

# Introductory Physics for Teachers of Physics

## *Preface*

*Everything you care about in life is always one generation from extinction.*

Joel Pugh

Unlike most textbooks, this work is *not* intended to represent a body of material to be presented to your classes. As implied by the title, this is a work *for you*, providing most (at least) of the material you should know before attempting to lead a class of students through the mysteries of physics.

In one sense, there is a great body of knowledge, preserved for eternity in books and journals, which new generations may read and rediscover and build upon. But history has shown numerous instances in which new, fundamentally correct ideas have been rejected because of a widespread belief in some earlier misinterpretation. Science does not uniformly move forward. Without a spark of curiosity and critical guidance to avoid the pitfalls and blind alleys followed by centuries of predecessors, it is unlikely that newcomers to the field will be able to maintain, much less to advance, physics relative to its current level of achievement.

Who will lead us to a higher overview of the field? Many who start will fall by the wayside, becoming observers, consumers and, we may hope, supporters of science and technology. Some will become practitioners who will carry on the level of technology that civilization has learned to expect, perhaps contributing minor advances and inadvertently placing minor roadblocks. Some few will ask key questions to push understanding forward.

Can we encourage those questions? Can we build doubt in the minds of those who are able and willing to reexamine what we thought we understood? Can we help our students to appreciate the difference between “Believe this, because I said so” and “Believe this because this critical experiment shows it must be this way and/or logic requires it must work this way”?

Children are born with a strong sense of curiosity. Can we encourage that curiosity, while revealing some of the answers they seek, without squelching their sense of exploration? Einstein expressed his attitude toward creation and science with the question, “Did God have any choice?” Could the universe have been constructed any differently from the model of it we have constructed in our minds? As teachers, that’s the question we must always keep before us, and the question we must keep before our students as they travel the road behind us and, we hope, overtake and pass our own level of understanding.

### **Methods**

For nearly a century, there has been a succession of reports that the “discovery”, or “project”, method is more effective than simply telling students what they do not know. On the one hand, it seems illogical. If students are not exposed to important topics, how can we expect them to

know? On the other hand, it is almost obvious. Teaching and learning are distinct processes, and of these, learning must be regarded as more important. Most of our learning occurs outside of the classroom, in graduate research and/or on-the-job experience, in a largely self-directed discovery format. Experience has shown that the guide to learning does not lie so much with what the teacher does and thinks as with what the student does and thinks.

The studies reported quite generally agree that students involved in project learning do better across the board, not just in the area encompassed within the projects. Reading such reports leads quite naturally to the question, “If the alternative method is so much better, why doesn’t everyone teach that way?”

The first answer a teacher encounters is that project learning is, at least initially, more difficult because it requires more effort, and ingenuity, than traditional methods. Finding, and subsequently organizing, suitable projects requires imagination, a good understanding of the material to be investigated, and a grasp of the abilities of students to research, analyze, and carry through the study. Graduate research, which is typically organized as project learning, is generally restricted to carefully selected students who have mastered the basics of the particular subject, and even then is not always as successful as anticipated.

A second difficulty is more serious for teachers of introductory physics. The material we expect students to master is very well defined, as presented in the many textbooks published for these courses. The history professor may argue that a student who has explored one aspect of 17<sup>th</sup> century European history is well prepared to continue with a quite different aspect of the subject, and perhaps even ready to carry out a similar study of 16<sup>th</sup> century Chinese history. No one is expected to know *all* of history so the method of acquiring information is critical. There is a widespread suspicion, even, that there is validity to the story of the economics professor who was able to give the same final exam every year — because the answers were different each year. While we may believe our methods of presentation improve and some of our insights continue to increase, basic physics is not substantially different from half a century ago. There are certain fundamental ideas that the student must learn before continuing. Yet there appears to be a consensus among teachers experienced in this area that project learning and textbooks are largely incompatible. By discovery learning we do not mean finding the page on which the answer is presented. If we supply answers, we frustrate the attempt at discovery learning.

More fundamental, however, is the character of the subject matter. It is simply not true (despite claims often seen to the contrary) that if students make observations in the laboratory, the “truth” will be revealed. For tens or hundreds of thousands of years, people dropped objects, launched missiles, and carried out other observations with ensuing discussions of the results. Yet, from this extensive effort, not one experimenter was able to understand the basic principles of motion and how motion changes until Newton and his colleagues grasped the fundamental concepts in the late 17<sup>th</sup> century. And even Newton required many years and many collaborators. Few, indeed, of our students can claim a mental capacity to match or surpass Newton. The students do need guidance, even with “discovery” teaching. If we do not supply answers, the chance of students achieving understanding becomes vanishingly small. The primary source of the necessary information is the textbook, rivaled only by lectures. Yet these generally get in the way of discovery learning or project learning. Compromise is necessary, if we expect a high percentage of the learners to reach an acceptable level of understanding.

