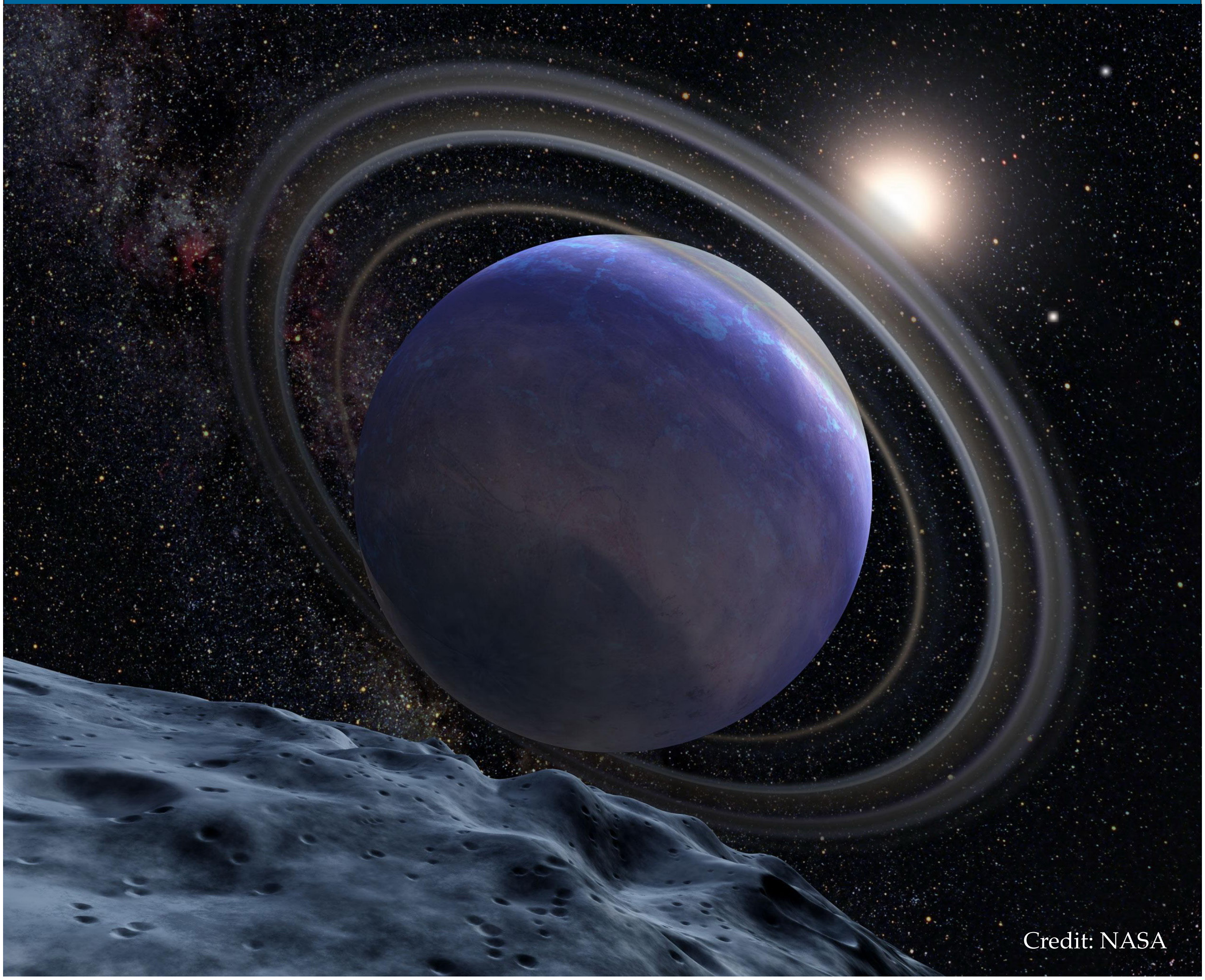
Six Ideas That Shaped Physics

Third Edition

Instructor's Manual



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Contents: *Instructor's Manual*

M1

Introduction

M1.1 What Is *Six Ideas That Shaped Physics*?

Six Ideas goals

Six Ideas That Shaped Physics is more than a textbook. It is an entire structure of connected materials that supports an innovative approach to the college-level calculus-based introductory physics course that helps students

- See physics from a thoroughly 21st-century perspective,
- Appreciate crucial 20th century developments in physics,
- Understand the hierarchical nature of physics concepts,
- Understand modeling as a core scientific activity,
- Sidestep well-known conceptual errors,
- Develop strength and confidence in solving problems, and
- Practice truly thinking like physicists

by using *active, student-centered* and *research-based* learning methods both inside and outside the classroom. It represents the culmination of more than 25 years of experimentation and discovery about *what really works* in inspiring students to greater levels of achievement.

Course materials

The integrated set of course materials include

- A six-volume textbook (or eBook),
- Web-based computer software,
- Detailed problem solutions,
- Web-based support for two tested approaches to homework,
- Supplementary text materials (pending),
- Lesson plans and worksheets (pending), and
- Guidance for both students and instructors

You can access resources other than the textbook (or eBook) from the main *Six Ideas* website at:

www.physics.pomona.edu/sixideas/

This instructor's manual provides an overview of all of these materials and how to use them in creating an actual course.

Students can meet high standards in a well-designed course

By thoughtfully deploying the materials and designing assignments, one can create (calculus-based) introductory physics courses having many different topic sequences and a wide range of levels. Even so, the materials seek to make physics more accessible not by "dumbing down" the presentation but by rather by providing tools and resources for making students *smarter*. The materials intentionally set higher-than-usual standards for sophistication in students' physical thinking, but a well-designed course can make achieving those standards practical at almost any institution. The purpose of this manual is to help you create such a well-designed course.

The goal of this particular chapter is to provide an overview of the *Six Ideas* structure to help you understand the big picture), while pointing to places in the manual where features are discussed in greater depth.

M1.2 Making Time for an Active Classroom

Creating an active classroom is key to student success

Creating an active classroom is the key to achieving these goals. Perhaps the single most important and robust result of more than three decades of physics education research is that students learn physics measurably better in classrooms where they actively practice physical reasoning for themselves while getting prompt feedback from expert thinkers.

"Flipping" the classroom creates time for such activities

Making time for such activities in class means significantly cutting back (or even eliminating) class time spent lecturing. But students do need to learn the concepts and ideas that form the basis for what they are practicing. This requires what has recently been called "flipping" the classroom: instead of hearing the ideas and concepts in a lecture during class and practicing thinking outside of class (on homework assignments), students in a "flipped" classroom learn the concepts and ideas *outside* of class and practice using them *in* class (as well as on homework assignments).

The *Six Ideas* textbook is designed to replace lectures

"Flipping" a course can be done in two different ways. The method most commonly associated with the term is to record one's lectures as videos and make them available online. The *Six Ideas* approach, however, is to have the *textbook* serve the role of presenting the ideas and concepts.

One reason this approach is less common is *most* textbooks are ill-suited to replace a lecture: they are usually not written in a discursive style, and do not deliver logically complete chunks of information corresponding to the length of a class session (like a lecture can). However, the *Six Ideas* texts have been deliberately and carefully designed to serve as replacements for lecture. The writing style is deliberately expansive and more "lecture-like" than the tight encyclopedic prose of many texts. Each chapter is also a logical unit appropriate for exploration in a single class session (indeed, a student can read a chapter in roughly 50 minutes at a normal reading speed). These features make it easier for students to learn the concepts from the text.

Features that make the textbook *better* than a lecture

The textbook also offers a number of features that make it a *better* source of concepts and ideas than a lecture:

- A two-page chapter opener provides an overview and review.
- Formula boxes highlight important equations and emphasize that each has a conceptual context, specific uses, and important limitations.
- Wide margins provide space for students to write notes and questions.
- Marginal notes guides the reader and help with locating ideas.
- Problem-solving checklists and annotated examples illustrate expert-like problem-solving skills.
- The layout pays careful attention to what is on facing pages to make reading easier.
- Exercises (with answers) help students practice active-reading skills.

Chapter M2 on "Using the Textbook" discusses these features (and how you can encourage students to use them) in more detail.

Roadblocks to "flipping" and how to overcome them

Another reason that textbooks are rarely used to replace lecture is that, empirically, students will not spontaneously read a textbook unless somehow compelled (though the same may also be true about online lectures). Chapter M3 on "Best Practices" describes several empirically successful methods for strongly motivating students to read before class.

Lectures can also be psychologically comforting for both professors and students even when ineffective. Understanding the psychological pressures to lecture and know how to convince students (and yourself) of the value of active learning and why it is worth the effort makes moving to an active classroom easier. One must also understand when lectures *are* appropriate. The "Best Practices" chapter also discusses these issues in depth.

M1.3 Support for Creating an Active Classroom

Features that support an active classroom

The *Six Ideas* materials have a number of features that make creating an active classroom less daunting and time-consuming than it might be with a more standard textbook:

- "Two-minute problems" provide conceptual challenges for small and large-group discussion.
- The back of each volume provides a simple but flexible response system.
- Certain two-minute problems support "active demonstrations," where students make predictions before the demonstration takes place.
- Certain "Basic Skills" problems provide detailed, multi-step tasks that provide the basis for great class activities.
- The website will (eventually) provide class plans and worksheets for every chapter in the book.

Again, chapter M2 discusses these features in more detail.

Using two-minute problems (an overview)

In particular, the "two-minute problems" provide an easy and effective way to create an active classroom. These problems pose conceptual questions with multiple-choice answers, making it easy to gather responses using a response system (which might be as fancy as an electronic system or as simple as pointing to the letters that one will find on the back of each book). One only needs to select several problems, ask students to think for two minutes about the problem individually and then spend another two minutes coming to a consensus with one or two neighbors, gather classroom responses, and discuss the results to provide a valuable classroom activity. Chapter M3 discusses "best practices" for gathering responses and leading a useful and non-threatening class discussion.

Chapter M3 also discusses why worksheets, roving mentors, and small whiteboards are valuable features of an active classroom.

M1.4 Homework as Practice

Homework problems in the *Six Ideas* books are different and need to be graded differently

Even with an active classroom, problem sets remain an essential part of students' learning experience. However, the homework problems in the *Six Ideas* textbooks are different than homework problems in many textbooks and need to be handled differently. **WARNING!** Early experience has taught us that grading *Six Ideas* homework problems solely on the basis of correctness *can cause the course to crash and burn* (in the sense that students rebel and/or tune out). The homework problems in the *Six Ideas* books are meant to serve as challenges that push students to think in new and challenging ways. When one tries new things, one often fails. A successful grading system for a *Six Ideas* problem set therefore mostly rewards the honest effort that students expend in pushing themselves, and encourages them to reflect themselves on the quality of their effort.

A sports metaphor for the process of learning physics

A metaphor that can connect with students' experience is that of learning a sport. Class activities and homework in a *Six Ideas* course are analogous to team practice. In a practice, the coach pushes players to try new skills and techniques, which will be difficult at first, but can be mastered with repetition and feedback. When one begins to learn a skill, no one expects perfection: rather one is rewarded for persistence and diligence. In this metaphor, exams correspond to league games: here one finally must display mastery of the skills they have practiced, and a good score reflects that mastery. Grading on *Six Ideas* homework and exams should reflect the differences clarified by this metaphor.

A grading system where students correct their own work

Chapter M3 on best practices describes in detail homework systems that serves all of these goals. The systems' key feature is that *students correct their own work*, using full problem solutions that they can access online. You decide what problem solutions they can see and when they can see them using an online system to create a protected list that only your students can access. Once students have corrected their own work, their solutions can be rapidly graded using a simple rubric that mostly rewards their effort (with a bit of reward for the quality and reasonableness of their initial effort).

The third edition also includes short answers to many (mostly odd-numbered) homework problems. Students can use these problems for additional practice as they study for exams.

M1.5 How the Texts are Organized

The six ideas

The *Six Ideas* textbook is organized into six units, each focused on developing a single foundational idea.

Unit C:	Conservation Laws Constrain Interactions	(Conservation laws)
Unit N:	The Laws of Physics are Universal	(Newtonian mechanics)
Unit R:	The Laws of Physics are Frame-Independent	(Special Relativity)
Unit E:	Electric and Magnetic Fields are Unified	(Electromagnetism)
Unit Q:	Particles Behave Like Waves	(Quantum Physics)
Unit T:	Some Processes are Irreversible	(Thermal Physics)

In some units (e.g. Unit R), the big idea provides the starting point, but in others is developed throughout (e.g. Unit C) or represents the final goal (e.g. Unit N). In all cases, the unit structure itself underlines the hierarchical nature of physics concepts.

Reasons for this structure: (1) Emphasizes hierarchy

There are three reasons for this organization. One is pedagogical. Students often fail to appreciate that concepts in physics are organized hierarchically, with some concepts being more important than others. They tend to perceive the ideas in an introductory physics course as being like beads on a string, touching but basically independent (just "one darned thing after another"). By organizing the course these six core ideas, the principle that physics is hierarchical is built into the course structure, which helps teach this difficult but important lesson.

(2) Convenience in carrying

The second reason is for student convenience. Introductory physics textbooks are often literally massive tomes that require significant effort to haul around in earth's gravitational field. Dividing the textbook into six units make it easier to physically carry a unit along with one and helps make each seem less daunting. The goal is to make students feel more comfortable with making the textbook a more intimate part of their lives.

(3) Curricular flexibility

The final reason is that this structure provides instructors with flexibility. Six units divide naturally into two semesters, three quarters, or three semesters. The units have letters instead of numbers because they are fairly independent and can be used in any order (after chapters C1-C6, and C8–C9).

The original design order was the one given above. This particular order has some real advantages for a two-semester course, in that the first semester ends with relativity, which is generally a lot of fun for students (which can help encourage them to enroll in the next semester). The second semester, ends with thermal physics, which is less intense and strange than either electricity and magnetism or quantum physics, and therefore puts somewhat less stress on students during a busy end of a semester. Unit R appearing before unit E and unit Q appearing before unit T also makes certain explanations in units E and T a little bit easier.

However, many other orders and sequences are possible. A sequence that would be closer to a traditional course would be CNT followed by ERQ (or perhaps a bit better, REQ). Since 2009, the introductory course at Pomona has taken a "dessert first" approach where we assign chapters C1-C6, C8-C9, followed by units R, most of Q, and most of T in the first semester, while the students who need to go over the remainder of unit C, unit N, and unit E in the second semester. A number of colleges teach "five ideas" that shaped physics (usually omitting either unit T or Q), and many people use R and Q as the basis for a modern physics course.

The third edition improves flexibility

Two of the important goals in the third edition was to make the units even more independent and also to provide instructors with more flexibility within units. For example, basic material on waves that appeared in unit E in the first two editions now properly appears in unit Q, and the treatment of electromagnetic waves in unit E now no longer depends on this material. The material within units has been reorganized in ways to allow certain chapters to be omitted without loss of continuity (this also allows instructors more flexibility in determining the course's level).

Chapter M4 of this manual (and also the prefaces to each unit) discuss how each unit is organized, what chapters may be omitted, and which chapters are needed for other units. The one universal constraint is that chapters C1–C6 and C8–C9 in unit C now provide the minimal mechanics foundation for all of the units in an introductory course where students have seen some high-school physics. Once students have worked through these chapters, one may present the remaining units pretty much as one pleases.

M1.6 Computer Applications

Types of apps

Since the beginning of the *Six Ideas* project, we have sought to take advantage of computer technology to improve students' learning experience. Advances in this technology make certain things accessible to introductory students that have been inaccessible in the past. The *Six Ideas* project includes a variety of supporting computer apps (soon to be entirely web-based) that enable new kinds of instruction. The provided apps fall into three categories:

- Apps that simulate a physical situation or illustrate a model (e.g. Drude)
- Apps that provide quick access to data (e.g. NucInfo)
- Apps that automate certain kinds of otherwise tedious calculations (e.g. Newton, StatMech, SchroSolver)

Some of these apps (particularly those in the last category) are integrated into the text presentation because they augment students' abilities in especially important ways. Others are optional.

The *Six Ideas* philosophy regarding computer apps

The *Six Ideas* project, however, does *not* require students to learn to code in any language. Requiring students to write software can provide huge benefits in principle, but also significant costs. We considered this early on but eventually rejected it, because it requires too much overhead and because even simple computer languages are not friendly enough for students to focus on the physics instead of the computer language.

Our guiding principles (particularly with apps in the final category) have rather been to

- Keep each app's task as focused and simple as possible.
- Design user interfaces to be as obvious and foolproof as possible.
- Ensure that what the app is doing is as transparent as possible.

In particular, for apps that automate certain kinds of calculations, we require (when possible at all) that each student practice the algorithm by hand before seeing the app and also verify that the app simply automates what he or she could do by hand given sufficient time. We consider this an very important principle that ensures that the student does not see the app as a black box, but rather as an extension of his or her abilities.

Three crucial apps described in the textbook

Three apps of this type are so crucial that they are discussed in the text itself: *Newton* (in unit N), *Schrosolver* (in unit Q) and *Statmech* (in unit T). Chapter N3 discusses a graphical technique for constructing the trajectory of a particle obeying Newton's second law: the *Newton* app automates this procedure and unit N deploys it often to allow students to explore situations where analytic solutions to Newton's laws are impossible. *Schrosolver* allows students to find numerical solutions to the one-dimensional time-independent Schrödinger equation and explore the basic features of such solutions and why energy is quantized in quantum mechanics. Unit T teaches students how to construct what the text calls a "macropartition table" that lists the macroscopic states available to a system consisting of a handful of harmonic oscillators and counts the number of quantum states corresponding to each macroscopic state. Once students have practiced this construction, they can use *Statmech* to automate the procedure, applying it to larger systems. This provides a crucial part of the argument that leads them to an understanding of entropy and irreversibility.

Newton and *Statmech* are currently available as web apps (see links on the Resources page of the website) and *Schrosolver* will be soon. One can visit the old *Six Ideas* site (see a link on the home page of the new site) to find desktop versions (and many others) for OS X, Windows, and Linux platforms. Our goal is (as time permits) to convert *all* of the apps currently listed on the Resources web page into web apps.

Two other apps mentioned in the textbook

MBoltz and *Planck* are also mentioned in the text and are currently available as web apps. Chapter T6 of unit T describes how to use these apps to perform certain calculations concerting the Maxwell-Boltzmann and Planck distributions. These apps are crucial if one covers this now-optional chapter.

Using WolframAlpha

WolframAlpha also makes certain symbolic calculations accessible that were not before. Units E and T in particular now take advantage of this capability to explore certain ideas that require evaluating integrals or derivatives that would be impractical for students at this level to evaluate by hand.

ProbViewer is necessary for viewing problem solutions

Please note that the *ProbViewer* app (also currently available in web app form) is essential for any homework system that involves students viewing problem solutions online.

M1.7 A Few Brief Comments about Labs

No labs

Lab exercises are a very important part of any introductory physics course. Teaching a *Six Ideas* course (particularly one involving units R and Q) may require re-sequencing a more traditional laboratory section or even creating some new labs. But a lab program also depends in unique ways on the equipment available at a given institution, the budget available for new equipment, the culture of a department, and many other factors. Because I (the author) am a theoretical physicist, I also (frankly) felt that I had no special vision or expertise to offer in this particular department.

For these reasons (and others), I decided early in this project not to attempt to offer a polished lab program as part of the *Six Ideas* package. At Pomona, I and my colleagues have (of course) developed a lab program appropriate for our current "dessert-first" course, and many other *Six Ideas* users have developed innovative lab sequences as well. I am willing to share lab materials with those who ask, and would love to facilitate a discussion among *Six Ideas* users about laboratories and to make innovative labs that others have developed available (perhaps through the *Six Ideas* website). Please contact me if you have specific questions about labs or have something interesting to share. Chapter M3 also offers a few ideas about the latest educational research about labs.

M1.8 Evaluating the Course

The unexamined course is not worth giving

A famous philosopher once said that "The unexamined course is not worth giving" (or something like that). I strongly encourage every professor not only to evaluate students' performance but also the *course's* performance in achieving its goals. Neither task is ever quite as easy as one might think it should be, but over the decades, the quantity and quality of available tools for evaluating a success in meeting certain kinds of goals has increased dramatically. This section will discuss certain tools and how to use them (and you will find more discussion in chapter M3 as well).

Customized evaluations

Before we delve into these specialized tools, though, it is worth mentioning that customized course evaluations can provide a great way to evaluate the success of certain specific features of your course design. For example, suppose that you have chosen a specific approach to encourage students to read the text before class. By asking students on an (suitably anonymous) course evaluation to describe the percentage of class days they came prepared, you can get some useful data about how well the approach worked.

Published evaluation tools

Three well-known tools for evaluating course performance are the *Force Concept Inventory* (FCI)[1], the *Basic Electricity and Magnetism Assessment* (BEMA)[2], and the *Colorado Learning Attitudes about Science Survey* (CLASS)[3]. All are multiple-choice tests that require about a half an hour for students to complete. The FCI examines how well students can apply the concepts of Newtonian physics to common situations. The BEMA is similar, except that it examines students' understanding of basic concepts of electricity and magnetism. The CLASS examines the extent to which students' attitudes and understanding of science are like those of experts. One offers these tests both before and after instruction to determine the effect of that instruction.

The advantages of these tools are that (1) they have been professionally reviewed and polished, (2) they have been given to thousands of students nationwide in a variety of contexts, and (3) one can access the results in published articles, which makes it easier to interpret the performance of your particular course.

FCI (for mechanics)

For example, an article by Richard Hake[4] discusses the difference between traditional lecture-based physics classes and what Hake calls "interactive engagement" classes (courses that involve a significant active-learning component) in terms of students' pre-instruction and post-instruction performance on the FCI. Hake defined the **normalized gain** g on the FCI to be the average increase in students' scores on the FCI divided by the average increase that would have resulted if all students had perfect scores on the post-instruction test (in fact, average post-instruction scores even at selective institutions rarely exceed 80%). After analyzing pre- and post-test results from more than 6000 students, Hake argued that the normalized gain g is a meaningful measure of how well a course teaches Newtonian ideas to students. In particular, Hake found that an introductory physics course that can be characterized as "traditional" in teaching style get average normalized gains of 0.23±0.04, a quite narrow range in spite of the wide range of student initial scores. By contrast, the normalized gains earned by "interactive engagement" courses Hake are 0.48 ± 0.14, a statistically significant difference. Hake examines and discards a number of possible explanations for these results, and concludes that the teaching methods make the difference. Hake's results make it relatively easy to assess the effectiveness of a given course relative to these norms. (A recent article[5] discusses the efficacy of half-length versions of the test, which reduces administration time.)

