RESOURCE LETTER

Resource Letter ALIP–1: Active-Learning Instruction in Physics

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This Resource Letter provides a guide to the literature on research-based active-learning instruction in physics. These are instructional methods that are based on, assessed by, and validated through research on the teaching and learning of physics. They involve students in their own learning more deeply and more intensely than does traditional instruction, particularly during class time. The instructional methods and supporting body of research reviewed here offer potential for significantly improved learning in comparison to traditional lecture-based methods of college and university physics instruction. We begin with an introduction to the history of active learning in physics in the United States, and then discuss some methods for and outcomes of assessing pedagogical effectiveness. We enumerate and describe common characteristics of successful active-learning instructional strategies in physics. We then discuss a range of methods for introducing active-learning instruction in physics and provide references to those methods for which there is published documentation of student learning gains.
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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, in ways we shall explicitly identify. Interest in and use of these instructional methods in the United States have grown dramatically over the past 25 years, driven by a large and continually expanding research base that validates their effectiveness. There is a substantial body of evidence that demonstrates that these methods, in their most modern form, offer potential for significantly improved learning in comparison to traditional lecture-based methods in college and university physics instruction. 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 end-of-chapter problems can be said to be engaged in learning activities, these do not—by themselves, or even together—satisfy the criteria specified above.)

Although one might adopt the three characteristics as a minimal, if perhaps sufficient definition for "active-learning instruction in physics," we believe that they do not provide an adequate description. Decades of research and practice have demonstrated that methods that meet the three cited criteria also share a substantially larger group of common characteristics, although in varying proportions and in many and diverse formats. We list those common characteristics here and, in Sec. V, describe them in more detail along with citations to relevant references in this Resource Letter.

Research-based active-learning instructional methods in physics, as defined in this Resource Letter, share most or all of the following characteristics:

(a) Instruction is informed and explicitly guided by research regarding students' pre-instruction knowledge state and learning trajectory, including:
  (1) Specific learning difficulties related to particular physics concepts;
  (2) Specific ideas and knowledge elements that are potentially productive and useful;
  (3) Students' beliefs about what they need to do in order to learn;
  (4) Specific learning behaviors;
  (5) General reasoning processes.
(b) Specific student ideas are elicited and addressed.
(c) Students are encouraged to "figure things out for themselves."
(d) Students engage in a variety of problem-solving activities during class time.
(e) Students express their reasoning explicitly.
(f) Students often work together in small groups.
(g) Students receive rapid feedback in the course of their investigative or problem-solving activity.
(h) Qualitative reasoning and conceptual thinking are emphasized.
(i) Problems are posed in a wide variety of contexts and representations.
(j) Instruction frequently incorporates use of actual physical systems in problem solving.
(k) Instruction recognizes the need to reflect on one's own problem-solving practice.
(l) Instruction emphasizes linking of concepts into well-organized hierarchical structures.
(m) Instruction integrates both appropriate content (based on knowledge of students' thinking) and appropriate behaviors (requiring active student engagement).

Active-learning instructional methods are similar to other instructional methods in that they are ultimately intended to give students a solid conceptual foundation in physics, and to aid them to reason effectively and succeed at problem-solving tasks. However, they differ from traditional lecture-based methods in putting far greater emphasis on engaging students in a variety of specific classroom activities. Many of these active-learning methods engage students in directly finding answers through hands-on laboratory activities. They aim to generate, through interactions with peers and instructors, understandings that eventually match those of physicists. Some methods use technological tools; some make extensive use of mathematical modeling; some do neither. Sometimes students interact with the physical world indirectly, through the medium of videos of physical events or computer simulations that are analyzed and modeled by student-friendly software. Simple observational experiments using no special educational technology form the foundation of other instructional materials. Some make use only of paper and pencil, yet still engage students in learning activities that are demonstrably more effective than traditional lectures and homework.

Active-learning instructional methods strongly encourage learning from peers, emphasize rapid feedback, and guide students to express and reflect on their own reasoning processes. 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 $\approx 20\%$ 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 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.

Section III—Historical perspective that traces the development of active-learning physics instruction in the U.S. from its origins during the 1800s.

Section IV—Research-based assessment methods and assessment outcomes for active-learning instruction.

Section V—Common characteristics of active-learning instructional strategies in physics.

Section VI—Active-learning instructional materials for introductory algebra- and calculus-based physics courses: (a) lecture-based; (b) laboratory-based; (c) hybrid lecture-lab materials; (d) tutorials and problem-solving worksheets; (e) computer simulations and intelligent tutors.

Section VII—Active-learning instructional materials for intermediate- and advanced-level physics courses.

Section VIII—Active-learning instructional materials for courses targeted at preservice teachers and nonscience students.

Section IX—Conclusions.

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.

American Physical Society Forum on Education Newsletter: <http://www.aps.org/units/fed/newsletters/index.cfm>

Journal of Physics Teacher Education Online: <http://www.phy.ilstu.edu/jpteo/>

Physical Review Special Topics - Physics Education Research: <http://prst-per.aps.org/>. Generally addressed to researchers.