Keep in mind, also, the well documented “Hawthorne effect”. Students and workers perform better when they believe those in control have made a change for their benefit.

## Presentation

If we believe (as most do) that teachers teach the way they are taught, then a course on teaching physics should apply the methods we envision the new teachers adopting as their own in the classroom. What compromise is necessary and/or appropriate for letting students learn while providing guidance that will get them to the desired level of understanding?

This trial version of “Introductory Physics for Teachers” seeks such a compromise, emphasizing how the material should be presented to students which means, typically, the kinds of questions to be raised in the minds of the students as they meet new material.

First, each chapter begins with a very brief consideration of why this topic is important **to students**, followed by some comments about things the **teacher** should watch for. This is followed by a “pre-test” to give you some indication of whether this material is really new or something you have met many times before.

Second, most chapters begin with one or more questions intended to start the learner along the path of inquiry in parallel with acquisition of basic structure. The amount of serious inquiry will vary for each reader, of course, as will the level of success in achieving insight into the topic. The questions are followed by a structured presentation that emphasizes what “real” students are likely to think about the topic, based on past classroom experiences.

One effective scheme for student-directed learning is the Guided Design plan of Charles Wales and his colleagues at the University of West Virginia. Very limited experience with application of this technique to physics has shown that it can be very helpful. It has been adapted to an introductory non-calculus class exploring motions in the solar system, to small-group projects on electric meters and, less fully, to explorations of optics and some elementary considerations of thermodynamics. It certainly should be considered among other options for student-centered teaching.

The most popular new technique is called “modeling”, based in large part on “white boarding” whereby students develop and expose their developing constructs in real time before their classmates. A slower pace provides an opportunity for construction of a more thorough conceptual foundation in those topics that are covered.

The goal of the introductory course is to put students on a valid track toward learning and understanding, preferably having acquired tools that will assist their further progress. If, when you get into the classroom, whether the primary thrust of the course is conventional or project learning, you find your students have avoided the pitfalls and enjoyed the successes, you will be able to congratulate yourself on a job well done. If you recognize that your students make the same errors as most others, at least you will be prepared to recognize the difficulties, know that these are not new misunderstandings, and take corrective action.

Where possible it will be helpful to undertake this correction with carefully chosen questions. We have nature on our side in this. There is only one<sup>1</sup> correct physics model to describe the

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<sup>1</sup> As discussed in section 2.1, physics is a summary of observations of the universe. We have only one accessible universe, and therefore only one physics. The primary exception would

universe, which means that almost any error of understanding of physics will lead to contradictions. Ideally, as a teacher you can lead students to see those contradictions, provided they set for themselves a standard of requiring logical consistency. In practice, you can sometimes lead students to see the errors of their misinterpretations.

### **Topical Layout**

Current physics is more interesting than the physics before 1900. The problem is that the language of physics is built upon the earlier discoveries, and is more easily understood as it applies to objects that can be seen, touched, and measured in the elementary laboratory.

Accordingly, the discussion here begins at the beginning. However, you will very likely notice that the approach here is quite different from traditional textbooks, which typically emphasize only 17<sup>th</sup> and 18<sup>th</sup> century physics during the first semester, borrowing heavily from the 19<sup>th</sup> century concept of energy. Physics does fit together to give a coherent picture, but only if it is correct. We know now that many of the assumptions of earlier centuries were incorrect, and therefore inconsistent with each other. In particular, some of the most fundamental concepts of physics are still expressed in the language developed before there was any understanding of the fundamental principles. Some of these represent hurdles that today make real understanding more difficult.

In the present work, there is a serious effort to be honest with the reader, so that by the end of each chapter, the elementary concepts have not only been introduced but have been put into a modern context, showing how they fit with more modern views. It is all well and good that students should encounter the “obvious” solution in kinematics that velocities can simply be added together, but it is better if they recognize this “obvious” solution is not really true; it is only an approximation. Momentum is a fundamental concept in dynamics, but students should recognize that some of the rules for momentum are different when the objects are very small. It is helpful to learn that force times distance is important, but it is at least as important to recognize that force times distance often has nothing to do with work.

