1

INTRODUCTION

1.1 OVERVIEW

What is *Six Ideas That Shaped Physics?*

Six Ideas That Shaped Physics is a new approach to the two-semester calculus-based introductory physics course, developed with the support of the Introductory University Physics Project (IUPP). It represents the culmination of over a decade of development, testing, and evaluation at Pomona College. The course was officially tested by IUPP at University of Minnesota during 1991/92 and at Amherst and Smith Colleges during 1992/93. The course has also been tested at a number of colleges and universities before publication of the first edition, including Pomona College, Smith College, St. Lawrence University, Beloit College, Hope College, Franklin and Marshall College, and UC-Davis. Feedback from these early users have helped shape the material before you.

***Six Ideas* is more than just a textbook**

Six Ideas That Shaped Physics is more than just a new introductory physics text: it offers a comprehensive plan for the entire course, suggesting tested ideas for organizing classes, homework assignments and lab experiences in ways that help students more effectively learn. The text and teaching materials use notation, terminology, and arguments consciously designed to help students avoid well-known conceptual problems; provide exercises that focus on developing students' conceptual knowledge and problem-solving skills; and provide tools to help involve students in active learning both inside and outside the classroom.

This manual is meant to offer ideas and guidance as you adapt the course

Even so, there is no single way to use these materials effectively, and you will have to shape the course in your own way. The purpose of this instructor's manual is to offer what we have learned in teaching the course so far and provide you guidance and ideas that might help you adapt the text and course for your institution. This manual is divided into the following chapters:

An annotated list of chapters in this manual

1. ***Introduction*** (this chapter) summarizes the structure, features, and goals of the course, pointing to other chapters for details.
2. ***Using the Text*** lists and discusses the rationale for features of the text and offers suggestions on how the text might be most effectively used.
3. ***In the Classroom*** looks at ways of encouraging active learning even in large classes.
4. ***Evaluation*** offers suggestions for designing homework assignments, exams that guide students toward effective learning behaviors.
5. ***Thoughts about Labs*** discusses the merits and problems of the laboratory program we developed for the *Six Ideas* course.
6. ***Putting It All Together*** summarizes the things to keep in mind when creating a course plan, and discusses an example syllabus
7. ***Content Issues*** discusses the rationale behind the selection and order of topics presented in the text.
8. ***Answers to Problems*** provides short answers to all two-minute problems and homework problems, in a form that you can duplicate to hand out to students if and when you like.
9. ***Problem Solutions*** provides complete, worked-out solutions for all homework problems.
10. ***Sample Exams*** provides a set of two exams for each unit that were used at Pomona College recently.

1.2 GOALS AND PRINCIPLES

Shortcomings of the traditional introductory course

For more than 30 years, the majority of introductory calculus-based physics courses taught in the United States have been based on a certain model of the course that I will call the "traditional" course. The textbook for such a course closely follows the outline and general approach used in Halliday and Resnick's classic text. Class sessions in a traditional course are commonly devoted to lectures and demonstrations with little student involvement. A student in such a course is often expected to do homework that is typically graded on the basis of how well they did the problem on their first attempt (or maybe only on whether they got the correct numerical answer).

This traditional introductory physics course structure has a number of problems that researchers have carefully documented in recent years. Pressures from users wanting specific topics have caused texts to grow to the point that there is so much material to "cover" that students do not have time to develop a deep understanding of any part, and instructors do not have time to use classroom techniques that would help students really learn. Even with all this material, the traditional course, focused as it is on *classical* physics, does not effectively show what physics is like *today*, and thus presents a skewed picture of the discipline to the 32 out of 33 students nationwide who never take another physics course.

But the most important shortcoming of the traditional course is that it generally fails to *teach physics*. Studies have shown that even students who earn high grades in a traditional introductory physics course often cannot

Four skills that a physics course should teach

1. apply basic physical principles to realistic situations,
2. solve realistic problems,
3. perceive or resolve contradictions involving their preconceptions,
4. organize the ideas of physics hierarchically

What such students *do* effectively learn is to solve standard homework-type problems either by searching for analogous examples in the text and copying them without much understanding, and/or doing a random search through the text for a formula that has the right variables. The high pace of the course drives students to adopt these kinds of non-thinking behaviors even if they don't want to.

These problems exist not necessarily because the traditional course was poorly designed but at least partly because both the context for the introductory physics course and the type of students taking it are dramatically different now then they were in the Cold War context of the early 1960s when the traditional course was designed. The course now serves a larger number of students, who bring a much broader range of skills and motivations to it. It is also much more important now than before that even the students who are not destined to be rocket scientists (and never take another physics course) carry away from the course an understanding of physics that will serve them in a wide range of employment and societal contexts (This might include making informed decisions about the funding of physics research, which was not much of an issue during the Cold War!) This starkly different context for the course thus calls for a strikingly different approach.

