# HANDBOOK OF
# RESEARCH ON SCIENCE EDUCATION

EDITED BY

SANDRA K. ABELL
NORMAN G. LEDERMAN

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Sandra K. Abell

and

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Routledge
Taylor & Francis Group
New York London

Senior Acquisitions Editor: Naomi Silverman
Editorial Assistant: Joy Tatusko
Cover Design: Tomai Maridou
Full-Service Compositor: MidAtlantic Books & Journals, Inc.

This book was typeset in 10.5/12 pt. Palatino Roman, Italic, Bold, and Bold Italic.

First published by
Lawrence Erlbaum Associates, Inc., Publishers
10 Industrial Avenue
Mahwah, New Jersey 07430
www.erlbaum.com

Reprinted 2010 by Routledge

Routledge
Taylor & Francis Group
270 Madison Avenue
New York, NY 10016

Routledge
Taylor & Francis Group
2 Park Square
Milton Park, Abingdon
Oxon OX14 4RN

**Library of Congress Cataloging-in-Publication Data**

Handbook of research on science education / edited by Sanda K. Abell and Norman G. Lederman.
p. cm.
ISBN 0-8058-4713-8 (case : alk. paper) — ISBN 0-8058-4714-6 (pbk. : alk. paper)
1. Science—Study and teaching—Research. I. Abell, Sandra K. II. Lederman, Norman G.
Q181.H149 2006
507.1—dc22
2006031809

ISBN 978-0-8058-4713-0 (case)
ISBN 978-0-8058-4714-7 (paper)
ISBN 978-0-2038-2469-6 (ebook)

Printed in the United States of America

10 9 8 7 6

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# Preface

Although some have predicted the end of science (Horgan, 1996), the scientific enterprise thrives and scientists generate new knowledge at an incredible rate. (A recent report from the US National Science Foundation stated that over 92,000 scientific articles were published in 2001 in comparison with about 70,000 in 1991 (Hill, 2004).) Essential to the vibrancy of science, scientists continue to ask questions of the world. In the July 1, 2005 issue of the journal *Science*, the editor compiled responses from senior scientists and published the 125 questions that science "should have a good shot at answering" (Kennedy & Norman, 2005, p. 75) in the next 25 years, many from relatively young sciences such as neuroscience, genomics, biomedical science, geophysics, astrophysics, and bioengineering. According to Siegfried (2005), in that same journal issue:

> When science runs out of questions, it would seem, science will come to an end. But there's no real danger of that. The highway from ignorance to knowledge runs both ways: As knowledge accumulates, diminishing the ignorance of the past, new questions arise, expanding the areas of ignorance to explore. (p. 77).

For many years, science education researchers prided themselves on following research approaches and paradigms that approximated those of science. Thus, it is interesting to consider the similarities between science and science education. How does science education as a discipline compare? Our field has a much shorter history than that of the natural sciences. Our research has appeared in science education journals and books for fewer than 100 years. Yet we have generated a substantial body of knowledge during this time, knowledge from which new questions have emerged. Like the sciences, our questions are partly shaped by the society in which we live and partly by the research community in which we work. Research in science is guided by and builds upon prior research. However, in the science education community, researchers are often opportunistic, studying what is convenient to them rather than building on previous investigations. We believe that a handbook of research in a discipline such as science education provides a foundation upon which future research can be built.

The purpose of this volume is twofold. First, the authors look backward in time in an attempt to capture where science education has been and what we currently know. Secondly, the authors project into the future, positing research agendas for

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The National Association for Research in Science Teaching (NARST) endorses the *Handbook of Research on Science Education* as an important and valuable synthesis of the current knowledge in the field of science education by leading individuals in the field.

various subfields in the discipline. When we invited authors to take part in the project, we asked that they tackle these two purposes:

> We are asking authors to write an "integrative review" of the research in each topic area. Authors will pull together the existing research on the topic and work to understand the historical trends and patterns in that body of scholarship. Authors will describe how the issue is conceptualized within the literature, how methods and theories have shaped the outcomes of the research, and where the strengths, weaknesses, and gaps are in the literature. Reviews will end with implications for practice and future research derived from the review. (S. Abell & N. Lederman, personal communication, October 15, 2002)

This book is intended as a comprehensive research handbook for the field of science education. Two research handbooks in the field were produced in the previous decade. The first, edited by Gabel (1994), the *Handbook of Research on Science Teaching and Learning*, was published in cooperation with the National Science Teachers Association. It is now over 10 years old and no longer represents the scope of research in the field. The second, edited by Fraser and Tobin (1998), the *International Handbook of Science Education*, although international in its collection of authors, did not present a comprehensive review of the research in science education. Rather it was an in-depth sampling of the work of various researchers, demonstrating a slice in time of research in the field. Both of these volumes responded to the inadequacy of the single review chapters for science education contained in general education research handbooks such as those produced by the American Educational Research Association. The work represented in this volume is international and comprehensive in scope. It provides both veteran and emerging science education researchers with a coherent synthesis of the empirical and theoretical research concerning teaching and learning in science, and paves the way for future research.

## OVERVIEW OF THE BOOK

One of our first steps as editors was to map out our construction of the structure of the discipline of science education. We first created five organizing categories in which to place the research in the field: Science Learning; Culture, Gender, and Society and Science Learning; Science Teaching; Curriculum and Assessment; and Science Teacher Education. We thought that this organization would capture most, if not all, of the published science education research (although we were aware that no organizational scheme would achieve consensus among our colleagues). These organizers became the five major sections in this *Handbook*.

The more difficult step was deciding what chapters should appear within each section. The decisions we made were unique, based on our experiences as science educators and researchers. Our decisions certainly would not match the organization other researchers would impose on the field. Current trends and length restrictions led us to make strategic decisions on chapters to include or not to include. For example, given the recent importance of the literature on language and science, we included two chapters on language and science learning. However, as we envisioned, these chapters serve different purposes. The first, by William Carlsen, appears in the first section of the book, Science Learning. It is meant to be a theoretical overview of language and learning and how such theory has informed science education research. The second chapter on language and science education research appears in the third section of the book, Science Teaching. That chapter, by Gregory Kelly (once Carlsen's doctoral student), reviews classroom-based research on discourse in science education. We also made strategic decisions on chapters not to include. For example, although research on college science teaching has increased in the past decade (demonstrated in part by a dedicated strand at the annual NARST meeting), we chose to include this research by science discipline instead of by grade level, along with subject-specific studies at middle and high school levels, in the Science Teaching section of the *Handbook*. However, we decided that the research on elementary science teaching was less science discipline-specific and more age-related, and therefore deserved its own chapter.

The organization of this *Handbook* highlights other recent trends in the field. For example, the second section of the book, Culture, Gender, and Society, acknowledges the contributions of research focused on context to understanding science learners. The chapters in this section demonstrate the importance of learners' gender, culture, and special needs, as well as the larger societal context (urban, rural, postcolonial), in learning science. In the final section of the book, Science Teacher Education, we have presented a comprehensive synthesis of the research in the area of science teacher education for the first time. Twenty years ago, few studies in science education focused on science teacher learning. Currently such research comprises the largest submission to the NARST annual meeting, necessitating the development of two separate dedicated strands. The chapters in this section are thus a unique contribution to the field.

As editors, we also influenced the direction of the book in other ways. Once we had a structure for the *Handbook* in place, we brainstormed authors for the various chapters. First and foremost, we wanted authors who were leading experts in their research area, and who had published a significant quality and/or quantity of research. As veteran science education researchers with a total of 40+ years in the field, and as past presidents of NARST, our collective expertise was a good place to begin the brainstorming. However, we recognized that our expertise was limited in certain areas of the field and was somewhat North American centric. Thus we also consulted other resources during the author selection process, including the NARST annual meeting programs of recent years, other conference proceedings, and the ERIC database. In addition to selecting high profile researchers, we tried to ensure that our selection represented the international and gender diversity that exists in our research community. We believe that the final list of authors indeed meets these selection criteria.

An additional task we faced as editors was to engage thoughtful reviewers in providing feedback to authors on the first drafts of chapter manuscripts. The peer review process is critical to maintaining quality in our work. The reviewers we selected, along with the editors, provided insight and made recommendations that improved the final chapters in many ways. Some authors also involved their own colleagues in the review processes. The reviewers are acknowledged in the chapters they reviewed. Through section and chapter organization, author selection, and review work, we crafted this *Handbook*. It represents our current construction of the structure of the discipline of science education.

## THEMATIC ELEMENTS

We have had the honor of interacting with many authors and reviewers to shape the contents of this book. We have had the privilege of reading all of the chapters and interpreting various themes that emerged from our reading. In this section we highlight three such themes.

One of the striking features of the field of science education as represented in the chapters in this *Handbook* is that it is influenced by the prevailing learning theory of the day. Few would argue that perspectives on learning have changed drastically over the past 100 years. Even the most superficial analysis indicates at least five "general families" of learning theory held dominance in educational matters over the past century—mental discipline, natural unfoldment, apperception, behaviorism, and cognitive science. These differing perspectives have influenced how science education researchers view learning, teaching, and the assessment of both.

