exact. Instead, we can ask students to give us a *range* of plausible values for a parameter in addition to, or instead of, a "best" value.

Once students have a good model, what do you do next? Ask them, what does that parameter *mean*? Here it's the acceleration of gravity. On a distance-time graph, one parameter (the slope) is the speed. For a wave, it might be the frequency, or the spring constant.

Sometimes a parameter can give rise to a new concept. If you plot a current-voltage graph for a device (that is, current on the vertical axis) and see that it's a direct proportion, there's something special about that slope—the parameter for the relationship. It seems to be a property of the device; we call it conductance. If you reverse the axes, the slope is the resistance.

The Math Curse

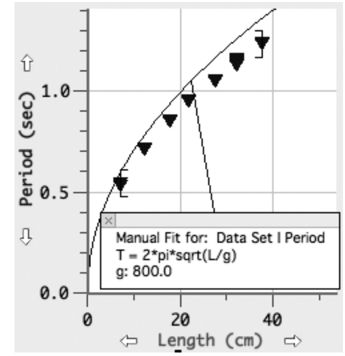
As physics teachers, we often find ourselves teaching some math. But there is a genuine tension: too much math, and you lose the physics. You may wonder if, by focusing on data analysis, you have to give up content.

We hope not. We believe that with great software to do some of the gruntwork for the students, we can include more math in the service of learning the physics better—and not take up any more time. To do that, however, one must choose carefully. We have suggestions for what to focus on, what to hit again and again: Functions. Parameters. Scatter Plots. This introduction also suggests things to consider leaving out, such as least-squares fitting and (gasp!) averaging data.

Even well-prepared students have trouble with math in physics class, so be patient. Many students have never seen concepts from their math class outside those walls, so it is not surprising that they're sometimes befuddled.

We in the sciences also use a different mathematical vocabulary from our colleagues in that other department. For example, we often use variables other than *x* and *y*. We use subscripts and say "v-nought" for v_0. These seem like small things, but they're not.

If you want a mantra, keep saying "relationships, not numbers."



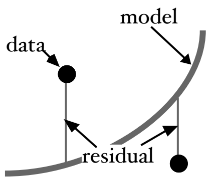
Pendulum data with a model. We have one parameter, *g*; we're trying *g* = 800 cm/s².

Linearizing

Transforming data to make it linear is an important technique, but it is not for the faint-hearted nor for the beginning student. Until we had the technology to fit curves by eye, it was one of the only techniques we had, so it was essential. Not any more. In this book, we still use it when we need three parameters: we linearize the data and use a least-squares fit for the line (that's two parameters) adjusting the third as a slider to make the data straight and therefore the residuals zero.

Residuals

If you can, have students use *residual plots* when they do their fits. In case this is new to you, a *residual* is the (vertical) distance from the model to a data point. Residuals help you evaluate the quality of a fit. If the model goes through the points as well as it can, the residuals will be randomly scattered about zero. If this is not the case—if you see a consistent pattern, or the residuals are not centered at zero—you must either accept the flaws in the model, change some parameter values, or change the form of the function.[1]



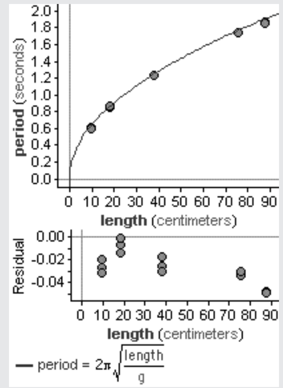
The illustrations in the center column show the same pendulum data as on the previous page, but now with residual plots. We're trying out two possible values for the parameter *g*.

You can also think of a residual plot as taking the model and pulling on it, deforming the graph until the model is the horizontal axis. If the model is good, the points will all be pretty close to this new axis, and you can expand the scale of the residual plot to show more detail.

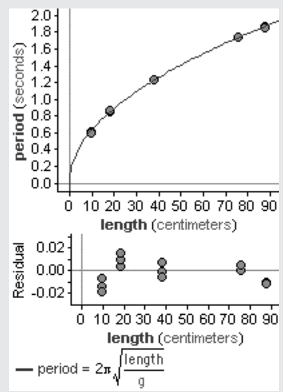
Residual plots are good for a number of reasons:

- They give you finer control for getting better parameter values;
- The greater detail in the data sometimes reveals features that are invisible at the scale of the main plot;
- Playing with parameter values while watching the residual plot often gives you insight into the function, and how functions interrelate.

1 If we were in a statistics class, we would also have to worry about heteroscedasticity: the *spread* of the residuals should be about the same over the domain.



The pendulum data with g = 947 cm/s². Notice how the main plot looks OK, but you can see that the residuals are decreasing systematically, and not centered at zero.



Same data, but now the parameter g is 985 cm/s². The residuals are pretty flat, and are centered near zero.

