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ABSTRACT

The purpose of this resource letter is to provide an overview of research on the learning and teaching of physics. The references have been selected to meet the needs of two groups of physicists engaged in physics education. The first is the growing number whose field of scholarly inquiry is (or might become) physics education research. The second is the much larger community of physics instructors whose primary interest is in using the results from research as a guide for improving instruction. Following an Introduction in Section 1, the references have been organized into sections. Section 2 contains bibliographies and conference proceedings. Readers unfamiliar with the literature might find it helpful to begin with the reviews and overviews in Section 3. Section 4, the core of the Resource Letter, is devoted to empirical studies. The references in section 5 contain some theoretical perspectives. A few references from related fields are listed in Section 6. In Section 7 are examples of instructional materials that have been developed on the basis of findings from research and that also have been evaluated through documented use with students. Section 8 identifies some earlier Resource Letters that can provide useful background for readers interested in conducting research in physics education. Articles that fit into more than one category are cross-references. References within sections and subsections are mainly ordered chronologically, from earliest to latest. (Author)

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RL- PER1: Resource Letter on Physics Education Research

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The purpose of this Resource Letter is to provide an overview of research on the learning and teaching of physics. The references have been selected to meet the needs of two groups of physicists engaged in physics education. The first is the growing number whose field of scholarly inquiry is (or might become) physics education research. The second is the much larger community of physics instructors whose primary interest is in using the results from research as a guide for improving instruction.

I. INTRODUCTION

Experienced instructors recognize that in spite of their best efforts many students emerge from their study of physics with serious gaps in their understanding of important topics. In the last two decades, physicists have begun to approach this problem from a scientific perspective by conducting detailed systematic studies on the learning and teaching of physics. These investigations have included a wide variety of populations, ranging from young children to professional physicists. This Resource Letter is not intended to provide either a complete listing or a historical record of this research. Rather it is meant to contribute to the establishment of a research base that can serve as a resource for ongoing improvement and enrichment of student learning in physics.

Although some studies involving precollege students are included, the primary emphasis is at the university level. A major consideration in the selection of references has been their intellectual and physical accessibility to readers of the American Journal of Physics. Most of the articles cited are from the American Journal of Physics and The Physics Teacher. Additional sources include Physics Today, Computers in Physics, the Journal of Research in Science Teaching, Science Education, and a few other multidisciplinary journals on the teaching and learning of science and mathematics. Except for the International Journal of Science Education (formerly the European Journal of Science Education) and Physics Education, which are published in English and widely distributed, journals from outside of the United States are not included. References to conference proceedings and books have been kept to a minimum.

In the selection of references, careful consideration has been given not only to quality but also to breadth in objectives, methods, and subject matter. The emphasis is on systematic investigations of student learning. Thus, many insightful and inspirational reflections based on teaching experience have not been included. Descriptions of the development and implementation of innovative courses have not been cited unless they also expand our knowledge of how students learn. Also absent are articles in which the effectiveness of instruction is primarily assessed by the performance of students on traditional end-of-chapter problems, by their own assessment of their learning, or by how they (or their instructors) feel about an educational innovation. Choices have been made among similar studies by different investigators. When there are multiple papers by the same authors on similar topics, only the more readily available are cited.

The references have been organized into sections. Section II contains bibliographies and conference proceedings. Readers unfamiliar with the literature might find it helpful to begin with the reviews and overviews in Section III. Section IV, the core of the Resource Letter, is devoted to empirical studies. The references in Section V contain some theoretical perspectives. A few references from related fields are listed in Section VI. In Section VII are examples of instructional materials that have been developed on the basis of findings from research and that also have been evaluated through documented use with students. Section VIII identifies some earlier Resource Letters that can provide useful background for readers interested in conducting research in physics education. Articles that fit into more than one category are cross-referenced. For the most part, references within sections and subsections are ordered chronologically, from earliest to latest.

II. GENERAL REFERENCES

A. Bibliographies

There is an extensive literature on research in science education. Readers interested in exploring this literature should consult one or more of the following bibliographies.

1. *Research on students' conceptions in science: A bibliography*, P. Carmichael, *et al.*, Centre for Studies in Science and Mathematics Education, (University of Leeds, Leeds UK, 1990). This bibliography should be useful to readers who are interested in learning about studies with precollege students.
2. *Bibliography: Students' Alternative Frameworks and Science Education*, 4th Edition, H. Pfundt and R. Duit,

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(IPN Reports-in-Brief, Kiel Germany, 1994). This bibliography is also available on the Internet at the ftp site *ftp.topgun.idbsu.edu* in the directory /pub/plrnr in the files: *plr11mac.bin* and *plr12mac.bin* (Word for the Macintosh), or *plr11pc.doc* and *plr12.pc.doc* (Word for Windows).

Two additional bibliographies that focus on physics are also available on the same site.

3. D. I. Dykstra Jr., F. Monte, and S. Schroeder, Boise State University, filename: *plr03mac.bin* (Word 5.1 for the Macintosh), *plr03pc.doc* (Word for Windows).
4. D. Maloney, Indiana University - Purdue University, Fort Wayne, filename: *plr16mac.bin* (Word 5.1 for the Macintosh), *plr16pc.doc* (Word for Windows).

B. Conference Proceedings

Physics education research has been a major theme at several national and international conferences. Readers who would like to explore beyond the papers cited in this Resource Letter may wish to consult the published proceedings listed below.

5. *Research on Physics Education, Proceedings of the First International Workshop,* La Londe Les Maures, France, edited by G. Delacôte, A. Tiberghien and J. Schwartz, (Éditions du CNRS, Paris FR, 1983).
6. *Relating macroscopic phenomena to microscopic particles, Proceedings of an international seminar,* Utrecht, the Netherlands, Oct. 23-26, 1989, edited by P. L. Lijnse, P. Licht, W. de Vos and A. J. Waarlo, (CD-gbs Press, Utrecht NL, 1990).
7. *Research in Physics Learning: Theoretical Issues and Empirical Studies, Proceedings of an International Workshop,* Bremen, Germany, March 4-8, 1991, edited by R. Duit, F. Goldberg and H. Niedderer, (IPN, Kiel Germany, 1992).
8. *Conference on the Introductory Physics Course on the occasion of the retirement of Robert Resnick*, Troy, NY, May 20-23, 1993, edited by Jack Wilson, (John Wiley & Sons Inc., New York NY, 1997).
9. *The Changing Role of Physics Departments in Modern Universities: Proceedings of the International Conference on Undergraduate Physics Education (ICUPE),* College Park, MD, July 31-Aug. 3, 1996, edited by E. F. Redish and J. S. Rigden, AIP Conf. Proc. **399** (American Institute of Physics, Woodbury NY, 1997).

III. REVIEWS, OVERVIEWS, AND PERSPECTIVES

A number of reviews, overviews, and perspectives on research in physics education have been written by physicists. The articles below include extensive references and provide a good background for an initial study of the literature in this field.

10. "Research on conceptual understanding in mechanics," L. C. McDermott, Phys. Today **37**(7), 24-32 (1984). This article identifies critical elements of research on student understanding in physics and reviews the early research on conceptual and reasoning difficulties in mechanics.
11. "Scientific approaches to science education," F. Reif, Phys. Today **39**(11), 48-54 (1986). This article takes a more theoretical perspective than the one above.
12. "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 (Lawrence Erlbaum Associates, Hillsdale NJ, 1990) 3-30. This paper presents a broad review of research on conceptual understanding.
13. "Instructional design, cognition, and technology: Applications to the teaching of scientific concepts," F. Reif, J. Res. Sci. Teach. **24**:4, 309-324 (1987). This article presents a good overview of how cognitive science and educational theory can contribute to the design of effective instruction.
14. "Learning to think like a physicist: A review of research-based instructional strategies," A. Van Heuvelen, Am. J. Phys. **59**, 891-897 (1991). This article reviews research on student learning of physics with a focus on general issues such as knowledge representation and concept organization. Some instructional strategies are discussed.
15. "Research on problem solving: Physics," D. P. Maloney, in *Handbook of Research on Science Teaching and Learning*, edited by D. Gabel (MacMillan Publishing Company, New York NY, 1993) 327-354. This article provides a very detailed and comprehensive review of the extensive literature in education and cognitive science on the use of physics problems as a context for examining cognitive processes and approaches to problem solving.
16. "Teaching physics: Figuring out what works," E. F. Redish and R. N. Steinberg, Phys. Today, **52**(1), 24-30 (1999). This paper discusses research on improving instruction in engineering physics. The focus is on what has been learned about the teaching of concepts and about the attitudes that students bring to their study of physics.

Perspectives of research groups have appeared in published versions of the Millikan Award Lectures,[1] in the 1996 ICUPE Proceedings (see ref. 9), and in Guest Comments in the AJP. These also provide extensive lists of references.

17. "Millikan Lecture 1990: What we teach and what is learned — Closing the gap," L. C. McDermott, Am. J. Phys. **59**, 301-315 (1991).
18. "Millikan Lecture 1994: Understanding and teaching important scientific thought processes," F. Reif, Am. J. Phys. **63**, 17-32 (1995).
19. "Bridging the gap between teaching and learning: The role of research," L. C. McDermott, AIP Conf. Proc. **399**, 139-165 (1997). (See item [9].)

[1]The Robert A. Millikan Award recognizes "notable and creative contributions to the teaching of physics." This is an annual award of the AAPT (American Association of Physics Teachers).

20. "How can we help students acquire effectively usable physics knowledge?" F. Reif, AIP Conf. Proc. **399**, 179-195 (1997). (See item [9]).
21. "Guest comment: How we teach and how students learn — a mismatch?" L. C. McDermott, Am. J. Phys. **61**, 295-298 (1993).
22. "Who needs physics education research?" D. Hestenes, Am. J. Phys. **66**, 465-467 (1998).

Since many conceptual and reasoning difficulties identified among younger students are also common among undergraduates, familiarity with the pre-college literature is important for physicists who conduct research with students of any age. The two reviews below are concerned with student learning in high school.

23. "Pupils and paradigms: A review of literature related to concept development in adolescent science students," R. Driver and J. Easley, Studies in Sci. Educ. **5**, 61-84 (1978).
24. "Learning and instruction in pre-college physical science," J. Mestre, Phys. Today **44**(9), 56-62 (1991).

The information contained in the papers above is also useful for faculty who teach physics or physical science to K-12 teachers. An additional set of articles on the application of physics education research to the preparation of teachers can be found in the following on-line book.

