HANDBOOK OF
RESEARCH ON SCIENCE EDUCATION

EDITED BY
SANDRA K. ABELL
NORMAN G. LEDERMAN

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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

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.

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CHAPTER 2

Student Conceptions and Conceptual Learning in Science

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Alice is a 14-year-old high school student, and in her science classes she has been taught quite a lot about the scientific concept of energy. Prior to these lessons Alice certainly used the word "energy" in her every day speech, whether in talking about "having no energy," referring to the "high energy music" of her favorite band, or trying to reduce "energy consumption" to preserve the environment. During the lessons, Alice struggled to come to terms with some of the scientific ideas, which often seemed to go against common sense. Indeed, her teacher had warned that "this is always a difficult topic to get hold of." Nevertheless, by the end of the teaching, Alice (who is a bright girl) was able to use the idea of energy in answering questions about batteries and bulbs, chemical reactions, and photosynthesis. However, she still struggled, for example, to see how the products of an exothermic chemical reaction could have the same mass as the reactants, even though "energy has been transferred to the surroundings," and it didn't make sense to her that a soda can on her desk "has gravitational potential energy," even though it "just sits there."

It is clear that Alice has learned something about the concept of energy. How might we conceptualize what has happened to Alice in these particular lessons? What do we mean when we say that Alice has "learned something about energy"? What factors act to influence her learning? What happens to Alice's existing ideas about energy being consumed, in the face of her new learning? Why should she find some of the scientific energy ideas strange and difficult to understand?

There are many questions that might be posed about any such learning event. The aim of this chapter is to review the different approaches taken to characterizing science concept learning. We begin by providing a brief historical overview of trends in the way in which research on conceptual learning has developed over the last 40 years or so. We then introduce the key features that have guided our structuring of the review, before presenting the detailed review itself. Given the sheer volume of literature addressing student conceptions and conceptual learning in science, it is not possible to be comprehensive in coverage. Rather, we have cited studies which, in our judgment, best illustrate the key features guiding our review, including work, where possible, that has been influential in various parts of the English-speaking world.

Although there are significant and fundamental differences among some of the approaches taken to conceptualizing science learning, it is also the case that other differences arise simply because different aspects of the learning process are being addressed. Bearing this point in mind, we believe that some approaches offer potentially complementary perspectives. We return to this theme in the concluding section, where we discuss the ways in which these ideas about learning might be drawn upon to illuminate and inform science teaching and learning in classroom settings.

STARTING POINTS AND TRENDS IN CHARACTERIZING SCIENCE CONCEPT LEARNING

Perspectives on student concepts and conceptual learning in science have been heavily influenced by the seminal work of the Swiss genetic epistemologist Jean Piaget. This influence was particularly dominant during the 1960s and 1970s, as can be confirmed by looking through the citations of Piaget in papers published in the main science education journals of that period (see Erickson, 2000, p. 276). Piaget described an interactive learning process whereby an individual makes sense of the world through cognitive schemes, which are themselves modified as a result of the individual's actions on objects in the world. This model is summarized in the statement "L'intelligence organise le monde en s'organisant elle-même"[1] (Piaget, 1937). Piaget emphasized the significance of the child's social environment for knowledge development, claiming that: "Society is the supreme unit, and the individual can only achieve his inventions and intellectual constructions insofar as he is the seat of collective interactions that are naturally dependent, in level and value, on society as a whole" (Piaget, 1971, p. 368). Nonetheless, in most of Piaget's writing—and writing addressing the significance of Piagetian theorizing for science education—knowledge is portrayed as schemata in the individual's head, with little prominence being given to wider social aspects. The proposed mechanism for changes in intellectual organization as a result of interactions with the world (termed *adaptation*) involves the processes of assimilation and accommodation (Piaget, 1952). Assimilation is the process by which an individual interprets particular sensory information and in so doing includes that information in his/her existing cognitive structure. Accommodation is the process by which cognitive structure adapts in order to make sense of specific information. Assimilation and accommodation cannot be dissociated: whenever an individual interacts with sensory information, both assimilation and accommodation take place.

