

Introduction and Motivation

The Master doesn't talk, he acts.

When his work is done

*[his students] say, "Amazing:
we did it, all by ourselves."*

Lao Tse, Tao Te Ching [Mitchell 1988]

INTRODUCTION

Teaching physics can be both inspirational and frustrating. Those of us who enjoy learning physics get to rethink and pull together what we know in new and coherent ways. We enjoy the opportunity to create new demonstrations, invent new derivations, and solve interesting problems. For those of us who love doing physics, teaching can be a delightful learning experience. Occasionally we find a student who has the interest and ability to understand what we are trying to do and who is inspired and transformed by our teaching. That makes all the frustrations worthwhile.

On the other hand, there are frustrations. We may have students who seem unable to make sense of what we do—sometimes a lot of them. They are confused and even hostile. We may make intense efforts to reach these students, either by making our classes more entertaining or by simplifying what we ask them to do. While these efforts may lead to better student evaluations, they rarely result in our students understanding more physics. They can lead to a “dumbing down” of the physics that we find frustrating and disappointing.

Can we reduce this frustration and find ways to reach those students who don't seem to “get it”? In the past two decades, there has been a growing understanding of why so many students respond badly to traditional physics instruction and of how to modify our instructional methods to help them learn more. A number of researchers and curriculum developers have begun to weave the results of education research and new technological tools into more effective learning environments.

One result of this interweaving of research and technology is the *Physics Suite*. In the *Physics Suite*, the Activity-Based Physics (ABP) Group¹ is creating a new kind of educational environment. Since there is a growing diversity of environments for introductory physics, the ABP Group has opted for a modular structure, one that can be implemented a step at a time or adopted in a total makeover, affecting all parts of the course. This book is about how our teaching of physics can change as a result of these new environments. It discusses the elements of this modular structure, how to use them, and the educational philosophy, cognitive theory, pedagogical research, and modern technology on which the *Physics Suite* is based.

TYPICAL MATERIALS FOR A PHYSICS CLASS

Typically, all the materials offered by a publisher for a physics class derive from the text (see Figure 1.1). Affiliated materials are available associated with the text, usually including everything from a “quick summary” for students to colored transparencies for instructors. There may be a CD with (often uninteresting) simulations that offer little or no guidance for either students or instructors in how to use it to make it pedagogically effective. Adopting institutions may add a laboratory with lessons developed on site. But the text is primary, and its selection usually depends critically on content—what is covered and whether it is treated correctly. Those are certainly important criteria.

But extensive research has shown that effective student learning seldom comes from the text. Students frequently have difficulty making sense of a physics text, and, as a result, only a small minority actually read the text in the careful and thoughtful way we expect. Effective student learning comes from “brains-on” activities—those times when they are thinking hard and struggling to make sense of what they are learning. Effective instruction happens when we create environments in which students are encouraged and helped to engage in those kind of activities. Well-tested innovations that focus on building reasoning through carefully planned and structured *activities* in lectures, recitations, laboratories, or workshops are more

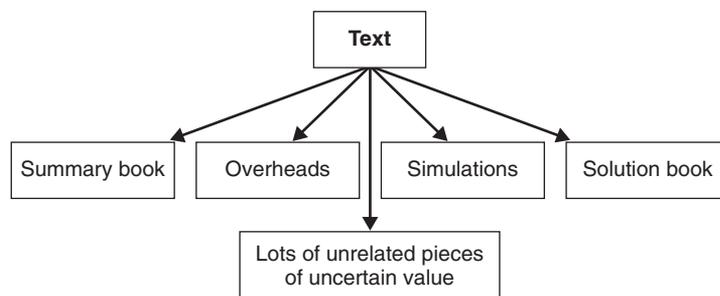


Figure 1.1 Typical layout of materials associated with a physics course.

¹Pat Cooney, Karen Cummings, Priscilla Laws, David Sokoloff, Ron Thornton, and myself.

likely to produce strong student learning. For most students, these activities play as important a role as does reading the text.

The Physics Suite is much more than a text with a collection of ancillaries developed after the fact. The Physics Suite builds on integrating a series of strong activity-based elements with the text. The Physics Suite focuses on getting students to learn to *do* what they need to do to learn physics.

