Toward a scientific practice of science education

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Publisher's Note
The publisher has gone to great lengths to ensure the quality of this reprint but points out that some imperfections in the original may be apparent.

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Foreword

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Marjorie Gardner
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This book reflects a vision of a field that is in the process of development. We believe that a revised and advanced field of science education can emerge from the convergence and synthesis of several current scientific and technological activities. This book includes some examples of research progress of the kind that we hope will form the integrated discipline of science education.

The papers in this volume were presented at a conference that was an effort toward this revision and advancement. At a previous meeting in 1986, members of the communities of science educators, cognitive scientists, and educational technologists met to discuss and formulate a research agenda for science education. In addition to a report of the group's conclusions (Linn, 1987), the meeting accomplished a step toward forming an inclusive community of research and development for science education.

The participants in the 1986 meeting agreed that there is an important agenda for research in science education and that the communities of science educators, science-education researchers, cognitive scientists, and technologists bring important perspectives and capabilities to that scientific activity. They did not completely agree on every point that should be on the agenda or on the relative importance of the points, but that is as it should be. The community should not try to work in a single-minded way, but rather should pursue a collection of overlapping but nonidentical goals and thereby discover which directions are most productive. The shared sense of the group, however, was that important programs of research and development are being pursued, and that some of the community's effort should be directed toward bringing these various activities into closer contact. This led to our decision, along with our colleagues, to hold a conference in 1988, at which the papers in this volume were presented. We invited individuals working on the social context of science learning, in addition to technology, cognitive science, and science education researchers.

The conference that this volume presents was, in part, a test of the hypothesis developed at the 1986 meeting, namely, that there is an important agenda for research in science education and that the various communities of researchers are engaged in work that is significant for the development of a new integrated field. We decided to test this hypothesis directly by bringing together individuals from the various communities to present their work and encourage discussion among the participants.

The first condition for developing a new intellectual field is the existence of research problems that are productive and about which the community can interact meaningfully. We believe that this condition is met, and we present this book as our evidence. These are not the only examples of work that would be synthesized in the field of science education; any meeting represents a partial sample. But the point we wish to make is that significant examples exist, and we hope that our colleagues agree that these papers definitely establish that.

Another condition for developing this field is that individuals working in its various subcommunities interact productively about each other's problems as well as their own. This is harder to demonstrate in a volume of research papers, but on the basis of our experience in the two meetings, we are optimistic about that as well. The discussions were mutually engaging and spirited, and participants' comments about the meetings were positive. Many individuals at the meetings met each other for the first time and apparently were favorably impressed. Most of the final versions of papers that you can read here differ significantly from the versions that were presented, reflecting comments and questions that were given by other participants. The shared sense of engagement, including agreements as well as significant unresolved issues, is reflected in the summary section that Linn contributed to this book. The development of a genuine scientific community is a long-term process, of course, but we see the success of these meetings as a positive sign.

Organization of the Book

The papers in this book are in four sections, reflecting four research traditions that we feel can come together in a scientific practice of science education.

First, there is a community of science-education researchers whose intellectual homes are in the study of curriculum and teaching of scientific disciplines. Discipline-based research and development was the main activity of the science-education field during the important period of curriculum reform in the 1950s and 1960s and continues to play a major role.

A second community of researchers in cognitive science studies general principles of learning, knowing, understanding, and reasoning. Cognitive science is, itself, a field in the process of development, forming as a convergence of parts of artificial intelligence, cognitive psychology, linguistics, philosophy, and other disciplines. The research in this developing field differs from earlier research, especially in psychology, in a way that is important for science education. Modern cognitive science attends to the content of information that people learn, know, understand, and reason with. Earlier research on cognition was abstract and content-free; however, in cognitive science beginning in the late 1950s, simulation models of cognitive structures and processes include hypotheses about the specific information structures that are known and understood and the specific reasoning operations that are applied to those structures.

Until about 10 years ago, the communities of discipline-based educators and cognitive scientists had very little in common. Since the late 1970s, however, there has been an increasing tendency for cognitive scientists to be concerned with problem solving, knowing, and learning in subject-matter domains, especially in mathematics and science. And simultaneously, there has been an increasing tendency for scientific discipline-based researchers to make use of theoretical and empirical methods developed in cognitive science in their research and development of instruction. Both of these trends are evident in the papers in the first two sections of this volume. Much work remains before the science of cognition and discipline-based educational research and development are well integrated, but there is a strong and growing intellectual basis for that integration, if the communities of researchers choose to develop it.

The third section of papers is concerned with the social context of learning, a topic on which a body of interdisciplinary research and development is beginning to grow. Studies of cognition in everyday settings are shedding interesting new light on the capabilities of individuals to reason successfully about quantities and causal relations in the world, and relations between this everyday reasoning and school learning are just beginning to be examined. Investigations of social organization of schools, including socially determined attitudes toward schooling and participation in group activities, benefit strongly from use of concepts and methods developed in the social sciences. We are hopeful that a convergence of methods and concepts of social science, cognitive science, and discipline-based educational study can develop productively to broaden the scientific base of science education.

The final section of this book presents discussions of educational technology in science and mathematics education. Development of advanced technology for education has had somewhat disconnected components, with some efforts related primarily to discipline-based concerns, some to cognitive studies, a few to social concerns, and several to general concerns of artificial intelligence. The development of complex technological systems can serve as a vehicle for further integration of these various intellectual strands as papers in this volume indicate.

The Idea of a Scientific Practice

The title we chose for this volume is a coined term, and it may bear a brief discussion. As we envision the developing field of science education, it would become an integrated disciplinary activity including development of resources and materials for science education as well as development of ideas about learning, knowing, and reasoning in science. The field would also be engaged in continuing evaluation, refinement, and restructuring of these resources and ideas. We believe that the model of basic research by a group of scientists, with results that inform practice by a group of educators, is misconceived. The search for knowledge and understanding and the development of educational resources must be concurrent concerns and interactive activities. The alternative vision, which we prefer, has inquiry coupled with development of resources so that development is guided by and informs the growth of scientific principles and concepts, and scientific inquiry addresses questions that are important in practice. Such a melding of inquiry and practice might well be called either a practical science or a scientific practice of science education. By either name, we hope that these papers contribute to its development; we'll hope and work for its continued progress.

ACKNOWLEDGMENT

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I VIEW FROM THE DISCIPLINES

Marjorie Gardner
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Whether from the natural or from the synthetic world, science is a whole fabric, a beautifully interwoven tapestry. Humans split it into disciplines for study purposes. We compartmentalize in order to handle its many subtle complexities, yet we yearn to integrate as evidenced by so many efforts toward interdisciplinary science and mathematics.

For the opening session of the Research Conference, active researchers from each of the four traditional areas of science instruction—biology, chemistry, mathematics, and physics—were asked to summarize recent research results, current trends, and recommendations for important research projects for the future. The purpose was to set the framework for the more interdisciplinary sections to follow. James Stewart from the University of Wisconsin at Madison reports on biology; Dudley Herron from Purdue University reports on chemistry; Jack Lochhead from the University of Massachusetts at Amherst reports on mathematics; and Lillian McDermott from the University of Washington reports on physics. Their chapters and reference lists provide the reader with a useful summary, a wealth of ideas and sources.

McDermott notes that there has been more research on learning and teaching of physics than in any other science discipline. She discusses physics educational research from three perspectives, that of the cognitive psychologist, the physics instructor, and the science educator. Major attention is then given to research efforts directed toward elucidating students' understanding of physics concepts, scientific representations, and the reasoning required for the development and interpretation of both concepts and representations. Questions for future studies are identified for each of the three areas she discusses.

Herron takes the constructivist point of view as he reviews recent research in chemical education and looks to the future. Citing research done in the United

States and internationally, he critiques research efforts related to problem solving and conceptual understanding. In surveying research in these two major areas, Herron explores misconceptions, experts versus novices, and representations. The chapter concludes with a section that looks to the future by summarizing our current knowledge and identifying research that is needed.