The IUPP project

In response to this problem, John Rigden and others founded the Introductory University Physics Project. The purpose of this NSF-funded project was to gather physicists from around the nation to discuss how we might change our approach to teaching the calculus-based introductory course at the eve of the 21st century. Between 1987 and 1995, project participants reviewed the current state of the introductory course, developed some principles outlining a different general approach to the course, held conferences on various issues associated with the course, requested proposals for new model curricula, selected a subset of proposed curricula (including *Six Ideas*) and supported their further development, formally tested these curricula in 1991/92 and 1992/93, and set up an independent team to evaluate the results and make them available to the community. (For more details about the IUPP and the evaluation team reports, see the articles about the IUPP listed in the bibliography at the end of this chapter.)

Some design principles

Since *Six Ideas* was created in the context of this project, I designed the course to be consistent with three basic principles articulated by the IUPP steering committee early in the project:

1. **The pace of the course should be reduced** so that a broader range of students can achieve a desirable level of competence and satisfaction.
2. **There should be more contemporary physics** in the course to give students a clearer picture of what physics is like as a discipline and motivate student interest.
3. **The course should use one or more "story lines"** to motivate student interest and help students understand how the ideas of physics are logically connected.

The design of *Six Ideas* was also strongly driven by a fourth principle that was much discussed but never quite explicitly endorsed by IUPP:

4. **The course should embrace what educational research has to say** about conceptual and structural problems with the traditional course.

Finally, to make the course practical in the broadest range of situations, I also took the following as a basic principle:

5. **The course should stake out a middle ground** between the traditional course and exciting but radical courses that require substantial investments in infrastructure and/or training. It should be useful in fairly standard teaching environments and should be easy to adopt and use.

The course's fundamental philosophical principle

But the design of the *Six Ideas* course was fundamentally driven by a deeper philosophical principle that lies behind the essentially objective principles listed above: the principle that the introductory calculus-based physics course should serve *all* of the students taking it (not just the ones that go on to higher-level courses) and serve them not just by teaching physics content (and, one hopes, developing their enthusiasm for the subject) but also by teaching the physical reasoning skills they need to really *use* that content in future contexts. Facts and formulas quickly vanish from students' minds, but a course that develops their reasoning skills gives them a gift that can last a lifetime.

The most fundamental goal of the *Six Ideas That Shaped Physics* texts and this instructor's manual is therefore to provide you with the tools to construct an introductory course that more effectively teaches a broad range of students the four thinking skills listed on the previous page. The *Six Ideas* text provides a nontraditional and thoroughly contemporary approach to the subject that helps students confront preconceptions and organize the ideas hierarchically. This instructor's manual will help you use the features of the text effectively and structure your course in ways that help students actively practice and master physical reasoning skills in realistic contexts, so that they can carry away something useful from the course even if this is their only exposure to physics.

A sports (or music) metaphor for this course

Focusing on skills as opposed to factual content requires a shift in attitude on the part of both the instructor and the students. I often describe this attitude shift to my students using the following analogy. In this course, doing the reading, coming to class, and doing homework are like *practicing* for something like a soccer team (or musical group). The instructor is less a source of information and more a coach (or conductor) who structures practice and sets standards. Moreover, participants progress not by absorbing information but rather by practicing the skills individually and learning to work effectively with others. The exams are like league games (or concerts) where students test their skills in a situation where performance counts. In this approach, the instructor is not so much the students' evaluator as an ally in helping them develop their strengths.

1.3 COURSE DESIGN ISSUES

Creating an effective course involves resolving course design questions

I have tried very hard to create a textbook that expresses the philosophy just described (and plan to talk about some of the ways that it does so shortly). However, I would like to emphasize first that creating a course that *effectively* teaches physics thinking skills requires more than choosing an appropriate textbook: *all* aspects of the course (the text, the syllabus, the homework, the exams, and the way that the students are evaluated) must work together to help students practice the skills and reward them when they learn effectively. One of the most important things that we learned in the IUPP trials is how strongly structural elements like these drive students' attitudes and performance.

Example: How can I make students come to class prepared?