1. Intelligence organizes the world by organizing itself.

Although Piaget was primarily interested in development as a result of maturation, rather than learning as a result of instruction (Piaget, 1964), his empirical work addressed the development of children's knowledge about various aspects of the natural world, including life (Piaget, 1929); time (Piaget, 1946); and mass, weight, and volume (Piaget, 1930). Drawing upon this body of empirical work, an account of conceptual change based upon the development of content-independent logical structures was proposed (Piaget & Inhelder, 1956). Characteristic stages in the development of logical thinking were set out, based upon students' abilities to perform tasks involving skills such as conservation and seriation (the serial ordering of items). The concrete operational stage, for example, runs between approximately 2 and 12 years and is characterized by the development and coordination of conceptual schemes, including conservation, classification, and seriation. Children at the concrete operational stage are not capable of performing operations at a purely symbolic level, however; that competence is characteristic of the formal operational stage.

Piaget's work has influenced perspectives on student conceptions and conceptual learning in several ways. His account of how individuals come to know can be seen in much writing about students' conceptions, conceptual change, and personal constructivism through references to assimilation and accommodation. Piaget's methods for probing an individual's understanding, which involve an interviewer asking children questions without attempting to "lead" their responses (Piaget, 1929), have also been drawn upon in research on students' alternative conceptions. Furthermore, Piagetian stage theory has been drawn upon to inform science curriculum design and sequencing [e.g., *Science Curriculum Improvement Study* in the United States (Andersson, 1976) and *Cognitive Acceleration through Science Education* in Britain (Adey & Shayer, 1993)].

Various criticisms of the use of Piagetian theory in science education have been advanced. Carey (1985), Donaldson (1978), and Driver (1978) questioned the empirical basis on which claims for characteristic stages in logico-mathematical thinking were founded. Specific criticisms include the following: (a) tasks requiring identical logico-mathematical reasoning are made easier or more difficult by the degree of familiarity with the task's context (Donaldson); (b) tasks characteristic of a given stage can be performed by much younger children (Driver); and (c) the analysis used in Piagetian research is designed to validate existing theory rather than account for children's reasoning (Driver; Carey).

Although there has been a decline in the influence of Piagetian approaches since the 1970s, there remains a significant line of research on domain-general reasoning skills in science learning (e.g., Koslowski, 1996; Kuhn, 1991; Kuhn, Amsel, & O'Loughlin, 1988; Metz, 1997), as well as accounts of science learning that draw on Piaget's work (e.g., Adey & Shayer, 1993; Lawson, 1985; Shayer, 2003).

Perhaps the most significant break from the Piagetian account of conceptual learning in science can be traced back to the developmental psychology of David Ausubel (1968). Ausubel argued that the most significant influence on the learners' conceptual development is their existing conceptual knowledge in the target domain. During the early 1970s, a small number of empirical studies were conducted that accounted for students' science learning in terms of domain-specific factors, rather than explaining learning in terms of global logico-mathematical reasoning skills (e.g., Driver, 1973; McClosky, 1983; Viennot, 1979).

An empirical research program was subsequently developed (Novak, 1978), focusing upon the content of students' domain-specific reasoning (or students' alternative conceptions; Driver & Easley, 1978) about natural phenomena and involving researchers from around the world. Two particularly influential books in the development of research on pupils' alternative conceptions were *The Pupil as Scientist* by Rosalind Driver (1983) and *Learning in Science: The Implications of Children's Science*, edited by Roger Osborne and Peter Freyberg (1985). The latter provides an account of the work carried out by a group of researchers in the Learning in Science Project (LISP) at Waikato University, New Zealand. The "alternative conceptions" or "misconceptions" (Gilbert & Watts, 1983) movement gained further strength from a series of major international conferences organized by Joe Novak at Cornell University (Novak, 1987), and the number of publications in this field of science education research increased into the thousands (see, for example Bell, 1981; Driver, Guesne, & Tiberghien, 1985; Gunstone, 1987; Wandersee, Mintzes, & Novak, 1994). Helga Pfundt and Reinders Duit of the IPN in Kiel, Germany, developed a comprehensive bibliography, *Students' Alternative Frameworks and Science Education*, which is now in its fifth edition (Pfundt & Duit, 2000). All of the evidence suggests that there are strong commonalities in the alternative conceptions of students from different cultures, and, furthermore, these ideas about the natural world have a profound influence on what is learned as a result of science teaching, and some ideas are extremely resistant to change (Driver, 1989).

During the 1970s and 1980s, accounts of the *origins* of students' thinking about the natural world tended to be based upon a Piagetian view of the knower-known relationship, with knowledge portrayed in terms of entities in the individual's head, which developed through that individual's interactions with the material world. Such views of knowledge were later challenged (Matthews, 1992) on the grounds that they advanced an empiricist account of the generation of scientific knowledge, an argument that will be returned to later in the chapter. Furthermore, they failed to make any distinction between an individual's *beliefs* about the world and *knowledge* of the world that has been publicly warranted as reliable.