25. *Connecting Research in Physics Education with Teacher Education,* edited by A. Tiberghien, E. L. Jossem, and J. Barojas. [*http://www.physics.ohio-state.edu/~jossem/ICPE/BOOKS.html*]

IV. EMPIRICAL STUDIES

In selecting the references for this section, we have been guided by several criteria that can be summarized as follows: (1) The focus is on the phenomenon being studied, which in this case is the learning of physics by students. (2) The research is conducted in a systematic manner. (3) The procedures are described in sufficient detail so that they can be replicated.

The primary consideration in all cases has been that the investigation be focused on the student as a learner, not on the instructor or on the material covered. The authors must show that they attempted to find out what students actually thought and explain how that information was determined. They should provide evidence that the investigation was conducted carefully and systematically. The authors should describe the context for the study, such as the physical setting, time frame, and the size and characteristics of the student population involved. If the response to instruction is being probed, it is necessary to note specific features of the course, including length, sequence of topics, and any special characteristics. Since in an educational framework results can be sensitive to environmental and contextual details, the completeness of the description is of considerable importance. Enough information should be given so that, under similar conditions, the experiment is reproducible. For this to be possible, the report of the research should include a thorough description of the instrument used to assess understanding, the degree of interaction between the student and the investigator, the depth of the probing, the form of the data obtained, and the method of analysis of the data. The authors should indicate awareness of possible weaknesses in the procedures and indicate that they have taken appropriate precautions.

The goals and the perspective of the investigators should be explicitly stated. These may influence both the design of the experiment and the interpretation of the results by the authors. The limits of applicability of the results should be made clear. The reader should be able to determine the degree to which the findings have general relevance and are not idiosyncratic.

In the selection of references, preference has been given to papers in which the approach and the rules of evidence are close to those traditional in the physics community. However, experiments in physics education differ in a number of respects from the idealization of a traditional physics experiment. Among the differences are: (1) a limited ability to identify and control all the variables, (2) the necessity of using a strongly interacting probe; and (3) the degree of quantification that is appropriate.

Classrooms, students, and teachers are all complex systems. Experiments with such systems involve many variables, some of which are unknown. It is difficult to determine the effect of past experience and cultural environment on students and teachers. The formal education of students prior to their enrollment in undergraduate courses may significantly affect how they interpret what is taught. As in traditional physics research, it is sometimes impossible to identify all the relevant variables or to perform a controlled experiment in which only a single variable is changed. (For example, experiments are not repeatable for individual quantum events.) Yet, both in physics education and in quantum physics, experience demonstrates that reliable and reproducible results can be obtained.

In an idealized physics experiment, an effort is made to ensure that the effect of a probe on the system that is being measured is small. However, it is not always possible to find such a probe, especially in quantum systems. In physics education research, weak coupling is not always desirable. For example, to learn what is really going on in the minds of students, the investigator often must interact strongly with them.

The level of quantification must be appropriate to the situation that is being studied. In traditional physics experiments, the goal is to obtain quantitative results with the uncertainty in the measurements well specified and as small as possible. However, a meaningful interpretation of numerical results requires a sound qualitative understanding of the underlying physics. In studies involving students, the value of quantitative results also depends on our understanding of qualitative issues, which usually are much less well understood than in the case of physical systems. To be able to determine the depth of students' knowledge and the nature of their difficulties, it is necessary to probe the reasoning that lies behind their answers. The analysis of numerical data alone may lead to incorrect interpretations. Detailed investigations with a small number of students can be very useful for identifying conceptual or reasoning difficulties that might be missed in large-scale testing. On the other hand, if the population involved is too small, the results may be idiosyncratic and important information may be missed.

The empirical studies in this section have been divided into overlapping categories that vary considerably in scope and type. Most of this research has focused on conceptual understanding or problem-solving performance. The effectiveness of laboratory instruction and lecture demonstrations has also been investigated, but to a much more limited extent. There also has been some research on other aspects of student learning, such as the ability to apply mathematics in physics. In addition, several studies have examined student attitudes and beliefs.

A. Conceptual understanding

This subsection is organized into content areas in the way that the traditional introductory course is taught. In each content area, the papers have been classified into three overlapping categories: (a) identification and analysis of student difficulties, (b) development and assessment of instructional strategies, and (c) development and validation of broad assessment instruments.

1. Mechanics

a) Identification and analysis of student difficulties

The references below are divided into overlapping subcategories according to their main emphasis:
(1) kinematics, (2) dynamics, and (3) relativity and frames of reference.

Kinematics

In the following papers, the authors identify and analyze specific difficulties that students have with the kinematical concepts and their graphical representations, and with the relationship of concepts and graphs to the real world.

26. "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).
27. "Investigation of student understanding of the concept of acceleration in one dimension," D. E. Trowbridge and L. C. McDermott, Am. J. Phys. **49**, 242-253 (1981). The two papers above report on an investigation of student understanding of the concepts of position, velocity, and acceleration. Individual demonstration interviews, conducted with 200 university students, indicated that even after instruction many students confused position with velocity and velocity with acceleration.
28. "Even honors students have conceptual difficulties with physics," P. C. Peters, Am. J. Phys. **50**, 501-508 (1981). A variety of conceptual difficulties were identified among students in an introductory honors physics course. Although mostly about kinematics, the discussion includes dynamics, electricity and magnetism.
29. "Student preconceptions about vector kinematics," J. M. Aguirre, Phys. Teach. **26**, 212-216 (1988). This paper discusses student difficulties with vector kinematics. More detail is given in a related paper: "Students' conceptions about the vector characteristics of three physics concepts," J. Aguirre and G.L. Erickson, J. Res. Sci. Teach. **21**, 439-457 (1984).
30. "Student difficulties in connecting graphs and physics: Examples from kinematics," L. C. McDermott, M. L. Rosenquist and E. H. van Zee, Am. J. Phys. **55**, 503-513 (1987). A long-term study involving several hundred students helped identify student difficulties in relating kinematical concepts, their graphical representations, and the motions of real objects. Instructional strategies designed to address some of these difficulties are described in ref. 58.
31. "Student difficulties with graphical representations of negative values of velocity," F. M. Goldberg and J. H. Anderson, Phys. Teach. **27**, 254-260 (1989). Interviews and written tests conducted at four universities probed student understanding of negative velocity.
32. "Displacement, velocity and frames of reference: Phenomenographic studies of students' understanding and some implications for teaching and assessment," J. Bowden, G. Dall'Alba, E. Martin, D. Laurillard, F. Marton, G. Masters, P. Ramsden, A. Stephanou and E. Walsh, Am. J. Phys. **60**, 262-269 (1992). This study involved high school students from several countries. It was found that as problems became easier to solve quantitatively, the level of conceptual understanding became more difficult to determine. This paper includes a discussion of a general technique used in education research to reliably extract an understanding of what students are thinking from interview transcripts.
33. "Cognition for interpreting scientific concepts: A study of acceleration," F. Reif and S. Allen, Cognition and Instruction **9**:1, 1-44 (1992). Diagrams of trajectories of two-dimensional motions were shown to 5 students in introductory physics and 5 physics faculty. Analysis of how the two groups interpreted the diagrams enabled the investigators to identify the underlying knowledge and skills required.

Dynamics

The references below focus on the identification of student difficulties with dynamics, including Newton's Laws, circular motion and the concepts of energy and momentum.

34. "Spontaneous reasoning in elementary dynamics," L. Viennot, Eur. J. Sci. Educ. **1**, 205-221 (1979). This paper presents the results of an investigation conducted among European students drawn from the last year of secondary school through the third year of university. The students demonstrated a strong tendency to assume a direct linear relationship between force and velocity.
35. "Factors influencing the learning of classical mechanics," A. Champagne, L. Klopfer and J. Anderson, Am. J.

Phys. **48**, 1074-1079 (1980). More than 100 students in an introductory university course were given a short-answer test on force and motion prior to instruction. Many non-Newtonian ideas were observed, including: a constant force produces constant velocity and in the absence of forces, objects are either at rest or slowing down.

36. "Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects," M. McCloskey, A. Caramazza and B. Green, Science **210**, 1139-1141 (1980). University students, many of whom had studied physics, were asked to predict the motions of objects moving in constrained curved paths. Many believed that an object would "remember" the curve after it left the constraint.
37. "Naive beliefs in 'sophisticated' subjects: Misconceptions about trajectories of objects," A. Caramazza, M. McCloskey and B. Green, Cognition **9**, 117-123 (1981). About 50 undergraduates were asked to trace the path of a pendulum bob if the string were cut at different positions along its path. Only about one-fourth responded correctly.
38. "Understanding of gravity," R. F. Gunstone and R. White, Sci. Educ. **65**, 291-299 (1981). Simple lecture demonstrations were shown to several hundred first-year university students in Australia. The students exhibited a strong tendency to observe their prediction regardless of what actually happened.
39. "Students' preconceptions in introductory mechanics," J. Clement, Am. J. Phys. **50**, 66-71 (1982). The results of this study indicate that many students believe that motion implies a force, both before and after the study of introductory mechanics. A detailed comparison is made between student quotes and the writings of Galileo.
40. "Rule-governed approaches to physics: Newton's third law," D. P. Maloney, Phys. Educ. **19**, 37-42 (1984). More than 100 university students with different backgrounds in physics were asked to compare the forces that two interacting objects exerted on each other. About two-thirds thought that they would be of different magnitude in some circumstances.
41. "Common-sense concepts about motion," I. A. Halloun and D. Hestenes, Am. J. Phys. **53**, 1056-1065 (1985). The authors found that students have many common-sense views about motion both before and after formal instruction. This paper is part of a sequence that led to the development of the FCI. (See Section IV.A.1.c.)
42. "Student understanding in mechanics: A large population survey," R. F. Gunstone, Am. J. Phys. **55**, 691-696 (1987). On a multiple-choice test given to 5500 high school students, a majority predicted that two equal masses on an Atwood's machine would "seek" the same level.
43. "Student understanding of the work-energy and impulse-momentum theorems," R. A. Lawson and L. C. McDermott, Am. J. Phys. **55**, 811-817 (1987). In an investigation conducted after instruction on the work-energy and impulse-momentum theorems, most students were unable to relate the algebraic formalism to motions that they observed. (Further research on this topic is reported in ref. 70.)
44. "Students' concepts of force as applied to related physical systems: A search for consistency," M. Finegold and P. Gorsky, Int. J. Sci. Educ. **13**:1, 97-113 (1991). A study involving more than 500 university and high school students in Israel examined the extent to which students consistently applied alternative concepts of force in different contexts.
45. "Effect of written text on usage of Newton's third law," R. K. Boyle and D. P. Maloney, J. Res. Sci. Teach. **28**:2, 123-140 (1991). The investigators examined the beliefs about Newton's third law of 100 university students before instruction. Half of the students were given a handout describing forces with explicit statements of the third law. No student without the handout applied the third law correctly and of those with the handout, fewer than half applied it correctly.
46. "Motion implies force: where to expect vestiges of the misconception?," I. Galili and V. Bar, Int. J. Sci. Educ. **14**:1, 63-81 (1992). This study examined the persistence of misconceptions in a range of populations from 10th-grade students to pre-service technology teachers.
47. "Research as a guide for teaching introductory mechanics: An illustration in the context of the Atwood's machine," L. C. McDermott, P. S. Shaffer, and M. D. Somers, Am. J. Phys. **62**, 46-55 (1994). A study of student understanding of the Atwood's machine revealed serious difficulties with the acceleration of the two masses, the internal and external forces, and the role of the string. The development of a tutorial to address these difficulties is also described. (The tutorial can be found in ref. 210.)
48. "A cross-college age study about physics students' conceptions of force in pre-service training for high school teachers," R. Trumper, Phys. Educ. **31**:4, 227-236 (1996). A study conducted in Israel noted difficulties with the concept of force among pre-service high school physics teachers.
49. "A hierarchical model of the development of student understanding of momentum," T. Graham and J. Berry, Int. J. Sci. Educ. **18**:1, 75-89 (1996). Observations of more than 500 British 17-18 year old physics students provided a basis for classification of the development of the concept of momentum into stages.
50. "The effect of context on students' reasoning about forces," D. Palmer, Int. J. Sci. Educ. **19**:6, 681-696 (1997). This study compared how a group of high school physics students and a group of pre-service teachers responded to a variety of simple physics questions in which the physics was the same but the contexts were different.
51. "Conceptual dynamics: Following changing student views of force and motion," R. K. Thornton, AIP Conf. Proc. **399**, 241-266 (1997). (See ref. 9.) A framework is constructed for identifying the state of student under-