A second theme of the research reviewed in this *Handbook* is that the predominance of various research methodologies change over time. Some of this fluctuation corresponds directly with changing views of learning. Early research on teaching and learning focused on the identification and exercise of various mental faculties as a direct result of the dominance of mental discipline theory. In the 1970s, process-product research methodologies clearly reflected the dominance of behavioristic learning theories. The emergence of qualitative methodologies mirrored the replacement of behaviorism with cognitive theories of learning.

A final theme that emerges from the *Handbook* chapters is that the teaching and learning of science is discipline-specific. What is considered effective instruction in a biology class is not the same as effective instruction in another class, science or otherwise. Teachers do not teach and learners do not learn biology in the same ways as they do physics or social science or humanities. This theme appears in the sections on science learners and learning, in the discipline-specific chapters on science teaching, and in the section on science teacher education. In that section, authors examine the notion of pedagogical content knowledge as a framework for science teacher education research. Lee Shulman, who invented this idea (1986), began his career as a science educator. He cautioned us not to allow the disappearance of subject matter from educational research. The existence of this *Handbook* is a testimony to the value of science subject matter in our research.

## THE FUTURE OF SCIENCE EDUCATION

Much like the authors in the July, 2005 issue of *Science* demonstrate that science is alive and well, the chapters in this *Handbook* illustrate the vitality of science education as a discipline. We have learned much about science learners and learning, and science teachers and teaching, over the past 80 or so years of research. According to the chapter authors, many questions remain open for investigation. Surely many other questions we have not yet thought to ask.

As we continue to ask and investigate questions in science education, we believe it is crucial to keep a few guidelines in mind.

1. The ultimate purpose of science education research is the improvement of science teaching and learning throughout the world. We must take care that the proximate causes of our research (e.g., achieving publications that count for tenure, writing conference papers so our universities will fund our travel, preparing new researchers, getting grant dollars) do not derail us from achieving our ultimate purpose. Thus we call for rigor in design, data collection, interpretation, and write up.
2. To achieve the ultimate purpose of improving science teaching and learning, our research must be grounded in the real world of students and teachers and school systems and society. Ours is an applied field, and we must ensure that our research makes sense in the real world. Our research must address, and attempt to answer, the questions and concerns of teachers. To have educational warrant, our research must answer questions of educational importance.
3. To achieve the ultimate purpose of improving science teaching and learning, we as researchers need to be open to new theoretical frameworks, research methodologies, and strategies, even as we embrace existing tried and true methods. We are long past the paradigm wars that dominated education research in the 1980s. Mixed methods research (Chatterji, 2004; Johnson & Onwuegbuzie, 2004) is a new paradigm ripe for application to science education settings. Longitudinal studies that employ mixed methods will be essential to understanding student and teacher learning over time. In addition, theoretical frameworks that embrace postmodern thinking will help us see the world in new ways.
4. Translating our research for teachers is an essential component of our work. If we write only for other researchers, we will never achieve this ultimate goal. Teachers and researchers often describe the gap between research and practice. It is our responsibility to translate our research so that practitioners and policy makers can ultimately decide whether what has been offered is of practical value. This *Handbook* is written for researchers. We leave it to others to undertake the important work of interpreting and transforming its contents for other stakeholders.

These guidelines, along with the research agendas suggested by chapter authors, can help our field advance. Although we are not quite ready to state the 125 questions that the science education community has a shot at answering in the upcoming 25 years, the guidelines and research agendas can help science education researchers fulfill the mission, reflected in the NARST slogan, to improve science teaching (and learning) through research. If we keep our eyes on this goal, then we will continue to raise new research questions that will diminish our current ignorance while expanding the areas of ignorance yet to be explored.

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# PART I

## Science Learning

# CHAPTER 1

# Perspectives on Science Learning

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The past two decades have been an exciting time for research on science learning. During this time, science educators have created or adapted an impressive array of new research practices and conceptual tools that we can use to analyze student learning in science classrooms and in other settings. The results of those analyses have given us new insights into science learning as it occurs in individual students and in social, cultural, historical, and institutional contexts.

## INTRODUCTION: PERSPECTIVES AND RESEARCH TRADITIONS

### Purposes of This Chapter

The literature on science learning is diverse. It has been conducted by researchers from different cultural and intellectual backgrounds, using different methods, working in different settings. These researchers have based their work on different ideas about the nature of science, the purposes of science education, and the nature of science learning. Some aspects of this diversity are explicit and apparent to readers; for example, most research articles include descriptions of the settings and participants in the research and the methods used by the researchers. Other aspects of this diversity are harder to discern; authors can never fully reveal the assumptions that underlie their work or the intellectual influences that have shaped it.

This diversity of methods and viewpoints can make reading research on science education a frustrating experience. There seem to be no rules that everyone follows, no beliefs that everyone shares, no findings that everyone agrees on. Where is the order in this welter of confusing findings? How can we say that we are making progress in the field?

One way to find order and to see the progress in the literature on science learning is to recognize that within the broad field of science education there are groups of researchers who share common intellectual heritages and seek to build on one another's work. By recognizing the differences among those research traditions, we can see how researchers in each tradition are advancing knowledge as they understand it. We can also see how, in spite of their differences, researchers in all traditions are contributing to a collective effort that deepens and enriches our understanding of science learning.

In this chapter, I seek to provide a reader's guide that draws attention to the conceptual, methodological, and stylistic choices that the authors make in reporting research on science learning, and to how those choices are related to underlying beliefs about the nature and purposes of science education research. I have labeled these the *conceptual change tradition*, the *sociocultural tradition*, and the *critical tradition*. Rather than trying to provide historical overviews or general reviews of the literature in each tradition, I have chosen to focus on one exemplary article from each tradition, using quotations and commentary to discuss the authors' choices, the beliefs that underlie those choices, and the contributions that the tradition makes to our collective understanding of science learning.

In choosing to describe perspectives on student learning in terms of three research traditions, and in summarizing three individual articles to exemplify those traditions, I have oversimplified both the exemplary papers and the field in general. Representing research on science learning by focusing on three examples is a little like representing the visible spectrum by showing examples of the three primary colors. Subtlety and nuance are lost. Furthermore, the choice of three particular colors as primary is an accident of human physiology rather than a physical characteristic of light. Nevertheless, we continue to find the primary colors useful as we seek to understand color and color vision. I hope that these examples can be similarly useful. As with colors, there are very few pure examples of research within one of these traditions, both because the traditions themselves are multivoiced and because science educators are eclectic in their use of practices and conceptual tools from different traditions that will help them to achieve their research goals.

My choice of these three traditions is also idiosyncratic and historically situated. For example, I have included the extensive literature on uses of instructional technology in science education (e.g., Feurzeig & Roberts, 1999; Linn & Hsi, 2000; White & Frederiksen, 1998) in a broadly defined Conceptual Change tradition, though many researchers in both fields would consider the work in these fields as belonging to distinct traditions. Similarly, an author writing about perspectives on science learning in 1990 or in 2010 would probably identify traditions that are different from the ones I have chosen.

Thus the contrasts that I make among the traditions will not be very useful for classifying research studies, and I have not attempted to summarize research results. I hope, however, that by representing a range of perspectives and voices that researchers bring to the challenges of understanding and improving science learning, this chapter can help readers gain additional insights into the research itself. This chapter is not a substitute for reading research on science education, but an invitation that I hope will make the process of reading interesting and informative as we pursue our individual and collective goals in science education.

## Core Goals and Issues

Research on student learning in science can be broadly characterized as focusing on the development of *scientific literacy.* Scientific communities have developed knowledge and practices that are potentially valuable to members of the general public in their roles as workers, consumers, family members, and citizens. *Scientific literacy* is a term that can be used to designate the science-related knowledge, practices, and values that we hope students will acquire as they learn science.

For researchers in science education generally, scientific literacy includes a sense of empowerment or agency in two senses. The first of these I call *social agency.* Successful learners of science can gain respect for their knowledge, skills that enable them to do useful work, and access to jobs and to communities that would otherwise be closed to them. The second I call *agency in the material world.*[1] Successful learners of science can describe and measure the world around them with precision, predict and explain phenomena, and act effectively to influence natural and technological systems. Following Sharma and Anderson (2003), I also sometimes refer to these two kinds of agency as dialogues: learners' *dialogues with nature* and *dialogues with other people.*

Researchers in science education also generally agree on one central finding about current school practice: *Our institutions of formal education do not help most students to learn science with understanding.* This is a robust finding, encompassing both large-scale studies of science achievement (e.g., Blank & Langesen, 2001; Schmidt et al., 2001), as well as thousands of smaller studies conducted in a single classroom or a few classrooms. Given any reasonable definition of scientific literacy, the research shows that neither most students in schools nor most adults are achieving it. Furthermore, the benefits of science education are not evenly distributed. In the United States, for example, there is a large and persistent *achievement gap* that separates students by race, ethnicity, and social class (Blank & Langesen, 2001; Kim et al., 2001; see Chapter 8, this volume). Similar achievement gaps exist within and among countries worldwide. This leads to a two core questions that research on science learning should address:

1. Why don't students learn what we are trying to teach them?
2. Why does the achievement gap persist?

The importance of the three research traditions examined in this chapter lies largely in the provocative and useful responses that each tradition provides to these questions. The practices and theories developed through this research give us a deeper understanding of how students learn, why they fail to learn, and how we might create educational systems that are more responsive to their needs.