In recent years, the "discursive turn in psychology" (Harré & Gillett, 1994) has involved a shift in focus away from viewing meaning-making purely in terms of cognitive processes in the individual, toward an account of individuals as they function in social contexts. Central to this development has been the rediscovery of the work of Vygotsky and other Soviet psychologists of the sociocultural tradition.

Overall, we therefore see a trend in characterizing students' science concept learning, which takes us from the individually oriented perspectives of Piaget toward those sociocultural perspectives that bring together the individual with the social. In the following section we introduce the framework that we have drawn upon to structure our account of this development.

STRUCTURING THE REVIEW

Given the range of approaches taken to conceptualizing science learning, we have found it helpful to identify two key features that we use as organizing dimensions in developing and presenting the review. The first dimension is taken from the influential paper by Anna Sfard (1998), in which she proposed two key metaphors for learning: the *acquisition* metaphor and the *participation* metaphor.

According to Sfard (1998), human learning has been conceived of since the dawn of civilization as an *acquisition* of something; in recent decades, "the idea of learning as gaining possession over some commodity has persisted in a wide spectrum of frameworks, from moderate to radical constructivism and then to interactionism and sociocultural theories" (p. 6). Gaining possession implies that something is stored or held somewhere. Sfard makes clear that it is *concepts* that are learned and then stored in the learner's head: "Since the time of Piaget and Vygotsky, the growth of knowledge in the process of learning has been analysed in terms of concept development. Concepts are to be understood as basic units of knowledge that can be accumulated, gradually refined, and combined to form ever richer cognitive structures" (p. 5).

By way of contrast, Sfard (1998) saw the *participation* metaphor as offering a fundamentally different perspective on learning, in which "the learner should be viewed as a person interested in participation in certain kinds of activities rather than in accumulating private possessions" (p. 6). According to this perspective, "learning a subject is now conceived of as a process of becoming a member of a certain community" (p. 6).

In developing this review, we start with approaches to conceptualizing science concept learning that belong to the *acquisition* perspective and then move on to those that relate to *participation*. From the outset, it is important to recognize that the acquisition-participation dimension is *not* a continuum. The two metaphors offer fundamentally different perspectives on learning, or, as Sfard (1998) stated, "the acquisition/participation division is ontological in nature and draws on two radically different approaches to the fundamental question, 'What is this thing called learning?' " (p. 7). The majority of approaches to conceptualizing science learning that we review here relate to the acquisition perspective.

The second dimension to be addressed involves the distinction between individual and social perspectives on learning. This takes us from a starting point where the main focus is on the *individual* learner and moves toward approaches where increased account is taken of various *social* aspects of the learning process and of knowledge itself.

SCIENCE CONCEPT LEARNING AS ACQUISITION: COGNITIVE APPROACHES

Following the ideas set out in the previous section, we first consider those approaches that see science learning as involving a process of *acquisition* and focus on the *individual* in providing an account of that learning.

Learning as Conceptual Change

Recognition that prior knowledge influences learning (Ausubel 1968), together with Piagetian ideas of accommodation and assimilation, and work from the philosophy of science (Kuhn, 1970; Lakatos, 1972) all underpinned a seminal paper by Posner, Strike, Hewson, and Gertzog (1982) on conceptual change in science learning. In the paper by Posner et al., the conditions needed for a major change in thinking within a scientific field (such as the shift from an Earth-centered to a Sun-centered model of the solar system) were considered analogous to the conditions needed to bring about accommodation or conceptual change in individual learners. Posner et al. identified four conditions that must be met before such an accommodation can occur. These conditions are that a learner must first be *dissatisfied* with existing ideas and then that the new ideas must be seen as *intelligible*, *plausible*, and *fruitful*. Empirical evidence from students' learning about the special theory of relativity was then used to illustrate and exemplify this model of conceptual change learning. Though taking the view that learning is a rational activity, Posner et al. recognized that such accommodations might take considerable time, involving "much fumbling about, many false starts and mistakes, and frequent reversals of direction" (p. 223). The conditions of intelligibility, plausibility, and fruitfulness contribute to the status of an idea. During conceptual change the status of different ideas within a person's conceptual ecology (the range of ideas they hold) changes (Hewson, 1981; Hewson & Hennesey, 1992; Hewson & Lemberger, 2000). The implications of this model for teaching were outlined in the original paper and further discussed by Hewson, Beeth, and Thorley (1998). In addition, Scott, Asoko, and Driver (1992) outlined two broad approaches to conceptual change teaching. The first of these is based upon promoting cognitive conflict and follows from the model proposed by Posner et al., whereas in the second the learner's existing ideas are built upon and extended.

