

*Toward a
scientific
practice of
science
education*

*Edited by
Marjorie Gardner
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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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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 the important programs of research and development are being pursued, and that some of the community 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 hard 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 Lin 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 discipline-based researchers choose to develop it.

The third section of papers is concerned with the social context of learning, a topic on which a book

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 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

Support of the conference on which this book was based was provided by the National Science Foundation under grant MDR-8550921, the Lawrence Hall of Science; the Graduate School of Education, University of California, Berkeley; and by the Institute for Research on Learning.

I View from the Disciplines

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Whether from the natural or from the synthetic world, science is a whole fabric, a beautiful 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 representation. 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

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

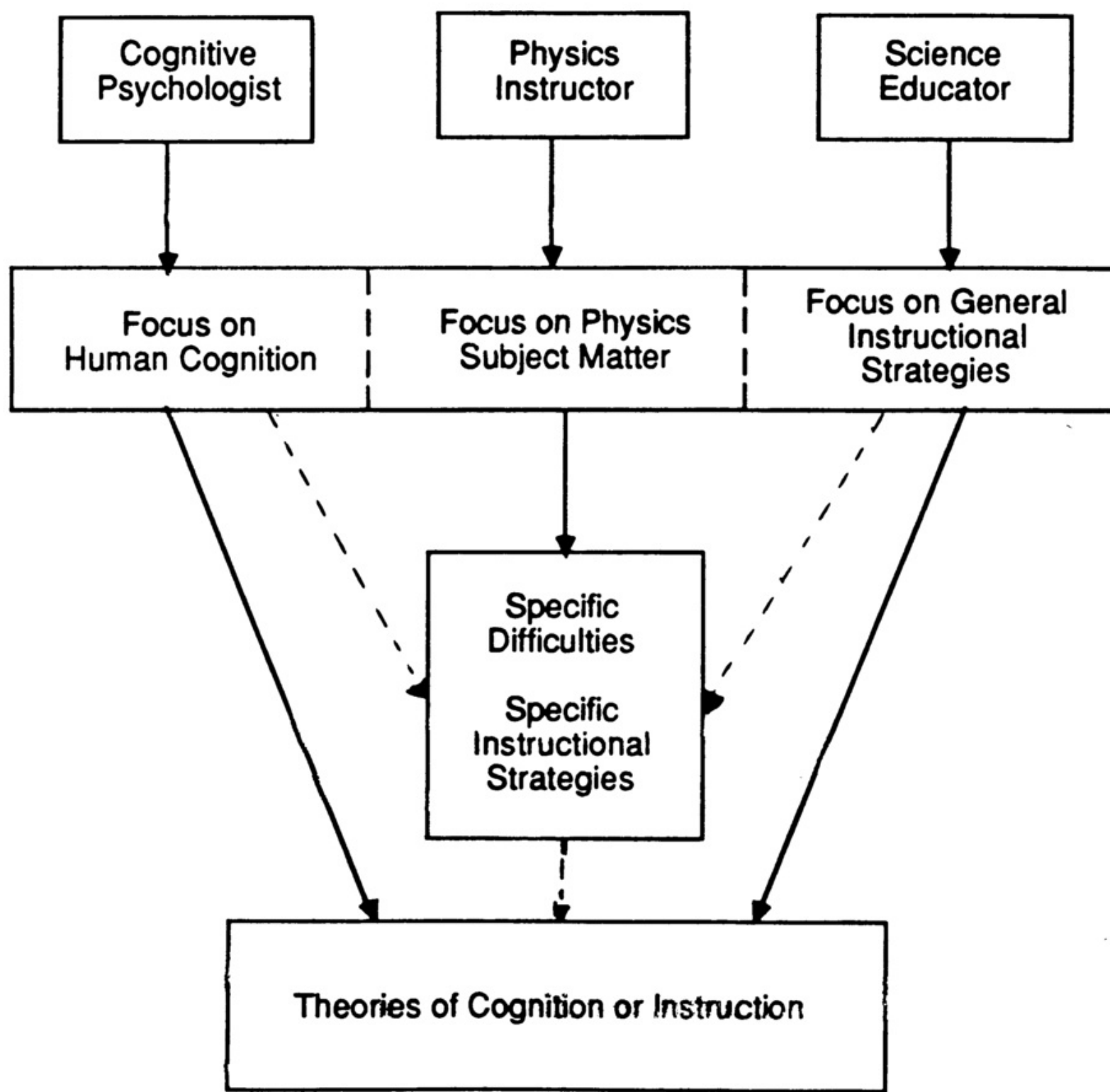
Introduction

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 perspectives 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 why students find difficult about physics and to use this information to help make instruction more effective.² The

PERSPECTIVES ON RESEARCH IN PHYSICS EDUCATION



[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 empiric 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 [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 investigators 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. This 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, and 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 in 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.