For example, one of the robust results of educational research is that lectures are generally inefficient in conveying information to most students, and are even less effective at teaching reasoning skills. If we want to devote at least some class time to the kind of active-learning exercises that more effectively teach reasoning skills, then students must primarily learn the course content from reading the text. Because of this, I have tried very hard to create a text that not only provides resources for active learning but can serve effectively as the primary source of information. But no matter how well the *text* is designed, the *course* will fail if students do not prepare for the active-learning exercises in class by reading and thinking about the text ahead of time. One of the basic course-design questions that you as an instructor have to resolve is thus ***"How can I most effectively ensure that students come to class prepared?"***

Example: How can I assign tough problems without being discouraging

As a second example, consider the goal of helping students learn to apply physics principles effectively to realistic contexts. The *Six Ideas* text supports this goal by offering a variety of homework problems that require the student to do just that. But such problems are typically much more difficult than the plug-and-chug problems that one often finds in traditional textbooks, partly because by their very nature, they do not fit into patterns that students can learn by rote. But this means that getting a good homework grade depends on turning in a complete and correct solution the first time, students will likely become very very frustrated and discouraged. (This happened to a couple of the teachers who tested the course, and the consequences were not happy!) A basic course-design problem to be resolved is thus ***"How can I structure homework assignments so that students can practice tough problems and learn from their mistakes without becoming discouraged?"***

A list of other questions to think about

Here are some other course-design and teaching questions that one should probably think about before stepping into the classroom on the first day:

3. What can I do in the classroom that will help students effectively practice physics thinking skills, particularly in a large class?
4. What can I do to make students feel more free to ask questions and participate in class discussion?
5. How can I find out what difficulties students are having with the text and effectively address those difficulties in class?
6. How do I handle students who don't want to participate in activities? How should I handle students who don't come to class at all?
7. Do I want to *require* students to attend? Do I want to give them points for attending? If I don't do either of these things, what can I do to make students *want* to attend?
8. How can I resist the natural internal and external pressures to lecture?
9. How can I help students understand and appreciate the differences between this course and other science courses that they may have taken, and help them adjust their study habits appropriately?

10. How can I make demonstrations an opportunity for active learning?
11. How quickly should I move through the material? Can my students handle the design pace of the course (see below), or does the pace need to be reduced? If so, what is the best way to reduce the pace?
12. How can I use computers most effectively in the course? How should I use computers during class sessions? Should I assign computer work outside of class? What kind of computer-based assignments work?
13. How can I structure recitation sections to encourage collaborative problem-solving and motivate students to participate?
14. What standards do I want to enforce for the quality of work on homework assignments? What do I want students to get out of these assignments? How can I most efficiently assign grades and manage the paper-flow associated with such assignments?
15. What kinds of rules do I want to establish for late assignments? How can I build an appropriate amount of flexibility into these rules?
16. How can I create exams that (a) reward successful application of physics thinking skills, (b) are long enough to test a variety of such skills, (c) are short enough so that students can complete them in a reasonable time, (d) are hard enough to be challenging, (e) are easy enough so that students don't get discouraged, and (f) are nonetheless easy to grade?
17. What kinds of things can I do to get my students excited about physics?
18. How are student attitudes affected by my evaluation methods, and how can I help keep those attitudes positive (without giving all of them A's)?
19. (Assuming you have responsibility for the laboratory part of the course) What are my goals for the laboratory portion of the course? How can I design laboratory exercises that address these goals?
20. Finally, how can I address all of these concerns while keeping the course structure simple, flexible, and elegant?

Careful consideration of these issues is important!

Let me emphasize again that careful consideration of these questions can be *very* important. One of the most surprising things that we learned in the early trials of *Six Ideas* is that details about course structure (particularly about how students are evaluated) can influence beyond their seeming significance students' attitudes and success in the course. For example, students will quickly find the least time-consuming way to get a good grade in the course: it thus is essential that homework and tests be designed so that the *easiest* way to finish them satisfactorily is also the *right* way. Care in planning a course can thus pay off handsomely in terms of both positive attitudes and good performance.

This manual will provide ideas, not definitive answers to these questions

My goal in this manual is *not* to provide definitive answers to any of the questions listed above: such answers depend too much on things like the culture of your institution, your personal teaching style, the abilities and interests of your students, the quality of assistants you have available, and even the architecture of your teaching space. Instead, my aim is to raise these questions for your consideration, discuss them in the context of a *Six Ideas* course, and offer some possible solutions that might be consistent with the goals of the course. Chapters 2 through 6 of this teaching manual are devoted to a detailed exploration of precisely these kinds of issues.

Please contribute to the discussion!

Eventually, I hope that you will be able to contribute to the community discussion of these issues by offering your own insights for publication on one of our web sites! (See the Quick Guide at the beginning of this manual or the preface in any text unit for the URL to the *Six Ideas* web site.)