A significant point of confusion in this whole area of work concerns the different meanings that are attached to the term *conceptual change*. Sometimes *conceptual change* refers to the process of learning, and at other times it refers to the products. Furthermore, *conceptual change* sometimes refers to situations where one concept (seen as a unit of knowledge) is *exchanged* for another; sometimes where a concept is *modified* in some way, for example by differentiation into two; sometimes where the *relationship* between concepts changes; and sometimes where new concepts are *added* without loss of the original ideas. The interest in student misconceptions, or alternative conceptions, in the 1980s led to a focus on conceptual change as revolutionary, with new ideas replacing the original ones (through a process of exchange), rather than evolutionary and gradual, with the possibility of several views existing simultaneously (through a process of addition) and used in different contexts (see, for example, Sinatra, 2002).

What Changes During Conceptual Change?

Posner et al.'s (1982) model of conceptual change focused on the *conditions* under which radical accommodations occur. Alongside this, the focus of much work in developmental cognitive psychology has been on *what* changes, exploring the performance of learners at different ages and attempting to explain this in terms of the ways in which concepts are mentally represented and related and the cognitive processes by which they are acquired and change.

One of the early proponents of domain-specific approaches, Susan Carey, proposed two forms of knowledge restructuring in learning, one similar to that demonstrated in the shift from novice to expert and one analogous to that of theory change in science. In the first, "weak" restructuring, the relations between concepts are changed. In the second, "strong" restructuring, the concepts themselves change (Carey, 1985), and this is regarded as difficult to achieve. Considerable attention has been given to these latter situations where radical restructuring is needed, particularly in the context of learning physics concepts.

The idea that learning occurs as discrete concepts are formed and then linked into more complex conceptual structures has largely given way to a view that concepts are part of larger relational structures from the start. Vosniadou (1994), for example, argued that concepts are embedded into larger theoretical structures of two types, with the term *theoretical* being used to describe a relatively coherent explanatory structure. *Framework theories*, which develop from early infancy, consist of fundamental ontological and epistemological presuppositions. *Specific theories* are beliefs about the properties or behavior of objects, which arise from observation and/or are transmitted by the pervading culture. These specific theories are constrained by the assumptions of the underpinning framework theories. Specific and framework theories provide the basis for the generation of situation-specific mental models in response to the demands of a particular situation. Exploration of these mental models, for example in the context of the development of ideas about astronomical phenomena or force, provides insight into the underlying theoretical base. Conceptual change, according to this perspective, is thought to occur by enrichment or revision of a specific or a framework theory, a process that requires a gradual suspension of presuppositions and their revision or replacement with a different explanatory framework (Vosniadou & Ioannides, 1998). From this perspective, misconceptions are generated on the spot, during testing, from the deeply held framework theory, rather than being deeply held beliefs.

Following the seminal work of Keil (1979), ontological categorization is also seen as being of fundamental importance in the learning of science concepts. Chi (Chi, 1992; Chi, Slotta, & de Leeuw, 1994) argued that the meaning of a concept is determined by the ontological category to which it is assigned. Misconceptions thus arise when a concept is assigned to an inappropriate ontological category, for example, seeing the concept of "heat" as belonging to the category of "matter" instead of the category "process." Chi and Roscoe (2002) distinguished between the reassignment of concepts within levels of an ontological category and change, which requires a shift from one category to another, which is much more difficult.

DiSessa and Sherin (1998) pointed out some difficulties with the "standard" model of conceptual change. They argued that the notion of "concept" needs to be replaced by more carefully defined theoretical constructs within a knowledge system, which allow us to understand how that system functions. Focusing on the cognitive processes by which we gain information from the world, they proposed entities such as "co-ordination classes" and "phenomenological primitives," or p-prims. Co-ordination classes include cognitive strategies such as selecting and integrating information and are "systematically connected ways of getting information from the world" (p. 1171). Phenomenological primitives are described as abstractions from experience that need no explanation and form primitive schemata that constitute the basis of intuitive knowledge. For example, people usually expect that greater effort produces greater results and may apply this principle across a range of contexts. Intuitive "rules" such as these have also been identified by Stavy and co-workers (Stavy & Tirosh, 2000; Tirosh, Stavy, & Cohen, 1998). They believed that many of the alternative conceptions reported in the literature are, in fact, due to the use of rules such as *more of A-more of B*, which are relatively stable and resistant to change.

