I. INTRODUCTION

We provide a guide to the literature on research-based active-learning instruction in physics. This refers to instructional methods that are based on, assessed by, and validated through research on the teaching and learning of physics. Active-learning instruction involves students in their own learning more deeply and more intensely than does traditional instruction, particularly during class time. The methods are very diverse: they may incorporate techniques such as real-time computerized data collection and display, Socratic “guided inquiry,” interactive computer simulations, and structured problem-solving, along with many others.

The methods we describe share three common features: (1) they are explicitly based on research in the learning and teaching of physics; (2) they incorporate classroom and/or laboratory activities that require all students to express their thinking through speaking, writing, or other actions that go beyond listening and the copying of notes, or execution of prescribed procedures; (3) they have been tested repeatedly in actual classroom settings and have yielded objective evidence of improved student learning. (Another term that has often been used for research-based active-learning instruction in physics is “Interactive Engagement” [Ref. 10]. We don’t believe there are significant distinctions between the intended meanings of these terms.)

We acknowledge that it is possible to satisfy criterion #2 without satisfying the other two criteria. Indeed, the terms “active learning” and “interactive engagement” have themselves been applied to practices that are not explicitly based on or validated by research. Our practice for citation in this Resource Letter is to require that all three criteria be met for instructional methods originating after 1970. However, as discussed below, these post-1970 research-based methods have origins that are directly traceable to still earlier developments in the history of physics education, and those earlier developments will be discussed in a separate section.

(We should also note that although students involved in reading a textbook, taking notes during lecture, or solving
understandings that eventually match those of physicists.

Answers through hands-on laboratory activities. They aim to actively-engaging methods engage students in directly finding in a variety of specific classroom activities. Many of these methods mean far greater emphasis on engaging students in putting far greater emphasis on engaging students to reason effectively and succeed at problem-solving. Some of the techniques might be helpful in “traditional” instructional environments; however, it is only when applied in contexts explicitly based on research into student learning that superior learning gains have been clearly and repeatedly demonstrated. Henceforth, we will refer to “active-learning instructional methods” without explicitly stating that they are research-based.

A large body of peer-reviewed research for which we provide references indicates that typical learning gains for the majority of students on qualitative, conceptual physics questions, when engaged in “traditional” instructional activities, are around 10–15 percentage points on standard diagnostic exams; see, for example, Ref. 10. (This represents the pre-to-post-instruction gain, and corresponds to correcting ≈20% of incorrect pretest responses). By contrast, research-based active-learning materials and methods produce gains up to and often more than double that amount on similar questions. For example, in a recent study (Ref. 74), a sample of more than 3000 students from ten universities showed gains from active-learning instructional materials to be more than four times those obtained through standard instruction. The active-learning methods also generally produce gains on more than four times those obtained through standard instruction. The active-learning methods also generally produce gains on traditional, quantitative physics problems that are equivalent or superior to gains observed with traditional instruction.

To be considered for inclusion in this Resource Letter we required that curricular materials, methods, and tools be useful for undergraduates in colleges and universities. Many of the materials we reference are also suitable for use in high schools; however, that is not our focus. All materials are research-based in the sense that they were developed using the methods of research in physics education and have been subjected to efforts to evaluate the learning of students who use them. Our minimum criterion for inclusion is that a curriculum or instructional program must have a citable peer-reviewed publication that documents, in some fashion, evidence for the pedagogical efficacy of the method or material. (Historical references in Sec. III are not uniformly held to this standard, and websites containing materials that are research-based, but not necessarily research-validated, are included in Sec. II E.) An additional constraint is that we only included curricular materials that are readily available either in print or CD/DVD, or online. The references we cite all have a very strong and specific focus on physics; space limitations preclude us from including any of the vast body of literature on active-learning instruction in other (or in general) contexts. Finally, we only cite materials in English, because English is the predominant common language of our audience.

The organization of the remainder of this Resource Letter is as follows:

Section II—General references to journals, conference proceedings, books, and online resources that deal extensively with active-learning instruction in physics.
II. GENERAL REFERENCES

A. Journals
Curricula and research results related to active-learning instruction in physics are published in a wide variety of journals, including education journals related to cognitive science, educational psychology, computers, and general science, but the journals listed below have the most pronounced focus on physics.

American Journal of Physics. Generally addressed to university and college instructors, with many articles of significance to researchers. A source for authoritative research on physics education since the 1970s.
Journal of Physics Teacher Education Online: <http://www.phy.ilstu.edu/jpteo/>
Physics Education. Addressed to pre-college teachers, and university and college instructors.
The Physics Teacher. Addressed to pre-college teachers, and university and college instructors.

B. Conference proceedings
1. The Changing Role of Physics Departments in Modern Universities: Proceedings of International Conference on Undergraduate Physics Education, edited by E. F. Redish and J. S. Rigden (AIP, Woodbury, NY, 1997), AIP Conference Proceedings 399; Part One: Presentations; Part Two: Sample Classes. Part Two includes a unique collection of extended, detailed descriptions of some of the most influential active-learning physics curricula of the past 20 years. One of the most influential and wide-ranging conferences of recent years. (E-I)

Beginning in 2003, the annual proceedings of the Physics Education Research Conferences have been published by the American Institute of Physics and are accessible online to subscribers at <http://proceedings.aip.org/>. Many of the proceedings papers are also available for free download at <http://www.per-central.org/conferences/>.

These conferences include:


C. Books

3. Teaching Introductory Physics, A. B. Arons (Wiley, New York, 1997). A massive compendium of insights into teaching and learning of physics gained over Arons’s 40 years as a pioneer of active-learning instruction. Also contains a large number of qualitative, concept-oriented questions on a wide array of topics. (E)

4. Five Easy Lessons, R. D. Knight (Addison Wesley Longman, San Francisco, CA, 2003). An instructor’s guide to accompany Knight’s research-based textbook and workbook (Ref. 113). A unique and valuable compilation of research results and instructional ideas covering the introductory university physics course. (E)

5. Teaching Physics with the Physics Suite, E. F. Redish (Wiley, New York, 2003). A wide-ranging discussion of research findings and instructional approaches, with a particular focus on cognitive insights. Part of the “Physics Suite” series. (E)


D. General articles


on the teaching and learning of physics, including many reports related to active-learning physics instruction. Valuable reference but now somewhat out of date. (E-A)


E. Online resources

This is a collection of websites that contain active-learning instructional materials or links to such materials. In most cases, the materials are in whole or part based on physics education research or on instructional principles derived from such research. However, their instructional effectiveness has not necessarily been validated by published, peer-reviewed studies. Materials are organized alphabetically.