A NEW ALTERNATIVE: THE PHYSICS SUITE

The ABP Group has created a new structure consisting of a broad array of integrated educational materials: *The Physics Suite*. These materials are shown schematically in Figure 1.2. Two

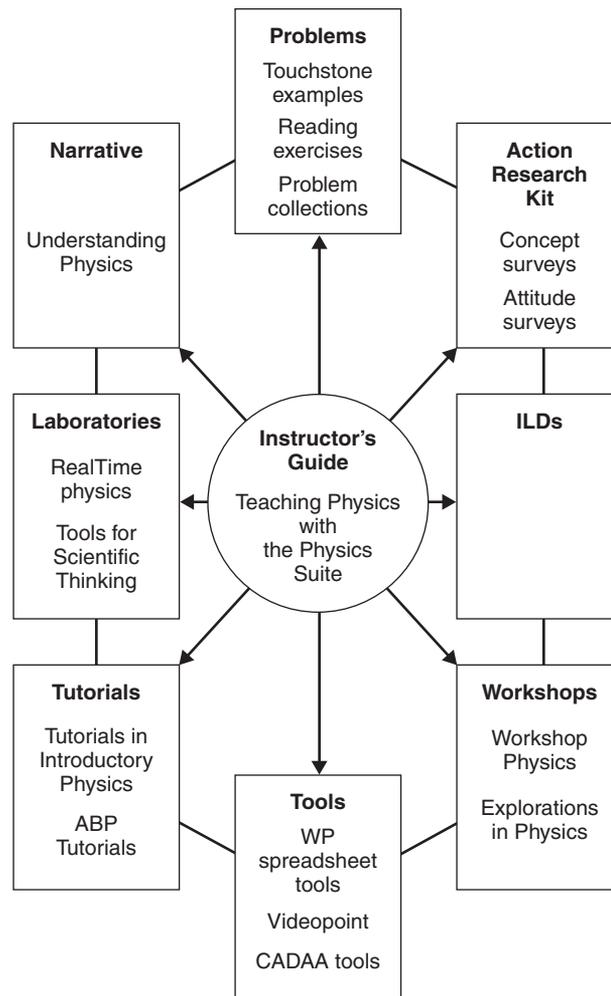


Figure 1.2 Elements of The Physics Suite

particular themes of many Suite elements are: (1) the use of guided activities to help students construct their learning, and (2) the use of modern technology, particularly *computer-assisted data acquisition and analysis* (CADAA). The Physics Suite consists of the following materials:

- *The Instructor's Guide: Teaching Physics with the Physics Suite (Redish)*—This book: a guide not only to the materials of the Suite (and other curricular materials that fit well with the Suite), but a discussion of the motivation, theoretical frame, and data describing its effectiveness.
- *Narrative: Understanding Physics (Cummings, Laws, Redish, and Cooney)*—A revised version of the classic Halliday, Resnik, and Walker text, modified to focus more strongly on issues where students are known to have difficulties from educational research. The new narrative also stresses the empirical base for physics knowledge, explaining not only what we know but how we know it. (See chapter 10 for more details on how the text has been changed.)
- *Problems*—Since problem solving is one of the places where students learn the most in a physics class, the Suite is enriched by a careful choice of sample problems in the narrative (Touchstone Problems) and by supplementary problems of a variety of types including estimations, representation translations, and context-rich real-world problems. These are contained in the narrative, on the Resource CD in the back of this book, and in a supplementary book of problems.
- *Action Research Kit*—A collection of tools for evaluating the progress of one's instruction, including a variety of concept tests and attitude surveys. These are on the Resource CD that comes with this volume.
- *ILDs: Interactive Lecture Demonstrations (Sokoloff and Thornton)*: Worksheet-based guided demonstrations that use CADAA to help students build concepts and learn representation translation.
- *Workshops*—Three sets of full workshop/studio materials are associated with the Suite.
 1. *Workshop Physics (Laws)*: A full lab-based physics course at the calculus level using CADAA, video, and numerical modeling.
 2. *Explorations in Physics (Jackson, Laws, and Franklin)*: Developed as part of the Workshop Science project, a lab-based curriculum that uses less mathematics and is designed for use with nonscience majors and preservice teachers.
 3. *Physics by Inquiry (McDermott et al.)*: A workshop-style course appropriate for pre- and in-service teachers.
- *Tools (Laws, Cooney, Thornton, and Sokoloff)*: Computer tools for use in laboratory, tutorial, and Workshop Physics include software for collecting, displaying, and analyzing CADAA data, software for extracting and plotting data from videos, and spreadsheets for analyzing numerical data.
- *Tutorials*—Two sets of materials for use in recitation sections that use guided small-group activities to help build understanding of concepts and qualitative reasoning:
 1. *Tutorials in Introductory Physics (McDermott et al.)*—A collection of worksheets by the Physics Education Group at the University of Washington (UW).
 2. *ABP Tutorials (Redish et al.)*—Additional tutorials in the UW mode but ones that integrate the technological tools of the Suite—CADAA, extraction of data from videos, and simulations. These also extend the range of topics to include modern physics.

- *Laboratories*: A set of laboratories using CADAA to help students build concepts, learn representation translation, and develop an understanding of the empirical base of physics knowledge. Two levels of labs belong to the Suite.
 1. *RealTime Physics (Thornton, Laws, and Sokoloff)*: Appropriate for college level physics.
 2. *Tools for Scientific Thinking (Thornton and Sokoloff)*: Similar to RealTime but at a slower pace for high school physics.