All of the above utilize some form of mental model, or system that develops and changes as a result of cognitive processes. The view that evolutionary pressures have led to the development of innate dispositions to interpret the world in particular ways was discussed by Matthews (2000), who also suggested that some conceptual structures can be triggered, rather than learned in the usual sense of the word. He considered, for example, that some of the p-prims, proposed by DiSessa, have the character of triggered concepts. Drawing on connectionist theories, he suggested that certain neural networks are designed to respond quickly and thus reinforce an initial bias. Conceptual change might then be viewed as a "process by which additional cognitive structures are built that, once firmly established, can over-ride rather than merge with, the functioning of competing innate structures" (p. 528). Such innate structures might correspond or give rise to the "naïve physics" and "naïve psychology" proposed by Carey (1985) or DiSessa's naïve "sense of mechanism" (DiSessa & Sherin, 1998) and perhaps lie behind Vosniadou's (1994) framework theories and Stavy's intuitive rules (Stavy & Tirosh, 2000).

Beyond "Cold" Conceptual Change

Although Posner et al. (1982) noted that motivational and affective variables were not unimportant in the learning process, the model of conceptual change they proposed was based on a view of learning as a rational activity. Pintrich, Marx, and Boyle (1993), in their critique of "cold" conceptual change models, proposed that the conditions of dissatisfaction with existing conceptions and the intelligibility, plausibility, and fruitfulness of the new, although necessary, are not sufficient to support conceptual change. Cognitive, motivational, and classroom contextual factors must also be taken into account as the individual student in the classroom is subject to influences from the broader social setting.

Cognitive Approaches: Summary and Implications

The following fundamental insights about science concept learning are common to the majority of cognitive perspectives:

1. Individuals' beliefs about the natural world are *constructed*, rather than *received*.
2. There are strong commonalities in how individuals appear to think about the natural world.
3. A person's existing ideas about a given subject greatly influence his/her subsequent learning about that subject.

In addition, some have argued that there are more general aspects of reasoning, such as Piaget's logico-mathematical reasoning skills, or the skills described by Kuhn et al. (1988), which influence the learner's response to instruction.

These insights have significant implications for our understanding of how science concepts are taught and learned. The facts that scientific knowledge cannot be *transferred* during teaching, and that existing thinking influences learning outcomes, offer a starting point to explaining why some aspects of science are difficult to learn. Furthermore, the research into students' thinking about aspects of the natural world has been drawn upon by science educators involved in the design and evaluation of teaching sequences (see, for example, Clement, 1993; Minstrell, 1992; Psillos & Méheut, 2004; Rowell & Dawson, 1985; Stavy & Berkowitz, 1980; Tiberghien, 2000; Viennot & Rainson, 1999) and in decisions about sequencing of ideas and age placement in the science curriculum (Driver, Leach, Scott, & Wood-Robinson, 1994). Science educators have also drawn upon research into more general aspects of students' scientific reasoning in developing teaching materials focused on the general reasoning skills of students (e.g., Adey & Shayer, 1993).

If the above points constitute a shared ground among cognitive perspectives, where do the points of difference lie? One area for debate concerns the existence and relative importance of domain-general and domain-specific aspects of reasoning in accounting for conceptual learning and conceptual change in science. Thinking back to the case of Alice, some of her difficulties with learning about energy might be explained, from a domain-specific perspective, in terms of the ontology of her existing concepts ("How come the mass hasn't changed when energy has been transferred to the surroundings?"). Instruction might therefore be designed to make it plausible that energy is not a substance, and to allow Alice to compare the scientific account of energy explicitly with her prior thinking.

From a domain-general perspective, Alice's difficulties might be accounted for in terms of the prevalence of abstract entities in the scientific account of energy and Alice's capacity to operate with those abstract entities. We are not aware of research that accounts for the teaching and learning of specific conceptual content from a domain-general perspective. Rather, the instructional solution might involve teaching thinking skills, or possibly not addressing the more abstract aspects of the energy concept until Alice has developed the appropriate thinking skills.

Another area of debate is the relative coordination or fragmentation of the elements of conceptual thinking in science learners. Are Alice's ideas about energy coordinated and coherent, or fragmented and lacking in logical coherence? Depending on the answer to this question, the challenge for Alice's science teacher might involve presenting a scientific account of energy and contrasting it explicitly with students' theories, or helping students to appreciate how a single, coherent theory can explain a wide range of phenomena.