Concepts

The discussion in this section focuses on a line of research in which qualitative interpretation of

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, which are 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 student 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) as well as 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 concep

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 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 student 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 when 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, & Mestrich](#)).

1987).

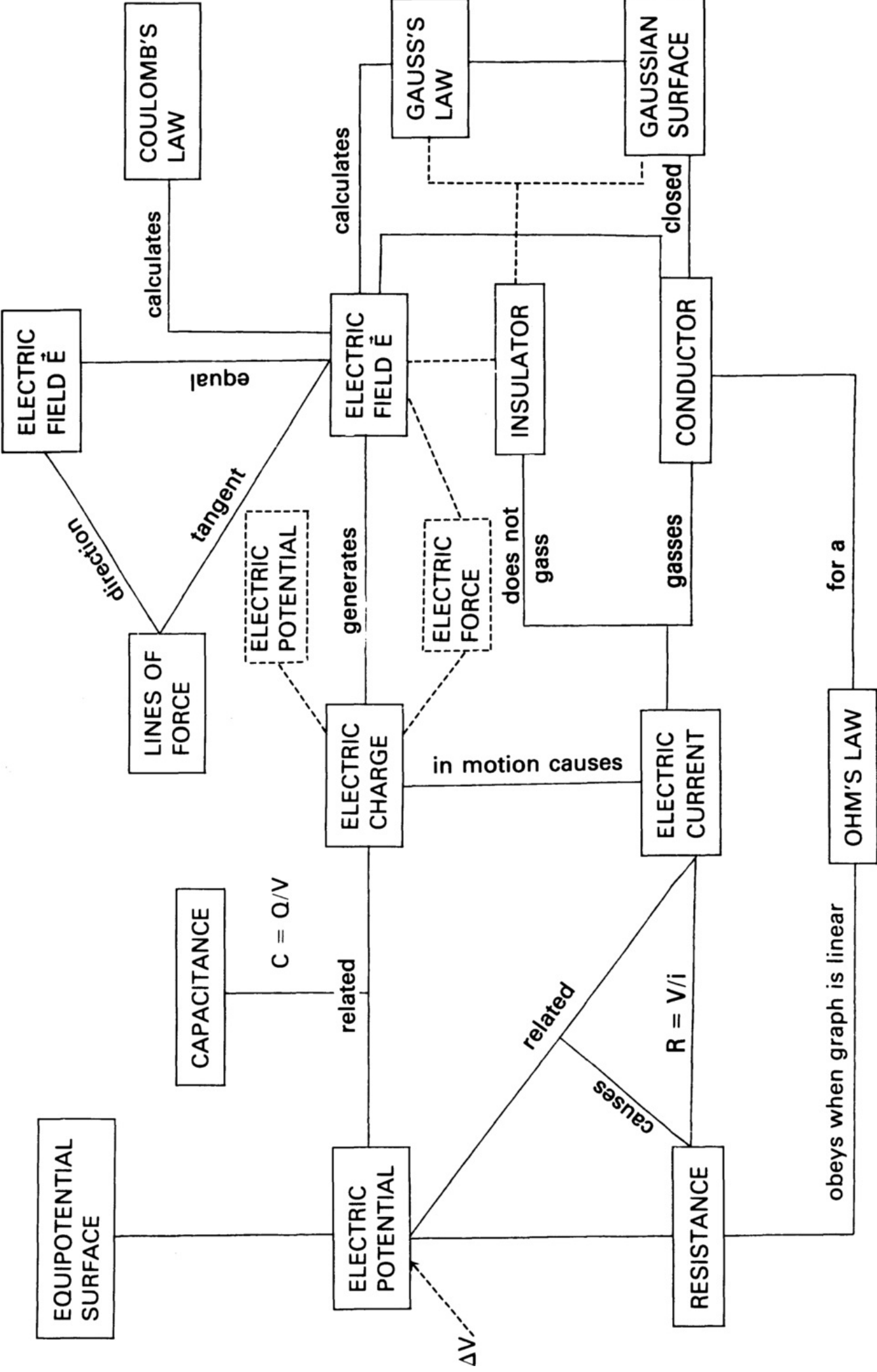
Quite apart from the problems caused by differences in the everyday and technical use of a word, other linguistic complications may be introduced in the course of defining scientific terms. For example, [Kenealy \(1987\)](#) examined how various populations interpreted the statement: "Acceleration is 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 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 other 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.



