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Advanced physics in the high schools

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Advanced Physics in the High Schools

A study by the National Research Council makes several recommendations for improving the Advanced Placement program in the US.

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The Advanced Placement (AP) program has a major impact on the science experience of many high-school students. It can affect admission to college, course choices and performance in college, and subsequent career decisions. Therefore, it is important to understand the consequences of this program for physics and to ensure its quality.

The AP program is the culmination of science education in more than 60% of American high schools. In some other schools, a similar role is played by the smaller but also growing International Baccalaureate (IB) program. Some students completing AP or IB courses receive college credit based on policies of individual colleges and on students' performance on comprehensive final examinations. These courses require substantial effort, and make a lasting impression on those who take them.

A study committee of the National Research Council (NRC) recently completed a two-year analysis of advanced high-school science and mathematics education in the US.[1] Included in the NRC study is an extensive examination of advanced programs in physics, chemistry, biology, and mathematics with an emphasis on calculus. (The College Board, the national nonprofit association that developed the AP program and also the Scholastic Aptitude Test, recently reviewed the entire AP program but did not focus specifically on physics.[2]) Here we discuss the conclusions of this work that are most important for high-school physics education, from our standpoints as co-chair (Gollub) of the NRC study and chair (Spital) of its Physics Panel. Due to space limitations, we focus the discussion on AP Physics, which is by far the largest advanced physics program; the interested reader should refer to the NRC study for an extensive discussion of IB Physics and other approaches to advanced high-school physics.

The AP program was launched in 1955 by the College Board to provide college-level courses for advanced high-school students. The AP program is built around elective, end-of-course examinations that are graded on a five-point scale. The College Board produces content outlines for its courses, largely by surveying colleges and universities about their introductory courses. Most colleges and universities use the national AP examinations as a basis for granting credit or advanced placement to incoming students. The two AP physics courses, AP Physics B and AP Physics C, emulate typical introductory college courses without calculus and with calculus, respectively.[3]

Growth and new challenges

Twenty years ago, advanced programs affected only a few students. Over the past decade, however, AP participation has grown exponentially (see figure 1). In 2000, 433 000 AP exams were taken in math and science, an increase of almost a factor of three in a decade. In physics, the annual number of AP exams is nearly 60 000, representing approximately 51 000 individual students (since some take separate exams in both mechanics and electromagnetism). However, the College Board estimates that only about 66% of AP students take the exam, so the number of students taking AP physics courses may be closer to 78 000 per year. Clearly, these are no longer courses designed primarily for an elite audience of exceptional, high-ability learners. Those few truly exceptional students in each school may require courses offering greater independence.

What is driving this rapid rate of growth? One factor is that US high schools face intense criticism from college educators, policymakers, education reformers, and the public for graduating a significant number of students who are not well prepared for college and do not possess the needed technological and problem-solving skills to enter the workplace. Many educators view the national AP programs as usefully complementing the decentralized system of American secondary education. At least 26 states provide subsidies or other legislative support for AP programs in their schools.

However, the dominant motivator for rapid growth seems to be that advanced courses are now essential to students seeking admission to selective colleges and universities. Admissions officers at these institutions report that successful applicants are expected to take the most demanding courses available to them. Many high-school students also hope to receive college credit and possibly place out of introductory college courses, thereby progressing more rapidly and potentially reducing the cost of higher education. Some states even require their public

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colleges and universities to grant AP credit for this reason. On the other hand, many of the more selective institutions (or departments) are reluctant to grant credit or placement in advanced courses for levels of achievement that the program sponsors recommend (3 on the 5-point exam scale).

