# 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.

# Contents

# Foreword

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This book reflects a vision of a field that is in the process of development. We believe that a revise and advanced field of science education can emerge from the convergence and synthesis of sever current scientific and technological activities. This book includes some examples of research progre 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 ar advancement. At a previous meeting in 1986, members of the communities of science educator cognitive scientists, and educational technologists met to discuss and formulate a research agenda f science education. In addition to a report of the group's conclusions (Linn, 1987), the meetir accomplished a step toward forming an inclusive community of research and development for scien education.

The participants in the 1986 meeting agreed that there is an important agenda for research science education and that the communities of science educators, science-education researcher cognitive scientists, and technologists bring important perspectives and capabilities to that scientif activity. They did not completely agree on every point that should be on the agenda or on the relativ importance of the points, but that is as it should be. The community should not try to work in a singl minded way, but rather should pursue a collection of overlapping but nonidentical goals and thereb discover which directions are most productive. The shared sense of the group, however, was th 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 o decision, along with our colleagues, to hold a conference in 1988, at which the papers in this volun were presented. We invited individuals working on the social context of science learning, in additic 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 198 meeting, namely, that there is an important agenda for research in science education and that th various communities of researchers are engaged in work that is significant for the development of new integrated field. We decided to test this hypothesis directly by bringing together individuals fror 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 th are productive and about which the community can interact meaningfully. We believe that th condition is met, and we present this book as our evidence. These are not the only examples of wo that would be synthesized in the field of science education; any meeting represents a partial sampl But the point we wish to make is that significant examples exist, and we hope that our colleagu agree that these papers definitely establish that.

Another condition for developing this field is that individuals working in its vario 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 meeting we are optimistic about that as well. The discussions were mutually engaging and spirited, ar participants' comments about the meetings were positive. Many individuals at the meetings met eac other for the first time and apparently were favorably impressed. Most of the final versions of pape that you can read here differ significantly from the versions that were presented, reflecting commen and questions that were given by other participants. The shared sense of engagement, includin 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 proces 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 con together in a scientific practice of science education.

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

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

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

The third section of papers is concerned with the social context of learning, a topic on which a boo of interdisciplinary research and development is beginning to grow. Studies of cognition in everyda settings are shedding interesting new light on the capabilities of individuals to reason successful about quantities and causal relations in the world, and relations between this everyday reasoning ar school learning are just beginning to be examined. Investigations of social organization of schoo including socially determined attitudes toward schooling and participation in group activities, benef 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-base 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 ar mathematics education. Development of advanced technology for education has had somewh disconnected components, with some efforts related primarily to discipline-based concerns, some cognitive studies, a few to social concerns, and several to general concerns of artificial intelligenc The development of complex technological systems can serve as a vehicle for further integration 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 envisio the developing field of science education, it would become an integrated disciplinary activi including development of resources and materials for science education as well as development ideas about learning, knowing, and reasoning in science. The field would also be engaged continuing evaluation, refinement, and restructuring of these resources and ideas. We believe that th model of basic research by a group of scientists, with results that inform practice by a group educators, is misconceived. The search for knowledge and understanding and the development educational resources must be concurrent concerns and interactive activities. The alternative visio which we prefer, has inquiry coupled with development of resources so that development is guided b and informs the growth of scientific principles and concepts, and scientific inquiry address questions that are important in practice. Such a melding of inquiry and practice might well be calle either a practical science or a scientific practice of science education. By either name, we hope th 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 Scien Foundation under grant MDR-8550921, the Lawrence Hall of Science; the Graduate School 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 i order to handle its many subtle complexities, yet we yearn to integrate as evidenced by so mar efforts toward interdisciplinary science and mathematics.

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

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

Herron takes the constructivist point of view as he reviews recent research in chemical educatio and looks to the future. Citing research done in the United States and internationally, he critique research efforts related to problem solving and conceptual understanding. In surveying research 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 knowledg and identifying research that is needed.

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

Lochhead describes the recent, rapid, almost explosive advancements in the mathematical scienc as well as the heavy demands on mathematics education for advances in research. He identifies neede changes throughout the chapter and calls for flexibility, and the capacity to respond to rapid chang He also examines some of the predictable changes in terms of the curriculum and instruction materials, modes of instruction and student learning strategies (e.g., problem solving, metacognitior The role and use of calculators and computers are explored in terms of current research. Lochhea 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 research became more apparent and elevated awareness of the need for longitudinal studies and tea efforts. Three common threads are identifiable in the four chapters: attention to problem solving, t constructivist view of how students learn, and the role of technology in instruction. Little cros disciplinary work is being done. Researchers identify themselves as mathematicians, chemist physicists, biologists or geologists when doing educational research. All four authors recognize th students construct knowledge for themselves and that their knowledge of rules, formulas, ar algorithms is virtually useless unless they can apply what they've learned to novel situations. In th three science papers, there's further acknowledgment of the importance of understanding the origin student misconceptions. The need for interdisciplinary collaborative effort and/or perhaps mo importantly for Research Centers where resources can be garnered for in-depth and longitudin studies become evident.