1.4 AN OVERVIEW OF THE TEXT UNITS

An overview of the six units of the text

The full version of *Six Ideas That Shaped Physics* is divided into six units (three per semester). The purpose of each unit is to explore in depth a single idea that has changed the course of physics during the past three centuries. The following list gives each unit's letter name, its length (where 1 d = one day ≡ one 50-minute class session), the idea, and the corresponding general area of physics.

First Semester (37 class days excluding exam days):

Unit *C*	(14 d)	*Conservation Laws Constrain Interactions*	(conservation laws)
Unit *N*	(13 d)	*The Laws of Physics are Universal*	(forces and motion)
Unit *R*	(10 d)	*The Laws of Physics are Frame-Independent*	(special relativity)

Second Semester (42 class days excluding exam days):

Unit *E*	(16 d)	*Electric and Magnetic Fields are Unified*	(electrodynamics)
Unit *Q*	(15 d)	*Particles Behave Like Waves*	(quantum physics)
Unit *T*	(9 d)	*Some Processes are Irreversible*	(statistical physics)

Dividing the course into such units was my way of addressing the "storyline" IUPP principle. The core idea in each unit provides students with motivation and a sense of direction, and helps keep everyone focused. Moreover, this structure helps make it clear that some ideas and principles in physics are more important than others, and that in physics knowledge has a fundamentally hierarchical organization. This theme is emphasized throughout the course.

Descriptions of each unit

Here is an overview of the fundamental content and emphasis of each unit:

Unit *C* (*Conservation Laws Constrain Interactions*): This unit discusses conservation of momentum, energy, and angular momentum as fundamental laws. The unit introduces vectors and the concept of velocity, but does not deal with acceleration or the full details of kinematics and avoids any significant use of calculus. This section draws heavily on metaphors of momentum, energy, and angular momentum as "stuff" that is transported or transformed by interactions. The focus on interactions lays the foundation for an understanding Newton's laws in a way that makes it harder to fall into standard misconceptions.

Unit *N* (*The Laws of Physics are Universal*): This unit provides an introduction to the kinematics of acceleration and the newtonian model of how a single object responds to an external force. The unit culminates in a description of orbital mechanics and a discussion of the newtonian synthesis of terrestrial and celestial mechanics. This unit carefully develops vector calculus.

Unit *R* (*The Laws of Physics are Frame-Independent*): This unit is a modern exposition of special relativity that unfolds in a step-by-step manner the logical consequences of the assertion that the laws of physics are the same in every inertial reference frame, culminating in a discussion of the ultimate speed limit and conservation of four-momentum. The approach relies heavily on the use of spacetime diagrams and geometric analogies.

Unit *E* (*Electric and Magnetic Fields are Unified*): The first part of this unit carefully develops the concept of time-independent electric and magnetic *fields*, culminating in a discussion of Gauss's and Ampere's laws. The second part discusses why the principle of relativity requires that electric and magnetic fields are linked, how relativity implies that we must Gauss's and Ampere's laws for the cases of time-dependent fields, and the implications of these changes, including induction and electromagnetic waves. (Students need to understand only the relativistic concepts of Lorentz contraction and the fact that nothing can go faster than light to understand the arguments in this unit.)

Unit *Q* (*Particles Behave Like Waves*). In its current form, this unit starts with an introduction to superposition and interference of waves. A study of the photoelectric effect, electron interference, and the behavior of spinning particles leads to a discussion of the principles of quantum physics, which are then applied to atomic and nuclear physics.

Unit *T* (*Some Processes are Irreversible*) This unit describes thermal physics from a mostly microscopic viewpoint, with special emphasis on the statistical interpretation of entropy. The unit ends with a general derivation of the maximum possible efficiency of a heat engine using only the second law of thermodynamics and a discussion of the implications of this limitation.

Comments on the non-standard order and unit letter names

The non-traditional order of these units has evolved in response to observations of early trials. The rationale behind this ordering is discussed briefly in the preface to each text unit and much more fully in chapter 7 (***Some Content Issues***) of this manual. These units are given letter-names instead of numbers to make it more natural for you to omit units or teach them in a different order if that is helpful in your institutional context. Chapter 2 (***Using the Text***) discusses your options in this regard in much more detail.

This course is not really a survey course

Even though (for mostly practical reasons) the six units span the main subject areas of physics, the point is not to survey the discipline so much as it is to explore the six core ideas: this strong unit structure gives the course a very different texture than that of a traditional course. Moreover, the first two IUPP principles mandate a reduction in the pace of the course while increasing the proportion of the course devoted to contemporary physics. The only way to reconcile these contradictory goals is to cut a lot of the classical material presently "covered" in the traditional survey course. Yet cutting is very difficult: every topic has its enthusiastic defenders, and every cut has implications for student who need to take the MCATs, meet engineering requirements, prepare for the physics major, and so on. I have attempted to address these problems in two ways.