16. Assessment Instrument Information Page, North Carolina State University: <http://www.ncsu.edu/PER/TestInfo.html>. Large collection of links and references to research-based diagnostic exams in many areas of physics, with brief descriptions of each one and citations of relevant publications. (E-I)


20. Interactive Online Lectures, University of Illinois: <http://research.physics.illinois.edu/per/ol.html>. Interactive web-based materials that allow students to engage with a simulated lecture, before or outside of class. (E)


22. Open Source Physics: <http://www.opensourcephysics.org/>. Includes curriculum resources emphasizing interactive computer simulations on physics, astronomy, and computer modeling. (E)


25. Physical Sciences Resource Center: <http://www.compadre.org/>. Provides a vast array of curricular resources, many of which are based on physics education research. (E-I)

26. Physics Education Research Central: <http://www.compadre.org/per>. Contains links to a broad collection of publications on physics education research, many of which are directly associated with active-learning instructional materials. (E-I)

27. Physics JiTT Resources: <http://jittdl.physics.iupui.edu/jittd/physics/index.html>. Materials for “Just-in-Time-Teaching,” in which student responses to pre-instruction exercises guide the instructor in designing and structuring the day’s lesson. (E)


29. Physics Teaching Technology Resource, Rutgers University: <http://paer.rutgers.edu/pt3/>; Physics Union Mathematics: <http://pum.rutgers.edu>. These materials are based on and support the work described in Refs. 128–129. (E)

30. Physics Teaching Web Advisory, Kansas State University: <http://www.physicspathway.org/>. Provides research-based guidance for instructors on specific physics topics, as well as a library of physics demonstration videos. (E)

31. Project Galileo [Interactive Learning Toolkit - BQ], Harvard University: <https://galileo.harvard.edu/login/>. Includes materials generated to support Peer Instruction (Ref. 104), as well as other materials; requires online registration. (E)

32. PTEC Library: <http://www.ptec.org/search/browse.cfm?browse=gsss>. Contains links to curricular materials and research reports associated with the education of physics teachers. (E-I)


34. Science Education Initiative, University of Colorado: <http://www.colorado.edu/sei/departments/physics.htm>. Links to a variety of research-based instructional
materials for intermediate- and upper-level physics. Some of these are discussed separately in Sec. VII. (E-I)


36. Spiral Physics, Monroe Community College: <http://web.monroecc.edu/spiral/>. Research-based, active-learning workbooks that emphasize multiple-representation problem-solving techniques in mechanics and in electricity and magnetism. (E)


38. Visual Quantum Mechanics, Kansas State University: Powerful simulation software that allows construction of “artificial” atomic energy levels, emission and absorption of photons, and many related phenomena of modern physics.
(a) <http://web.phys.ksu.edu/vqm/>;
(b) <http://web.phys.ksu.edu/vqm/software/>;
(c) <http://www.ztek.com/physics/physics.html#Anchor-Visual-6296>. (E)

III. HISTORICAL PERSPECTIVE

Present-day active-learning instructional methods in physics are the products of a long chain of developments reaching back over a century. Some of the references relate to physics at the K-12 (pre-college) level, but they and their authors played essential roles in developing modern methods of active-learning instruction in college-level physics. (Note: Although we frequently use the phrase “active-learning instruction” in this section, it’s important to recognize that most instruction before 1970 was not based explicitly on research on student learning in physics. It thus lacked many of the features of modern active-learning instruction identified in Sec. I.)

A. U.S. origins

Laboratory-based instruction in physics spread rapidly in the United States during the late 1800s. Among both high-school and college instructors there was widespread support for the so-called “inductive method” in which experiment precedes explicit statement of principles and laws.


Wead (Ref. 39, p. 120) states, “The book which is the most conspicuous example now in the market of this inductive method is Gage’s [‘Textbook on the Elements of Physics’]. Here, although the principles and laws are stated, the experiments have preceded them; many questions are asked in connection with the experiments that tend to make the student active, not passive, and allow him to think for himself before the answer is given, if it is given at all.”


41. “The teaching of physics in the secondary school,” Edwin H. Hall, in The Teaching of Chemistry and Physics in the Secondary School, A. Smith and E. H. Hall (Longmans, Green, New York, 1902), pp. 229–371. Endorses instructional methods in which the pupil is kept “just enough in the dark as to the probable outcome of his experiment…to leave him unprejudiced in his observations,” since “the experimenter should hold himself in the attitude of genuine inquiry” (p. 278). (E)

The increasing focus on laboratory work led, ironically, to an overemphasis on formal methods and precision of measurement to the detriment of qualitative understanding of physics concepts and of the nature of scientific investigation. A “New Movement” among high school and college physics instructors arose as a reaction against this, and re-emphasized the importance of active student investigation in the pursuit of deep understanding of physics concepts.

42. The Teaching of Physics for Purposes of General Education, C. Riborg Mann (Macmillan, New York, 1912). A leader of the New Movement, Mann insisted that students’ laboratory investigations should be aimed at solving problems that are both practical and interesting. Includes extensive supporting analysis and a very useful bibliography. (E)

B. Postwar curricular reforms

Further development of active-learning instruction in physics was resumed in 1956 by the Physical Science Study Committee (PSSC), supported by the National Science Foundation (NSF). The PSSC curriculum was distinguished by strong emphasis on conceptual understanding, and on student investigations in the laboratory that were only lightly guided through questions, suggestions, and hints. It rejected traditional efforts that had relied heavily on superficial coverage of a large number of topics, memorization of terse formula-tions, and use of “cookbook”-style instructional laboratories with highly prescriptive lists of steps and procedures designed to verify known principles. (A contemporary curric-ulum development effort in England with similar themes, not covered in this review, was sponsored by the Nuffield Foundation.)

43. “The Physical Science Study Committee,” G. C. Finlay, Sch. Rev. 70(1), 63–81 (Spring 1962). Emphasizes that students are expected to be active participants by wrestling with lines of inquiry, including laboratory investigations, that lead to basic ideas of physics: “In this course, experiments…are not used simply to confirm an earlier assertion.” (E)

A contemporary project that utilized somewhat similar instructional principles, but which put heavier emphasis on
historical and cultural aspects of physics, was the Harvard Project Physics course.

44. “The Project Physics course, then and now,” G. Holton, Sci. & Educ. 12, 779–786 (2003). A review and reflection by one of the three original leaders of the project. (E)

The reform efforts soon expanded to include the elementary schools and, backed by the NSF, an explosion of more than a dozen new science curricula aimed at younger students was generated. Leading physicists again played a central role in several of these curriculum-reform projects. Prominent in most of them was a strong and explicit emphasis on learning through hands-on activities using real objects with varying degrees of guidance and support provided by instructors; in general, the outcome of the activity was not known to the students in advance. The method can be broadly characterized as utilizing the investigational process of science as a means of teaching scientific concepts themselves. (Various terms have been used in this context without clear consensus on their precise definitions or the distinctions among them, e.g., “inductive method,” “discovery,” “inquiry,” and “guided inquiry.”)