Notice, also, how the repeated measurements act as error bars. You can't see them on the main plot because of the scale, but you can see them in the residual plots.

Don't Average! Plot All of the Data!

In a traditional lab activity, we often ask students to repeat measurements and average. Then we plot the average value and use it in subsequent calculations. If we're sophisticated, we calculate the standard error, and plot the average value with error bars that extend two or three standard errors from the point. This used to be a good idea, and it still is—for students who understand what standard error means.

In most settings, though, we recommend a different strategy: *plot all of the data*. That way, instead of error bars, you have swaths of data from your multiple measurements, little clouds of points. A spread of points acts like an error bar, graphically showing students the uncertainty, using the very data they took.

Why do it this way? If we're interested in the relationship between the variables, looking at all the data serves our purpose without the distraction (and lost time) of computing averages. Averages, after all, throw away data, and with computers we don't have to throw any away to make plotting easier. And an average (like a best-fit parameter) sometimes deceives students into thinking that it is an exact value. Multiple points, on the other hand, help students see the inherent uncertainty. When they explore possible parameter values using a slider, it is easier for them to give us a range of possible, plausible values.

Do we object to error bars? Not at all. But we should perhaps use them first for the *a priori* accuracy of a measurement (How well do you think you were able to time the period?) rather than for something as difficult as a two-standard-error spread from an average.

Neither do we object to averaging as an important tool. But if we're going to spend time on math in science class, we would rather spend it on models—the mathematical functions that embody concepts of science.

The Inquiry Connection: Thoughtful, Independent Students

Ultimately, we want students to engage in inquiry: to ask their own questions, design their own procedures, and basically be independent, skeptical, creative, hard-nosed experimentalists from the first day of class. We want to throw away the cookbook.

Unfortunately, that's impractical. Complete openendedness can result in chaos and enormous student (and teacher, and parent, and administrator) dissatisfaction. Nevertheless, this book takes steps towards more open-ended labs. This section describes our strategies and how you can use them. The first caveat is that students have to be ready for more independence. With that in mind, we have designed these materials so that you can adjust what you offer.

The second caveat is that, in general, students are readier than we think.

We are far from the first to tread these paths. If you're looking for more inquiry-oriented materials, you have a lot to choose from. For a complete, powerful pedagogical system developed at the high-school level, learn about *Modeling Instruction*, developed by David Hestenes and his colleagues at Arizona State. Another, at the college level, is called *ISLE*: the Investigative Science Learning Environment, from Eugenia Etkina, Alan Van Heuvelen and their group at Rutgers. You should also know about *Workshop Physics*, from Priscilla Laws and her colleagues at Dickinson and elsewhere. Lillian McDermott and her group at the University of Washington have done much of the ground-breaking research, and have published *Physics by Inquiry*.

Other materials and ideas, notably *Real Time Physics* and *Interactive Lecture Demonstrations* from Ron Thornton and David Sokoloff (parts of the formidable *Physics Suite* materials), support inquiry as well. To see it all together in a thin volume, get Ed Redish's *Teaching Physics with the Physics Suite* (Wiley, 2003).

These people and their work are amazing. All of their projects are philosophically aligned with ours. They all believe fundamentally that learning happens when students engage with phenomena directly, ask their own questions, and develop their own explanations.

The Vague Question

At the beginning of a lab, you need to orient students to the phenomenon they're going to study, and to what you expect of them. We start this process with a vague question. You may find this to be a silly pedagogical trick, but we like it:

Every lab begins with a vague and unanswerable question. (It's in the **Question** section on the first page of each chapter.) For our pendulum lab, it's, "What is the period of a pendulum?"

You can't answer this without more information. So a good response is, "It depends." That is what we train students to say when we ask one of these questions. (Eventually they do this in unison.)

That rote answer sets up the payoff question: "Depends on what?" At this point, the students list, and we record, all their ideas about what the period could depend on. When they have a good list, perhaps supplemented by us, we can say something like, "Many of these could affect the period of a pendulum. Which do you think are most important?" We take a few answers, and then continue with something like, "Well, in the lab we're going to do, we can't focus on everything, so we're going to focus on the length of the string and the mass of the bob."

The point is to encourage and validate as many student ideas as possible. When some kid says, "the temperature," write it down. Do that no matter how loony the idea is. If you have time, probe: "How do you suppose temperature will affect the period of a pendulum?" You may be surprised by the answer (e.g., it will make the air thinner, so there will be less air resistance, so the bob will swing faster). We don't correct or discuss these at this time, but we may want to come back to them later. Even if you don't return to these ideas, you get immediate information about how students are thinking, and students get the correct impression that you care how they are thinking and what ideas they have.