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, 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.

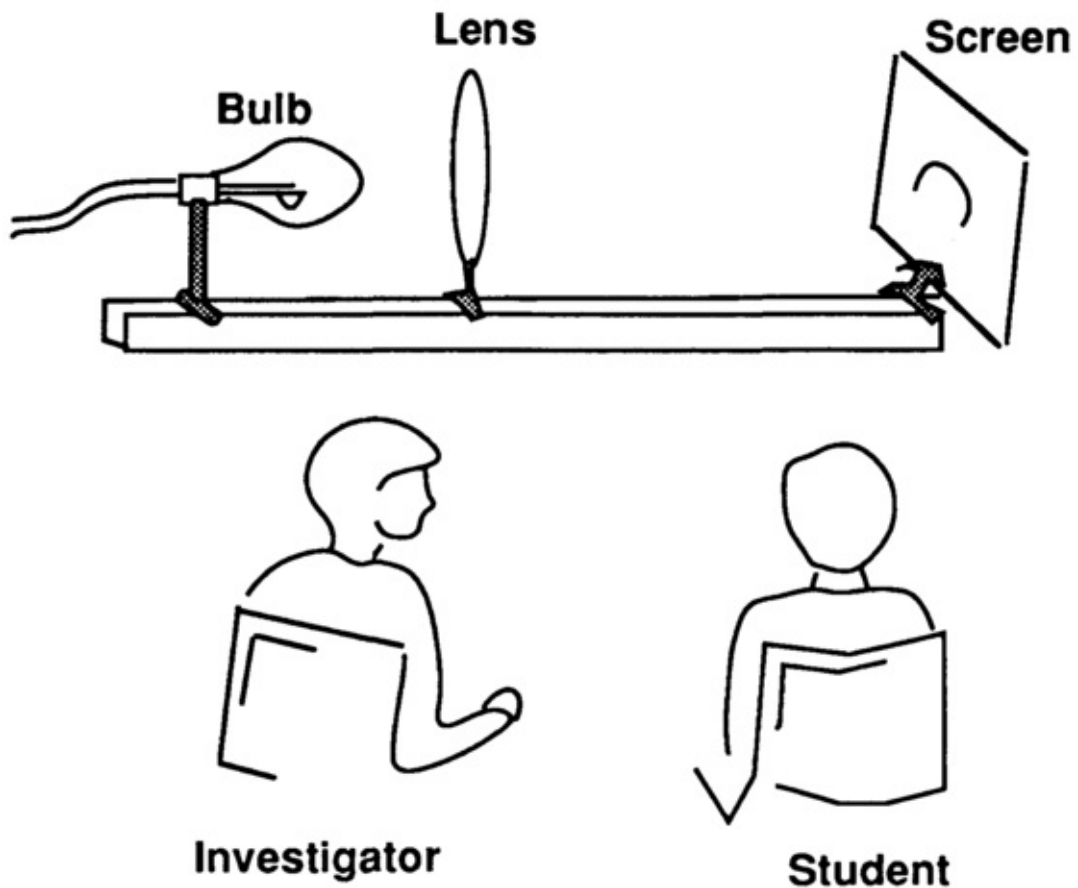
From studies such as the foregoing, we can gain some insight about the state of knowledge with which many students begin formal study of optics. As a result of instruction in optics in high school or college, most of these naive ideas are superseded by concepts the physicist uses to explain how light is transmitted from a source to an observer and how objects can be seen. The vestiges of some of the 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 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 year period he spent with the Physics Education Group at the University of Washington ([Goldberg and 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](#).



Interview Data Summary

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

[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](#)).