We begin by introducing terminology and notation (Chapter 1), then give a brief preview of the primary building blocks of physics (Chapter 2). Think of this as looking at a map to see the overall layout of where we are headed, before plunging in to get a more detailed feeling for the features of the land. This survey is followed by a look at the tools students must have to understand new material, emphasizing some points often inappropriately taken for granted, such as necessary and sufficient conditions, proportionality, and spatial visualization (Chapter 3)<sup>2</sup>.

Chapter 4 looks at how we describe motion (linear kinematics), followed in Chapter 5 by a consideration of what causes changes in motion, the “break-through” discovery on which Newton laid the groundwork of the entire subject of physics. Motion in curved paths (Chapter 6) is

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be in certain new physics disciplines still under development, where alternative models are under active consideration.

<sup>2</sup> It is a bit unnerving to discover an entire class of experienced physics teachers (educated in all parts of the country), as well as colleagues writing and reviewing papers in physics, who lack these background concepts.

critically important in all branches of physics, but requires special attention because it brings in new variables and synthesizes kinematics (of Chapter 4) with dynamics (of Chapter 5). It also serves as preparation for introduction of energy (Chapter 7) and its transfer (Chapter 8), striving for a better understanding of elementary processes, which have continued to cause misunderstandings as attempts are made to simplify the topic amid new theoretical developments. The introductory unit is concluded with a consideration of why things happen, a critical question seldom considered in beginning courses and often mis-stated by “experts”.

One must be particularly careful to avoid the “popularization” approach to physics that teaches fantasy. Fantasy is easier to accept than solid physics because no one expects it to really fit with anything else. For example, one author describes the struggle to understand Einstein’s relativity (from a book “for simple readers”). The struggle appeared hopeless until she suddenly recognized the mass-energy relationship could be treated like the disappearance of an individual in one country and appearance, in altered “substance”, in another location. No one expects such a transportation to be consistent with other experience, so by analogy she could accept disappearance of mass and appearance of energy. The two “models” are equally logical, and are equally false, by all careful examinations. When we leave science and turn to fantasy, anything becomes possible. Do not lead students down that path!

### Coverage

Topics to be covered in an introductory course are generally agreed upon in only a broad sense. There are textbooks, and teachers, who choose to largely skip problems involving rotations. Certainly many courses omit almost all physics beyond 1900, or touch on these topics only at the end of the course.

Selection of subject matter here has been based primarily on three criteria.

- a. Is it part of the standard curriculum (or implicit in the topics normally covered in the standard curriculum); or
- b. Is it likely to be part of the questions in students’ minds, based on their readings in newspapers or other material out of class; or
- c. Will it help students to understand the material, especially from the first category?

For example, there are some topics included that typically are covered only in later courses, such as physical chemistry. Chemistry majors can rely on having such a course included in their curriculum, but not all students in introductory physics will be chemistry majors. Most physics majors and, perforce, those with less than a full major in physics or chemistry, are unlikely to see this material. Therefore some of the fundamental topics typically included in physical chemistry that satisfy the other criteria have been included. Also, whereas standard courses generally ignore geodesics, it is difficult to argue that a student without some exposure to the concepts of general relativity and the reason for its development from special relativity will grasp the significance of current studies of the role of mass and energy as a foundation for the Newtonian concept of force. Nor will students be likely to understand current discussions of space, time, and dark matter without some background in this area. At the least, the more advanced topics may be treated as frosting on the cake, or as pointing out where some of the tools for more advanced work are stored if they turn out to be needed.

It is only fair to point out, also, that a number of topics appear because the author, in

retrospect, wishes someone had been able to clarify these topics for him nearer the beginning of his teaching career.

## **Help**

Everyone teaching a physics course has had a first time. It can be a bit intimidating, especially for those with less than a full physics major as background. It is important to know that there are many experienced physics teachers, and organizations of teachers, that are willing to help. As a teacher you probably recognize that there are few experiences as pleasant as being able to communicate information you know to someone else who wants and needs that information. Teachers like to help teachers, as well as their students. Don't hesitate to take advantage of the help available.

The present resource is one form of that help. It is designed to get you "up and running" as quickly as possible, while covering the nitty-gritty details of material to be presented and methods of presenting it, starting at the beginning. In short, these are the topics you will be presenting (or, in some instances, background for the primary topics). To present the topics, you must have a clear understanding. Thus, the subject matter may look much like a presentation for students, but with the distinction that we assume here that you have a better background than most students and therefore it is not necessary to spend time on algebra, graphing, and other preparation. If the discussion leads to a desire for greater depth, an attempt has been made to offer background reading that goes well beyond traditional introductory course material.