## Commonplaces and Contrasts

The next three sections of this chapter are devoted to an examination of the three traditions. Each section begins with a detailed examination of a single recently

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[1] I use the term *material world* to include the naturally occurring systems and phenomena that are studied by life, earth, and physical scientists, as well as technological systems created by humans.

published article that illustrates the perspectives and research methods typical of that tradition and exemplifies the kinds of insights into science learning that the tradition affords. Each section concludes with a more general look at the contributions that research in that tradition has made to our understanding of science learning, the influence of that research on policy and practice, and at the limitations of the tradition. Finally, the chapter concludes with some final thoughts on current issues and future progress in research on science learning.

As I compare and contrast the three articles and the traditions that they represent, I characterize each tradition in terms of five *commonplaces*—aspects of science learning that are explicitly or implicitly addressed by all research studies on science learning. These commonplaces are briefly described below and addressed in greater depth in the analyses of the research articles.

1. Intellectual history and related disciplines. All three traditions arise out of earlier work in science education and in related disciplines, such as psychology, sociology, linguistics, anthropology, and philosophy. The three traditions differ, though, in their intellectual roots and in the related disciplines that have most influenced them.
2. Ideas about the nature of science. Researchers in all three traditions share an understanding that our ideas about science learning and scientific literacy depend in part on our ideas about science. These traditions share an understanding that science is more than a body of knowledge or a set of methods for developing new knowledge. All three traditions share a view of science as a subculture with specialized language, values, and practices. The three traditions characterize science and scientific knowledge, though, in quite different ways, and those differences are reflected in their approaches to science learning.
3. Ideas about science learners and science learning. Researchers in all three traditions share a view of science learners as agents in their own right, who come to science learning with their own knowledge, language, beliefs, cultural practices, and roles in communities and power relationships. They recognize that learning arises out of the interactions between learners and the knowledge and practices they encounter in science classrooms. The three traditions differ, though, in their approaches to characterizing both learners and the process of science learning.
4. Research goals and methods. The most important research on student learning during this period has relied more on qualitative than on quantitative methods, and it has generally been conducted on a modest scale, focusing on individual learners, small groups, or learning in a few classrooms. The traditions differ, though, in the kinds of knowledge they seek to develop, in the degree to which they mix qualitative and quantitative methods, and in their methodological traditions and standards.
5. Ideas for improving science learning. All three traditions have convincing answers to the questions about the failures of formal science education above; they identify important barriers to successful learning that are rarely successfully addressed in school science. All three traditions have ideas about how schools and science teaching could be changed so that students would learn more successfully. The traditions, though, differ in the barriers to successful learning that they identify and in the suggestions that they develop for helping more students learn successfully.

## CONCEPTUAL CHANGE TRADITION: SCIENTIFIC LITERACY AS CONCEPTUAL UNDERSTANDING

Of the three research traditions, the conceptual change tradition is the one with the longest history and the most influence within the science education community. Like all of the research traditions, it encompasses a wide variety of perspectives and practices. Many of its methods and perspectives can be traced back to the developmental research of Jean Piaget (see Chapter 3, this volume). Piaget recognized the importance of children's thinking and developed the clinical interview as a method for investigating how children make sense of the world. Many of his investigations, especially early in his career, focused on children's understanding of scientific topics. Piaget's core interests, though, were developmental and psychological, so his research did not lead directly to the conceptual change tradition.

Conceptual change research emerged when investigators began to link Piaget's methods with ideas about the historical development of scientific knowledge, notably those of Kuhn (1970) and Toulmin (1961, 1972). Posner, Strike, Hewson, and Gertzog brought these strands together in a seminal article in 1982, suggesting that individual learners had "conceptual ecologies" like those used by Toulmin to describe scientific disciplines, and that learning in individuals resembled the complex process of theory change in science.

Since conceptual change research became prominent in the early 1980s, this tradition has generated an impressive amount of research worldwide. Reinders Duit's bibliography of conceptual change studies (Duit, 2004) covers more than 500 single-spaced pages. Conceptual change researchers have described alternative frameworks for every topic in the school curriculum (see, for example, Chapter 15 of *Benchmarks for Science Literacy*, American Association for the Advancement of Science [AAAS], 1993, or the reviews by Driver, Squires, Rushworth, & Wood-Robinson, 1994).

### An Example of Conceptual Change Research

One recent article that illustrates a number of important theories and practices is "Linking Phenomena with Competing Underlying Models: A Software Tool for Introducing Students to the Particulate Model of Matter," by Joseph Snir, Carol Smith, and Gila Raz (2003). This section summarizes the article and then discusses ways in which it exemplifies the perspectives and practices of research within this tradition.

Snir et al. (2003) addressed a problem in science learning that was well documented in previous conceptual change research and introduced in the first paragraph of their article:

> The particulate model of matter is one of the central ideas in modern science. It is also a central subject in the middle and high school science curriculum. Yet, as is well known, this topic is very hard for students to learn and internalize. . . . We believe that understanding the particulate model of matter is difficult because it requires that students develop an understanding of two profoundly important, but counterintuitive, ideas. The first one is the idea of the *discontinuity of matter* and the second is the idea of an *explanatory model* as a metaconcept in science. (p. 795)

As is typical in conceptual change research, Snir et al. (2003) defined the learning problem in conceptual terms and focused on a specific scientific domain, in this case theories about the nature of matter. Their focus on a specific scientific model or theory was also typical of conceptual change research. Their article was devoted to (a) helping readers to understand the depth and difficulty of this learning problem; (b) presenting a strategy for helping students achieve their learning goals; and (c) presenting and discussing data on student learning from two studies, one conducted in a laboratory and the other in a classroom setting. Their approach to each of these parts of the article is discussed below.

## Understanding the Learning Problem

Although the study focused on learning by middle-school students, the article barely mentioned middle-school students—or any students at all—in its first four pages. Instead, the article begins with a prolonged explication of the historical and philosophical significance of scientific models in general and the particulate model of matter in particular. The authors quoted the Nobel Prize–winning physicist Richard Feynman:

> If, in some cataclysm, all the scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* . . . that *all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another*. In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied. (Feynman, Leighton, & Sands, 1963, Chapter 1, as cited in Snir et al., 2003, p. 795)

The authors then described the key features and multiple uses of particulate models of matter in current scientific practice, as well as the historical struggles of scientists to develop the particulate model in its current form. Thus the article begins with a description of how scientists' dialogues with nature led to the development of the particulate model, and how it continues to play a critical role in scientists' dialogues with nature today. The introduction continues with a discussion of "the general conception of an explanatory model," noting that scientific models are understood to be (a) not true descriptions of a system, (b) limited in scope, (c) evaluated according to their power to explain and predict observed phenomena, and (d) not unique—the same system can be modeled in more than one way. Thus the article begins with a careful explication of current scientific knowledge and practice as a goal for science education.

Snir et al. (2003) devoted the next five pages of their article to a detailed review of the research literature on attempts to teach students to use particulate models to reason about properties of materials and changes in materials. They made the case that Feynman's simply stated idea makes sense only in the context of a complicated conceptual ecology that students develop when they "make the transition from a tangible, observable continuous world to an abstract unseen one that consists of discrete particles at a microscopic level" (p. 802).

The authors argued that students could understand and use particulate models of matter only if they were building on some critical macroscopic understandings about matter (e.g., even bits of matter that are too small to weigh, have weight;

understanding of the relationships among volume, weight, and density) and on their development of some understandings about the nature and uses of models in general. They argued that previous attempts to teach middle-school students about particulate models of matter had generally tried to "take on too much too fast," paying insufficient attention to some of these critical conceptual issues.

Thus, the educational challenges involve not only deciding what part of the particulate model to teach first and what prerequisite conceptions must be in place to create these conceptual puzzles, but also how to build students' general understanding of what a model is. We believe the best approach is to involve students in explaining a series of phenomena and in evaluating the explanatory adequacy of alternative models. This approach gives students the opportunity to construct the particulate model slowly in their mind in response to puzzling but concrete phenomena (Snir et al., p. 803).

## Presenting a Strategy for Helping Students Achieve Their Learning Goals

The next 11 pages of the article are devoted to detailed presentation and discussion of a software tool that the authors developed to help students accomplish their learning goals. The tool presented simulations of three critical experiments, involving (a) mixing of water and alcohol (a puzzling phenomenon, inasmuch as the volume of the mixture is slightly less than the total volume of the separate liquids), (b) thermal expansion of an iron ball, and (c) the reaction of copper and sulfur—the critical observation being that copper and sulfur always combine in the same proportions regardless of the amounts of the reactants available.