Equity and access

As our nation becomes more diverse, racial and socioeconomic gaps persist in high-school students' access to and success in advanced study. Inner-city and rural schools, and especially those with high percentages of underrepresented students, are less likely to offer advanced courses.[4] Many schools in low-income communities are poorly equipped to provide advanced study because they lack highly qualified teachers or sufficient laboratories, equipment, and other curriculum materials. In racially and ethnically diverse schools, African Americans, Hispanics, Native Americans, and students with low socioeconomic status are still much less likely to enroll in AP courses even when they are available. And, in an internal survey, the College Board found that those who do enroll do not fare as well on the examinations (on average) as white or Asian American students.[5]

The problem of inequitable access to advanced study is exacerbated in schools with high minority populations because science teachers in those schools also tend to be less experienced. As with most subject areas, the pedagogical skills and content knowledge of the physics teacher are the most important factors determining the success or failure of physics instruction. In view of the severe nationwide shortage of qualified physics teachers revealed by a recent American Institute of Physics survey,[6] improving access to advanced physics clearly requires a substantial investment in teacher preparation and professional development. The Physics Teacher Education Coalition (PhysTEC)[7] is a collaborative venture of the American Physical Society, AIP, and the American Association of Physics Teachers, involving physics departments and science education programs at a few selected universities. PhysTEC represents a promising start toward improving teacher preparation and effectiveness (see PHYSICS TODAY, November 2001, page 30).

The report issued by the NRC study strongly advocates improved preparation of students, especially in mathematics. While such an effort would benefit all students, it is particularly important for improving minority participation and success. In turn, better preparation would require integrated curricular planning between middle and high schools. Several recent reports[8] indicate that the selection of students for advanced courses in high school begins with the timing of their first algebra course in middle school. Indeed, the Physics Panel regards fluency in mathematics (especially algebra) as an indispensable prerequisite for advanced physics. Furthermore, the NRC study highlights the detrimental impact of allowing some students to enroll in courses for which there are reduced academic expectations, and, based on empirical studies, recommends against such courses.[9]

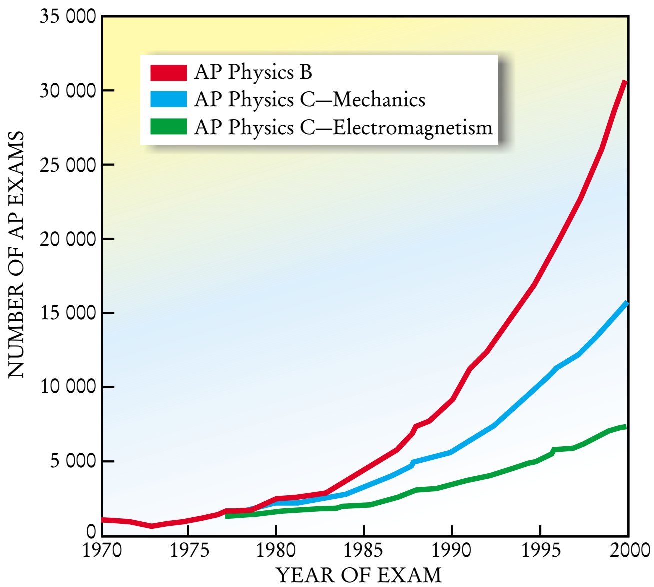


FIGURE 1. RAPID GROWTH of the Advanced Placement program in physics. With such dramatic growth in exams in non–calculus-based AP Physics B and calculus-based AP Physics C, and in other subjects as well, the AP program is increasingly influencing all aspects of secondary science and mathematics education. (Data provided by R. Morgan of the Educational Testing Service.)

Rethinking advanced high-school physics

Although providing college-level learning in high school is a primary purpose of the AP program, that is by no means the only way to define "advanced study" of physics or any other science. It is quite possible for a program to deepen students' understanding of science and mathematics without being aimed at duplicating or replacing college courses. College courses are not always appropriate for high-school students, even those at an advanced level. The Physics Panel concluded that the current AP Physics B course, specified by the topical outline given in the table on page 51, includes too many disparate topics to allow most high-school students to achieve an adequate level of conceptual understanding. We discuss some possible remedies later in this article.

The NRC committee argues that it is essential for advanced study programs to focus on the goal of helping students achieve deep conceptual understanding. One can think of students as moving along a continuum from novice to expert as they acquire content knowledge, mastery of concepts, and problem-solving skills. Students move along this continuum at different rates. To some extent, the rate of progress is limited by the many competing demands on the time of a contemporary high-school student; realistic advanced physics curricula must consider this limitation.