One of the most widely used of the new curricula was the Elementary Science Study (ESS), produced by a team that included MIT physicist Philip Morrison.


In the three-phase “learning cycle” propounded by Berkeley theoretical physicist Robert Karplus, students’ initial exploration activities led them (with instructor guidance) to grasp generalized principles (concepts) and then to apply these concepts in varied contexts. This instructional program was strongly influenced by the Swiss psychologist Jean Piaget.


C. Broadening impact on university physics instruction

A workshop on physics teaching, organized by Karplus and his collaborators, focused on design and assessment of instructional activities that would most effectively apply and develop students’ logical reasoning abilities. The workshop materials had a significant influence on physicists who were interested in building on research to develop more effective active-learning instructional methods at the college level.


Arnold Arons at Amherst College had been engaged since the 1950s in developing a novel approach using active-learning instructional methods for a calculus-based college physics course. Arons’s methods provided the foundation for an enormously influential line of development.

51. “Structure, methods, and objectives of the required freshman calculus-physics course at Amherst College,” A. B. Arons, Am. J. Phys. 27, 658–666 (1959). Arons characterized the nature of this course’s laboratory work as follows: “Your instructions will be very few and very general; so general that you will first be faced with the necessity of deciding what the problem is. You will have to formulate these problems in your own words and then proceed to investigate them.” [Emphasis in original.] (E)

Arons moved to the University of Washington in the late 1960s and, soon joined by Lillian McDermott, continued to implement these instructional methods at the university level. Together they continued systematic development of activity-based college physics courses, building on and extending inquiry-based active-learning principles embodied in elementary science curricula such as SCIS and ESS. In 1973, McDermott and her students initiated a systematic research program to support and expand on the instructional efforts (Ref. 59).

52. “Definition of intellectual objectives in a physical science course for preservice elementary teachers,” A. Arons and J. Smith, Sci. Educ. 58, 391–400 (1974). Instructional staff for the course were explicitly trained and encouraged to conduct “Socratic dialogues” with students. (E)


Arons and McDermott placed great emphasis on the need for students to formulate and express reasoned written or verbal responses to questions that the students themselves raised during instruction. These efforts focused initially on
improving the preparation of prospective K-12 science teachers, and teacher preparation was a common theme of other active-learning physics programs.


Education of graduate teaching assistants was also discussed by McDermott in (Ref. 93), in the context of preparing them to teach through a process of inquiry using the research-based Tutorials in Introductory Physics (Ref. 136).

D. Building a research base

During the 1970s, education researchers worldwide began systematic efforts to probe students’ thinking on a variety of science topics, initially at the elementary and secondary levels. Most of this work was tied only loosely, or not at all, to concurrent development of instructional materials and methods at the post-secondary level. In the mid-1970s, Frederick Reif, Lillian McDermott, and John Clement in the U.S. (as well as Laurence Viennot in France), along with their students and collaborators, were among the first to systematically investigate understanding of specific physics concepts by students enrolled in university-level physics courses. These investigations led to the development and implementation of research-based active-learning instructional methods and curricula.

57. “Teaching general learning and problem-solving skills,” F. Reif, J. H. Larkin, and G. C. Brackett, Am. J. Phys. 44, 212 (1976). Students’ reasoning in physics was investigated through observations of student groups engaged in problem-solving tasks, through “think-aloud” problem-solving interviews with individual students, and through analysis of written responses. This paper foreshadowed much future work on improving problem-solving ability through explicitly structured practice, carried out subsequently by other researchers. (E)


59. “Investigation of student understanding of the concept of velocity in one dimension,” D. E. Trowbridge and L. C. McDermott, Am. J. Phys. 48, 1020–1028 (1980). The primary data sources in this groundbreaking paper were “individual demonstration interviews” in which students were confronted with a simple physical situation and asked to respond to a specified sequence of questions. Curricular materials were designed to address specific difficulties identified in the research; students were guided to confront directly and then to resolve confusion related to the physics concepts. This paper provided a model and set the standard for a still-ongoing program of research-based curriculum development that has been unmatched in scope and productivity. (E)

60. “Students’ preconceptions in elementary mechanics,” J. Clement, Am. J. Phys. 50, 66–71 (1982). Describes evidence from written tests and problem-solving interviews, and argues that preconceptions may be treated as “zeroth-order models” that can be modified to achieve greater precision and generality. Curricular materials growing out of this research are described in Ref. 131. (E)

A systematic investigation of student ideas related to Newtonian mechanics was later reported in widely cited papers.


These findings were applied to the development of an instructional strategy for mechanics that—with explicit reference to the work of Arons—emphasized use of Socratic dialogue.

63. “Promoting student crossover to the Newtonian world,” R. R. Hake, Am. J. Phys. 55, 878–884 (1987). Hake’s “Socratic dialogue inducing” (SDI) labs led to significantly higher scores on mechanics exams than had been observed in a comparable “conventional” course at a similar institution. See also (Ref. 117). (E)

The principles of active-learning instruction were reviewed and expanded by emphasizing the advantages of using “multiple representations” in solving physics problems.


E. Impact of technology

A significant development in the history of active-learning instruction in physics was the rapid advance in microcomputer use for real-time data acquisition, graphing, and analysis. Coupled with the use of ultrasonic motion sensors and other types of sensors, the new tools enabled rapid feedback in the instructional laboratory to a degree not previously possible.

developing microcomputer-based instructional curricula for university-level physics. Argues that a well-designed science laboratory is “one of the few places where students can really participate in the processes of science.” (E)

67. “Learning motion concepts using real-time microcomputer-based laboratory tools,” R. K. Thornton and D. R. Sokoloff, Am. J. Phys. 58, 858–867 (1990). Discusses the potential for improving students’ understanding of physics concepts and graphical representations using the new tools, but emphasizes that they have to be coupled to research-based curricula to bring about effective student learning. (E)


71. “Research and computer-based instruction: Opportunity for interaction,” L. C. McDermott, Am. J. Phys. 58, 452–462 (1990). Describes the development of Trowbridge’s “Graphs and Tracks” instructional software (one of the earliest research-based physics curricula based on computer simulations), and the use of simulations as a tool for research on students’ reasoning. (E)

Most of the developments in active-learning instruction in physics since 1990 can be traced in some form to one or more of the intellectual traditions identified in the above brief historical summary. Although distinct and to some extent developed in parallel to each other, they include many common and cross-cutting themes.

The continued development and ultimate success of these methods have been founded on rigorous, research-based assessments of student learning. In Sec. IV, we describe some of the diagnostic instruments that have been developed to assess student knowledge, as well as some of the key research results related to persistence of learning gains.