standing of the laws of mechanics and explores the dynamics of how student views develop through instruction.

Relativity and frames of reference

52. " 'Spontaneous' ways of reasoning in elementary kinematics," E. Saltiel and J. L. Malgrange, Eur. J. Phys. **1**, 73-80 (1980). A study of 700 university students and 80 eleven-year olds identified student difficulties with relative motion and reference frames.
53. "Alternative conceptions in Galilean relativity: frames of reference," S. Panse, J. Ramadas, and A. Kumar, Int. J. Sci. Educ. **16**:1, 63-82 (1994).
54. "Alternative conceptions in Galilean relativity: distance, time, energy and laws," J. Ramadas, S. Barve, and A. Kumar, Int. J. Sci. Educ. **18**:4, 463-477 (1996).
55. "Alternative conceptions in Galilean relativity: inertial and non-inertial observers," J. Ramadas, S. Barve, and A. Kumar, Int. J. Sci. Educ. **18**:5, 615-629 (1996).
The three papers above describe a series of studies in which undergraduate students in India were asked questions about transformations between different frames. Both kinematical and dynamical issues were considered and student responses classified.
56. "A case study of conceptual change in special relativity: the influence of prior knowledge in learning," Peter W. Hewson, Eur. J. Sci. Educ. **4**, 61-76 (1982). A series of interviews with a graduate tutor in introductory physics probed his understanding of special relativity. Implications of this case study are discussed in detail in ref. 178.

b) Development and assessment of instructional strategies

The primary focus in almost all of the studies cited above was on the nature or prevalence of student difficulties. In some instances, however, the design of effective instruction was an integral part of the investigation.

57. "Diagnosis and remediation of an alternative conception of velocity using a microcomputer program," P. W. Hewson, Am. J. Phys. **53**, 684-690 (1985). This paper examines student learning using a computer program designed to diagnose and remediate difficulties with kinematical concepts. For a more detailed analysis, see "Effect of instruction using microcomputer simulations and conceptual change strategies on science learning," A. I. Zietsman and P. W. Hewson, J. Res. Sci. Teach. **23**:1, 27-39 (1986).
58. "A conceptual approach to teaching kinematics," M. L. Rosenquist and L. C. McDermott, Am. J. Phys. **55**, 407-415 (1987). Results from research were used to guide the design of a laboratory-based curriculum that has been shown to be effective in addressing some of the difficulties in kinematics that were identified in ref. 30.
59. "Facilitation of scientific concept learning by interpretation procedures and diagnosis," P. Labudde, F. Reif and L. Quinn, Int. J. Sci. Educ. **10**, 81-98 (1988). The authors present a general instructional strategy for helping students develop coherent procedures for interpreting scientific concepts and for correcting deficiencies in their pre-existing knowledge.
60. "Learning motion concepts using real-time microcomputer-based laboratory tools," R. K. Thornton and D. R. Sokoloff, Am. J. Phys. **58**, 858-867 (1990). The authors describe the use of microcomputer-based laboratory (MBL) activities to help students overcome some common conceptual difficulties in kinematics.
61. "Explaining the 'at rest' condition of an object," J. Minstrell, Phys. Teach. **20**, 10-14 (1982). The author describes a carefully structured questioning sequence designed to address the failure of many students to recognize that a stationary surface can exert a force on an object with which it is in contact. This study represents a form of "action research," through which teachers gain insight into how their students are thinking.
62. "Modeling instruction in mechanics," I. A. Halloun and D. Hestenes, Am. J. Phys. **55**, 455-462 (1987). An introductory university physics course was developed to test an instructional theory that emphasizes mathematical modeling and study of paradigmatic problems. Nearly 500 students were divided into test and control groups. The students in the test group did substantially better, especially those who performed poorly on the pre-test.
63. "Not all preconceptions are misconceptions: Finding 'anchoring conceptions' for grounding instruction on students' intuition," J. Clement, D. Brown and A. Zeitsman, Int. J. Sci. Educ. **11** (spec. issue), 554-565 (1989). This paper illustrates in the context of a high school class in mechanics how the (often incorrect) ideas that students bring to a physics class can be used as "anchoring conceptions" around which successful instructional strategies can be built.
64. "Overview, Case Study Physics," A. Van Heuvelen, Am. J. Phys. **59**, 898-907 (1991). Results from research guided the design of the Overview, Case Study (OCS) method. This method helps students build a hierarchical knowledge structure of mechanics based on a spiral of increasing sophistication. OCS students performed significantly better on the tests described in refs. 73 and 80 than did a control group that had received traditional instruction.
65. "Socratic pedagogy in the introductory physics laboratory," R. R. Hake, Phys. Teach. **33**, 1-7 (1992). In this laboratory-based approach to teaching dynamics, students perform simple experiments that serve as a basis for Socratic dialogues.
66. "Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics," J. Clement, J. Res. Sci. Teach. **30**:10, 1241-1257 (1993). The author describes how a succession of analogies can be used to form a bridge for transforming students' commonsense ideas to the Newtonian view.
67. "The impact of video motion analysis on kinematics graph interpretation skills," R. J. Beichner, Am. J. Phys. **64**, 1272-1277 (1996). The author investigated the use of

video software in helping students develop graph-reading skills. Various combinations were tried, ranging from no use of video, to video demonstrations, to student-captured videos in laboratory experiments. Greater use and integration with other components of instruction correlated strongly with improved scores on the TUG-K described in ref. 72.

68. "On the effectiveness of active-engagement microcomputer-based laboratories," E. F. Redish, J. M. Saul, and R. N. Steinberg, Am. J. Phys. **65**, 45-54 (1997). Gains on multiple-choice and on open-ended questions were compared for students with tutorials incorporating microcomputer-based laboratory (MBL) tools and for students without these experiences. The students with MBL tutorials performed better on both types of questions. A description of the tutorial approach can be found in ref. 47. (See also ref. 210.)

69. "Using interactive lecture demonstrations to create an active learning environment," D. R. Sokoloff and R. K. Thornton, Phys. Teach. **35**, 340-347 (1997). This paper describes a general strategy for increasing student engagement in lectures through the use of microcomputer-based lecture demonstrations. Applications in the teaching of kinematics and dynamics are presented and evaluated.

70. "The challenge of matching learning assessments to teaching goals: An example from the work-energy and impulse-momentum theorems," T. O'Brien Pride, S. Vokos and L. C. McDermott, Am. J. Phys. **66**, 147-156 (1998). Evidence is presented that difficulties with the two theorems extend beyond the introductory level. (See ref. 43.) The article describes a research-based tutorial that was developed to address these difficulties. (See ref. 210.) Issues related to the assessment of student understanding are discussed.

71. "Do they stay fixed?" G. E. Francis, J. P. Adams, and E. J. Noonan, The Physics Teacher, **36**, 488-490 (1998). This study probed the extent to which student gains on the FCI resulting from interactive-engagement instruction persisted beyond the conclusion of the course. (The tutorials from ref. 210 were used.) The study found little decline in FCI scores over several years following instruction.

Ref. 47 also discusses the development of an instructional strategy to address difficulties with the concept of tension in a string.

c) Development and validation of broad assessment instruments

A few comprehensive instruments to assess student understanding in mechanics have been published. The papers cited in this subsection relate to four multiple-choice tests that are easy to administer and grade. Their use with a variety of student populations has provided compelling evidence that many students who do well on quantitative examination questions have serious conceptual difficulties. The tests have been used as an indicator of the initial state of different populations and in some instances as a standard by which to judge the effectiveness of instruction.

In comparing instructors or instructional strategies, any single instrument must be used with great care since many variables are involved in any teaching situation. The test may be incomplete and the questions may be subject to misinterpretation by the student. As a measure of instructional effectiveness, the results from multiple-choice tests alone should be viewed with skepticism.[2] It is often impossible to tell when incorrect reasoning leads to a correct answer. Good performance on broad assessment instruments that do not require explanations should be considered as a necessary, rather than sufficient, criterion for meaningful learning. See the comparison of multiple-choice to open-ended questions in refs. 70 and 79.

The Test of Understanding Graphs in Kinematics (TUG-K) is a multiple-choice on the interpretation of graphical representations of motions.