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:

2. **Physics Education Research Conference**, AIP Conference Proceedings: 2003, Vol. **720**; 2004, Vol. **790**; 2005, Vol. **818**; 2006, Vol. **883**; 2007, Vol. **951**; 2008, Vol. **1064**; 2009, Vol. **1179**; 2010, Vol. **1289**; 2011, Vol. **1413**. (E-A)

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 issues. Part of the "Physics Suite" series. (E)
6. **Applying Cognitive Science to Education**, F. Reif (MIT Press, Cambridge, MA, 2008). Compiles and systematizes a lifetime of work devoted to exploring the general principles of learning in science, with particular emphasis on active-learning instruction in physics. (I)

D. General articles

7. "Millikan Lecture 1990: What we teach and what is learned—Closing the gap," L. C. McDermott, Am. J. Phys. **59**, 301–315 (1991). An influential summary of more than 15 years' research experience in developing active-learning instructional materials. (E)
8. "Millikan Lecture 1994: Understanding and teaching important scientific thought processes," F. Reif, Am. J. Phys. **63**, 17–32 (1995). Contains concise discussions of many key principles Reif introduced, including qualitative reasoning strategies, hierarchical knowledge structures, explicit problem-solving strategies, students' beliefs about the nature of physics learning, and the importance of rapid feedback. (E)
9. "Millikan Lecture 1995: Do they just sit there? Reflections on helping students learn physics," D. Zollman, Am. J. Phys. **64**, 114–119 (1996). Emphasizes the role of technology in active-learning physics instruction, with a particular focus on interactive video. (E)
10. "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," R. R. Hake, Am. J. Phys. **66**, 64–74 (1998). Widely cited analysis of test data from thousands of students in dozens of courses indicating the superior effectiveness of active-learning instruction in physics ("interactive engagement") in comparison to traditional, lecture-based methods. (I)
11. "Resource Letter: PER-1: Physics Education Research," L. C. McDermott and E. F. Redish, Am. J. Phys. **67**, 755–767 (1999). Extensive collection of research 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)

12. “Teaching physics: Figuring out what works,” E. F. Redish and R. N. Steinberg, Phys. Today **52**(1), 24–30 (1999). Clear and accessible overview of research-based instructional methods in physics with a review of evidence for effectiveness. (E)

13. “Millikan Lecture 1999: The workplace, student minds, and physics learning systems,” A. Van Heuvelen, Am. J. Phys. **69**, 1139–1146 (2001). Discussion of several key principles of active-learning instruction focusing on how students can become better at solving real-world problems through active learning and working in teams, and by using multiple representations in widely varied contexts. (E)

14. “Recent advances in classroom physics,” B. A. Thacker, Rep. Prog. Phys. **66**, 1833–1864 (2003). Discussion and comprehensive collection of references on recent developments in physics instruction, including active-learning instructional methods. (E-I)

15. “Transforming physics education,” C. Wieman and K. Perkins, Phys. Today **58**(11), 36–41 (2005). Brief overview of recent research with emphasis on interactive lectures and the University of Colorado Interactive Science Simulations; see Ref. 145. (E)

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)

17. *E & M TIPERs (“Tasks Inspired by Physics Education Research”)*: <http://tycphysics.org/tipers.htm>. Also available in printed form: **E & M TIPERs: Electricity and Magnetism Tasks (Inspired by Physics Education Research)**, C. J. Hieggelke, D. P. Maloney, S. E. Kanim, and T. L. O’Kuma (Pearson Prentice-Hall, Upper Saddle River, NJ, 2006). A large collection of exercises that strongly emphasize interpretation of diverse diagrammatic representations. (E)

18. *Explorations in Physics, Dickinson College*: <http://physics.dickinson.edu/~eip_web/eip_homepage.html>. Active-learning materials for non-science majors. (E)

19. *Humanized Physics Project*: <http://physics.doane.edu/hpp>; related materials from a predecessor project are at <http://www.phys.ttu.edu/~batcam/Courses.html>. Large collection of instructional modules emphasizing biological and physiological applications, targeted at the algebra-based general physics course. (E)

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

21. *Internet Computer Coaches for Introductory Physics Problem Solving, University of Minnesota*: <http://groups.physics.umn.edu/physed/prototypes.html>. Interactive programs that provide extensive feedback and hints to coach students in the use of an expert-like problem-solving framework. (E)

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

23. *Paradigms in Physics, Oregon State University*: <http://www.physics.oregonstate.edu/portfolioswiki/>. Comprehensive set of upper-level materials for a restructured physics majors’ curriculum. (E-I)

24. *PER User’s Guide*: <http://perusersguide.org>. Comprehensive and encyclopedic collection of links to research-based instructional materials in physics, accompanied by many related resources. (E-I)

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

26. *Physics Education Research Central*: <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/jitt/sampler/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)

28. *Physics Problems, University of Maryland*: <http://www.physics.umd.edu/perg/problems.htm>. Large collection of problems in a variety of formats on diverse topics. (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)

33. *RELATE Mechanics WIKI Home*: <http://scripts.mit.edu/~srayyan/PERwiki/>. An experimental physics textbook using the “Modeling Applied to Problem Solving” (MAPS) Pedagogy. (E)

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)

35. **Six Ideas That Shaped Physics [Units C, E, N, Q, R, and T], Second Edition**, T. Moore (McGraw-Hill, New York, 1997–2009): <http://www.physics.pomona.edu/sixideas/siimtc.html>. Includes an online instructor's manual for the published set of highly original printed texts. (E)
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)
37. *University of Maryland Physics Education Research Group*. (a) *Scientific Community Labs*: <http://umdperg.pbworks.com/w/page/10511229/FrontPage>. Materials designed to simulate participation in a real scientific community. (b) *Thinking Problems in Math Physics*: <http://umdperg.pbworks.com/w/page/34231836/Methods-of-Mathematical-Physics>. Collection of research-based instructional materials in mathematical physics. (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.