The materials of the Suite can be used independently, but their approach, philosophy, and notation are coherent. As a result, you can easily adopt one part as a test of the method when it is convenient and appropriate, or you can integrate several Suite elements, transforming all parts of your class.

Detailed discussions of the various components of the Suite are given in chapters 7–9, and considerations of how they might be used are presented in chapter 10. Those who are familiar with the research and motivation behind modern physics education curriculum reform are invited to turn to those chapters directly. If you are not familiar with the research and theory behind these materials, read the rest of this chapter and the next few chapters where I present some motivation and background.

MOTIVATION

Why do we need the Physics Suite? Most of us learned perfectly well from a text. What is different today? A number of things have changed and are going to be changing even more in the future.

- The students we are teaching have changed.
- The goals we want to achieve with these students have changed.
- We know much more today about how students learn than we used to.
- We have more tools to work with—both technology and new learning environments—than we used to.

I organize my discussion of these points around two questions:

1. Who are we teaching and why?
2. Why Physics Education Research (PER)?

Who are we teaching and why?

Since both the difficulties in teaching physics and their solutions depend on the population of students we are considering, let's begin by considering who our students are—and who they are likely to be in the next few years.

The growth of other sciences

When I began my serious study of science as a high school student more than four decades ago, it seemed to me that only in physics could I do “real” science. By this, I meant discovering fundamental laws of nature and making sense of their implications. As a high school

student, I was particularly taken by the beautiful match between the mathematics, which I adored, and the physics, which I took to represent the real world. To a certain extent, I was right—at least for me. Physics is the crown jewel of the sciences, making an elegant link between the understanding of the deeply fundamental and the powerfully practical. Einstein’s “ $E=mc^2$ ” and the nuclear bomb that so affected the politics and even the daily sensibilities of many normal citizens during the last half of the last century are only the tip of the iceberg. Quantum mechanics leads us to a deep understanding of the structure of matter, resulting in developments like the transistor and the laser that continue to profoundly change our way of life.

What I missed as a high school student was the immense progress soon to be achieved by the other mature sciences, such as biology and chemistry, and the immense growth soon to be shown in the then infant sciences of computer science and neuroscience, among others. Today, a high school student with an interest in science can have exciting opportunities for a productive and fascinating career in a wide range of sciences, from building models of the universe to modeling neural processes of the brain. Physics is now only one of many mutually enhancing jewels in the crown of science.

Progress in these other sciences has been facilitated by advances in physics in many ways, from improvements in gravitational theories to the development of fMRI (functional magnetic resonance imaging), a tool that uses nuclear magnetic resonance to noninvasively track changes in brain metabolism as people think about different things. Students going into these other sciences need to understand physics as part of their scientific education, but what exactly do they need from us? What role can (and should) physics play as a part of the education of a professional scientist in biology or chemistry? What role can (and should) physics play as a part of the education of a technical professional such as an engineer or paramedic?

The goals of physics for all

Physics instruction has traditionally played two very obvious roles in the education of scientists: both to recruit and train professional physicists-to-be and to “filter out” those students who might not be able to handle the mathematics of engineering or the memorization required in medical school. The former role becomes a smaller fraction of our teaching activities as the number of students studying other sciences grows. The latter no longer seems appropriate for present circumstances, when engineers, scientists, and medical professionals have an increasing need to understand both the systems they are working with and the complex tools they are using to probe them.

Improving our teaching of physics is more important today than ever before. First, a larger fraction of the population is graduating from high school and going on to universities than in previous times. More of these students than ever before are either interested in a scientific career or are concerned about finding jobs in an increasingly technological workplace.

Second, especially for those of us in publicly supported institutions, the governments and the populace that employ us are more likely today to hold the educational system (and therefore its teachers and administrators) directly responsible for the students’ learning—or lack of it—than they were in the past. In other times, individual students were seen to be personally responsible for their learning and less attention was paid to the effectiveness of

teaching.² Today, workplace demands for more technologically trained personnel require that we do whatever we can to help facilitate the successful education of our students.

The task of the physics teacher today is to figure out how to help a much larger fraction of the population understand how the world works, how to think logically, and how to evaluate science. This is doubly important in democratic countries where a significant fraction of the adult population is involved in selecting its leaders—leaders who will make decisions not only on the support of basic science, but on many issues that depend intimately on technological information. It would be of considerable value to have a large fraction of the populace who could not be fooled by the misuse of science or by scientific charlatanism.

Are we already achieving these goals?

Does traditional physics teaching “work” in the introductory physics classroom? Unfortunately, the answer seems to be a resounding “no.” Detailed examinations by many physics education researchers have shown that traditional physics instruction does not work well for a large fraction of our students. Many of our students dislike physics; many feel that it has no relation to their personal lives or to their long-term goals; and many fail to gain the skills that permit them to go on to success in advanced science courses.