IV. ASSESSMENT OF STUDENT LEARNING

Active-learning instructional methods are based on research in student learning and are tested by research-based assessment methods. A wide variety of assessment methods have been used, including one-on-one interviews, written free-response (or “open-response”) questions, multiple-choice tests of various types, etc. In this section, we briefly describe a few of the most popular assessment instruments and discuss some of the evidence these instruments have yielded regarding persistence of learning gains.

A. Research-based diagnostic instruments

72. “Force Concept Inventory,” D. Hestenes, M. Wells, and G. Swackhamer, Phys. Teach. 30, 141–158 (1992). First published in 1992, the FCI grew out of earlier work described in Refs. 61 and 62. It involves nonquantitative questions using nontechnical language, set in familiar “everyday” physical contexts. The FCI was one of the earliest research-based tests designed to assess student learning in physics, and has been used throughout the world to probe students’ thinking and to assess the effectiveness of new methods of physics instruction. A revised version was published in 1995 in the book by Mazur (Ref. 104) and is available online in many languages (password-protected) at (Ref. 132). (E)

Another widely used test for investigating students’ physics ideas, under development since the late 1980s, grew out of Thornton and Sokoloff’s assessments of standard instruction and of reformed curricula that often used microcomputer-based laboratory tools.


74. “Comparing the force and motion conceptual evaluation and the force concept inventory,” R. K. Thornton, D. Kuhl, K. Cummings, and J. Marx, Phys. Rev. ST Phys. Educ. Res. 5, 010105 (2009). Compares the FCI and FMCE based on test data from thousands of students at ten institutions. Showed that learning gains with research-based active-learning curricula were consistently higher than with traditional instruction, regardless of which test was used. (I)

75. “Surveying students’ conceptual knowledge of electricity and magnetism,” D. P. Maloney, R. K. O’Kuma, C. J. Hieggelke, and A. Van Heuvelen, Am. J. Phys. 69(S1), S12–S23 (2001). Contains the Conceptual Survey in Electricity and Magnetism (CSEM), a widely used diagnostic exam, along with extensive data obtained from administration of the test to thousands of students in a variety of different physics courses. (E)

76. “Evaluating an electricity and magnetism assessment tool: Brief electricity and magnetism assessment,” L. Ding, R. Chabay, B. Sherwood, and R. Beichner, Phys. Rev. ST Phys. Educ. Res. 2, 010105 (2006). Describes the Brief Electricity and Magnetism Assessment (BEMA) with a variety of data obtained in constructing and validating the test; does not contain the test itself. There is some overlap between the CSEM and the BEMA. (E)

There is a large collection of other research-based diagnostic exams at (Ref. 16).

B. Persistence of learning gains

Several studies (for example, Ref. 70) indicate that student-learning gains persist or even increase during the weeks and
months following active-learning instruction. Long-term (years long) longitudinal studies of student conceptual understanding are not common owing to the great practical difficulties associated with them. However, consistent findings from a number of studies strongly suggest that the improved conceptual-learning gains from active-learning physics instruction are retained over periods of years. For example (Ref. 116), students who had used the Matter & Interactions curriculum (Ref. 114) displayed greater absolute retention of electricity and magnetism concepts than students who had followed a traditional course of study, for periods up to 115 weeks post-instruction. Similarly, upper-level physics students who had used Tutorials in Introductory Physics (Ref. 136) in their introductory courses several years previously demonstrated superior performance when compared with classmates who had not used Tutorials. Other studies with similar outcomes probed a variety of different curricula.

77. “Longitudinal study of student conceptual understanding in electricity and magnetism,” S. J. Pollock, Phys. Rev. ST Phys. Educ. Res. 5, 020110 (2009). Students in a junior-level electricity and magnetism course who had used Tutorials in Introductory Physics (Ref. 136) in their freshman introductory course had better course grades and higher scores on a conceptual test than students who had taken introductory courses that did not use Tutorials. Also see (Ref. 152). (E)


79. “Preparing teachers to teach physics and physical science by inquiry,” L. C. McDermott, P. S. Shaffer, and C. P. Constantinou, Phys. Educ. 35, 411–416 (2000). Students who had used Physics by Inquiry (Ref. 164) 1 year previously had better performance on electric-circuits questions than students who had just finished studying the same concepts using traditional curricula. (E)

80. “Does active engagement curricula give long-lived conceptual understanding?” J. Bernhard, in Physics Teacher Education Beyond 2000, edited by R. Pinto and S. Surinach (Elsevier, Paris, 2001), pp. 749–752; also available at <http://webstaff.itn.liu.se/~jonbe/fou/didaktik/papers/girep2000_active.pdf>. Materials adapted from RealTime Physics (Ref. 121) were translated into Swedish and used in introductory physics courses. Students’ learning gains were superior to those in traditional courses and were well retained up to 2.5 years post-instruction even with no additional instruction in mechanics. (E)

We next outline the principles on which research-based, active-learning physics instruction has been founded and continues to develop.

V. COMMON CHARACTERISTICS OF ACTIVE-LEARNING INSTRUCTIONAL METHODS IN PHYSICS

Active-learning instruction in physics, by our definition—also, following Hake (Ref. 10), sometimes referred to as “interactive-engagement” instruction—generally incorporates a number of characteristics indicated by the representative references in this section. We stress that it is our own analysis that leads to this synthesis, and that nothing in the current research literature is either so comprehensive or so explicit in identifying this or any other set of common characteristics of active-learning physics instruction. This is not to say, however, that analogous lists do not exist.

81. “Implications of research on learning for the education of prospective science and physics teachers,” J. P. Mestre, Phys. Educ. 36, 44–51 (2001). Provides a list of desirable attributes for physics courses suggested by research on learning; substantially overlaps the list presented in this Section. (E)

A. Instruction is informed and explicitly guided by research regarding students’ pre-instruction knowledge state and learning trajectory

“Knowledge state” refers to students’ pre-existing physics ideas and learning tendencies, the ways in which students attempt to apply their pre-existing understanding to issues that emerge during the course of instruction.

McDermott and her students were among the first to apply this principle in university-level physics instruction (Ref. 59), exploring student thinking through one-on-one interviews, and through use of written free-response diagnostic questions that focus on qualitative, conceptual reasoning. Most of their many papers are listed at <http://www.phys.washington.edu/groups/peg/pubs.html>; some give detailed accounts of how research on student learning is used to develop instructional materials, for example (Ref. 137).

82. “The challenge of matching learning assessments to teaching goals: An example from the work-energy and impulse-momentum theorems,” T. O. Pride, S. Vokos, and L. C. McDermott, Am. J. Phys. 66, 147–157 (1998). Describes how research on student learning was used to create more effective instructional materials on dynamics. (E)


A variety of diagnostic instruments using multiple-choice and short-answer items have been developed to help assess students’ intuitions and conceptual knowledge in different areas of physics; some of these were described in Sec. IV.

