

THE INTRODUCTORY CALCULUS-BASED PHYSICS TEXTBOOK

Each year, more than 150 000 college students across the US enroll in calculus-based introductory physics courses. Most of these courses are taught in the traditional mode, with students sitting passively through two or more lectures per week and reporting once or twice a week to recitation classes and laboratory sessions. Students often plow through as many as 500 pages of equation-laden text each semester and complete one or two written assignments per week. And faculty members expend considerable effort conducting the whole enterprise.

Despite all this time and effort, the traditional course seems to be an ineffective and often unpopular educational vehicle. Many students completing the course cannot demonstrate mastery on tests of the most basic concepts, such as the Mechanics Baseline Test developed by David Hestenes and Malcolm Wells.¹ For example, the average score on this test, which is administered after the course is completed, was 67% for 314 students from two universities. (Fewer than 40% correctly answered the sample problem shown in figure 1.) As a gateway to careers in the physical sciences and engineering, an introductory physics course should attract students to those disciplines rather than turn them away. Yet, of the throngs of students enrolled in beginning courses, only a trickle (fewer than 5%) are inspired to enroll in higher-level physics courses. Clearly, fundamental changes are needed in course content and presentation.

This premise was the spark that in 1987 ignited the Introductory University Physics Project (IUPP), a major initiative co-sponsored by the American Physical Society and the American Association of Physics Teachers, and funded by the National Science Foundation. (See the article by John S. Rigden, Donald F. Holcomb and Rosanne DiStefano in *PHYSICS TODAY*, April 1993, page 32.) IUPP sought to revitalize introductory physics and to inspire the creation of new course models and teaching materials. Recognizing the shortcomings of the "standard model"

Physics professors who teach the introductory course frequently complain about the first-year textbooks. Here are some of the books being developed in response.

Joseph Amato

The focus of this month's book section is undergraduate texts, and we have divided it into two parts. The first is Joseph Amato's extensive overview of the trends in introductory physics textbooks published in recent years. The second is our regular book review section devoted exclusively to reviews of upper-division undergraduate textbooks. All the books chosen were published within the past year; other such textbooks will continue to be reviewed as they come out.

course, IUPP adopted the following guidelines for curricular reform: reduce the number of topics covered (following the slogan "Less Is More"); include more contemporary physics; organize the course material around a strong motivating theme.

In thinking about textbook reform, IUPP participants and others have been

influenced by the work of education researchers who, during the previous decade, have studied what students learn and do not learn from conventional lectures, laboratories and textbooks.² These researchers realized that student misconceptions often remain firmly entrenched throughout the introductory course, and true understanding lags far behind the apparent development of problem-solving skills.

Modifications of the traditional textbook are also driven by the changing demographics of the student population. Moreover, anecdotal evidence strongly suggests that the mathematical preparation throughout today's student body is not as rigorous as it was in the past. For too many of today's students, our courses

and texts have become impossibly difficult, dry and demoralizing.

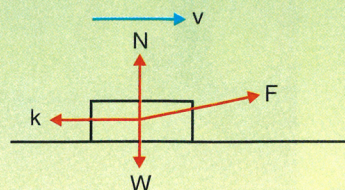
In the past five years, a number of new introductory texts and supporting materials have been published. In almost every case, the authors have acknowledged a debt to IUPP: The new texts (or revised earlier editions) are shorter than the familiar textbooks, and coverage of 20th-century physics has improved. Moreover, the authors have endorsed the findings of education researchers by writing supplementary materials such as workbooks, teacher guides and supporting software, and by introducing a wide variety of novel exercises designed to probe and enhance conceptual understanding. Reviewing all the latest materials would be a formidable task; instead, this article discusses and compares a sampling of them to give a general flavor of the changes that are coming. (The books discussed are listed at the end of this article.)