That way, even though you may have a particular agenda—we're going to study the effect of length and mass on the period—students have some ownership of the overall design of the lab. More importantly, before they buckle down and focus on a small number of variables, they get to spend a few minutes thinking open-endedly about all the variables that could affect an outcome.

Notice how this directly supports our focus on relationships between variables. Asking students to list possible variables helps them understand what variables are, and gives them practice thinking about possible relationships between them.

Making Prediction Humane

Physics education researchers have much to say about prediction. Eugenia Etkina, Alan van Heuvelen, and their colleagues make an interesting point when they caution us not to have students make a prediction unless they have experience to base it on. It's not fair, they claim, and it sets the students up for failure.

Whether it's fair depends on where the lab falls in the learning cycle. If students have studied the phenomenon already, and this lab is really for testing their emerging ideas or verifying what everyone agrees on, there's no problem; prediction is a natural part of preparation.

But if you are introducing students to a concept, make sure they have something to predict from. This does not have to take much time. The day before the pendulum lab, for example, show the students the equipment. Hold the string and the bob and show them how it swings. Then shorten the string and do it again. Ask what was different between the two phenomena. Students may say "it goes faster." Work to define terms. Do you really mean faster, as in speed, as in distance over time? Well, no, they mean more "back and forths." Ask how we could measure this. Show them the stopwatch. Do a sample measurement, perhaps having several students drive the stopwatches.

By doing this, you have helped the students get ready for the equipment and the measurement challenges they will face. As a bonus, they now have a quantitative data point to use in their prediction.

Prediction

Every lab has a prediction page for students to fill out before the lab. And every prediction page asks students to sketch a graph of what they think the data will look like. It is astoundingly hard for students—and teachers—to commit in writing to a prediction. Most people resist it; maybe that shows how important it is. We think explicit prediction serves several important purposes:

- First, it gets students to think about the concepts ahead of time; this helps them prepare for the lab. They will have an idea about what to expect.
- Second, student predictions give you a chance to do some assessment. Whether a prediction is right should not be part of a student's grade, but the predictions are still worth looking at. You can find out whether the students as a group are as prepared as you think they are. Having seen the predictions, you can anticipate problems—both class-wide and for specific students. You can also track whether students' predictions are becoming more sophisticated. More about this in a bit.
- Third, prediction fosters independence. It is hard because it is risky; prediction can be wrong. But without being willing to say what you think will happen, you'll never become independent. So we want students to predict, and then we want them to look back at their predictions in as positive a way as possible. Have students reflect, even in the whole group, and talk about what parts of their predictions were correct, and what were not. ("I was right that longer strings would make the period longer, but I thought that heavier weights would move slower, and that was wrong.") Reassure them that there's no way they could predict everything. Ask if there were any surprises. Remind

students, and yourself, that surprise can be the most exciting part of science; you get surprised, and then you have to figure out why the data did what they did. That's when you learn the most. And if you never predict, you can never be surprised.

Progress in Prediction

You will see student predictions at different levels of sophistication. Remember, we're asking them to predict (among other things) what the graph of their data will look like; we ask them to draw the graph and perhaps to describe the relationship in words.

At first, students make qualitative arguments about direct or indirect variation. They might say, "The longer the string, the longer the period." Their graphs might look more or less linear, even when the phenomenon is not.

Later, students may show appropriate curvature in the graph, but not identify it with a function.

Later still, they may predict the actual functional form.

There is a similar progression in students' predictions of specific values. At first, their graphs probably will not have values attached, but as students grow more sophisticated, their predictions will—perhaps with prodding—become more quantitative. The values on the prediction graphs may be ridiculous at first, but gradually they will become plausible, and then actually precise. Eventually, students will recognize what they cannot know ahead of time, and allow for that in their predictions.

Ultimately, we want students to be able to analyze a situation and predict with great care what will happen. Then, when they do the lab, and measure as well as they can, their prediction will still be off—but that will be because of some interesting effect or an artifact of measurement they had not anticipated.

How Do You Know When You're Done?

Every set of student instructions for a lab begins with this heading. We decided we needed it because whenever we tested one of these labs, and tried to be more open and less cook-booky, students often asked whether they were done. They couldn't tell. So we created a list.

Students who are ready for even more open-endedness can do the labs using only this list—and perhaps some setup help—as a set of guidelines. The box below shows that section from the pendulum lab.

We have included these lists as separate files on the CD in case you want to format them and project them during the lab as a common class list.

> **How Do You Know When You're Done?**
>
> - ❏ You have a graph that shows the period of a pendulum for at least five different *lengths* (with the same mass). There are at least three observations for each length.
> - ❏ You have a similar graph, showing the period for five different *masses* (but with the same length). Again, three observations minimum per mass.
> - ❏ You can show convincingly that the **period** vs. **length** graph is not linear. Ideally, you have a mathematical model—a function—that describes the data well.
> - ❏ You can explain how **period** depends on **mass**, and back up your conclusion with data.