The nature of the difficulty appears to be a kind of “impedance mismatch.” The professor sends out information and sees it reflected back in a similar or identical form (Figure 1.3), but little understanding has actually gotten through to the other side.

Figuring out what doesn’t work and what we can do about it

If we are to improve the situation, the best approach is to use our scientific tools to understand what is going on. We need to observe the phenomena we want to understand and try to make coherent sense of what we see. From educators and cognitive psychologists, we learn two important lessons.

- To understand what will work, we have to concentrate on what the student is learning instead of on what we are teaching.



Figure 1.3 The fact that something “comes back as we sent it out” does not mean that much has “gotten through to the student,” especially if students possess a large inertia!

²In the end, every student is indeed responsible for his or her own learning. But the issue is whether students are to learn everything on their own—no matter what we throw at them—or whether they can learn more with the aid of appropriately designed learning environments and interactions with trained mentors. This is discussed in more detail in chapter 2 under the heading, “The Social Learning Principle.”

- We have to do more than evaluate our students' success. We have to listen and analyze what they are thinking and how they learn.

If we really want to change how our students think about the physical world, we have to understand how they think.

Introducing Sagredo

At this point in our discussion, I need to introduce a voice other than my own. Not everything in this book will be obvious to the professional physicist teaching physics, even to one with years of experience. Much of what has been learned in PER is surprising and counter-intuitive. Occasionally, contradictory ideas about teaching seem obviously true. In order to make it easier for you to keep track of both sides of the discussions, I introduce my virtual colleague, Sagredo.

Sagredo is a successful researcher at a large research-oriented state university. He is dissatisfied with what his students learn in his introductory physics classes and has not been able to improve the situation despite significant and time-consuming efforts. In a grand old physics tradition [Galileo 1967], I will use Sagredo as a personification of the thoughtful, intelligent physicist who has little or no experience with physics education research. I've chosen Galileo's impartial but intelligent listener, Sagredo, since this book is intended for an audience of professional physicists and physics teachers, most of whom are highly sophisticated in their knowledge of physics but who may not have thought deeply about the issues of how people *think about* physics.

To the last sentence of the previous paragraph, Sagredo might well respond, "I learned physics with traditional instruction from teachers who didn't think about how I thought. Why can't my students do it the same way as I did?" The reason is that we are not only concerned about training physicists.

I recall well the first time I ever taught electromagnetism (to a class of sophomore physics majors at Maryland using Purcell's lovely and insightful text [Purcell 1984]). Suddenly, it seemed, everything made coherent physical sense. Before that, I knew all the equations and could even solve lots and lots of Jackson problems [Jackson 1998] with some alacrity, but I hadn't really "made physics of it" as a graduate student—and I hadn't realized that I hadn't. Amused by the different feeling associated with my new knowledge, I realized that I had studied electromagnetism with Maxwell's equations five times through my high school, college, and graduate school years.

"But," responds Sagredo, "perhaps you needed that. Perhaps one cannot expect someone to understand physics the first time through." Certainly one rarely learns something at the first look. We often have to see something many times before we really learn it. But then we have a problem. Very few of our students will have the opportunity to do what I did—study the physics many times at many levels and eventually teach it. We have to decide the value of one step in a six-step process. If you know your children will take music lessons for 10 years, it might suffice to begin with a year of scales and finger exercises, to strengthen their hands. But it might not. Many, perhaps most, children will rebel and not even make it to a second year.

So the hard question for us is: Is it possible to provide some useful understanding of physics to students in a one-year physics course? Or does the real utility of the course only

come in providing a foundation for future physics courses? If the latter is true, few of the students who are now taking introductory high school or university physics would be well advised to continue their efforts, since most will not take any future physics courses. Fortunately, as we begin to understand how students learn physics, we begin to see that remarkable improvements in understanding are possible for a large fraction of students in our introductory courses.

At this point, Sagredo complains: “But if you modify introductory physics so that the average student does better, aren’t you going to bore the very best students? These students are important to us! They are the future physicists who will be our graduate students and our successors.” Sagredo, I agree that we would need to be concerned if that were the case. If we were to improve our instruction to the middle 50% while degrading it for the top 5%, it could be a disaster for the profession. What is particularly gratifying is that the improved learning that takes place as a result of instructional reform based on an understanding of how students think is not limited to the “middle of the road” student who was previously getting by but was not getting much of long-lasting value from the course. Over the past decade, physics education research has consistently documented that the top students in the class show even stronger gains than the midrange students from research-motivated cognitive-based curriculum reforms. (See, for example, [Cummings 1999].)