Retooling the traditional texts

It is commonly believed that physics textbooks have grown inexorably from edition to edition in response to demands for broader coverage. In fact, however, the earliest edition of David Halliday and Robert Resnick's classic 1960 text, *Physics for Students of Science and Engineering*, is nearly

JOSEPH AMATO is an associate professor of physics and astronomy at Colgate University in Hamilton, New York. The introductory physics course he teaches features many novel laboratory exercises and uses examples from astronomy and astrophysics to spur student interest in classical mechanics.

7. A person pulls a block across a rough horizontal surface at a constant speed by applying force F . The arrows in the diagram correctly indicate the directions, but not necessarily the magnitudes, of the various forces on the block. Which of the following relations among the force magnitudes W , k , N , and F must be true?



- (A) $F = k$ and $N = W$ (B) $F = k$ and $N > W$
 (C) $F > k$ and $N < W$ (D) $F > k$ and $N = W$
 (E) None of the above

CAN YOUR STUDENTS ANSWER THIS QUESTION? In a 1990 test given to 314 students who had completed an introductory physics course, fewer than 40% got the right answer (C). The problem is extracted from the Mechanics Baseline Test developed by David Hestenes and Malcolm Wells. The average score on the test was 67%. (Adapted from ref. 1.)

FIGURE 1

identical to the current editions of most conventional texts in terms of its organization and its approach to classical physics. Apart from added coverage of modern physics, the most significant changes have been confined to the artwork, page layout and to vastly expanded collections of end-of-the-chapter problems.

IUPP alerted the textbook authors and publishers to the teaching community's growing dissatisfaction with the standard survey-style physics course and its supporting texts. The authors of these texts have responded in varying degrees. For example, Jearl Walker, working with Halliday and Resnick, has recently completed the fifth edition of *Fundamentals of Physics*. The extended version of this new edition is 1142 pages long, about 15% shorter than the fourth edition. Its organization is quite similar to earlier editions, with some compression of the material on thermodynamics and electromagnetism. A short description of the statistical interpretation of entropy has been added. An attractive innovation is the inclusion of "checkpoints," or short exercises embedded in the text, which probe students' qualitative understanding as they read through the text. Similar exercises complement the familiar, and exemplary, questions and problems at the end of each chapter.

In his latest text, *Principles of Physics*, Raymond A. Serway has organized topics into groups that emphasize the unifying power of physical principles. For example, electric and magnetic fields and forces are introduced alongside inverse-square gravitational forces to illustrate the broad applicability of Newton's laws. Simple harmonic motion comes late in the text, so that mass-spring systems, pendulums and LRC circuits can be discussed together. Similarly, mechanical waves, sound waves and electromagnetic waves are treated in consecutive chapters. By reorganizing and condensing the material, and by omitting several nonessential topics, Serway has produced a book that at 930 pages is nearly 250 pages shorter than the third edition of his text, *Physics For Scientists and Engineers* (1992). Still, the core topics are treated in the traditional way, and the book has a familiar feel to it. In Serway's words, *Principles* is an "evolutionary" step rather than a "revolutionary" one.

Among the other recent texts that have been influenced by the IUPP guidelines is one with a markedly different approach: *Physics*, by Marcelo Alonso and Edward J. Finn (1992). It has been widely used outside the US but is relatively unknown here. In response to IUPP's call for more 20th-century physics, Alonso and Finn have infused the text with contemporary topics as integral rather than ancillary parts of the narrative. More than most authors, they illustrate how a small set of physical principles governs a wide range of phenomena from microscopic to astronomic scales. For example, the usual

chapter on kinematics contains a discussion of Hubble's law and the age of the universe. Newton's laws are derived as consequences of momentum conservation, and applications include gravity-boost orbits and space exploration. The chapter on gravitation includes a clear discussion of the critical density of the universe and its large-scale structure. Phase space and dynamical chaos are introduced following a study of oscillations. The text's 1100 pages also include chapters on relativity, statistical physics, quantum mechanics and atomic and nuclear physics. However, the book is pitched at a more advanced level than the conventional text, so that it may not be an optimal choice for the majority of beginning students.