You may want to add more tasks to the list, for example, "You have completed the *Tasks, Questions, and Exploration* page," or "You have completed your lab write-up according to the class guidelines" (whatever those may be in your class).

Analysis During the Lab

Whenever we can, we like to have students begin their data analysis *while they are taking data*. Usually this means making the scatter plot, sometimes even adding a model function. This is not always practical, but if you're lucky enough to have computers on your lab tables (with enough space left over for all the equipment) or a cart with laptops, you could make it work.

There are really two advantages to in-lab data analysis. First, if students make a graph right away, so points appear immediately, they will see bad data points and can correct them. Often the problem is just a key entry mistake, but if the students wait for a few hours or days before they process the numbers, they may not catch it.

Second, if they have made a coherent prediction, and they are plotting the data as they get it, they will be constantly comparing the prediction to the data, thinking about the pattern in the data *the whole time* instead of just during the data analysis phase.

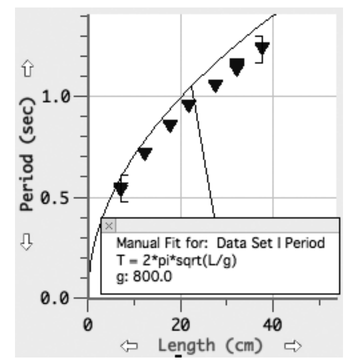
Looking at the data may even change what measurements they take. In the pendulum lab, most groups, after taking a few convenient data points, see that the data look more or less linear, even though the "book" model has a square root. (This always happens with square roots.) If they're looking at the data as they take it, students will see that they need to concentrate on small lengths, at short periods, in order to see the shape of the function. It is much better for students to realize this on their own instead of your having to specify it ahead of time in some procedure handout.

Another practical advantage of in-lab data analysis is that as you walk around, you can monitor how groups are doing by glancing at the graphs on their screens instead of having to figure everything out from hand-written measurements.

Probing for Understanding in Modelmaking

As lab groups analyze data, it pays to ask a few questions to see if the students understand what they are doing. If your students are like ours were when we began field tests, you will be alarmed at some of the things they will say.

Ask students what individual points mean. Some students disconnect data from its origins immediately upon plotting it. A student should be able to tell you, "This is from when we did ten swings in 11.4 seconds, and the length was 32 cm." Some students have a hard time decoding Cartesian coordinates in a physics context. A few questions from you will keep them from getting lost simply because they have forgotten how axes work.



Ask students what it would mean if a point were in some forbidden zone. For example, point to a spot in the illustration near (50, 0.5) and ask what a point there would mean. You're testing the Cartesian business again, but also common sense. Ask what such a point would *mean*. Students should be able to say, "The pendulum would be about *this* long and go back and forth *this* fast—naw, that couldn't happen."

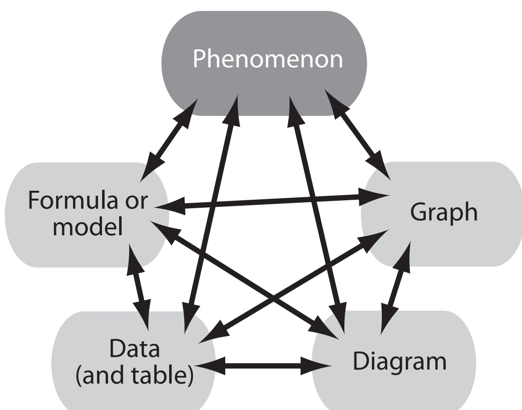
Ask students why an incorrect model curve is where it is (move the model off the data if necessary). In the illustration, the curve is too high. Why? Because the only parameter, **g**, is too small. Follow up with, "but if **g** is too small, shouldn't the curve be *below* the points?" Here you're testing understanding of the algebra: since **g** is in the denominator (though still under a square root) the curve goes up when **g** goes down.

Finally, ask students what that (wrong) model means physically. Ask, “If the data were here, where the model is, how would the situation be different?” There are two answers, and you want both: the “symbolic” answer is that `g` would be smaller, and that means that gravity is less. The “relationship” answer is that any given length of pendulum would have a longer period—it would go more slowly—than a real pendulum. A good combination answer might be, “Maybe the pendulum is on the moon.”

There are countless other questions to ask about graphs—you should always ask about the meanings of parameters, for example—but these will get you started.

The point is that a scatter plot with a curve plotted on it is an amazing tool for displaying and understanding a phenomenon. For students to really do inquiry, quantitatively, about a relationship in physics, they need to understand how this tool works.

In a way, understanding here is all about translating from one representation to another. Some folks make a diagram like this one; it may help:



We want students to be able to translate fluently between the phenomenon—the real world—and any of the four interrelated representations.