72. "Testing student interpretation of kinematics graphs," R. J. Beichner, Am. J. Phys. **62**, 750-762 (1994). The appendix includes the TUG-K. Administration of the test to about 900 students in high school and college yielded results consistent with those from other types of studies on the interpretation of motion graphs. The paper also includes a detailed discussion of the development and validation of multiple-choice tests.

The most widely used and thoroughly tested assessment instrument is the Force Concept Inventory (FCI). Each test item requires that students distinguish between correct Newtonian answers and erroneous "common-sense" beliefs. Widespread administration of the FCI has raised the awareness of faculty to the failure of most lectures to promote conceptual development.[3]

73. "The initial knowledge state of college physics students," I. A. Halloun and D. Hestenes, Am. J. Phys. **53**, 1043-1056 (1985). The authors present a multiple-choice instrument, the Mechanics Diagnostic Test, that has evolved into the FCI (next ref.). Use of the test in an introductory college physics course is described. The paper also discusses the construction of effective multiple-choice tests.

74. "Force Concept Inventory," D. Hestenes, M. Wells and G. Swackhamer, Phys. Teach. **30**, 141-158 (1992). This paper contains the Force Concept Inventory (FCI) and a detailed discussion of the Newtonian concepts it is constructed to probe. Results from administration of the FCI before and after instruction are given for some high school and university classes.

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[2] See, for example, the letter "On not choosing multiple choice," T. R. Sandin, Am. J. Phys. 53, 299-300 (1985).

[3] For an anecdote describing the impact on a university instructor of results from the FCI, see E. Mazur, *Peer Instruction: A User's Manual* (Prentice Hall, NJ, 1997), p. 4.

75. "What does the force concept inventory actually measure?," D. Huffman and P. Heller, Phys. Teach. **33**, 138-143 (1995).
76. "Interpreting the Force Concept Inventory: A response to March 1995 Critique by Huffman and Heller," D. Hestenes and I. Halloun, Phys. Teach. **33**, 502-506 (1995).
77. "Interpreting the Force Concept Inventory: A reply to Hestenes and Halloun," P. Heller and D. Huffman, Phys. Teach. **33**, 503-511 (1995).
The three papers above carry on a dialogue on the subject of correlations among student errors on the FCI.
78. "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). This paper presents a collection of pre- and post-instruction FCI data from instructors at a large number of high schools, colleges, and universities. Most "active-engagement" classes (as defined by the instructors) showed much greater improvement than traditional classes.
79. "Performance on multiple-choice diagnostics and complementary exam problems," R. N. Steinberg and M. S. Sabella, Phys. Teach. **35**, 150-155 (1997). This paper compares the responses of introductory university physics students on the FCI and on open-ended examination questions that probe the same concepts. Students did not always perform similarly on the two types of questions.

The Mechanics Baseline Test (MBT) is another multiple-choice test. It contains a greater range of topics than does the FCI and is intended for use after instruction.

80. "A Mechanics Baseline Test," D. Hestenes and M. Wells, Phys. Teach. **30**, 159-166 (1992). The test is included in the paper.

In the study described in ref. 70, two questions that appear on the MBT were given to students with explanations required. The results differed considerably when the explanations were and were not taken into account.

A fourth multiple-choice test is the Force and Motion Conceptual Evaluation (FMCE). Multiple questions on each concept allow this test to be used as a diagnostic for particular difficulties of individual students.

81. "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 results from traditional introductory courses on a subset of the questions on the FMCE are compared with those from courses in which instruction included activities supported by microcomputer-based laboratory (MBL) tools. The performance of the MBL students was significantly better. The FMCE is included in the Appendix.

2. Electricity and magnetism

Student understanding of concepts in electricity and magnetism has not been investigated in as great detail as in mechanics. Published articles on student difficulties have dealt primarily with two topics: DC circuits and electric fields.

a) Identification and analysis of student difficulties

DC circuits

Student difficulties with DC circuits have been documented in many studies.

82. "Student conceptions of simple electric circuits," N. Fredette and J. Lochhead, Phys. Teach. **19**, 194-198 (1980); "Student misconceptions of an electric circuit: What do they mean?," N. Fredette and J. Clement, J. Coll. Sci. Teach. **10**, 280-285 (1981). These two papers discuss the responses of college students to the task: "Combine a battery, bulb, and one wire to make the bulb light."
83. "Potential difference and current in simple electric circuits: A study of students' concepts," R. Cohen, B. Eylon and U. Ganiel, Am. J. Phys. **51**, 407-412 (1983). The authors analyzed responses from multiple-choice tests given to 145 high school students and 21 in-service physics teachers in Israel. Although the teachers did better than the students, many had similar conceptual difficulties.
84. "Conceptions of French pupils concerning electric circuits: structure and evolution," J.-J. Dupin and S. Johsua, J. Res. Sci. Teach. **24**:9, 791-806 (1987). A study in France examined the views on electric current held by students ranging in age from 12 to 22 years. It was found that some simple misconceptions disappear with instruction, but teaching seems to have little effect on others.
85. "A study of students' understanding of electricity in five European countries," D. M. Shipstone, C. v. Rhöneck, W. Jung, C. Kärrqvist, J. Dupin, S. Johsua and P. Licht, Int. J. Sci. Educ. **10**, 303-316 (1988). A study that was conducted among high school students in 5 countries revealed substantially the same difficulties everywhere.
86. "Macro-micro relationships: the missing link between electrostatics and electrodynamics in student reasoning," B.-S. Eylon and U. Ganiel, Int. J. Sci. Educ. **12**:1, 79-94 (1990). In a study conducted in Israel, high school students who lacked a coherent microscopic model could not predict the behavior of transients in simple circuits.
87. "Variable uses of alternative conceptions: A case-study in current electricity," P. Heller and F. N. Finley, J. Res. Sci. Teach. **29**:3, 259 (1992). Fourteen in-service elementary and middle school teachers were found to have a coherent, but incorrect, model of current.
88. "Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding," L. C. McDermott and P. S. Shaffer, Am. J. Phys. **60**, 994-1003 (1992); erratum, *ibid.* **61**, 81 (1993). This paper identifies specific difficulties that many undergraduate students have with DC circuits. Instructional strategies designed to address these difficulties are described in ref. 100.
89. "Images of electricity: How do novices and experts model electric current?" S. M. Stocklmayer and D. F.

Treagust, Int. J. Sci. Educ. **18**:2, 163-178 (1996). This study found that experts have images of electric current that differ significantly both from those of novice students and from the models that are usually taught. Experts draw on a field concept more than on a particle model.

90. "Seeking the causal connection in electricity: shifting among mechanistic perspectives," J. Gutwill, J. Frederiksen, and M. Ranney, Int. J. Sci. Educ. **18**:2, 143-162 (1996). The authors examined the reasoning used and the evolution of perspectives among 22 high school students as they solved problems on electric circuits.

91. "The persistence of students' unfounded beliefs about electrical circuits: The case of Ohm's law," A. Métioui, C. Brassard, J. Levasseur, and M. Lavoie, Int. J. Sci. Educ. **18**:2, 193-212 (1996). Interviews and written tests were used to probe the understanding of Ohm's law among Electrical Engineering Technology students in Quebec.

Electrostatics and magnetostatics

92. "Charged poles," D. P. Maloney, Phys. Educ. **20**, 310-316 (1985). Results from a study conducted in an algebra-based physics class strongly suggest that, even after instruction, many students are confused about the interactions between electric charges and magnetic poles.

93. "Students' understanding of the transfer of charge between conductors," C. Guraswamy, M. D. Somers, and R. G. Hussey, Phys. Educ. **32**:2, 91-96 (1997). Individual demonstration interviews were used to investigate student understanding of charge and the behavior of charged conductors. After instruction, few students were able to identify the forces of a charge on a conductor or to describe how charges were shared between touching conductors.

Electric and magnetic fields

Since many of the basic concepts in electricity and magnetism are not familiar from direct experience and are quite abstract, students can be expected to have conceptual difficulties. The few published studies are quite provocative, but far from complete.

94. "On the quality of knowledge in the field of electricity and magnetism," M. G. M. Ferguson-Hessler and T. de Jong, Am. J. Phys. **55**, 492-497 (1987). The authors investigated how first-year university students organized their knowledge of electromagnetism. Successful problem solvers had a more coherent knowledge structure.

95. "Novice use of qualitative versus quantitative problem solving in electrostatics," C. McMillan III and M. Swadener, J. Res. Sci. Teach. **28**:8, 661-670 (1991). Six students in a calculus-based physics class were observed as they solved electrostatics problems. The successful students differed from the others only in mathematical facility, not in qualitative understanding. Both groups had difficulty with qualitative questions and had similar misconceptions.

96. "Students' reasoning about the superposition of electric fields," L. Viennot and S. Rainson, Int. J. Sci. Educ. **14**:4, 475-487 (1992). This paper discusses the difficulties of French and Algerian university students with Gauss's Law and with the electric field in an insulator. For a further analysis that includes Swedish students, see "Students' understanding of superposition of electric fields," S. Rainson, G. Tranströmer and L. Viennot, Am. J. Phys. **62**, 1026-1032 (1994). Instruction that addresses these issues is described in ref. 101.

97. "Confusion by representation: On students' comprehension of the electric field concept," S. Törnkvist, K.-A. Pettersson and G. Tranströmer, Am. J. Phys. **61**, 335-338 (1993). Analysis of more than 500 written responses and nearly 100 interviews revealed difficulties with the concept of electric field lines among second-year students at the Royal Institute of Technology in Stockholm.

98. "Mechanics background influences students' conceptions in electromagnetism," I. Galili, Int. J. Sci. Educ. **17**:3, 371-387 (1995). Difficulties with electromagnetism were identified in a study that included 10th-graders and pre-service technology teachers in Israel.

99. "The kinds of mental representations — models, propositions, and images — used by college physics students regarding the concept of field," I. M. Grea and M. A. Moreira, Int. J. Sci. Educ. **19**:6, 711-724 (1997). Brazilian sophomore engineering students participated in the study. The discussion is within a theoretical educational framework.

b) Development and assessment of instructional strategies

100. "Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of an instructional strategy," P.S. Shaffer and L.C. McDermott, Am. J. Phys. **60**, 1003-1013 (1992). This paper describes the application of the results from the research described in ref. 88 to the development of both a laboratory-based curriculum for an inquiry-oriented course and a supplementary tutorial curriculum for a lecture-based course. See refs. 210 and 218.