BEMA (for E&M)

For the BEMA, published results[6] show that pre-instruction scores rarely deviate significantly from chance independent of setting, so while a calibrating pre-test is still desirable, one can use the class-average post-instruction score directly as a measure of how well the course has taught the concepts of electricity and magnetism. Published results[7] involving 2000 students indicate that students in traditional lecture-based classes experienced scores of $46\% \pm 3\%$, those in interactive-engagement classes scored about $56\% \pm 2\%$.

CLASS (for attitudes)

The CLASS must be offered as a pre-test and post-test because the entire point is to track *changes* in students' attitudes about science. The striking result it that CLASS scores in traditional lecture-based classes typically *decrease* significantly (meaning that students attitudes become less like those of experts). Gains, even in interactive-engagement classes, are rare. However, results can depend on many factors and need to be interpreted with care.[8]

While these tools have many advantages and have gained a degree of community acceptance, they do have some disadvantages. The topics explored in a *Six Ideas* course do not completely overlap with those assumed in the FCI and BEMA. For example, the FCI does not examine students' understanding of conservation laws, which is strongly emphasized in a *Six Ideas* course. Similarly, the BEMA does not explore Maxwell's equations in much depth, and what little there is focuses on their integral formulation. We have not yet tried similarly validated tests concerning relativity, quantum physics, and thermal physics (which are more recent but do exist: see chapter M3). Even so, the FCI and BEMA can provide evidence that in spite of differences in topics and focus, *Six Ideas* courses do at least as well as other courses in teaching the standard material.

1. D. Hestenes, M. Wells, and G. Swackhammer, "Force Concept Inventory", *Phys.Teach.* **30**, 3, pp. 141-158 (1992).
2. www.compadre.org/PER/items/detail.cfm?ID=3775.
3. http://www.colorado.edu/sei/class/.
4. "Interactive engagement versus traditional methods: a six-thousand student survey of mechanics test data for introductory physics courses," *Am. J. Phys,* **66,** 1, pp. 64-74 (1998).
5. "Experimental validation of the half-length Force Concept Inventory," Jing Han,Kathleen Koenig,Lili Cui,Joseph Fritchman,Dan Li, Wanyi Sun, Zhao Fu, and Lei Bao, *Phys. Rev. ST Phys. Educ. Res*. 1**2**, 020122 (2016).
6. "Evaluating an electricity and magnetism assessment tool: Brief electricity and magnetism assessment," Lin Ding, Ruth Chabay, Bruce Sherwood, and Robert Beichner, *Phys. Rev. ST Phys. Educ. Res*. **2**, 010105 (2006).
7. "Tale of two curricula: The performance of 2000 students in introductory electromagnetism," Matthew A. Kohlmyer, Marcos D. Caballero, Richard Catrambone, Ruth Chabay, Lin Ding, Mark P. Haugan, M. Jackson Marr, Bruce Sherwood, and Michael F. Schatz, *Phys. Rev. ST Phys. Educ. Res*. **5**, 020105 (2009).
8. "A new instrument for measuring student beliefs about physics and learning physics: the Colorado Learning Attitudes about Science Survey," W. K. Adams, K. K. Perkins, N. S. Podolefsky, M. Dubson, N. D. Finkelstein, and C. E. Wieman *Phys. Rev. ST Phys. Educ. Res*. **2**, 010101 (2006).

M1.9 Evidence of Success

In this section, we discuss how *Six Ideas* courses at various institutions perform according to these tools. (Note that these are all results for the 2nd edition: we have not yet had time to gather results for the 3rd edition.)

FCI results

At Pomona College, we gave students the FCI as a pretest and a post-test in 2004 and 2006. Pomona students' pre-test scores were high to begin with (with an average score of about 75%.) Even so, we recorded the following normalized gains for those years:

Pomona College FCI g: Fall 2004: 0.59 Fall 2006: 0.68

As one can see, these normalized gains are at the high end of Hake's range for interactive-engagement courses.

We do not have more recent results because in 2009, we changed the our introductory course so that Newtonian mechanics is now spread over two semesters, making it much harder to test student progress using the FCI.

Dr. Vic DeCarlo has graciously given me permission to post unpublished results for the *Six Ideas* course at DePauw University. The normalized gains that they found for the FCI are also at the high end of Hake's "interactive-engagement" range:

DePauw University FCI g: Fall 2002: 0.58 Fall 2003: 0.60

Students achieved these gains in spite of having significantly lower pre-test scores (in the 40% to 50% range), showing that *Six Ideas* courses can work well for students having a broad range of initial preparations.

Researchers at Washington University published a paper (Cahill, et al., "Multiyear, multi-instructor evaluation of a large-class interactive-engagement curriculum," *Phys. Rev. ST Phys. Educ. Res.* **10**, 020101, 2014) that analyzes in great detail the differences between a *Six Ideas* class and a traditional introductory physics class at that institution. Classes at Washington University were significantly larger (about 120 students per section) than at Pomona and at DePauw. Pre-test FCI scores were about 65%. Technically, the researchers calculated a gain c instead of Hake's normalized gain g that is different in how it handles the scores of students who actually got worse between the pretest and post-test, but since most improved, the results should be somewhat comparable. The FCI gains c for classes in 2009-2011 were

Washington Univ. FCI c: *Six Ideas*: 0.29 ± 0.01 Trad.: 0.17 ± 0.01

Each c-gain was somewhat more than one standard deviation below Hake's average g-gain for the corresponding types of course. Even so, we do see that the *Six Ideas* course delivered a statistically significant improvement over the traditional course even in a large-classroom setting.

BEMA results

We gave the BEMA at Pomona at the end of E&M instruction using the so-called "draft 3rd edition" of unit E (which was actually quite different than the current published 3rd edition). The post-instruction final score was:

Pomona College BEMA post (Spring 2007): 58%

This is basically the same as the national post-test average for interactive-engagement courses, even though a *Six Ideas* course spends only about half as much time on electricity and magnetism as a typical introductory course.

The article by Cahill, et al. referenced above also analyzes results for the BEMA at Washington University. The final scores were

Washington Univ. BEMA post: *Six Ideas*: 39% Trad.: 38%

These are not significantly different, and both were significantly below the national average BEMA post-test score of 46%. We do not understand why the gains similar to those at Pomona were not realized at Washington University, but at least the *Six Ideas* course's shorter treatment of E&M did not adversely affect the performance of Washington University students.

CLASS results

Finally, the article by Cahill, et al. also analyzed changes in CLASS results for the traditional course and the *Six Ideas* course at Washington University. The results at the end of the fall term (2009-2011) were

Washington Univ. CLASS (Fall): *Six Ideas*: +2.3% Traditional: –3.8%

The difference was statistically significant, and (as mentioned above), actual *increases* in CLASS scores are quite rare.

Sadly, instruction in electricity and magnetism hurt things in both classes, but the downward shift in the traditional class was worse:

Washington Univ. CLASS (Spring): *Six Ideas*: –6.0% Traditional: –12.5%

The difference was again statistically significant.

Six Ideas students do as well (and usually better) on standard material in spite of spending less time on it.

The bottom line is that these tools in a number of different contexts show that students in *Six Ideas* classes do better (or at worst the same) as in traditional courses, even as they spend more time on contemporary physics topics. Large class sizes (such as those at Washington University) seem to reduce the gains, but do not erase the benefits.

We are planning to offer a new round of testing this academic year at Pomona and would welcome receiving information from your tests.

M1.10 Bibliography

This section provides a possibly useful list of resources that were important to me as I prepared various editions. At present, this list is somewhat out of date, emphasizing things that I read before preparing the first edition (1999). But I have added some later resources that I found valuable, and will add more in the future. (Chapter M3 also provides some best-practice resources.)

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:

(Note that this approach grew out of an NSF-funded review of the introductory physics course called the Introductory University Physics Project. The goals of this project were to support the development and dissemination of curricula that provided new visions for the introductory curriculum for the 21st century. *Six Ideas* is the only surviving progeny of this 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).

"Experimental validation of the half-length Force Concept Inventory," Jing Han,Kathleen Koenig,Lili Cui,Joseph Fritchman,Dan Li, Wanyi Sun, Zhao Fu, and Lei Bao, P*hys. Rev. ST Phys. Educ. Res*. 1**2**, 020122 (2016).

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 30 years. The *International Journal of Science Education* and (since 2005), *Physical Review Special Topics: Physics Education Research* (which, as of January 2016, is now named *Physical Review Physics Education Research*) are also excellent resources for peer-reviewed articles.]

Resources for the Course Philosophy and the First Edition:

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

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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).

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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).

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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).

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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).

Important articles used in preparing the 3rd edition:

J. Jewett, "Energy and the Confused Student, I–V," *Phys. Teacher,* **46** (2008) starting pages 38, 81, 149, 210, and 269 (various different issues).

R. E. Pepper, S. Chasteen, S. J. Pollock, and K. K. Perkins, "Our best juniors still struggle with Gauss's law: Characterizing their difficulties," Physics Education Research Conference (2010) Proceedings (available online at www.compadre.org/PER/items/detail.cfm?ID=10464).

M2 Using the Textbook

M2.1 Overview

The purpose of this chapter is to explore the features of the textbook in depth, discuss why they were designed as they were, and how both instructors and students can best use these features. Each volume of the *Six Ideas* textbook includes a brief two-page summary entitled "Introduction for Students" immediately preceding the first chapter: this provides a very brief treatment of some of the features that are most useful to students. But this chapter will provide a deeper exploration of the philosophy behind these features.

This chapter discusses textbook features in depth

Here is a list of the sections in this chapter:

Please note that these sections refer to features of the *printed* books. The e-book (SmartBook) version includes all of the features discussed above, but has additional features as well. I am not discussing these features at present because the SmartBook version is new even to me. I did not personally design its extra features, and have not yet had an opportunity to evaluate or develop best practices concerning these features. I hope to be able to include some discussion of the SmartBook version in future versions of this manual, but for the meantime, please contact your McGraw-Hill Higher Education representative for help concerning these features.

The e-book version has other features not discussed here

M2.2 Chapter Summaries

Each chapter in the *Six Ideas* textbook *begins* with a two-page chapter summary (occupying facing pages). This opener provides the student with a terse version of the chapter's content that provides an outline of the argument and quick access to the most important concepts and equations.

Such a summary is obviously valuable to students *after* they have read the chapter. It provides an accessible review of the chapter's core principles with the details of the argument stripped away. This means that when studying for an exam, a student will typically only need to re-read the summary rather than having to re-read the entire chapter. One can also easily jump

Chapter summaries are useful for studying and review from the summary to the chapter (guided by the section headings and marginal notes) to review details of the argument that may not be clear.

But the summaries are also good to read *before* reading the chapter

But why have I presented this summary at the *beginning* of the chapter rather than the end? One of the most difficult tasks a learner faces in encountering new material is to set it in the appropriate intellectual context. Reading the overview *before* the chapter allows one to see more clearly the context in which the chapter's argument is embedded, allowing a glimpse, if you will, of the forest before one is distracted by all the trees. This is helpful just as studying a map of a territory is helpful before actually beginning a journey. Placing the summary at the beginning therefore encourages the student to do this kind of orienteering work before *diving* into the chapter.

Remember also that a chapter is meant to replace a lecture for the purpose of exposition. Just as it would be good practice in a lecture or talk to provide an initial overview, it seems only logical to do the same here!

It also presents an alternative angle on the material

This overview also provides not only a *shorter* version of the chapter's argument, but also often a somewhat *different* angle on that argument (shaped by the requirements of brevity). Seeing the argument presented two different ways can help students develop a deeper understanding of that argument.

The opening chapter overview will therefore be most effective in achieving these goals if students read it *before* reading the chapter as well as using it as a study aid afterward. I strongly recommend that you (the instructor) encourage students to do this.

M2.3 Wide Margins and Marginal Notes

Typographers know that very wide columns of text (requiring the eye to scan large distances right to left) are difficult and tiring to read. Some full-size textbook layouts efficiently solve this problem by having the text appear in two columns (a strategy this textbook adopts for the problems at the end of the chapter). But we have deliberately chosen a less efficient layout with one column of text near the spine and wide blank margins away from the spine.

The wide margins provide space for student notes and questions

These margins serve several important purposes. The most important is that they provide space for student notes. I strongly recommend that students mark up the margins extensively with comments and (especially) questions as they read. Writing down these questions makes them more concrete in the student's mind and accessible when the student has an opportunity to get those questions answered in class, recitation, or office hours.

Writing notes and questions also plays an important role in helping students keep engaged and active when reading (see Mueller and Oppenheimer, *Psychological Science*, **25**, 6, 2014 about the specific value of handwritten notes during a lecture: the principle here should be similar). We all know how easy it is to scan text without it ever actually entering one's mind. The simple discipline of expecting oneself to develop questions about the material and writing down those questions as they occur greatly helps keep one focused on and really thinking about what one is reading. Teaching this discipline can help students become more effective readers of future textbooks as well.

Filling in the details of calculations is also a valuable habit for students to develop. I have tried to encourage this explicitly using in-chapter exercises (see below), but students can also use the margins for this purpose in places where the steps between equations may not be completely obvious.

Sidebars in the margins provide guidance

The wide margins serve other purposes as well. The marginal notes provide handles that help guide students through complicated arguments and quickly locate particular items when studying later. I have tried very hard to make these marginal comments as useful as possible.

I have also used the margins in some cases to hold small figures that would waste space if they were to occupy the full text column. This allows greater flexibility in laying out the pages.

I will say in this context that I have used that flexibility to design the layout to maximize the effectiveness of facing pages in the printed text. I have thought very carefully about how to arrange arguments so that all the information (text, figures, and equations) a reader might need for understanding a lengthy and/or tricky argument appear on a single spread of facing pages. If information (particularly figures or equations) from a previous spread is needed, I have often repeated that information on the facing pages so that the reader does not have to flip a leaf to refer back to something. I do this because I know that having to flip the page requires extra mental energy that the reader will often not likely expend, even at the cost of being fuzzy about some idea. Thinking about this therefore improves the text's readability.

The content of facing pages has been chose for maximum efficiency

M2.4 Exercises

As noted in the previous section, students in STEM fields benefit from developing habits of (1) filling in missing calculations in a textbook or article, and (2) posing internal questions that help test one's understanding. One purpose of the exercises is to nudge students in this direction. Each chapter in the *Six Ideas* text has two to four exercises that either ask students to fill in missing steps or raise a question that a student should be able to answer if he or she understands the reading. Answers to all exercises appear at the end of the chapter, so a student can get instant feedback on any attempt made.

Exercises help students develop habits of active reading

The second edition included a larger number of exercises. In this edition, I have reduced the number to an average of three (keeping only the most crucial), so that students do not see the task of actually *doing* the exercises while preparing for class quite so daunting (many of the removed exercises became Basic-level homework problems).

I strongly encourage my students to do the exercises as part of their class preparation and describe why this is valuable. Since answers are provided, I have no way of checking their effort, and I suspect many do not bother. However, the exercises are available to those willing to spend the extra effort. Also, when students complain that they have read the text but still don't understand how to do the homework, one of the things I ask is whether they have been writing marginal notes and completing the exercises.

Ways of using these exercises

M2.5 Problem-Solving Checklists

For more than 30 years, researchers have documented the differences between experts and novices in solving physics problems (modeling.asu.edu/Projects-Resources/HarperK-ExpertVsNovice.pdf provides a useful summary of some of the differences). Once one understands these differences, the question becomes: how can we most efficiently move students from novice-like problem-solving patterns to more expert-like patterns?

Providing problem-solving frameworks is a popular solution. A good framework provides something like scaffolding that helps students build the complicated mental structure involved in a solution without being overwhelmed by the cognitive task of making the all the pieces fit together in a complete and self-supporting way right from the beginning. Just as with a building, the ultimate goal is to remove the scaffolding eventually, but students can benefit from explicit scaffolding at the beginning.

Problem-solving frameworks can provide useful scaffolding for beginning students

The different approaches used in the various editions

The trick is to find the right balance between scaffolding that is sufficient to support the load without being either too confining or too specialized, and then to find the right time to remove the scaffolding. The goal is to help students see some metacognitive strategies for approaching problems, to perceive common patterns in related types of problems, and to recognize how the provided examples and problem solutions exhibit these patterns.

In the first edition, I provided students with fairly rigid and detailed frameworks for various types of problems, and tried to compel them (in various ways) to explicitly use those frameworks when writing solutions. I quickly realized that students strongly resisted this approach, partly because it involved extra work, partly because it seemed like overkill for the simple problems where it was first deployed, and partly because it actually added to their conceptual overload.

In the second edition, I tried what I thought would be a more user-friendly approach that involved a simpler and more flexible general outline and more visual and less verbal methods (such as cartoon balloons and interaction diagrams) for describing the reasoning involved in a solution. Again, I quickly learned that students were still quite unwilling to use this approach (partly, as I later recognized, because using the visual methods effectively and efficiently required already possessing the expert-like skills that the approach was trying to teach). Moreover, it proved extremely difficult in printed materials (including problem solutions) to model this approach. Finally, this approach was not really helping students develop skills that would be useful for the more general types of problems that they would encounter in non-mechanics units or in other physics courses.

In the third edition, therefore, I have adopted a prose-based and less coercive approach. Chapter C5 develops a general checklist that outlines an expert-like framework that works for almost any kind of physics problem. Various chapters in units C and N also illustrate more specific checklists for more specific types of problems. These checklists provide useful and practical guidance without coercively forcing a solution into an unnatural format. They merely specify what tasks a solution should accomplish while giving students a lot of freedom in determining how to achieve those goals.

Encouraging the students to use the framework:
(1) by example

I believe that a crucial part of making this approach effective is help students understand how examples in the text (as well as the online solutions) exemplify these checklists. Toward this end, the textbook annotates many of the examples in units C and N with color comments illustrating features of the solution that fulfill the checklist items. I strongly recommend that when you do examples in class, you refer explicitly to the checklists as you work. When students have questions on one of the homework problems, I also try to get them started by going through the checklist. I recommend that you train your TAs to respect and use the checklists where possible as well.

(2) by practice annotating solutions themselves

An essential part of this process is that students begin (at least in expert-like solutions) to recognize the patterns *themselves*. Several exercises in unit C require the students to provide their own annotation of a solution. I also strongly recommend this as a periodic class activity, perhaps as part of an activity where they also practice filling in certain missing parts of the problem.

(3) by other means yet to be explored

This approach is new enough (even to me) that I have not had time yet to develop best practices for requiring or pushing students to use the checklists themselves. In the future, I will be testing various approaches, including requiring that specific homework problems display features of the general and/or specific checklists and/or requiring students to annotate a few of their own solutions. I will report in this manual (and on the *Six Ideas* website) my reflections on the results of such trials. I'd also be happy to hear your reflections on any experiments you undertake. But one of the advantages of the current system is that it is unobtrusive enough to provide some useful guidance to students without actually requiring anything concrete from either the instructor or student.

M2.6 Two-Minute Problems

The "two-minute problems" that appear at the end of each chapter have been a feature of all editions of the *Six Ideas* textbook. These are mostly conceptual problems with multiple-choice answers, analogous to Eric Mazur's "ConcepTests" and/or the problems that appear on tests like the Force Concept Inventory. These problems challenge students to reason about new situations using the chapter's concepts.

These problems were initially designed to support active learning in class

These problems were originally designed to serve primarily as in-class activities (suitable for both large and small classrooms). When I use a two-minute problem this way, I ask students to work individually for two minutes on each problem, then work in groups for two minutes. At the end of the four-minute period, students present the group's consensus answer using some kind of classroom response system.

Using the letters on the back cover as a response system

The large letters on the back of each printed textbook provide a low-tech classroom response system. A student or student group can respond by holding the book up and pointing to the letter in question. The letters A, B, C, D, E, F, and T comprise all the possible responses to the questions in the texts (including true-false questions). The letter Z provides a response to indicate that the student or group was unable to answer the question decisively in the time allotted. This edition also includes some questions with double-letter answers (for example, AA, BB, etc.), which a student can indicate by pointing at the letter with two fingers instead of one. I myself was initially surprised by how easily one can gather responses this way, even in classrooms holding as many as two hundred students.

The purpose of the "two-minute" description

The "two-minute" designation does not necessarily imply that a given two-minute problem is easy. A few require fairly complex reasoning (meaning that few students can solve the problem correctly in two minutes), and more are deliberately misleading, meaning that students are likely to make errors without careful (perhaps time-consuming) thought.

However, I believe that most of the problems can be solved by a well-informed student in that time limit. Moreover, I strongly recommend that (as a first approximation) students *assume* that the problems require only short lines of reasoning and strive to work within this time limit. First of all, this requires students to keep focused and develop their intuitive and quick-reasoning skills. Secondly, it limits the amount of class time spent on these exercises. The main purpose of these problems as a class activity is to get students thinking and give them some curiosity about (and investment in) the answers, not *necessarily* to provide enough time for everyone to work through to the right answer. While it would be wonderful for everyone to be able to do this, the wide range of skills in any classroom means that some will be able to do this much faster than others. The trick is to find the optimal balance that delivers maximal benefit without wasting too much of most people's time. I have tried to design the problems so that two minutes is a zeroth order approximation to this sweet spot.

Other uses for these problems

Though I had originally designed these problems as classroom activities, over the years, I have found many other uses for these questions, including as quiz questions, pre-class exercises, and even as homework problems.

Some of the new two-minute problems in this edition were based on questions I originally developed for quizzes, and a number of new Basic-level problems in this edition ask students to justify the answer to certain two-minute problems. Chapter M3 discusses some other possible uses.

M2.7 Homework Problem Categories

A list of the categories

I have divided the homework problems into five different categories that make it easier for one to create homework assignments that match the level of your students. The categories are:

- Basic
- Modeling
- Derivations
- Rich Context
- Advanced

The old second-edition Synthetic category has been split into the Modeling and Derivation categories in this edition for reasons discussed below.