39. **Aims and Methods of the Teaching of Physics**, C. K. Wead [Circulars of Information of the Bureau of Education, No. 7–1884] (Government Printing Office, Washington, [D.C.,] 1884). The inductive method is discussed on pp. 117–122. Also includes extensive coverage of analogous methods used in contemporary physics instruction in Europe. (E)

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."

40. **A Textbook on the Elements of Physics for High Schools and Academies**, A. P. Gage (Ginn, Heath, and Co., Boston, 1882). Perhaps the first U.S. active-learning physics text. (E)
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 formulations, and use of "cookbook"-style instructional laboratories with highly prescriptive lists of steps and procedures designed to verify known principles. (A contemporary curriculum 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.

45. "Reflections on a decade of grade-school science," J. Griffith and P. Morrison, Phys. Today **25**(6), 29–34 (1972). Emphasizes the importance of students engaging in "the process of inquiry and investigation" to build understanding of scientific concepts. (E)

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.

46. "The Science Curriculum Improvement Study," R. Karplus, J. Res. Sci. Teach. **2**, 293–303 (1964). Describes the early implementation of Karplus's learning cycle. (E)

47. "Science teaching and the development of reasoning," R. Karplus, J. Res. Sci. Teach. **14**, 169–175 (1977). Discussion of the psychological and pedagogical principles underlying the Science Curriculum Improvement Study (SCIS), including the learning cycle and the work of Piaget. (E)

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.

48. Workshop on Physics Teaching and the Development of Reasoning, F. P. Collea, R. G. Fuller, R. Karplus, L. G. Paldy, and J. W. Renner (AAPT, Stony Brook, NY, 1975). Available online at <http://digitalcommons.unl.edu/karplusworkshop/>. (E)

49. "Can physics develop reasoning?" R. G. Fuller, R. Karplus, and A. E. Lawson, Phys. Today **30**(2), 23–28 (1977). Description of pedagogical principles of the workshop. (E)

50. College Teaching and the Development of Reasoning, edited by R. G. Fuller, T. C. Campbell, D. I. Dykstra, Jr., and S. M. Stevens (Information Age Publishing, Charlotte, NC, 2009). Includes reprints of most of the workshop materials. In the context of discussion of Piaget's work, also contains summary descriptions of some of the active-learning instructional methods in physics developed since the late 1970s. (E)

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)

53. "Combined physics course for future elementary and secondary school teachers," L. C. McDermott, Am. J. Phys. **42**, 668–676 (1974). Describes an inquiry-based laboratory course in which prospective elementary and high school teachers work together. (E)

54. "Cultivating the capacity for formal reasoning: Objectives and procedures in an introductory physical science course," A. B. Arons, Am. J. Phys. **44**, 834–838 (1976). Focuses on teaching strategies for improving students' reasoning skills. (E)

55. The Various Language: An Inquiry Approach to the Physical Sciences, A. Arons (Oxford University Press, New York, 1977). A hybrid text and activity guide for a college-level course; provides extensive questions, hints, and prompts. The original model for **Physics by Inquiry** (Ref. 164). (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.

56. "Orientation for the new teaching assistant—A laboratory based program," J. Spears and D. Zollman, Am. J. Phys. **42**, 1062–1066 (1974). An active-learning approach to the education of graduate teaching assistants that helped them contrast inquiry-based learning to "cookbook-style" instruction. (E)

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)

58. "Spontaneous reasoning in elementary dynamics," L. Viennot, Eur. J. Sci. Educ. **1**, 205–221 (1979). Provides an analysis of high school and college students' "spontaneous" ideas regarding forces in a variety of physical systems. (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.

61. "The initial knowledge state of college physics students," I. A. Halloun and D. Hestenes, Am. J. Phys. **53**, 1043–1055 (1985). Development and administration of a research-based test of student understanding revealed the ineffectiveness of traditional instruction in altering college physics students' mistaken ideas about Newtonian mechanics. (E)

62. "Common sense concepts about motion," I. A. Halloun and D. Hestenes, Am. J. Phys. **53**, 1056–1065 (1985). Comprehensive and systematic inventory of students' ideas regarding motion. (E)

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.

64. "Learning to think like a physicist: A review of research-based instructional strategies," A. Van Heuvelen, Am. J. Phys. **59**, 891–897 (1991). Further development of active-learning instruction in physics with a particular emphasis on the need for qualitative analysis and hierarchical organization of knowledge. Explicitly builds on the work of many of the authors cited above. (E)

65. "Overview, Case Study Physics," A. Van Heuvelen, Am. J. Phys. **59**, 898–907 (1991). Influential paper that discussed methods for making systematic use in active-learning physics instruction of multiple representations such as graphs, diagrams, and verbal and mathematical descriptions. (E)

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.