101. "Superposition of electric fields and causality: From research to teaching," S. Rainson and L. Viennot, AIP Conf. Proc. **399**, 679-687 (1997). (See ref. 9.) Instructional strategies are described for addressing the difficulties with superposition of fields described in ref. 96.

3. Light and optics

a) Identification and analysis of student difficulties

Nature of light, color and vision

102. "Commonsense knowledge in optics: Preliminary results of an investigation into the properties of light," C. La Rosa, M. Mayer, P. Patrizi and M. Vicentini-Missoni, Eur. J. Sci. Educ. **6**:4, 387-397 (1984). Ideas about light, color, and geometrical optics were explored through interviews with teachers and open-ended written questions

administered to high school students. On the basis of their observations, the authors propose a progression of stages in student thinking about light.

103. "Student conceptions of light: A case study," D. M. Watts, Phys. Educ. **20**, 183-187 (1985). A detailed description is given of the views of a high school student on the nature of light. Many of the common misconceptions are represented in the discussions quoted.

104. "The understanding of the properties of light by students in India," A. B. Saxena, Int. J. Sci. Educ. **13**:3, 283-289 (1991). This article reports the results from a multiple-choice test that was administered to both secondary school and undergraduate students in India. The results were similar to those obtained in refs. 107 and 108.

105. "Prospective elementary school teachers' prior knowledge about light," S. Bendall, I. Galili and F. Goldberg, J. Res. Sci. Teach. **30**:9, 1169-1187 (1993). Preservice elementary school teachers were interviewed about the nature of light.

106. "Light propagation and visual patterns: Preinstruction learners' conceptions," D. Langley, M. Ronen, and B.-S. Eylon, J. Res. Sci. Teach. **34**:4, 399-424 (1997). This study explored the ideas about light propagation and image formation of Israeli 10th graders.

Geometrical Optics

107. "Student difficulties in understanding image formation by a plane mirror," F. M. Goldberg and L. C. McDermott, Phys. Teach. **24**, 472-480 (1986). During interviews, university students were shown an object in front of a mirror and asked what an observer at various locations would see. Many students could not make correct predictions either before or after instruction.

108. "An investigation of student understanding of the real image formed by a converging lens or concave mirror," F. M. Goldberg and L. C. McDermott, Am. J. Phys. **55**, 108-119 (1987). Even after instruction, many students could not apply the formalism of geometrical optics to predict or account for the image formed by a converging lens or concave mirror.

109. "The effects of prior knowledge and instruction on understanding image formation," I. Galili, S. Bendall and F. Goldberg, J. Res. Sci. Teach. **30**:3, 271-301 (1993). Individual demonstration interviews conducted with students in a college physics course for prospective teachers suggested that, after instruction, students' prior conceptions of light become "hybridized" with the physicist's model.

110. "Students' conceptual change in geometrical optics," I. Galili, Int. J. Sci. Educ. **18**:7, 847-868 (1996). The author discusses how students' conceptual models in geometrical optics change with instruction.

Physical Optics

111. "An investigation of student understanding of single-slit diffraction and double-slit interference," B. S. Ambrose, P. S. Shaffer, R. N. Steinberg, and L. C. McDermott, Am. J. Phys., **67**, 146-155 (1999). This article identifies specific difficulties that many students have in selecting and applying an appropriate model to account for the pattern produced on a screen when light is incident on one or two narrow slits. It also was found that students at introductory and more advanced levels have seriously mistaken beliefs about photons and the wave model for matter.

b) Development and assessment of instructional strategies

112. "Lenses, pinholes, screens and the eye," F. Goldberg, S. Bendall and I. Galili, Phys. Teach. **29**, 221-224 (1991). The authors describe an instructional strategy to increase student understanding of real images. Two demonstrations are used: a real image formed on a screen by a converging lens and a "screen reproduction" produced by a pinhole.

113. "Many rays are better than two," D. J. Grayson, Phys. Teach. **33**, 42-43 (1995). Having students draw many rays from each point on an object appears to help them understand why covering half a lens doesn't block half the image. (See ref. 108.) In a class of 35 South African university students, improvement on the post-test compared to the pretest indicated that this strategy was effective.

114. "Making the invisible visible: A teaching/learning environment that builds on a new view of the physics learner," F. Goldberg and S. Bendall, Am. J. Phys. **63**, 978-991 (1995). The study of light provides a context in which prospective elementary teachers develop conceptual understanding and an awareness of their own learning.

115. "Computer simulations as tools for teaching and learning: Using a simulation environment in optics," B.-S. Eylon, M. Ronen, and U. Ganiel, J. Sci. Educ. Technol. **5**:2, 93-110 (1996). The authors evaluate the effect of a ray-tracing simulation program on students' spontaneous use of appropriate concepts. They found that the effectiveness of the program depends heavily on the learning environment in which the program is used.

116. "Development and assessment of a research-based tutorial on light and shadow," K. Wosilait, P. R. L. Heron, P. S. Shaffer, and L. C. McDermott, Am. J. Phys. **66**, 906-913 (1998). Evidence is presented that university students at the introductory physics level and beyond often cannot account for simple phenomena involving light and shadow. The authors describe the research through which specific difficulties were identified. The article describes the iterative process through which a tutorial to address student difficulties in geometrical optics was developed and assessed. (See ref. 210.)

4. Properties of matter, fluid mechanics, and thermal physics

Investigations conducted among young children indicate that serious misconceptions about heat and temperature are common. Since there is little published research involving university students, many of the references below are to studies with younger students.

Heat, temperature, and thermodynamics

117. "The teaching of the concept of heat," J. W. Warren, Phys. Educ. **7**, 41-44 (1972). This paper discusses the inability of first-year university students to separate the concepts of heat, internal energy, and temperature.

118. "Misconceptions in school thermodynamics," A. H. Johnstone, J. J. MacDonald and G. Webb, Phys. Educ. **12**:4, 248-251 (1977). A 'thermodynamics approach test' was administered to 98 middle and high school students in Scotland. Eight prevalent "misconceptions" were identified. Several of these pertain to chemical reactions.

119. "Children's conceptions of heat and temperature," G. L. Erickson, Sci. Educ. **63** (1979) 221-230. It was observed in this study that many students aged 11-16 believe that heat and cold are substances and that temperature is a measure of their amount. Few students were able to distinguish between heat and temperature.

120. "The influence of intellectual environment on conceptions of heat," M. G. Hewson and D. Hamlyn, Eur. J. Sci. Educ. **6**, 254-262 (1984). Interviews were conducted with Sotho children and adults from an arid region of South Africa. Sotho subjects were less likely than Western subjects to use a caloric model. The authors concluded that cultural metaphors influence the interpretation of physical situations.

121. "A microcomputer-based diagnostic system for identifying students' conception of heat and temperature," R. Nachmias, R. Stavy and R. Avrams, Int. J. Sci. Educ. **12**:2, 123-132 (1990). The authors describe the structure of their microcomputer-based diagnostic system for investigating students' conceptions of heat and temperature.

122. "Students' reasonings in thermodynamics," S. Rozier and L. Viennot, Int. J. Sci. Educ. **13**:2, 159-170 (1991). A study conducted in Paris analyzed responses of university students and in-service teachers to situations in which more than two variables change. Some specific student difficulties with the ideal gas law can be traced to this complication.

123. "Critical review on the research aimed at elucidating the sense that notions of temperature and heat have for the students aged 10 to 16 years," A. Tiberghien, in *Research on Physics Education, Proceedings of the First International Workshop,* La Londe Les Maures, France, edited by G. Delacôte, A. Tiberghien and J. Schwartz (Éditions du CNRS, Paris, 1983) 75-90. This article summarizes the published research on children's understanding of heat and temperature.

124. "Students' conceptions of the second law of thermodynamics — an interpretive study," S. Kesidou and R. Duit, J. Res. Sci. Teach. **30**, 85-106 (1993). This paper reports the views of German high school students, who have had four years of physics instruction, on thermal equilibrium, the concepts of heat and temperature, and the first and second laws of thermodynamics.

125. "'Work' and 'heat': On a road towards thermodynamics," P. H. van Roon, H. F. van Sprand, and A. H. Verdonk, Int. J. Sci. Educ. **16**:2, 131-144 (1994). The difficulties first year Dutch university students have with the concepts of thermodynamic system, heat, work, and temperature are probed.

126. "Children's and lay adults' views about thermal equilibrium," M. Arnold and R. Millar, Int. J. Sci. Educ. **16**:4, 405-419 (1994). Detailed interviews were used to probe views on heating and cooling held by British high school students and university-educated adults not trained in science. Both groups revealed similar misconceptions.

Pressure, density, and the structure of matter

127. "Earth science, density, and the college freshman," J. W. McKinnon, J. Geol. Educ. **19**:5, 218-220 (1971). This paper describes how student difficulties with ratio reasoning can lead to difficulties with the concept of density, even among university students.

128. "Grade 12 students' misconceptions relating to fundamental characteristics of atoms and molecules," A. K. Griffiths and K. R. Preston, J. Res. Sci. Teach. **29**, 611-628 (1992). The authors report on the views of 30 randomly selected high school students in Newfoundland about the nature and structure of atoms and molecules.

129. "Student understanding of the volume, mass, and pressure of air within a sealed syringe in different states of compression," K. C. de Berg, J. Res. Sci. Teach. **32**, 871-884 (1995). The author studied the responses of high school students in England who had studied physics or chemistry to qualitative tasks involving pressure, volume, and mass of a gas in a syringe. Only about one-third of the students demonstrated a qualitative understanding of these concepts.

130. "Pupils' conceptions of matter and its transformations (age 12-16)," B. Andersson. See ref. 6, *Relating macroscopic phenomena to microscopic particles,* pp. 12-35. This paper reviews some of the research literature on the ideas of high school students about matter, including chemical reactions (such as burning), phase transitions, conservation of matter, and the nature of atoms and molecules.

5. Waves and Sound

131. "A study of tertiary physics students' conceptualizations of sound," C. J. Linder and G. L. Erickson, Int. J. Sci. Educ. **11** (spec. issue), 491-501 (1989). In this study, many students claimed that sound is not a wave and created other models to account for sound phenomena.

132. "Spontaneous reasoning on the propagation of visible mechanical signals," L. Maurines, Int. J. Sci. Educ. **14**:3, 279-293 (1992). In a study of student understanding of factors affecting the speed of wave propagation, students were found to emphasize the shape and manner of creation of the wave rather than the properties of the medium.