Basic problems

Basic problems typically require only a simple argument and/or the use of a single formula. They are good for practicing how to use a given concept or formula in a simple context. Assigning too many of these problems will not develop a student's problem-solving skills (and indeed may prompt them to adopt counterproductive strategies such as formula-hunting), but such problems can be valuable to students who are studying or who need more foundational practice before tackling more complicated problems.

Some of the Basic problems in the new edition have also been designed to serve as classroom activities. These problems typically have many parts that lead students step-by-step through a complex idea or calculation (for example, the process of summing up the dot products in a line integral). Such problems can be very valuable for helping students develop a practical understanding of certain challenging concepts.

Modeling problems (and a note of caution!)

Modeling problems generally require at least some model-building, meaning that student must deploy use general physical principles to create a reasonable physical model of a (more or less) realistic situation. Such problems almost always involve more than one equation or formula, and may even involve synthesizing ideas presented in several chapters. These are the types of problems that truly develop students' problem-solving skills. The bulk of the problems that I assign for homework are of this type.

But beware! Modeling problems can be quite challenging, particularly to first-year students who were quite successful in high school at solving problems by tweaking example solutions or applying rote patterns without understanding. One of the things we learned early on in the development of the *Six Ideas* curriculum is that a course can *actually fail* if one grades student work on such problems solely on whether the student's solution is correct. These problems are challenging enough that many students (even very good students) will not do them correctly the first time. The point of these problems is to have students learn by failing to do something hard as well as succeeding. But students become too stressed out to learn fruitfully from this unless most of their grades depend on making a good effort, with only a minor portion of the grade depending on doing the problem right the first time. Chapter M3 discusses homework grading in much more detail.

The analogy that I use with students is that doing homework is like showing up for sports practice or practicing between piano lessons. Your coach or piano teacher is not doing their job if they only assign tasks that you can perform with perfect accuracy the first time. One grows by trying, making mistakes, learning from those mistakes, and practicing again. A good coach or teacher will reward a student who puts in the time to become better at accomplishing a difficult task, and will help the student learn from profitably about how to learn from mistakes. Werner Heisenberg understood this: he is quoted as saying "An expert is someone who knows some of the worst mistakes that can be made in his subject, and how to avoid them."

Students used to tweaking example solutions will often complain that the *Six Ideas* textbooks do not include enough examples. I generally respond that the real world does not present problems in a way that can be neatly mapped to a set of examples in some textbook. Really learning how to solve problems means developing new and more subtle skills. I encourage the student to look at the provided examples not as providing a detailed algorithm that can be slavishly copied, but rather providing one example of how one might reason through a model. The pattern that the example provides is deeper and more "meta" than a detailed algorithm, and needs to be appreciated at that level. Part of the point of a college education is to help students move beyond slavish copying of examples, valuable as that is at first.

Derivation problems

Derivations are problems that also require multiple steps of reasoning and/or calculation, but not significant model-building. Rather, these problems typically involve working through a sequence of mathematical steps to arrive at a non-obvious theoretical conclusion. I do not typically assign many of these problems for homework, but in a few cases, such problems are valuable for helping students better "own" important theoretical conclusions.

The "Synthetic" category (in the first and second editions) included problems of this type along with problems where students were required to devise models for realistic situations. Since both types of problems involved synthesizing multiple concepts and/or formulas into a coherent argument, the "Synthetic" name seemed apt. But I eventually realized (as my appreciation of the importance of model-building developed) that problems involving model-building were sufficiently different from those involving derivations to make it useful to separate them into their own categories.

Rich Context problems

Rich Context problems are like modeling problems on steroids. They typically require building more complex models and/or making estimations to make up for missing information and/or decisions about what to calculate to answer a non-quantitative question. The problems describe situations that are almost always realistic (at least in a science-fiction sense) and more closely resemble the questions that real-life situations typically present.

These problems, which are typically more challenging than Modeling problems, are especially designed to be more suitable than standard problems for collaborative group work. Pat and Ken Heller at the University of Minnesota have been pioneers in educational research on collaborative learning and its benefits. A summary of their expertise on collaborative problem solving appears at http://groups.physics.umn.edu/physed/Research/CGPS/CGPSintro.htm and their discussion of what they call Context-Rich problems, and why group problem solving requires such problems appears at http://groups.physics.umn.edu/physed/Research/CRP/crintro.html.

I typically assign one or two such problems a week, and set up an opportunity for students to meet to work on these problems. However, for better or worse, I have not typically required students to do these problems in groups nor do I set up those groups as formally as the Hellers do. This may be a missed opportunity. I recommend reading the Hellers' materials very carefully and evaluate the value for your students yourself. A more detailed treatment of their work appears here: https://www.aapt.org/Conferences/newfaculty/upload/Coop-Problem-Solving-Guide.pdf.

Advanced problems

Advanced problems are mostly theoretical derivation-type problems that go well beyond the level that I would expect students to have. These problems are mostly to provide instructors guidance on how to work through more subtle theoretical issues that might come up in class and/or as challenges for very advanced students. I almost never assign problems of this type except for special students or in very unusual situations.

M2.8 Answers to Selected Problems

New in this edition is that the very last page of each volume provides short answers to selected homework problems. These are mostly odd-numbered problems, but I have omitted odd-numbered problems that provide their own short answers (often the case with derivation problems), where the short answer represents the entire answer (as is sometimes the case with basic problems), or whether the answer is a figure or something else that cannot be easily represented in short form. When only few odd-number problems are available in some categories, I have sometimes included answers to a few even-numbered problems as well.

These answers help students without allowing them to cheat

Because the short answers do not generally represent the complete answer, they provide students with the opportunity to check their work without being able to use them to cheat. For this reason, I do not worry about assigning a problem whose answer appears on this list (and sometimes I do that deliberately). The solutions I require from students are much more involved than providing a simple answer, and the grades that I assign virtually ignore the answers. I hope that students use these answers to either build their confidence or push them to think more carefully (depending on how their own answers compare).

They are also useful as a study aid

Providing these answers also gives students a useful way to study for exams. A week or more before an exam, I often provide students with a list of problems that they might work as practice for the exam, choosing problems whose answers are available. I then encourage students to contact me if they have trouble obtaining the answers provided. Even if I don't provide such a list, students will often on their own initiative study this way.

These answers are only valuable if they are correct, and sharp-eyed instructors and students have caught a number of errors in the first printing of the book. Please consult the errata and also instruct your students to do so.

M2.9 Support for Active Learning

One of my most important goals for this project was to provide instructors with resources to create an "active engagement" classroom. I have already mentioned features of the textbook that enable it to replace lectures for exposition, and that the two-minute problems and certain basic problems have been explicitly designed for use as class activities. The letters on the back cover of each book provide a simple low-tech response system that one can use to gather answers (see chapter M3 for more details).

Active demonstration

Let me also point out that some problems have also been designed to serve as active demonstrations. An active demonstration is a demonstration that requires that students predict the outcome of the demonstration beforehand, or otherwise make some kind of calculation based on a real-life situation demonstrated to them. For example, when I teach unit N, I typically show the situation depicted in problem N8T.8 (which students find perennially confusing). The students always love the nose-crushing pendulum demonstration behind problem C10T.12 (even though most can correctly predict the answer). I also often use E1M.12 as a class activity, using a demonstration to make the result more tangible to students.

The text assumes an active-learning environment

Let me also say that multiple aspects of the textbook's design assume active learning and work best only in that environment. For example, I have found by experience that teaching students how to solve Gauss's law (in either form) is extremely difficult for students to learn unless they *personally* work through a guided calculation such as problem E12M.1 in a context where they can get personalized help and feedback. Once they have done this, they become much more comfortable with similar problems.

The textbook also assumes that students have an opportunity to play with certain crucial computer applications such as Newton, StatMech, Schrosolver, and so on. I use Newton as the center of class activities in almost every class session in the latter part of unit N.

M2.10 Flexibility

Look in the preface for information about chapters that might be omitted

One of my major goals for the third edition was to increase the flexibility available to instructors to teach the units in various orders and to chose the level and/or pace of the course by omitting or including certain chapters. Each unit preface now provides detailed information about what chapters may be omitted and how the chapters depend on each other. Chapter M4 provides even more detailed information about such dependencies. I strongly recommend that you review this information carefully (with the needs and abilities of your students in mind) as you design your course.

Notes on pacing

The chapter-per-class session design provides some guidance about how to pace the course, but let me be clear. The pace of a course where one assigns one chapter per session is pretty grueling, even for very able students: this should be taken as the *maximum possible* pace, not as a normal or average pace. When possible, I recommend that you omit some chapters and devote some class days to consolidation and further practice, to allow students to catch their breath. The current design of the textbook provides even more opportunities than ever to thoughtfully set your pace and sequence of topics.

M2.11 Online Errata

Prod students to use the online errata to correct their books

I (and my colleagues at McGraw-Hill) have worked very hard to make this edition as error-free as possible, but perfection is impossible. I have posted known errata on the *Six Ideas* web site. I strongly recommend that you immediately go to those errata and make corrections in your own copy of the book, and that you recommend that students do the same. This is particularly important for the answers to selected problems appearing at the end of the book (which can otherwise badly mislead students).

One problem with the e-book version is that it is tough to manually make these corrections, so students using the e-book version will need to be especially mindful. However, I will be working with McGraw-Hill to correct errors in the e-book as quickly as possible. Keep an eye on the website for announcements about this.

M3

Best Practices

M3.1 Overview

This chapter on best practices will explore issues that (in our my experience) often arise in the design of a *Six Ideas* course (particularly on that involves interactive engagement) and recommend various practices that have worked well in responding to those issues in the past and discuss their pros and cons as well as suggesting some possible alternatives (and their pros and cons). The chapter's sections are as follows:

Section M3.2 poses questions about course design that sections M3.3–M3.7 discuss. The final section provides a sample syllabus for the *Six Ideas* course we offer at Pomona College, whose unusual sequence illustrates some of the freedom that one has in using the books. Courses presenting chapters in a more sequential order are easy to adapt from this example.

This chapter provides ideas not one-size-fits-all solutions

Even though I will discuss some best practices that we have developed at Pomona (and at other institutions to the extent that I understand them), I do *not* recommend that you simply adopt these practices without reflection. Institutions have different cultures, you have different strengths and weaknesses as a teacher than I do, and your students may not be similar to mine in ability, background, needs, or motivation. I remember attending a talk at a conference where a professor from the United States Military Academy described a very rigorous and demanding active-learning exercise that I knew that my students, able as they usually are, would *never* tolerate. One must thoroughly understand what is practical for you at your institution.

Therefore, the primary purpose of this chapter is not to provide one-size-fits-all solutions but rather to raise some relevant questions and present some *possible* solutions. Even though students are similar enough nationwide that the problems and desired behaviors are likely to be the same, you will have to think through which of any suggested solutions might work for you in your setting.

Please send me your suggestions!

I would greatly appreciate hearing about your experiences in either using my suggestions or creating new solutions adapted to your setting (use the email address from which I responded to your instructor registration request). If you are willing, I might describe your solution in a future edition of this chapter!

M3.2 Twenty Questions about Course Design

This section provides a list of twenty questions that I have learned by experience that one should ask oneself before starting to construct a course design:

Topics, Pace, and Level Questions
1. What are the goals and purposes of this class?
2. What topics must I include in this class to achieve those goals?
3. What is an appropriate pace and level for my particular students?

Interactive-Engagement Questions

4. How should I sell students and myself on interactive engagement?
5. When should I lecture, and how can I get myself to stop?
6. How can I encourage students come to class and arrive prepared?
7. How do I choose and manage class activities?
8. How can I ensure that students participate fully in activities?
9. How can I turn demonstrations into active-learning opportunities?

Homework Questions

10. What is my purpose in assigning homework?
11. How can I enable students to try (and maybe fail) tough problems?
12. How can I keep homework grading practical?
13. How should I encourage (appropriate) collaborative work?

Evaluation

14. How can I use grades to nurture positive behaviors and attitudes?
15. How should I create exams and quizzes that reward desired behaviors?
16. How can I make them sufficiently easy to grade?
17. How should I handle late/missed assignments?

Laboratory

18. How should I integrate this course with its laboratory (if any)?

Overall Design

19. How can I handle all these issues with a simple overall design?
20. How should I examine how things have worked?

Of course, twenty is an arbitrary number: one can easily find more questions to ask or group the issues differently. The list above presents what I think are a reasonably inclusive (but not too long) set of questions that apply to a suitably broad range of circumstances.

In the following sections, look for the ***bold-italic*** marginal comments to find where each of the questions above are addressed.

M3.3 Topic, Pace, and Level

1. What are the goals and purposes of this course?

The core question that sets the stage for all others is: ***what are the goals and purposes of this course?*** What is the place of this course in the department and the institution's curriculum? Who is the audience? What knowledge and skills do students need to gain in this course and why? Will students be self-motivated (because of intrinsic interest) or captive (because the course is required for a major to which the student is committed)? How important is making the students excited about physics relative to making them competent for taking other courses? Having a clear picture of the course context and the student audience and their needs *must* be the starting point, because almost all of the other choices one makes in designing the course will be to ensure that the course succeeds in what it needs to do for its audience.

My personal purpose in creating the *Six Ideas* texts was to better empower students taking a *Six Ideas* course to:

- Apply basic physical principles to effectively answer realistic questions,
- Understand the nature of physical models and the art of model-building,
- Perceive and resolve contradictions involving one's preconceptions,
- Grasp the hierarchical nature of physics concepts, and
- Appreciate the scope of physics applications in the 21st century.

If you have gotten this far, you probably share many of these goals (though your emphases may differ, you may have more to add, and/or you may want to express them somewhat differently for your students). But for the moment, let's accept these basic goals. Then the question becomes, how does one realistically achieve these goals for your audience in your context?

Physics education research has consistently and abundantly shown that, in virtually every context and with virtually any audience, the only known successful method for addressing at least the first three goals is to construct the course to involve ***interactive engagement***. I believe that this is so important and universally true that the rest of my discussion will *assume* that we will be creating such a course. This does not mean that the *Six Ideas* books are useless in lecture-based contexts (I have some evidence that people using the book in a lecture-context achieve marginally better results than those using a traditional book). But as far as I know, truly significant gains in student performance on the first three goals are possible only in the context of an interaction-engagement course. My purpose in much of the rest of this chapter will to present some options for doing this successfully in a variety of classroom settings.

2. What topics must I include?
and
3. What is the appropriate level and pace?

A goal not stated above that you will almost certainly consider important in designing your course is to "cover" a certain set of topics, usually because students need to know about such topics for future courses. Indeed, your situation may be so restrictive that a certain list of topics is virtually required.

However, this is an issue that I recommend that you examine carefully and with an open mind, because there is a genuine cost to both students' understanding and attitudes if one tries to "cover" too much. I therefore recommend that you ask yourself exactly why do my students need to know about this? What would happen if we did not cover that topic?

One might reasonably level the charge against the *Six Ideas* series that, because it includes contemporary physics not usually taught at the introductory level, it only makes the problem worse. This emphasis on contemporary physics is partly rooted in the genesis of the *Six Ideas* project as a response to an NSF-funded panel in the late 1980s examining the introductory physics course. The panel called for reform proposals that fulfilled the following contradictory criteria: (1) they should reduce the overall pace of the course, and (2) they should include some 20th-century physics. Fulfilling these criteria meant drastically reducing the classical physics content of the course, which involved omitting certain entire topics (such as geometric optics), but also streamlining and focusing the remaining material to make it more efficient. For example, unit E is about half the length of most traditional treatments of electricity and magnetism, but students are able (as indicated by the BEMA exam, see chapter M1) to achieve comparable mastery.

Even so, I will be the first to admit that "covering" the material at a pace of one chapter per 50-minute class session represents a pretty daunting pace (and not much different in this regard from a traditional course). This design pace sets an upper limit that one should really not exceed in designing the course. Even so, this chapter-per-session gives you more feedback about creating an appropriate pace than most textbooks do.

The streamlining of the classical material, however, gives you new options for slowing down the pace. Offering the course in three semesters instead of two (by working through two chapters a week instead of three) provides a significantly reduced pace, one quite appropriate for students with weaker backgrounds (as long as they still are familiar with calculus). If I were doing this, I would assign a chapter for the first two 50-minute class sessions in a week and devote the third to activities that provide review and consolidation. One might instead reduce the pace by studying four or five ideas instead of six in two semesters (in the latter case, one might schedule a consolidation class session every two weeks).

The third edition (also as discussed in chapter M2) gives you many new opportunities for omitting material within the units, particularly in units Q, R, and T. Chapter M4 provides detailed information about the possibilities for omission (look also at the preface to each unit).

You can also use this information to adjust (to some degree) the *level* of the course. For example, in the third edition, you can elect to teach unit Q either with or without complex numbers. You can avoid or delay discussion of the cross product in unit C. You can decide whether or not to teach the integral version of Maxwell's equations, or even decide to omit Maxwell's equations completely. You can omit the conceptually challenging chapter on distributions in unit T or the chapters on energy and momentum in unit R. Again, see chapter M4 for details.

This course does assume some facility with calculus, though the use of calculus is slowly and deliberately increased through units C and N to make it possible for students to take a first semester of calculus concurrently. If your students need some review of calculus, please refer them to appendices NA and NB in unit N. Also please note that in this edition, I have less shy about using some pretty demanding integrals and derivatives (particularly in units E and T), because I think that online tools such as WolframAlpha now make this much more reasonable for introductory students. If your students are not familiar with such tools, I recommend spending some class time introducing these tools and how to use them effectively.

As time passes, I am planning to post some online chapters that provide alternatives and/or extensions to chapters in the main textbook. First on my agenda is to provide some materials supporting a short unit on geometric optics, but I am also considering writing something about electromagnetic field lines, something that might allow one to skip past chapters Q6–Q8, and so on. I am open to other suggestions as well. When these materials exist, they will provide even more options and flexibility.

To summarize, I strongly recommend carefully and creatively pondering what topics you might omit and construct a syllabus that "covers" *fewer* than one chapter per 50-minute (or 1.5 chapters per 75-minute) class session, possibly by scheduling some "consolidation" class sessions.

M3.4 Interactive Engagement

Overview

As I have already stated, I think that constructing an interactive, student-focused classroom is so important (in virtually any context) that I am going to simply *assume* in this section that you want to do this. But the prospect of doing this may be daunting, particularly if you have never observed an interactive-engagement class in operation, and/or you are facing a classroom with a large number of students. In this section, I hope to give you some ideas for creating an active-learning environment in various kinds of settings and preparing your students to participate effectively.

M3.4.1 What is Interactive Engagement?

What do I mean by an interactive-engagement class? Such a class requires that students frequently actively respond to challenges that require them to think and/or do something. The challenges may come from the instructor, a worksheet, or other students. The activities should push the student to thoughtfully apply the concepts and get some kind of immediate feedback on their work from the instructor, TAs, and/or other students. One can organize such activities in many ways, including ways that can work in even the largest classrooms. For an overview of the theory and a (somewhat dated but still useful) overview of the range of possible engagement schemes, see http://www.physics.umd.edu/perg/papers/redish/jena/jena.html.

The reason for doing this is that research has consistently and abundantly indicated that interactive-engagement courses are significantly more effective at teaching students by a variety of measures. The classic study in physics is the 1998 study by Hake (which one can view online at http://web.mit.edu/jrankin/www/Active_Learning/hake_active_phys.pdf), but study after study subsequently have simply reinforced Hake's conclusion, You can view a more recent cross-disciplinary meta-analysis of many studies at http://www.pnas.org/content/111/23/8410.full.pdf.

The core problem is that interactive engagement takes *time*. If one adds this time to a lecture-based class, then it significantly reduces the amount of material one can cover. One relatively recent solution to this problem has been to "flip" the classroom by video-recording the lecture and requiring students view the lecture outside of class, thus opening up the class session for activities. The *Six Ideas* solution involves replacing the lecture by reading from a textbook that has been specially designed to serve in that role. However, neither of these models work unless students actually do what we ask them to do outside of class. I will return to this problem in a minute.

M3.4.2 Selling Interactive Engagement

4. How should I sell students (and myself) on interactive engagement?

The other main problem is that lecturing (even though it is less effective) feels good to both the student and the professor. Active learning requires work, and students don't like to work. Active classrooms are noisy, seemingly chaotic, and require a professor to be responsive and engaged in a way that is harder than delivering a nice, polished lecture.

The solution to both of these problems is the same: *become informed*. The first step is to make sure that you are sufficiently informed about the benefits of interactive engagement to be fully committed to it. When you fully absorb the truth that students will learn little of use from even the most brilliant and beautifully organized lecture, you will better be able to resist the internal pressure to lecture, and also be able to respond to pressure from students.

The second step is to sell the students on active learning. Explain *why* you are doing what you are doing, backing it up with an appropriate amount of evidence and/or argument. Students are much more likely to participate fully if they understand *why* they must work harder.

Analogies to sports practice or music lessons

I start this on the first day of class. In my printed syllabus, I provide an argument by analogy to something they have likely experienced in their growing up: sports practice or music lessons. I claim that learning to think like a physicist is not merely a matter of absorbing information, but a practiced skill analogous to learning a sport or an instrument. What would you think of a coach who spent all of your practice time talking about the sport and demonstrating moves, and then expected you to come to the next practice doing the moves perfectly? What would you think of a piano teacher who spent your entire lesson playing a piece beautifully and then expected you to come back able to perform it as beautifully? Everyone knows that learning a sport or a musical instrument requires guided practice coupled with corrective feedback from an expert. Why would one expect learning to think like a physicist to be any different?

Use the first day of class

I reinforce this on the first day of class by verbally summarizing the argument and (sometimes) offering actual experimental evidence from a published article (such as the one by Hake) supplemented by data gathered from previous iterations of this very class (if available). I also reinforce this by concluding that first class session with an example activity (problem C1R.3 is a favorite). This helps students know what to expect (and prevents me from undermining my whole pitch by lecturing the whole first session).

The other thing I always do on the first day of class is to spend *some* time on an in-class activity. The first class session sets the tone for the entire class, and it does not help to lecture for the entire first class about why lecturing is bad! It also helps your students understand more practically what interactive learning means and see it in context.