66. "Tools for scientific thinking—Microcomputer-based laboratories for physics teaching," R. K. Thornton, Phys. Educ. **22**, 230–238 (1987). Describes initial steps in 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)

68. "Calculus-based physics without lectures," P. W. Laws, Phys. Today **44**(12), 24–31 (1991). Describes the principles and origins of the Workshop Physics Project at Dickinson College (Ref. 125), begun in collaboration with Thornton and Sokoloff in 1986. (E)

69. "Computer supported lab-work in physics education: Advantages and problems," E. Sassi, in **Physics Teacher Education Beyond 2000**, edited by R. Pinto and S. Surinach (Elsevier, Paris, 2001), pp. 57–64; also available at <http://www.dsf.unina.it/Gener/did/drafts/wp6/papers/paper_lecture_final.doc>. Explores the introduction of real-time data collection tools in Europe. (E)

70. "Effective learning environments for computer supported instruction in the physics classroom and laboratory," R. K. Thornton, in **Connecting Research in Physics Education with Teacher Education**, edited by M. Vicentini and E. Sassi (International Commission on Physics Education, 2008); <http://web.phys.ksu.edu/icpe/Publications/teach2/Thornton.pdf>. Recent review that traces historical developments. Emphasizes that pedagogical benefits of the tools largely disappear if they are used in a traditional "equation-verification" context instead of focusing on conceptual understanding. (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.

73. "Assessing student learning of Newton's laws: The Force and Motion Conceptual Evaluation and the evaluation of active learning laboratory and lecture curricula," R. K. Thornton and D. R. Sokoloff, Am. J. Phys. **66**, 338–352 (1998). The FMCE has a particularly strong emphasis on graphical representations and ability to transform between and among representations. (E)

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, T. L. 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)

78. "Do they stay fixed?" G. E. Francis, J. P. Adams, and E. J. Noonan, Phys. Teach. **36**, 488–490 (1998). Superior learning gains (compared to traditional instruction) resulting from using **Tutorials in Introductory Physics** (Ref. 136) were retained up to a period of 3 years after instruction. (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)

83. "Addressing student difficulties in applying a wave model to the interference and diffraction of light," K. Wosilait, P. R. L. Heron, P. S. Shaffer, and L. C. McDermott, Am. J. Phys. **67**(S1), S5–S15 (1999). Detailed discussion of how knowledge of students' specific learning difficulties enabled development of improved curricular materials in physical optics. (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.

84. "Conceptual Dynamics: Following changing student views of force and motion," R. K. Thornton, in **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 Conference Proceedings **399** (AIP, Woodbury, New York, 1997), pp. 241–266. Analyzes changes in student responses over time to the Force and Motion Conceptual Evaluation diagnostic test (Ref. 73). (E)

85. "How do you hit a moving target? Addressing the dynamics of students' thinking," D. E. Meltzer, in **2004 Physics Education Research Conference**, edited by

J. Marx, P. R. L. Heron, and S. Franklin, AIP Conference Proceedings **790** (AIP, Melville, New York, 2005), pp. 7–10. Discussion of possible future directions for research on student learning trajectories. (I)

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)

87. "Student expectations in introductory physics," E. F. Redish, J. M. Saul, and R. N. Steinberg, Am. J. Phys. **66**, 212–224 (1998). Introduced the Maryland Physics Expectations Survey (MPEX), the first widely used instrument for assessing student attitudes and beliefs in college-level physics courses. (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)

89. "New instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey," W. K. Adams, K. K. Perkins, N. S. Podolefsky, M. Dubson, N. D. Finkelstein, and C. E. Wieman, Phys. Rev. ST Phys. Educ. Res. **2**, 010101 (2006). Describes a sophisticated and rigorous development process that produced a new instrument for assessing students' beliefs and expectations in physics. (I)

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).

91. "Expert and novice performance in solving physics problems," J. Larkin, J. McDermott, D. P. Simon, and H. A. Simon, Science **208**, 1335–1342 (1980). Describes research on "chunking" and "compiling" of concepts and how these processes relate to expert practice in physics problem solving. (I)

92. "Implications of cognitive studies for teaching physics," E. F. Redish, Am. J. Phys. **62**, 796–803 (1994). Influential paper that delineated general cognitive principles that underlie a great deal of present-day research in active-learning instruction in physics. (E)

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.

94. "Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics," J. Clement, J. Res. Sci. Teach. **30**, 1241–1257 (1993). (E)

95. "Teaching science for understanding," J. A. Minstrell, in **Toward the Thinking Curriculum: Current Cognitive Research**, edited by L. B. Resnick and L. E. Klopfer (Association for Supervision and Curriculum Development, Alexandria, VA, 1989), pp. 129–149. (E)

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 Etkina 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.

96. "Using qualitative problem-solving strategies to highlight the role of conceptual knowledge in solving problems," W. J. Leonard, R. J. Dufresne, and J. P. Mestre, Am. J. Phys. **64**, 1495–1503 (1996). Students initiated problem solving by first writing a "strategy," which involved stating and justifying the major principles or concepts needed to solve a problem along with a procedure for applying them. (E)

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.