133. "University physics students' conceptualizations of factors affecting the speed of sound propagation," C. J.

Linder, Int. J. Sci. Educ. **15**:6, 655-662 (1993). The author investigates student understanding of sound propagation.

134. "Using education research to develop waves courseware," D. J. Grayson, Comput. Phys. **10**:1, 30-37 (1996). Difficulties with two-dimensional kinematics were investigated in the context of mechanical waves. A computer program enabled students to investigate differences between spatial and temporal motion graphs.

135. "Making Sense of How Students Make Sense of Mechanical Waves," Michael C. Wittmann, Richard N. Steinberg, and Edward F. Redish, The Physics Teacher, **37**:1, 15-21 (1999). This paper reports on an investigation of student understanding of pulses propagating along elastic strings. Student responses to multiple questions on closely related topics revealed the simultaneous presence of both correct and incorrect interpretations.

136. "Student understanding of light as an electromagnetic wave: Relating the formalism to physical phenomena," B. S. Ambrose, P. R. L. Heron, S. Vokos, and L. C. McDermott, Am. J. Phys. **67** (1999, forthcoming). This paper describes an investigation of the difficulties that students have with the interpretation of the diagrammatic and mathematical formalism commonly used to represent light as a plane EM wave. Results from this research were used to guide the development of a tutorial that has proved effective in addressing some specific difficulties that were identified.

6. Topics in modern physics

To date, there has been little published research on student understanding of topics in modern physics. See Section IV.A.1.a.3 for a discussion of student difficulties with special relativity. References on other topics are given below.

137. "Modern physics and students' conceptions," H. Fischler and M. Lichtfeldt, Int. J. Sci. Educ. **14**:2, 181-190 (1992). The authors cite results of a descriptive study of student conceptions in quantum mechanics.

138. "School students' understanding of processes involving radioactive substance and ionizing radiation," R. Millar and J. S. Gill, Phys. Educ. **31**:1, 27-33 (1996). This paper describes a study that probed the understanding of British high-school students on the subject of radiation. Many could not distinguish between damaging a substance by radiation and making it radioactive by radiation.

139. "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). This article reports on an investigation of student understanding of the photoelectric effect. The study took place in a sophomore course in modern physics. The results were used to guide the development of an interactive computer program to address the difficulties that were identified.

140. "Student difficulties in learning quantum mechanics," I. D. Johnston, K. Crawford, and P. R. Fletcher, Int. J. Sci. Educ. **20**, 427-446 (1998). This paper reports on an investigation of the conceptual structure of students who had successfully completed a course in quantum mechanics at an Australian university. The investigators found that student models were often technically advanced but structurally unsophisticated.

Ref. 111 includes a discussion of some student difficulties with photons.

B. Problem-solving performance

The ability of students to solve physics problems has been the subject of a considerable amount of research, especially in the context of mechanics. Studies have been conducted not only by physicists but also by other investigators who have used physics as a context in which to study the thought processes involved in problem solving in a broader sense.

1. Investigations of problem-solving behavior

141. "Understanding and teaching problem solving in physics," J. H. Larkin and F. Reif, Eur. J. Sci. Educ. **1**:2, 191-203 (1979). From a case study comparing the problem-solving approaches of an expert and a (good) novice problem solver, the authors identify critical elements needed for expert problem solving. An instructional strategy is described for teaching novices to take a more qualitative, global approach.

142. "Categorization and representation of physics problems by experts and novices," M. T. H. Chi, P. J. Feltovich and R. Glaser, Cognitive Science **5**, 121-152 (1981). This study identified differences in the ways that experts and novices solve physics problems. It was found that experts categorized problems according to "deep structure," while novices tended to categorize according to surface features.

143. "The relation between problem categorization and problem solving among experts and novices," P. Hardiman, R. Dufresne and J. Mestre, Mem. Cognit. **17**, 627-638 (1989). The authors observed how 45 novices and 10 experts categorized and solved problems. They found that the better novices made more use of explanatory statements and physics principles in setting up the problems.

144. "Effects of knowledge organization on task performance," B. Eylon and F. Reif, Cognition and Instruction **1**, 5-44 (1984). The results of this study suggest that a hierarchical presentation of information improves the ability of students to solve certain types of problems.

2. Development and assessment of instructional strategies

145. "Teaching general learning and problem solving skills," F. Reif, J. H. Larkin and B. C. Bracket, Am. J. Phys. **44**, 212-217 (1976). The authors investigated the abilities needed to understand a relation such as a definition or a law. An instructional strategy was developed to teach a general method for acquiring such an understanding.

146. "Teaching problem solving — A scientific approach," F. Reif, Phys. Teach. **19**, 310-316 (1981). The author identifies cognitive issues that need to be addressed in or-

der to develop an effective instructional strategy for teaching problem solving.

147. "Constraining novices to perform expert like problem analyses: Effects on schema acquisition," R. Dufresne, W. J. Gerace, P. T. Hardiman and J. P. Mestre, Journal of the Learning Sciences **2**, 307-331 (1992). The authors describe a computer tool designed to help students become more expert problem solvers. The program requires students to consider principles, concepts, and procedures.

148. "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).

149. "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).
The two papers above describe a strategy for teaching problem-solving skills that is based on collaborative learning. The authors identify several important factors, such as the nature of the problems used, the structure of the group, and the training of teaching assistants.

150. "Comparing problem solving performance of physics students in inquiry-based and traditional introductory physics courses," B. Thacker, E. Kim, K. Trefz and S. M. Lea, Am. J. Phys. **62**, 627-633 (1994). This article presents evidence that performance on quantitative problems by students who have had experience in solving qualitative problems can be as good as (and sometimes better than) performance by students who have spent more time on traditional problem solving. (See also ref. 100.)

151. "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). An instructional strategy is described for teaching problem solving. Students first write a qualitative description, then identify relevant concepts and principles, and lastly apply these in finding a solution.

152. "Problem-based learning in physics: Making connections with the real world," B. J. Duch. AIP Conf. Proceedings **399** (1997) 557-565. (See ref. 9.) This paper discusses an evaluation of the use of context-rich problems in cooperative group learning. (See also refs. 148 and 149.)

C. Effectiveness of laboratory instruction and lecture demonstrations

Laboratory instruction and demonstrations have traditionally been considered by physicists to be very important for teaching physics. Yet, as the list of references below suggests, there have been relatively few systematic efforts to assess their effectiveness.

153. "Results of a remedial laboratory program based on a Piaget model for engineering and science freshmen," R. Gerson and R. A. Primrose, Am. J. Phys. **45**, 649-651 (1977). This paper demonstrates that a laboratory designed to improve students' formal reasoning was more effective in preparing engineering students deficient in algebra for calculus than was a traditional college algebra class.

154. "Teaching physicists' thinking skills in the laboratory," F. Reif and M. St. John, Am. J. Phys. **47**, 950-957 (1979). The authors identify specific skills that can be taught in the laboratory and demonstrate how a carefully structured course can teach those skills effectively.

155. "The influence of physics laboratories on student performance in a lecture course," D. D. Long, G. W. McLaughlin and A. M. Bloom, Am. J. Phys. **54**, 122-125 (1986). The performance of 2500 students in the lecture part of an algebra-based university course was correlated with whether or not the students took the laboratory component. The laboratory seemed to have little effect for students at the top and bottom of the class but a significant positive effect for the middle 60 percent.

156. "Learning statistical analysis of measurement errors," M.-G. Séré, R. Journeaux and C. Larcher, Int. J. Sci. Educ. **15**:4, 427-438 (1993). A study was conducted in France to determine what 20 students in a first-year physics laboratory course had learned about the statistical concepts taught. Students had specific difficulties in understanding the role and value of statistical tools in assessing confidence in a measurement.

157. "Why may students fail to learn from demonstrations? Social practice perspective on learning in physics," W.-M. Roth, C. J. McRobbie, K. B. Lucas, and S. Boutonné, J. Res. Sci. Teach. **34**:5, 509-533 (1997). The authors observed a class of Australian high-school seniors and conducted interviews and post-tests to probe their response to demonstrations. They classify general difficulties that could cause students to miss the point of a demonstration and make suggestions for how to improve its effectiveness.

158. "First-year physics students' perceptions of the quality of experimental measurements," S. Allie, A. Buffler, L. Kaunda, B. Campbell, and F. Lubben, Int. J. Sci. Educ. **20**, 447-459 (1998). The paper reports an investigation of student understanding about the reliability of experimental data. The research was conducted with first year science students at a university in South Africa. The investigators analyzed the types of reasoning used by the students and found a strong dependence on context.

D. Ability to apply mathematics in physics

A minimum level of mathematical proficiency, as determined by prescribed pre-requisite courses, is usually assumed for an introductory physics course. Instructors frequently assume that students will be able to apply the mathematics taught in these courses to physics problems. However, both research and teaching experience indicate that many students lack this ability. The papers below address this issue.

159. "Translation difficulties in learning mathematics," J. Clement, J. Lochhead and G. S. Monk, Amer. Math.

Mon. **88**, 286 (1981). This paper reports on the pitfalls freshman engineering majors encounter when they are asked to construct equations to match situations described in words.

160. "The mathematical knowledge of physics graduates: Primary data and conclusions," E. Breitenberger, Am. J. Phys. **60**, 318-323 (1992). The author discusses a survey of the mathematical sophistication of entering physics graduate students at a major university.

161. "Teaching algebraic coding: Stakes, difficulties and suggestions," G. Rebmann and L. Viennot, Am. J. Phys. **62**, 723-727 (1994). The authors discuss the difficulty of many university physics students in applying and interpreting algebraic sign conventions consistently. Examples from dc circuits, thermodynamics, and optics are given.

162. "The vector knowledge of beginning physics students," R. D. Knight, Phys. Teach. **33**, 74-78 (1995). A study involving about 300 university engineering students probed their understanding of vectors. After mathematics and physics courses in high school and a semester of college calculus, only one-third indicated familiarity with finding magnitudes or recognizing vector components.

E. Attitudes and beliefs of students

The attitudes and beliefs that students bring with them to class may influence what they learn in a physics course. The papers below report on studies conducted with university students in introductory courses.

163. "Learning physics vs. passing courses," H. Lin, Phys. Teach. **20**, 151-157 (1982). The author interviewed 25 students who were doing poorly in a university calculus-based physics course. He determined that many of their difficulties were related to inappropriate attitudes about learning and the nature of what is learned in a physics course.