"View from the Disciplines" serves as a backdrop for the more interdisciplinary areas 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 scientif discipline. Until recently, most investigations have focused on mechanics, particularly on kinematic and on the relation between force and motion.[1] The field of inquiry is now considerably broader ar includes several other content areas such as heat, electricity, and optics.

Physics has been chosen as a domain for investigation by cognitive psychologists, scienc educators, and physicists. These groups share some of the same goals, but their primary motivation f doing research is often different. As a consequence, they often do not ask the same questions and eve when they do, they may interpret the same answers in different ways. The broad range in perspectiv is illustrated by the diagram in Fig. 1.1 In actual practice, differences among the groups are not 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 l strongly influenced by the background and orientation of the author. The point of view taken here that of a physics instructor whose primary motivation for research is to understand better wh students find difficult about physics and to use this information to help make instruction mo effective.[2] The

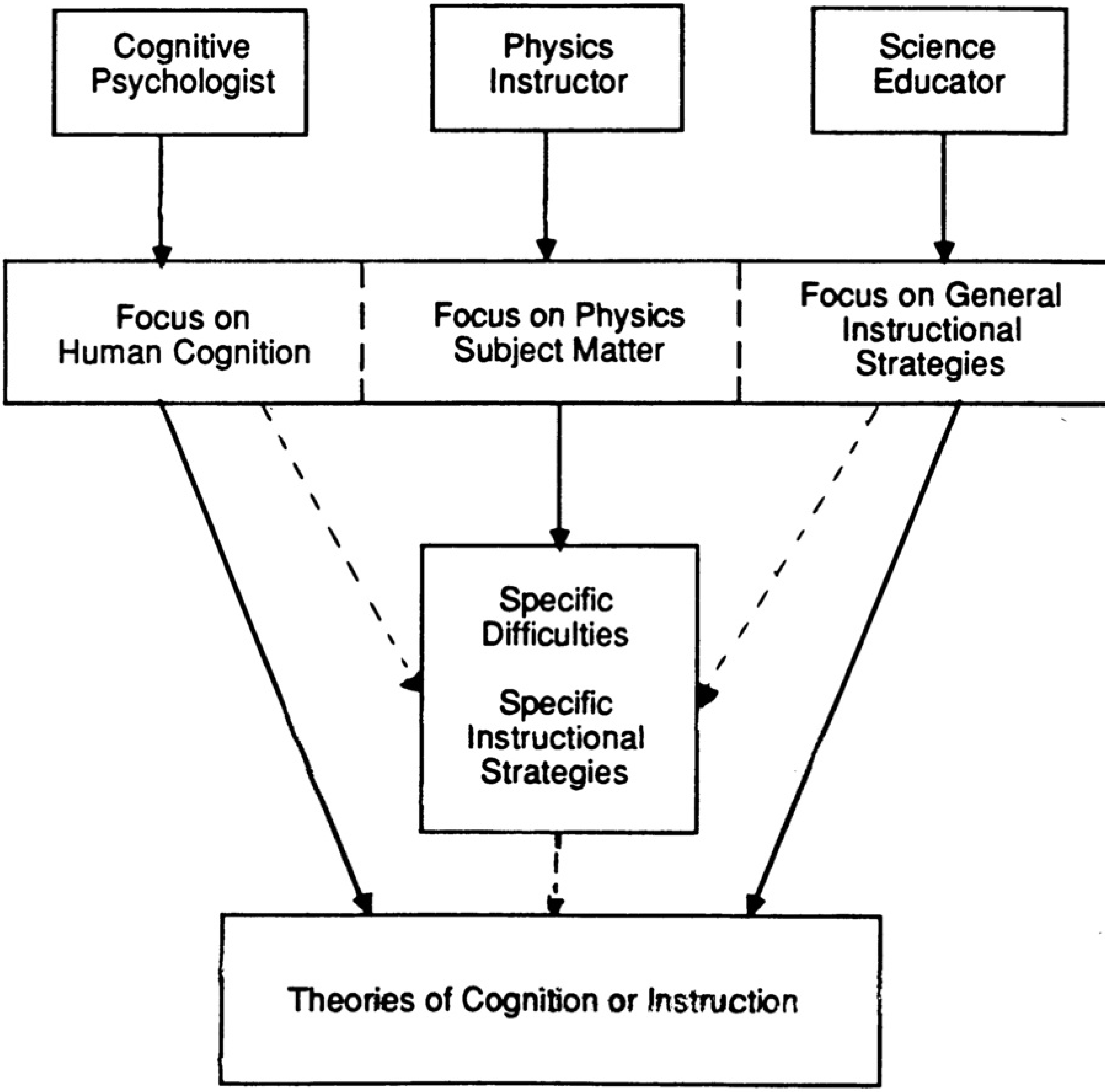



FIG. 1.1. Physics has been chosen as a domain for investigation by cognitive psychologists, science educators, and physicists.

direction and methods for research are derived from an interest in physics for its own sake and a interest in teaching that particular subject. The emphasis in the research is to identify specif difficulties and to develop instructional strategies to address these difficulties. This focus is not mea to imply a lack of interest on the part of the author in the general theoretical and instructional issu that concern the cognitive psychologist and science educator; rather, the approach reflects a pragmat 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 b 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, th perspective is closer to that of cognitive psychologists. Physics has proved to be an appealing doma for studies that focus on problem-solving. The interest that drives the research of these investigatio is often less on specific subject matter and more on underlying thought processes. An important go for cognitive psychologists is the development of theoretical models of human cognition that can b used as a basis for planning instruction.[4]

Still another approach toward research in physics education characterizes the work of scien educators. The title, as used in this paper, does not refer to the science instructor who is a subje matter specialist, but is reserved for those who are directly concerned with the education of teache or with curriculum and instruction in the schools. As indicated in Fig. 1.1, science educators a usually more broadly interested in teaching science in general than physics in particular. Althoug physics may provide the context, the focus for research is often on the development of instruction 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 bee influenced by the experience of the Physics Education Group at the University of Washington. Th group, which is an integral part of the Physics Department, is actively involved in teaching physics students with a wide variety of preparation. The instructional environment provides a setting f conducting research and curriculum development from