Although the principles of physics are, of course, essential, the promotion of scientific habits of mind is more important than particular choices concerning content. Students must learn to form and communicate their ideas with clarity and precision. Most important, they need to develop the habit of analyzing problems logically, constantly searching for connections to general underlying principles. Students need to learn that important physics knowledge comes from deep conceptual understanding and not from memorizing disconnected facts. They should understand general principles well enough to reason effectively about unfamiliar situations. For students who have been taught to rely on memory for academic success, new ways of thinking, learning, and teaching are required.

Stimulating interest in further physics study should be a key goal of advanced high-school programs. Physics has a big advantage here, since the ability to derive interesting conclusions from general principles comes earlier in physics than in other sciences. Many students find this ability enormously stimulating and liberating; it is unquestionably one of the strongest inducements to further physics study. Squandering this advantage by imposing boring or tedious requirements on high-school students is a serious mistake. Good teachers know that students learn best what they find interesting; they ignore the rest as much as possible.

What do students find interesting? As experienced teachers, we have found that students at all levels like intellectual challenges that are within their reach; skilled teachers know how to pose problems that keep students stretching their thought processes in new ways. Connections to surprising or everyday phenomena also increase their interest. On the other hand, rote memorization of facts or equations, or following narrowly prescribed instructions, turns most students off. When we force uninteresting material on students, we must realistically expect them to learn very little. Time is simply too precious to waste on such low-return activities.

Advances in understanding learning

Recent advances in the understanding of how people learn[10] suggest many opportunities to improve the effectiveness of AP and other advanced physics courses. This potential is especially clear if we think of learning physics as the development of deep conceptual understanding of principles and phenomena, including the ability to apply knowledge to new situations. The relevant insights from learning research may be summarized in a few basic principles:

▷ Learning is facilitated when knowledge is structured around major concepts and principles.

▷ A learner's prior knowledge is the starting point for effective learning.

▷ Awareness and self-monitoring of learning ("meta-cognition") are important for acquiring proficiency.

▷ Learners' beliefs about their ability to learn affect their success.

▷ Recognizing and accommodating differences in the ways people learn are essential.

▷ Learning is shaped by the context in which it occurs.

▷ Learning can be strengthened through collaboration.

Applying these ideas to advanced science and mathematics courses led the NRC study committee to some important recommendations to various parties involved in secondary science education: the College Board, teachers, school systems, and some university physics and education faculty members. Advanced physics courses, the study recommends, should be based on the following:

▷ **Effective physics curricula.** Curricula should emphasize depth of understanding instead of exhaustive coverage of content. Students need time to examine and discuss new ideas using a variety of examples and contexts. Teachers need time to asses students' progress and flexibility to adapt their strategies in response. For these reasons, the Physics Panel is skeptical of rigid time allocations that are sometimes imposed on teachers by course designers. Clearly, a curriculum that leaves little time for anything but the continual introduction of new material makes achieving depth of understanding impossible.

▷ **Effective instruction.** Teachers should engage students in inquiry by providing opportunities to experiment, critically analyze information, make conjectures and argue about their validity, and solve problems both individually and in collaboration. Ideally, instructors should recognize and take advantage of differences among learners by using multiple representations of ideas and posing a variety of tasks.

▷ **Effective in-class assessment.** Teachers of advanced physics need to assess the depth of understanding of their students continually and to modify instruction accordingly. Consequently, teachers must require advanced physics students to explain their reasoning in everything they do during the course. External, end-of-course examinations have a different purpose: They certify mastery. Both types of assessment should emphasize depth of understanding, the primary goal of advanced study.

▷ **Not replicating college courses.** The College Board should abandon its practice of designing AP physics courses primarily to replicate typical introductory college courses with their exhaustive lists of topics. Instead, the College Board should focus greater attention on helping students to achieve deep conceptual understanding. Improvements using the best college courses as models have already been made in AP calculus.