I have reduced the pace by cutting topics...

One is to simply bite the bullet and cut major topics. I have chosen (for a variety of reasons) to cut virtually everything about fluid mechanics and sound, most of rotational mechanics, most electrical engineering topics, everything about surface and line integrals, geometric optics, light polarization, and so on. Chapter 7 (***Some Content Issues***) discusses some of the rationale behind these particular choices for omission. Please note, however, that *Six Ideas* does provide a firm foundation for further study in all of these topics (for example, the wave material in unit *Q* can support further discussion of sound, optics, etc.).

... and also by streamlining what remained

My second approach was to simplify and streamline the presentation of topics that *are* discussed. A typical chapter in a traditional textbook is crammed with interesting but tangential issues, applications, and assertions (which some of my friends have come to call *factons*). The core idea of each *Six Ideas* unit provides a handy filter for reducing the number density of factons: virtually everything that is not *essential* for developing that idea has simply been eliminated. This greatly reduces the "conceptual noise" encountered by students, helping them focus on learning the really *essential* ideas at a lower perceived pace.

Because of its conversational writing style and other pedagogical features, the total page count of the *Six Ideas* texts is similar to that of a traditional text, but if you compare typical chapters discussing the same general material, I think that you will find that the *density* of concepts in the *Six Ideas* text is much lower than in a typical traditional text, leading to a more gentle perceived pace.

This course is *not* a "dumbed down" version of the traditional course

While I have tried to reduce the pace and make the ideas more accessible, I have emphatically not designed *Six Ideas* course to be a "dumbed-down" version of the traditional course. Its aim is not to require *less* of students, but rather to enable them to do *more* by leading them progressively to more sophisticated reasoning skills. The design pace (one text chapter per day) makes for a pretty challenging course, appropriate for relatively well-prepared students at good colleges and universities. It can be adapted for a broader range of students by removing material and proceeding at a gentler pace. Chapter 2 of this manual (***Using the Text***) offers a detailed discussion of ways to adjust the pace.

Its level is similar to the traditional course but its expectations are not

The level of the *Six Ideas* text is intended to be roughly the same as a typical traditional textbook, though with differences in emphasis and expectations. The *Six Ideas* text strongly emphasizes qualitative concepts, model-building, and logical reasoning relative to traditional texts, and de-emphasizes memorization of facts and formulas. It is much more explicit about describing general processes for successfully solving problems, but deliberately less likely to provide examples to be slavishly followed.

Pedogogical features of the text

The text has many features that not only help it replace lectures as students' primary source of information in the course but also positively contribute to the development of model-building and problem-solving skills, help students organize ideas hierarchically, encourage qualitative as well as quantitative thinking, and support active learning both inside and outside of class. These text features are discussed briefly in the *Introduction for Students* in each unit and much more fully in the Online Preface and chapter 2 (***Using the Text***).

1.5 LABS

This manual suggests guidelines rather than specifying a lab program

The IUPP participants all agreed that a good lab program is an essential part of the introductory course. Rather than offer a specific set of developed laboratory exercises, I chose to design (and test) a set of *guidelines* for developing a sequence of labs that progressively build lab skills (with particular emphasis on writing and uncertainty analysis). My intention is to provide you with these guidelines (and an example of a lab program realizing these guidelines) and let you design your own program appropriate to your own institution.

While these guidelines proved to be successful in greatly improving students' understanding of experimental uncertainty and writing skills, students' *attitudes* about the lab were not as positive as we had hoped, and results from other IUPP trials have offered some interesting alternatives to ponder. These issues are discussed in chapter 5 (***In the Laboratory***) of this manual.

1.6 EVIDENCE OF EFFECTIVENESS

You might be encouraged to know that hard evidence we have collected in recent years seems to indicate that a properly-structured *Six Ideas* course can indeed effectively teach students to correctly apply the concepts of newtonian mechanics (at least). In this section we review some of the evidence for this claim.

The Force Concept Inventory (FCI) test

We have recently been giving our students Halloun and Hestenes' *Force Concept Inventory* (FCI) test both before and after the first semester to measure students' gain in understanding (see the bibliography for the source of this test). The FCI is a purely qualitative test of a student's ability to apply newtonian concepts to simple everyday situations (and reject alternative non-newtonian explanations). The questions *look* so easy that many professors are initially confident that their introductory students will be able to answer them perfectly, but in fact *post*-instruction scores range from below 50% in some traditional-format high-school classes to about 80% in the best college and university programs.