While selling students on the first day is crucial (in my experience), it is not sufficient. One needs to remind them every so often why things in this class are (perhaps) different from what one might expect. When homework is first due, I not only remind them *what* they need to do, but also *why*. If I ask them to write a summary of an idea out in longhand, I remind them *why* (summarizing and writing creates a strong memory). I allow them to bring a "cheat sheet" to exams (see below) and I explain *why*. One can reinforce the sports and/or music analogy almost every class session (I often talk about my own struggles to learn things in those contexts).

A few students won't be sold, and many that are sold will backslide, so one must also motivate desired behaviors with grade pressures (see below). But being transparent about the reason behind those grading pressures increases students' acceptance of those pressures.

5. When should I lecture and how can I get myself to stop?

In spite of lecturing's dismal record for building student competence, there are good reasons for *some* short in-class lectures. It is crucial that students see your personal enthusiasm about physics. Humor (which at least for me often requires some pre-class thinking) can make a huge difference in students' attitudes about the class. Some orientation and motivation at the beginning of class about where we have been, where we are going, and how this chapter fits into that trajectory provides something valuable that the textbook really cannot provide.

However, it is so very easy, once one has started, to keep on going (isn't there some physical law about that?). The literature suggests that students naturally begin to tune out of a lecture after about 15 minutes, so I try very hard to divide any lecturing I do in a class into segments of 15 minutes or less, separating the parts with activities of some kind: this is my ***15-minute rule***. I also strive (but don't always succeed) to spend at least half of a given class session on activities: this is my ***majority activity rule***. I don't always succeed in obeying these self-imposed rules, but I do try, and I also write information on my class plans about how long various planned lecture segments actually took so that I get better at estimating.

M3.4.3 Ensuring that Students Come to Class Prepared

6. How can I encourage students to come to class prepared?

Now (as I have mentioned before), the whole "flipped" scheme where students come to class to participate in activities fails if (1) students don't come to class or (2) they come to class without having done the reading. When I first developed the *Six Ideas* approach, I thought that if I conducted each class *assuming* that the students had read the chapter, they would soon get the picture that I wasn't going to lecture and that they had better come prepared to avoid embarrassing themselves with their peers. I was naïve. Students require some additional inducement to come to class prepared.

The pre-class-exercise method

I have tried a number of alternative schemes over the years, but two have survived the test of time as being both practical and reasonably effective. The first is assigning ***special pre-class exercises***. In one recent iteration of this, I assigned three pre-class exercises (usually two-minute problems, but occasionally including a very simple basic problem or two) that were due at the beginning of class. (Students were expected to provide a short explanation in addition to the letter or numerical answer). An undergraduate grader graded each paper on a four-point scale, one for handing it in on time and in class, and basically one point for each correct response (though the grader gave some partial credit). Students who do not attend class may submit answers electronically before class, but will only get the correctness points (since the goal is being prepared *for class*). Late papers were not accepted, because I made answers available either during class or shortly thereafter (see below). The student's two lowest class scores during the semester are ignored, and the remaining scores count as about 10% of the student's grade: large enough to motivate most students, but not so large to encourage wide-scale cheating.

For this to work well, one must select problems that are pretty easy (but only if one has read the chapter) and collectively cover the whole chapter. Dropping the two or three lowest scores greatly reduces the number of students pestering professors with excuses.

The advantages of this method are that it:

- Is relatively easy to manage and grade (an undergraduate TA can do it).
- Provides an incentive for attending class as well as for reading.

The disadvantages are that:

- Finding appropriate questions is tricky for some chapters.
- Cheating (by copying someone else's answers) is relatively easy.
- Compliance could be better.

In my fall 2016 class, I used this method. The average class attendance exceeded 90% (according to my own records), and on the course evaluation, 61% of students self-reported being prepared 80% to 100% of the classes attended, and 18% being prepared 60% to 80% of the classes attended (with the remainder reporting being prepared for less than 60% of classes attended). This is tolerable compliance, but one might wish for better.

I wanted to present students with the answers at the very beginning of class to give instant feedback, but the number of students arriving late made this awkward and opened up other cheating opportunities. I ended up simply posting the answers online, which I think was less effective.

Possible variations

One reasonable variation would be grading on a three-point scale (so that students only have to get two of the three problems right). Requiring only two of the answers to be correct recognizes that even students who have done the reading may not be able to answer all the questions correctly, so this reduces stress. On the other hand, it also reduces the stakes, making it easier to come to class unprepared.

Another possibility would be to use a "just-in-time" approach where students submit answers electronically sufficiently in advance that the professor could adjust what is presented in class in response. The advantage here is that students would get some benefit back from their efforts. But evaluation would have to be primarily on the basis of effort, because one won't get useful information if the problems are such that everyone gets them right. The trick would be to somehow distinguish those who are really trying from those who are not. Also one would have to separately reward attendance.

Compliance with any of these variations might be improved with some method of evaluating in-class work (see below).

The daily homework method

A completely different (but successful) method is ***daily homework***. We used this method successfully at Pomona for some time and Washington University professors currently use it in a large-classroom setting there. In this scheme, instead of assigning a weekly homework set (of, say, 7 to 9 problems), one assigns three homework problems due at the beginning of *every* class session. One homework problem is an M or R problem based on the *previous* class session's assigned reading, but two problems are B or simple M problems from the assigned chapter for the current day's class session. One should choose the problems to be fairly straightforward if the students have read the chapter, but also so that answering them successfully requires reading the *whole* chapter. One grades all three problems using whatever homework grading scheme one elects (see below).

The advantages of this method are that:

- It requires no *extra* effort beyond that spent grading the homework.
- Cheating and/or gaming the system is very difficult.
- Average preparedness is probably the best of all tested options.

Its disadvantages are that:

- Finding appropriate problems can tricky for some chapters.
- It requires students to work *constantly*, which can be grueling.
- The paper flow needs to be carefully and creatively managed.
- It does not automatically reward class attendance.
- Students may not be exposed to enough challenging problems.
- Some may think it unfair to be graded on material not discussed in class.

This method does *seem* to yield the best compliance (though I do not have data to back that up), plausibly because doing the homework requires not only reading but really processing the material. But we dropped it at Pomona because the daily grind wore students out and because some colleagues did not consider it fair to grade students on material not discussed in class.

The *Six Ideas* website discusses some other options that we have tried (including asking students to write summaries or submit questions, giving in-class quizzes and so on) that we found less successful: see http://www.physics.pomona.edu/sixideas/reading.html for more information.

M3.4.4 Two-Minute Problems and Response Systems

7. How do I choose and manage activities?

The two-minute problems are a good starting point

How does one choose activities? A good place to start are the two-minute problems, which have I have deliberately designed to push students to reason about and process the material in the chapter, often in ways that are subtle and/or counterintuitive. The two-minute problems are the primary tools that I have provided to help one create an interactive classroom, and an activity plan that only involves having students work some of the chapter's two-minute problems would often work quite well.

Be aware that the "two-minute" name can be misleading from an instructor's perspective. "Two minutes" is intended as a ballpark estimate of the time that a *student* should think about a problem. When it is possible, I often have students think about each problem individually for two minutes, then discuss the problem in a group for two minutes and then use some method (see below) to convey the consensus of the group to the class. I summarize the responses that I am seeing and often have someone explain the reasoning behind at least the correct response. All of this can easily take ten or even more minutes of class time, so one must plan accordingly. This means that one should choose problems carefully so that they really expose conceptual problems that your students are likely to have and therefore are worth spending all of that class time. Problems that 80% or more of your students get right are usually *not* worth the time (unless they need encouragement!).

Gathering responses using clickers

One can gather responses from the class in several ways. The high-tech approach is to use "clickers" or some kind of other electronic classroom response system. The fact that many students now have smartphones or computers presents new possibilities (see, for example, the tools offered at http://polleverywhere.com). These kinds of tools are especially good for very large classes, when the privacy of responses is essential, and/or when it is valuable to keep detailed records of student responses, but in the smaller classes that I typically teach, more informal methods are more time-efficient. In addition to the up-front problem of getting student familiar with the technology, I have found that one of the time sinks is that most people will respond fairly rapidly, but a few drag their feet and so I found that most people (including me) became impatient waiting for the last few responses to come in. Then one has to process the responses by graphing them or something similar, interpret the responses for the class, and so on. All this takes time.

Gathering responses using the letters on the back of the book

The letters on the back of each printed volume provide a straightforward free tool for gathering classroom responses to two-minute problems. When you request a response, each student simply holds up the book with the back facing you and points to the appropriate letter. You then quickly scan the class and say something like "Well, I see that about two-thirds are answering A and most of the rest are answering C, but I see a few other responses." This is usually enough detail for the purposes of the class. Unless the student cranes his or her neck in a noticeable way, students cannot generally see what other students are pointing at, so the responses are reasonably private.

You might think that this would be impractical in larger classes, but I have seen this method work in 120-student classes at Washington University. One can see which letters the students point to from quite a large distance, and estimating rough percentages is easier than one might think. Try it!

Gathering responses using small whiteboards

However, the classroom response method I currently use in all of my classes is the small whiteboard. I learned this method from Corrine Manogue at Oregon State University (see http://physics.oregonstate.edu/portfolioswiki/props:start#whiteboards). I give each student group a small whiteboard (about 9 inches × 12 inches), a marker, and an eraser. When I ask for a response, each group writes the response on the whiteboard and holds it up.

The main advantages of whiteboards is that they allow student groups to respond to more than one question at once and they allow for non-letter responses (including graphs and/or equations). This gives one more flexibility in choosing activities (see below). The boards are also relatively cheap: one can purchase a 4-ft by 8-ft by 1/4-inch sheet of white melamine-coated board (it is used for lining showers) fairly cheaply at a home improvement store and saw it up into about 35 boards, so the per unit cost is small (the erasers are actually the most expensive part). The boards do get dirty after a while, but last for five or more years. They offer about the same amount of privacy as the letters on the back of the book, and can be used in even larger classes.

Think about how to deal with incorrect answers gently. I generally ask a group who has given the right answer to summarize their logic, but I also often explain why other responses might *seem* logical, and/or encourage anyone who is *willing* to talk about their reasoning without putting them on the spot. The trick is to teach the right answer without discouraging students.

M3.4.5 Problem-based Activities and Worksheets

Homework problems as activities

The book provides some problems under the "homework" heading that are also great as classroom activities. Problems that divide up a complicated procedure into many small steps are especially valuable as activities that help prepare students to do the homework. The current edition provides a number of such problems: look for those that have a number of small parts. (Especially important examples are E12M.1 and E13M.1, which I have found to be almost *essential* in teaching students how to use Gauss's and Ampere's laws, but you can find a number of useful examples in every unit.) I have found that problems with short, bite-sized parts are very helpful for keeping students moving and for me to be able to quickly assess where they are.

The value of worksheets

Students work through such problems at varying paces, so it is usually not practical to gather student responses using a classroom response system (though whiteboards make gathering a wider variety of responses possible when synchronization is practical). I have found it much more useful to give each student a worksheet that describes all the activities we are going to accomplish during the current class period (even if some of those activities are two-minute problems for which we are going to gather class responses) and provides space for their work. Students work in groups during class to fill out their sheets. I train students early in the course to expect to pick up a sheet as they enter the classroom, and I generally have some students who begin working even before I officially start the class.

Monitoring students' progress

While they are working, I circulate among the groups assessing their progress, answering questions, and helping them get unstuck or started. I have found by experience that I can keep track of about 15 students (5 to 7 groups) myself, but my classes usually have about 30 students, so I hire an upper-level undergraduate major to do the same thing. This can work in larger classrooms as well (as long as the classroom architecture allows for circulation), but I recommend hiring one teaching assistant (TA) per 15 students above the first 15. This process of giving students individualized feedback on precisely the issues that they find difficult is tremendously valuable, and its clear value also makes selling an activity-based classroom easier.

Undergraduates are quite adequate as TAs as long as they have a version of the worksheet with written-out solutions (partly because you are handy in case of questions), though graduate students would likely be even better. The TAs often appreciate the opportunity to reinforce their own knowledge (there is nothing like teaching an idea to really learn it), so I usually do not have trouble finding willing undergraduates. The TAs usually have enough time at the beginning of the class to review the sheet, so giving the solution sheet to the TA as they arrive is usually sufficient.

8. How can I ensure that students participate fully in activities?

Until recently, I have allowed students to keep the sheets as they leave class, but this spring I started collecting the sheets as the students leave and graded them based on their effort (which figures in a small way into their course grade). Some of the advantages of collecting the sheets are that it:

- Gives students an incentive to work efficiently and keep focused.
- Underlines that working on these sheets is important and valued.
- Helps me see the kinds of difficulties students are having.
- Provides an independent means for giving credit for attendance.

Some of the disadvantages of the method are that it:

- Requires grading.
- Requires some method for returning sheets to the students (who find the sheets valuable for studying and will want to know their grade).

"Grading" these sheets is actually very easy (the effort that a student has put into a sheet can be assessed in seconds). In a small class, it is also relatively easy to return the sheets (we use a box that contains a file folder for each student). But grading and returning may make this method impractical for classes larger than about 60 students (though some use of scanning technology and student graders might make this more workable).

An example worksheet appears at the end of the chapter, and I plan to post more examples in the instructor's section of the *Six Ideas* website.

Example worksheets

M3.4.6 Active Demonstrations

Another productive source of classroom activity is the *interactive demonstration*. Demonstrations are a traditional part of the physics classroom, but making them interactive greatly enhances their teaching value. An interactive demonstration engages the student by requiring them to make either a qualitative or quantitative prediction before the demonstration. This focuses their attention on the physical principles involved and gives them a stake in the outcome (increasing their engagement).

9. How can I turn demonstrations into active-learning opportunities?

David Sokoloff and Ronald Thornton have developed the concept of the the interactive demonstration perhaps more than anyone else in the community. Their book *Interactive Lecture Demonstrations: Active Learning in Introductory Physics* (Wiley, 2006) is an excellent summary of their many years of work in the area. You can also find a short introduction to the idea in their paper "Using interactive lecture demonstrations to create an active learning environment," *The Physics Teacher,* 35, 340 (September 1997), which you can access online at http://aapt.scitation.org/doi/pdf/10.1119/1.2344715.

Sokoloff and Thornton's work on interactive demonstrations

Thornton and Sokoloff's basic 8-step procedure for doing an interactive demonstration (which I have slightly modified to allow for qualitative as well as their usually quantitative demonstrations) is as follows:

1. The instructor describes the demonstration and asks students to make a prediction about what will happen when it is performed.
2. Students record their names on a worksheet that will be turned in.
3. Students discuss the demonstration in small groups.
4. Students record the prediction on their prediction sheet.
5. The instructor gathers predictions from the class.
6. The instructor performs the demonstration, using microcomputer-based laboratory (MBL) tools to gather and display data if appropriate.
7. Some students describe the results for the class.
8. The instructor discusses analogous physical situations with different "surface" features but illustrating the same physical concepts.

Thornton and Sokoloff focus on demonstrations involving graphical and/or quantitative predictions, but I have found that the same basic procedure works well for demonstrations where the outcome is qualitative. A number of two-minute problems in the text (particularly those with counter-intuitive outcomes) can be turned into good demonstrations (examples include C2T.13, C4T.5, C6T.5, C6T.6, C6T.10, C10T.12, N8T.8, and many others.

The point of having students discuss and write down predictions is so that they become fully engaged in the demonstration, have an opportunity to ask thoughtful questions about it, and practice applying physical principles to realistic situations. By making a prediction, they also develop a stake in the outcome and pay close attention during the actual demonstration. Thornton and Sokoloff have documented the significant learning advantages of interactive demonstrations compared to standard demonstrations.

The value of interactive demonstrations

How class worksheets naturally support this scheme

One of the reasons that I have moved to using worksheets to gather student responses generally is that they fit in naturally to Sokoloff and Thornton's procedure. When I do an interactive demonstration, I simply make a portion of the general class worksheet serve as the "prediction" worksheet that they describe.

M3.5 Homework

11. How can I enable students to try (and maybe fail) tough problems?

As I have mentioned in chapters M1 and M2, the homework problems in a *Six Ideas* course have features that require special attention. I strongly recommend assigning mostly "Modeling" problems, because it is precisely these kinds of problems that require students to practice applying physical principles to realistic situations and become more sophisticated in building physical models. These problems also generally force students to move beyond mindless strategies (such as simply hunting for the formula that has the right variables or tweaking an example) that worked well in high school.

The issue, however, is that such problems are *difficult* for introductory students, and they will inevitably make errors, as they would when learning any challenging skill for the first time. In a sports or music practice session, one would not expect to do everything perfectly at the first attempt. Rather, one must try and try again until one can do it correctly. Making errors, and learning from those errors, is therefore *part of the process*.

Grading M and R problems inappropriately can have major negative consequences!

Standard homework grading schemes that award points only for doing things correctly actively work *against* this learning process. Indeed, we found early in the *Six Ideas* development process that standard grading practices can cause the course to *fail* pretty badly. If students can only receive points for doing things correctly, and doing things correctly the first time is almost impossible, students become quite stressed, which negatively impacts their learning. Such a grading scheme also incorrectly signals that doing things correctly is the only valuable thing about doing homework.

To be sure, one wants to give students *some* incentive for doing things correctly, but the main value of *practice* (whether in sports, music, or physics) is showing up and making the effort, so this is what a homework grading scheme should *primarily* reward. Students need to feel that it is OK to make a good effort that does not quite reach the mark, and to see how one can learn from one's errors and make progress.

M3.5.1 General Principles

10. What is my purpose for assigning homework?

The point is that a successful *Six Ideas* homework scheme re-conceptualizes homework not as an opportunity for summative assessment (that is, an opportunity to grade the quality of a student's work) but rather as another opportunity for *practice* with feedback (that is, a continuation out of class of the practice-with-feedback opportunities they have experienced in class). A successful homework grading scheme will therefore

1. Primarily reward student effort,
2. Give students *some* incentive to do the problems correctly, but so much weight so that they are stressed if they make errors, and
3. Provide students with feedback so that they can learn from their errors.

This contrasts with a traditional grading scheme that awards points only for correct answers (ignoring the students' reasoning, which is even more important) and gives little feedback beyond the credit.

M3.5.2 The Key is having Students Correct Their Own Work

12. How can I keep homework grading practical?

However, one of the main reasons that the traditional scheme exists is because grading by checking answers is easy, and providing any kind of individualized feedback is very time-consuming. Any alternative homework scheme must be similarly practical.

Over the years, I have experimented with a number of homework evaluation schemes, and I have developed several that work. However, *all* the successful schemes I have developed share a common feature: *students get feedback by comparing their own work to posted solutions and correcting their work themselves*. This provides the detailed feedback that the students need without requiring a grader to write corrections on each solution.

Requirements for a successful self-correction scheme

Such self-correction schemes have certain common requirements:

1. One must ensure that students make a good effort *before* checking the solutions (which usually involves checking their initial work somehow).
2. Solutions must be easy to post in an accessible but secure location.
3. The posted solutions must be sufficiently complete to provide student-accessible feedback on reasoning as well as calculations
4. One must be able to grade the corrected solutions quickly and easily for desired features.

Online solution viewing is handled for you

The schemes that I will describe below offer modestly different methods for handling requirements 1 and 4, but I have handled requirements 2 and 3 for you. First, I have provided very complete solutions to all of the homework problems in the *Six Ideas* texts, These solutions have much more detail than is typical in introductory-level solution manuals precisely to provide beginning students the information that they need to assess their reasoning as well as their results. I have also provided a secure scheme for posting these solutions online. Registered instructors can use a web-based tool (accessed through the instructor's page) to create a list of solutions that the students can view, and can assign to each selected solution a time window during which students can see it. You (the instructor) can then give the list a name that also serves as a password for that list. When you have set up the list, students run a web app called "ProbViewer," type in the password, and view whatever solutions are presently viewable. The solutions are available to any student with the password at any time on any device capable of displaying a web page, but you can completely control who sees each solution and when. Every instructor can therefore independently and securely post for their students (and their students alone) problem solutions to view. Instructions are on the password-protected instructor's page.

M3.5.3 My Current Favored Approach

Outline of the scheme

The method I personally use at present takes advantage of the fact that most students have smartphones that can scan pages. Every week, I assign seven problems as homework. (These problems are mostly M-level problems, but I typically include at least one R-level problem.) Each Wednesday, I ask students to email me a PDF scan of their initial efforts for that week's homework before class. The posted solutions to that week's homework become viewable online on Wednesday evening. Students use the solutions to correct their work, marking corrections on their papers using a green or purple pen. The corrected solutions are due on Friday.

I then prepare for the grader a sheet (one sheet for each student in the class) that displays a copy of the following rubric for each assigned problem:

The currently favored grading rubric

I C
❒ ❒ Description (Sufficient/Clear/Coherent) ($1\frac{1}{2}$)
❒ ❒ Model (Correct Principles/Correct Application)
❒ ❒ Good Notation (Symbolic Algebra/Units&Vectors)
❒ ❒ Valid Math (Sufficient/Correct)
❒ Plausible (Right Units/Magnitude/Sign)

× — — Fraction = TOTAL ☐

The "I" column represents marks for the student's initial effort and the "C" column represents marks for the student's corrected effort. The grader will mark each box as follows: ❒ = full credit, ⍁ = $\frac{1}{2}$ point off, ☒ = 1 point off, ❒ = $1\frac{1}{2}$ points off. The grader might also use ~~❒ ❒~~ for a small issue that persisted in the correction = $\frac{1}{2}$ total points off (= $\frac{1}{4}$ point for each box). Each box is worth one point (except in the "Description" category, where each box is worth 1.5 points), roughly a half point for each of the desired features listed in parentheses. (The grader can underline the feature or features that need more student attention.) To earn the "plausible" point, the student's final result for the initial effort must have been plausible OR the student has written a note explaining that the result is *not* plausible.

The "Fraction" at the bottom represents the fraction of the problem the student completed during each phase (no marks here means that the problem was complete both initially and after correction). Doing the wrong problem earns an automatic 2 points of initial credit: the student must supply a "correction" that summarizes the solution to the right problem to earn correction points. The grader adds the points each column, multiplies the result by the fraction for that column, adds the column results and rounds to the nearest half-point. The maximum score on each problem is 10. (See the sample syllabus at the end of this chapter for more detail).