97. "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving," P. Heller, R. Keith, and S. Anderson, Am. J. Phys. **60**, 627–636 (1992). Describes "Cooperative Group Problem Solving" in which student groups are guided to implement a step-by-step general problem-solving strategy in which physics principles and appropriate representations are explicitly expressed and applied. (E)

98. "Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups," P. Heller and M. Hollabaugh, Am. J. Phys. **60**, 637–644 (1992). Describes "context-rich" problems, discussed further in Ref. 124. (E)

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:

99. "Cognition of learning physics," J. Larkin, Am. J. Phys. **49**, 534–541 (1981). Discussed the use of multiple representations as a characteristic of expert problem solvers. (I)

100. "Toward a modeling theory of physics instruction," D. Hestenes, Am. J. Phys. **55**, 440–454 (1987). Provided a theoretical framework for the development of Modeling Instruction (Refs. 132–135). (I-A)

101. "A view from physics," L. C. McDermott, in **Toward a Scientific Practice of Science Education**, edited by

M. Gardner, J. G. Greeno, F. Reif, A. H. Schoenfeld, A. diSessa, and E. Stage (L. Erlbaum, Hillsdale, NJ, 1990), pp. 3–30. Succinctly outlines the particular utility of multiple representations in physics education. (E)

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. Psillos, P. Kariotoglou, V. Tselfes, 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

104. **Peer Instruction: A User's Manual**, E. Mazur (Prentice Hall, Upper Saddle River, NJ, 1997). Peer Instruction is a method of interactive lecturing; short segments of a lecture are interspersed with students working collaboratively to answer qualitative, conceptual multiple-choice questions ("ConcepTests"). Provides an overview of the method and a large collection of ConcepTests. (E)

105. "Peer Instruction: Ten years of experience and results," C. H. Crouch and E. Mazur, Am. J. Phys. **69**, 970–977 (2001). Detailed documentation of improved student learning in physics lecture courses at Harvard that were based on Peer Instruction. (E)

106. "Transforming the lecture-hall environment: The fully interactive physics lecture," D. E. Meltzer and K. Manivannan, Am. J. Phys. **70**, 639–654 (2002). Review of active-learning instruction in physics and description of the "fully" interactive lecture. This variant of Peer

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/>. (E)

107. "Designing effective questions for classroom response system teaching," I. D. Beatty, W. J. Gerace, W. J. Leonard, and R. J. Dufresne, Am. J. Phys. **74**, 31–39 (2006). Provides detailed strategies for designing effective questions in a "question-driven" instruction approach. Instruction focuses on the use of a classroom response system to pose, collect answers for, and discuss carefully designed questions. (E)

108. "Peer Instruction: Engaging students one-on-one, all at once," C. H. Crouch, J. Watkins, A. P. Fagen, and E. Mazur, in **Research-Based Reform of University Physics**, edited by E. F. Redish and P. J. Cooney (AAPT, College Park, MD, 2007), Reviews in PER Vol. 1, <http://www.per-central.org/document/ServeFile.cfm?ID=4990>. Extensive and detailed discussion of Peer Instruction and the research studies that demonstrate its efficacy. (E)

109. "Testing a new voting machine question methodology," N. W. Reay, P. Li, and L. Bao, Am. J. Phys. **76**, 171–178 (2008). Describes another method for designing interactive question sequences to be used with classroom response systems, and provides data that support the effectiveness of the method. (E)

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)

111. "Using interactive lecture demonstrations to create an active learning environment," D. R. Sokoloff and R. K. Thornton, Phys. Teach. **35**, 340–347 (1997). Describes ILDs with observations of learning gains as high as 90% of maximum possible gain. (E)

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

112. "Real-time data display, spatial visualization ability, and learning force and motion concepts," M. Kozhevnikov and R. Thornton, J. Sci. Educ. Tech. **15**, 111–132 (2006). Student performance on standard tests of spatial visualization ability improved after participating in Interactive Lecture Demonstrations and active-learning laboratories. See also Ref. 70. (I)

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*

114. Matter & Interactions, Third Edition; Vol. 1, Modern Mechanics and **Vol. 2, Electric and Magnetic Interactions**, R. W. Chabay and B. A. Sherwood (Wiley, New York, 2010); E & M simulations: <http://www4.ncsu.edu/~rwchabay/emimovies>. Integrates classical and modern physics with a strong emphasis on microscopic models. Interspersed throughout with conceptual questions, exercises using computer modeling, and activities using simple physical equipment. (E)

115. "Matter & Interactions," R. Chabay and B. Sherwood, in **Research-Based Reform of University Physics**, edited by E. F. Redish and P. J. Cooney (AAPT, College Park, MD, 2007), Reviews in PER Vol. 1, <http://www.per-central.org/document/ServeFile.cfm?ID=4989>. Extensive discussion of the curriculum and its design principles; includes a survey of student-learning data that show outcomes superior to those from traditional instruction. (E)

116. "Tale of two curricula: The performance of 2000 students in introductory electromagnetism," M. A. Kohlmyer, M. D. Caballero, R. Catrambone, R. W. Chabay, L. Ding, M. P. Haugan, M. J. Marr, B. A. Sherwood, and M. F. Schatz, Phys. Rev. ST Phys. Educ. Res. **5**, 020105 (2009). Description of careful studies documenting improved student learning, as well as better total retention of conceptual material than traditional instruction more than 2 years after instruction had ended. (E)