The college interface

The effects of AP on the connections between colleges and secondary schools go far beyond admissions. Each college makes its own decision about granting college credit for AP work, and the criteria vary widely. Harvard University recently decided to grant college credit only for the highest possible AP exam score of 5, but many institutions still grant credit for any score of 3 or higher. The NRC study recommends that, when awarding credit and placement in courses beyond the introductory college level, institutions should base their decisions on an assessment of each student's understanding and capabilities in the discipline, using multiple sources of information (such as local placement exams and student interviews). AP examination scores alone are generally insufficient for these purposes.

Some students who have completed AP physics courses in high school take no further physics in college, while others retake the comparable college course, forgoing acceleration to improve mastery or avoid the risk of doing poorly in a subsequent course. These students present a particular challenge to college faculty, who find themselves having to teach students with a broad range of backgrounds in physics and mathematics in the same course.

Research on physics pedagogy at the college level has stimulated a movement toward replacing traditional lecture-based methods with novel approaches that engage students more actively in the learning process.[11] A number of groups—for example, those led by Edward Redish, Lillian McDermott, Patricia Laws, and Eric Heller—have shown how to improve college courses using empirical research[12] (see the article by Redish and Richard Steinberg in PHYSICS TODAY, January 1999, page 24). However, these teaching and learning reforms have not yet reached many college campuses, and so advanced high-school courses still tend to be modeled on traditional college courses. Because the experiences of many future high-school teachers are still being shaped by traditional courses, this situation retards the improvement of high-school instruction. Stronger cooperation between high schools and colleges will clearly be needed to implement the NRC report recommendations.

At present, the first high-school physics course is generally taken after biology and chemistry, and only 24% of high-school students take physics at all. The fraction of students taking a second year of physics is naturally even smaller; many simply do not have room in their schedules, or their schools are unable to offer it. Recently, some schools have begun to change the order in which science courses are taught, with physics coming first (see PHYSICS TODAY, September 2001, page 11). Should this effort gain momentum, the numbers of students who take a second year of physics could rise dramatically, and the character of this second-year course would undoubtedly change.

A single version of Newtonian mechanics

Recognizing that college physics students need a firm foundation on which they can build and that familiarity with Newtonian mechanics is universally expected, the Physics Panel recommends a nationally standardized unit in Newtonian mechanics for advanced high-school courses to replace the multiple versions—AP Physics B, AP Physics C, IB Higher Level Physics, and others—presently offered. This unit would customarily be taught in a single semester and would contain largely the same content as the current AP Physics C curriculum (see the table). To make the course more widely accessible, however, formal calculus should not be required, although slopes and areas would be used.

The omission of formal calculus should have no adverse effect on achieving the goals of advanced secondary physics instruction. On the contrary, it should permit increased emphasis on conceptual understanding by eliminating the need to spend time studying calculus-intensive problems. Moreover, calculus is at best concurrent with advanced physics in the vast majority of high-school programs. Therefore, very little calculus can be used in teaching mechanics in any case. Thus students should not be expected to perform path integrals to find the work done by a force, but would need to understand the connection between work and change in kinetic energy. They would be able to find the work done by a position-dependent force $\mathbf{F}(\mathbf{x})$ by finding the area under the force curve in simple cases.

Content Outlines for Advanced Placement Physics Courses[3]

Topics	AP Physics B (%)	AP Physics C (%)
I. Newtonian mechanics	**35**	**50**
A. Kinematics	7	9
B. Newton's laws	9	10
C. Work, energy, power	5	7
D. Systems of particles, momentum	4	6
E. Circular momentum and rotation	4	9
F. Oscillations and gravitation	6	9
II. Fluid mechanics and thermal physics	**15**	
A. Fluid mechanics	5	
B. Temperature and heat	3	
C. Kinetic theory and thermodynamics	7	
III. Electricity and magnetism	**25**	**50**
A. Electrostatics	5	15
B. Conductors, capacitors, dielectrics	4	7
C. Electric circuits	7	10
D. Magnetostatics	4	10
E. Electromagnetism	5	8
IV. Waves and optics	**15**	
A. Wave motion (including sound)	5	
B. Physical optics	5	
C. Geometrical optics	5	
V. Atomic and nuclear physics	**10**	
A. Atomic physics and quantum effects	7	
B. Nuclear physics	3	