Stewart begins by noting that the biological sciences are the most commonly taught sciences at all levels as well as the most rapidly changing due to the current biological "revolution." The first half of the chapter is concerned with the current state of biological sciences educational research; the second part deals with the future and identifies some of the important research that needs to be done. Stewart notes that much of the research to date has been of the correlation studies type as he surveys results of these studies at the elementary, secondary, and university levels. More sophisticated studies concerned with genetics and evolution are then reviewed. Studies of the uses of advanced technology including the computer are surveyed. In looking to the future, he calls for a research consortium in biological science education. The research for such a consortium might include continuation of descriptive research studies, problem-solving research, and research related to the findings of cognitive scientists.

Lochhead describes the recent, rapid, almost explosive advancements in the mathematical sciences as well as the heavy demands on mathematics education for advances in research. He identifies needed changes throughout the chapter and calls for flexibility, and the capacity to respond to rapid change. He also examines some of the predictable changes in terms of the curriculum and instructional materials, modes of instruction and student learning strategies (e.g., problem solving, metacognition). The role and use of calculators and computers are explored in terms of current research. Lochhead turns near the end of the chapter specifically to recommended areas for future research.

As the "View from the Disciplines" was unveiled, the current somewhat fragmentary nature of research became more apparent and elevated awareness of the need for longitudinal studies and team efforts. Three common threads are identifiable in the four chapters: attention to problem solving, the constructivist view of how students learn, and the role of technology in instruction. Little cross-disciplinary work is being done. Researchers identify themselves as mathematicians, chemists, physicists, biologists or geologists when doing educational research. All four authors recognize that students construct knowledge for themselves and that their knowledge of rules, formulas, and algorithms is virtually useless unless they can apply what they've learned to novel situations. In the three science papers, there's further acknowledgment of the importance of understanding the origin of student misconceptions. The need for interdisciplinary collaborative effort and/or perhaps more importantly for Research Centers where resources can be garnered for in-depth and longitudinal studies become evident.

"View from the Disciplines" serves as a backdrop for the more interdisciplinary areas of Instructional Design, Science Education in the Social Context, and the Impact of Technology.

1 A View From Physics

Lillian C. McDermott
University of Washington

INTRODUCTION

There has been more research on the learning and teaching of physics than on any other scientific discipline. Until recently, most investigations have focused on mechanics, particularly on kinematics and on the relation between force and motion.[1] The field of inquiry is now considerably broader and includes several other content areas such as heat, electricity, and optics.

Physics has been chosen as a domain for investigation by cognitive psychologists, science educators, and physicists. These groups share some of the same goals, but their primary motivation for doing research is often different. As a consequence, they often do not ask the same questions and even when they do, they may interpret the same answers in different ways. The broad range in perspective is illustrated by the diagram in Fig. 1.1 In actual practice, differences among the groups are not as sharply defined as they appear in the diagram.

The nature of a paper on the status and future of research in physics education is likely to be strongly influenced by the background and orientation of the author. The point of view taken here is that of a physics instructor whose primary motivation for research is to understand better what students find difficult about physics and to use this information to help make instruction more effective.[2] The

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[1]For an overview of research on conceptual understanding in mechanics, see McDermott (1984).

[2]For examples of the author's approach to research in physics education, see Trowbridge & McDermott (1980, 1981); Goldberg & McDermott (1986, 1987); McDermott, Rosenquist, & van Zee (1987); Lawson & McDermott (1987). For examples of the application of this research to curriculum development, see Hewson (1985); Rosenquist & McDermott (1987).

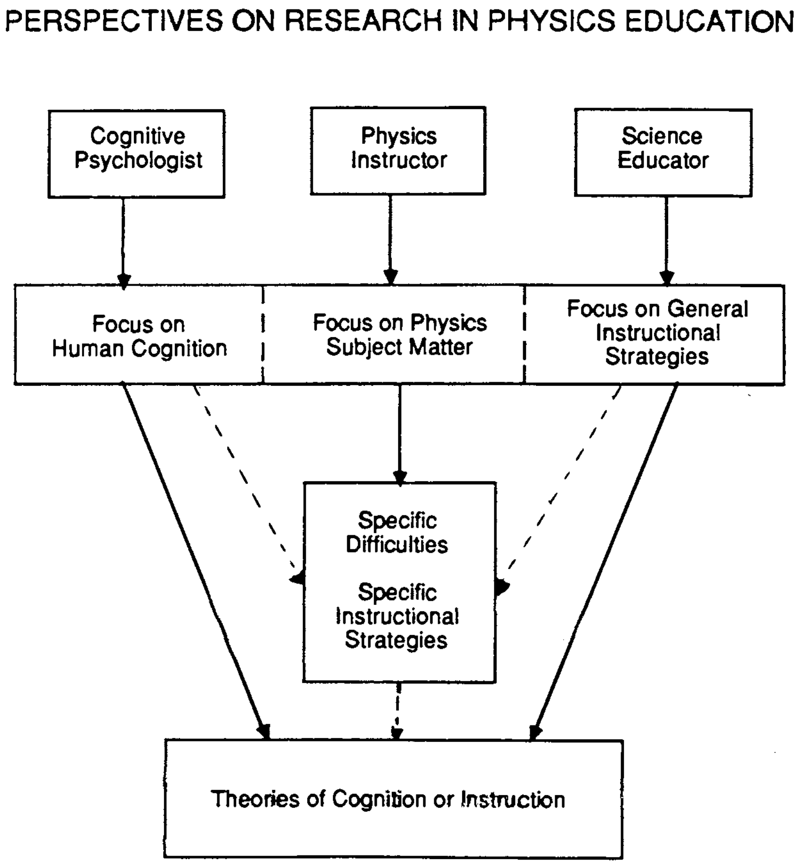

FIG. 1.1. Physics has been chosen as a domain for investigation by cognitive psychologists, science educators, and physicists.

direction and methods for research are derived from an interest in physics for its own sake and an interest in teaching that particular subject. The emphasis in the research is to identify specific difficulties and to develop instructional strategies to address these difficulties. This focus is not meant to imply a lack of interest on the part of the author in the general theoretical and instructional issues that concern the cognitive psychologist and science educator; rather, the approach reflects a pragmatic attitude toward instruction that is common among physicists who teach the subject. The empirical emphasis is also a consequence of the belief that the most effective way to improve instruction is by first concentrating on specific instances and generalizing only at later stages.

Some physicists hold a contrasting point of view.[3] As shown in the diagram in

[3]For a discussion by a physicist with a more theoretical perspective, see Reif (1986, 1987 a & b); Hestenes (1987).

Fig. 1.1, this perspective is closer to that of cognitive psychologists. Physics has proved to be an appealing domain for studies that focus on problem-solving. The interest that drives the research of these investigations is often less on specific subject matter and more on underlying thought processes. An important goal for cognitive psychologists is the development of theoretical models of human cognition that can be used as a basis for planning instruction.[4]

Still another approach toward research in physics education characterizes the work of science educators. The title, as used in this paper, does not refer to the science instructor who is a subject matter specialist, but is reserved for those who are directly concerned with the education of teachers or with curriculum and instruction in the schools. As indicated in Fig. 1.1, science educators are usually more broadly interested in teaching science in general than physics in particular. Although physics may provide the context, the focus for research is often on the development of instructional strategies and theories of instruction that extend beyond the teaching of physics.[5]

The particular view that is presented in this paper has evolved over several years and has been influenced by the experience of the Physics Education Group at the University of Washington. The group, which is an integral part of the Physics Department, is actively involved in teaching physics to students with a wide variety of preparation. The instructional environment provides a setting for conducting research and curriculum development from a strong disciplinary perspective. We have found it useful to organize these activities into categories that correspond to various aspects of student understanding in physics. Our investigations are directed toward elucidating the following aspects of student understanding: the concepts of physics, scientific representations (e.g., diagrams, graphs, equations), and the reasoning required for the development and interpretation of both concepts and representations. We make use of problems primarily to gain insight into conceptual and reasoning difficulties rather than to examine problem-solving capability as an end in itself. There is a major emphasis in our research on the ability of students to make connections among concepts, representations, and real world phenomena.