B. Materials primarily for the laboratory

1. *Socratic Dialog-Inducing Labs*

117. "Socratic pedagogy in the introductory physics laboratory," R. R. Hake, Phys. Teach. **30**, 546–552 (1992). "SDI" labs (Ref. 63) are designed to promote mental construction of concepts through conceptual conflict, analysis using multiple representations, peer discussion, and Socratic dialogue with instructors. Curricular materials are archived at <http://www.physics.indiana.edu/~sdi/>. (E)

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)

119. "Constructing student knowledge in science," R. F. Tinker and R. K. Thornton, in **New Directions in Educational Technology [Volume 96 of NATO ASI Series on Computer and Systems Sciences]**, edited by Eileen Scanlon and Tim O'Shea (Springer-Verlag, Berlin, 1992), pp. 153–170. Explicit discussion of the ways technology can be used to enable inquiry-based learning, set in the context of the Tools for Scientific Thinking project. (E)

120. "Learning physics concepts in the introductory course: Microcomputer-based Labs and Interactive Lecture Demonstrations," R. K. Thornton, in **Conference on the Introductory Physics Course**, edited by J. Wilson (Wiley, New York, 1997), pp. 69–85. Reviews research showing increased learning gains using technology-based active-learning methods. (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)

122. "*RealTime Physics*: Active learning labs transforming the introductory laboratory," D. R. Sokoloff, P. W. Laws, and R. K. Thornton, Eur. J. Phys. **28**, S83–S94 (2007). Gives description of and guiding principles for **RealTime Physics**, as well as 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)

C. 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)

126. "Millikan Lecture 1996: Promoting active learning based on physics education research in introductory physics courses," P. W. Laws, Am. J. Phys. **65**, 14–21 (1997). Overview with examples of **Workshop Physics**, with discussion of some general issues related to active-learning instruction in physics. (E)

127. "Women's responses to an activity-based introductory physics program," P. W. Laws, P. J. Rosborough, and F. J. Poodry, 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)

3. *Investigative Science Learning Environment: Physics Active Learning Guide*

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)

129. "Investigative Science Learning Environment – A science process approach to learning physics," E. Etkina and A. Van Heuvelen, in **Research-Based Reform of University Physics**, edited by E. F. Redish and P. J. Cooney (AAPT, College Park, MD, 2007), Reviews in PER Vol. 1, <http://www.per-central.org/document/ServeFile.cfm?ID=4988>. Detailed review of the design principles of the **Physics Active Learning**

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

4. *SCALE-UP*

130. "The Student-Centered Activities for Large Enrollment Undergraduate Programs (SCALE-UP) project," R. J. Beichner, J. M. Saul, D. S. Abbott, J. J. Morse, D. L. Deardorff, R. J. Allain, S. W. Bonham, M. H. Dancy, and J. S. Risley, in **Research-Based Reform of University Physics**, edited by E. F. Redish and P. J. Cooney (AAPT, College Park, MD, 2007), Reviews in PER Vol. 1, <http://www.per-central.org/document/ServeFile.cfm?ID=4517>. Home page is at <http://scaleup.ncsu.edu/>. SCALE-UP is a method of structuring and conducting interactive classes combined with curricular materials specially designed for that purpose. (E)

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)

133. "Modeling instruction in mechanics," I. A. Halloun and D. Hestenes, Am. J. Phys. **55**, 455–462 (1987). Description of an early form of Modeling Instruction; students' test scores are compared to those in traditional classes. (E)

134. "A modeling method for high school physics instruction," M. Wells, D. Hestenes, and G. Swackhamer, Am. J. Phys. **63**, 606–619 (1995). Review of pedagogical principles and descriptions of typical classes using the Modeling method. (E)

135. "Modeling theory applied: Modeling Instruction in introductory physics," E. Brewe, Am. J. Phys. **76**, 1155–1160 (2008). A concise "user's guide" for applying modeling instruction in college physics courses. (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)

138. "Replicating and understanding successful innovations: Implementing tutorials in introductory physics," N. D. Finkelstein and S. J. Pollock, Phys. Rev. ST Phys. Educ. Res. **1**, 010101 (2005). This close replication of the implementation of Tutorials employed at the University of Washington yielded virtually identical student learning gains, providing an unusually clear-cut validation of the effectiveness of the curricular materials when they were used in a manner faithful to that intended by their developers. (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*

140. **Activity-Based Tutorials: Vol. 1, Introductory Physics; Vol. 2, Modern Physics [The Physics Suite]**, M. C. Wittmann, R. N. Steinberg, E. F. Redish, and the University of Maryland Physics Education Research Group (Wiley, New York, 2004). Older versions are available (password-protected) at [Vol. 1:] <http://www.physics.umd.edu/perg/abp/abptutorials/tutlist.htm> and [Vol. 2:] <http://www.physics.umd.edu/perg/qm/qmcourse/NewModel/qmtuts.htm>. These guided-inquiry worksheets are inspired by and modeled on **Tutorials in Introductory Physics** (Ref. 136). (E)