164. "Two approaches to learning physics," D. Hammer, Phys. Teach. **27**, 664-670 (1989). Case studies of two students in an algebra-based university physics course revealed that they differed greatly in their understanding of what it means to "understand" physics.

165. "Cognition in scientific and everyday domains: Comparison and learning implications," F. Reif and J. H. Larkin, J. Res. Sci. Teach. **28**:9, 733-760 (1991). The spontaneous cognitive activities that occur in everyday life are compared with those required for learning science. The authors pinpoint differences and show how application of everyday cognitive expectations in a science class causes difficulties.

166. "Students' beliefs about conceptual knowledge in introductory physics," D. Hammer, Int. J. Sci. Educ. **16**:4, 385-403 (1994).

167. "Epistemological beliefs in introductory physics," D. Hammer, Cognition and Instruction **12**:2, 151-183 (1994).

The two papers above report on studies in which the author explored students' views about the nature of physics knowledge and their approaches to the cognitive content of physics. The author characterized their attitudes and beliefs along several dimensions.

168. "How novice physics students deal with explanations," J. S. Touger, R. J. Dufresne, W. J Gerace, P. T. Hardiman, and J. P. Mestre, Int. J. Sci. Educ. **17**:2, 255-269 (1995). Introductory physics students were asked to explain open-ended problem situations and to select which of a variety of types of explanations they preferred. Their recognition of appropriate concepts was highly situation dependent. They were frequently unable to interpret explanations given in everyday terms.

169. "Models in physics: Perceptions held by prospective physical science teachers studying at South African universities," J. J. A. Smit and M. Finegold, Int. J. Sci. Educ. **17**:5, 621-634 (1995). A study was conducted to determine how 200 pre-service physical science teachers in South Africa and Namibia interpreted the word "model" in a physics context. Many interpreted the term as a physical construct rather than as an abstract idea. This confusion exacerbated difficulties with the interpretation of physical models for light.

170. "Guest comment: Why undergraduates leave the sciences," E. Seymour, Am. J. Phys. **63**, 199-202 (1995). The author reports on the results of an extensive three-year study on the reasons why undergraduates leave science-based disciplines. More than half of the students who intended to major in physical science did not complete a major in science. Those who left did not differ in measured ability from those who remained.

171. "Differences in students' perceptions of learning physics," M. Prosser, P. Walker, and R. Millar, Phys. Educ. **31**:1, 43-48 (1996). The authors conducted open-ended pre- and post-surveys of first-year physics students at an Australian university. Most students had a superficial and inappropriate view of physics learning.

172. "Views about science and physics achievement: The VASS story," H. Halloun, AIP Conf. Proc. **399** (1997) 605-613. (See ref. 9.) The author describes the development of the Views About Science Survey (VASS) to probe student attitudes about the nature of science. He classifies student attitudes in four broad profiles of increasing sophistication and correlates the profiles with performance.

173. "Student expectations in introductory physics," E. F. Redish, J. M. Saul, and R. N. Steinberg, Am. J. Phys. **66**, 212-224 (1998). The authors developed a survey to probe student cognitive attitudes and beliefs about physics. The Maryland Physics Expectations (MPEX) Survey is included in the appendix. Results from 1500 students at 6 colleges and universities indicate that student attitudes about physics tend to deteriorate, rather than improve, as instruction progresses.

F. Reflections on research into student reasoning

There are some papers that take a broad view on the interpretation or implications of experimental studies that do not easily fit into a content-oriented categorization.

174. "Analyzing students' reasoning: Tendencies in interpretation," L. Viennot, Am. J. Phys. **53**, 432-436 (1985). This paper discusses the danger of interpreting student responses through the filter of a physicist's perspective. Two examples from dynamics are cited.

175. "Research and computer-based instruction: Opportunity for interaction," L. C. McDermott, Am. J. Phys. **58**, 452-462 (1990).

176. "Use of the computer for research on student thinking," D. J. Grayson and L. C. McDermott, Am. J. Phys. **64** (1996) 557-565.
The two papers above describe the use of the computer as an instructional aid and as a research tool to examine student reasoning.

177. "More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research," D. Hammer, Am. J. Phys. **64**, 1316-1325 (1996). The author reflects upon what physics education research can bring to the discussion of instructional goals and strategies.

V. THEORETICAL PERSPECTIVES

As is appropriate in the early stages of any scientific field, most of the research in physics education has been empirical rather than theoretical. At present, there are no models of mental processes or theories of instruction nearly as well developed as the models and theories of physics. In order to build a theory of student learning in physics, it is necessary (in addition to a strong command of the subject) to have an understanding of human thought processes in a more general sense.

The relevant concepts for describing mental processes are not easily identified, operationally defined, or readily quantifiable. Theories of instruction do not have the same predictive capability nor are they falsifiable in the same sense as theories that pertain to the physical world. Despite these differences, a theoretical perspective can be useful for interpreting, organizing, and generalizing observations. Models for how students develop conceptual understanding and the ability to solve physics problems can help guide the development of instructional strategies. As in all sciences, comprehensive theories may reveal previously unrecognized relationships, identify questions for further investigation, and set new directions for research.

A. Concept development

In the references cited in this subsection, a major goal of the research has been the development of mental models that can be used to describe the process of conceptual change in students.

178. "Accommodation of a scientific conception: Toward a theory of conceptual change," G. J. Posner, K. A. Strike, P. W. Hewson and W. A. Gertzog, Sci. Educ. **66**:2, 211-227 (1982). A model that identifies elements needed for conceptual change is illustrated with an example in which students begin to make sense of special relativity.

179. "The role of conceptual conflict in conceptual change and the design of science instruction," P. W. Hewson and M. G. A'Beckett-Hewson, Instr. Sci. **13**, 1-13 (1984). The authors present a model for learning that describes conceptual change in terms of conflict between existing conceptions and new conceptions. The learner may adopt a new conception if it is "intelligible, plausible, and fruitful."

180. "Studying conceptual change: Constructing new understandings," D. I. Dykstra. See ref. 7, *Research in Physics Learning: Theoretical Issues and Empirical Studies*, pp. 40-58. Conceptual change is characterized by stages of "differentiation, class extension, and reconceptualization."[4]

181. "Facets of students' knowledge and relevant instruction," J. Minstrell. See ref. 7, *ibid.*, pp. 110-128. Student knowledge is described in terms of 'facets' that relate to content, strategies or reasoning. Instruction is viewed as an effort to help students modify existing facets, add new facets, and incorporate existing and new facets into a correct conceptual framework.

B. Problem-solving performance

Some theoretical research has been directed toward elucidating the process through which students develop skill in problem solving. In some instances, physics is used as a context to develop a model for problem-solving in a more general sense. The models for problem-solving performance discussed in the references below focus on physics and reflect a range of expertise that varies from novice to expert.

182. "Expert and novice performance in solving physics problems," J. H. Larkin, J. McDermott, D. Simon and H. A. Simon, Science **208**, 1135-1142 (1980). The authors examine the role of physical intuition in problem solving and conclude that experts use highly structured patterns of information to index and apply their knowledge.

183. "Knowledge structures and problem solving in physicists," F. Reif and J. I. Heller, Educ. Psychol. **17**, 102-127 (1982). The authors give a detailed description of a theoretical approach to problem solving in mechanics.

184. "Acquiring an effective understanding of scientific concepts," F. Reif, in *Cognitive Structure and Conceptual Change,* edited by L.H.T. West and L. Pines (Academic Press, Orlando FL, 1985), 133-151. Problem solving is described in terms of three main stages: description and analysis of the problem, construction of a solution, and testing of the solution. The ability to solve problems depends not only on the learning of procedures but also on the ability to draw on appropriate ancillary knowledge.

185. "Non-formal reasoning in experts and science students: The use of analogies, extreme cases and physical

[4] For a more detailed discussion, see Dykstra, D. I., "Studying conceptual change in learning physics," *Sci. Educ.*76(6): (1992) 615 - 652. This paper, which is published in a widely distributed journal, is more oriented towards science educators than the paper in the Bremen conference proceedings.

intuition," J. Clement, in *Informal Reasoning and Education,* edited by J. F. Voss, D. N. Perkins and J. W. Segal (Lawrence Erlbaum, Hillsdale NJ, 1991), 341-381. The author studied the uses of analogy by expert problem solvers and developed an instructional strategy in which analogies are used to help students build a "bridge" from their spontaneous conceptions to a more scientific understanding.

VI. PAPERS FROM RELATED FIELDS

Knowledge of relevant aspects of cognitive science, cognitive psychology and neuroscience are likely to play an essential role in the eventual development of accurate and useful theories. The extensive literature in these fields contains information relevant to physics education research. None of the references cited here requires an extensive background in either education or psychology.

A. Cognitive studies and physics education research

A number of physicists have considered how findings from cognitive psychology can help us understand how people learn in general and how they learn physics in particular. The papers below draw on relevant research in cognitive psychology.

186. "Can physics develop reasoning?" R. G. Fuller, R. Karplus and A. E. Lawson, Phys. Today **30**:2, 23-28 (1977).
187. "Wherefore a science of teaching?" D. Hestenes, Phys. Teach. **17**, 235-242 (1979).
188. "Solving physics problems -- how do we do it?" R. G. Fuller, Phys. Today **35**:9, 43-47 (1982).
189. "Implications of cognitive studies for teaching physics," E. F. Redish, Am. J. Phys. **62**, 796-803 (1994).

A number of books provide useful overviews for those interested in learning more detail about cognitive science.

190. *Readings in Cognitive Science,* A. Collins and E. E. Smith, (Morgan Kauffmann, San Mateo, CA, 1988). This is a collection of articles in cognitive science.
191. *The Mind's New Science: A History of the Cognitive Revolution,* H. Gardner, (Basic Books, New York NY, 1987). This is a brisk and entertaining review of the history of cognitive science up to 1985. Contributions ranging from anthropology to linguistics are covered.
192. *The Growth of Logical Thinking from Childhood to Adolescence,* B. Inhelder and J. Piaget (Basic Books, New York NY, 1958). This classic work by one of the founders of the cognitive approach contains many examples of how young children interpret the physical world.

A few references from educational specialists also give a useful overview of the relevant psychology.