FCI data from around the nation

A recent article by Richard Hake (see the bibliography) argues that the most useful measure for comparing the gains on the FCI test achieved by various classes at various institutions is the *normalized gain* g, defined to be the actual gain in a class' average test score (from pre-test to post-test) divided by the maximum possible gain (the perfect score minus the initial class average). For a set of 14 traditional courses from around the nation, Hake found that the normalized gain was $g = 0.23 \pm 0.04$ (note the narrow range!).

FCI data for *Six Ideas* students

In contrast, the normalized gains on the FCI test for *Six Ideas* students at both Pomona College and Ohio State University in recent years have ranged from about 0.55 to over 0.72. The latter result (observed in Ulrich Heinz's classes at Ohio State during the fall of 2001) is comparable to the best gains reported in the literature for even the very best active-learning classes. For more detailed and up-to-date information, see the *Six Ideas* web site.

1.7 A BIBLIOGRAPHY

My fourth principle committed me to use as fully as I could what I knew about the most recent research done concerning physics education. Much of what I know I learned at IUPP-related conferences and conferences of the American Association of Physics Teachers (AAPT), but here is a bibliography of some important published books and articles on the subject for your further study (and also so that you can see something of the roots of many of the ideas in the rest of this instructor's manual).

Books About Teaching Introductory Physics:

A. B. Arons, *Teaching Introductory Physics,* New York: Wiley, 1997.

E. Mazur, *Peer Instruction: A User's Manual,* Upper Saddle River: Prentice-Hall, 1997. (Note that Eric and I have independently developed very similar approaches to active-learning activities in large-classroom settings.)

S. Tobias, *They're Not Dumb, They're Different: Stalking the Second Tier,* Tucson: Research Corporation, 1990.

About the IUPP Project:

J. S. Rigden, D. F. Holcomb, and R. Di Stephano, "The Introductory University Physics Project," *Phys. Today* **46**(4), 32-37 (1993).

R. Di Stefano, "The IUPP evaluation: what we were trying to learn and how we were trying to learn it," *Am. J. Phys* **64**(1), 49-57 (1996).

R. Di Stefano, "Preliminary IUPP results: Student reactions to in-class demonstrations and to the presentation of coherent themes," *Am. J. Phys.* **64**(1), 58-68 (1996).

L. A. Coleman, D. F. Holcomb, and J. S. Rigden, "The Introductory University Physics Project 1987-1995: What has it accomplished?" *Am. J. Phys.* **66**(2), pp. 124-137 (1998).

Articles about the Force Concept Inventory (FCI) Test

D. Hestenes, M. Wells, and G. Swackhamer, "Force Concept Inventory," *Phys. Teacher* **30**(3) 141-158 (1992). (Eric Mazur's book, described above, contains a more recent revision of this test.)

D. Hestenes and M. Wells, "A Mechanics Baseline Test," *Phys. Teacher* **30**(3) 159-166 (1992). (This test is similar to the FCI except that it is more quantitative and thus less suited for use before instruction.)

A. M. Saperstein, "Learning via Study versus Learning via Living," *Phys. Teacher* **33**(1), 26-27 (1995). (Uses FCI data to argue that people in their late teens learn some newtonian mechanics simply by life experience.)

D. Huffman and P. Heller, "What does the Force Concept Inventory Actually Measure?" *Phys. Teacher* **33**(3) 138-143 (1995).

D. Hestenes and I. Halloun, "Interpreting the Force Concept Inventory: A Response to the March 1995 Critique by Huffman and Heller," *Phys. Teacher* **33**(8) 502, 504-506 (1995).

D. Huffman and P. Heller, "Interpreting the Force Concept Inventory: A Reply to Hestenes and Halloun," *Phys. Teacher* **33**(8) 503, 511-517 (1995).

R. R. Hake, "Interactive-engagement versus traditional methods: a six-thousand-student survey of mechanics test data for introductory physics courses," *Am. J. Phys.* **66**(1), 64-74 (1998).

Selected Articles about Research into Science Education

(This is just a sampling of articles about science education research, mostly from *American Journal of Physics.* An enormous amount has been written on the subject in the last 20 years. The *International Journal of Science Education* is also a noteworthy source of articles.]

D. Hestenes, “Wherefore a Science of Teaching,” Phys. Teach. **17**, 235-242 (1979).

D. E. Trowbridge and L. C. McDermott, “Investigation of student understanding of the concept of velocity in one dimension,” *Am. J. Phys.* **48**, 1020-1028 (1980).

D. E. Trowbridge and L. C. McDermott, “Investigation of student understanding of the concept of acceleration in one dimension,” *Am. J. Phys.* **49**, 242-253 (1980).