In this paper, the organizational structure for discussion of research will be provided by a loose classification scheme consisting of four categories: (a) concepts, (b) representations, (c) reasoning, and (d) problem solving. These are not mutually exclusive. An investigation may fit equally well into more than one category. The choice has been determined by the aspect of research that a particular study is used to illustrate. To call attention to recent work outside of mechanics, the illustrations have been drawn from other content areas whenever possible.

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[4]For a discussion by a cognitive psychologist about implications from research for physics instruction, see Larkin (1980).

[5]For a discussion by a science educator about applications of research results to physics instruction, see Gilbert & Watts (1983); Champagne, Gunstone, & Klopfer, (1985).

CONCEPTS

The discussion in this section focuses on a line of research in which qualitative interpretation of a concept is required. The task presented to the students may involve real objects and actual events or deal with a hypothetical situation. Most investigations in which actual equipment is used involve one-on-one interviews or small group activities in which there is dialogue between the investigator and students. Sometimes a laboratory demonstration provides the basis for written questions simultaneously administered to a large group. In other investigations, the task is presented only in written form and student response is entirely in writing.

Criteria for Understanding

The determination of what constitutes adequate conceptual understanding depends on the type of study and on the point of view of the investigator. In investigations based on actual phenomena that the student observes or can easily imagine, the emphasis is on the ability of students to use a concept (or set of concepts) correctly in performing a specified task. The criteria may include some or all of the following: (a) The ability to apply the concept to the situation observed and to describe the reasoning used; (b) the ability to recognize circumstances under which the concept is or is not applicable; and (c) the ability to distinguish clearly between the concept under scrutiny and similar but different concepts that might apply to the same situation. In some investigations, the emphasis may be on student facility with different ways of representing the concept (e.g., diagrams, graphs, equations) or with the ability to make connections among these representations and the real world.

Many studies do not involve actual apparatus. Questions about a physical situation may be described on paper or on a computer screen. There may or may not be supplementary interviews. In cases in which the student responds only in writing or by typing on a keyboard, it is much more difficult and often impossible to extract the amount of conceptual detail that the interview situation allows. On the other hand, mass testing by questionnaire or computer allows the investigator to estimate the prevalence of a particular response.

Some studies place less emphasis on the ability to apply concepts than on the ability to relate a set of concepts that may be applicable under certain general conditions. The students are encouraged to think about the concepts from a theoretical perspective. For example, there have been a number of studies in which students are asked to draw "maps" showing relationships among concepts. From the ways in which students group the concepts, indicate a hierarchy, and show connections, inferences are drawn about the level of conceptual understanding. In such cases, the criterion for understanding refers to the accuracy and level of sophistication that the student demonstrates in drawing the diagram.

Misconceptions

Although the methods of research are diverse, some generalities emerge. Students have certain incorrect ideas about physics that they have not learned through formal instruction, or at least that they were not intentionally taught. Some have resulted from misinterpretation of daily experience; others are of a different origin. To the degree that these ideas are in conflict with the formal concepts of physics, the physicist considers them to be "misconceptions." The term misconceptions will be used here although it is recognized that some investigators would rather refer to alternate conceptions.

It has been shown by a number of studies that students often complete a physics course with some of the same misconceptions with which they began. Furthermore, certain errors are characteristic of student responses to certain types of questions (see footnote 1). These observations have led some investigators to hypothesize that students bring to the study of physics a strongly held system of beliefs about how the world operates (McCloskey, 1983). A contrasting point of view is that students' knowledge of the world is fragmentary and unstable, with a tendency to shift according to the context (di Sessa, 1988). There is disagreement about whether certain observed regularities in response occur because students have a mental model for cause and effect or for some other reason. For example, perhaps the similar features among answers are simply elicited by the way in which the questions are asked (Viennot, 1985a, 1985b).

Although there is a difference of opinion about whether or not students have a consistent system, there is no doubt that there are some common misconceptions that do not disappear spontaneously as the relevant material is taught. To bring about conceptual change, it is frequently necessary to make a conscious effort to help students reject certain ideas and accept others (Strike & Posner, 1982). The way such instruction is designed may be influenced by the inferences made about how students think.

Constructivist Epistemology

The results from research are consistent with the view that the mind is not a blank slate upon which an instructor may write correct statements that the student can learn passively. It is also clear that, whatever their origin, incorrect ideas that are well entrenched in the student mind may interfere with the ability to learn what is being taught. These circumstances have led to an interest in constructivist epistemology among science educators. Basic to this approach are the beliefs that (a) Each individual must actively construct his or her own concepts, and (b) that the knowledge that a person already has will determine, to a large extent, what he or she can learn. The implications for instruction that can be derived from these tenets may be used to guide the design of curriculum from precollege through undergraduate levels (Driver & Bell, 1986; Schuster, 1987).

Linguistic Complications

It is not only common experience with the physical world that leads students to develop ideas that contradict those of the physicist. Linguistic elements also play an important role. Often the picture conjured up in a student's mind is different from the meaning the words are intended to convey. For example, a physics student who reads a problem about a ball that is "dropped" in an ascending elevator may not realize that in this case the ball initially moves upward with respect to the ground. When words have both a technical and colloquial meaning, the concepts that are associated with them may be muddled. Terms like *force* and *energy* that are understood in an unambiguous way by physicists are often interpreted by students in a context-dependent manner (Touger, Dufresne, Gerace, & Mestre, 1987).

Quite apart from the problems caused by differences in the everyday and technical use of a word, other linguistic complications may be introduced in the course of defining scientific terms. For example, Kenealy (1987) examined how various populations interpreted the statement: "Acceleration is the time rate of change of velocity." The definition is from one of the most widely used high school physics textbooks in the United States (Williams, Trinklein, & Metcalfe, 1984, p. 48). Participants in the survey included students in eighth grade through college and high school science teachers. A significant fraction of answers identified acceleration as an amount of time required to change a velocity.

Examples of Research

Theoretical Constructions: Concept Mapping in Electricity

An example of research in which a theoretical construction by the student constitutes the primary source of data is provided by the concept-mapping studies of Moreira (1987). One study involved engineering students in an introductory physics course at a Brazilian university. The students were asked to draw maps showing relationships among the main physical concepts that they had studied in electricity. They were also asked to write key words along the lines linking the concepts to make explicit the relationship between them. Upon completion, the maps were discussed on an individual basis with the students who drew them.

The map shown in Fig. 1.2 is a copy of one drawn by a student. The student has selected electric charge as the most important concept and linked it to electric current, electric field, and electric potential. However, the field and the potential are not linked to each other. (These links and the others shown as dotted lines were added during discussion of the map.) Electric force and potential difference did not appear on the original drawing. The ensuing discussion revealed that the student made no distinction between the concepts of potential and potential difference.