a strong disciplinary perspective. We hav found it useful to organize these activities into categories that correspond to various aspects of stude understanding in physics. Our investigations are directed toward elucidating the following aspects student understanding: the concepts of physics, scientific representations (e.g., diagrams, graph equations), and the reasoning required for the development and interpretation of both concepts an representations. We make use of problems primarily to gain insight into conceptual and reasonin difficulties rather than to examine problem-solving capability as an end in itself. There is a maj emphasis in our research on the ability of students to make connections among concept representations, and real world phenomena.

In this paper, the organizational structure for discussion of research will be provided by a loo classification scheme consisting of four categories: (a) concepts, (b) representations, (c) reasonin 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 particul study is used to illustrate. To call attention to recent work outside of mechanics, the illustrations hav 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 deal with a hypothetical situation. Most investigations in which actual equipment is used involve on on-one interviews or small group activities in which there is dialogue between the investigator ar students. Sometimes a laboratory demonstration provides the basis for written questio simultaneously administered to a large group. In other investigations, the task is presented only 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 stu and on the point of view of the investigator. In investigations based on actual phenomena that th student observes or can easily imagine, the emphasis is on the ability of students to use a concept ( set of concepts) correctly in performing a specified task. The criteria may include some or all of th following: (a) The ability to apply the concept to the situation observed and to describe the reasonin used; (b) the ability to recognize circumstances under which the concept is or is not applicable; ar (c) the ability to distinguish clearly between the concept under scrutiny and similar but differe concepts that might apply to the same situation. In some investigations, the emphasis may be student facility with different ways of representing the concept (e.g., diagrams, graphs, equations) 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 described on paper or on a computer screen. There may or may not be supplementary interviews. cases in which the student responds only in writing or by typing on a keyboard, it is much mo difficult and often impossible to extract the amount of conceptual detail that the interview situati allows. On the other hand, mass testing by questionnaire or computer allows the investigator 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 s of concepts that may be applicable under certain general conditions. The students are encouraged think about the concepts from a theoretical perspective. For example, there have been a number studies in which students are asked to draw "maps" showing relationships among concepts. From th ways in which students group the concepts, indicate a hierarchy, and show connections, inferences a drawn about the level of conceptual understanding. In such cases, the criterion for understandi refers to the accuracy and level of sophistication that the student demonstrates in drawing th diagram.