A flexible second semester

In the US, circumstances differ greatly from one high school to the next, including varied levels of student preparation and ability, disparate levels of expertise among the teaching staff, and vastly different laboratory facilities and equipment. Therefore, there are benefits in allowing schools to select the content of the second semester of advanced physics to the best advantage of their students.

For example, teachers at one high school might choose to spend the entire year on the study of mechanics (as is currently done at many high schools participating in the AP Physics C program). Other schools with more mathematically sophisticated students might use the second semester for a traditional introduction to electricity and magnetism, along the lines of the corresponding AP Physics C syllabus (see the table). Other possibilities might include an introduction to a more recent part of physics, such as an introduction to relativity and its applications to physics and astronomy, or an interdisciplinary study of biological physics.

The notion of a flexible second semester offers an opportunity to increase the interdisciplinary content of advanced high-school physics, a recommendation made in the NRC report for all the sciences. The rationale is that disciplinary boundaries are weakening and that conceptual understanding is enhanced by exploring ideas in varied domains. For example, applying potential energy concepts to collisions between reacting gas molecules can contribute to student understanding of chemistry. Since the primary goal of advanced study ought to be deep conceptual understanding, the breadth of the second semester curriculum should be sufficiently constrained to avoid compromising that goal. Probably a single major topic should be explored in depth.

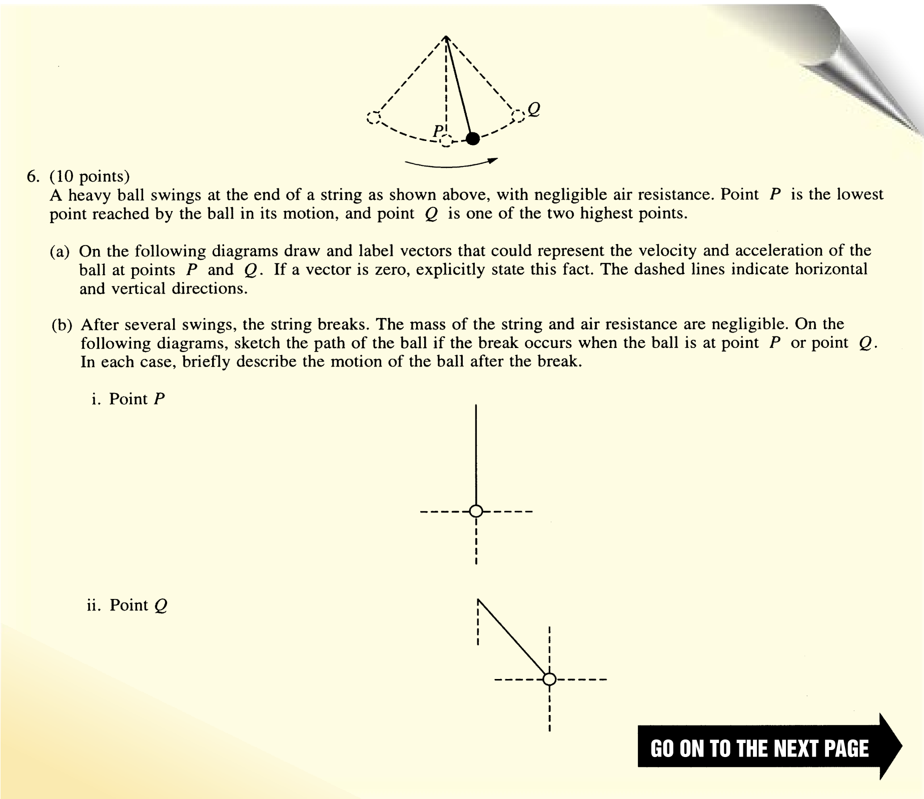
Would something valuable be lost by not insisting on a common curriculum for the entire year of advanced high-school physics? The answer depends on what one values most. For example, graduates of programs following the advice of the NRC Physics Panel probably could not place out of a full year of introductory college physics. On the other hand, although good statistics are lacking, a relatively small proportion of AP students apparently achieve this objective in any case. Moreover, the level of conceptual mastery in mechanics that is expected of and achieved by most students, particularly those in AP Physics B courses, should be significantly higher than at present.