WHY PHYSICS EDUCATION RESEARCH?³

The ABP Group brings together individual physics education researchers and curriculum developers who are working as a part of a community effort to improve both our understanding and our implementation of physics teaching. An important component of this effort is the word “community.” We share the philosophy with a growing cadre of physicists that to teach physics more effectively, we need to work together as a research and development community. We need to work together in the way that scientists in a science and industry sector work together to improve both our knowledge of how the world works and of how to make use of that knowledge. We share the conviction that by using the tools of science—observation, analysis, and synthesis—we can better understand how students learn and find ways to improve how we teach as a result.

Why do we need to go beyond the usual observations we have made, both of our teachers when we were students and of our students now that we are the teachers? To answer this question, we need to think about the nature of our knowledge—both of science and of teaching.

To understand how people learn science and how we might use science to learn about how people learn, we need to think a bit about the nature of the knowledge we are learning. We often say that the goal of science is to discover the laws of nature. This is not quite precise enough for our purposes. It’s better to say that we are a community working together to create the best way of thinking about the world that we can. This places the knowledge firmly where it really resides—in the head of the scientist as a part of a scientific community.

³Much of this section is based on my Millikan lecture [Redish 1999].

Knowledge as a community map

A good metaphor for the process of science is the building of a map. A map of the world should not be mistaken for the world,⁴ but it can nonetheless be of great value in getting around. What is perhaps most important about the scientific map of the world is that it is more than just the collection of the maps of individual scientists. The culture of science includes the continual interaction, exchange, evaluation, and criticism we make of each others' views. This produces a kind of emergent phenomenon I refer to as a *community consensus knowledge base*, or more briefly, a *community map*. I visualize this as an idealized atlas of science. Just as an atlas contains many individual charts, so the atlas of science contains many distinct, coherent, but incomplete areas of knowledge. These areas are supposed to agree where they overlap, but it is not clear that the entire universe can be encompassed in a single map.⁵ No single individual, no matter how brilliant, has a map identical to this community consensus map.⁶

At this point, Sagredo might again complain. “But science isn’t just the collection of individual scientists’ knowledge. What we know in physics is the *correct* description of the real world.” Sagredo, I agree. But we have to be a bit more explicit about what this “correct” knowledge is and where it resides. If no one individual has the complete map, but all knowledge ultimately lies in someone’s head, in what sense does the knowledge of the world we have gained as a community exist? The key is in the phrase “as a community.”

Real maps are constructed in a manner similar to the way we construct science. They are built by many surveyors. No one surveyor has made all the measurements that lead to a map of the United States, for example. Furthermore, each atlas differs in some detail from every other atlas, yet we have little doubt that a true atlas could exist (though it would, of course, have to be dynamic and limited to a preset resolution).

In mathematics, if we have a series of functions that get closer and closer to each other in a prescribed way, then we say the sequence has the Cauchy property.⁷ Even if we can’t find the true limit analytically, we find it convenient to act as if such a limit exists.⁸ The natural mathematical structures of sets of functions behave much more nicely if we “complete” the space by adding the sets of Cauchy sequences to our space. It’s like adding the real numbers that fall in between the rationals. We can never calculate them exactly, but it would be very hard to describe the phenomenon of motion if we left them out. (See Figure 1.4.)

In many areas of physics, the sequence of knowledge functions has converged—for all practical purposes. The community consensus on such items as the classical mechanics of the planets of the solar system or the thermodynamics of weakly interacting gases, for example,

⁴Lewis Carroll describes a community of mapmakers who are creating increasingly accurate maps. Finally, they create a map of the area that is 1-1 in scale. Unfortunately, the local inhabitants refuse to let them unroll it “because it will block the sun and kill the crops” [Carroll 1976, p. 265].

⁵Mathematically, this is even true of a sphere, which cannot be mapped by a single non-singular map to a Euclidean plane. See, for example, [Flanders 1963].

⁶In some areas, a specific individual’s map may be better than the community’s map.

⁷Mathematically stated, a sequence of functions $\{f_n(x)\}$ is said to be *Cauchy* if two functions taken from far enough out in the sequence will be as close together everywhere as you want. (Given any $\epsilon > 0$ there is an N such that if $m, n > N$, $|f_n(x) - f_m(x)| < \epsilon$ for all x .)

⁸For mathematical details, see for example, [Reed 1980, p. 7].

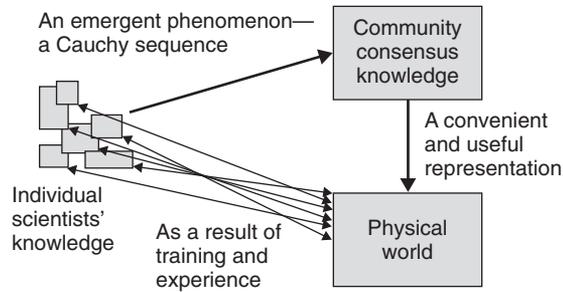


Figure 1.4 Representation of the process of building the scientific map of the physical world.

is exceedingly strong—in part because we know the resolution that is relevant to most problems in these subjects. Just as we don't find it useful to have a map of New York that specifies the cracks in the sidewalk, we don't need to calculate the location of a satellite to nanometer accuracy.