The importance of students’ learning trajectory was emphasized in an explicit analysis of the evolution of students’ ideas.


The various aspects of students’ knowledge state and learning tendencies that have been addressed in active-learning physics instruction include: (1) specific learning difficulties related to particular physics concepts (Refs. 59 and 63), further developed in Sec. V B; (2) specific ideas and knowledge elements that are potentially productive and useful (Ref. 60); and (3) students’ beliefs about what they need to do in order to learn, as well as their actual learning behaviors.

86. “Helping physics students learn how to learn,” A. Elby, Am. J. Phys. 69(S1), S54–S64 (2001). Focuses on guiding students to adopt more sophisticated beliefs and practices related to knowledge and learning. (E)


88. “Student resources for learning introductory physics,” D. Hammer, Am. J. Phys. 68(S1), S52–S59 (2000). Reviews much previous work to emphasize potentially productive beliefs and knowledge elements in students’ thinking that can play a positive role in their learning of physics. (E)


90. “Uncommon knowledge: Student behavior correlated to conceptual learning,” R. K. Thornton, in Research on Physics Education: Proceedings of the International School of Physics “Enrico Fermi” Course CLVI, edited by E. F. Redish and M. Vicentini (IOS, Amsterdam, 2004), pp. 591–601. Discusses several specific student behaviors during laboratory activities that were linked either to relatively high or relatively low learning gains. (E)

A student’s knowledge state also includes general reasoning processes, to the extent that these can be treated as distinct from reasoning processes that are themselves closely linked to a specific physics concept. Exploring and improving these general processes was an approach characteristic of Karplus and his collaborators (Ref. 49) and has also been addressed by Reif (Ref. 6).


B. Specific student ideas are elicited and addressed

Several distinct methods have been employed, with McDermott’s probably the best known.

93. “Oersted Medal Lecture 2001: ‘Physics Education Research—The key to student learning,’” L. C. McDermott, Am. J. Phys. 69, 1127–1137 (2001). The instructional strategy of McDermott and co-workers was designed to help students confront and address specific learning difficulties. This strategy, often summarized as “elicit, confront, and resolve,” perhaps has been the most thoroughly tested and validated of all active-learning instructional methods in physics. Dozens of peer-reviewed publications by researchers working in diverse institutional and instructional contexts have documented substantial learning gains resulting from this approach. See also Ref. 59. (E)

Other approaches for addressing and utilizing students’ ideas include, for example, guiding students to “refine” their ideas to “reconcile” them to physics concepts (Ref. 86). Other terms that have been applied to this process include “bridging” between more familiar and less familiar concepts and “weaving” of loosely connected initial ideas into more complete understanding.


C. Students are encouraged to “figure things out for themselves”

As discussed by Hake (Ref. 63), where the above quotation appears, and much earlier by Karplus and Arons, this refers to a pedagogical strategy in which students are guided to reason through and investigate concepts and key ideas through a process of questioning, experimentation, and discussion (often called “guided inquiry”), in contrast to receiving these ideas fully and clearly developed in advance of (or instead of) an activity. The goal is for students to develop personal insight rather than accept facts and principles solely on the basis of authority. This pedagogical principle, which is an obvious extension of the “inductive” methods advocated in the 1800s (Ref. 39), is discussed in many references. 20th-century advocates of this strategy such as Karplus often linked it to research by Piaget which suggested that learning is largely based on grappling with, accommodating to, and ultimately assimilating unfamiliar concepts (Ref. 47).

The investigative activity may take many forms depending on the specific classroom context (laboratory, lecture, recitation; small or large group; etc.). In the initial stages of instruction, instructors tend to ask leading questions rather than provide students with either direct answers or detailed
formulations of generalized principles (which may come later). Alternatively, instructors may guide students to formulate their own questions, as in the ISLE curriculum of Etikina and Van Heuvelen (Ref. 129). Students may be solicited to offer hypotheses or predictions regarding the outcome of experiments, to debate the merits of various hypotheses, and to test them through experimentation or reasoning. Carefully structured question or activity sequences are often used to guide this process, both with and without use of equipment and materials.

D. Students engage in a variety of problem-solving activities during class time

This characteristic may be considered the specific implementation method for the strategy described in Sec. V C; it stands in contrast to having students spend most of the time listening to an instructor speak (Refs. 52, 104, and 110). In this context, “problem-solving activities” does not normally refer to the solution of standard textbook-type quantitative problems. Instead, students are challenged with a wide variety of thought-provoking activities that might include hands-on experiments (brief or extended), written or verbal predictions of experiment outcomes, qualitative questions requiring verbal or diagrammatic responses, multiple-choice conceptual questions utilizing electronic response systems, and collaboration and discussion with the other students. More broadly, students are guided to retrieve and apply the concepts needed to solve problems in realistic physical settings in novel and diverse contexts, and to justify or explain the reasoning they have used.

E. Students express their reasoning explicitly

Expressions of reasoning can be generated both verbally by interacting with instructors and other students, and in written explanations as part of responses to quizzes, in-class worksheets, homework, and exam problems, as discussed in many references above. These verbal and written expressions help students more clearly expose—and therefore modify—their own thought processes.

A specific application of this principle has been designed to improve students’ problem-solving ability; it is in some ways an extension of Ref. 57 and is analogous to methods described in Refs. 65 and 97.


F. Students often work together in small groups

Student group work is designed to lead students to express their own thinking and to comment on and critique each others’ thinking regarding problems and questions under consideration. This strategy has been widely used and discussed in the context of physics education.


G. Students receive rapid feedback in the course of their investigative or problem-solving activity

“Rapid” may connote feedback on a minute-to-minute basis or even shorter; it includes feedback from instructors through frequent questions and answers, and feedback from fellow students through small-group interactions (Refs. 8 and 63, and Refs. 104 and 110). A significant advance was the immediate feedback provided through automatic computerized data logging and instantaneous graphical displays (Refs. 66 and 70). The feedback works in two directions, since instructors benefit by acquiring a clearer picture of students’ evolving thinking and are able to adjust instruction accordingly in a rapid and flexible manner.

H. Qualitative reasoning and conceptual thinking is emphasized

Nonquantitative means of problem solving are used to strengthen students’ understanding of fundamental concepts and processes of physics, and to avoid having students focus on mastery of mathematical algorithms as a substitute for understanding. This principle has been widely discussed and applied in physics education for over 100 years (Refs. 39 and 42).