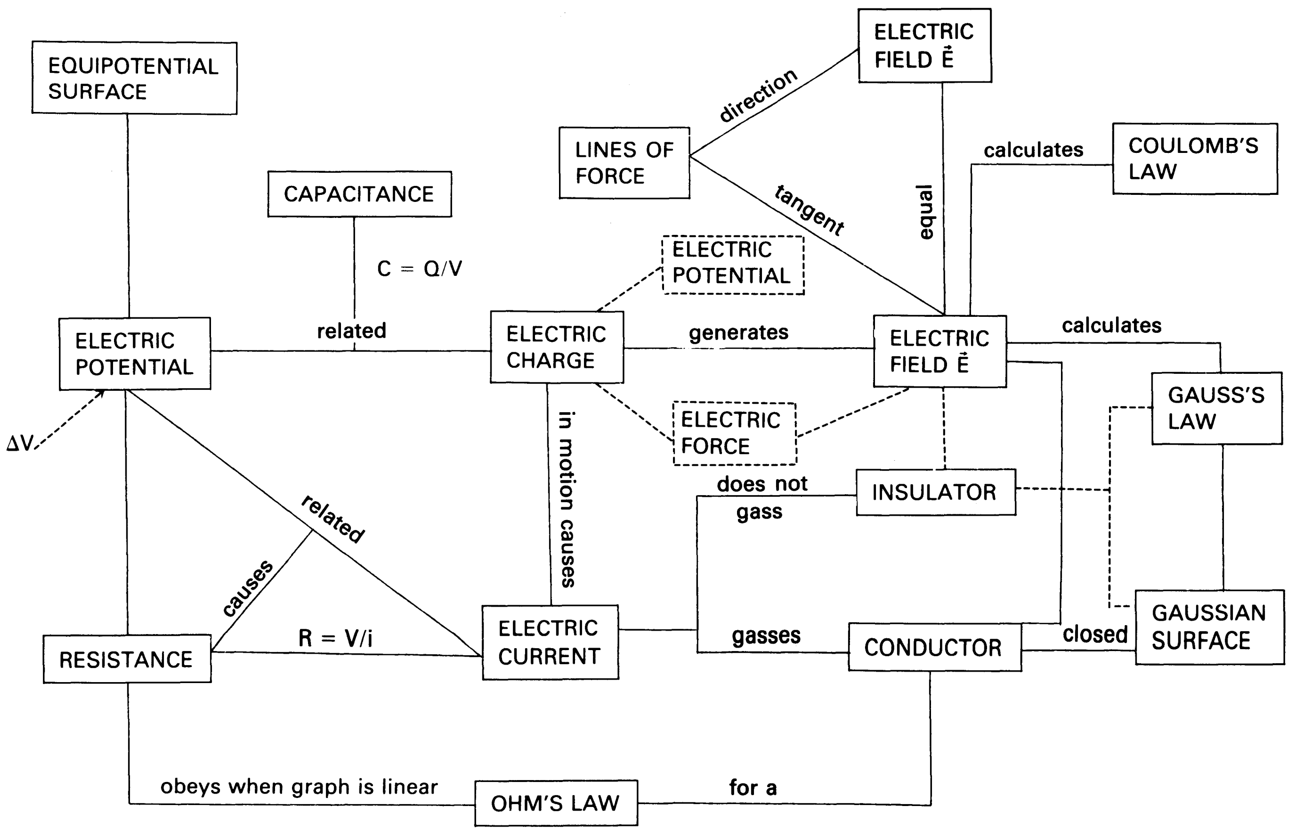


FIG. 1.2. Concept map in electricity drawn by a Brazilian engineering student taking introductory physics (Moreira, 1987).

Real Phenomena: Light and Image Formation in Geometrical Optics

Student observation, or visualization, of real phenomena forms the basis of much of the research on conceptual understanding in physics. To illustrate how different investigations can make a cumulative contribution to our knowledge of how students think about physical phenomena, we review briefly some of the research involving geometrical optics. Other topics (e.g., dynamics, electric circuits, or heat and temperature) could also have been used for illustration.

Children's Ideas about Light. A number of studies have identified some incorrect ideas about light that are common among children and adolescents (and sometimes among adults) who have not studied the topic formally.[6] It appears that before about the age of twelve children do not usually recognize light as an entity independent of its source or its effects. In the early teens, children begin to identify light as an entity that can travel in space and that can be obstructed and reflected. Their understanding of how light propagates is limited, however. Many believe that light travels farther from its source at night than during the day. They do not separate the idea of light from how bright it is. They also may think of light as a force acting on an object. Often seeing is considered an activity of the observer rather than the result of the reception of light by the eye.

From studies such as the foregoing, we can gain some insight about the state of knowledge with which many students begin formal study of optics. As a result of instruction in optics in high school or college, most of these naive ideas are superseded by concepts the physicist uses to explain how light is transmitted from a source to an observer and how objects can be seen. The vestiges of some of these ideas may remain, however, and may interfere with the development of a student's understanding of how an image is formed and seen.

Formal study of geometrical optics typically begins with the study of image formation by mirrors and lenses. Students learn how a lens or mirror can form an image of an object and how the location and size of the image can be predicted. They often do experiments with mirrors and lenses in the laboratory and almost always work problems involving images.

Student Understanding of Real Images. Documentation from research is beginning to bring about more awareness on the part of high school and college teachers that the ability to solve standard physics problems is no indication that a sound conceptual understanding has been achieved. Problems in geometrical optics are no exception, even though this topic is generally considered one of the

[6]For sources for the statements in the summary, see Piaget (1974); Tiberghien, Delacote, Ghiglione, & Matalon (1980); Guesne (1984); Stead & Osborne (1980); Watts (1985); Andersson, & Kärrqvist, (1983); Eaton, Anderson, & Smith, (1984); Feher & Rice (1985; Jung (1987).

simplest in a physics course. The following example illustrates how little we sometimes know about what students really understand if we look only at their ability to solve standard problems.

The illustration is taken from research conducted in collaboration with Fred Goldberg during the 2-year period he spent with the Physics Education Group at the University of Washington (Goldberg & McDermott, 1986, 1987). The work described is based on a task from an investigation on student understanding of the real image formed by a single mirror or lens. The students involved were volunteers from the introductory physics sequence required for majors in engineering, physics, and other physical sciences. Calculus is required for this course. Most of the data were collected from individual interviews in which students were asked a series of questions about a simple demonstration that they could observe. Each was shown the same demonstration and asked the same questions. The demonstration was a simple optical system consisting of a lens, a light bulb, and a screen, all mounted on an optical bench. A real, inverted image of the lighted filament of the bulb was visible on the screen, as can be seen in Fig. 1.3.

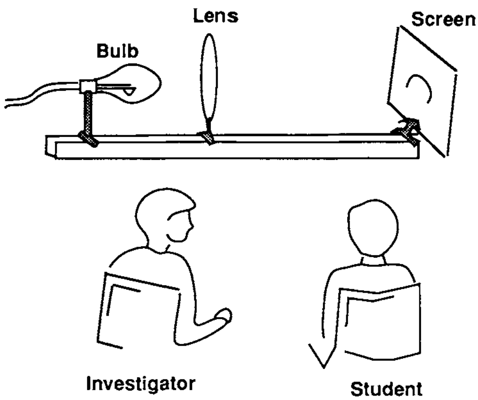


FIG. 1.3. Investigator asks student: "Suppose I were to cover the top part of the lens, leaving the bottom half uncovered. Would anything change on the screen?" The table shows the percentage of students who gave the correct answer both before and after instruction (Goldberg & McDermott, 1987).

Interview Data Summary

	Pre (N=36)	Post (N=23)
Complete image (correct)	0%	35%
Half of image	95%	55%
Other	5%	10%

Before discussing a question that caused the students difficulty, we first consider a task that they could perform. In exploratory interviews, we found that students who had completed geometrical optics could generally use the thin-lens formula to solve the following problem: Given the focal length and the object distance, predict the location, characteristics, and magnification of the image. The students could also solve the problem by drawing an appropriate ray diagram. Furthermore, they were able to check their solutions by using laboratory apparatus and could make the proper connections between the numbers from their algebraic solutions and the corresponding distances on an optical bench.

Let us now contrast what the students could do with what they could not do. During the individual demonstration interviews, the investigator asked the following question: "Suppose I were to cover the top part of the lens, leaving the bottom half uncovered, would anything change on the screen?" The results in Fig. 1.3 indicate that many students did not realize that the complete image could still be seen with only part of the lens.