The tool focused the students' attention on key aspects of each phenomenon, then guided students through explanations of the phenomena based on four different models, a particulate model representing their learning goals and three alternative models designed to incorporate common student misconceptions. A series of screens guided students through the application of each model to each phenomenon, both illustrating how the model explained the phenomenon and comparing predictions of the model with actual experimental results. Only the particulate model consistently produced predictions aligned with the experimental results.

The authors summarized the key elements of the software (and implicitly the key elements of a strategy for conceptual change teaching about this topic) as follows:

> 1. It is designed to help students filter central facts from many experimental details.
> 2. It combines both tutorial and tool elements, while adjusting the mode to the nature of the learning. If one conceives of learning science on three levels—factual, conceptual, and metaconceptual (Snir, Smith, & Grosslight, 1993)—then we used the tutorial mode for the factual level and the tool mode for the conceptual and metaconceptual levels.
> 3. It allows students to compare, on the same screen, surface and model levels of description.
> 4. It acknowledges the existence of alternative models and students' initial ideas.
> 5. It facilitates the introduction of model evaluation based on consistency with a range of facts, rather than simply one observation, as a central part of the curriculum. (p. 814)

## Research Methods, Results, and Conclusions

The next 10 pages of the article are devoted to presentation of data from two studies: a laboratory study in which nine American fifth- and sixth-grade students explained their thinking as they used the software and a classroom study in which 28 Israeli seventh-grade students used the software as part of a unit on matter.

In each study, the researchers carefully tracked the reasoning of individual students as revealed on pretests, posttests, and their performance as they were using the software. There were measures of retention in each study: students in the laboratory study were interviewed a week after they used the software; students in the classroom study took a delayed posttest the next year. The classroom study also included teaching about macroscopic conceptions of matter (e.g., identifying solids, liquids, and gases as matter; relationships among weight, volume, and density), demonstrations of the actual phenomena, and a control group of students who studied a similar curriculum without the software. The teachers of the experimental classes were the authors, Joseph Snir and Gilda Raz. In addition to the concepts that were the focus of this study (particulate models of matter and general understanding of models), the pretests and posttests included measures of students' macroscopic understanding of weight, volume, and density.

The results of these studies were complex, but some of the key conclusions were as follows:

1. Both the think-aloud data from students using the software and class discussions revealed that most (but not all) students engaged in the activities intended by the authors: comparing and evaluating models based on their ability to predict observed results of the experiments;
2. Focusing on seven key, tenets of the particulate nature of matter,

   > In the experimental group, we found that 30% of the students had a perfect understanding of these seven simple points, compared to none in the control group. If we allow students one error, we find that 47% of the experimental students understood at least six of the seven points compared to 22% of the control students. (Snir et al., 2003, p. 823)

3. Thirty percent of the students in the experimental group wrote open-ended responses indicating that what makes the particulate model a good model is its ability to explain a wide range of phenomena. In contrast, none of the students in the control group answered in this way (p. 823)
4. Finally, the data provided evidence that students' macroscopic and microscopic understandings of matter mutually support one another. Students who by the time of the delayed posttest showed that they had a strong macroscopic understanding of matter were the ones most likely to have internalized the assumptions of the particulate model. (p. 825)

Similarly, these students were also the ones who showed the best understanding of the nature of models in general.

The article concludes with an argument that the key features of the software were responsible for the successful learning of the students in the experimental classes, and that the successful learners had undergone a fundamental long-term change in the way they viewed matter and models of matter. Their new, stable understanding included three mutually supporting components: an understanding of key macroscopic ideas about matter, understanding of key components of a particulate model of matter, and understanding of the nature and functions of models in general.

## General Characteristics of Conceptual Change Research

The results in the article by Snir et al. (2003) are more detailed and the arguments more subtle than I could portray in the brief summary above. I hope, however, that the brief summary is sufficient to illustrate some of the key characteristics that their research shares with other research in the conceptual change tradition. I discuss some of those characteristics in the following sections, then conclude with some thoughts on the power and limitations of conceptual change research.

## Characteristics of Conceptual Change Research

I discuss these characteristics in terms of the five commonplaces introduced at the beginning of this chapter. The first of these commonplaces, the intellectual history of the research tradition, is discussed briefly at the beginning of this section. The other four commonplaces—view of the nature of science, view of students and learning, methods, and implications for practice—are discussed briefly below.

***Science as a theoretical dialogue with nature.*** Although conceptual change researchers recognize the importance of both aspects of scientific literacy discussed in the introduction—social agency and agency in the material world—they give primacy to agency in the material world. Snir et al. (2003) for example, characterized science as an ongoing theoretical dialogue with nature, in which scientists have developed successively more powerful models to account for a wider range of phenomena. For these authors and for other conceptual change researchers, the power of science lies both in its general use of model-based reasoning to understand nature and in the specific models that scientists have developed. Thus the task of science education is to include students in scientists' ongoing dialogue with nature and to give them access to the power of scientific ideas.

***Learners as rational but inexperienced thinkers and learning as conceptual change.*** Like other conceptual change researchers, Snir et al. (2003) characterized the students who they worked with as coming into the research setting with their own ideas about matter. These ideas (labeled *misconceptions, naïve conceptions, alternative frameworks*, etc.) are less powerful and precise than scientific theories, but they generally work for the students' purposes and within the limits of their experience. Thus the task of the researchers is both to give students access to new experiences with the material world that are incompatible with students' naïve ideas—the three key experiments—and to help students see the power of the particulate model to account for these new experiences. This is a complex process of *conceptual change*; students learn with understanding only if they modify their conceptual ecologies to accommodate the more sophisticated scientific conceptions. Much of the detailed work of the conceptual change research program—the contents of

Duit's (2004) 500-page bibliography—has been mapping out the conceptual ecologies for specific topics and for students of different ages.

***Research methods for analyzing students' conceptions.*** Snir et al. (2003) used methods typical of conceptual change research—written tests, clinical interviews, and think-aloud protocols of problem solving—to construct an argument about the understanding of the students before and after instruction. In the article and its supporting literature, they took great care to describe and defend the validity of their methods for assessing the specific beliefs of the students with respect to the scientific topic of study: the particulate nature of matter and the nature and uses of scientific models.

As significant as what they included in their research description is what the authors did *not* consider essential information. They provided no information about themselves and their intellectual or cultural backgrounds. Although they noted the age and nationalities of the students, they provided no other information about their cultural backgrounds or social class. They did not investigate the students' general experience or learning styles. In these respects, too, they were typical of conceptual change researchers. They took great care to investigate the conceptual ecologies of their informants around the scientific topics they studied and to situate their research in a scientific context, but neither they nor the reviewers of their research thought it necessary to report on the social or cultural contexts of their work.

***Teaching methods for conceptual change learning.*** This article differs from much conceptual change research in that it focused on an instructional intervention. Although instructional studies are common in this research tradition, they are outnumbered by studies that document students' current conceptions and their responses to traditional science instruction. Those studies have almost inevitably found traditional instruction to be inadequate and have recommended instructional methods like those used by Snir et al. (2003). Their summary of the key characteristics of their software has great resonance within the conceptual change tradition, because it focuses only on the qualities that conceptual change researchers generally believe are essential for successful science learning—and missing from most science teaching. Their underlying belief is that successful student learning will be driven by situations of *conceptual conflict* like those that have driven historical advances in scientific communities, where students can see the contrast between their conceptions and alternative scientific conceptions and the superior power and precision of the scientific conceptions.

## Power and Limitations of Conceptual Change Research

One reason for the popularity of conceptual change research is that it has produced productive answers to the first of our two key questions: Students fail to learn what we try to teach them because they come to school with alternative conceptual frameworks that shape their perceptions and interpretations and that are not addressed by school science. This is a productive answer in part because it suggests a course of action: Identify the students' alternative frameworks and address them explicitly in instruction. Furthermore, conceptual change researchers have developed conceptual and methodological tools that they can use to follow this course of action.

Another reason for the popularity of conceptual change research has been that it makes effective use of the intellectual resources of science educators. The primary qualifications for doing conceptual change research are knowledge and skills acquired through scientific training and educational experience. Scientific training teaches people to be attuned to rational and coherent theories as the content of discussions with professors and colleagues, so it prepares science educators to attune themselves to these kinds of meanings in students' language and thinking. Thus, conceptual change research has been a source of personal and professional growth for many scientists and science educators, opening up new dimensions of communication with students that lead to improved practices in science teaching and teacher education.

Conceptual change research has also had a substantial influence on educational policy. The authors of the U.S. national standards documents (AAAS, 1993; National Research Council, 1996) consulted conceptual change research findings in writing content benchmarks, and their recommendations for teaching practice were influenced by conceptual change research. Many textbooks now include lists of common misconceptions in their teacher's editions.