I. Problems are posed in a wide variety of contexts and representations

Physics education research has shown convincingly that knowledge of physics concepts is not adequate for real-world application if acquired and practiced only in few and limited contexts utilizing a narrow range of representations. In order to deepen conceptual understanding in active-learning physics instruction, problem-solving and investigative activities are expressly designed to incorporate diagrammatic, graphical, pictorial, verbal, and other means of representing ideas and posing questions, and they are deliberately set in widely diverse physical contexts. This is discussed in nearly all of the references. Among the more influential were Refs. 64 and 98, and the following ones:


101. “A view from physics,” L. C. McDermott, in Toward a Scientific Practice of Science Education, edited by...
J. Instruction frequently incorporates use of actual physical systems in problem solving

Active-learning instruction often emphasizes “translating” between, on the one hand, phenomena and processes in actual physical systems and, on the other hand, diverse forms of representation of these same processes (such as diagrammatic, mathematical, and verbal). Whenever practical, students are guided to answer questions and solve problems by engaging in hands-on activities with real objects (Refs. 59, 63, and 66; also see Ref. 123).

K. Instruction emphasizes the need to reflect on one’s own problem-solving practice

This characteristic is a direct analogue of day-to-day practices of working scientists (Refs. 8 and 64). Reflection may be achieved by: (a) enunciating specific goals and planning specific solution strategies in advance; (b) checking results frequently during the problem-solving process; (c) searching for coherent patterns; (d) considering alternative approaches; (e) performing final checks of the reasonableness and consistency of results; and (f) reviewing the entire process to reflect on how one’s thinking evolved, and to assess the effectiveness of one’s strategies, often referred to as an emphasis on “metacognitive” issues.

L. Instruction emphasizes linking of concepts into well-organized hierarchical structures

Expert-like thinking requires both conceptual understanding (including links among concepts), and ready access to appropriate concepts through a well-organized hierarchical “filing system” (Refs. 8, 64, 92, and 100). Thus, broad general principles such as conservation laws and related problem-solving strategies based on these principles are often the primary goal of knowledge-building activities in active-learning physics instruction (Refs. 64, 65, and 96).

M. Instruction integrates both appropriate content (based on knowledge of students’ thinking) and appropriate behaviors (requiring active student engagement)

Active-learning instruction emphasizes the content of instructional materials as much as it does the specific instructional activities; explicit attention to students’ specific thinking patterns and learning behaviors is required. Instruction based on research that probes these patterns and behaviors is often called “research-based” instruction. Instruction that employs some of the same learning activities or technological tools, but in which the content does not focus on specific challenges identified through research into student learning, is not as successful.

102. “Evaluating innovation in studio physics,” K. Cummings, J. Marx, R. Thornton, and D. Kuhl, Am. J. Phys. 67(S1), S38–S44 (1999). Contrasts students’ learning gains in three different learning environments which, however, were all characterized by highly engaging activities, quite different from standard lecture instruction. They all incorporated small classes, collaborative group work, high levels of student-faculty interaction, and very limited use of lectures. The two research-based curricula produced far higher learning gains than the third ostensibly analogous active-learning curriculum, which differed from the other two in not being closely guided by research on students’ thinking, and in not explicitly addressing known difficulties in students’ reasoning regarding the targeted physics concepts. (E)

103. “Physics learning and Microcomputer Based Laboratory (MBL): Learning effects of using MBL as a technological and as a cognitive tool,” J. Bernhard, in Science Education Research in the Knowledge-Based Society, edited by D. Psilos, P. Kariotoglou, V. Tselves, E. Hatzikraniotis, G. Fassoulopoulos, and M. Kallery (Kluwer, Dordrecht, 2003), pp. 323–331. When inquiry-based labs using computer technology were rewritten to emphasize accurate verification of known formulas (instead of having students work to develop underlying concepts associated with known student difficulties), results on diagnostic tests were significantly worse. (E)

VI. ACTIVE-LEARNING INSTRUCTIONAL MATERIALS FOR INTRODUCTORY ALGEBRA- AND CALCULUS-BASED PHYSICS COURSES

We include here selected references to research-validated instructional materials and to papers that provide information regarding implementation and effectiveness of the materials. Materials within each of Secs. VI A–E are organized in chronological order of most recent publication of the primary (first) reference, which in some cases is years or decades after the publication date of the original version of the materials; additional references within subsections are organized chronologically; otherwise, organization is alphabetical.

A. Materials primarily for use in lecture sessions or lecture-based courses

1. Peer Instruction


Instruction minimizes lecture time and focuses on extended question-and-answer sequences that gradually ramp up the level of conceptual complexity. In conjunction with use of a specially designed student workbook (along with other active-learning materials), the method produced very high student learning gains on an electricity and magnetism diagnostic exam. The workbook is available at http://www.physicseducation.net/.


2. Interactive Lecture Demonstrations

110. Interactive Lecture Demonstrations: Active Learning in Introductory Physics [The Physics Suite], D. R. Sokoloff and R. K. Thornton (Wiley, New York, 2008). Interactive Lecture Demonstrations (ILDs) are used in the physics lecture classroom where the teacher performs actual experiments in front of the class. They are sequences of carefully chosen short demonstrations intended to help students learn fundamental concepts. Students make individual written predictions, discuss them with their neighbors, and predict again. Most often, real-time data-logging tools are used for data collection, analysis, and modeling. The “correct” answer is determined by experiment. For student learning results, see also Ref. 70. (E)


There is evidence that students’ spatial visualization ability improves through use of Interactive Lecture Demonstrations, as well as Workshop Physics activities.


3. Physics for Scientists and Engineers: A Strategic Approach

113. Physics for Scientists and Engineers: A Strategic Approach with Modern Physics, Second Edition, and Student Workbook, R. D. Knight (Pearson Addison Wesley, San Francisco, 2008). Inspired by the work of Van Heuvelen (Refs. 64 and 65), the workbook provides a wealth of conceptual questions using multiple representations for the full introductory physics course. The Instructor’s Guide for these materials (Ref. 4) describes the “interactive-lecture” style intended for their use. There also is a version for algebra-based courses. (E)

4. Matter & Interactions


B. Materials primarily for the laboratory

1. Socratic Dialog-Inducing Labs


2. Tools for Scientific Thinking

118. Tools for Scientific Thinking: Motion and Force Curriculum and Guide; and Heat and Temperature
Curriculum and Guide. R. K. Thornton and D. R. Sokoloff (Vernier Software, Beaverton, OR, 1990; 1993). One of the first guided-inquiry college-level curricula to make full use of microcomputer-based laboratory technologies including motion sensors and real-time graphing. Activities start by having students make and explain predictions of experimental outcomes; students then work together in small groups to test these predictions in the laboratory. See also Refs. 66 and 67. (E)