The package of support materials accompanying all the traditional texts continues to expand, as more media are adapted to learning. In addition to the standard student study guides and instructor's manuals, the publishers now make available such ancillary materials as videodisks with physics demonstrations and images, overhead transparencies of figures from the texts, software and workbooks to facilitate spreadsheet modeling, interactive software for problem solving and computerized test banks.

Reorganization of material, compressed narration and inclusion of contemporary topics are welcome developments in the evolution of physics textbooks. By themselves, however, they are unlikely to satisfy the need for reform in physics education. True reform requires that the traditional textbook, the "standard model" course format, or both, be radically modified or abandoned.

Reforming the traditional texts

Publishers are just starting to introduce texts that support substantial departures from the standard course. Three notable examples are the materials prepared by Priscilla W. Laws and her colleagues, by Frederick Reif and by Randall D. Knight. All three confront pedagogical issues head-on, while preserving the basic organization of the standard introductory course.

Laws is the originator and principal author of *Workshop Physics*, an activity-based curriculum. (See the article by Laws in PHYSICS TODAY, December 1991, page 24.) Researchers have warned that lectures are a particularly poor way to foster understanding of physics.³ In *Workshop Physics*, passive learning modes such as lectures are entirely replaced by active modes, in which students learn about topics by direct experimentation. Much of this work is done collaboratively. Lab work is fully integrated with class time, an arrangement made possible by scheduling three two-hour class sessions per week. The primary teaching materials are contained in four workbooks, or activity guides, which include complete directions for the in-class activities as well as space for written student

responses. Students can consult an off-the-shelf textbook as a reference.

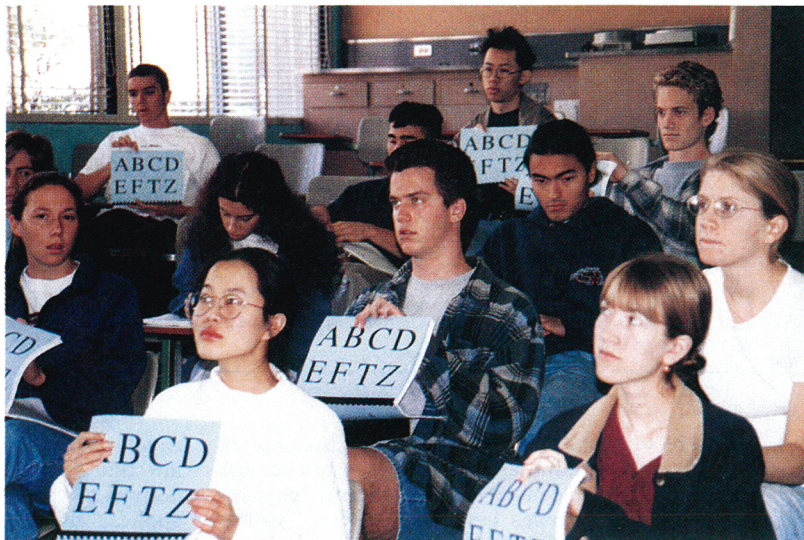
Each activity begins with a prediction, proceeds to an experimental verification of that prediction and concludes with an interpretation of the experiment or a guided derivation of the relevant mathematics. Unlike the standard teaching strategy, each derivation follows a hands-on encounter with an associated phenomenon and is assigned lower priority than is customary. To complete an activity within a single class period, students take advantage of desktop computers, computer-based lab apparatus (developed by Laws, Ronald Thornton and David Sokoloff) and easily assimilated analysis software such as the familiar spreadsheet. The activity guides divide the two-semester course into four modules: mechanics I, mechanics II, thermal physics and electromagnetism. Wave phenomena are not treated, and there is no sustained effort to include modern physics.