The evidence that conceptual change research can be used to improve teaching practice is sketchier than the evidence that students' alternative frameworks affect their learning, but still substantial. The article by Snir et al. (2003) is typical of much of this research in that it provides an "existence proof"—an example of successful teaching for understanding by individual teachers for a small number of students. These existence proofs show that under the right conditions many students can learn science with levels of understanding that are currently achieved by only a small elite. Furthermore, this article, like others in this tradition, emphasized the potential scalability of the teaching methods. Other teachers can be given access to the software tool, the demonstrations are easily replicable, and other students can be expected to have similar misconceptions.

There is little evidence, however, that these practices are spreading to large numbers of teachers, suggesting that there may be difficulties in taking these innovative to scale that are not addressed in the article. Some of those difficulties are inherent in any attempt to implement innovative practice on a large scale and are beyond the scope of this chapter (see, for example, Cohen & Hill, 2000; Elmore, 2002; Gamoran et al., 2003). There are questions that we could pose about the research itself. In the study by Snir et al. (2003), for example, a number of students did not achieve the learning goals. The authors reported that these were the students who had not previously mastered key macroscopic understanding of mass, volume, and density. But why did some students fail to master the prerequisite knowledge, especially in the classroom study where that knowledge was included in the instructional program? Was there some deeper source of difficulty that the conceptual change research methods did not discover?

These questions about a particular study are connected to questions about the larger conceptual change research program. For example, what might scientific literacy involve beyond conceptual understanding? A view of students as proto-scientists who understand the world on the basis of implicit theories is not the whole story. Conceptual change researchers generally recognize that scientific understanding is more than just understanding core concepts, but their data collection methods and analytical tools focus on conceptual frameworks.

Furthermore, the theories and methods of conceptual change research have produced more productive answers to the first of the two key questions posed in the introduction than to the second (about the achievement gap between students of different races, cultures, or social classes). Although conceptual change research has been done in many countries, there is little evidence that students of different cultures or social classes have significantly different conceptual frameworks, or that conceptual differences are responsible for group differences in achievement. Conceptual change teaching can improve the learning of many students, but it shows little evidence of reducing the achievement gap. For tools and methods that help us to address these unanswered questions, we will need to look to other traditions.

## SOCIOCULTURAL TRADITION: SCIENTIFIC LITERACY AS PARTICIPATION IN A DISCOURSE COMMUNITY

The conceptual change tradition explains the failure of students to learn the science that they are taught in schools in terms of hidden conflicts—conflicts between scientific conceptual frameworks and the conceptual frameworks that students develop through their own experience. Sociocultural researchers are also concerned about hidden conflicts, but they see those conflicts in quite different terms.

Like conceptual change research, sociocultural research in science education brings together ideas and practices from several longstanding intellectual traditions. Both perspectives draw on developmental psychology, but on different branches in the field. Whereas conceptual change research used ideas and methods developed by Piaget, sociocultural research has depended more on the research of Lev Vygotsky and his followers (see Chapter 3, this volume). In contrast to Piaget's emphasis on how children learn from their encounters with the material world, Vygotsky focused on how children learn from their participation in activities with other people.

Sociocultural researchers also share with conceptual change researchers an interest in research on scientific communities and scientific practices. Again, however, their interests are different. Whereas conceptual change researchers focus on intellectual history and philosophy of science, sociocultural researchers focus more on analyses of the culture and language of scientific communities (e.g., Kelly, Carlsen, & Cunningham, 1993; Latour & Woolgar, 1979; Traweek, 1988). Sociocultural researchers in science education also base their research on anthropological studies of how people learn to use practices and resources from their intellectual and cultural contexts in their approaches to reasoning and problem solving (e.g., Cole, Gay, Glick, & Sharp, 1971; Lave & Wenger, 1991; Rogoff & Lave, 1984; Scribner & Cole, 1983). Finally, sociocultural researchers are influenced by sociocultural research that focuses on careful analysis of the language that people use in particular situations and its meaning in social and cultural context (e.g., Gee, 1991a, 1991b; Michaels, 1991; O'Connor & Michaels, 1993; Tannen, 1996).

Although these are longstanding lines of research, their application to problems of science education is more recent. The record of science education research in the sociocultural tradition is substantial, but there is no 500-page bibliography like Duit's (2004). An article that illustrates the concerns and analytical methods of sociocultural research in science education is "Maestro, What is 'Quality'?: Language, Literacy, and Discourse in Project-Based Science" (Moje, Collazo, Carrillo, & Marx, 2001).

## An Example of Sociocultural Research

Moje et al. (2001) analyzed science teaching and learning in a bilingual seventh-grade classroom. In many ways this class exemplified the best of what our current science education system has to offer. "Maestro Tomas" was a well-qualified teacher who had close and supportive relationships with his students. The air quality and water quality units he used were developed by a team of highly qualified teachers, researchers, and curriculum developers, who were supporting Maestro Tomas as he taught the units (Krajcik, Blumenfeld, Marx, Bass, & Fredricks, 1998). In spite of these admirable aspects of the classroom, the authors saw reasons to doubt how effective the unit had been. Their paper included (a) an explanation of their theoretical approach, (b) the methods and the results of their research, and (c) a discussion of the implications of their research for science education.

## Theoretical Approach

The first five pages of the article are devoted to a literature review that describes the authors' theoretical approach. Like other sociocultural researchers, Moje et al. (2001) viewed conceptual frameworks as cultural products that are embedded within practices (such as explaining phenomena in the material world) and Discourses (Gee, 1996): "ways of knowing, doing, talking, reading, and writing, which are constructed and reproduced in social and cultural practice and interaction" (p. 470). Moje et al. argued that students in science classrooms are likely to experience not only conceptual conflict, but also conflict among multiple Discourses, each associated with its own community of practice, that intersect in science classrooms:

> Although several different intersecting Discourses can be at work in any one classroom, at least three are particularly salient for this discussion: disciplinary or content area, classroom, and social or everyday Discourses. These Discourses represent distinct ways of knowing, doing, talking, reading, and writing, and yet they overlap and inform one another in important ways. For example, the Discourses of classroom instruction are informed by what teachers and student believe about the nature of knowledge in the discipline . . . Similarly, the ways that students take up classroom or disciplinary Discourses are shaped by the social or everyday Discourses they bring to the classroom. (p. 471)

## Research Methods and Results

Moje et al. (2001) used these ideas to analyze science teaching and learning in a seventh-grade classroom with students drawn from populations for which conceptual change teaching has generally been less successful. This is the longest section of the article—12 pages.

> The teacher of the seventh-grade class, whom we call Maestro Tomas, was a native Spanish speaker of Dominican descent who had been reared in both the Dominican Republic and the United States. All but one student in the class of 32 were Latino or Latina, and some were relatively recent immigrants to the United States; 27 of these students demonstrated some level of proficiency in both Spanish and English. The remaining five students had very recently immigrated from Spanish-speaking countries, and so we identified them as Spanish-dominant, English language learners. (pp. 474–475)

Moje et al. (2001) observed Maestro Tomas and his students as they studied two project-based units, on air quality and water quality. Typically for sociocultural research, they relied on ethnographic data collection and analysis techniques:

> Primary data sources included participant observation documented in field notes, formal and informal interviews with the teacher and students, and artifact collection, . . . student writings and curriculum work sheets. All classroom sessions were audio taped, and several were also videotaped. Another level of data collection included an electronic discussion of the analyses with Maestro Tomas. (p. 475)

The authors saw "competing Discourses" as a dominant theme that emerged from their analyses:

> Our analyses of the Discursive demands of the curriculum enactment in this one classroom yielded a number of themes, but the dominant theme was one of competing Discourses. Each of the Discourses in the classroom had its own rules and expectations, usually implicit, and often in conflict. Maestro Tomas and his students had difficulty recognizing and orienting themselves to the demands and practices of these competing Discourses. Some of their difficulties arose from the nature of the curriculum itself, which encouraged students to contribute information in their everyday Discourses and included texts that presented information in a variety of Discourses, such as a fictional play in which the villains are the "awful eight pollutants." Thus, the curriculum introduced competing Discourses, but privileged the scientific (via pre-and posttesting, writing assignments, and final projects). (p. 482)

For Moje et al. (2001) the problem was not so much that scientific Discourse was privileged as that the privileging was hidden: The curriculum neither explicitly compared Discourses nor made it clear that scientific discourse was the preferred mode of expression on assignments and tests.

While the use of different Discourses might be justified as a means of making the curriculum more engaging for students, one effect was that students saw fewer models of the privileged scientific Discourse than they otherwise might have. Neither was it always clear that this Discourse was meant to be privileged, nor were its rules and expectations made explicit. The effects of these ambiguities were apparent in the students' work.