141. "Comparing three methods for teaching Newton's third law," T. I. Smith and M. C. Wittmann, Phys. Rev. ST Phys. Educ. Res. **3**, 010205 (2007). Students' performance on Newton's third-law questions from the FMCE (Ref. 73) improved significantly after using relevant tutorials from either **Tutorials in Introductory**

Physics, **Activity-Based Tutorials**, or **Open-Source Tutorials** (Ref. 142). Students who used **Open-Source Tutorials** had higher gains than those who used either of the other two tutorials. (E)

142. **Tutorials in Physics Sense-Making (Open-Source Tutorials)**. Individual tutorials: <http://umdperg.pbworks.com/w/page/10511239/Tutorials%20in%20Physics%20Sense-Making>; All materials: <http://www.spu.edu/depts/physics/tcp/tadevelopment.asp>. These tutorials are based on principles and methods discussed by Elby (Ref. 86). In addition to building students' conceptual understanding, they focus on strengthening physical intuition, developing understanding of scientific reasoning, and relating physics to everyday experience. The tutorials are accompanied by extensive instructor's materials including annotated videoclips. (E)

E. Computer simulations and intelligent tutors

1. *MasteringPhysics*

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*

144. "The Andes physics tutoring system: An experiment in freedom," K. VanLehn, B. van de Sande, R. Shelby, and S. Gershman, in **Advances in Intelligent Tutoring Systems [Studies in Computational Intelligence 308]**, edited by R. Nkambou, J. Bourdeau, and R. Mizoguchi (Springer-Verlag, Berlin, 2010), pp. 421–443. Andes is a highly sophisticated "intelligent tutor" that provides step-by-step help and guidance to students as they solve quantitative physics problems in an online environment. This paper provides a detailed description of its design principles and a survey of assessment data documenting student learning. The system itself is available at <http://www.andestutor.org/sets/>. (I)

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)

146. "When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment," N. Finkelstein, W. K. Adams, C. J. Keller, P. B. Kohl, K. K. Perkins, N. S. Podolefsky, S. Reid, and R. LeMaster, Phys. Rev. ST Phys. Educ. Res. **1**, 010103 (2005). Instruction on electric circuits using simulations yielded higher gains on a diagnostic test than did instruction using actual laboratory equipment. (E)

147. "Oersted Medal Lecture 2007: Interactive simulations for teaching physics: What works, what doesn't, and why," C. E. Wieman, K. K. Perkins, and W. K. Adams, Am. J. Phys. **76**, 393–399 (2008). Discussion of the design, underlying research principles, and applications of the simulations. (E)

148. "A study of educational simulations part I—Engagement in learning," W. K. Adams, S. Reid, R. LeMaster, S. B. McKagan, K. K. Perkins, M. Dubson, and C. E. Wieman, J. Interactive Learn. Res. **19**, 397–419 (2008); "A study of educational simulations part II—Interface design," W. K. Adams, S. Reid, R. LeMaster, S. B. McKagan, K. K. Perkins, M. Dubson, and C. E. Wieman, J. Interactive Learn. Res. **19**, 551–577 (2008). Detailed description of research and development process underlying creation of the simulations. Includes many insightful observations regarding pedagogical effectiveness of specific features and strategies. (A)

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 pretests, 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)

150. "Investigating student understanding in intermediate mechanics: Identifying the need for a tutorial approach to instruction," B. S. Ambrose, Am. J. Phys. **72**, 453–459 (2004). Discussion of research on which **Intermediate Mechanics Tutorials** are based, along with some student-learning data that demonstrate effectiveness of some of the materials. (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)

152. "Longer term impacts of transformed courses on student conceptual understanding of E&M," S. J. Pollock and S. V. Chasteen, in **2009 Physics Education Research Conference**, edited by M. Sabella, C. Henderson, and C. Singh, AIP Conference Proceedings **1179** (AIP, Melville, NY, 2009), pp. 237–240. Students in a course using research-based materials (Ref. 151) did significantly better on a diagnostic exam than students in the traditionally taught course. Also see

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

C. Optics

153. "Active learning in intermediate optics through concept building laboratories," M. F. Masters and T. T. Grove, Am. J. Phys. **78**, 485–491 (2010). Laboratory approach relying on direct confrontation of misconceptions through experimental tests of predictions. Materials available at <http://users.ipfw.edu/masters/Optics%20CCLI%20Project/optics_ccli_project.htm>. (E)

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)

155. "Student ideas regarding entropy and the second law of thermodynamics in an introductory physics course," W. M. Christensen, D. E. Meltzer, and C. A. Ogilvie, Am. J. Phys. **77**, 907–917 (2009). Provides evidence for effectiveness of some of the materials in introductory and sophomore-level courses. (E)

156. "Student understanding of basic probability concepts in an upper-division thermal physics course," M. E. Loverude, in **2009 Physics Education Research Conference**, edited by M. Sabella, C. Henderson, and C. Singh, AIP Conference Proceedings **1179** (AIP, Melville, NY, 2009), pp. 189–192. This and the following reference provide promising, albeit ambiguous, evidence of student learning gains in upper-level courses using the thermal physics curricular materials. (E)

157. "Investigating student understanding for a statistical analysis of two thermally interacting solids," M. E. Loverude, in **2010 Physics Education Research Conference**, edited by C. Singh, M. Sabella, and S. Rebello, AIP Conference Proceedings **1289** (AIP, Melville, NY, 2010), pp. 213–216. (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).