3. RealTime Physics

121. RealTime Physics: Active Learning Laboratories, Modules 1-4, Second Edition [The Physics Suite], D. R. Sokoloff, R. K. Thornton, and P. W. Laws (Wiley, New York, 2004). (An online Teachers’ Guide is available.) RTP uses real-time data-logging tools including features for mathematical and statistical modeling. It promotes conceptual and quantitative learning by allowing students to test their predictions of experimental outcomes through direct observations of the physical world, supported by a detailed student-activity guide. Students work together most often in groups of three. See also Ref. 70 for student learning results. (E)


4. Problem-Solving Labs

123. University of Minnesota Physics Education Research and Development, Problem-Solving Labs, Download Laboratory Manuals: [http://groups.physics.umn.edu/physed/Research/Lab%20Manuals/Lab%20Manuals.html]. These materials are based on the developmental work and assessments discussed in Refs. 97 and 98. (E)

3. Hybrid lecture-lab materials

1. Cooperative Group Problem Solving

124. University of Minnesota Physics Education Research and Development, Cooperative Group Problem Solving: [http://groups.physics.umn.edu/physed/Research/CGPS/CGPSintro.htm]. Comprehensive approach to restructuring introductory physics courses, based on work described in (Refs. 97 and 98). Includes: (a) Context Rich Problems, On-Line Archive: [http://groups.physics.umn.edu/physed/Research/CRP/on-lineArchive/ola.html], a collection of the “context-rich” problems described in Ref. 97 that use everyday situations as a context, may include extraneous information or require estimations, and do not directly state a target variable; (b) Manuals for problem-solving labs using specially designed context-rich problems (see Ref. 123); and (c) Cooperative Group Problem Solving in Physics, Patricia Heller and Kenneth Heller (University of Minnesota, Minneapolis, 1999), a comprehensive guide to the instructional method [http://groups.physics.umn.edu/physed/Research/CGPS/GreenBook.html]. (E)

2. Workshop Physics

125. Workshop Physics Activity Guide, Modules 1-4, Second Edition [The Physics Suite], P. W. Laws (Wiley, New York, 2004). Designed for a calculus-based introductory physics course without formal lectures that meets in a collaborative, active-learning classroom for 6 h each week. Employs computer tools for data collection and modeling and provides a detailed student-activity guide; students work together, usually in groups of two to four. Discussed in detail in Ref. 68; see also Ref. 70 for student learning results. (E)


127. “Women’s responses to an activity-based introductory physics program,” P. W. Laws, P. J. Rosborough, and F. J. Poody, Am. J. Phys. 67(S1), S32–S37 (1999). Reports a common challenge often observed in active-learning instruction, that is: Some students who may be familiar and comfortable with traditional instructional methods never accommodate to the new methods, and remain dissatisfied with their instructional experience. (E)


128. The Physics Active Learning Guide, Student Edition, and The Physics Active Learning Guide, Instructor Edition, A. Van Heuvelen and E. Etkina (Addison Wesley, San Francisco, CA, 2005). Building on principles described in Refs. 64 and 65 and further developed in Ref. 129, these detailed activity guides help students use multiple representations and qualitative reasoning, and develop a systematic approach to problem-solving. Students are guided to form hypotheses and test them through direct observation by designing experiments. (E)

Guide, including description of the curriculum with data regarding student learning gains. (E)

4. SCALE-UP


5. Preconceptions in Mechanics

131. Preconceptions in Mechanics: Lessons Dealing with Students’ Conceptual Difficulties, Second Edition [first edition: Kendall Hunt, Dubuque, IA, 1994], C. W. Camp and J. J. Clement (AAPT, College Park, 2010). This curriculum originated in and developed from the research described in Refs. 60, 61, and 62. Although primarily intended for high school courses, many of the activities are suitable for introductory college courses as well. In Ref. 94, there is discussion of the development process of the curriculum materials, along with student-outcome data showing strong learning gains in high-school physics classes. (E)

6. Modeling Instruction Program

132. Modeling Instruction Program: <http://modeling.asu.edu/>. Modeling grew out of Hestenes’s work (Ref. 100). Student groups carry out experiments, using graphical, diagrammatic, and mathematical representations to model physical systems. Some curricular materials are password-protected and available to participants in Modeling workshops; others are freely available at <http://modeling.asu.edu/Curriculum.html>. (E)


D. Tutorials and problem-solving worksheets

1. Tutorials in Introductory Physics

136. Tutorials in Introductory Physics; Homework for Tutorials in Introductory Physics; Instructor’s Guide for Tutorials in Introductory Physics, L. C. McDermott, P. S. Shaffer, and the Physics Education Group (Prentice-Hall, Upper Saddle River, NJ, 2002–2003). Guided-inquiry worksheets emphasizing written explanations of qualitative reasoning, targeted at a wide variety of challenging concepts in introductory physics. Material is based on the Ph.D. research of more than 20 graduate students over a period of decades at the University of Washington (UW), as reported in a large body of AJP articles. Instructor’s Guide contains pretests, exam questions, and instructor’s notes for each of the tutorials. A separate homework volume provides extensions and applications of concepts developed in the tutorials. (E)

137. “Development of a computer-based tutorial on the photoelectric effect,” R. N. Steinberg, G. E. Oberem, and L. C. McDermott, Am. J. Phys. 64, 1370–1379 (1996). Provides a detailed account of the genesis of one of the many UW tutorials, showing how research on student learning conducted in parallel with development of curricular materials led to improvements in tutorial design and learning outcomes. (E)


139. “Effectiveness of different tutorial recitation teaching methods and its implications for TA training,” K. M. Koenig, R. J. Endorf, and G. A. Braun, Phys. Rev. ST Phys. Educ. Res. 3, 010104 (2007). Materials from Tutorials in Introductory Physics were used in several different instructional environments that varied in the amount of student and teacher engagement. The most effective teaching method was students working in cooperative learning groups with the instructors questioning the groups using Socratic dialogue. This method matches the original implementation at the University of Washington. (E)

2. University of Maryland tutorials


143. “What course elements correlate with improvement on tests in introductory Newtonian mechanics?” E.-S. Morote and D. E. Pritchard, Am. J. Phys. 77, 746–753 (2009). “MasteringPhysics” is an online homework system with self-paced tutorials that incorporate extensive hints and feedback based on physics education research. This study showed that use of an early version correlated more strongly with high performance on both the MIT final course exam and the FCI (Ref. 72) than other course elements such as written homework, group problem solving, and class participation. The system was originally developed by D. E. Pritchard of MIT but is currently owned by Pearson Education; see: <http://www.masteringphysics.com/site/index.html>. (E)

2. Andes


3. Interactive Science Simulations

145. University of Colorado, Interactive Science Simulations: <http://phet.colorado.edu/>. Large collection of very sophisticated and powerful interactive simulations on many topics in physical science. Related research reports are archived at <http://phet.colorado.edu/en/research>. (E)


VII. ACTIVE-LEARNING INSTRUCTIONAL MATERIALS FOR INTERMEDIATE- AND ADVANCED-LEVEL PHYSICS COURSES

Material following the first reference within subsections is organized chronologically.