For example, Maestro Tomas asked students to respond—in English or Spanish—to this prompt midway through the study of air quality:

> Imagine a factory opens in your neighborhood. Write a story about what would happen to the neighborhood and how would the air be affected.
>
> The students responded to this kind of assignment enthusiastically, but they also responded in ways that would more appropriately be labeled creative writing rather than scientific or even informational writing. Of the 32 papers produced by students, all were

> written as journal-like responses, suspense stories, and journal entries written by fictional characters; 23 were stories or fictional journal entries, whereas the other nine were straightforward responses to the question, written as if an entry in a journal. . . . In fact, despite Maestro Tomas's focus on writing and reading as informational tools, and despite the enthusiasm and creativity that students brought to the writing of these papers, only 11 of the 32 pieces incorporated terms or phrases drawn from the project work. (pp. 483–484)

## Discussion and Implications

To resolve these conflicts in ways that enable students to master scientific discourse, Moje et al. (2001) turned to the ideas of Kris Gutierrez and her colleagues about the creation of *congruent third spaces:*

> Gutierrez et al. (1999) argued that the weaving together of counterscripts (what we have been calling everyday Discourses) with official scripts (or in this case, scientific Discourses) constructs a third space "in which alternative and competing discourses and positionings transform conflict and difference into rich zones of collaboration and learning." (Gutierrez, Baquedano-Lopez, Alvarez, & Chiu, 1999, as cited in Moje et al., p. 487)

Moje et al. further suggested criteria for the successful creation of congruent third spaces and the ways in which Maestro Tomas and his students had fallen short of this ideal:

> To develop congruent third spaces for language, literacy, and science learning in diverse classrooms, four characteristics of classroom interaction seem necessary: (a) drawing from students' everyday Discourses and knowledges, (b) developing students' awareness of those various Discourses and knowledges (cf. New London Group, 1996), (c) connecting these everyday knowledges and Discourses with the science discourse genre of science classrooms and of the science community, and (d) negotiating understanding of both Discourses and knowledges so that they not only inform the other, but also merge to construct a new kind of discourse and knowledge. Maestro Tomas and the written curriculum achieved the first step of constructing congruent third spaces for the development of scientific literacy, but needed to take that first step further. (p. 489)

## General Characteristics of Sociocultural Research

Although the brief summary of the article by Moje et al. (2001) does not do justice to the interest of their results or the complexity of their arguments, it does illustrate some of the key characteristics that their research shares with other research in the sociocultural tradition. I discuss some of those characteristics below, then conclude with some thoughts on the power and limitations of sociocultural research on science learning.

## Characteristics of Sociocultural Research

Many of the characteristics of sociocultural programs of research and development are apparent in the article by Moje et al. (2001). As in the section on conceptual change research, I use the commonplaces from the introduction—view of the nature of science, view of students and learning, methods, and implications for practice—to characterize this research tradition and compare it with the conceptual change tradition.

***Science as a discourse community.*** In contrast to conceptual change researchers' emphasis on scientists' dialogues with nature, sociocultural researchers focus primarily on scientists' dialogues with people. For Moje and other sociocultural researchers, scientists are participants in communities of practice with shared linguistic and social norms, values, and patterns of activity. Scientists' language and practices give them agency in both the social and material worlds. Thus, a primary task of science education is to help students control the linguistic and cultural resources that they need to participate in this privileged Discourse.

***Learning as control of multiple discourses.*** Like other sociocultural researchers, Moje et al. (2001) portrayed students as participants in multiple communities of practice, each with its own language, values, and practices. Students entering school have not participated in scientific communities of practices, though some students come from home communities whose language and practices are much closer to scientific language and practice than others. Students learn science when they are able to adopt scientific language, values, and social norms for the purposes of participating in scientific practices, such as inquiry and application of scientific concepts.

Thus there are interesting parallels and differences between the arguments of Moje et al. (2001) and those of conceptual change researchers like Snir et al. (2003). Researchers in both traditions attribute students' difficulties in learning science to hidden conflicts. At this point, however, the arguments diverge. Rather than conceptual conflicts, Moje et al. saw conflicts among Discourses—"ways of knowing, doing, talking, reading, and writing, which are constructed and reproduced in social and cultural practice and interaction" (p. 470). In this situation, conceptual change teaching methods, which rely heavily on rational argument within a shared scientific Discourse, are not likely to be sufficient. Maestro Tomas and his students needed to find ways of resolving conflicts not only among conceptual frameworks, but also among values, social norms, and ways of using language.

***Research methods for analyzing learners' culture, language, and practices.*** In contrast with Snir et al. (2003), who collected data in carefully controlled settings that would allow for a detailed analysis of students' conceptions, Moje et al. (2001) used more naturalistic methods, seeking to understand how Maestro Tomas and his students talked, wrote, and acted as they worked together. They sought to understand how these individuals operated within the social context of the classroom. Rather than conceptual knowledge, their analyses of learning focused on students' use of language, including choice of vocabulary and genre.

It is also interesting to note what these authors and their reviewers considered essential information about their methods. In contrast with Snir et al. (2003), Moje et al. (2001) informed readers about the linguistic and cultural backgrounds of each author, Maestro Tomas, and all of his students.

> The research and development team was composed of two Latinas, two Latinos (one of whom was Maestro Tomas), and two European Americans, one male and one female. All

> Latino and Latina members are fluent Spanish and English speakers, whereas the European American team members are monolingual. (Moje et al., p. 475)

They did not have formal instruments for structured data collection or detailed descriptions of their analytical methods. Thus, while the conceptual change researchers paid careful attention to the details of methods for data collection and analysis, the sociocultural researchers paid careful attention to the backgrounds, possible biases, and intellectual resources of the researchers themselves.

***Teaching methods for sociocultural learning.*** Sociocultural researchers focus their attention on methods that help learners master language and culturally embedded practices, beginning with the problem of how teachers and students can communicate meaningfully across linguistic and cultural differences. Moje et al. (2001) focused on the development of congruent third spaces in classrooms, where everyday and scientific Discourses and knowledge can be negotiated and merged to create new understanding. Within these third spaces sociocultural conflicts can be resolved, and students from different home cultures can contribute intellectual resources to the classroom community. Although conceptual conflict is a commonly proposed mechanism for learning in the conceptual change tradition, many sociocultural researchers focus on *apprenticeship* as a metaphor for learning (e.g., Collins, Brown, & Newman, 1989; Lave & Wenger, 1991).

## Power and Limitations of Sociocultural Research

Although roots of the sociocultural research tradition extend back for decades, it is only in the last 10 years that its significance has been widely recognized by science educators. Compared with conceptual change research, sociocultural research has had less influence on science education policy and practice. This can be attributed partly to its relatively short history in the field, and partly to the methodological challenges that sociocultural research presents. It has been difficult to use sociocultural methods to collect quantitative data or to translate sociocultural ideas about teaching into prescriptions for reproducible practice. [Though, like conceptual change research, sociocultural research has produced "existence proofs" of excellent teaching based on sociocultural ideas. See, for example, Heath (1983, Chapter 9), O'Connor & Michaels (1993), and Rosebery, Warren, & Conant (1992)].

Furthermore, the ideas and methods of the sociocultural tradition are less familiar and more challenging to science educators than conceptual change ideas and methods. People who, like most science educators, have trained to be scientists or science teachers have had relatively little exposure to the linguistic and anthropological concepts that are central to sociocultural research. Education in the sciences emphasizes immersion in communities of scientific practice, but not awareness of the ways in which other communities of practice differ in cultural practices, values, and habits of mind that scientists take for granted. Thus, science educators must struggle to see hidden sociocultural conflicts and to make use of the cultural resources that children bring to science learning.

The struggle is worthwhile, however, because sociocultural research produces deep and compelling insights with respect to the two questions posed in the introduction to this chapter. With respect to the first question, about why students fail to learn science, sociocultural research adds to and deepens the insights of conceptual change research. We can see that students in school must deal with hidden cultural conflicts as well as hidden conceptual conflicts. Furthermore, the methods of sociocultural research can reveal those conflicts in particular classrooms and show how they inhibit students' science learning.

With respect to the second question, about the origins and persistence of the achievement gap, sociocultural research produces compelling insights. This research tradition reveals the many ways in which scientific discourse communities are built around the language, values, and social norms of their (mostly European middle class) members. Similarly, schools privilege the language, values, and social norms of their (mostly European middle class) teachers. Thus middle-class European children enter school with significant advantages over children from other social and cultural backgrounds.

Sociocultural researchers recognize that these advantages have emotional as well as intellectual consequences and, more fundamentally, that science learning is an emotional as well as an intellectual process. Many sociocultural researchers (e.g., Kurth, Anderson, & Palincsar, 2002; Ogbu, 1992; Steele, 1992, 1999) have investigated the effects of the accumulated weight of cultural differences on students' willingness to keep trying to succeed in school. Research by sociocultural researchers on engagement and alienation helps us to understand how apparently simple unmotivated behavior has deep roots in students' cultural histories and personal development, as well as in the ways that schooling privileges other cultures and values at the expense of their own. Thus, sociocultural researchers transform the essential motivational problem of teaching from one of remedying motivational deficiencies to one of finding new and more productive ways of making use of the cultural resources that all children bring to school.