## *Misconceptions*

Although the methods of research are diverse, some generalities emerge. Students have certa incorrect ideas about physics that they have not learned through formal instruction, or at least th they were not intentionally taught. Some have resulted from misinterpretation of daily experienc 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 use 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 son 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 son investigators to hypothesize that students bring to the study of physics a strongly held system 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 conte (di Sessa, 1988). There is disagreement about whether certain observed regularities in response occ because students have a mental model for cause and effect or for some other reason. For exampl perhaps the similar features among answers are simply elicited by the way in which the questions a asked (Viennot, 1985a, 1985b).

Although there is a difference of opinion about whether or not students have a consistent syster there is no doubt that there are some common misconceptions that do not disappear spontaneously the relevant material is taught. To bring about conceptual change, it is frequently necessary to make conscious effort to help students reject certain ideas and accept others (Strike & Posner, 1982). Th 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 a instructor may write correct statements that the student can learn passively. It is also clear tha whatever their origin, incorrect ideas that are well entrenched in the student mind may interfere wi the ability to learn what is being taught. These circumstances have led to an interest in constructivi epistemology among science educators. Basic to this approach are the beliefs that (a) Each individu must actively construct his or her own concepts, and (b) that the knowledge that a person already h will determine, to a large extent, what he or she can learn. The implications for instruction that can b derived from these tenets may be used to guide the design of curriculum from precollege throug 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 th contradict those of the physicist. Linguistic elements also play an important role. Often the pictu conjured up in a student's mind is different from the meaning the words are intended to convey. Fo example, a physics student who reads a problem about a ball that is "dropped" in an ascending elevat may not realize that in this case the ball initially moves upward with respect to the ground. Wh words have both a technical and colloquial meaning, the concepts that are associated with them ma be muddled. Terms like *force* and *energy* that are understood in an unambiguous way by physicists a often interpreted by students in a context-dependent manner (Touger, Dufresne, Gerace, & Mestr

1987).

Quite apart from the problems caused by differences in the everyday and technical use of a wor other linguistic complications may be introduced in the course of defining scientific terms. F example, Kenealy (1987) examined how various populations interpreted the statement: "Acceleratio is the time rate of change of velocity." The definition is from one of the most widely used high scho physics textbooks in the United States (Williams, Trinklein, & Metcalfe, 1984, p. 48). Participants the survey included students in eighth grade through college and high school science teachers. 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 prima source of data is provided by the concept-mapping studies of Moreira (1987). One study involve engineering students in an introductory physics course at a Brazilian university. The students we asked to draw maps showing relationships among the main physical concepts that they had studied electricity. They were also asked to write key words along the lines linking the concepts to mak explicit the relationship between them. Upon completion, the maps were discussed on an individu 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 electr charge as the most important concept and linked it to electric current, electric field, and electr potential. However, the field and the potential are not linked to each other. (These links and the othe shown as dotted lines were added during discussion of the map.) Electric force and potenti difference did not appear on the original drawing. The ensuing discussion revealed that the stude made no distinction between the concepts of potential and potential difference.