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 geometric 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 to a single image

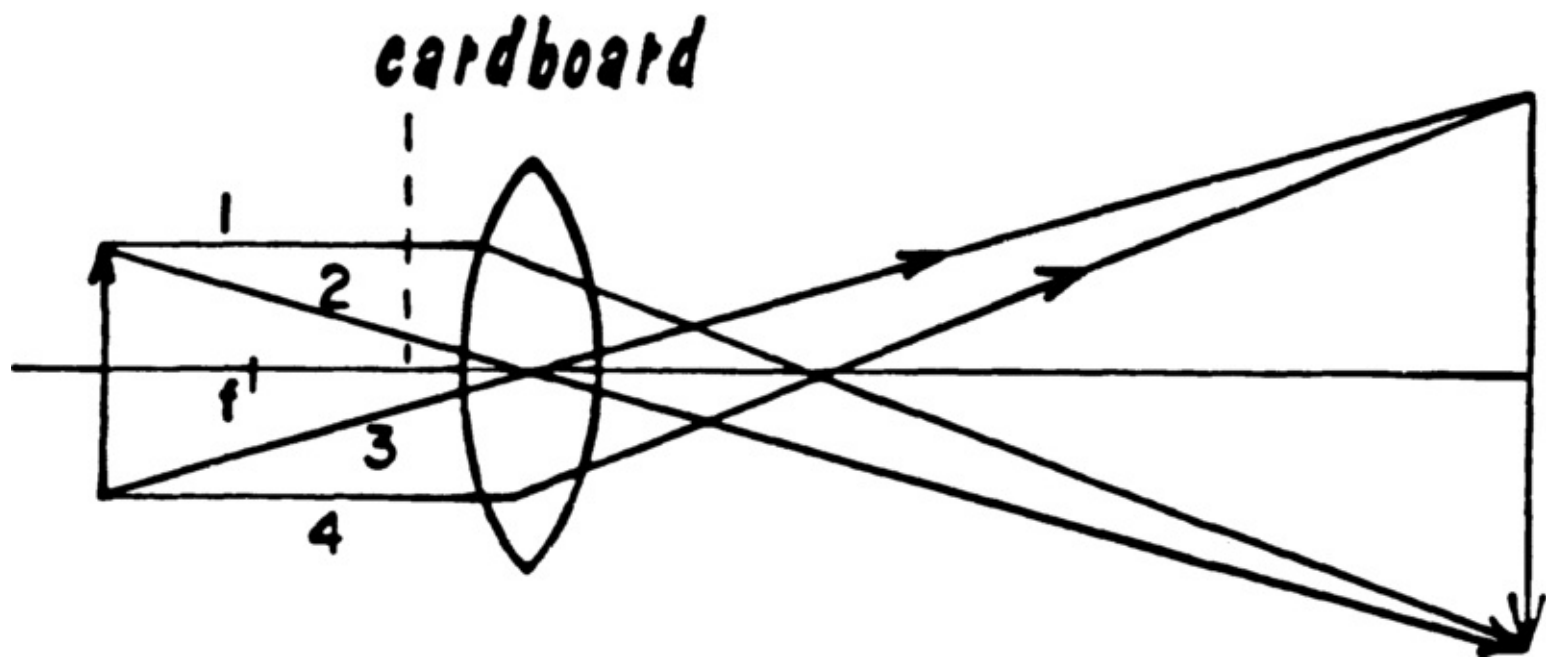


FIG. 1.4. A student was able to draw this essentially correct ray diagram even though the reasoning that half the lens would produce half the image was incorrect (Goldberg & McDermott, 1987).

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 20 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 be 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? Why

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 was essentially correct in form. The student knows the geometrical algorithm for construction but was 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.

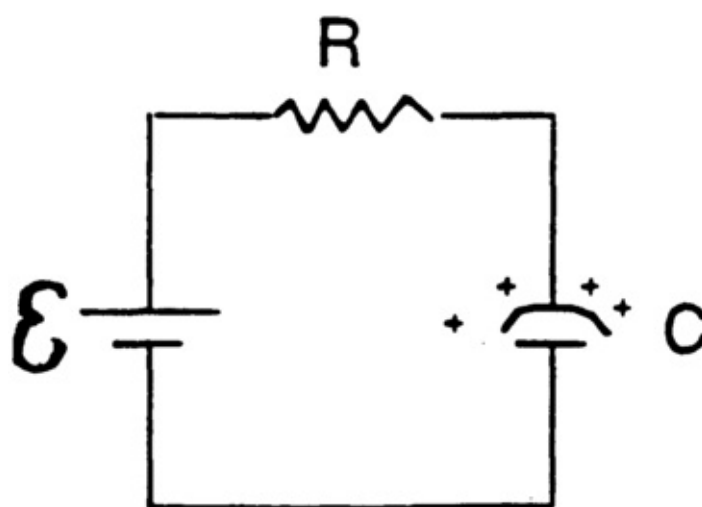
Circuit Diagrams

Electric circuit diagrams are another form of scientific representation that students often do not



Actual circuit

(a)



Student drawing

(b)

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

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