The mathematical level of *Workshop Physics* is somewhat lower than is typical for introductory calculus-based physics, but the course format forces students to identify and articulate their preconceptions and to test them by simple experiment. The in-class activities are best suited to small classes, and indeed, most of the schools that have adopted *Workshop Physics* are undergraduate institutions rather than large universities. Nonetheless *Workshop Physics* has been used for the laboratory portion of traditional courses in some larger institutions.

Reif has written a one-semester textbook, with a companion workbook, called *Understanding Basic Mechanics*. It covers classical mechanics and systems of particles and emphasizes qualitative understanding more than is usual in introductory physics courses. The sequence of topics is reasonably standard and does not include waves or contemporary physics. The text is remarkably terse and precise, almost to a fault, so that it appears to be intended more as a reference book than as the primary source of new information. The author believes that too much of the time spent by students on their studies is unsupervised and unproductive. The purpose of the workbook is to organize this time for higher efficiency and, through the exercises, to promote qualitative understanding hand-in-hand with quantitative skills. Often, for example, the same question is asked in both qualitative and quantitative modes.

Understanding Basic Mechanics is interesting because it suggests a possible format for a new teaching package consisting of a sparse "meta-text," a closely coupled workbook and a substantial set of visualization tools accessed by computer. Indeed, Reif is presently developing simulation software for his course.

Knight's objective was to develop a curriculum and supporting written materials that adhere to IUPP recommendations, address the concerns articulated by physics education researchers and remain compatible with the teaching constraints of large-enrollment classes. He has



STUDENTS INDICATE THE CORRECT ANSWER to a question posed in Thomas Moore's class at Pomona College by pointing to the letter "B." The lettered card is the back cover of Moore's textbook, made to facilitate the kind of interactive classes championed by Eric Mazur of Harvard University. (Photo courtesy of Thomas Moore.) FIGURE 2

written a textbook, *Physics: A Contemporary Perspective*, and an accompanying workbook, which are remarkable for their clarity and attention to pedagogical detail. The book's light conversational style and thorough, transparent analyses should permit students to read the text profitably and to gain a preliminary understanding of the course material without requiring blow-by-blow repetitions in lectures. This is Knight's strategy: the fewer lecture hours needed to explicate the text, the more time available in class for active learning. The workbook plays a key role in this strategy; its qualitative exercises allow students to practice single concepts or skills before tackling the more challenging, multitask end-of-chapter problems in the text.

A good example of the author's awareness of common misconceptions can be found in the text's opening chapter. Step by step, Knight leads his readers from a simple stroboscopic picture of motion to the more abstract representations needed to interpret one- and two-dimensional motion and to introduce the concepts of vector velocity and acceleration. All of this is done qualitatively, using a motion diagram, before quantitative analysis begins. Overall, the book's mathematical level is intermediate between that of *Workshop Physics* and that of the traditional text.

Inspired by IUPP, Knight selected a story line as a basis for organizing his materials and filtering out non-essential topics. His theme—understanding the link between macroscopic phenomena and the underlying microscopic structure of matter—is supported by clear and interesting discussions of wave propagation, interference and diffraction, quanta, wave-particle duality, the Heisenberg uncertainty principle and the one-dimensional Schrödinger equation. Key chapters devoted to statistical physics, however, are uncharacteristically complicated and need revision. Modern applications include quantum well devices, nuclear-energy scales, molecular bonds, quantum tunneling and the scanning tunneling microscope.