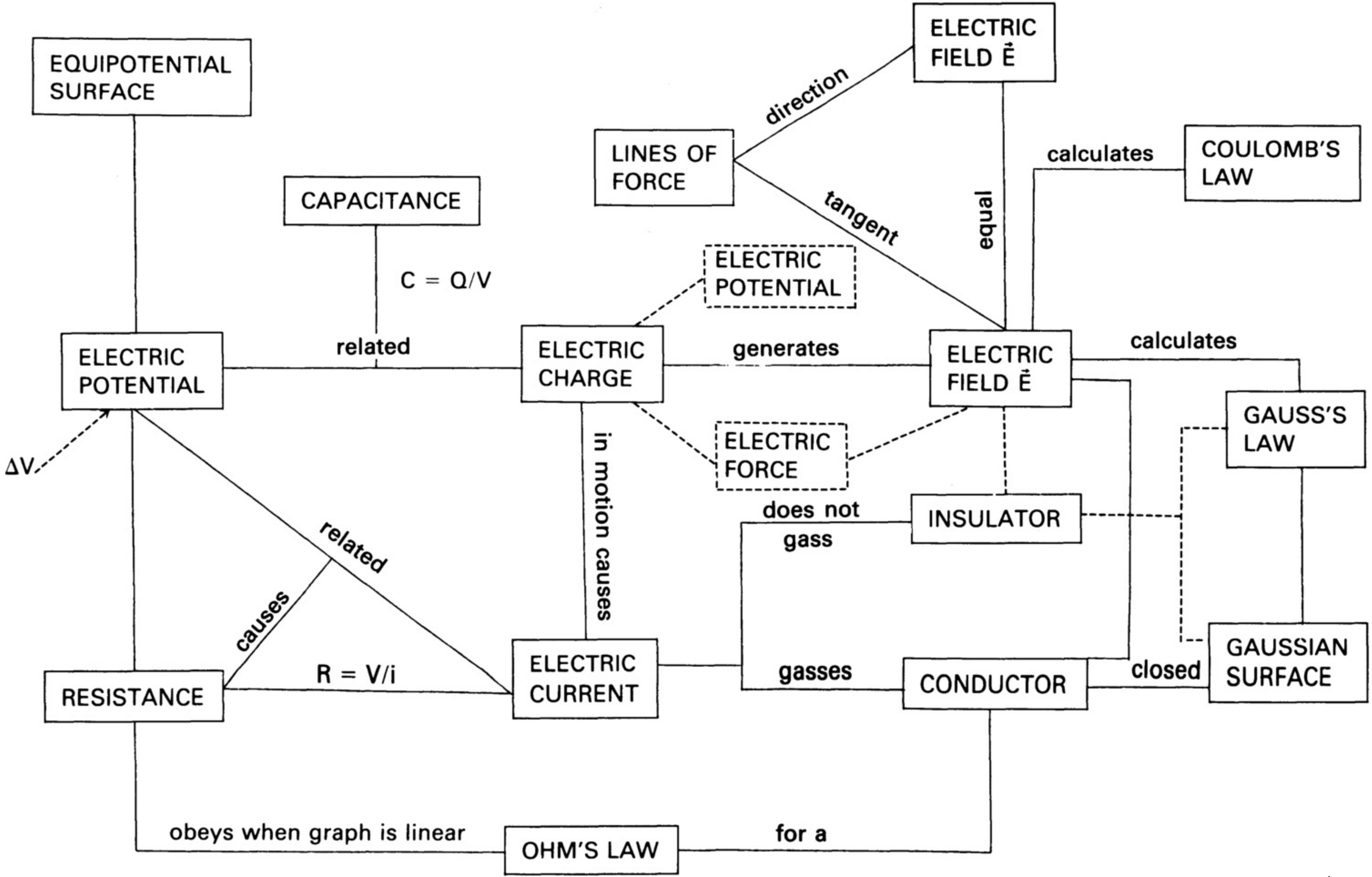

EQUIPOTENTIAL SURFACE
CAPACITANCE
C = Q/V
related
ELECTRIC POTENTIAL
ΔV
ELECTRIC CHARGE
generates
ELECTRIC POTENTIAL
ELECTRIC FORCE
in motion causes
LINES OF FORCE
direction
tangent
ELECTRIC FIELD E⃗
equal
calculates
COULOMB'S LAW
ELECTRIC FIELD E⃗
calculates
GAUSS'S LAW
INSULATOR
does not gass
gasses
CONDUCTOR
closed
GAUSSIAN SURFACE
related
causes
R = V/i
RESISTANCE
ELECTRIC CURRENT
obeys when graph is linear
OHM'S LAW
for a

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 o conceptual understanding in physics. To illustrate how different investigations can make a cumulativ contribution to our knowledge of how students think about physical phenomena, we review brief some of the research involving geometrical optics. Other topics (e.g., dynamics, electric circuits, heat and temperature) could also have been used for illustration.