Keep in mind, also, that *The Physics Teacher* emphasizes laboratory and demonstration apparatus and techniques and "hooks" that practicing teachers have found helpful to improve attention and comprehension by their students. *The American Journal of Physics* places less emphasis on pedagogy and more on deeper understanding of physics topics encountered in the undergraduate curriculum. *Physics Education*, a British publication, deserves more attention than it usually receives in the U.S. Papers presented at the national and regional meetings of *The American Association of Physics Teachers* are a major source of new information, as well as an invaluable source of contacts with other physics teachers. In some regions of the country, *The American Physical Society* also provides a meeting place and information for physics teachers, as do state academies of science and local meetings of teachers. The Internet is typically a first step toward locating these and other contact points.

Above all, remember that physics should be fun, for you and for your students. Preparation for examinations and later courses is important, but the best preparation is to get students interested in the topics they encounter and help them to explore what those topics mean for them in their daily activities.

## **Audience**

The present discussion makes the basic assumption that to teach introductory physics, one should have a grasp of the essential qualities of introductory physics beyond the superficial acquaintance expected from a conventional introductory textbook. Physics is based on a logical structure. The student who grasps that logical structure will have an easier, and more rewarding, time than the student who views the course as a recipe for problem solving, with many apparently arbitrary steps and ingredients.

It is not difficult, if one looks, to find inconsistencies in nearly all introductory-level textbooks.<sup>3</sup> Why do our students not find these? Are they being taught to look for gaps in the logical structure (or is the implicit message: memorize it now, and you can think about it next year)?

Unlike most introductory textbooks, there has been a sincere effort to achieve the goal set by Feynman and Leighton<sup>4</sup>, that is that there should be “nothing in this book that has to be ‘unlearned.’” That suggests a challenge for the reader. The field of introductory physics includes many topics, most of which can be described at many levels of sophistication (and there is certainly no claim that the discussion reaches to the most complex levels of any of these topics). On a chapter by chapter basis, have we succeeded in achieving a level of honesty such that, while leaving some topics open-ended, nothing here must later be unlearned. Are there hidden or subtle conflicts that have been overlooked? If so, can you find them, to help us eliminate them?

This is the essence of the challenge to those who venture into the physics classroom. Can we convince our students that there is a consistent logical structure to the subject we teach? Can we raise a generation of “trouble makers” who will look for and question inconsistencies? Such teaching is not always easy, but it can be more fun!

Robert P. Bauman  
Birmingham, July, 2007

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<sup>3</sup> See, for example, Robert P. Bauman, “Physics that Textbook Writers Usually Get Wrong,” *Phys. Teach.* "I. Work", **30**, 264-269, "II. Heat and Energy", **30**, 353-356, "III. Forces and Vectors", **30**, 402-407 (May, Sept., Oct., 1992); and Robert P. Bauman, *The Tiger and the Physicist*, American Assoc. of Physics Teachers, *in press*.

<sup>4</sup> Richard P. Feynman, *QED*, Princeton Science Library, 1985; p. xxiii.

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## Glossary

The following terms are defined within the text, but require special attention, or definition.

**conserved:** A “conserved” quantity is *always* constant for *the universe*, or for the *system and its surroundings*. (In general, it is not constant for the system.)

**factitious:** A factitious quantity is carefully *defined, for a special purpose*. (By contrast, a *fictional* quantity, such as a fairy or a troll, has uncertain properties.)

**heat:** A term related to transfer, or to the effects, of thermal energy. An undefined, or multiply defined, quantity. Because it has several different meanings, one can only guess, from the context, what the author intended.

**isolated:** A sometimes convenient label for careless description, but not defined. No measurements could be made on an isolated system.

**physical particle:** Any object (of any size) that can change its kinetic energy, *only*.

**preserved:** A preserved quantity is constant for the system during the process under consideration. (A “constant of the motion”, although there may be no motion.)

**work:** A measure of the amount of energy transferred, between a system and its surroundings, because of a force acting through a distance. (A force times a distance may, or may not, be equal to work done.)

## Symbols

$\sim$	proportional to ( <i>cf. similar</i> )
$\approx$	approximately equal to ( <i>cf. congruent</i> )
$\infty$	infinity
$\bar{Z} = \langle Z \rangle$	= average value of $Z$

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