In summary, sociocultural researchers have developed analytical tools that they can apply to issues that conceptual change researchers relegate to craft. In particular, sociocultural research helps us to understand science learning as a linguistic, cultural, and emotional process, as well as a process of conceptual change.

## CRITICAL TRADITION: SCIENTIFIC LITERACY AS EMPOWERMENT

Researchers in the conceptual change and sociocultural traditions both attribute students' difficulties in learning science to hidden conflicts, either conceptual or cultural. Researchers in the critical tradition recognize the existence and importance of these conflicts, but they are centrally concerned with the ways in which these conflicts are shaped and how their outcomes are determined by power and ideology.

Critical researchers in science education are heirs to a long intellectual history of scholars who sought to show how dominant classes manipulated "truth" to their advantage, including scientific truth (e.g., Foucault, 1977; Scott, 1998). Feminist critics of science (e.g., Harding, 1991; Keller, 1985) have been especially influential among science educators. Other critical researchers in education have focused on how students in school who are not members of dominant classes have been marginalized and labeled "disadvantaged" or "at risk" (e.g., Delpit, 1995; Natriello, McDill, &

Pallas, 1990). In recent years, critical researchers in science education have combined these two strands to investigate specifically how some students are marginalized in our science education system. An article that illustrates the concerns and analytical methods of critical research in science education is "The Culture of Power and Science Education: Learning from Miguel," by Angela Barton and Kimberly Yang (2000).

## An Example of Critical Research

Barton and Yang (2000) sought to understand and report on the life history and science learning of a young father, "Miguel," who was living in a homeless shelter in New York City with his wife, "Marisol," and their two children. Their article begins with a two-page vignette that describes the essential facts of Miguel's case: He was a Puerto Rican high-school dropout who never took science in high school in spite of a continuing interest in nature. He later earned a high-school equivalency diploma and supported Marisol and their children by working as an industrial painter of fire trucks. When his company downsized, however, Miguel was not able to find new employment, so his family came to the homeless shelter where Barton and Yang met and interviewed him.

The authors sought to describe and explore the implications of Miguel's life history and of the beliefs that he revealed in his interviews. After the opening vignette, their article includes a discussion of the culture of power in schools and in science education (three pages), a description of their research orientations and methods (one page), an interpretation of Miguel's story (six pages), and a discussion of the implications of cases like Miguel's for science education (four pages).

## The Culture of Power

Barton and Yang (2000) positioned themselves as advocates for Miguel and in opposition to the "culture of power" that has a pervasive influence on schools and school science:

> The "culture of power" and its effects are part of nearly every institution in the United States, including the institution of schooling. . . . Delpit (1988) argues that without making the rules for the culture of power explicit, those who are not familiar with the culture of power will lack opportunities for upward mobility, be perceived as deficient, inferior, or disadvantaged, and be viewed as the cause of society's problems. (pp. 873–874)

Like other researchers taking a critical perspective, Barton and Yang (2000) saw abundant evidence that the culture of power affects science education as well as other aspects of schooling:

> Textbooks and other curricular materials often hide the people, tools, and social contexts involved in the construction of science. The result is often a fact-oriented science which appears decontextualized, objective, rational, and mechanistic (Brickhouse, 1994). Science labs and classrooms are typically structured hierarchically with the teacher and the text controlling what knowledge counts (Brickhouse, 1994). (Barton & Yang, p. 875)

## Research Methods and Interpretations

Barton and Yang's (2000) critical perspective was also apparent in their explanations and justifications of their research methods. They were explicit in describing their own backgrounds and perspectives:

> As co-authors we come to this research from two different perspectives: One of us is an ethnic minority, the daughter of immigrants, bi-lingual, and raised on the west coast in a family that during her lifetime moved from "poor immigrant status" to upper-middle class professional. The other of us is a white, middle-class woman raised on the east coast with experience as a homeless individual in the same metropolitan area as the family presented in this paper. (p. 877)

For Barton and Yang (2000), ideas about the culture of power provided a critical lens for understanding Miguel's life story. Their case study of Miguel focused on "four key experiences in which culture, power, school, and science played out in Miguel's life: studying/doing herpetology, dropping out of school and school science, critiquing peer culture, and child rearing" (p. 878). Briefly, they reported the following:

***Studying/Doing herpetology.*** "Miguel often expressed a love of nature, and had for a while maintained his own black-market herpetology business, raising reptiles and selling them for a profit.

He was drawn to a way of explaining the world around him that went beyond books. The world—the turtles, rats, snakes, and other creatures he studied—was real life. However, the science to which Miguel referred was always outside of school, always a part of his own research into the world around him" (Barton & Yang, 2000, p. 878).

***Dropping out of school and science.*** Miguel's teachers and counselors placed him on a vocational track, never suggesting that taking a science course was even a possibility. In Miguel's school, science was clearly meant for people other than him. "In retrospect, Miguel believed these actions on the part of his teachers and his counselors only reinforced his belief that school science and scientific careers were not realistic options for youth from the 'hood'" (Barton & Yang, 2000, p. 879). In response, "Miguel dropped out of school when he was a junior, and when in his words, he had 'done all of the time [he] could handle'" (Barton & Yang, p. 879).

***Critiquing peer culture.*** Miguel's experiences led him to a complex understanding of the difficult relationships between his own culture and the culture of power. On the one hand, he recognized how the institutions of society had denied him opportunities. On the other hand, he recognized that the street culture in which he grew up, valuing "an image of toughness" and failing to look toward the future, had also prevented him from developing the knowledge and skills he needed to succeed. "As Miguel stated, 'Puerto Ricans are not respected in American culture, and in turn we [Puerto Ricans] make no effort to gain respect'" (Barton & Yang, 2000, p. 881).

***Child rearing.*** Miguel removed his daughter from an after-school program at the shelter and was reluctant to send her to a predominantly Puerto Rican public school, stating that he "'preferred to send [his] children to a school populated predominately by whites and run by whites.' In his opinion, 'they [Puerto Ricans] can learn from others because they are succeeding and we [Puerto Ricans] are not'" (Barton & Yang, 2000, p. 881).

## Discussion and Implications

Barton and Yang (2000) told a story of frustration and disappointment. They saw the reasons for Miguel's frustration in the ability of "those in power [to] set the discursive norms and values, leaving those belonging to other cultural perspectives to be perceived as different and deficient" (p. 886). What can science educators learn from Miguel and his experiences? Barton and Yang suggested an answer, posing the question: "How might Miguel's story and our understanding of the culture of power inform efforts to promote equitable science education reforms?" (p. 885).

> We believe that part of the answer to this question lies in moving beyond the rhetoric of "science for all" to critically understanding how culture and power influence what creating an inclusive science community might mean. One way to ameliorate this situation is to examine what has been traditionally considered school science versus non-school science. The silencing of scientific knowledge that does not fall in the realm of recognized school science has resulted in exclusion of certain populations toward the formal learning of science (Eisenhart, Finkel, & Marion, 1996). (Barton and Yang, p. 886)

## General Characteristics of Critical Research

This brief summary of Barton and Yang's (2000) article illustrates some of the key characteristics that their research shares with other research in the critical tradition. I discuss some of those characteristics in the following section, then conclude with some thoughts on the power and limitations of critical research on science learning.

## Characteristics of Critical Research

Many of the characteristics of critical programs of research and criticism are apparent in Barton and Yang's (2000) article. As in the sections on conceptual change and sociocultural research, I use the commonplaces from the introduction—a view of the nature of science, a view of students and learning, methods, and implications for practice—to characterize this research tradition and compare it with the conceptual change tradition.

***Science as inherently ideological and institutional.*** Researchers in all three traditions recognize that scientific truth is not absolute; scientists are inevitably limited by the perspectives and resources available to them. Conceptual change researchers see scientific truth as historically situated: Scientists of any generation are limited by the data available to them and the perspectives that they have inherited from their intellectual forbears. Sociocultural researchers see scientific truth as also culturally situated: Different cultures or subcultures decide what is true according to their own culturally specific standards and forms of argument. Critical researchers see truth as the servant of power: Dominant classes of people arrange the "rules of the game" so that their knowledge and their ways of thinking and acting are seen a superior to those of other classes. Thus claims that scientific knowledge is objective or disinterested mask the ways in which scientific knowledge and practice serve the culture of power.

***Science learning as indoctrination or the development of critical consciousness.*** Critical researchers see students as participants in power relationships and institutions: Some students are given preferred access to the power of scientific knowledge and practice while others are excluded. They see current science education largely as a form of indoctrination: Students are taught to accept as truth knowledge that is designed to serve the interests of the powerful. They advocate an alternative kind of science learning—the development of critical literacy: Students need to learn not only how to participate in scientific communities but also to question and criticize the relationships between those communities and other powerful interests.