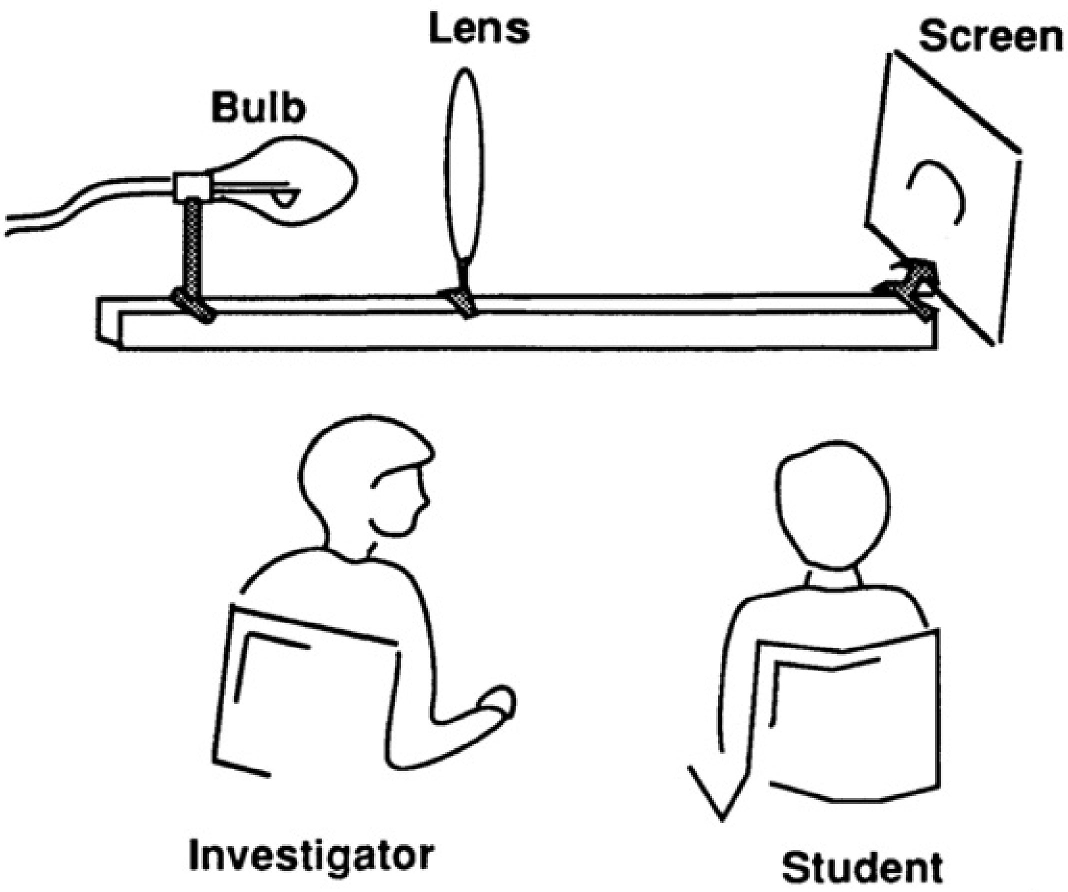
*Children's Ideas about Light.* A number of studies have identified some incorrect ideas about ligh that are common among children and adolescents (and sometimes among adults) who have not studie the topic formally.[6] It appears that before about the age of twelve children do not usually recogniz light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

From studies such as the foregoing, we can gam some insight about the state of knowledge wi which many students begin formal study of optics. As a result of instruction in optics in high school college, most of these naive ideas are superseded by concepts the physicist uses to explain how light 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 how an image is formed and seen.

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

*Student Understanding of Real Images.* Documentation from research is beginning to bring abo more awareness on the part of high school and college teachers that the ability to solve standa physics problems is no indication that a sound conceptual understanding has been achieved. Problem in geometrical optics are no exception, even though this topic is generally considered one of th simplest in a physics course. The following example illustrates how little we sometimes know abo 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 McDermott, 1986, 1987). The work described is based on a task from an investigation on stude understanding of the real image formed by a single mirror or lens. The students involved we volunteers from the introductory physics sequence required for majors in engineering, physics, an other physical sciences. Calculus is required for this course. Most of the data were collected fro individual interviews in which students were asked a series of questions about a simple demonstratio that they could observe. Each was shown the same demonstration and asked the same questions. Th demonstration was a simple optical system consisting of a lens, a light bulb, and a screen, all mounte on an optical bench. A real, inverted image of the lighted filament of the bulb was visible on th 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 the 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 foc length and the object distance, predict the location, characteristics, and magnification of the imag The students could also solve the problem by drawing an appropriate ray diagram. Furthermore, the were able to check their solutions by using laboratory apparatus and could make the prop connections between the numbers from their algebraic solutions and the corresponding distances on a optical bench.

Let us now contrast what the students could do with what they could not do. During the individu demonstration interviews, the investigator asked the following question: "Suppose I were to cover th top part of the lens, leaving the bottom half uncovered, would anything change on the screen?" Th results in Fig. 1.3 indicate that many students did not realize that the complete image could still b 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 the university as prestudents, and those who had completed the optics portion of the university cour as poststudents. None of the prestudents gave the correct response. About one third of the poststuden made a correct prediction. In spite of the fact that these students knew how to use the thin-len formula, many did not know how to answer a basic question that they had not been asked before. B far the most common response was that only half the image would be seen if the upper half of the le were blocked. Most students claimed that the bottom half of the image would disappear, a predictio 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 support of their answers can give us some insights into their thinking. A particularly interesting for of incorrect reasoning on the lens task is illustrated by the explanation offered by a student who dre 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 wa drawn so that it passed through the focal point and ray #2 was shown undeviated. The image w located at the point where the two rays intersected. The student described the ray-tracing procedu correctly, but then went on to say: "Now if you block off the top part of the lens, that would block o rays #1 and #2 from getting through, so the bottom of the image would be blocked. The bottom part 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 typic examination but seemed to have totally missed a crucial concept in geometrical optics: From eac point on an object, there are an infinite number of rays which, to close approximation, will converge a single image