Building the community map for education

If what we learn about physics education is to lead to a stable and growing community map, the community needs to document what we know and to present conjectures and hypotheses for criticisms and questioning. This is particularly important in education.

Human behavior in all realms is beset by wishful thinking—we tend to really believe that what we *want* to be true *is* true. To some extent, the most important part of the process by which science builds its community consensus knowledge base is the part that identifies and purges the wishful thinking of individual scientists. Some parts of the process critical for this task include:

- *Publication* of results, documented with sufficient care and completeness that others can evaluate and duplicate them
- *Repetition* of experiments using different apparatus and different contexts⁹
- *Evaluation* and critiquing of one scientist's results by others through refereeing, presentations and discussions in conferences, and through follow-up evaluations and extensions

When it comes to education, wishful thinking is not just present; it is widespread and can take a variety of forms.

- A dedicated and charismatic teacher may, by force of personality, inspire her students into learning far above the norm. That teacher may then try to disseminate her curriculum to other less charismatic individuals, only to find the method is no longer effective.

⁹We try to make experiments as similar as possible, but it is not, of course, possible to ever reproduce an experiment exactly—even if the identical apparatus is used. These small variations help us understand what variables are important (e.g., the colored stripes on the resistors) and which are not (e.g., the color of the insulation on the wires).

- A teacher delivering an inappropriately rigorous course may find that his students seem to learn little and to dislike it intensely. “Ah,” he is heard to remark, “but when they’re older they will realize that I was right and come to appreciate the course and what they’ve learned.”
- A teacher concerned about how little his students are learning may try a number of changes to improve the situation, but find that nothing seems to help. “Oh well,” he says, “those students are just not able to learn physics under any circumstances.”¹⁰

I have personally observed each of these responses from physics colleagues whose science and whose teaching efforts I respect. Each of these situations is more complex than the individual teacher has realized. In each of these situations, much more can be done if a deeper understanding of learning and teaching is brought to bear.

Building a community knowledge base about education requires using our full array of scientific tools—observation, analysis, synthesis, plus the community purging and cleaning tools of publication, repetition, and evaluation. Sagredo complains at this point. “Do we really need all this effort? Oh, I know you’re right about some teachers, and I recognize your three ‘wishful thinkings’—I’ve occasionally been there myself. But there are some good teachers. I’ve had one or two. Why don’t we just let them concentrate on the teaching and carry most of the introductory load?”

Yes, Sagredo, there have always been excellent teachers—teachers who can reach not only the very best students, but who can energize and educate even the less motivated and less capable students. But there are far too few of them, and their skill has not been easily transferable to other concerned and dedicated, but less naturally talented, teachers. We want to understand what it is those teachers are doing successfully so as to be able to transform successful teaching from an art, practiced only by a few unusual experts, to a technology that can be taught, learned, and facilitated by powerful tools. Building an understanding of the educational process through using the tools of science is beginning to enable us to carry out this transformation.

The impact on teaching of research on teaching and learning

Sagredo is still not convinced. “How can education research in someone else’s class tell me anything about what is happening in my own? Every situation is different—different students, different teacher, different university. Each of those differences is important.” You are right, Sagredo, there are differences and they matter. But a lot of what has been learned is robust enough to illuminate what is happening in many different situations. Let me illustrate this with specific examples of how research has affected two instructors.

Even good students get the physics blues

An example of how building a scientific community of physics education researchers can spread and transform individuals is told by Eric Mazur, a chaired professor at Harvard

¹⁰Note from this example that wishful thinking does not necessarily imply a rosy view of a situation. It may be that the wishful thinking is that “the situation is so bad that there is nothing I can do about it and therefore I don’t have to make an effort.”