***Research methods for discovering and analyzing ideologies and power relationships.*** Barton and Yang's (2000) approach to describing their backgrounds, credentials, and research methods differs from the approaches of the other focus articles in ways that reveal differences in the beliefs of the authors about what counts as significant knowledge and how knowledge claims can be validated. The authors of the other two focus articles used the traditional "scientific" passive voice in describing their methods and described themselves in the third person. They sought to reassure readers that they had taken appropriate steps to avoid bias in their reporting. For Snir et al. (2003), this meant careful attention to instruments and methods. For Moje et al. (2001), it meant triangulating among multiple data sources and submitting their knowledge claims to extensive intersubjective verification.

In contrast, Barton and Yang (2000) described their research methods in less than one page, writing in the first person. They informed readers about their backgrounds and interests so that readers could decide for themselves how to interpret the case study. Their goal was not to generate independently verifiable knowledge claims; instead they aspired to "intersubjectively shared theoretical perspectives and life experiences" (p. 877).

Underlying Barton and Yang's (2000) description of methods were different beliefs about the nature of the knowledge they produced and about their relationship with their informants, their readers, and social institutions. Critical researchers question whether "unbiased" or "fair-minded" knowledge is possible. They find bias to be inherent in our backgrounds and perspectives, so knowledge that claims to be unbiased typically serves the interests of powerful interests and institutions. Thus the fairest position researchers can take is to be honest about their perspectives, their biases, and whose interests they seek to serve.

***Teaching methods to achieve critical literacy.*** Critical researchers have also developed ideas about how changes in the organization and ideology of schooling can be used to improve instruction, including changed power relationships in schools and the acceptance of knowledge that is currently outside the bounds of school science. They maintain that successful learning involves changes in powerful adults as well as powerless students. For examples of successful critical pedagogy, critical researchers often point to programs on the margins of the formal institutions of schooling, such as alternative schools or out-of-school programs like the one at the homeless shelter attended by Miguel's daughter (Barton, 1998) or the programs for disenfranchised poor started by Paulo Freire (1970/1993). Other critical researchers examine the practices of teachers in public schools, often minority teachers, who engage children in meaningful, important learning (e.g., Delpit, 1995; Ladson-Billings, 1994). A common theme that runs through all of these accounts of successful learning is that learners achieve critical literacy—the ability to see and criticize how power works to privilege some people and some forms of knowledge at the expense of others.

## Power and Limitations of Critical Research

Critical research has had less influence on policy and practice than the other traditions, in part because critical researchers openly question the premises on which policy is made, science teaching practice is based, and science achievement is measured. In particular, they challenge science educators to think about our own roles in maintaining injustice and inequality in our schools. Researchers in all three traditions proclaim their commitments to social justice and their desire to improve the science literacy of less successful students. The conceptual change and sociocultural traditions implicitly assume that these improvements can come at little or no cost to students who are currently successful in school (including the children of science educators). The critical tradition challenges that assumption. Critical researchers point out that the competition for positions of power and influence in society has always been a zero-sum game, with losers as well as winners. Are comfortable professionals like science educators willing to work for the fundamental changes in society that would really change the relationships among those of us who are more and less powerful?

Critical researchers would respond to the two key questions posed in the introduction, about the ineffectiveness of our science education system and the persistence of the achievement, by challenging their implicit premises. Is it not possible that the science education system is doing quite well what it was designed to do—to restrict access to the true power of scientific reasoning to a small elite? The remaining students are fed a thin gruel of "facts" presented in ways that reinforce the correctness of their inferior position in society. The hidden message is that the people who produce and distribute the facts are different—smarter and better qualified than the students could ever be. It is not quite right to say that the people who benefit from the culture of power, including teachers, professors, and science educators, are deliberately making this happen. However, we are acquiescing in a system that serves our interests and the interests of our powerful sponsors far better than it serves the interests of the powerless students entrusted to our care.

In summary, critical researchers have developed analytical tools that reveal the hidden workings of the culture of power in the institutions that society has made responsible for science education and in the knowledge that they teach. In particular, critical research helps us to understand the ways in which the achievement gap is not an unfortunate accident; it persists because it serves the interests of those who benefit from their preferred access to and control over scientific knowledge.

# CONCLUSION

Looking collectively at these three research traditions, where do we stand? We still must decide whether the glass—our understanding of how people learn science and how to improve science learning—is half full or half empty. On the half-empty side, it is clear that as a field we still have a lot to learn about science learning. Here are three important issues that are not fully addressed by the three focus articles or by the research traditions that they exemplify.

## Relationships among Traditions

One question that we face concerns what we can understand about science learning by looking collectively at research from the three traditions. Are these traditions, like subdisciplines of biology, looking in complementary ways at different subsystems? In that case, the collective insights from the three traditions provide us with a richer and deeper understanding of science learning than we could achieve from any one of the traditions alone—the whole is greater than the sum of its parts. Or, alternatively, are the three traditions more like contending political parties or schools of thought, each rejecting the ideas of the others and arguing for the superiority of its theories and methods? In that case, we have to choose one tradition while rejecting many of the claims of the others—the whole is less than the sum of its parts.

I see our current situation as being somewhere between these two alternatives. On the one hand, there are real and important conflicts among the traditions, particularly with respect to questions of epistemology and research method. For example, critical theorists see science education communities as facing a basic choice about whose interests we will serve with the knowledge that we produce. Will we produce knowledge that reflects the perspectives and serves the interests of the powerful or the powerless in our society?

While acknowledging the importance of this question, conceptual change and sociocultural researchers are more sanguine about the possibility of producing knowledge that transcends the interests and perspectives of its sponsors. For example, Shakespeare's art and Galileo's science gave us insights into the human condition and the material world that could not have been anticipated by their wealthy sponsors. Is it not possible that, in our modest ways, science educators could do the same? Conceptual change and sociocultural researchers are also concerned that critical researchers' stances of open advocacy and relative lack of concern about procedures for verification of knowledge claims will undermine long-term programs of knowledge building. Thus each tradition holds ideas about the nature of grounded knowledge and the research methods appropriate to achieving that knowledge that are considered to be deeply problematic by practitioners of the other traditions.

The differences in perspectives among the traditions run deep, as do the common interests and concerns that lead people to do research on science learning. Resolving these differences must ultimately be a communal effort. Individual researchers may achieve syntheses that they find personally satisfying, but those syntheses can bring science educators together around common perspectives only in so far as they are accepted by the communities of practice associated with the different traditions. We should never expect differences in perspective and method to be completely resolved, but there are reasons to hope that researchers in different traditions can become increasingly respectful of one another's insights and understanding of one another's methods.

## Understanding Learners' "Dialogues with Nature"

Sharma and Anderson (2003) characterized scientific communities as carrying on two simultaneous dialogues: a dialogue with nature in which scientists seek to create and understand new experiences with natural systems and phenomena, and a dialogue among people in which scientific communities submit the knowledge claims of their members to a process of collective validation. In studying science learning, all three of the research traditions discussed in this chapter have given us more insight into learners' dialogues among people than into learners' dialogues with nature. Our ideas and our language are strongly constrained by our individual and collective experiences with the material world, but none of the traditions has produced fully satisfactory accounts of the interactions among experience, individual cognition, and social communication.

## Developing Prescriptions for Policy and Practice

Research on learning has given us increasingly powerful analytical tools that improve our understanding of why educational institutions fail to engender scientific literacy in many students. As a field, we have been far less successful in translating that analytical power into practical results. We need to find better ways to use this understanding as a basis for design work in science teaching and teacher education—programs and strategies that move beyond existence proofs to help large numbers of science learners. We also need better ways of using our understanding to develop arguments that influence policies and resources for science education.

## Putting the Issues in Perspective

On the other hand, it is hard not to be impressed with the progress that our field has made in understanding science learning. As I write this, it has been over 25 years since I attended my first NARST Conference in 1979. The theme of that conference was "Paradigms for Research in Science Education." The three research paradigms discussed were (a) the behaviorist theory of Robert Gagne, (b) the verbal learning theory of David Ausubel, and (c) the developmental theory of Jean Piaget.

Looking back at these three theories, I can see the precursors to some of the theories that I have written about in this chapter, especially conceptual change. At the same time, I cannot help but be struck by how inadequate they look in comparison with the research described in this chapter. Those theories relied on thin, impoverished descriptions of scientific knowledge. They depended mostly on laboratory studies for their data; they largely lacked the analytical power to make sense of science learning in natural situations, inside or outside of school classrooms. They had little to say with respect to the two key questions about science learning posed at the beginning of this chapter. As a field, we have learned a lot since 1979, and we still have a lot to learn—all things considered, not a bad place to be.

## ACKNOWLEDGMENTS

Thanks to Fouad Abd-El-Khalick, David Jonassen, and Ron Marx, who reviewed this chapter.

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## Science Education and Student Diversity: Race/Ethnicity, Language, Culture, and Socioeconomic Status

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## Special Needs and Talents in Science Learning

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## Inquiry as an Organizing Theme for Science Curricula

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## Science Teacher as Learner

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## Science Teacher Attitudes and Beliefs

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