Potential users of *Physics: A Contemporary Perspective* should be aware that several fundamental topics have been omitted from the syllabus. They are angular mo-



BATTERIES AND BULBS ILLUMINATE the understanding of electric and magnetic interactions in a course developed by Ruth Chabay and Bruce Sherwood. Their book encourages students to get direct experience with physical phenomena. (Photo courtesy of Bruce Sherwood, Carnegie Mellon University.) FIGURE 3

mentum, Gauss's law and Ampere's law. One might justify the omission of each topic by arguing that it is notoriously difficult for students to grasp and is not needed to support the theme. Knight decided to emphasize electromagnetic phenomena rather than to focus on mathematical formalism, but his omission of Gauss's and Ampere's laws is likely to be controversial. Indeed, there has never been a consensus among physics teachers concerning which topics are essential to the introductory course. This lack of accord may be partly responsible for the overabundance of subject matter in the traditional text and the rapid-fire style of delivery in traditional courses. In pedagogical terms, the number of critical topics is probably lower than we wish to admit.

Reinventing the traditional texts

Two recent introductory physics textbooks stand out as especially creative: *Six Ideas that Shaped Physics*, by Thomas A. Moore, and *Electric and Magnetic Interactions*, by Ruth W. Chabay and Bruce A. Sherwood. In both cases, the authors have dared to restructure the course material radically and, in doing so, to change the priorities of individual topics to match their pedagogical goals. Because the texts are so novel, you may wonder at first if either approach can be adopted without unreasonable effort. However, a closer look suggests that neither approach would require an overhaul of the existing course infrastructure. Moreover, the authors have provided detailed recommendations and materials for day-by-day course planning.

Six Ideas was inspired and supported by IUPP and is still being tested at several schools. The textbook provides an overview, rather than a survey, of physics by identifying six powerful insights that have shaped our contemporary understanding of the physical world. Examples are: "The laws of physics are universal" and "matter behaves like waves." The text is divided into six corresponding units, and each unit is subdivided into chapters, one for each 50-minute class period. The entire course can be covered in two semesters.

Six Ideas is pitched at a higher level than Knight's *Physics* and is therefore comparable to the conventional

text. By omitting fluids, geometric optics and AC circuits, Moore has found space for quantum mechanics, nuclear physics, thermal physics and an extended discussion (three weeks) of relativity. The unit on thermal physics includes a fine discussion of the statistical interpretation of entropy, aided by a dedicated software package. *Six Ideas* begins by discussing conservation laws: momentum, energy and angular momentum. These laws are treated as postulates made plausible by a simple fluid picture: Interactions transfer linear and angular momentum from one body to another and transform energy from one form to another. The advantage of putting conservation laws before Newton's laws is that it high-

lights the conservation laws, which are more fundamental than $F = ma$, and allows students to examine a large assortment of physical phenomena without employing calculus (which they may be just learning).

Like Knight, Moore writes in a clear, conversational style that should appeal to students. Similarly, he intends the text to be the primary source for new material, so that class time is free for discussion and collaborative exercises rather than for lectures.

But *Six Ideas* is more than a textbook. The author has included a wide variety of teaching material as well as detailed plans for using it. For example, each chapter contains short exercises embedded in the text, to challenge students to test their understanding as they are reading. As Moore explains, these exercises are preferable to the usual worked examples in conventional texts, because students typically use those examples as problem-solving templates rather than as study aids. Four distinct types of problems are included at the end of each chapter. They are (1) two-minute problems, used to generate discussion in class; (2) basic-skill problems, which exercise students in a single skill or concept; (3) "synthetic" problems, requiring students to synthesize several skills or ideas; and (4) what Moore calls "rich-context" problems, in which too little or too much information is provided (these problems are best suited for collaborative learning). The use of these teaching tools is carefully explained in the instructor's manual, which contains a wealth of valuable suggestions for teaching *Six Ideas*, as well as for teaching science in general.

Most of *Six Ideas* is clear and well-calibrated to motivated, thoughtful students. However, a fair fraction of unit 4 (electromagnetism) may be prohibitively difficult for the average student. Moore shuns the integral expression of Gauss's and Ampere's laws, substituting their vector differential form instead. He argues that it is much easier to discuss electromagnetic waves from the differential form of Maxwell's equations than from the integral form. He may be correct, but the heavy reliance on partial differentiation and the laborious exposition of divergence and curl, seem to offset any advantages. The gap between

phenomena and mathematics seems particularly wide at this point.