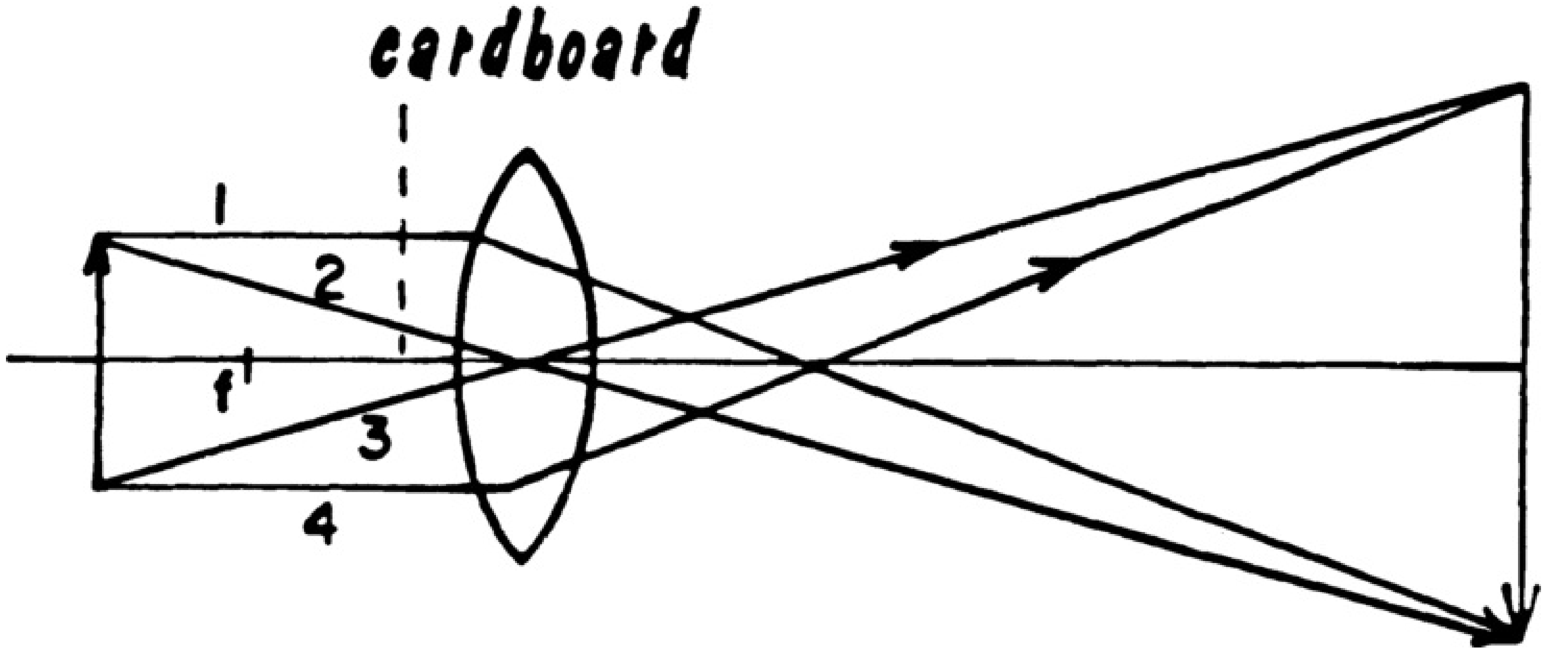



FIG. 1.4. A student was able to draw this essentially correct ray diagram even though the reasoning that half the lens would produc half the image was incorrect (Goldberg & McDermott, 1987).

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

The results on the lens task cannot be explained on the basis that the participants in the study we poor students. It has been our experience that students who participate in interviews generally recei a grade of A or B in physics. The less capable students seldom volunteer. Moreover, when a multipl choice version of this question was asked on final examinations administered to more than 2 introductory physics students, only about one fourth recognized that the entire image would rema intact if half the lens were blocked.

## *Questions for Future Study*

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

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

## Representations

An inability to use and interpret scientific representations of various kinds (e.g., diagrams, graph equations) is quite common among physics students. A number of studies have explored this aspect 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 a physical situation or in the solution of a theoretical problem. Examples are free-body diagrams mechanics, ray diagrams in optics, and circuit diagrams in electricity. Diagrams offer a way organize information into an easily accessible form, to show conceptual relationships that may not 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 essentially correct in form. The student knows the geometrical algorithm for construction but unable to interpret the information the ray diagram contains and do the reasoning necessary to make prediction. Had the student drawn the third ray that can be used to locate the image, he or she mig have realized that at least one ray would emerge from the lens. (This particular ray is drawn from th head of the arrow through the focal point. After passing through the lens, it emerges parallel to th principal axis.) However, in that case, the lack of understanding of the ray diagram might have passe undetected. In spite of having learned the procedure for drawing a ray diagram, the student cann extract from it the implicit information.