Laboratory experiences

Effective laboratory work must be an essential part of any high quality advanced physics program. Although the need for "hands-on" activities in science has been emphasized, what really matters is not "hands-on" but "minds-on." If we want students to take their laboratory work seriously, it must be every bit as intellectually challenging as the conceptual or theoretical discussion that attempts to explain it.

To keep things interesting, it is best that students not be told the answer in advance. Therefore, laboratory exploration of phenomena should generally precede and motivate the formal introduction of theory. Furthermore, it is important to keep students thinking along the way. They should make as many scientific decisions as possible, from the conception and design of the experiment all the way through the analysis, presentation, and critical review of the results.[13]

This kind of "inquiry-based" lab work should be contrasted with the traditional "cookbook" lab, in which students follow a narrowly prescribed procedure to verify established theoretical principles. Although a 1998 College Board survey of introductory college physics courses showed that approximately 80% of lab experiences in those



6. (10 points)
A heavy ball swings at the end of a string as shown above, with negligible air resistance. Point P is the lowest point reached by the ball in its motion, and point Q is one of the two highest points.

(a) On the following diagrams draw and label vectors that could represent the velocity and acceleration of the ball at points P and Q. If a vector is zero, explicitly state this fact. The dashed lines indicate horizontal and vertical directions.

(b) After several swings, the string breaks. The mass of the string and air resistance are negligible. On the following diagrams, sketch the path of the ball if the break occurs when the ball is at point P or point Q. In each case, briefly describe the motion of the ball after the break.

i. Point P

ii. Point Q

GO ON TO THE NEXT PAGE

FIGURE 2. CONCEPTUAL understanding should be the focus of tests. On this problem from a 1998 AP Physics B examination, there is nothing to calculate, yet the problem tests mastery of important ideas involving Newton's laws and projectile motion. The problem is similar to the questions asked in the Force Concept Inventory (FCI),[15] which can be used to measure the progress of beginning mechanics students.

courses were of the cookbook variety, it is well known that such labs lead students to describe their lab work as "boring" or a "waste of time." Since time spent doing labs with entirely predictable results could be allocated instead to something more interesting and productive, the Physics Panel doubts that doing such labs is better than doing none at all. The American Association of Physics Teachers has compiled advice on introductory physics labs, including the importance of using labs to further conceptual learning, that supports these conclusions.[14]

Improving the AP examinations

Scoring well on a final examination such as the AP physics exam is a tangible goal that motivates both students and teachers. Success leads to feelings of triumph and also looks good on college applications, provided advanced physics is taken before the senior year.

Because of the high stakes and potential benefits of AP examinations, too often it is the examinations, rather than educational goals, that drive the instructional process. Students will generally do what is necessary to score well on examinations, and their teachers will generally assist those efforts. Thus, it is imperative that final assessments measure depth of understanding. Unless they are rewarded for exploring physics deeply, students and teachers will not make serious efforts to do so. We are pleased that recent AP physics examinations are much better in this regard than those of a decade ago, although further improvements are still possible.

It is difficult to give a complete definition of a good examination question; there are surely many different ways to test conceptual understanding. However, problems that can be solved simply by inserting numerical values into memorized formulas are clearly inappropriate choices. Similarly, highly predictable, formulaic problems that can be solved by standard procedures should be rare compared to questions testing conceptual understanding and higher-order thinking skills. In general, we want students to draw reasoned conclusions from general principles and explain their reasoning. Thus it is best to create problems in a wide variety of contexts and to avoid leading students through the solution with a long series of interrelated subquestions.