In reporting the results, we refer to the students who had taken physics in high school but not yet at the university as prestudents, and those who had completed the optics portion of the university course as poststudents. None of the prestudents gave the correct response. About one third of the poststudents made a correct prediction. In spite of the fact that these students knew how to use the thin-lens formula, many did not know how to answer a basic question that they had not been asked before. By far the most common response was that only half the image would be seen if the upper half of the lens were blocked. Most students claimed that the bottom half of the image would disappear, a prediction consistent with their knowledge that the image in this situation is inverted.

It is not only the mistakes that students make that are of interest. The explanations they give in support of their answers can give us some insights into their thinking. A particularly interesting form of incorrect reasoning on the lens task is illustrated by the explanation offered by a student who drew an essentially correct ray diagram, similar to the one shown in Fig. 1.4.

The student drew two rays from the top of the object: (a) one parallel to the principal axis (ray #1), and (b) the other toward the center of the lens (ray #2). After passing through the lens, ray #1 was drawn so that it passed through the focal point and ray #2 was shown undeviated. The image was located at the point where the two rays intersected. The student described the ray-tracing procedure correctly, but then went on to say: "Now if you block off the top part of the lens, that would block off rays #1 and #2 from getting through, so the bottom of the image would be blocked. The bottom part of the object, which corresponds to the upper part of the image, would still be there."

Thus we have a situation in which a student was able to do all that is usually required on a typical examination but seemed to have totally missed a crucial concept in geometrical optics: From each point on an object, there are an infinite number of rays which, to close approximation, will converge at a single image

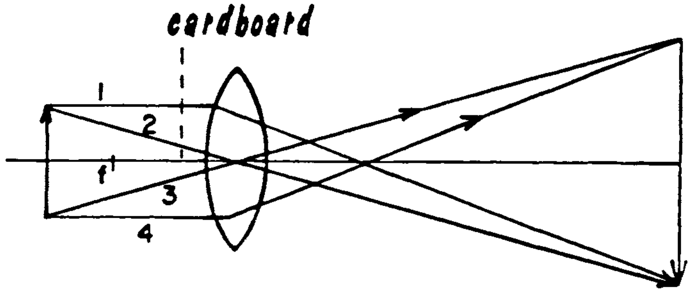


FIG. 1.4. A student was able to draw this essentially correct ray diagram even though the reasoning that half the lens would produce half the image was incorrect (Goldberg & McDermott, 1987).

point after passing through the lens. It is unlikely that a complicated numerical problem involving several applications of the lens formula would have revealed as much about conceptual understanding as the simple qualitative question asked. It is also worth noting that the belief that the two rays used to locate the image are necessary, rather than merely sufficient, must have developed during the course of instruction. Unlike some misconceptions, this one cannot be attributed to misinterpretation of everyday experience.

The results on the lens task cannot be explained on the basis that the participants in the study were poor students. It has been our experience that students who participate in interviews generally receive a grade of A or B in physics. The less capable students seldom volunteer. Moreover, when a multiple-choice version of this question was asked on final examinations administered to more than 200 introductory physics students, only about one fourth recognized that the entire image would remain intact if half the lens were blocked.

Questions for Future Study

The example taken from geometrical optics illustrates the kind of conceptual detail that research can provide. As mentioned earlier, most of the research so far has involved concepts in mechanics. To guide the design of curriculum, we need answers to questions such as those below for *all* topics in introductory physics.

What ideas do students have before instruction that might interfere with developing a sound conceptual understanding? Which ideas can be built upon to promote learning and which need to be changed? Are linguistic elements of such critical importance that they need to singled out for special attention? What conceptual difficulties do students encounter during instruction? What strategies can help overcome these difficulties? How can students learn to distinguish related concepts? What instructional techniques can help students make connections between concepts and real world phenomena? We need to know more about how conceptual understanding can be developed and how conceptual change can be fostered.

REPRESENTATIONS

An inability to use and interpret scientific representations of various kinds (e.g., diagrams, graphs, equations) is quite common among physics students. A number of studies have explored this aspect of student knowledge in which elements other than conceptual understanding are involved.

Diagrams

Diagrams are a form of scientific representation frequently used in physics as an aid in the analysis of a physical situation or in the solution of a theoretical problem. Examples are free–body diagrams in mechanics, ray diagrams in optics, and circuit diagrams in electricity. Diagrams offer a way to organize information into an easily accessible form, to show conceptual relationships that may not be evident from a physical layout or verbal description, and to make predictions.

Ray Diagrams

The ray diagram drawn by the student for the lens task described in the previous section is essentially correct in form. The student knows the geometrical algorithm for construction but is unable to interpret the information the ray diagram contains and do the reasoning necessary to make a prediction. Had the student drawn the third ray that can be used to locate the image, he or she might have realized that at least one ray would emerge from the lens. (This particular ray is drawn from the head of the arrow through the focal point. After passing through the lens, it emerges parallel to the principal axis.) However, in that case, the lack of understanding of the ray diagram might have passed undetected. In spite of having learned the procedure for drawing a ray diagram, the student cannot extract from it the implicit information.

As might be expected, secondary school students also have difficulty with ray diagrams. In a study conducted in India, Ramadas (1982) found that very few students could draw correct ray diagrams for even simple situations. From an analysis of responses to written test questions, she found that the students were generally unable to abstract from the situation described the information needed to construct an appropriate diagram.

Circuit Diagrams

Electric circuit diagrams are another form of scientific representation that students often do not interpret properly. Difficulties occur both in drawing dia-

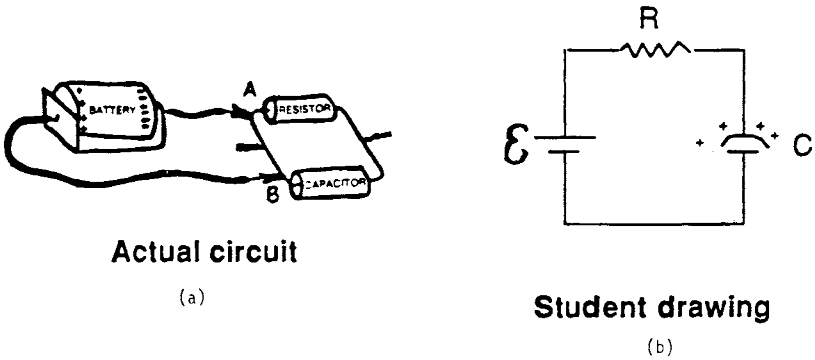
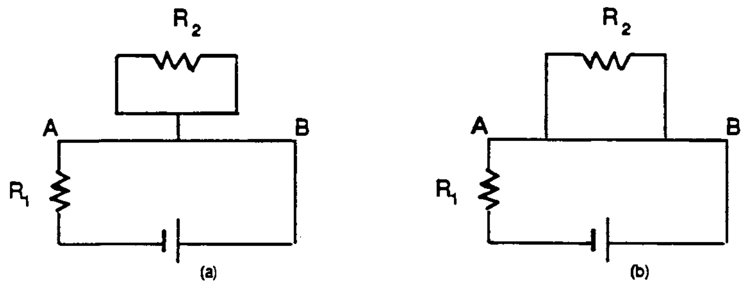


FIG. 1.5. (a) An actual circuit shown to a student during an individual interview; (b) Circuit diagram drawn by the student, who ignores the wire *AB* that connects the resistor and capacitor across the battery (Fredette & Clement, 1981).

grams to represent real circuits and in interpreting diagrams to answer questions about hypothetical circuits.

When Fredette and Clement (1981) asked students to draw circuit diagrams of actual circuits, they found that students frequently did not represent on their diagrams wires that "shorted out" elements in the circuit. The students seemed to think that shorting wires do not merit inclusion in a circuit diagram because they "don't really do anything." An example is provided by the circuit shown in Fig. 1.5a. In the diagram in Fig. 1.5b, which was drawn by a student, the wire *AB* that connects the resistor and capacitor across the battery is ignored. The failure to represent this wire may indicate one or more related problems. The student may not recognize that virtually all of the current will be in the shorting wire and may not interpret the situation as eliminating electrically the resistor and capacitor from the circuit. The student may not understand that the purpose of a circuit diagram is to show electrical connections as clearly and explicitly as possible.