This rubric allows for rapid grading while still giving students useful feedback

The marking scheme may seem strange initially, but a grader who has learned the system can mark a paper very quickly. The rubric also requires marks only for things the student has done poorly, so a grader is likely to make only a few marks per solution. The result is that even an undergraduate grader can evaluate a problem and give useful feedback in a few seconds.

Features of this method

Note also that the rubric rewards student *effort* in displaying expert-like problem-solving habits, and while correctness is rewarded somewhat, a student who screwed up both the model and the math completely, but did other things well and made a complete correction will still earn 8 to 8.5 points. The rubric's structure also pushes students to develop specific habits that I have found by experience they won't develop without some pushing.

As long as students are honest, one should be able to tell from their final submissions what constitutes their initial effort, as corrections will be in either green or purple. Submitting the initial efforts electronically simply provides an incentive for students to remain honest. One does not need to check every electronically submitted solution against the final version; one only needs to do this often enough to maintain a strong deterrent effect. The deterrent effect indeed seems pretty strong: I have yet to catch a student cheating by trying to pass off a corrected solution as an initial effort.

What to do if electronic submission is impractical

However, if electronic submission is impractical, a variation might be to have students physically hand in the initial efforts and have a grader mark the initial effort column before returning the solution for correction. This also has the advantage of giving the students useful feedback about what needs fixing *before* they correct the solution (not all introductory students can see what they are doing wrong even with the solution in front of them). But it has the disadvantage of requiring a robust system for shuffling the papers between graders and students and almost certainly requires a longer interval between initial effort and correction. Even so, before we could count on students having smartphones, we did this kind of two-pass system all the time at Pomona, and such two-pass systems have been used successfully even in very large introductory courses such as the course at Washington University.

M3.5.4 An Earlier and Simpler Variation

Another usable rubric

Before we developed the rubric described in the previous subsection, we used the following grading rubric:

____ / 3 Initially Complete
____ / 1 Initially Plausible
____ / 1 Initially OK
____ / 2 Clear
____ / 3 Correct

(The numbers specify the number of points to be assigned to each category.) The students still submitted an initial effort either electronically or physically, and then submitted a corrected version. The last five points apply to the final corrected version. The grader simply writes the number of points each solution earned in each category in the slots provided to the left.

Comparing the two rubrics

Compared to the previous rubric, this rubric had the advantage of being somewhat simpler (it required the grader to make fewer decisions and was a bit easier for the students to interpret). It also (by virtue of its vagueness) allowed the grader more flexibility for handling unusual cases. But vagueness was also a disadvantage in that it made the grading less objective and the grades less useful to the students, and graders often spent extra time writing explanations to students about why they got the score they did. This rubric was also a bit too generous to the student in that a diligent initial effort and a good correction typically earned a student 9 points even if the initial solution was completely wrong. This rubric was also less clear about what the grader should do in the not uncommon situations where the final solution was missing parts or the student did the wrong problem initially.

However, the primarily reason that I moved to the new rubric is that it is more specific about the features of a good solution, and its structure parallels the main parts of an expert-like solution as it is presented in Unit C. When I began using the new rubric, I saw a decisive improvement in the quality of students' solutions as they were more specifically goaded by the new rubric (and the scores they received on the first problem set) to do better. I have personally graded many student papers using both rubrics, and even though the second rubric seems simpler, I have found that the two rubrics end up requiring about the same amount of grading time and effort (particularly if one accounts for the time I spent writing extra comments).

Pre-grading and post-grading

In the days before students electronically submitted initial efforts, we graded the initial efforts completely using the second rubric, and then "corrected" the last 5 points of the grade after students submitted corrections. Some years, we only allowed students to submit four corrections per week (out of seven problems) to cut down grading time.

Why using a rubber stamp instead of a rubric sheet did not work well

During most of the time when we used the second rubric, we put the rubric on a rubber stamp that the grader used to stamp a copy of the rubric on each solution. This saved paper compared to providing the grader with a separate sheet containing a copy of the rubric for each assigned problem. But we stopped doing this because (even after we pleaded) students rarely provided enough room on their papers for the stamp, and the graders had to spend a lot of extra time searching for somewhere to place the stamp.

M3.5.5 The Earliest Method

An early rubric still useful in upper-level classes

When I first began having students correct their own work decades ago, I used an even simpler rubric. I offer not because I recommend it for use in a *Six Ideas* class, but because it offers a useful lesson about the difference between introductory and upper-level students. The rubric looks like this:

Original Effort Scale	**Correction Effort Scale**	**Initial Effort Quality**
4 = satisfactory effort	3 = satisfactory correction	3 = no correction needed
3 = missing explanations, steps	2 = minor errors not corrected	2 = minor initial errors
2 = missing major portions	1 = major errors not corrected	1 = major initial errors
1 = little done 0 = nothing done	0 = no correction attempted	0 = needed a total rewrite

Rather than use a stamp, I simply wrote something like 4 / /   on the initial effort (assuming that the effort was satisfactory), and then filled in the other two slots when grading the correction, yielding, for example, 4 / 3 / 2 = 9 if the initial effort had minor errors but the correction was sufficient.

Why this rubric did not work well for lower-level classes

This rubric is simple for students to understand and allows for quick grading without requiring either stamps or extra sheets. I still use it regularly in my upper-level classes. But I quickly abandoned it for introductory classes because students in such classes (1) need more specific guidance about (and motivation to provide) certain solution features (such as checking for plausibility) than advanced students do, (2) do not always recognize when and how a solution may be substandard, and (3) need a *bit* more generous credit for effort (a diligent but wrong initial effort typically earns between a 7 and 8 on this scale). Introductory students would regularly get frustratingly low scores using this rubric because they often would not recognize the errors they needed to correct (and so get both low initial effort and correction effort scores), but also did not get enough feedback from their previous scores to do better. On the other hand, advanced students already basically know how to solve problems and are more able to discern their errors by comparing to an expert solution, so this rubric works fine for them.

M3.5.6 What About Computerized Grading?

Why I have found computerized homework grading systems to be inadequate

A number of relatively polished computerized homework grading systems are now available. Systems include publisher-independent tools such as WebAssign, ExpertTA, LON-CAPA, WebCT, Blackboard, and publisher-produced tools such as MasteringPhysics (Pearson) and Connect (McGraw-Hill). The practical advantages of such systems (particularly for large classes) is obvious. Why not use such a system instead of the comparatively complicated and time-consuming paper-based systems described above?

The nature and quality of these tools is changing rapidly, so to be scrupulously honest, I have not evaluated some of these tools at all and have not looked at others in years. But I have not yet found a computerized homework system that I personally am comfortable using with a *Six Ideas* course. Let me explain why.

Six Ideas homework problems are different than those in traditional textbooks

One important issue is that *Six Ideas* Modeling (M) and Rich-Context (R) problems in particular are quite different than standard textbook homework problems. These differences are deliberate and important. Physics education research has highlighted a number of pedagogical problems with typical textbook homework problems. The core issue is that typical textbook problems present a precisely defined situation (often similar to a text example) to which one can often apply a single formula to calculate a numerical answer. These features enable and motivate students to employ solution strategies (such as formula-hunting or example copying) that are less taxing than actually thinking about the physics concepts involved. Such problems therefore often do not help students practice the desired problem-solving skills.

Pushing students to develop genuine competence in applying physical models to realistic situations requires creating homework problems that can only really be solved by reasoning using the physical models, not mindless shortcuts. I have designed the M and R problems in the *Six Ideas* texts so that students *must* construct physical models that knit together more than one formula in a thoughtful way. Many of these problems de-emphasize numerical results or have multiple valid results (depending on the assumptions or approximations a student makes), and focus more on the reasoning that a student uses and the models they construct.

So one of the disadvantages of standard computerized homework grading programs is that they do not have M and R-type problems. Now, I know that a team is working hard on adding problems from the *Six Ideas* texts into McGraw-Hill's Connect system. As I write this, I am not sure about their progress, and I have not been able to personally evaluate the system. I will update this manual when I know more.

Computerized homework systems cannot easily evaluate reasoning and models

The other significant issue is that all of the computerized systems I have seen focus on evaluating answers, usually numerical answers. I think other aspects of problem solving (such as the model one builds, the principles one employs, and whether the result is plausible) are more important, but such solution features are not easy for computers to evaluate. I also work very hard to convince students that the "solution" to a problem is *not* the final result, but rather the *model* (I teach them repeatedly the mantra "The answer is the model.") Any system that focuses on numerical answers undermines this lesson, which is already difficult enough to get across.

With some systems, it might be possible to evaluate principles, models, and plausibility using a sequence of well-chosen questions, but doing this would require an enormous amount of authoring work to convert the problems in the text to the appropriate sequence of questions. I hope that this is what the Connect team is trying to do.

Even so, all of this needs to be accomplished in such a way that is easier, quicker, and more natural for students than writing the solution out on paper. The systems I have seen so far are simply not close to meeting this bar.

The schemes described here are practical even in large courses

The favored rubric described above encourages students to write solutions with expert-like features and gives them credit for doing so. I believe that this is extremely valuable, and though it does require a human eye to interpret the solution, and educational benefits make it worth the expense. Moreover, grading with the rubric goes *much* faster than traditional hand-grading. I strongly recommend that you give it a try — I think you will be surprised. The people at Washington University have used a hand-graded system successfully for their 800-person course.

When I see a computerized system that can address the issues that I have raised above, you can bet that I will use it eagerly and happily (I hate grading). I think that the day will come. But the systems I have seen so far are still too short of the mark for me.

M3.5.7 Collaborative Learning on Homework

13. How should I encourage (appropriate) collaborative work?

I remember that when I was in college, I learned a *lot* from my peers. Part of the point of working in groups during the in-class activities discussed in section M3.4 is to leverage one's limited ability to help students directly by facilitating their learning from each other. There are similar advantages to working together on homework. How can we appropriately encourage this?

Exhort them to work together (within appropriate limits)

The first thing that one can do is explicitly encourage students to collaborate (within clearly specified limits). In the course syllabus, I typically exhort students to work with each other while solving homework problems, as long as they work together on the models and ideas, but not to the level of precise wording or detailed mathematical steps (which clearly excludes simple copying of a group-developed solution). Since homework in my courses is meant to be practice, it is much less important to have an accurate evaluation of individual students' capabilities than it is for students to learn effectively from the process, so I am not worried by any collaborative work that is short of enabling a student to coast on other peoples' effort. An actual person grading papers can also fairly quickly discern a copied effort from one that uses some group-developed ideas.

Support collaboration with non-competitive grading...

In my experience, it is also important to support this exhortation with other course structures that encourage collaboration. One should avoid any course grading scheme that incentivizes competition instead of cooperation (see the discussion in the next section).

... and time and space for collaboration

At Pomona, we also provide time and space for collaboration by holding on optional session or sessions we call "collaborative learning sessions." Students are encouraged to come to a certain place at a certain time to work together under the eye of a upper-level student who serves as a "mentor." We train the mentors in how to offer groups appropriate help by answering (and/or Socratically asking) questions while avoiding the pressures to provide results or do the problems for the student. Such sessions also give introductory students considering physics a chance to interact with an upper-level major, and provide an environment where they might feel more free to ask for needed help than they might be with an instructor present.

Refer to the Heller group's work for more details about best practices

The foundational work on collaborative problem-solving in physics was done by the Heller group at University of Minnesota in the 1990s. The classic papers describing their work are Heller, Keith, & Anderson, S. "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving" and Heller & Hollabaugh, "Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups" in the *American Journal of Physics*, **60**, 627-636 and 637-644, respectively. Perhaps their most important finding was that typical textbook homework problems are not well-suited for collaborative work, as student groups quickly devolved to solving such problems individually. The kinds of problems that successfully drove students to work together were problems that they described as being "context-rich." They state that such problems

- Need to be too challenging for an individual student, but not for a group, Must require groups to make a number of decisions on how to proceed,
- Need be relevant to the lives of the students, and
- Cannot be mathematically tedious or depend on knowing a trick.

(This list is paraphrased from the Heller group's website at http://groups.physics.umn.edu/physed/Research/CRP/crintro.html).

The Rich-Context (R) homework problems in the text are meant to be such problems (though I have interpreted the third bullet item to include science-fiction scenarios). I typically assign at least one and maybe two R problems per week, and encourage the students to focus on these problems during the scheduled collaborative learning sessions.

The Heller group also has recommendations for how one organizes student working groups. This would be important, I think, if one wants to make group work a central feature of one's course, and I very much encourage you to study the papers and the website mentioned above. But at Pomona, requiring group work and assigning people to groups and to specific group roles has proved culturally problematic. So we have made a decision to make the group work optional, hoping that the challenging nature of these problems will inspire people to work in groups voluntarily. I think that this means that not all students receive the full benefit of this collaborative work, but this is what works for us.

M3.6 Good Grading Practices

14. How can I use grades to nurture positive behaviors and attitudes?

The *ultimate* purpose of grading is to provide students (and others) with a sound evaluation of the quality of each students' individual performance. But because many students are highly motivated to get good grades, how one grades inevitably shapes student behavior. Designing a good course means being very aware of how grading structures shape behavior and using that wisely to encourage productive and discourage destructive behaviors.

I remember attending a conference early in my career where an invited presenter described the fate of two students in an introductory physics course. "Alice" was very interested in physics and really wanted to understand the ideas. "Beth" was only interested in getting a good grade. When Alice worked on homework and studied for tests, she made a strenuous effort (encouraged by her professor) to understand the concepts deeply and learn to apply them flexibly, which took a lot of time and effort. Beth learned that she could solve the homework problems rapidly using relatively mindless strategies involving tweaking examples in the book and hunting for formulas that seemed to have the right symbols, and studied for the multiple-choice exams mostly by memorizing lists of facts and definitions and learning exam-taking tricks. By the middle of the course, Alice, in spite of her efforts, was struggling to get a B, while Beth was earning an A. Exhausted by the struggle and discouraged by the results, Alice gave up and began using the same strategies as Beth, and was able this way to earn an A in the course. The presenter's conclusion was that both Alice and Beth were ill-served by a poorly designed grading system that actively worked against both their interests and the professor's interest.

I also saw early in the *Six Ideas* development process that a section of the Pomona course that a visiting professor was teaching while I was on sabbatical was getting a lot of student resistance and was not going well at all. When I investigated the situation, I learned that the only significant change that the professor had made from the way I had taught the course was that he was using a traditional (answer-focused) grading scheme for the assigned M- and R-type homework problems. Students were complaining that the problems were too hard, that there were too few examples in the text materials, and they were stressed out. This contributed to a bad atmosphere in the class.

Minor grading decisions can have major consequences!

My point is that even seemingly minor decisions about grading can have large effects on student behavior and classroom morale. Moreover, students are not always good judges about the root of the problem, and can end up blaming the text or the professor for issues that really have to do with choosing an inappropriate grading system. The flip side is that time spent thinking about designing a good grading system can have a huge payback in terms of positive student behaviors and good morale.

We have already seen in section M3.4 how I use grades as an incentive to come to class prepared and stay focused on classroom activities, and in section M3.5 how I grade homework in a way that rewards students for effort in learning from the homework even when they don't do every problem correctly. I would say that typically my students earn about 60% of their course grade from grading I intend primarily to incentivize good behaviors.

15. How should I create exams and quizzes that reward desired behaviors?

If class activities and homework are analogous to practicing a musical instrument or a sport, then quizzes or exams are analogous to recitals or games where each student must individually display mastery in a consequential situations. This is the main place in my courses where the grading is nearly purely evaluative instead of being designed to encourage certain behaviors. But even here, one must pay attention to the implied incentives. If you want students to be learn concepts and apply them qualitatively, then you need to test them on that. If you want students to be able to construct good physical models and use them to make predictions, then you need to test them on that. If exams do not accurately reflect your course goals, students will adapt their strategies after the first exam to address the goals actually implied by the exam rather than what you *say* your goals are.

M3.6.1 Designing Good Multiple-Choice Questions

16. How can I make them sufficiently easy to grade?

This does not mean that exams have to be difficult to grade. When I was young, I disdained multiple-choice exams as being useless for genuinely testing mastery. However, I saw later that *well-designed* multiple-choice exams can be very useful, particularly for evaluating concepts and qualitative reasoning. The Force Concept Inventory (FCI) is an example of a well-designed multiple-choice exam that offers a meaningful assessment of student understanding of Newtonian concepts (see Hestenes, Wells, and Swackhamer "Force concept inventory." *The Physics Teacher* **30**: 141-166, 1992). There are similar tests for evaluating electricity and magnetism (for example, the Basic Electricity and Magnetism Assessment, or BEMA), quantum physics (Quantum Mechanics Conceptual Survey, or QMCS), relativity (the Relativity Concept Inventory or RCI) and thermal physics (Thermodynamics Concept Survey, TCS). A curated and rated list of such assessment tools can be found at https://www.physport.org/assessments/.

The problem I originally had with multiple-choice exams was that I had (at that point in my life) only seen poorly designed exams. Designing a good multiple-choice exam that tests more than whether a student has memorized definitions or other facts can be quite difficult. Truly successful tests such as the FCI take years to develop, and require careful validation to ensure that the questions actually measure what they were intended to measure. The PhysPort website rates assessment tools according to the degree to which these validations have been performed.

Use validated multiple-choice assessment tools

The difficulty is that none of these assessment tools have been developed with *Six Ideas* in mind, and too often use terminology and/or notation or cover concepts that are incompatible with *Six Ideas* courses. Still, these tests can be a wonderful source of ideas for test or quiz questions that can be adapted for *Six Ideas* courses.

Use two-minute problems as test questions

These tests have also qualitatively inspired many of the two-minute problems in the *Six Ideas* text. Though I primarily designed these problems as classroom activities, and though they have not been validated as extensively as some of the assessment tools mentioned above, I have often used these problems (or variations) on quizzes or tests. A short-response question that requires drawing an arrow, graph, or writing a short sentence can be almost as easy to grade as a multiple-choice problem.

One advantage to writing test problems very much like the two-minute problems in the text is that it clearly signals to students that spending class time and studying these problems is well worth their effort. Some students devalue conceptual understanding in favor of problem-solving, so including problems like these helps restore the balance.

M3.6.2 Making Essay Problems Simpler to Grade

The importance of essay problems on an exam

Developing students' ability to solve problems that require building models and applying mathematical reasoning is a high priority in my courses, so I also need test students' abilities in this regard. One of my tests typically includes one or two problems requiring an essay-type response, and I tell students that these will be very much like the M-level problems in the text. Such problems typically constitute about a third to half the points on the test (with the remainder being multiple-choice or short response questions).

In fact, few M-level problems are both substantial and short enough to be used on an exam. I also like exam problems to involve ideas from several chapters in the book. Therefore, I usually end up writing new questions that can involve taking pieces from several M and/or B problems. But it is important that students see the M-level homework that they are doing as helping them prepare for these test questions.

Break problems into parts

One way to make grading of such problems simpler and fairer is to break them into more parts than they would likely have if they were a homework problem. If one does this, it is important to figure out how to make the parts fairly independent so that a student can screw up one without making it impossible to complete the others.

Spot-check certain skills

One can also simply ask for portions of a complete problem, such as requiring them to describe a model, make appropriate approximations, and/or set up equations without completing the problem. However, both students and I tend to find these kinds of problems less satisfying.

Use a grading rubric

Another trick that I have often used is to use a rubric to evaluate the response. If the rubric is displayed on the test and is the same or similar to the rubric used to grade homework, it can reinforce for students that doing well on the homework prepares them to do well on the exam. Because the favored homework rubric described in section M3.5 is relatively new, I have not yet used it on an exam, but I think that it could be very useful as a grading rubric for an essay solution.

If you literally cannot assign an essay-type problem on a test for policy or practical reasons, you should consider other ways to evaluate this skill, or students will get the clear message that problem-solving skills are not truly valued. For example, one might consider designating a few homework problems during the course that students need to complete and hand in during a supervised "recitation" session. If one is operating in a culture where students can be counted on not to cheat, one could skip the supervised section and simply make it a take-home assignment.

M3.6.3 Time Issues on Exams

It has taken me many years to learn how to write a useful exam with essay problems that students are not horribly rushed to complete in 50 minutes. Experience has shown that I must be able to write out a complete solution to the test (that would earn an A) in less than 15 minutes for most students to be able to complete it in an hour. One can actually do very little writing in 15 minutes. One should avoid questions that require writing explanations or complete sentences. The essay problem is, of course, the most time-demanding, so careful attention to limiting the amount of math and/or writing that one must do is very valuable.

Trade an exam session for a class period

I strongly feel that I can write a better exam that more reliably assesses students' abilities if I am not limited to 50 minutes. When practical, I often schedule a 2-hour exam-taking session outside of class and trade this time for a class session that students would like to have off (such as the Wednesday before Thanksgiving or the day before spring break). Students are often quite happy to make that trade. However, there are always a few students who won't be able to make the scheduled time for some reason, and one must figure out how to handle them. In some institutional cultures, it may be possible to force students attend such a session, but this does not work at Pomona.

Take-home exams?

In institutional cultures with a strong honor code, one might consider giving take-home exams. I can do this in upper-level courses at Pomona (though a closed-book, closed-notes exam probably would not work), because students are more grown up and more committed to the program. But the few times I have tried this at the introductory level, I have not been able to convince myself that no student has cheated.

M3.6.4 Practice Exams?

One semester, I needed for scheduling reasons to give only one midterm exam instead of my usual two, and I had to give it during the 50-minute class period. Because I wanted students to do well even though they had fewer exam opportunities, and because I wanted them to study blocks of material that I could not really hope to cover on the single midterm and final, I decided to give two take-home practice exams. These were exactly like a real 50-minute midterm in form and substance, except that I gave students the solutions and asked them to take the exam alone and under exam conditions, and then correct the exam themselves. They were given effort points for correcting the exam, but not substantially on the quality of their initial effort.