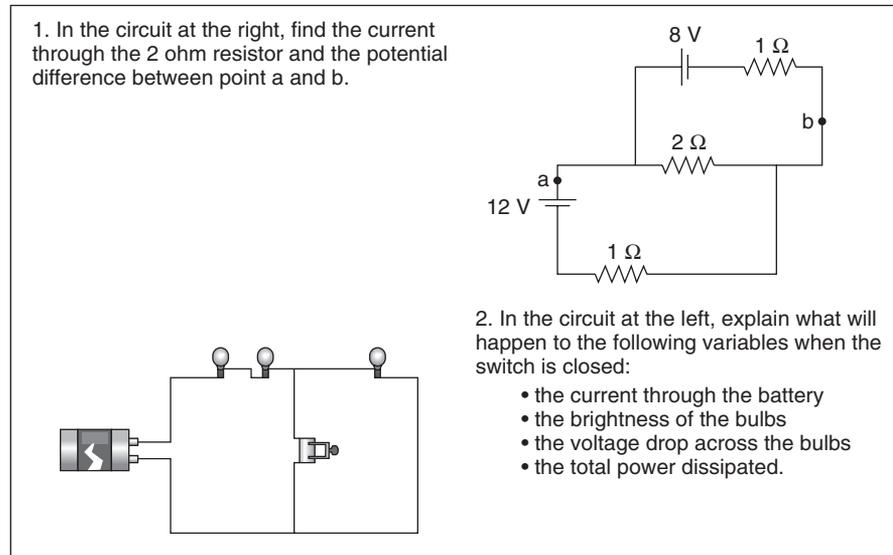


Figure 1.5 A quantitative and a qualitative problem in DC circuits (from [Mazur 1997]).

University. Mazur read the paper published by Ibrahim Halloun and David Hestenes in 1985 in which they described common student conceptual difficulties revealed by physics education research [Halloun 1985a]. Mazur was quite skeptical, being reasonably satisfied with the grades his students achieved on his examinations. Halloun and Hestenes had included a survey instrument in their paper, a 29-item multiple-choice test probing students' understanding of fundamental concepts in mechanics.¹¹ Mazur looked at the questions and found them trivial. He was certain his Harvard students would have no trouble with any of the questions. He decided to give the test to his introductory physics class after appropriate instruction [Mazur 1992]. Upon looking at the questions, one student asked: "Professor Mazur, how should I answer these questions? According to what you taught us, or by the way I *think* about these things?"¹² Mazur was appalled at how many "trivial" questions his students missed. (See, for example, the problem shown in Figure 4.1.) He began to look at his teaching as a research problem.

Mazur went on to study and document in detail the difference between the algorithmic problem-solving skills his students displayed and the conceptual understanding that he had been assuming automatically came along for the ride [Mazur 1997]. On an examination to his algebra-based physics class, he gave the problems shown in Figure 1.5.

¹¹An updated version of this exam, the Force Concept Inventory (FCI), is on the Resource CD distributed with this volume. Also see the discussion of the FCI in chapter 5.

¹²This confirms both Mazur's and my prejudice that Harvard students are good students. Many students have this same dichotomy but are not aware that it exists. The Harvard students actually did well on the exam—given our current understanding of what can be expected on this exam after traditional instruction—just not as well as Mazur expected.

The average score on the first problem was 75%; the average score on the second was 40%. Students found problem 2 much more difficult than problem 1, despite the fact that most physicists would consider the analysis of the second problem, the short circuit, much simpler; indeed, parts of it might be considered trivial. This study and many others¹³ show that students frequently can solve complex algorithmic problems without having a good understanding of the physics.

Before his epiphany, Mazur was a popular and entertaining lecturer. After his encounter with physics education research, he became a superb and effective *teacher*.

I wouldn't have believed it if I hadn't seen it

I can provide a second example of the value of the community exchange of research results from my personal experience. When Arnold Arons' book on teaching physics [Arons 1990] first appeared, I was absolutely delighted. Although I was not yet a physics education researcher, I had had a strong interest in physics teaching for many years. I had read many of Arons' papers and had great respect for them. I read the book cover to cover and annotated it heavily. In chapter 6 (p. 152) you will find the sentence: "This paves the way for eliminating misconceptions such as repulsion between a north magnet pole and a positive electric charge, and so on." I wasn't very worried about this. It isn't even underlined in my copy of Arons. (I underlined about a fifth of the sentences in that chapter.)

But in January of 1994, the Physics Education Group (PEG) at the University of Washington reported the results of a study of engineering students' responses to being taught about magnets [Krause 1995]. Traditionally, many teachers and textbook writers assume, just as I did, that students know little about the subject, so a good way to introduce it is by analogy with electric charge, the topic typically presented just before magnetism. The Washington PEG demonstrated that before the lectures on magnetism, more than 80% of their engineering students confused electric charges and magnetic poles as measured by the simple problem shown in Figure 1.6. After traditional instruction, this number remained above 50%. I was both flabbergasted and distressed at hearing this. I had taught the subject off and on for nearly 25 years and was teaching it at the time of the presentation. Furthermore, I believed that I listened carefully to students, and I was already sensitized to the issue that students bring their previous knowledge to any new learning experience. Yet I had never imagined such a confusion was common. I probed my class upon my return and, needless to say, found exactly the same results as the Washington group.

The Arons book is still one of the best "teacher-to-teacher" books available. But despite my respect for Arons' insights, I was skeptical about the importance of a possible student confusion between electric charge and magnetic poles. Indeed, I felt my personal experience contradicted it. The point was only convincingly brought home to me by the solid experimental data offered by the UWPEG.¹⁴

¹³For example, [Halloun 1985b].