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

#### *Circuit Diagrams*

Electric circuit diagrams are another form of scientific representation that students often do n interpret properly. Difficulties occur both in drawing dia

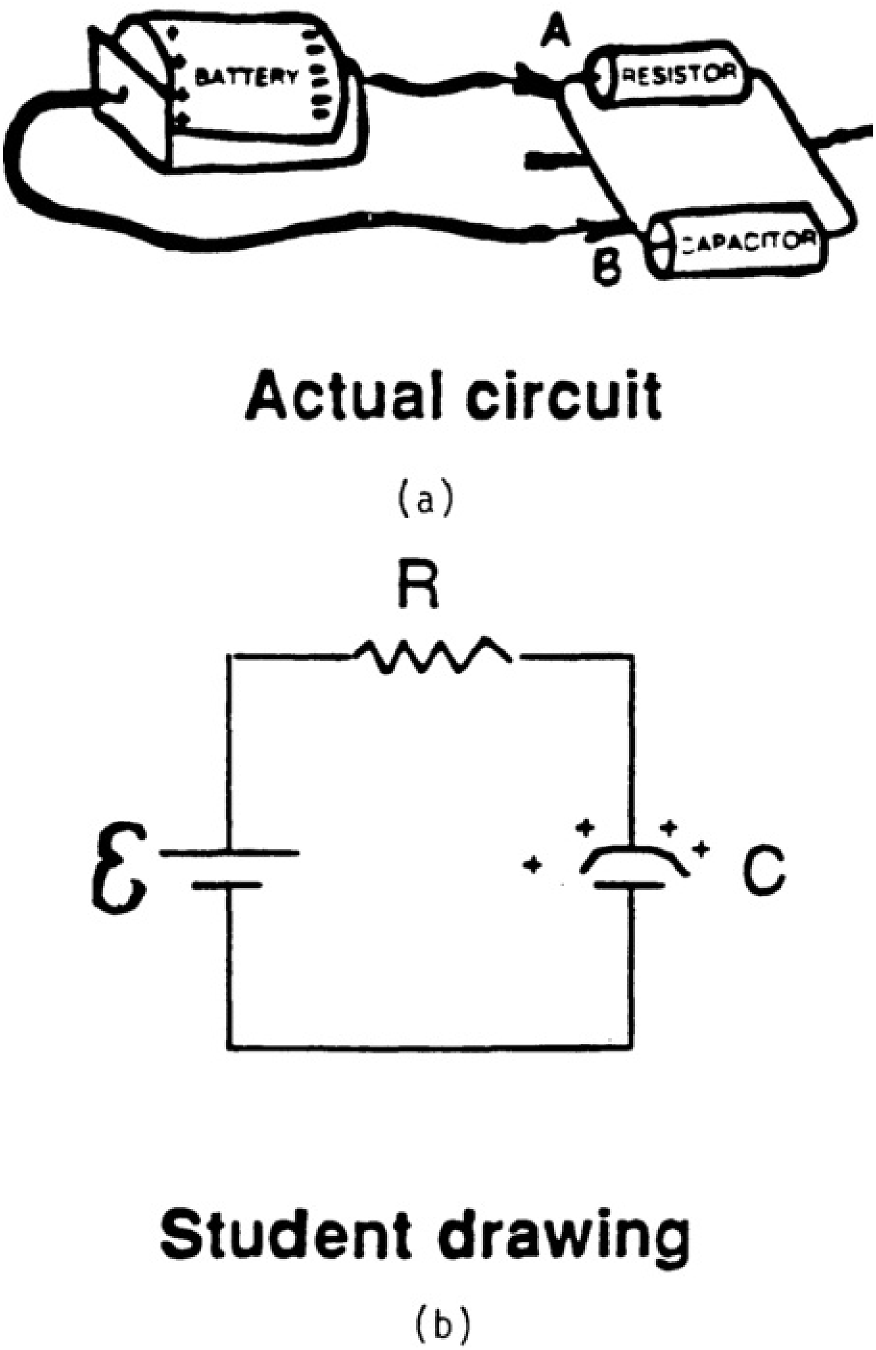



FIG. 1.5. (a) An actual circuit shown to a student during an individual interview; (b) Circuit diagram drawn by the student, who ignores the wire *AB* that connects the resistor and capacitor across the battery (Fredette & Clement, 1981).

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

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