Johsua (1984) found that responses by high school and university students to questions about identical electric circuits depended upon the way in which the circuit diagrams were drawn. When asked to describe the current between points *A* and *B* in the circuit of Fig 1.6, approximately 60% of the students answered correctly if the circuit was drawn as in Fig. 1.6a. However, only 25% answered correctly if the circuit was drawn as in Fig. 1.6b. Johsua found that students tended to view the lines on circuit diagrams as a "system of pipes" through which fluid can flow. In trying to decide how the current would be distributed, the students did not analyze the diagram to determine the potential difference between points *A* and *B*. Of course, the students' difficulties were not purely representational. As in most cases, difficulty with a scientific representation cannot be viewed apart from difficulty with the concepts involved.



Circuit	Correct	Wrong	No answer
a	62	31	7
b	26	68	4

FIG. 1.6. When asked to describe the current in the circuit between points *A* and *B*, approximately 60% of the students answered correctly if the figure was drawn as in (a), but only 25% answered correctly if the circuit was drawn as in (b) (Johsua, 1984).

Motion Graphs

Several recent investigations on scientific representation have been devoted to motion graphs. Similar types of errors have been found among students at all levels. Common difficulties include drawing and interpreting graphs as if they were spatial pictures and trying to use the height of a graph to extract information contained in the slope.

Microcomputer-based laboratories (MBLs), which were developed at the Technical Education Research Center (TERC), allow students to watch a graph being generated as an object moves. In particular, they can see an instantaneous graph of their own motion (Thornton, 1987). In one study 52 undergraduates, who were enrolled in a physics course for students majoring in the humanities, participated in a single MBL session. These students performed significantly better than calculus-level students on examination questions requiring interpretation of motion graphs (Thornton, 1987).

Graph-as-a-picture and slope/height confusion were the most prevalent difficulties identified by Mokros and Tinker (1987) during clinical interviews with 25 seventh and eighth graders. Mokros and Tinker examined the development of graphing skills among 125 students who participated in a series of MBL lessons, in which they made real-time graphs of their own motion. A multiple-choice quiz was administered as a posttest. The students were asked to match verbal descriptions and pictures of various motions with a set of motion graphs. The increased success in choosing correct responses on the posttest compared with preinstructional performance suggests that there was an improvement in ability to distinguish the graph of a motion from its physical appearance.

When a motion was described in words, 75% of the students selected an appropriate *position* versus *time* graph. However, when a motion was both described in words and sketched in a diagram, the students were less successful in choosing between the correct *velocity* versus *time* graph and one that resembled a picture of the motion. Another recent study suggests that the simultaneous movement of the student and production of the graph may be an important factor in the gains reported for MBL instruction. Even a short delay in feedback seems to be disadvantageous (Brasell, 1987).

In another investigation on graphing, students in a calculus-level physics course at the University of Washington were given the diagram of the ball and track shown in Fig. 1.7, as well as the following description: The ball moves with steady speed along the level segment, accelerates down the incline, and then continues at a higher constant speed along the last segment (McDermott, Rosenquist & van Zee, 1987; van Zee & McDermott, 1987). The students were asked to sketch position, velocity, and acceleration versus time graphs for the motion of the ball. The only correct response from 118 students is shown in Fig. 1.7.

From the types of errors that were made, it was possible to identify some specific difficulties. All but one student neglected the fact that each segment of the motion takes place in a shorter interval of time than the preceding one. There were many other more serious errors. A relatively common one was the drawing of two or more nearly identical graphs. More frequent was the apparent attempt to emulate the appearance of the track in the shape of the graphs. For example, half of the students represented the motion along the straight inclined track by a straight line on the x versus t graph instead of a curved line. Almost as many drew parallel lines for the first and third segments of that graph, perhaps because the corresponding track segments were parallel in space.

In an extension of this study, individual interviews were conducted to identify whether there were generalizable differences in approach between students who could sketch correct graphs and those who could not. It was found that the "experts" (successful students) differed from the "novices" (unsuccessful students) in several ways. Among the more striking contrasts in procedure were the following: (a) Experts generally began by defining the axes; novices started by drawing a line; (b) experts tried to match the shape of the graph to the way the variable was changing in time; novices often tried to match the shape of the graph to the shape of the path of the motion; (c) experts used a line to represent a constant value of x, v, or a during a time interval; novices sometimes represented a constant value with a single point; and (d) experts checked for consistency in slopes and heights among graphs; novices seemed to ignore or reject such relationships.

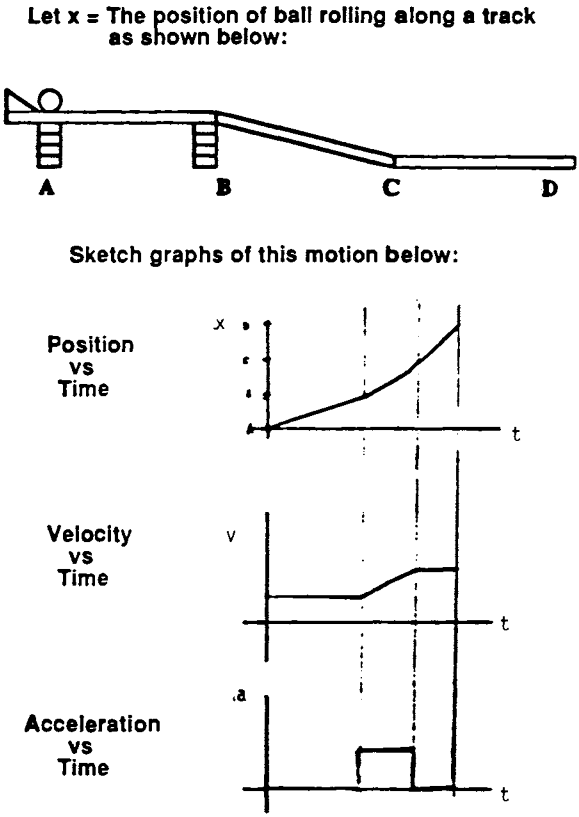


FIG. 1.7. Only one of the 118 calculus-level physics students was able to sketch these correct graphs for the motion of the ball on the track (van Zee & McDermott, 1987).

The generally poor performance on this task demonstrates a widespread inability even among mathematically able students to relate graphs to actual events. As in the case of the ray diagram and circuit diagrams previously discussed, there is a lack of understanding of the motion graph as a way of representing and analyzing real world phenomena.

Questions for Future Study

The examples above illustrate some of the difficulties students have with diagrams and graphs. The problems are not solely conceptual in nature, although lack of such understanding may play a critical role. To develop appropriate instructional strategies, we need to identify the specific difficulties students have with various representations. Diagrams, graphs, and equations all involve different ways of thinking. The nature of the problems encountered is different in each case.

An important question is the role of various representations in the development of conceptual understanding. Because different representations emphasize different aspects of a concept, the more ways one can represent a concept, the deeper one's understanding is likely to be. What type of instruction can help students make connections between a concept and various representations of that concept, between one representation and another, and between various representations and the real world?

Diagrams, graphs, and equations are useful in contexts other than physics. The ability to construct and interpret these representations is a valuable skill that is worth developing in its own right. Results from research indicate that the ability to use representations does not evolve spontaneously during instruction but must be specifically cultivated. What type of instruction can promote such development? How can students learn to transfer facility with a particular form of representation from one context to another?

REASONING

Many physicists would maintain that one of the most important benefits that can be derived from the study of physics is development of scientific reasoning skills. They see problem solving as contributing to this goal. However, there is no convincing evidence that reasoning ability improves as students work standard problems in an introductory course. Arons (1976, 1982, 1983, 1984 a, b) has written extensively about the necessity of designing instruction to promote development of the capacity to reason.