I was surprised at how valuable students found this to be. They were uniformly positive about the value of the practice exams when I questioned them, and I believe that they really did do better on the real exams as a result. The one thing that could have made this exercise even better would be if I had figured out a way to weight the grading of the practice exam somewhat more heavily on the initial effort rather than purely on the corrected effort, because putting *all* the evaluative grading weight on the two real exams was still too much. The right balance is tricky here: too much weight on the initial effort would incentivize cheating. But one can, I think, get away with *some* weight on the initial practice exam effort, because students will be genuinely curious about how well they did. In the future, I might also ask them to scan and electronically submit in an initial effort before they have access to the solutions, as is the case for homework. This would not prevent inappropriate collaboration or looking at the book, but would at least prevent cheating by looking at the solutions. Having some more meaningful but somewhat lower-stakes evaluation than true exams would be valuable.

M3.6.5 Absolute Grading Aids Collaboration

The importance of absolute grading scales

I also think it very important to establish an absolute grading scale instead of grading "on the curve." Absolute grading encourages and rewards cooperation and collaboration: everyone does better by working together and teaching each other. Grading on the curve, by contrast, encourages competition and even sabotage.

The values of "grading on the curve" is that one can deal naturally with an unintentionally difficult exam and be assured that one never gives out too many high grades. This makes the system attractive particularly for less-experienced professors. But I think that the costs to the course atmosphere far outweigh the benefits.

Allowing wiggle room

I describe my absolute standards in the syllabus handed out on the first day of class, and I strictly adhere to those standards. I do allow myself a bit of wiggle room by saying that if the average exam score is lower than a B–, I will adjust students' grades upward to put the average there, but I say that I will never adjust them *downward* from what they earn on the absolute scale. However, I have never had to use this wiggle room in the past decade because I have gotten better at designing appropriate tests. I also assure them that if they all earn As according to the scale, then I will gladly give them all As (even though because of grade inflation, I am required to write a report to my chair and the Dean every time more than half my grades are As). But I also tell them that getting an A is not easy but requires hard and focused work. See the example syllabus at the end of this chapter for details.

When I am able, I also try to give students updates about what grades I have recorded for them and where they stand at present. This helps me avoid grading errors and helps reinforce the good-behavior incentives that I have built into the system.

M3.6.6 Building in Flexibility

17. How should I handle late/missed assignments?

Early in my career, I had a lot of trouble with students begging for indulgences and exceptions because of some problem that they might or might not have foreseen. Such problems seem to grow exponentially instead of linearly with class size. I also had trouble setting appropriate boundaries (because I tend to be too compassionate, which sometimes invites manipulation).

Automatic drops

The solution was to build in a certain amount of flexibility into the assignments. I typically automatically drop the lowest scores for a certain number of pre-class assignments, in-class worksheets, and homework problems (though never more than a week's worth, which is about 1/14th of the assignments in a given semester). I tell students on the syllabus that these are to handle the normal pressures of college life, and that I will entertain requests for clemency only for truly unusual situations where the student can present an excuse from the Dean of Students and/or the Health Center. In practice, I am a bit more generous than I say I will be, but this enormously cuts down on the number of requests.

"Get Out of Jail Free"

Recently, I have also been handing out a "Get Out of Jail Free" card that a student can use to get a 24-hour extension on certain items or an extra drop on certain other items with no questions asked. Like the automatic drops, this allows students to prioritize the items in their schedules without me having to make a judgment about what is appropriate.

Practical issues with electronic submission

Finally, I have learned the following things about electronically submitting initial homework efforts:

1. Particularly the first few times, one should check that everyone has submitted something and email those that haven't. It can take some time for students to learn how to submit things reliably.

2. Check that they are submitting PDFs using a real scanner app, not sending photographs (which are often very hard to read).

3. Allow time (preferably more than 6 hours) between the deadline for initial efforts and the time when the problem solutions become available. This allows for the inevitable glitches and delays that some students will experience without allowing anyone to use those delays to cheat.

I now set the deadline for initial efforts at noon on Wednesday, but set the solutions to go live at 6 pm.

Make deterrence practical

Defining punishments that deter bad behaviors (such as some points off for late submission) is good. But don't state any punishments that you are actually not willing (or not practically able) to enforce (word gets around). Early in my career, I tended to set up harsh deterrent policies that I did not have the heart to actually apply (hoping that, like nuclear weapons, I would never have to use them). But this does not actually work. With years of practice, I now know how to set policies that I can feel good about enforcing.

M3.7 Laboratory Sections

18. How should I integrate this course with its laboratory (if any)?

I decided early on in the *Six Ideas* development process that I would not try to develop a lab sequence to go along with the textbooks. There were several reasons for this. First, I am a theorist, not an experimentalist, and I did not think I had any particular experience or insight into creating good labs. Secondly, the resources and lab expectations at various institutions are so varied that any program that I did offer would likely require quite a bit of adaptation to be useful elsewhere. Finally, I was trying to make the *Six Ideas* text reflect and respond to results from physics educational research, and there has been very little of that until relatively recently.

Reform efforts should probably focus on developing students' experimental skills

The main research work of which I am aware is a group that involves collaborators from Cornell, Stanford, and University of British Columbia. They maintain a website at http://sqilabs.phas.ubc.ca and recently ran a workshop at the 2017 AAPT New Faculty Workshop in June of 2017 (posted at http://www.aapt.org/Conferences/newfaculty/upload/170621_Holmes_Labs-1.pdf). The main research-based conclusions from this group are that (1) conventional "verification" labs have *zero* measurable effect on reinforcing concepts learned in class, (2) students' attitudes about experimental work often become less "expert-like" after such labs, (3) lab-based pedagogies that are instead focused on developing skills (such as evaluating models and dealing with uncertainty) do lead to measurable improvements in such skills. This group argues that institutions should reconsider both the goals and structure of the introductory lab and they offer some examples on their website of labs that they consider likely to be more successful than conventional labs.

This work suggests that even though students (and many instructors) *like* labs to closely parallel the course content, this may in fact be, from an educational point of view, a distraction. Therefore, even though *Six Ideas* courses present material (particularly in mechanics) in a non-traditional sequence, this may not be the best issue on which to focus revision efforts.

After choosing labs for their pedagogical value, one can usually link them to the course

We have also found that with very modest revising, labs that seem out of sequence can often be successfully linked to class material. For example, say that one wanted to use the pendulum lab on the sqilabs website early in the lab sequence to teach crucial skills about uncertainty analysis. This lab tests the formula $T = 2\pi\sqrt{L/g}$, which one can "derive" using dimensional analysis (as discussed in chapter C1). At the end of the lab, when the students find that the pendulum's period also depends on amplitude, you can point them ahead, saying that we will see why in chapter N10.

Then suppose that you want to follow with the mass-spring lab on that website. This lab tests Hooke's law and compares the spring constant k in that law with the k in the expression $T = 2\pi\sqrt{m/k}$ for the period. Students in a *Six Ideas* course know what a force is after the first week, and once we have defined k, they can "derive" the period expression by dimensional analysis, so there is again no reason why this lab cannot be done early. Again, at the end, you can tell students how the period formula emerges naturally from the mathematical model developed in chapter N10.

My point is that I would recommend focusing on choosing labs that are excellent at teaching experimental skills, and find ways to connect the lab to the course afterward. This may (in a few cases) involve teaching a few basic concepts in the lab ahead of the course, but this need not be a problem.

That being said, we at Pomona have historically spent some time developing new labs on *Six Ideas* topics (such as relativity and quantum mechanics) that don't normally appear in the introductory class. We have done a pretty classic speed-of-light experiment, and developed a muon-decay experiment that tests time dilation and the connection between energy and velocity, created an experiment to test the Boltzmann factor (using a Squiggle Ball hitting a ping-pong ball up a ramp), and moved a few basic quantum mechanics experiments from the modern physics lab to the introductory class. None were sufficiently brilliant to warrant much discussion here, though I am happy to correspond with anyone interested in more details. (In particular, the muon experiment *sounds* great, but it was expensive, required a nearby mountain and a long time to collect data, and has an undetermined systematic issue that made the results disagree with relativity. We don't do it any more.)

Contact me for more information about experiments developed at Pomona.

We have also learned by sad experience that re-inventing the lab program from scratch is unwise. Though being patient is hard when one has an exciting idea for a new way of doing things, developing and testing things in pieces and iteratively yields better results and a better student experience. In our experience, students are understanding and supportive if you want to try a new approach in one or two labs, and are very willing to offer helpful and useful comparative feedback, but are less happy and supportive when the whole lab program is awkward and half-baked because one tried to change too much all at once. I strongly recommend taking small steps over some years, and carefully evaluating each step before taking the next.

Don't try to reform too much at once!

M3.8 Integration and Evaluation

Combining all of these issues together into a course design that does what you want while remaining simple enough to understand and use like any engineering task: it requires an artful balance of competing goals, demands, and practical considerations. The example syllabus at the end of this chapter shows one of my attempts. It fits the student audience I have at Pomona fairly well, but would, I'm sure, require adaptation to work well elsewhere.

19. How can handle all these issues with a simple overall design?

Experience has taught me the value of simplicity. My tendency at first was to have many policies and structures that I thought would help ensure the outcomes that I wanted. But too many rules are too hard for students to absorb and for me to enforce, and sometimes it is worth trading surety for a structure that is much simpler but still offers a significant incentive for students to exhibit the behaviors that one seeks.

Strive for simplicity

For example, consider systems that encourage students to come to class prepared. Just hoping that they will do this naturally is simple but insufficient. The relatively simple methods described in section M3.4 yield about 80%of students being prepared. Giving a high-stakes quiz at the beginning of each class period might push this a bit higher, but would be more complicated (requiring time to develop the quiz, class time to take it, time to grade it and record the grades) and stressful for the students, and it still won't get you to 100%. So is the additional complexity and stress worth it?

Another example is the favored homework grading rubric described in section M3.5.3. It is still somewhat more complicated than its predecessor (discussed in section M3.5.4), but is the result of many iterations of simplification from my initial conception. My first trials were better at evaluating certain specific details of students' solutions, but were too complicated to understand and impractical to use. It took some effort to focus in on the truly important issues and find an easy way to evaluate them.

20. How should I examine how things have worked?

"The unexamined course is not worth giving."

Learning to do better always *requires* cycles of revision and evaluation. As I said in chapter M1, my mantra is that "an unexamined course is not worth giving." Not only do I closely monitor the class atmosphere during the course and quiz TAs about what they are hearing, but I also give students (now electronically) a questionnaire at the end that asks them to evaluate their experience, often with special questions about new course structures that I am trying out. The syllabus at the end of this chapter is the product of two decades of ideas tried, evaluated, and revised.

Tools for evaluating whether learning has taken place

End-of-class evaluations can help one improve the course experience for students, but one also wants to evaluate periodically how effective the course is in actually teaching concepts. Section M3.6.1 describes a number of validated tests that can help one assess whether and/or how much students' abilities have improved in certain subject areas. Some (such as the Force Concept Inventory) require being given as both a pre-test and a post-test, but others (concerning topics about which students typically know nothing initially) require only giving a post-test. I strongly recommend periodically testing what you are doing using one of these assessment tools.

Tool for evaluating whether students' attitudes about science have changed

The best existing tool for evaluating how your students' *attitudes* about science have changed during your course is probably the Colorado Learning Attitudes About Science Survey (CLASS), which you can access online at http://www.colorado.edu/sei/class/. This validated survey compares students' initial and final thinking about science with expert-like thinking. The website provides instructions on how to analyze the results. Be forewarned that during most introductory courses, students' thinking typically becomes *less* expert-like, so if you find positive shifts you are doing very well.

To summarize, I recommend that you use end-of-class questionnaires to evaluate your course design every time, and periodically test students' educational progress and changes in attitudes about science using validated assessment tools such as the FCI and the CLASS.

Comments about the course behind the

The following pages illustrate one complete course design, including a syllabus, an example class worksheet, and an example exam. The examples) are from Pomona's 2016 Physics 70 class for students (including potential majors) who have had some high-school physics. (They have been lightly tweaked on the basis of what we learned that fall.) The goal of this course is to give our potential majors a "dessert first" contemporary introduction to college-level physics without dragging them through yet one more presentation of Newtonian mechanics. We follow this course with two half-courses on classical physics (Physics 71 on Newtonian mechanics using units C and N and Physics 72 on Electricity and Magnetism using unit E). Students in the Physics 70 course can take an optional exam to determine whether their high-school background is sufficiently strong to allow them to skip either or both of the half-courses. But our experience is that even strong students often find in Physics 70 that college-level physics is sufficiently different from their high-school AP courses that they are more willing to review Newtonian mechanics in Physics 71 than they would have been initially.

This course also illustrates how one can take advantage of the flexibility built into the 3rd edition to teach material in a non-traditional order. This course, by the way, has been very successful for us. Since we replaced our original one-size-fits-all *Six Ideas* course (which used the design CNR/EQT sequence) by Physics 70 and a separate course for pre-meds, our average number of majors has increased by more than 50% (and the enrollment in our pre-med course has also increased).

SYLLABUS for PHYSICS 70 **FALL 2016***

MONDAY	WEDNESDAY	FRIDAY	LAB (T or W)
29 NO CLASS	31 **C1** (CLASS, essay) Introduction to the Course The Art of Model-Building	2 **C2** (T2, T7, T13) Particles and Interactions	No Lab
5 **C3** (T1, T7, T10) Vector Mathematics	7 **C4** (T2, T6, B1) **HW1:** Vector Mathematics **C1:** M8, D1ab, R7 **C2:** M3, M6 **C3:** M2, M5	9 **C5** (T2, B4, B7) Conservation of Momentum	Video Analysis (introduction)
12 **C6** (T4, T7, B3) Conservation of Angular Momentum	14 **C8** (T3, T6, T7) **HW2:** Conservation of Energy **C4:** M1, M6 **C5:** M5, M6 **C6:** M6, M9, R1	16 **C9** (T3, T6, B10) Potential Energy Functions	Reference Frames & Speed of Sound
19 **R1** (T3, T7, T9) Principle of Relativity	21 **R2** (T2, T6, T12) **HW3:** Coordinate Time **C8:** M6, M11, R1 **C9:** M4, M7 **R1:** M4, M10	23 **R3** (T2, T4, T6) The Spacetime Interval	Speed of Light
26 **R4** (T4, T6, B2) Proper Time **1st PRACTICE EXAM Due**	28 **R5** (T1, T4, T9) **HW4:** Coordinate Transformations **R2:** M5, M9 **R3:** M1, M5, M7 **R4:** M4, R1ab	30 **R6** (T3, T5, T9) Lorentz Contraction	Circuits and Photovoltaics
3 **R7** (B5, T6, T8) The Cosmic Speed Limit	5 **R8** (T2, T5, T7) **HW5:** Four-Momentum **R5:** M3, M5 **R6:** M3, D2, R4 **R7:** M3, R1	7 **R9** (T1, T4, B9) Consv. of Four-Momentum	Video Analysis (own project)
10 **Q1** (T2, T4, T8) Wave Models	12 **Q2** (T9, T10, T14) **HW6:** Standing Waves & Resonance **R8:** M9, D5 **R9:** M11, M13 **Q1:** M1, M3, R1	14 **Q3** (T1, T4, B3) Interference and Diffraction	Interference and Diffraction
17 FALL BREAK	19 **Q4** (T2, T5, T10) **HW7:** The Particle Nature of Light **Q2:** M1, M4, R1 **Q3:** M1, M12	21 **Unit R Exam**	No Lab
24 **Q5** (T2, T4, B6) The Wave Nature of Particles	26 **Q6** (T2, T8, B1) **HW8:** Spin **Q4:** M3, D1 **Q5:** M4, D1, R1	28 **Q7** (T1, T4, T7) The Rules of QM	Photoelectric Effect & Spectroscopy
31 **Q8** (T4, T7, T8) Quantum Weirdness	2 **Q9** (T1, T6, T9) **HW9:** The Wavefunction **Q6:** M2, M3 **Q7:** M3, M6, R1 **Q8:** B5, D1	4 **Q10** (T3, T7, B6) Simple Models	Spectroscopy & Quantum Dots
7 **Q11** (B2, B4, T10) Spectra	9 **Q12** (T1, T4, T7) **HW10:** The Schrödinger Equation **Q9:** M5, M8 **Q10:** M4, M6 **Q11:** M5, M7, R1	11 **Q13** (T2, B1, B6) Introduction to Nuclei	Coupled Oscillators
14 **Q14** (T1, T5, T10) Nuclear Stability	16 **T1** (T5, T6, T10) **HW11:** Temperature **Q12:** M2, D3 **Q13:** M10, D5, R1 **Q14:** B8, M4	18 **T2** (T4, T5, T6) Macrostates and Microstates	Lab Tours
21 **T3** (T1, T6, T7) Entropy and Temperature	23 **T4** (T3, T6, T11) **HW12:** The Boltzmann Factor **T1:** M3, M7, R2 **T2:** M2, M4 **T3:** M3, M7	25 THANKSGIVING	Lunch on Monday
28 **T5** (T3, T12, B2) The Ideal Gas	30 **T6** (B4, T6, T9) **HW13:** Distributions **T4:** M3, M6 **T5:** B10, M4, R1	2 **T10** (T2, B3, B6) Climate Change 1:15 pm Optional Discussion	Peltier Coolers & IR Spectroscopy
5 **T7** (T3, T8, T10) Gas Processes	7 Handout, **T9** (T3, T6, T9) **HW14:** Heat Engines **T6:** B6, M4 **T10:** M6, M8, R3 **T7:** M5, R1	9	No Lab
12 13 **Unit Q and T Exams 9:00 am**	14	16	

Underlined problems are “collaborative learning” problems. Items in parentheses are pre-class problems. You should have received emailed information prior to the first class about the CLASS survey and the essay on the strengths you personally bring to physics that you should bring to class the first day.

*This syllabus has been modified from the actual 2016 version.

PHYSICS 70 **GENERAL INFORMATION** **FALL 2016**

Instructor	**Office**	**Phone**	**E-mail**	**Office Hours**
Thomas Moore	Millikan 1151	x18726	tmoore@pomona.edu	MTR 3:30-5 pm

Texts: Moore: *Six Ideas That Shaped Physics* (3rd edition), units C, R, Q, and T (available in the Huntley Bookstore)

Other required supplies: (1) a **good scientific calculator** (with statistics functions, but a graphing calculator is not necessary), and (2) a **purple or green pen** (get several!). You will also be using your smartphone as a scanner (see below if you don't have one): Please get a good scanner app (for example, Scanner Pro or Scannable for iOS or CamScanner for Android) that scans to PDF files (there are several decent free apps). You will also likely find a ruler, a 3-ring binder, and a stapler handy.

Drawers: To the right of the elevator east of our classroom, you will find a cabinet with (1) small locked slotted mailboxes (on the right) and (2) large drawers with file folders (on the left). You may turn in homework (see below) to the slotted mailbox labeled "Physics 70" and retrieve graded work from the folder with your name on it in the large drawer labeled "Physics 70."

Learning Objectives: This course represents a guided inquiry into contemporary physics. Its main goals are (1) to develop an adequately clear big-picture understanding of relativity, quantum physics, and thermal physics to allow you to explain these topics to a high-school class, (2) to enable you to apply core physics principles correctly and thoughtfully to realistic situations, and (3) to adequately prepare you for subsequent physics courses. You will also practice using some specific skills, including

- How to model a physical situation by making suitable approximations.
- How to use mathematical tools, including drawing and interpreting graphs, keeping track of units, doing algebra using symbols, using single-variable calculus applied to vectors, and using and interpreting computer models.
- How to present a problem solution clearly in writing.

The focus on the model-building process (in addition to merely learning concepts) is one of the things that distinguishes a good college-level course from a high-school course, so the skills you will need to succeed in this course are thus somewhat different.

A Metaphor: Physics is more like learning to play a sport or a musical instrument than merely memorizing information: there are actual skills to learn that can only be mastered through practice. This course is therefore designed to give you guided practice with feedback. You should consider class sessions and homework to be *practice*, formal exams to be like *games or recitals*, and your instructor and mentors as *coaches*. You will receive credit in this class for both practice and performance.

General Class Structure: Physics education research has robustly shown that practice-oriented activities are *much* more effective than lectures at teaching both the concepts of physics and physics reasoning skills. We will therefore spend most of class time doing *activities* that give you practice (with instant feedback) in using the concepts discussed in the reading. *All* activities will assume that you have read the assigned reading BEFORE coming to class: this is *crucial* for you to learn effectively!

Pre-Class Exercises: Next to the reading assignment for each day on the syllabus is a list of two or three simple problems (in parentheses) to do *before* class. Bring your work to class and put in the tray in the back of the room as you come in. We will grade your pre-class work (as a unit) on a 3-point scale (3 = all correct, 2 = good effort but one or two errors, 1 = poor effort and/or entirely wrong, 0 = missing). The writeup for each problem can be *very* brief, but do show your work (or if the assigned problem is a two-minute problem, please provide a brief explanation for your answer). You should be able to get these very simple problems right with little effort if you have read the chapter beforehand. If you can't be present for class, get someone else to submit your pre-class exercises (preferred) or submit a scan via email before class (see scanning instructions below).

In-Class Worksheets: While participating in class activities, you will fill out a worksheet. Please place your finished worksheet to the tray at the back of the class as you leave. Someone will grade your worksheet on a 2-point scale (2 = complete and correct, 1 = partial, 0 = absent), add it to your pre-class score, and return the worksheet to your folder before the next class. Be sure to correct any mistakes as we talk about them in class, but work can be very sketchy compared to homework. If we don't have enough time to go over the entire worksheet, I will announce what I expect you to have completed in class.

Homework Problems: Much of your real learning takes place when you try to do substantial assigned problems AND learn from your mistakes. Before class each Wednesday, you should submit (via email) a scan of all pages of your solutions to that week's assigned homework problems (see the scanning instructions below). Do NOT turn in your actual written homework: you will need it for the next step. The scans provide a record of your initial effort.

After 6 pm each Wednesday, you can view solutions to the problems due that day by running the web-app ProbViewer (https://sixideasapps.pomona.edu/ProbViewer) and entering the password "Accio70Solutions!" Carefully compare each of your solutions with the posted solution. Use your green or purple pen to correct your solution as needed to make it right (this will make it easy for us to differentiate your corrections from your original effort). If you think your solution was initially right, mark it as such. Submit your corrected problem solutions (on actual paper!) to the Physics 70 mailbox before Friday's class or put them to the tray as you enter the classroom. See the last page for details about how we will grade your homework

Please Allow Space. Note also that you may need to extensively correct any given problem, so as you write up your initial efforts, please leave plenty of space on the same page for corrections as well. Your corrections should (if at all possible) go on the same physical page as your initial effort: this makes things much easier for the grader.