Like many college teachers today, Moore has followed the lead of Harvard University's Eric Mazur and introduced some active learning techniques into his classes at Pomona College. (See figure 2.) Mazur typically begins a class session with a seven-to-ten minute lecture. He then poses a short question designed to probe students' grasp of the concept just introduced. Based on student responses, Mazur either reviews the concept or proceeds to new material. Mazur has published a book containing discussion questions for classroom use.⁴

In *Electric and Magnetic Interactions*, Chabay and Sherwood have redefined the content and format of the introductory electromagnetism course. They argue that beginning students have little or no experience with electric and magnetic phenomena; therefore, the standard course, which begins by introducing fields, potentials and vector integrals in rapid succession, does little to build conceptual understanding of the underlying physics. Chabay and Sherwood's text works from the ground up. The authors begin by carefully constructing a microscopic vision of electrostatics and DC circuits, using only the concepts of Coulomb's law and the electric field. Whenever possible, students are expected to study the phenomena directly by performing imaginative and deceptively simple experiments using common, inexpensive materials provided in an accompanying kit, which runs about \$25. (See figure 3.) These experiments are designed to be done at home, or during lecture and recitation classes. Their virtue is that they use familiar apparatus—batteries, bulbs, magnets and compasses—rather than esoteric instruments; they can be scheduled to coincide exactly with the introduction of new topics; and they plunge students into the core process of science—observation, inference, explanation and discovery.

The simplicity of the approach, and the use of battery-and-bulb experiments, may obscure the authors' serious intent and their ambitious goals. Their primary objective is to encourage students to think very deeply about what they are seeing. *Electric and Magnetic Interactions* is part textbook, part workbook and part lab manual or activity guide (in the style of *Workshop Physics*). New topics are introduced with a minimum of discourse, using guided derivations (where students supply missing steps in the argument) to promote active student engagement. Mathematics is presented with unusual clarity, completeness and concern for conceptual pitfalls. After discussing circuits (including capacitors) in terms of charges and fields, the authors introduce the electric potential, and then revisit DC circuits from a more conventional vantage. Only then is Gauss's law discussed. By delaying the introduction of Gauss's law, the authors can place more emphasis on qualitative understanding early in the course and avoid the concept overload that plagues the conventional course. Magnetic phenomena are studied in a parallel manner: The student first examines the field from a single moving charge; then the field due to a single current element (Biot-Savart law); and finally the field contributions summed over many current elements. Once again, each topic is supported by simple, desktop experiments. Modern topics covered include the Hall effect, mass spectroscopy, the atomic origins of magnetism and, briefly, the considerations leading to the theory of relativity. Maxwell's equations are derived in integral form, and the book concludes with a study of radiation and some of its applications.

One cannot teach from the book without doing the labs, and the authors warn that importing the labs into a conventional course is likely to be unsuccessful. The

desktop experiments shift the emphasis from heavily quantitative (as in the traditional course) to a balance between quantitative and qualitative. Nevertheless, the mathematical level remains appropriate for a calculus-based course; students are expected to perform integrals over charge and current distributions, and to work with the surface and line integrals of Maxwell's equations.

Chabay and Sherwood have clearly chosen a "less is more" approach to teaching electromagnetism. To minimize conceptual noise, they have wisely included only those topics that students can study experimentally or can tackle as homework problems. In an attempt to sidestep potential misconceptions, they have chosen to avoid introducing field lines. However, the alternative, "vector sea" representation seems at least as confusing, and it is not clear that any simplification has been achieved. Choosing comprehension over coverage, the authors have omitted core topics such as interference and diffraction, and the usual ancillary topics leading to quantization, wave-particle duality and atomic physics. These ideas would certainly pass Chabay and Sherwood's criterion for inclusion

Rethinking the Undergraduate Curriculum

Some physics educators think that reform efforts should not stop with the introductory physics textbook. A group of 22 physicists active in educational issues got together on 20–22 September under the aegis of the American Association of Physics Teachers to discuss the need for revitalization of the undergraduate physics curriculum and the ways such changes might be brought about.