Several kinds of reasoning processes needed for scientific work could be developed in introductory physics. Among them are *proportional, ratio, analogical,* and *hypothetico-deductive* (model based) reasoning. The list is far from complete and the terms lack sharpness. However, they are sufficiently descriptive to convey the nature of certain reasoning skills that many physicists consider important.

Proportional and Ratio Reasoning

Although most students who survive a physics course can reason with proportions to some extent, many do not fully understand the meaning of the number obtained by carrying out the division specified in the statement of a proportion (Arons, 1976, 1983). For example, students often do not know how to interpret the meaning of the result obtained by dividing the mass of a substance by its volume. By referring to the formula they may recognize the result as the density, but they do not identify this number as the number of units of mass for each unit of volume. In other words, they do not picture a cubic centimeter of the substance as having a mass in grams numerically equal to the density.

Students have even more difficulty in reasoning with ratios when more than a simple proportion is involved. For example, unless numbers are supplied, many students cannot tell what happens to the electrostatic force between two charges when each charge is increased by a factor of four and the distance between them is halved. They cannot conclude that the force increases by a factor of 64.

Analogical Reasoning

The ability to reason by analogy is very important in physics. Physicists regularly use analogies to analyze unfamiliar systems in terms of systems they understand. Physics instructors make frequent use of analogies in teaching new concepts. For example, angular velocity and angular momentum are often introduced as analogous to the corresponding linear quantities. Relatively little attention is devoted to these topics in an introductory course partly because of time constraints, but also because the student is expected to understand the material by analogy to the linear situation. However, instructors know from experience that student understanding of dynamics is much poorer when rotations are involved.

There has been some research on the use of analogies for teaching concepts from physics. Gentner and Gentner (1983) examined how students used "flowing water" and "teeming crowd" analogies in making predictions about the current in an electric circuit. They were interested in determining whether the analogy had only a surface effect, that is, affected only the language used in speaking about the circuit or whether the analogy generated ideas that the students used in making predictions. It was found that there was a difference in the predictions that depended on which analogy was involved. The analogies seemed to have influenced the way the students thought about the circuits.

In another study, Clement (1987) found that high school students could reason with analogies if the corresponding quantities and relationships were made explicit and a great deal of time was devoted to consideration of the analogy. The focus of the research was not on analogical reasoning but on conceptual change in mechanics. Clement explored the effectiveness of using analogies to help students overcome some common misconceptions that seem to be firmly held. One of these involves the normal force exerted by a table on a book. Many students are unwilling to accept the idea that a table, an inert object, can exert a force upward on a book. In trying to address this difficulty, Clement used an approach similar to one used by Minstrell but placed greater emphasis on reasoning by analogy (Minstrell, 1982).

To make the existence of an upward force plausible, Clement introduces an anchoring situation to which the target situation (the book on the table) can be compared. For example, he might ask the students if a hand placed under a book exerts an upward force. Students usually admit that the hand exerts a force but

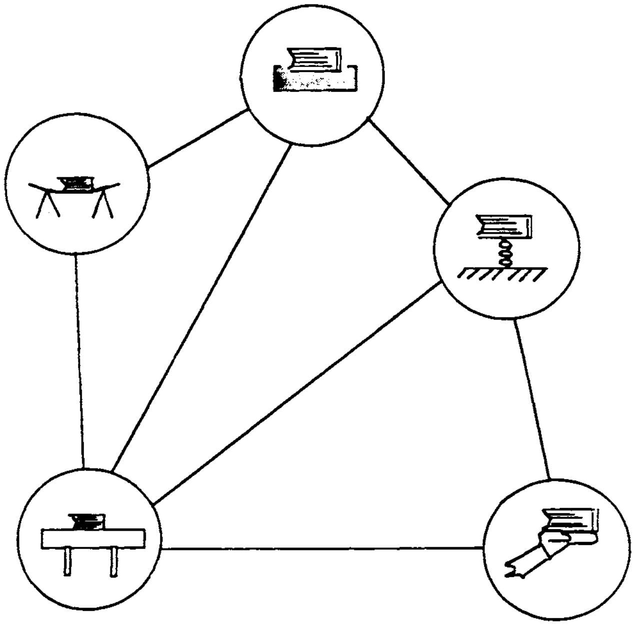


FIG. 1.8. An example of anchor, target, and bridging analogies that might be used to convince students that a table exerts an upward force on a book (Clement, 1987; Murray, Schultz, Brown, & Clement, 1987).

may not believe that an analogy between a hand and a table is valid. One is alive and one is not. To make this analogy more acceptable, Clement suggests one or more bridging analogies. A possible sequence is shown in Fig. 1.8. In this instance, a book on a coiled spring serves as an intermediate analogy. Although students usually recognize that the spring can exert an upward force when compressed from above, they often do not see the table and spring as analogous. Other bridging analogies may then be proposed, such as a book on foam rubber that sags or a book on a thin board that bends slightly. These analogies have the advantage that the deformation of the foam rubber or thin board suggests a mechanism that could account for the ability of the table to exert an upward force on the book.

When this teaching experiment was tried in several high school classes, there was a significant difference in favor of experimental over control groups in acceptance of the physicist's interpretation that the table exerts an upward force on the book. Similar results were obtained when analogies were used to help students understand frictional forces and Newton's third law. In each case, the instructors found that the students needed to participate in many discussions before they would accept the validity of the analogies that were suggested. When a belief is strongly held, it is particularly difficult to convince students that an analogy exists if acceptance of the analogy requires giving up the belief.

Clement and his associates have found that sometimes a long chain of bridging analogies is necessary to convince some students that the target and anchor systems are indeed similar with respect to the feature under consideration. To individualize instruction, the group has designed a prototypical computer program for an analogy-based tutor. The computer can generate a series of bridging analogies that can be selected to make long or short steps on the basis of student response (Murray, Schultz, Brown, & Clement, 1987).

Hypothetico-Deductive Reasoning

The construction of a scientific model involves many steps of inductive and deductive reasoning. The building of a model usually begins with an observation that may trigger an analogy. The analogy may suggest a hypothesis. The hypothesis is formulated with as few assumptions as possible. Deductions that follow are tested against other observations. The process is repeated. When necessary, new assumptions are made and new hypotheses generated. Constantly tested by observation, the model grows in complexity. It is continuously being verified and its predictive capability tested.

The process summarized above is important in physics. However, students in a traditional physics course seldom have the opportunity to become actively engaged in the type of thinking required. As a consequence, even good students who are mathematically able are often unable to reason from a scientific model and may not even understand what a scientific model is.

There are topics in introductory physics that can provide opportunities for students to gain direct experience in model-building (Arons, 1982). The study of electric circuits is one. There is some evidence that students who have developed a coherent model for an electric circuit from their own observations can remember and use this model to solve qualitative circuit problems that are difficult for students who have not had this experience (McDermott & van Zee, 1984).

Questions for Future Study

In addition to content, students taking physics are assumed to be learning the processes of science. It is not clear that in a typical introductory course that the ability to do scientific reasoning is consciously developed. To design instruction to accomplish this goal, we need to identify the specific difficulties students have with different types of reasoning.

To what extent is reasoning a critical element in conceptual understanding? Often students are expected to memorize the definition of a concept, such as velocity or acceleration, but are not expected to demonstrate that they can do the reasoning by which the concept is constructed. They may not be able to give a clear operational definition (or in Reif's terms, the procedural specification) that gives an unambiguous meaning to the concept (Heller & Reif, 1984; Reif, 1985; Trowbridge & McDermott, 1980, 1981). Does going through the step-by-step reasoning involved in the construction of a concept enhance a student's ability to apply the concept, especially in situations that have not been expressly taught?

How capable are students of using a suggested analogy if they are not specifically shown how to make the necessary correspondences (as they are by Clement). Can students be taught how to generate their own analogies for new situations? What disadvantages are there in teaching new ideas by having students reason by analogy? Can students learn how to recognize the limitations or are they likely to develop new misconceptions by making correspondences that are not valid? Would examining many instances in which a concept is applicable and helping students abstract a common feature be pedagogically wiser than suggesting analogies to them?