158. **Physlet® Quantum Physics: An Interactive Introduction to Quantum Theory**, M. Belloni, W. Christian, and A. Cox (Pearson Prentice Hall, Upper Saddle River, NJ, 2006). Physlets are computer applets that allow students to interact with graphical and diagrammatic representations of physical systems, yielding immediate feedback. Materials are also available at <http://www.compadre.org/quantum/search/browse.cfm?browse=Tutorial>, and are discussed in "Physlets for quantum mechanics," M. Belloni and W. Christian, Comput. Sci. Eng. **5**(1), 90–97 (2003). (E)

159. "Improving students' understanding of quantum mechanics," C. Singh, M. Belloni, and W. Christian, Phys. Today **59**(8), 43–49 (2006). Discussion of research on student learning in quantum mechanics, and of both the Physlet quantum-mechanics materials and the University of Pittsburgh Quantum Interactive Learning Tutorials (QuILTs); see <http://www.phyast.pitt.edu/~cls/quantum/>. (E)

160. "Reforming a large lecture modern physics course for engineering majors using a PER-based design," S. B. McKagan, K. K. Perkins, and C. E. Wieman, in **2006 Physics Education Research Conference**, edited by L. McCullough, L. Hsu, and P. Heron, AIP Conference Proceedings **883** (AIP, Melville, NY, 2007), pp. 34–37. Curricular materials are archived at <http://www.colorado.edu/physics/EducationIssues/modern/>. Content emphasizes reasoning development, model building, and real-world applications, and materials are designed for use with interactive-engagement instructional methods. (E)

161. "Interactive learning tutorials on quantum mechanics," C. Singh, Am. J. Phys. **76**, 400–405 (2008). A description of the development of the QuILTs (Ref. 159), including data reflecting student-learning gains after use of the materials. (E)

162. "Developing and researching PhET simulations for teaching quantum mechanics," S. B. McKagan, K. K. Perkins, M. Dubson, C. Malley, S. Reid, R. LeMaster, and C. E. Wieman, Am. J. Phys. **76**, 406–417 (2008). Detailed description of development and assessment of the University of Colorado quantum-mechanics simulations. (See Ref. 145.) (E)

163. "Transforming upper-division quantum mechanics: Learning goals and assessment," S. Goldhaber, S. Pollock, M. Dubson, P. Beale and K. Perkins, in **2009 Physics Education Research Conference**, edited by M. Sabella, C. Henderson, and C. Singh, AIP Conference Proceedings **1179** (AIP, Melville, NY, 2009), pp. 145–148. Discusses student learning outcomes in a transformed course, evaluated with a diagnostic instrument that focuses on conceptual learning; both strengths and weaknesses were revealed. Materials include tutorials, ConcepTests (Ref. 104), and many other resources, archived at <http://www.colorado.edu/sei/departments/physics_3220.htm>. (E)

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

167. “Using computers to create constructivist learning environments: Impact on pedagogy and achievement,” D. Huffman, F. Goldberg, and M. Michlin, J. Comput. Math. Sci. Teach. **22**(2), 151–168 (2003). Describes an implementation and assessment of the Constructing Physics Understanding (CPU) curriculum, targeted at nontechnical students. On-screen prompts guide students to make and test predictions with both real and simulated experiments. Description and sample activities are at <http://cpucips.sdsu.edu/web/cpu/>. (E)

C. Intuitive Quantum Physics

168. “Laboratory-tutorial activities for teaching probability,” M. C. Wittmann, J. T. Morgan, and R. E. Feeley, Phys. Rev. ST Phys. Educ. Res. **2**, 020104 (2006). Documents improved student learning of some probability concepts after use of the relevant tutorial from the “Intuitive Quantum Physics” project, archived at <http://umaine.edu/per/projects/iqp/>. (E)

D. Inquiry into Physical Science

169. **Inquiry into Physical Science: A Contextual Approach, Second Edition; Vol. 1, Global Warming; Vol. 2, Kitchen Science; Vol. 3, The Automobile**, R. Nanes (Kendall Hunt, Dubuque, IA, 2008). An inquiry-based activity guide that uses everyday contexts to initiate explorations into fundamental concepts in physics and chemistry. Targeted at preservice elementary teachers and other nontechnical students. (E)

170. “Inquiry-based course in physics and chemistry for preservice K-8 teachers,” M. E. Loverude, B. L. Gonzalez, and R. Nanes, Phys. Rev. ST Phys. Educ. Res. **7**, 010101 (2011). Detailed description of a course based on Ref. 169 that includes examples of activities and student-assessment questions, as well as data demonstrating improved student learning compared to traditional courses. Online auxiliary materials include curriculum and assessment samples, and grading rubrics. (E)

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 nonscience 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 and 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)

173. “Design principles for effective physics instruction: A case from physics and everyday thinking,” F. Goldberg, V. Otero, and S. Robinson, Am. J. Phys. **78**, 1265–1277 (2010). Detailed description of the design principles of **Physics & Everyday Thinking** with evidence for student learning gains; includes extensive analysis of actual student classroom transcripts to illustrate the principles in action. (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.

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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)