The meeting was occasioned by several factors, detailed in a draft report of what happened at the informal meeting. One was the call by various private and governmental panels for more effective science teaching; students do not seem to be learning how to think critically, or how to apply their training in real-world situations. A second factor was the growing recognition of a gap between the goals that physics faculties set for undergraduate education and what the students take away from their courses. A third was the realization that the traditional curriculum, largely designed for the student who will go on to graduate school and a research career, is not addressing the needs of the majority of students, who go straight from undergraduate school into jobs that involve much more applied work.

Robert Hilborn, current president of AAPT and chair of the September confab, told us that the participants had de-emphasized any ambitious, large-scale curriculum development. Instead, they had recommended measures to facilitate the dissemination of innovations in undergraduate physics education and to assist departments that wish to adopt these innovations.

For starters the participants will circulate their report to see whether it stirs up any enthusiasm among physics departments. They also plan to help establish a Web page listing innovative undergraduate programs with appropriate links to more information. And they will form a steering group to plan a 1997 Physics Department Chairs Conference to deal with curriculum reform and to work with the National Science Foundation to organize a larger meeting to develop additional plans for action.

The weekend meeting represented just a first dip of a big toe into the waters of departmental change. Whether the group will take the plunge depends on how warm the waters feel.

BARBARA GOSS LEVI

and might make a very good course even better.

Back to the future

The preface to the first edition of Halliday and Resnick's classic text contains the following remarks by the authors: "The most frequent criticisms made in varying degrees of textbooks used in [the calculus-based] course are these: (a) the content is encyclopedic, the discussions are largely descriptive rather than explanatory and analytical, and too many topics are surveyed; (b) the content is not sufficiently modern, and applications are drawn mostly from past engineering practice rather than from contemporary physics; (c) the organization of the material is too compartmentalized to reveal the essential unity of physics and its principles; (d) the approach is highly deductive and does not stress sufficiently the connection between theory and experiment."

Nearly 40 years later, physics educators are voicing the same criticisms. The authors of some of the standard textbooks are now offering an evolutionary path to change, incorporating new elements within the traditional structure. And other authors are designing teaching materials that are profoundly different and that encourage new—and hopefully better—pedagogical strategies.

But change can be painful. Are we ready to adopt distinctly new approaches to the introductory course? The most innovative materials encourage instructors to abandon the relative safety of lectures and to interact more closely with students, in the role of tutor or perhaps "coach" rather than resident expert. The materials also require teachers to devote more time and effort to teaching. Nonetheless if physics is to remain the gateway to the physical sciences and engineering, and if we are to have a positive impact on

the education of our students, then we must adopt strategies that promote understanding and inspire genuine enthusiasm for physics. The materials described above offer several attractive pathways to improved pedagogy, and they deserve careful consideration.

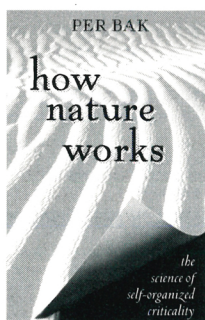
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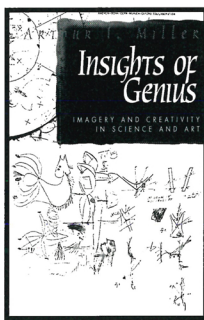


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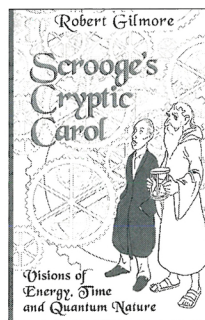
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