What is the most effective way to help students learn to use a scientific model to predict and explain simple phenomena? Is it sufficient to present a model as a set of rules that students can memorize and apply deductively, or is the ability to use a model best developed by requiring students to engage in the deductive and inductive reasoning that are part of the model-building process?

How can the study of physics contribute to the development of higher order thinking skills? What kinds of instruction can help students develop the ability to ask questions of themselves that can help them recognize what they do or do not understand? How can we elicit from students the type of qualitative reasoning that can guide them toward coherent understanding of a topic? What role does awareness of one's own thinking play in developing the conceptual understanding and scientific skills needed to do well in physics?

PROBLEM-SOLVING

The precision with which concepts are defined and the formal reasoning required to use and interpret them make physics a fertile field in which to investigate problem-solving. The primary objective in some studies in this area is to understand human thought processes. In others, the goal is to identify the knowledge and procedures needed to solve physics problems successfully. Some investigations are directed toward both of these outcomes.

Many studies on problem-solving focus on identifying differences between novices and experts. Often a major emphasis is to determine the nature of expertise and to use this knowledge to develop procedures to effect transition from the novice to the expert state. The research often has a strong theoretical element and the construction of performance models may play an important role.

Descriptive Performance Models

In some research projects, the emphasis is on describing differences in what novices and experts actually do. For example, Chi, Feltovich, and Glaser (1981) have shown that novices and experts classify physics problems into types in very different ways. Whereas experts consider general underlying principles, such as the conservation of energy, novices tend to concentrate on surface features, such as an inclined plane or a pulley.

Observation of a novice or expert in the process of solving a problem may lead to other generalizations about differences. A task analysis can be carried out that describes the procedures that were followed. Larkin (1983) found that novices typically work physics problems backwards in a linear fashion, identifying the unknown quantity and then searching for equations that contain it. Experts typically work forward, constructing a representation of the problem from general physics principles and then writing the appropriate equations.

By characterizing the differences between novice and expert behavior, it is hoped that techniques can be developed to teach novices suitable procedures that will help them make the transition from novice to expert. For example, Gerace and Mestre have developed a computer program, the Hierarchical Analysis Tool, that leads students to analyze problems qualitatively in the manner typical of experts (Dufresne, Gerace, Hardiman, & Mestre, 1987).

The computer may be used to simulate the differences between novice and expert behavior and to construct a dynamic performance model for the transition from novice to expert. For example, Larkin (1981) has designed a program (ABLE) that can "learn" from solving successively more complicated problems in mechanics and thus develop into a more expert program (MORE ABLE). A more recent program (FERMI) incorporates general problem-solving procedures that can be applied in different topics in physics, such as fluid statics or electric circuits (Larkin, Reif, Carbonell, & Gugliotta, 1988). It is anticipated that such computer models may guide development of effective, intelligent tutoring systems.

Prescriptive Performance Models

Another approach to developing a model for good problem-solving performance is theoretical and involves a hypothetical task analysis. From the determination of what is necessary in the way of tacit knowledge and implicit procedures to solve a problem successfully, Reif (1985, 1987) constructs a prescriptive model. In this case, there is no requirement that the model replicate what an expert actually does. It is recognized that an expert may use intuitive knowledge that may not be accessible to a novice. The important feature is that the procedures lead effectively to a solution. The expectation is that by learning these procedures, students will become better problem-solvers. The instructional materials that are developed on the basis of the research are evaluated in terms of the problem-solving performance of students.

From his prescriptive model, Reif has formulated guidelines for teaching scientific concepts. These include teaching an explicit procedure for specifying a concept as well as descriptive knowledge about the concept, asking the student to apply this procedure systematically in various specially selected cases, guiding the student to summarize knowledge acquired through examining these special cases, and teaching the student to detect, diagnose and correct errors.

Rule-based Problem-Solving Models

In research motivated by Siegler's rule-based studies (1976), Maloney (1985) analyzed responses on multiple-choice tests to infer the rules students used to compare the behavior of two systems. In a study that involved carts rolling on inclined planes, he identified patterns in student responses and noted that the strategies employed often seemed to depend on the order of the questions.

A different approach to problem-solving research is illustrated by the work of White and Frederiksen (1987). A goal of the research was the development of an effective method for use on a computer to teach students how to troubleshoot electric circuits. The procedures that experts appear to use to solve circuit problems were analyzed and put into the form of rules. The rules were arranged into sets (student models) that increase in size and complexity as they approach the level of the expert. Instruction on the use of this problem-solving model begins with the presentation of a simple set of rules sufficient for solving simple circuit problems. The students gradually progress to more difficult problems that require use of increasingly larger numbers of rules for solution. The rules are taught as the need for them arises. On the basis of their ability to solve more difficult problems, the students are described as moving from a novice to a more expert state.

Questions for Future Study

The ability to solve standard problems is frequently taken as a measure of student understanding in physics. It is often assumed that successful problem-solving involves all the other aspects of understanding that have been discussed.

How much does instruction in how to solve problems contribute to student understanding of concepts and representations? Does practice in problem-solving promote the development of scientific reasoning ability so that a student can reason successfully about new situations? When students follow prescribed procedures, are they thinking of the physics involved or is their attention devoted to following directions? What happens when problems are presented that cannot be solved by the patterns taught? To what extent do students transfer problem-solving techniques learned in one context to new areas and to domains outside physics?

How can the computer help improve problem-solving performance? Should it be used to calculate, to simulate, to provide drill and practice, to tutor? Is there sufficient similarity between computers and the human mind to gain useful insights for instruction from models of novice/expert behavior or from models of transition from novice to expert? How should intelligent tutoring systems be designed?

Is the fact that mathematical complexity does not have to limit the selection of problems for a physics course an advantage or a disadvantage? Removal of this constraint allows the use of real-world problems that may be quite complicated. For example, the inclusion of air resistance and other nonlinear phenomena makes possible consideration of more realistic situations in mechanics. Are students sufficiently motivated by real-world examples to warrant using them in place of problems that are conceptually simpler and more readily understood?

CONCLUSIONS

It is a consequence of the broad scope of activity in research in physics education that the brief overview presented here has omitted so much of what has been done in the last few years. Only a few examples of recent work in mechanics have been cited and even fewer illustrations taken from optics and electricity. Some topics, such as heat, have not been included. Suggestions for future study have been limited to questions for which a foundation was laid in the discussion.

The emphasis on subject matter reflects the disciplinary orientation from which the paper was written. Underlying the discussion is the belief that many of the difficulties students encounter in learning physics are a consequence of the nature of the material and must be addressed in that context. Other difficulties that may cut across subject matter boundaries are also often best treated in the same way since the ability to transfer reasoning skills from one context to another seems to develop slowly. Our knowledge about how students think is still too incomplete to provide a firm foundation for constructing useful theories of general applicability. Thus it seems prudent for the present to continue acquiring data rich in conceptual detail and to concentrate on developing instructional strategies that are demonstrably effective with specific content.

If the major goal of research is to improve instruction, then the ultimate test of its validity must involve students and teachers. We need to consider carefully what students should be expected to know and be able to do as a result of studying a particular body of material. It is important that the objectives for teaching introductory physics represent some sort of consensus among instructors. We must recognize that we cannot make realistic recommendations for improving instruction without consulting those who teach the subject at the level involved. To influence practice in the classroom, the results from research should be reported in journals that physics instructors read and in language that they can understand. The vocabulary used should be straightforward and not require familiarity with the psychological and educational literature to be comprehensible.

In working toward a scientific practice of science education, we must be sure to maintain continual blending of research with curriculum development and instruction. The three components reinforce one another and their joint presence helps insure that a project is kept relevant to the needs of students and teachers.

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