In figure 2, we present an example of a question from the 1998 AP Physics B exam that is in accord with this advice. There is nothing to calculate, yet the problem tests important concepts involving Newton's laws and projectile motion.

We do not mean to imply that good examination questions should not include mathematics; indeed, the ability to model physical reality using mathematics is an important aspect of conceptual understanding. However, conceptual understanding should be the primary objective for high-school students who pursue advanced study in physics.

A better future

Although current programs for advanced physics study make important contributions to secondary education, the ideas presented in this article look toward a future that is significantly different. Some people may not agree with the recommendations summarized here, although they are largely stimulated by the research on learning mentioned earlier. Educational systems are complex, so there is no way to predict the outcomes of the changes suggested by the NRC study committee and its Physics Panel. Still, the exploding demand for advanced high-school physics makes these issues urgent.

We hope that this article and the NRC study will stimulate a discussion involving all segments of the physics and science education communities, including the College Board, and that improvements in advanced high-school physics (and useful educational experiments) will emerge.

Readers of PHYSICS TODAY can contribute in many ways: College faculty members can implement courses that prepare future teachers effectively, as the American Physical Society has advocated; high-school physics teachers and parents can press school boards for the resources needed for effective programs of advanced study; and we all can encourage the College Board to implement the recommendations of the NRC study.

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References

1. *Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools*, National Academy Press, Washington, DC (2002), available online at http://www.nap.edu/catalog/10129.html (or search titles for Learning and Understanding). This report contains an extensive bibliography. The report of the Physics Panel is also available at the same Web address.
2. *Access to Excellence: A Report of the Commission on the Future of the Advanced Placement Program®*, College Entrance Examination Board, New York (2001), available online at http://apcentral.collegeboard.com/repository/ap01.pdf.ac_7907.pdf.
3. *Advanced Placement Course Description. Physics: Physics B, Physics C, May 2002, May 2003*, College Entrance Examination Board, New York (2001), known also as the "Acorn Book," available online at http://apcentral.collegeboard.com/repository/ap01.cd_phy_4325.pdf
4. J. Oakes, J. Rogers, P. McDonough, D. Solorzano, H. Mehan, P. Noguera, *Remedying Unequal Opportunities for Successful Participation in Advanced Placement Courses in California High Schools*, American Civil Liberties Union of Southern California, Los Angeles (2000).
5. *2000 National Summary Reports*, College Entrance Examination Board, New York (2000), available online at http://cbweb1s.collegeboard.org/ap/2000/national_2000.pdf.
6. M. Neuschatz, M. McFarling, *Maintaining Momentum: High School Physics for a New Millennium*, American Institute of Physics, College Park, Md. (1999), available online at http://www.aip.org/statistics/trends/reports/hsreport.pdf.
7. See http://www.phystec.org.
8. For example, see L. Horn, A. Nunez, L. Bobbitt, *Mapping the Road to College*, rep. no. NCES 2000-153, US Department of Education, Center for Education Statistics, Washington, DC (2000).
9. For example, see V. E. Lee, R. G. Croninger, J. B. Smith, *Educ. Eval. Policy Anal.* **19**, 99 (1997).
10. J. Bransford, A. L. Brown, R. R. Cocking, eds., *How People Learn: Brain, Mind, Experience, and School: Expanded Edition*, National Academy Press, Washington, DC (2000).
11. For example, see E. Mazur, *Peer Instruction: A User's Manual*, Prentice Hall, Upper Saddle River, N.J. (1997).
12. Further information can be found online at http://www.psrc-online.org, in particular http://www.psrc-online.org/resource/physics.html.
13. An excellent discussion of effective laboratory instruction can be found in Committee on Undergraduate Science Education, *Science Teaching Reconsidered*, National Academy Press, Washington, DC (1997), p. 16.
14. American Association of Physics Teachers, *Am. J. Phys.* **66**, 483 (1998).
15. D. Hestenes, M. Wells, G. Swackhamer, *Phys. Teach.* **30**, 141 (1992). ■