¹⁴Note further that this result had been known previously and even published, but not in a journal that I looked at regularly or that was conveniently available. See [Maloney 1985].

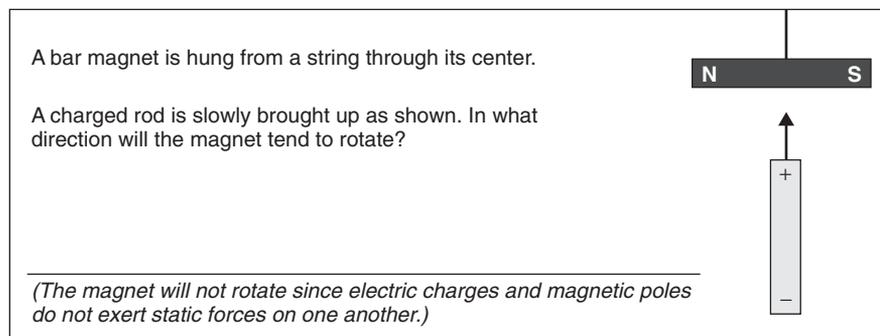


Figure 1.6 Problem that reveals student confusions about electric and magnetic poles.

SOME CAVEATS

Education research deals with an extremely complex system. At present, neither the educational phenomenology growing out of observations of student behavior nor the cognitive science growing out of observations of individual responses in highly controlled (and sometimes contrived) experiments has led to a single consistent theoretical framework. Indeed, it is sometimes hard to know what to infer from some particular detailed experimental results.

Yet those of us in physics know well that advancement in science is a continual dance between the partners of theory and experiment, first one leading, then the other. It is not sufficient to collect data into a “wizard’s book” of everything that happens. That’s not science. Neither is it science to spout high-blown theories untainted by “reality checks.” Science must build a clear and coherent picture of what is happening at the same time as it continually confirms and calibrates that picture against the real world.

At present, the combination of education research, cognitive research, and neuroscience does not provide us with a consistent or coherent picture of how students’ minds function when they learn physics. Indeed, many problems have been caused by inappropriately generalizing observations or by interpreting some tentative psychological theory as hard and fast. Using rules generated by behavioral research incautiously without reference to continual checks against experimental data (in the classroom!) can lead us to the wrong conclusions.

But in many cases, educational research has been able to tell us what does *not* work. And although it does not provide prescriptive solutions, I have found that the results of educational research and cognitive science help me to organize my thinking about my students and to refocus my attention. Instead of concentrating only on the organization of the physics content, I now also pay attention to what my students are doing when they interact with a physics course. This is not to suggest that an emphasis on content is somehow unimportant or should be neglected. What we are teaching is important, but it must be viewed in the context of how our students learn.

WHAT THIS BOOK IS ABOUT

In this book, my goal is to provide a guide for teachers of physics who are interested in implementing some of the best modern methods that have been developed as a result of the community's taking a scientific approach to figuring out how to teach physics. The elements of the Physics Suite (as well as some others that match well and are easily integrated into a course using Suite elements) are discussed in chapters 6–10.

It is important to realize, however, that although excellent student-centered approaches to teaching physics have been developed, none of them are “plug-and-play.” Student-centered instruction doesn't mean students are left on their own to do whatever they choose. These modern approaches require that instructors provide their students with substantial guidance and learn to work with their students in new ways. That requires that the instructor be reasonably well informed about the premises and methods that are being used.

Most of the literature that backs up these new methods discusses student difficulties together with explicit data documenting the frequencies and environments in which those difficulties occur, when they are known. (See the Resource Letter on Physics Education Research on the Resource CD distributed with this volume [McDermott 1999].)

As a theoretical physicist, I am uncomfortable with providing masses of data without trying to put them into a theoretical frame. Having such a frame helps make sense both of what is seen in the research literature and what is seen in the classroom. The appropriate frame for making sense of educational data is an understanding of how students (and people in general) think and reason. Therefore, I include a fairly extensive chapter on the relevant elements of cognitive science and their implication for instruction (chapter 2). This may seem strange as a component of what is essentially a physics book, but teaching physics is not only about physics: it is also about how we *think* about physics.

So it would be useful to have some understanding of how our students think. Sagredo is nervous about this. “I studied psychology in college. It was all about silly, unrepeatable things like dreams or irrelevant things like rats running mazes. There were all kinds of conflicting schools and fads that came and went. Is there anything really useful there for us?” Yes, Sagredo, I too took psychology in college (in 1960) and came away mostly disappointed, but much has happened since then. There are still schools and conflicting opinions, but interestingly enough, there is beginning to emerge a broad consensus, at least on a number of elements that can be useful for us.

In the next two chapters, I discuss those elements of a cognitive model of thinking and learning that are relevant for physics education, and I give guidelines and heuristics that can help us better understand and improve our teaching.