J. Clement, “Students’ preconceptions in introductory mechanics,” *Am. J. Phys.* **50**(1), 66-71 (1982).

M. McClosky, “Intuitive Physics,” *Sci. Am.* **248**(4) 122-130 (1983).

L. C. McDermott, “Research on conceptual understanding in mechanics,” *Phys. Today* **37**(7), 24-32 (1984).

I. Halloun and D. Hestenes, “The initial knowledge state of college physics students,” *Am. J. Phys.* **53**(11), 1043-1055 (1985).

I. Halloun and D. Hestenes, “Common-sense concepts about motion,” *Am. J. Phys.* **53**(11), 1056-1065 (1985).

R. A. Lawson and L. C. McDermott, “Student understanding of the work-energy and impulse-momentum theorems,” *Am. J. Phys.* **55**(9), 811-817 (1987).

R. R. Hake “Promoting student crossover to the Newtonian world,” *Am. J. Phys.* **55**(10), 878-884 (1987).

S. Tobias and R. R. Hake, “Professors as physics students: What can they teach us?” *Am. J. Phys.* **56**(9), 786-794 (1988).

D. Hammer, “Two approaches to learning physics,” *Phys. Teacher* **27**(12), 664-670 (1989). (This is a very sobering and important paper.)

L. C. McDermott, “Millikan Lecture 1990: What we teach and what is learned — closing the gap,” *Am. J. Phys.* **59**(4), 301-315 (1991).

A. Van Heuvelen, “Learning to think like a physicist: a review of research-based instructional strategies,” **59**(10), 891-897 (1991).

S. Tobias, “Guest Comment: Science education reform: What’s wrong with the process?” *Am. J. Phys.* **60**(8), 679-681 (1992).

L. C. McDermott and P. S. Shaffer, “Research as a guide for curriculum development: An example from introductory electricity, parts I and II,” *Am. J. Phys.* **60**(10), 994-1013 (1992). [See also *Am. J. Phys.* **61**(1), 81 (1993).]

L. C. McDermott, “How we teach and how students learn — a mismatch?” *Am. J. Phys.* **61**(4), 295-298 (1993).

L. C. McDermott, P. S. Shaffer, and M. C. Somers, “Research as a guide for teaching introductory mechanics: an illustration in the context of the Atwood’s machine,” *Am. J. Phys.* **62**(1), 46-65 (1994).

R. Beichner, “Testing student interpretation of kinematics graphs,” *Am. J. Phys.* **62**(8), 750-762 (1994).

E. F. Redish, “Implications of cognitive studies for teaching physics,” *Am. J. Phys.* **62**(9), 796-803 (1994).

F. Reif, “Millikan Lecture 1994: Understanding and teaching important scientific thought processes,” *Am. J. Phys.* **63**(1), 17-32 (1995).

D. Hammer, “More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for educational research,” *Am. J. Phys.* **64**(12), 1316-1325 (1996).

E. Bagno and Bat-Sheva Eylon, “From problem-solving to a knowledge structure: An example from the domain of electromagnetism,” *Am. J. Phys.* **65**(8), 726-736 (1997).

T. O’Brien Pride, S. Vokos, and L. C. McDermott, “The challenge of matching learning assessments to teaching goals: An example from the work-energy and impulse momentum theorems,” *Am. J. Phys.* **66**(2), 147-157 (1998).

R. T. Thornton and D. R. Sokoloff, “Assessing and improving student learning of Newton’s laws: the Force and Motion Conceptual Evaluation and the evaluation of active learning laboratory and lecture curricula,” *Am. J. Phys.* **66**(4), 338-351 (1998).

L. C. McDermott and E. F. Redish, “Resource Letter PER-1: Physics Education Research,” *Am. J. Phys.* **67**(9), 562-573 (1999).

A. Elby, “Another reason that physics students learn by rote,” *Am. J. Phys. Suppl.* **67**(7), S52-S57 (1999).

S. Vokos, P. S. Shaffer, B. S. Ambrose, and L. C. McDermott, “Student understanding of the wave nature of matter: Diffraction and Interference of Particles,” *Am. J. Phys. Suppl.* **68**(7), S42-S51 (2000).

D. Hammer, “Student resources for learning introductory physics,” *Am. J. Phys. Suppl.* **68**(7), S52-S59 (2000).

D. P. Maloney, T. L. O’Kuma, C. J. Hieggelke, A. Van Heuvelen, “Surveying students’ conceptual knowledge of electricity and magnetism,” *Am. J. Phys. Suppl.* **69**(7), S12-S23 (2001).