A. Mechanics

149. Intermediate Mechanics Tutorials: <http://umaine.edu/per/projects/IMT/>. Contains a large collection of pre-tests, tutorials, exam questions, homework, and instructor’s guides for a wide variety of topics in upper-level mechanics, modeled after the University of Washington’s Tutorials in Introductory Physics (Ref. 136). (E)


B. Electricity and magnetism

151. University of Colorado, Junior-level Electricity and Magnetism Course Materials: <http://www.colorado.edu/sei/departments/physics_3310.htm>. Includes tutorials, ConcepTests (Ref. 104) for interactive lectures, homework, lecture notes, and very detailed instructor’s notes. (E)

Ref. 77 which describes analogous results for students who had used other research-based materials several years previously. (E)

C. Optics


D. Thermal physics

154. Physics Education Research in Thermal Physics: <http://thermoper.wikispaces.com/>. Materials targeted at upper-level thermal physics courses; some are also useful for introductory courses. (E)


E. Modern physics and quantum mechanics

These materials are organized chronologically. In addition to the following sources, curricular materials on modern physics and quantum mechanics are included in Volume 2 of Activity-Based Tutorials (Ref. 140).


VIII. ACTIVE-LEARNING INSTRUCTIONAL MATERIALS FOR PRESERVICE TEACHERS AND NONSCIENCE STUDENTS

Materials in this section are primarily targeted at courses for nontechnical students who take physics to fulfill general-education requirements or as part of an elementary-teacher-education program. However, the materials are generally quite useful as supplements for many other types of courses as well. Subsections are organized chronologically according to most recent publication date of the first reference within each section; references within subsections are organized chronologically.

A. Physics by Inquiry

164. Physics by Inquiry, L. C. McDermott and the Physics Education Group at the University of Washington (Wiley, New York, 1996), Vols. I and II. Detailed activity guide that integrates quantitative and qualitative problem-solving exercises, hands-on laboratory activities, and expository text. A broad range of physical-science topics is included. Development of these
materials has been ongoing since the early 1970s, based on research on student learning and continuous class testing. Further information is at <http://www.phys.washington.edu/groups/peg/pbi.html>. (E)

165. “Improving the preparation of K-12 teachers through physics education research,” L. C. McDermott, P. R. L. Heron, P. S. Shaffer, and M. S. Stetzer, Am. J. Phys. 74, 763–767 (2006). Exam performance by 9th-grade students whose teachers had worked through Physics by Inquiry materials was superior to performance of undergraduate university physics students in traditional physics courses. Also see (Ref. 79). (E)

166. “Comparing the influence of physical and virtual manipulatives in the context of the Physics by Inquiry curriculum: The case of undergraduate students’ conceptual understanding of heat and temperature,” Z. C. Zacharia and C. P. Constantinou, Am. J. Phys. 76, 425–430 (2008). Shows that the Physics by Inquiry materials are effective even when transformed into a virtual environment using manipulatives that are simulated, rather than physical. (E)

B. Constructing Physics Understanding


C. Intuitive Quantum Physics


D. Inquiry into Physical Science


E. Physics & Everyday Thinking

171. Physics & Everyday Thinking. F. Goldberg, S. Robinson, and V. Otero (It’s About Time, Armonk, NY, 2008). Detailed activity guide targeted especially at prospective elementary-school teachers and other nontechnical students; makes heavy use of computer-assisted tools and computer simulations. Puts strong emphasis on students expressing and reflecting on their own ideas, and explicitly comparing and contrasting their thinking with that of scientists and other students. (E)

172. “Attitudinal gains across multiple universities using the Physics & Everyday Thinking curriculum,” V. K. Otero and K. E. Gray, Phys. Rev. ST Phys. Educ. Res. 4, 020104 (2008). In surveys of 182 students in nine courses at multiple institutions that used the Physics & Everyday Thinking curriculum (or a variant of it), “expert-like” attitudes on the CLASS instrument (Ref. 89) showed significant increases from pre- to post-instruction. This was in striking contrast to the findings of most other courses previously surveyed with the CLASS or similar instruments. (E)


IX. CONCLUSIONS

In a very real sense, methods for active-learning instruction in physics have been under development in the US for more than 130 years. As we have seen, there is a large body of evidence that demonstrates that these methods, in their most modern versions, offer potential for significantly improved learning in comparison to traditional lecture-based instruction in college-level physics courses. The literature we have identified has shown that the methods are very diverse, incorporating techniques such as real-time data logging, Socratic “guided inquiry,” interactive computer simulations, and structured problem-solving. These methods strongly encourage learning from peers, emphasize rapid feedback, and guide students to express and reflect on their own reasoning processes. Some of the individual techniques might be helpful in traditional instructional environments. However, superior learning gains have been clearly and repeatedly demonstrated only in contexts explicitly based on research into student learning, in which most of the “common characteristics” cited in the Introduction and in Sec. V are utilized in an integrated fashion. These characteristics include (1) guiding instruction according to students’ pre-instruction knowledge state as revealed through research on student learning; (2) eliciting and addressing students’ ideas; (3) encouraging students to figure things out for themselves; (4) engaging in diverse problem-solving activities during class time; (5) requiring students to express their reasoning explicitly; (6) having students work together in small groups; (7) providing rapid feedback to students; (8) emphasizing qualitative and conceptual reasoning; (9) posing problems in a wide variety of
contexts and representations; (10) incorporating use of actual physical systems in problem solving; (11) incorporating student reflection on their problem-solving practice; (12) emphasizing the linking of concepts into well-organized hierarchical structures; and (13) integrating both appropriate content and appropriate behaviors.

ACKNOWLEDGMENTS

We appreciate the valuable comments of several colleagues on an earlier version of this manuscript. We are particularly grateful to Sarah McKagan for her very thorough and careful review, and for suggestions that led to numerous improvements in the paper.

Rosse Telescope. In 1845 William Parsons, the Third Earl of Rosse, put the largest telescope of the nineteenth century into operation on his family estate in Birr in central Ireland. The four-ton, six-ft diameter speculum metal mirror was cast and figured by the Earl (1800-1877), who also designed the telescope. The instrument, with a focal length of about 60 ft, was used for visual observations of nebula, which were then drawn, quite accurately, by hand. The telescope is still in operation, but with a lighter, aluminum mirror that is coated with bronze to give the same reflectivity as the original mirror. Electric motors now move the telescope tube about instead of the five men who originally turned capstans. The picture was taken on a typical, slightly rainy day in September 1999. (Notes and photograph by Thomas B. Greenslade, Jr., Kenyon College)