193. *Educational Psychology,* D. Ausubel, (Holt, Rinehart and Winston, New York NY, 1968). A general introduction to the application of psychological ideas in education, this comprehensive book discusses concept development and discovery learning.
194. *Styles of integrated learning and teaching: an integrated outline of educational psychology for students, teachers and lecturers,* N. Entwistle, (John Wiley & Sons Inc., New York NY, 1981). This is one of the more accessible studies of the variability of styles and ways of approaching learning preferred by college students.
195. "Reassessment of developmental constraints on children's science instruction," K. E. Metz, Rev. Educ. Res. **65**:2, 93-127 (Summer, 1995). This article is a good review of the current state of understanding of the process of cognitive development.

B. Applications of cognitive studies to education

A number of references from education are particularly relevant to physicists interested in specializing in physics education research. Following are a few books and collections that can give the reader an entry into this extensive literature.

196. *Mental Models,* edited by D. Gentner and A. L. Stevens (Lawrence Erlbaum Associates, Hillsdale NJ, 1983).
197. *Cognitive Science and Mathematics Education,* edited by A. H. Schoenfeld (Lawrence Erlbaum Associates, Hillsdale NJ, 1987).
198. *Toward a Scientific Practice of Science Education,* edited by M. Gardner, J. G. Greeno, F. Reif, A. H. Schoenfeld, A. diSessa, and E. Stage (Lawrence Erlbaum Associates, Hillsdale NJ, 1990).
199. *Handbook of Research on Science Teaching and Learning,* edited by D. L. Gabel (MacMillan, New York NY, 1994).
200. *Cognitive Process Instruction,* edited by J. Lochhead and J. Clement (Franklin Institute Press, Philadelphia PA, 1979).
201. *Cognitive Structure and Conceptual Change,* L.H.T. West and A. L. Pines, (Academic Press, New York NY, 1984).
202. *Problem Solving and Comprehension,* A. Whimbey and J. Lochhead, (Lawrence Erlbaum Associates, Hillsdale NJ, 1991).

VII. RESEARCH-BASED INSTRUCTIONAL MATERIALS

The results of research in physics education are gradually beginning to be incorporated in the development of new curricula for students and handbooks for instructors. This section contains a short list of materials that have been recently published in the United States. In some instances, these have been developed by individuals and groups in conjunction with research. In other cases, the materials draw on research by others.

A. Instructional materials for students

For each of the student materials listed below, evidence of the research base is in published papers. We have not included materials (1) which are not yet published, (2) in which the basis in physics education research is undocumented in the literature, and (3) in which reference to education research is not specific to physics.

203. *ALPS: Mechanics (Vol 1), Electricity and Magnetism (Vol 2),* A. Van Heuvelen, (Hayden-McNeil Publishing, Plymouth MI, 1994).
204. *Overview Case Study (OCS) Study Guide,* A. Van Heuvelen, (Hayden-McNeil Publishing, Plymouth MI, 1995).
The above two items contain materials for a course in which students, guided by worksheets in interactive lectures, analyze physical situations. The first encounter with a topic is qualitative. Quantitative analysis follows. (See ref. 64.)
"Concepts first — A small group approach to physics learning," R. Gautreau and L. Novemsky, Am. J. Phys. **65**, 418-428 (1997) discusses an implementation and evaluation of the OCS materials.
205. *Understanding Basic Mechanics, Text and Workbook,* Frederick Reif, (John Wiley & Sons Inc., New York NY, 1995). Problem solving is taught through an instructional strategy that consists of three steps. An initial analysis includes a description of the problem situation, a summary of the goals, and a redescription of the situation in technical terms. The problem is then decomposed into subproblems. The third step consists of checking the solution. The steps are repeated if necessary. (See refs. 141, 144, 145, and 146.)
206. *Tools for Scientific Thinking,* David Sokoloff and Ronald Thornton, (Vernier Software, Portland OR, 1995).
207. *RealTime Physics,* David R. Sokoloff, Ronald K. Thornton, and Priscilla W. Laws, (John Wiley & Sons Inc., New York NY, 1999).
In the two curricula above, microcomputer-based laboratory activities engage students in graphing, including their own, in real time. Instant feedback helps relate the motions and their graphical representations. (See refs. 62, 69, 81, and 209.)
208. *Physics by Inquiry, Vols. I and II,* L. C. McDermott and the Physics Education Group at the University of Washington, (John Wiley & Sons Inc., New York NY, 1996). *Physics by Inquiry* is a set of laboratory-based modules in which the emphasis is on the development of concepts and scientific reasoning skills. Students work collaboratively in small groups, conduct investigations with simple equipment, and use their observations as a basis for constructing scientific models. These instructional materials are especially appropriate for preparing prospective and practicing teachers to teach physics and physical science at the pre-college level. (See refs. 26, 27, 30, 58, 88, 100, 107, 108, and 116.)
209. *Workshop Physics Activity Guide,* P. Laws, (John Wiley and Sons, Inc., NY, 1997). Instruction is based on a four-part learning sequence. Students make predictions about a phenomenon, reflect on their observations and try to reconcile any differences; they develop definitions and equations from theoretical considerations; they perform experiments to verify predictions based on theory; they apply their understanding in solving problems.
"Millikan lecture 1996: Promoting active learning based on physics education research in introductory physics courses," P. Laws, Am. J. Phys. **65**, 14-21 (1997)
"Calculus-based physics without lectures," P. Laws, Phys. Today **44**(12), 24-31 (1991).
The two papers above describe the Workshop Physics curriculum and its effectiveness in some detail.
210. *Tutorials in Introductory Physics,* preliminary edition, L. C. McDermott, P. S. Shaffer, and the Physics Education Group at the University of Washington (Prentice Hall, Upper Saddle River NJ, 1998). This supplementary curriculum can be used in conjunction with any standard introductory physics textbook. The tutorials are designed to be used in small group sessions in which three or four students work together collaboratively. Worksheets guide students through the reasoning required to develop and apply important concepts and principles. (See refs. 26, 27, 30, 43, 47, 58, 70, 88, 100, 107, 108, 111, and 116.)
211. *Minds on Physics*, Activities and Reader (6 volumes),W. J. Leonard, R. J. Dufresne, W. J. Gerace, and J. P. Mestre (Kendall/Hunt, Dubuque IA, 1999-2000). These volumes contain many activities to help students explore their existing concepts and learn to reason scientifically.

Some of the instructional materials listed above formed the basis of sample classes given at the 1996 ICUPE. These (and others) are described in greater detail in the proceedings of that conference. (See ref. 9.)

B. Guidance for instructors

Below are a few references on teaching physics that instructors may find useful. Although some of the instructor's guides have been developed for implementing the instructional materials above, their applicability extends beyond a particular curriculum.

212. *A Guide to Introductory Physics Teaching,* A. B. Arons, (John Wiley & Sons Inc., New York NY, 1990).
213. *Homework and Test Questions for Introductory Physics Teaching,* A. B. Arons, (John Wiley & Sons Inc., New York NY, 1994).
214. *Teaching Introductory Physics,* A. B. Arons, (John Wiley & Sons Inc., New York NY, 1997). The two volumes above and a new section on energy and momentum have been combined into a single volume.
Drawing on his extensive classroom experience, in the three items above, the author provides guidance for physics teachers on the nature of student difficulties and on instructional methods that he has found effective.
215. *Preconceptions in Mechanics: Lessons dealing with conceptual difficulties,* C. J. Camp, J. Clement, D. Brown, K. Gonzalez, K. Kudukey, J. Minstrell, J. Schultz, K. Steinberg, M. Veneman and A. Zietsman, (Kendall/Hunt, Dubuque IA, 1994). This volume discusses student preconceptions in mechanics and contains a series of lesson plans that are designed to build a bridge from common preconceptions to a more scientific view.

216. *Instructor's Manual for Understanding Basic Mechanics,* Frederick Reif, (John Wiley & Sons Inc., New York NY, 1995). This guide to the author's mechanics text and workbook (ref. 205) discusses problems and pitfalls involved in teaching mechanics. It also gives an overview of general cognitive and pedagogical issues, as well as many references.

217. *Peer Instruction, A User's Manual,* Eric Mazur, (Prentice Hall, Upper Saddle River NJ, 1997). The author describes a general strategy for promoting intellectual engagement by students in large courses. At several points during the lecture, the instructor presents a qualitative question and multiple-choice responses that together are designed to reveal common conceptual difficulties. Many examples are provided.

218. *Instructor's Guide for Physics by Inquiry,* L. C. McDermott and the Physics Education Group at the University of Washington, (John Wiley & Sons Inc., New York NY, 1998). The Instructor's Guide outlines the goals of particular exercises and experiments in ref. 208.

219. *Instructor's Guide for Tutorials in Introductory Physics,* L. C. McDermott, P. S. Shaffer, and the Physics Education Group at the University of Washington (Prentice Hall, Upper Saddle River NJ, 1998). The Instructor's Guide provides pretests, sample examination questions, and additional information on individual tutorials in ref. 210.

VIII. OTHER RESOURCE LETTERS RELEVANT TO PHYSICS EDUCATION

Of the approximately 120 Resource Letters that have been published in the past 30 years, only a few have physics education as their primary focus. Although the ones cited below are not on research, they address important related issues.

220. "Resource Letter: AT-1: Achievement Testing," H. Kruglak, Am. J. Phys. **33**, 255-263 (1965).

221. "Resource Letter: ColR-1: Collateral Reading for Physics Courses," A. M. Bork and A. B. Arons, Am. J. Phys. **35**, 71-78 (1967).

222. "Resource Letter: EP-1: Educational Psychology," J. W. George Ivany, Am. J. Phys. **37**, 1091-1099 (1967).

223. "Resource Letter: PCP-1: Pre-College Physics Curriculum Materials," L. G. Paldy and C. E. Swartz, Am. J. Phys. **41**, 166-178 (1973).

224. "Resource Letter: PhD-1: Physics Demonstrations," J. A. Davis and B. G. Eaton, Am. J. Phys. **47**, 835-840 (1979).

IX. CONCLUSION

Traditionally, physics instruction has been based on the instructor's view of the subject and perception of the student. As many of the references included in this Resource Letter demonstrate, the same instruction may appear very different to the instructor and to the student. Improving the match between teaching and learning requires knowledge about how students think. Results from research have proved to be extremely useful as a guide to the development of effective instruction.

In the past two decades, research in physics education has emerged as a field of scholarly inquiry in which physicists are actively engaged. They are conducting systematic investigations that are contributing to a steadily growing research base. For this resource to be useful to the physics teaching community, however, studies must be documented in the literature and subjected to the scrutiny and challenges of peers as in traditional areas of physics research. Only in this way is cumulative progress possible.

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