Homework Rules and Indulgences: I will automatically drop your *three* (3) lowest pre-class scores and your *five* (5) lowest individual problem scores before computing your final grade. This is meant to give you flexibility to deal with normal illnesses, field trips, athletic trips, big papers, unexpected romances, and so on, so I shouldn't need to hear excuses from you unless an emergency or significant illness keeps you out more than two class days in a row. If you are sick or away on a Friday, please have someone to submit your corrections for you (or email me *color* scans before class: see below). Note also that you must submit a corrected homework set (even if you don't actually correct anything) to earn credit. Late submissions will incur some point penalties: see the homework grading page for details.

Scan Submission Guidelines. Please email scanned initial efforts before Wednesday's class to Physics70@pomona.edu as a single scanned PDF file (if at all possible), using the naming convention HW<Num><YourLastName>.pdf (which should also be your subject line). For example, a student named Sascha Payne would submit the 2nd homework with subject and file name HW2Payne.pdf. (If you cannot submit a scan, let us know beforehand and submit a xerox of your solutions to the "Physics 70" mailbox.) In the rarer cases where you are emailing pre-class work or a color scan of corrected work, please use the prefix PC (followed by the chapter number) or CHW (respectively) instead of HW to help us differentiate these items.

Collaborative Learning Sessions: I recommend that you work in groups on all problems, especially on the "collaborative learning problems" underlined on the syllabus. These (R-level) problems are especially challenging problems that are designed to be done in groups. (However, please note that any work you hand in must always be in your own words.) You may work with others on Sunday and/or Tuesday nights at 7:00 pm in our normal classroom, where you can get help from one or more student mentors. The mentors are there to assist you when you are stuck, but not to help you get started or give or approve answers. Work on problems first and go to the mentors when you reach an impasse or have specific questions to ask.

Exams: You will take three exams during the course. All will include both short-answer conceptual problems (like the two-minute problems in the book) and one or two essay problems (like the textbook's M problems) and will be similar in style to the practice exam (see below). On each exam, you may use a calculator and an 8 ½ x 11-inch "cheat sheet" and a calculator, but no other aids. I will provide all numerical constants and conversion factors. The first (in class on October 21) will cover unit R, the second will cover unit Q and the third will cover unit T and review stuff you collectively found difficult on the practice exam on unit C. The last two exams will be given during the 3-hour final exam period for this class to give you extra time.

Practice Exam: This exam on unit C topics will be identical in style to the real exams. You will take this exam outside of class in one hour-long sitting using only a calculator and a cheat sheet, as if it were a real exam. Submit a scan (with prefix "PX") by 6 pm on Sunday 9/25. Solutions will appear on the course's Sakai site by 9 pm: use them to correct your exam as if it were homework, and submit the corrected exam (on paper) to me in class or the Physics 70 mailbox no later than 5 pm on Monday. Your score on this exam will be (1/3) × (pre-correction score) + (2/3) × (post-correction score) to make the stakes relatively low.

Grading scale: All grades in this class are based on a fixed scale,: **you are not competing with each other**. You can determine your letter grade on any item by dividing what you earned by what you could have earned, multiplying the result by 20, rounding down to the next *lower* integer, and consulting the chart below:

Integer:	20	19	18	17	16	15	14	13	12	11	10	9	≤ 8
Grade:	A+	A	A–	B+	B	B–	C+	C	C–	D+	D	D–	F

If the average class performance for any item is particularly low (indicating that the item was unusually difficult) I may adjust grades to be higher than this scale would indicate, but I will never adjust your grade to be lower. You will earn an A+ as your final grade if your final total score (out of 20) is above 19.70.

Grading Weights: See the chart below. Please note that no matter what your final calculated grade is, **you will fail the course if you receive an F for the lab OR both exams. You must pass *each* individual lab to pass the lab as a whole.**

Pre-class & Worksheets	Homework	Practice Test	R Test	Q Test	T Test	Lab	**Total**
10%	25%	9%	12%	12%	12%	20%	100%

Academic Honesty: While you may (and are encouraged to) collaborate on homework problems, any work that you hand must express i*n your own words* whatever approach to the solution you developed with your collaborators. In your work together, exchange *ideas*, not phrases and sentences. You should not copy a sequence of algebraic steps from someone else: work out any algebra on your own. Your work on exams must (obviously) be entirely your own.

HOMEWORK GRADING INFORMATION

We will use the following rubric to evaluate your work on each homework problem solution:

I	C	
❐	❐	Description (Sufficient/Clear/Coherent) ($1\frac{1}{2}$)
❐	❐	Model (Correct Principles/Correct Application)
❐	❐	Good Notation (Symbolic Algebra/Units&Vectors)
❐	❐	Valid Math (Sufficient/Correct)
❐		Plausible (Right Units/Magnitude/Sign)
× --	--	Fraction = TOTAL

The "I" and "C" columns represents marks for your initial and corrected efforts respectively. The grader will mark each box as follows: ❐ = full credit, ❐ = $\frac{1}{2}$ point off, ❐ = 1 point off, ❐ = $1\frac{1}{2}$ points off. You also might also see ~~❐ ❐~~ for a small issue that persisted in the correction = $\frac{1}{2}$ total points off (= $\frac{1}{4}$ point for each box). Boxes (other than "Description" boxes) are worth one point. The "Fraction" represents the fraction of the problem you did in each phase (no mark = complete). The grader will count the number of points recorded in the boxes in each column, multiply the result by the column's fraction, add the results for the two columns and round to the nearest half-point. The maximum score on each problem is 10.

Your grader may underline some of subcategories (the words or phrases listed in parentheses in each category title) to help clarify where the issues are. Adequately addressing each subcategory is nominally worth $\frac{1}{2}$ point, but especially egregious issues in any one subcategory might cost a full point (it is up to the grader's judgment).

Note that if you submit a clear and complete initial effort with good mathematical form, and your result is plausible (see below) and you also submit a complete and valid correction, you will earn a minimum of 8 points, even if your model is completely wrong and your math is also wrong. Therefore, this system mostly rewards effort (as appropriate for a practice activity).

Here are some comments about the individual categories (rows in the rubric):

Description: In this category alone, each box is worth $1\frac{1}{2}$ points. Your solution earns full credit in this category if it provides sufficient and adequately clear information (apart from your mathematics) to make your reasoning transparent to one of your peers. You can provide this information with descriptive English, lists, and/or labeled diagrams. Please also note that only work that is both legible and reasonably easy to follow qualifies as "Clear." (I recommend writing in pencil and liberally using an eraser.) "Coherent" solutions flow logically and without self-contradiction.

Model: Your solution will earn full credit in this category if your solution (implicitly or explicitly) uses the correct physical principles and also applies those principles correctly (which includes making appropriate and clearly stated approximations when necessary). This category is about correctness, not necessarily clarity, but if your model description is so unclear that the grader cannot even guess what your model is, you will lose points in *both* the Description and Model categories.

Good Notation: This category is to math what good grammar is to writing. Your solution will earn full credit in this category if (1) you do all your algebra with symbols (no algebra with numbers), (2) you include units with every numerical quantity that has them (in definitions and/or your post-algebra calculations), and (3) you use correct vector notation.

Doing all your algebra symbolically is crucial for making your work clear and easy to follow (for both you and the grader). You may use simple unitless numbers (particularly integers and simple fractions) in addition to symbols: what you should avoid is doing algebra with any quantities having units and/or unitless quantities that involve more than two or three digits. *Hint:* You are "doing algebra with numbers" if a symbol appears on the same side of an equation with such a number.

Unit *tracking* is very useful and highly recommended, but simply *including* units with every numerical quantity having units is enough. Correct vector notation is important: in particular, never (1) set a vector equal to a number or (2) divide by a vector.

Valid Math: You will earn full credit here if (1) you adequately display all of your steps, and (2) your math is correct.

Plausible: Your solution will earn full credit here if your initial result (whether a number or formula) has a plausible sign and units and (if a number) a plausible magnitude OR you have an explicit note recognizing that your result is *not* plausible. A corrected result should be plausible, but if an implausible result is not fixed, then the grader might use the circle notation to take off an extra half-point. You also may get points off if you made an error (or failed to catch an error) because of a bad habit such as (1) defining symbols poorly (for example, using the same symbol for different quantities), (2) doing algebra with numbers, (3) using bad vector notation, (4) not tracking units, or some similar problem.

Penalties. Initial efforts submitted between 1 pm and 6 pm on Wednesday will have one point deducted per problem; those submitted after solutions are posted at 6 pm will earn zero points in the "I" column (though you may still submit a "correction"). Final efforts submitted later than 5 pm on Friday get two points per problem deducted if they were submitted after the grader started grading (and thus required a special grading effort). Doing the wrong problem automatically earns 2 points of initial credit: write a version of the posted solution the actual problem in your own words to earn up to $4\frac{1}{2}$ more "correction" points. You may submit a similar "correction" for any problem you did not submit initially (to earn up to $4\frac{1}{2}$ points).

C2 Activity Sheet

Name ____________________________

Principles of Modern Mechanics: (Don't look at the book!)

1.

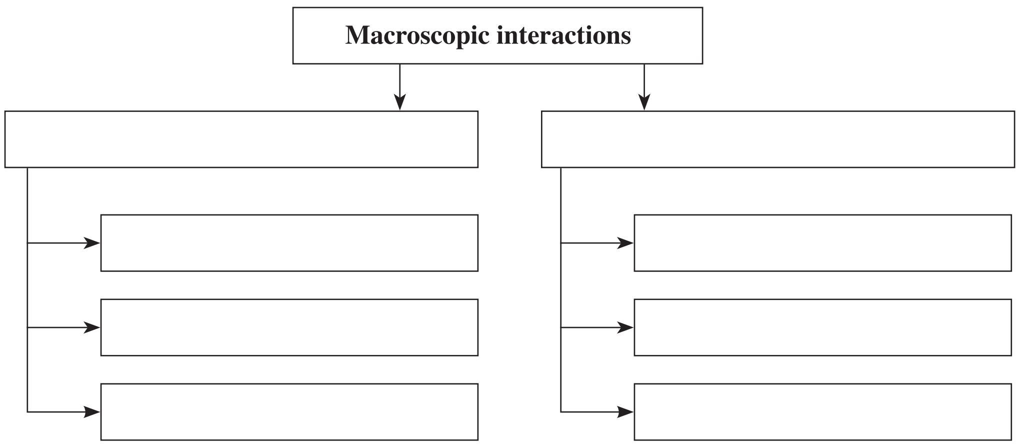
2.

3.

4.

5.

Classification of Macroscopic Interactions: (Don't look at the book!)

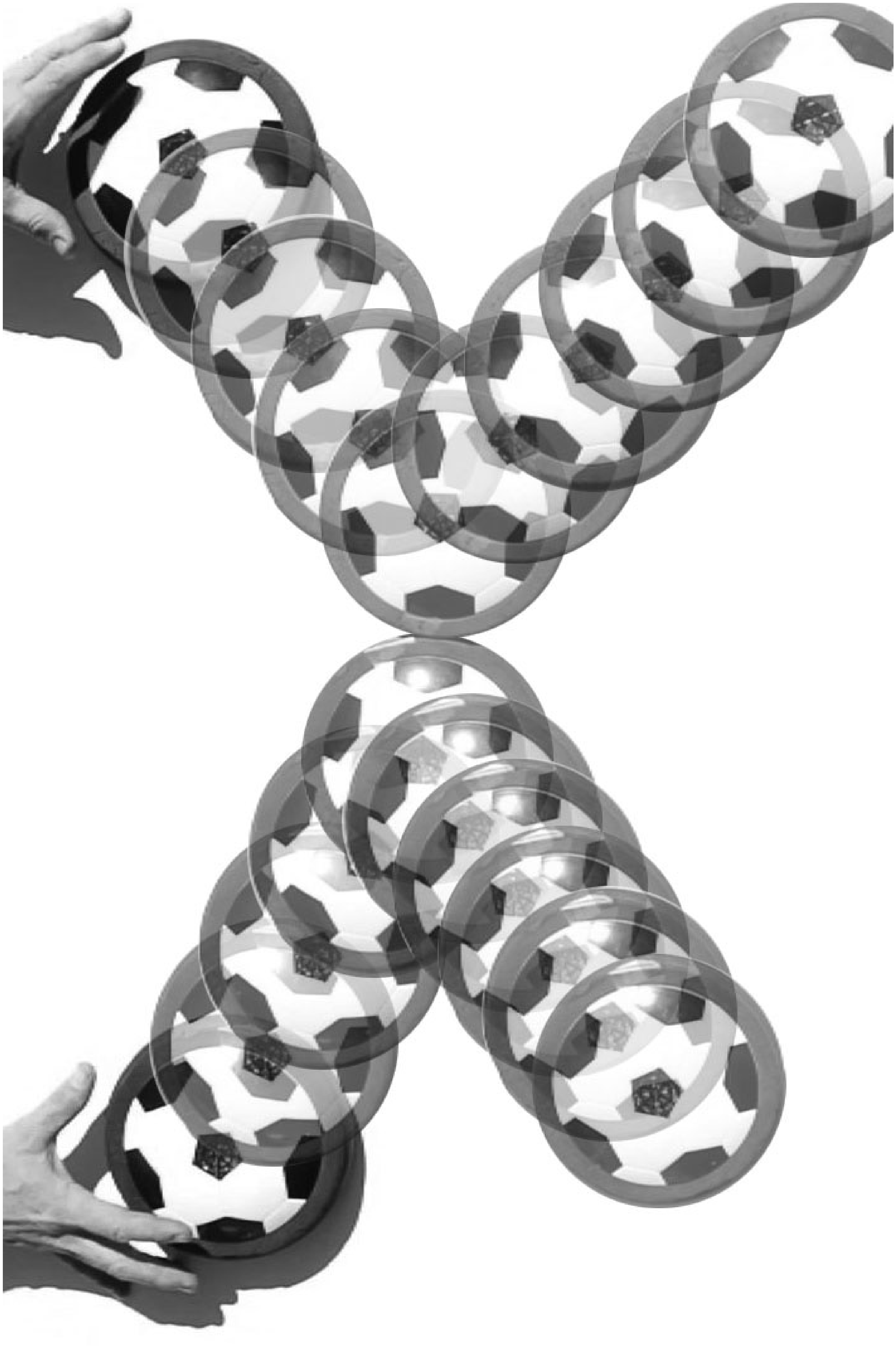


Active demonstration. We will launch an air-track glider of mass m toward another with mass M at rest and measure the speed $|\vec{v}_0|$ of the initially moving glider and the speeds $|\vec{v}_1|$ and $|\vec{v}_2|$ of the two gliders after the collision. According to the principle of momentum transfer, the ratio of the gliders' masses is

$\frac{m}{M} =$ ____________

Practice Problem. Do problem C2B.13. Write your answers in the space below. (This is the *lowest-priority* activity: do this after you have completed everything else, including the problem on the reverse side.)

Practice Problem: Do problem C2M.1. A blown-up version of the picture appears below.



Name________________________________

PHYSICS 70 PRACTICE EXAM

Initial Effort due Sept. 25 by 6 pm*

Corrections due Sept. 26 by 5 pm*

INSTRUCTIONS: This is a closed-book, closed-notes exam. You are allowed to use a calculator, a ruler, and an 8.5-inch by 11-inch "cheat sheet" covered on one side with whatever information you want, but no other aids.

Do your work in the blank space provided on this exam form, using the backs of sheets if you need to. The test has 50 total points. Try to take it in one sitting of 60 minutes (in order to simulate the pace of a real exam), doing the best that you can in that time and electronically submit a scan before 6 pm on Sunday. Then correct your work using the solution posted by 9 pm on the Sakai site and your trusty green or purple pen. Your final grade will be $\frac{1}{3}$ × (your pre-correction score) + $\frac{2}{3}$ × (your post-correction score).

CONSTANTS, FORMULAS and CONVERSIONS:

$G = 6.67 \times 10^{-11}$ J·m/kg^2 100 cm = 1 m
$c = 3 \times 10^8$ m/s
1 J = 1 kg·m^2/s^2
1 lb = 1 pound = 4.45 N = 4.45 J/m
1 ft = 12 inches, 1 inch = 2.54 cm

*This exam has been slightly modified from the actual practice exam given in 2016, but illustrates nicely the style of the exams I give.

UNITS SECTION (12 pts)

1. (4 pts) **Unit Conversion.** Simply write down the string of unit operators necessary to calculate what a 1 J of energy is in the old British imperial units of slugs, feet and seconds, where 1 slug = 14.59 kg, 1 ft = 12 inches, 1 m = 100 cm, and 1 inch = 2.54 cm. You need not calculate the final result.

2. (3 pts) **Unit Consistency.** Since all falling objects accelerate at the same rate, the time that it takes an object to orbit a planet will *not* depend on the object's mass but plausibly only on the planet's mass M, the orbit's radius R and the universal gravitational constant G, which has units of $\text{J}\cdot\text{m}/\text{kg}^2 = \text{m}^3/(\text{kg}\cdot\text{s}^2)$. Using dimensional analysis, find a plausible expression for this time in terms of M, G, and R.

3. (5 pts) **Unit Consistency and Notation Conventions regarding units.** In the space provided to the right of each equation or statement, either write that it is "OK" or briefly describe what is wrong with it. The quantities below have the units one would expect: $\vec{r}$, and h have units of meters, g has units of m/s^2, and $\vec{v}$ has units of m/s.

   (a) Since it has a mass $m = 1$ kg, the object's kinetic energy is simply $\frac{1}{2}m|\vec{v}|^2 = \frac{1}{2}|\vec{v}|^2$.

   (b) The magnitude of the object's angular velocity is $|\vec{\omega}| = \dfrac{\pi \text{ rad}}{\text{s}} = \dfrac{3.14}{\text{s}}$.

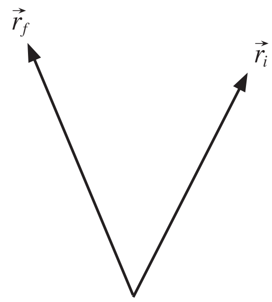
   (c) The maximum altitude reached is $h = 1 + \dfrac{|v|^2}{g}$.

   (d) The object's speed is $|\vec{v}_0|$ m/s.

   (e) The object's displacement is $\vec{r}_f - \vec{r}_i = \begin{bmatrix} -3 \\ 5 \\ 0 \end{bmatrix}$.

VECTORS SECTION (11 pts)

4. (4 pts) The arrows representing an object's initial and final positions $\vec{r}_i$ and $\vec{r}_f$ during a process. What is the object's change in position $\Delta\vec{r} \equiv \vec{r}_f - \vec{r}_i$ during that process? (Draw an arrow.)



5. (7 points) **Vector Mathematics, Vector Notation,** and **Notation Conventions.** In the space provided to the right of each equation or statement, either write that it is "OK" or briefly describe what is wrong with it. Don't worry about the units: focus on issues regarding vector operations and vector notation.

   (a) Two forces $\vec{F}_1$ and $\vec{F}_2$ act on an object. The magnitude of the total force on the object is $|\vec{F}_1| + |\vec{F}_2|$.

   (b) If all the forces acting on an object cancel, then $\vec{F}_{\text{net}} = 0$.

   (c) The object's final velocity is $\vec{v}_f = -12$ m/s.

   (d) During a process through which a gyroscope receives external angular momentum as it precesses, the change in its angular momentum has a magnitude of $|\Delta\vec{L}| = |\vec{L}_f| - |\vec{L}_i|$.

   (e) $\vec{p}_{2x} = -15$ kg·m/s.

   (f) Because the gravitational acceleration $\vec{g}$ points downward, $|\vec{g}|$ is negative.

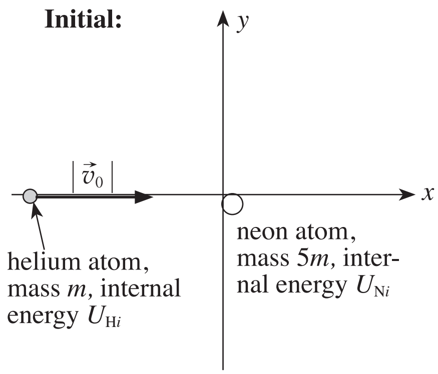
   (g) A symmetric object's moment of inertia can be calculated as follows: $I = \dfrac{\vec{L}}{\vec{\omega}}$.

PROBLEM SECTION (15 points)

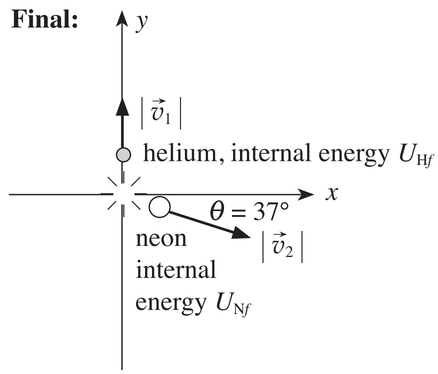
6. Imagine that in an atomic physics experiment, a helium atom moving at a speed of $|\vec{v}_0|$ hits a neon atom. Afterward, we observe that the helium atom rebounds with a velocity $\vec{v}_1$ of unknown magnitude whose direction makes a 90° angle with its original direction of motion, while the neon atom moves with a velocity $\vec{v}_2$ of unknown magnitude whose direction makes an angle of $\theta = 37°$ with respect to the helium atom's original direction of motion (see below). Note that $\cos\theta = 4/5$ and $\sin\theta = 3/5$ when $\theta = 37°$, and that the mass of a neon atom is very nearly 5 times that of a helium atom. What fraction of the original atom's kinetic energy has been converted into internal energy in this process?

   (*Hints:* You will have to use more than one conservation law. Solve one law for the atoms' final speeds in terms of $|\vec{v}_0|$ and substitute into the other. You will have better luck working with exact fractions in your symbolic calculations rather than with calculated decimal numbers, for example, use 4/5, not 0.80 or the exact value of cos 37°.) Be sure to check that your result makes physical sense. To decouple this section from the diagram drawing section, I have provided the diagrams you need as well some useful symbols. Note that energy, momentum, and angular momentum must be separately conserved in this situation, but one law is not relevant.)