R. E. Scherr, P. S. Shaffer, S. Vokos, “Student understanding of time in special relativity: Simultaneity and reference frames,” *Am. J. Phys. Suppl.* **69**(7), S24-S35 (2001).

A. Elby, “Helping students learn how to learn,” *Am. J. Phys. Suppl.* **69**(7), S54-S64 (2001).

E. Kim and S-J. Pak, “Students do not overcome conceptual difficulty after solving 1000 traditional problems,” *Am. J. Phys.* **70**(7), 759-765 (2002).

Selected Articles on Collaborative and Active Learning

P. Heller, R. Keith, and S. Anderson, “Teaching problem-solving through cooperative grouping. 1. Group versus individual problem solving,” *Am. J. Phys.* **60**(7), 627-636 (1992).

P. Heller and M. Hollabaugh, “Teaching problem-solving through cooperative grouping. 2. Designing problems and structuring groups,” *Am. J. Phys.* **60**(7), 637-644 (1992). (This paper was particularly important in shaping my thinking about collaborative recitation sessions.)

B. Thacker, E. Kim, K. Trefz, and S. M. Lea, “Comparing problem-solving performance of students in inquiry-based and traditional introductory physics students,” *Am. J. Phys.* **62**(7), 627-633 (1994).

D. E. Meltzer and K. Manivannan, "Promoting Interactivity in Physics Lecture Classes," *Phys. Teacher* **34**(3), 72-76 (1996). (Note that I was already using essentially this method in the 1992 pre-edition of *Six Ideas*.)

E. F. Redish, J. M. Saul, and R. N. Steinberg, "On the effectiveness of active-engagement microcomputer-based laboratories," *Am. J. Phys.* **65**(1), 45-54 (1997).

P. W. Laws, "Millikan Lecture 1996: Promoting active learning based on physics education research in introductory physics courses," *Am. J. Phys.* **65**(1), 13-21 (1997).

D. R. Sokoloff and R. K. Thornton, "Using Interactive Lecture Demonstrations to Create and Active Learning Environment" *Phys. Teacher* **35**(6), 340-347. (Conference presentations leading up to this paper greatly influenced my approach to doing demonstrations during class.)

Other Selected Articles and Books Describing Alternative Approaches to Teaching Introductory Calculus-Based Physics

R. K. Thornton and D. R. Sokoloff, "Learning Motion concepts using real-time microcomputer-based laboratory tools," *Am. J. Phys.* **58**(10), 858-867 (1990). (This alternative approach to the physics laboratory lead eventually to D. R. Sokoloff, P. W. Laws, and R. K. Thornton, *Real-Time Physics: Active-Learning Laboratories*, Portland: Vernier Software, 1992.)

A. Van Heuvelen, "Overview, Case Study Physics," *Am. J. Phys.* **59**(10), 898-907 (1998). (Alan and his OCS approach strongly influenced my approach to problem-solving frameworks and the organization of *Six Ideas.)*

P. W. Laws, "Calculus-Based Physics Without Lectures," *Phys. Today* **44**(12), 24-31 (1991). (This article describes *Workshop Physics*, perhaps the best of the fairly radical approaches to the introductory physics course.)

R. W. Chabay, and B. A. Sherwood, *Matter and Interactions*, New York: Wiley, 2002. (This book, as well as the articles and talks by Sherwood and Chabay leading up to it, has strongly influenced my approach to presenting electricity and magnetism.)

D. V. Schroeder and T. A. Moore, "A different approach to introducing statistical mechanics," *Am. J. Phys.* **65**(1), 26-35 (1997). (This article discusses the general approach to statistical mechanics used in Unit *T*.)

P. Laws et. al., *Workshop Physics Activity Guide*, New York: Wiley, 1997.

F. Reif, *Understanding Basic Mechanics*, and *Understanding Basic Mechanics Workbook*, New York: Wiley, 1997.

R. D. Knight, *Physics: A Contemporary Perspective*, preliminary edition, Reading MA, Addison-Wesley-Longman, 1997.

A. Van Heuvelen, "Experiment Problems for Mechanics," *Phys. Teacher* **33**(3) 176-180 (1995).

Reviews of Preliminary *Six Ideas* Materials

M. M. Payne, "Book Review — *A Traveler's Guide to Spacetime*: An Introduction to Special Relativity by Thomas A. Moore," *Am. J. Phys.* **64**(5), 668-670 (1995). (Unit *R* is based on this text.)

J. Amato, "The Introductory Calculus-Based Physics Textbook," *Phys. Today* **49**(12), 46-51 (1996). (In addition to reviewing a preliminary version of *Six Ideas,* it reviews many of the other texts mentioned above.)