Initial:



Final:



We are "given" $|\vec{v}_0|$ and we know that $\theta = 37°$, and we can look up m if we need to.

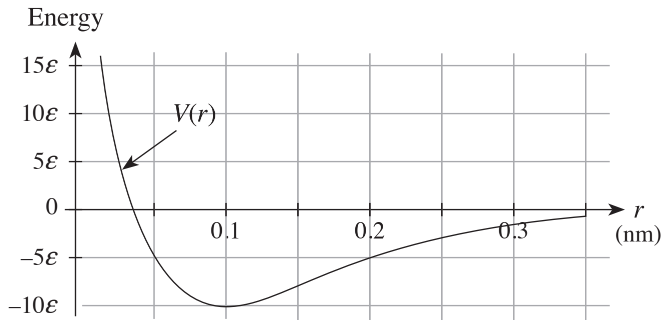
We want to determine

$$\frac{U_{Nf} + U_{Hf} - U_{Ni} - U_{Hi}}{\frac{1}{2}m|\vec{v}_0|^2}$$

RUBRIC

❐ ❐ ❐ Description (Sufficient / Clear / Coherent)
❐ ❐ ❐ Model (Stated: System / Assumptions / Laws used)
❐ ❐ ❐ Model (The two laws are applied correctly, noting vector nature when appropriate)
❐ ❐ Good Notation (Symbolic Algebra / Vectors)
❐ ❐ ❐ Valid Math (determining $|\vec{v}_1|$, $|\vec{v}_2|$, final ratio)
❐ Plausible

PE DIAGRAMS SECTION (12 pts)



Reading Potential Energy Diagrams. All of the questions below refer to the potential energy diagram above, which is a hypothetical potential energy function for the interaction of two atoms moving in one dimension relative to each other. The symbol ε stands for a very small quantity with units of energy. The potential energy goes to zero as the interatomic separation r goes to infinity. Explanations are optional, but if provided, they will be counted (for better or worse) in your grade. **NOTE:** "Bound" means "r cannot go to infinity."

7. (4 pts) Does this system have a (or some)

   stable equilibrium point(s)? ❒ yes ❒ no If yes, where? At r =

   unstable equilibrium point(s)? ❒ yes ❒ no If yes, where? At r =

8. (2 pts) Suppose the system has a total kinetic energy of $K = 5\varepsilon$ at a separation of $r = 0.1$ nm. How much energy must we add to the system to make it unbound (or is it already unbound)?

   ❒ We must add an energy of _____ε

   ❒ The system is already unbound.

9. (2 pts) Imagine that the two atoms are initially at rest at separation $r = 0.05$ nm. Describe what happens to r subsequently.

10. (2 pts) How much kinetic energy K must the system have when its atoms' separation is $r = 0.1$ nm if their maximum separation as it oscillates is 0.3 nm?

    _____ε

11. (2 pts) If the system has a total energy of $E = -2\varepsilon$, what are the allowed and forbidden regions for the atoms' separation r? (Indicate these regions on the diagram above or check this box: ❒ the system's total energy cannot be negative.

M4 Introduction

M4.1 Overview

One of my main goals for the 3rd edition of *Six Ideas That Shaped Physics* was to greatly increase instructors' flexibility in using the books. This was made urgent by the shift at Pomona to a different format for introductory course, one that required us to teach units R, Q, and T in the fall semester. But the author had also long felt that the 2nd edition restricted professors too much in choosing the level of the course and the topics covered.

This chapter will describe some of the new flexibility that professors using the 3rd edition have. Some of the material in this chapter is also in the prefaces to the various volumes, but I've added a few expansions, and I also thought it valuable to gather it here in one accessible place.

In the long term, I also hope to add new downloadable materials to the website to fill needs that particular professors might have. First on the agenda is materials on geometric optics, but we also hope to add other materials (at both a higher and lower level than the typical level of the text) that instructors might request. Please send me your ideas and requests.

The remaining sections discuss units in the canonical order CNREQT.

M4.2 Unit C

Here is a list of the chapters in this unit:

C1:	Model Building	(core)
C2:	Particles and Interactions	(core)
C3:	Vectors	(core)
C4:	Systems and Frames	(core)
C5:	Conservation of Momentum	(core)
C6:	Conservation of Angular Momentum	(basic AM, needed for Q)
C7:	More about Angular Momentum	(cross-product stuff, for N)
C8:	Conservation of Energy	(core)
C9:	Potential Energy Graphs	(core)
C10:	Work	
C11:	Rotational Energy	
C12:	Thermal Energy	(useful for T)
C13:	Other Forms of Internal Energy	(useful for T)
C14:	Collisions	(useful for R8–R9, *optional*)
CA:	Appendix: The Standard Model	

The "core" chapters C1–C6, C8, and C9 present the material assumed by other units, and any *Six Ideas* course should begin with *at least* these chapters. Chapter C6 on the basics of angular momentum is strictly required only for unit Q (where it provides the basis for understanding spin), but including it with the other chapters listed above gives students a basic introduction to the three great conservation laws.

Chapter C7 presents the more difficult aspects of angular momentum (the cross product definitions of angular momentum and torque) and gives the only example in unit C about how symmetry implies conservation. It is used later only in chapters N4, N11, and N12. Though I think that this chapter is valuable, one can delay it until closer to unit N (as we do at Pomona). Alternatively, one could simply spend some time in class presenting the cross-product definition of torque before chapter N4, and the cross-product definition of angular momentum before chapter N11, appealing to the basic definitions of these quantities presented in chapter C6 and some qualitative arguments rather than doing a formal derivation.

Chapter C14 (Collisions) is optional, though I think that it is valuable in its own right for helping students see how the conservation laws work together and helping them become better prepared for chapters R8 and R9. But if time is short, this chapter could be dropped.

If one really is in a bind for time, one could also consider dropping chapter C11 (Rotational Energy), which (though it provides a good stepping stone to other more hidden forms of energy) is not required for any other chapter in C or beyond. Chapters C12 and C13 provide valuable (though not strictly essential) background for unit T, but are not required for any other unit. But chapters C11–C13 *are* essential, I think, for students to develop a reasonably complete understanding of the Newtonian concept of energy at the introductory level, so I would argue that they should be a part of an introductory course that prepares students to go on in physics or engineering (and C12 and C13 at least should be a part of any course for pre-meds.)

M4.3 Unit N

Here is a list of chapters in Unit N:

N1:	Newton's Laws	(core)
N2:	Forces from Motion	(core)
N3:	Motion from Forces	(core)
N4:	Statics	(core)
N5:	Linearly Constrained Motion	(core)
N6:	Coupled Objects	(core)
N7:	Circularly Constrained Motion	(core)
N8:	Noninertial Frames	(core)
N9:	Projectile Motion	(core)
N10:	Oscillatory Motion	(core)
N11:	Kepler's Laws	(core)
N12:	Orbits and Conservation Laws	(*optional*)
NA:	Appendix: Differential Calculus	(for students needing a review)
NB:	Appendix: Integral Calculus	(for students needing a review)

The core material in this unit provides a pretty important foundation for all of the other units and for students' physics preparation generally. But is it *essential*? That depends a bit on the quality of students' high-school exposure to Newtonian mechanics.

For students who have never taken a high-school physics course, I would consider this unit *essential* before taking on units R, E, Q, and T. However, at Pomona, students with a decent high-school background take our "dessert first" Physics 70 course, which discusses the core of unit C (C1–C6, C8, C9) followed by units R, Q, and T (see chapter M3 for a course syllabus).

During Physics 70, students can take a placement test to see whether their high-school mechanics or EM will allow them to place out of Physics 71 (a half-course in the remainder of unit C and all of unit N) or Physics 72 (a half-course on unit E). We find that though our Physics 70 students having good high-school backgrounds are able to complete units R, Q, and T successfully without unit N (or the latter parts of unit C), the few students who have tried taking Physics 70 *without* an adequate high-school background clearly struggle. We also find many of those who have solid backgrounds discover in Physics 70 the value of strengthening their understanding of mechanics, and so don't even bother to try to test out of Physics 71. This underlines the value of unit N for all but the most-prepared students.

If one *must* make cuts to this unit, one might drop chapter N12, and then maybe the part of chapter N4 on torques. If one does not use unit Q or unit T, one might also cut chapter N10 (on the harmonic oscillator): this material is not needed for units E or R.

Chapters C1–C9 provide the necessary background for unit N. See the previous section for a discussion how one might avoid chapter C7.

Appendices NA and NB provide a review of calculus that could be valuable to some students. Indeed, one might consider assigning these in a class where many students are weak or rusty on calculus concepts.

M4.4 Unit R

This unit is designed to follow anywhere after unit N, though chapters C1–C5 and C8 could provide a minimal background for this unit. However, chapters C14 and N7 are pretty valuable (and note that C14 requires C6–C7).

Here is a list of chapters:

R1:	The Principle of Relativity	(core)
R2:	Coordinate Time	(core)
R3:	Spacetime Interval	(core)
R4:	Proper Time	
R5:	Coordinate Transformations	(core)
R6:	Lorentz Contraction	(core, useful for chapter E11)
R7:	The Cosmic Speed Limit	(useful for unit E)
R8:	Four-Momentum	(useful for some EQT problems)
R9:	Conservation of Four-Momentum	
RA:	Appendix: Converting Equations to SI Units	(helpful reference)
RB:	Appendix: The Relativistic Doppler Effect	

The shortest reasonable treatment of relativity using this unit would be to cover only the "core" chapters above. This would yield a five-session introduction to basic relativistic kinematics (with no dynamics or $E = mc^2$) and would provide everything that would be helpful for unit E. Adding chapter R4 and/or R7 would provide a richer introduction to pure kinematics.

The shortest introduction that includes dynamics would be to omit chapters R4, R6, and R7 and add a single class session devoted to sections R4.1 through R4.4 and section R7.4 (and possibly section R7.1). This would go over everything that is useful for unit Q in seven class sessions.

However, students find the material in chapters R4 and R6 some of the most interesting in the book, and chapter R6 is not only the most important for unit E but is also where they really test their understanding of relativistic kinematics in the context of tough paradoxes. Therefore, I recommend doing the whole unit if possible. I hope that by making the unit one chapter shorter in this edition, I have made a complete exploration a bit easier.

If you want to assign appendix RB on the Doppler shift, you can go over it any time after section R4.2. It could displace some of the latter sections of chapter R4, displace some of the middle sections of chapter R7, or supplement chapter R6 (which involves fewer new ideas than the other chapters).

Unit R is not *strictly* needed for any other unit. Though the principle of relativity and a few relativity concepts are used in unit E, most students have been exposed to what they need through popular culture (which might be reinforced if necessary by a bit of review in class). Some homework problems in units E, Q, and T also assume exposure to unit R, but one can avoid these.

So while this unit *could* be dropped entirely, it does present a contemporary physics topic that fascinates students but that few understand. It also provides a terrific illustration of how theoretical physics works. Anecdotally, is also perhaps the best unit for enticing students to major in physics. In the original design of the *Six Ideas* program, its placement just before the end of the first semester meant that students would end their first semester of physics with something exciting that they could take home for the holiday break and that would motivate them to come back for more next semester.

M4.5 Unit E

In the design sequence for *Six Ideas*, unit E follows units C, N, and R. Chapters C1–C5, C8–C10, and chapters N1–N7 provide the irreducible foundation for this unit. But there are also good reasons to go against history and schedule unit R before unit E. Knowing some relativity can make certain aspects of electricity and magnetism simpler, and unit E takes advantage of this (particularly in chapter E11).

However, I have been taken pains in the 3rd edition to arrange things so that students only need to know (1) the principle of relativity, (2) that *c* is the ultimate speed limit, and (3) the fact that moving objects are Lorentz contracted. These idea are simple enough to take on faith (and most students have learned them from popular culture), so I do not think that Unit R is truly a prerequisite.

Here's a list of chapters:

E1:	Electric Field	(core)
E2:	Charge Distributions	(core, sections 2.5 & 2.6 are *optional*)
E3:	Potential	(core, includes line integrals)
E4:	Static Equilibrium	(core, includes capacitors)
E5:	Current	(core, includes flux)
E6:	Dynamic Equilibrium	(core, covers simple circuits)
E7:	Analyzing Circuits	(*optional*)
E8:	Magnetic Fields	(core)
E9:	Currents Respond to Magnetic Fields	(core)
E10:	Currents Create Magnetic Fields	(core)
E11:	The Electromagnetic Field	(core, but the unit could end here!)
E12:	Gauss's law	
E13:	Ampere's law	
E14:	Integral forms	(*optional*)
E15:	Maxwell's Equations	
E16:	Faraday's Law	(not really needed for E18)
E17:	Induction	(not really needed for E18)
E18:	Electromagnetic Waves	
EA:	Appendix: The Electromagnetic Transformation Law	
EB:	Appendix: Radiation from an Accelerating Particle	

With this edition, one can now give students a a basic introduction to electric and magnetic fields in either 10 or 11 class sessions by ending with chapter E11 (in such a case, section E11.5 can be also omitted, because it is only relevant to chapters E15 and E18). Even in this edition, students experience a significant increase in difficulty starting in chapter E12. Chapter E11 now provides a natural ending point that addresses the unit's "big idea."

Except for chapter E7, chapters E1–E11 provide a sequentially developing and interlocking treatment that cannot be modified much. E7 is valuable material for anyone who might have contact with electronics (or even house wiring), and naturally fits after chapter E6, but is not required for anything later in this unit or any other unit.

Chapter E14 on the integral form of Maxwell's equations is now completely optional, though I know many users will want it. Indeed, one might elect to spend two class days on this chapter to teach it thoroughly.

Even if one wants to get to chapter E18, one *might* omit chapters E16 and E17, though I think that these chapters are valuable for other reasons. By omitting chapters E7 and E14 (or E16 and E17), *Six Ideas* users who need to present the unit in the 2nd edition's 16 class sessions can still do so.

I have provided appendix EA for professors and for students who have completed unit R and are interested in seeing the full relativistic argument. Technically, it requires only the principle of relativity and the velocity-addition formula, but the reasoning was too complicated to put into chapter E11 Appendix EB is for professors and advanced students who would like to see how one can derive equation E18.15. It essentially provides the same kind of argument as Appendix B in Purcell's classic Berkeley-series *Electricity and Magnetism* (2nd edition, McGraw-Hill, 1985), but using the differential version of Maxwell's equations and avoiding the concept of field lines.

This unit is not absolutely needed for any other unit. However, chapter E8 is useful for understanding the magnetic aspects of spin in chapter Q6, and the concept of potential is useful in chapter Q.

Because this unit is the most mathematically challenging in the book, I advise taking special care when assigning homework problems. I assign more B-level problems in this unit than elsewhere: some of these problems are very helpful for students trying to master new ideas.

I also strongly recommend that anyone assigning chapters E12 and E13 should have students do problems E12M.1 and E13M.1 as activities in class: students really need the guidance provided by these problems to become competent using Maxwell's equations in differential form. Once they see the pattern, though, they do become quite able to solve problems on their own. One year, we taught these chapters and chapter E14 sequentially, and gave students the choice to on an exam question to use either the integral or differential form. Almost all students chose to use the differential form, and most solved the problem correctly.

M4.6 Unit Q

In the original design sequence for *Six Ideas*, unit Q follows units C, N, R, and E, and comes before unit T. In the current edition, units R and E are not needed: chapters C1–C6, C8–C9, and N1–N11 provide the essential background for this unit, though we have found that students with a good high-school background can skip unit N (they basically need to know how to solve problems involving circular motion and understand a few basic things about oscillators). Certain homework problems draw on material in units R and E, but they can be easily avoided.

The optional chapters Q13 through Q15 do draw on concepts from relativity, but the only concept really needed is the equivalence between rest energy and mass, which I think many students will know from popular treatments. Otherwise, relativistic ideas appear rarely and in passing and are not crucial to the discussion. I therefore don't think that students really *need* to have gone through unit R before Q.

The topics from unit E that appear in unit Q are the concepts of electrostatic repulsion and attraction, the curved paths of particles in a magnetic field, the dipole model of magnets, electrostatic potential energy, and potential. However, these are basic ideas presented in most high-school physics classes, so students can probably even get by without having seeing unit E if necessary. The section on semiconductors involves perhaps the most intense use of concepts from unit E., but can be omitted.

Here is a list of chapters:

Q1:	Wave Models	(core: section Q1.6 is *optional*)
Q2:	Standing Waves and Resonance	(core)
Q3:	Interference and Diffraction	(core: section Q3.6 is *optional*)
Q4:	The Particle Nature of Light	(core)
Q5:	The Wave Nature of Particles	(core)
Q6:	Spin	(core)
Q7:	The Rules of Quantum Mechanics	(core)
Q8:	Quantum Weirdness	(*optional*)
Q9:	The Wavefunction	(core)
Q10:	Simple Quantum Models	(core)
Q11:	Spectra	(core, but includes an *optional* section on semiconductors.)
Q12:	The Schrödinger Equation	(*optional*)
Q13:	Introduction to Nuclei	(Q13 and Q14 are linked)
Q14:	Nuclear Stability	
Q15:	Nuclear Technology	(*optional*, requires Q13–Q14)
QA:	Complex Numbers	(For advanced students)

In this edition, one give students a a basic introduction waves, physical optics, and quantum physics in either 10 or 11 class sessions by ending with chapter Q11. (One *might* conceivably stop after Q5, though this would provide students only with an introduction to the wave-particle duality, but not any sense of where to go from there.)

Chapter Q12 is not needed for anything following and so could be omitted. Chapters Q13 and Q14 are linked and so should be included or omitted together. Chapter Q15 is optional, but requires Q13 and Q14. Chapter Q15 is pretty long, but it mostly involves reading, not a lot of new ideas. The first and second halves of Chapter Q15 are also pretty independent, so one could elect to cover one or the other, or both over two class sessions.

One of the improvements in this edition is that unit Q no longer requires students to know complex numbers. But if you *want* students to have the greater insight that knowing complex numbers provides, you can assign appendix QA any time after chapter Q9 (or after Q7 if one omits section QA.6). I have designed this appendix in the form of a chapter, so you can simply treat that way on your syllabus. Sections QA.5 and QA.6 are optional even within this optional appendix.

One of my goals is eventually to provide an online chapter that provides a bridge from chapter Q5 to chapter Q9 or Q10 without getting into spin and all the complexities of the quantum model. This will allow for a shorter and lower-level treatment of quantum mechanics. Write me if you want me to move this higher on my priority list.

M4.7 Unit T

In the original design sequence for *Six Ideas*, unit T follows all the other units. For the current edition, chapters C1–C6, C8–C9 provide the essential background for this unit. Chapters C10–C14 are valuable, but not required, and the unit also draws on *concept* of energy quantization, the quantum energy levels of the harmonic oscillator, and (for chapters T5 and T6) the results of the quanton-in-a-box model. But energy quantization is a widely known idea, and in this edition, whatever specific results are needed are presented, so unit Q adds depth but is not necessary. Material in units R and E appear only in a handful of homework problems, which one can avoid.

Here is a list of the chapters in this unit:

T1:	Temperature	(core)
T2:	Microstates and Macrostates	(core)
T3:	Entropy and Temperature	(core)
T4:	The Boltzmann Factor	(core)
T5:	The Ideal Gas	
T6:	Distributions	(*optional*)
T7:	Gas Processes	
T8:	Calculating Entropy Changes	
T9:	Heat Engines	
T10:	The Physics of Climate Change	(*optional*)

In this edition, chapters T1 through T4 now comprise the irreducible core of the unit, and by themselves completely address the unit's core question. If you are really short on time, these chapters alone could provide a useful introduction to statistical physics. Adding chapter T5 provides a valuable introduction to ideal gases. Chapter T6 is helpful for chapter T10, but also may be omitted without loss of continuity. I think that (in addition to the core) chapter T5 is essential for chapter T7, which in turn is essential for chapter T8, which in turn is essential to chapter T9, but one could choose to end the unit after any one of these chapters, depending on where one wants to go.

Chapter T10 benefits from chapters T1 and T6, but is otherwise completely independent and could be assigned after chapter C13 in unit C. I have made it the closing chapter because it is a wonderful example of how one builds a model to answer important physical questions. Whether unit T appears at the end of the first semester or the second, this chapter provides a nice bookend for chapter C1 on model building and underlines the value and importance of creating good models.

Note that this unit does take advantage of WolframAlpha to help with some nasty derivatives, so one might want to take some time to introduce students to that tool if they haven't seen it already. Chapter T6 is also significantly more sophisticated conceptually than the other chapters, so omitting this chapter provides one way of lowering the unit's level. (One of my goals for this edition was to isolate that difficult material so that it could be omitted more easily.)

M4.8 A Few General Notes

As described elsewhere, one should construct a syllabus that covers *no more* than one chapter per 50-minute class session (or three chapters per two 70-minute sessions). Even that is pretty ambitious, and a slower pace can be desirable or even necessary.

Here is a table of the length ranges of the various units:

C:	13–14 class sessions	(doesn't have to be all together)
N:	12–14* class sessions	*includes a class on NA+NB
R:	5–10* class sessions	*includes a class on RA+RB
E:	11–18 class sessions	
Q:	10–16* class sessions	*includes QA
T:	4–10 class sessions	

(One class session here = a 50-minute period: multiply by 2/3 to get the number of class sessions for 70-minute periods.) A *Six Ideas* course that does the minimum for all units thus has a minimum length of 55 class sessions, and full coverage requires at least 82 class sessions. A 14-week semester has roughly 42 class sessions, but one needs some time to get the class started, provide time for exams, and so on. Therefore, cutting *some* chapters is almost certainly necessary for a two-semester course (we certainly cut some chapters at Pomona). But this chart also shows that creating a course that has a significantly reduced pace is quite possible if one is willing to cut units to the bone (or even omit some units entirely). Doing only two chapters per three class sessions would allow you to cover about the minimum 55 chapters.

What works for you will depend greatly on your particular situation. I hope, however, that this chapter provides some useful guidance about how to make cuts thoughtfully.