In practice, however, there may be no simple, direct relationship between perspectives on learning and strategies for teaching (Millar, 1989), and Alice's teacher might well achieve similar success as a result of using several of the above strategies. It might therefore be the case that messages for practice lie at a more fundamental level, suggesting that teaching ought to provide opportunities to probe students' developing understanding in a formative way, allowing subsequent teaching to be responsive to students' learning. Insights about how to teach conceptual content in areas such as thermodynamics, chemical change, or plant nutrition will only arise through design research (Brown, 1992), where insights about domain-specific reasoning are drawn upon in the design of teaching materials, which are then tested and developed in a cyclical process (Lijnse, 1995). Such research does not in itself rest directly upon cognitive theory.

SCIENCE CONCEPT LEARNING AS ACQUISITION: SOCIOCULTURAL AND SOCIAL CONSTRUCTIVIST PERSPECTIVES

At this point in the review we take a significant step in moving from approaches to characterizing science concept learning that focus on the individual, while recognizing the influence of the social context, to those that take the social context as an integral part of the learning process. In short, we move from cognitive to sociocultural and social constructivist approaches.

Vygotskian Perspective on Learning

A fundamental theoretical reference point for sociocultural and social constructivist perspectives on learning was provided by Lev Semenovich Vygotsky (Vygotsky, 1934/1987). Central to Vygotsky's views is the idea that learning involves a passage from social contexts to individual understanding (Vygotsky, 1978). Thus, we first meet new ideas (new to us, at least) in social situations where those ideas are rehearsed between people, drawing on a range of modes of communication, such as talk, gesture, writing, visual images, and action. Vygotsky referred to these interactions as existing on the *social plane*. The social plane may be constituted by a teacher working with a class of students in school; it may involve a parent explaining something to a child. As ideas are explored during the social event, each participant is able to reflect on and make individual sense of what is being communicated. The words, gestures, and images used in the social exchanges provide the very tools needed for individual thinking. Thus, there is a transition from *social* to *individual* planes, whereby the social tools for communication become *internalized* and provide the means for individual thinking. It is no coincidence that Vygotsky's seminal book is titled *Thought and Language* (Vygotsky, 1962).

The *social* origins of learning are thus a fundamental and integral part of Vygotsky's account, and it is the job of the teacher to make scientific knowledge available on the social plane of the classroom, supporting students as they try to make sense of it. Vygotsky brought the activities of teaching and learning together through his concept of the Zone of Proximal Development or ZPD (Vygotsky, 1978). The ZPD provides a measure of the difference between what the student can achieve working alone and what can be done with assistance. The key point here is that the student's learning is conceived of as being directly connected to, and dependent upon, the supporting activity of the teacher on the social plane.

As well as drawing attention to the social origins of learning, Vygotsky also emphasized the role of the *individual* in the learning process. The process of internalization, as envisaged by Vygotsky, does not involve the simple transfer of ways of talking and thinking from social to personal planes. There must always be a step of personal sense making. Leontiev (1981), one of Vygotsky's contemporaries, made the point in stating that "the process of internalisation is not the transferral of an external activity to a pre-existing 'internal plane of consciousness.' It is the process in which this plane is formed" (p. 57). That is, individual learners must make sense of the talk, which surrounds them on the social plane, relating that talk in a dialogic way to their existing ideas and ways of thinking.

In this respect Vygotskian theory shares common ground with the constructivist perspectives outlined earlier, which emphasize that learners cannot be passive recipients of knowledge. It is perhaps with this point in mind that those contemporary approaches to conceptualizing science learning, which draw on Vygotskian *socio-cultural* theory, are often referred to as *social constructivist* perspectives.

Social Constructivist Views of Learning Science

Vygotskian theory has been directly drawn upon by a number of researchers in their development of an account of science learning (see, for example, Driver et al., 1994; Hodson & Hodson, 1998; Howe, 1996; Leach & Scott, 2002, 2003; Mortimer & Scott, 2003; Scott, 1998; Wells, 1999).

Hodson and Hodson (1998), for example, outlined a social constructivist perspective on teaching and learning science, which was "based on the Vygotskian notion of enculturation" (p. 33). They argued that this perspective provides an alternative to personal constructivist accounts of learning (see also Osborne, 1996), which they claimed often imply "that students who construct their own understanding of the world are building *scientific* understanding" (p. 34; emphasis as in original). This point takes us back to the empiricist critique of constructivism outlined earlier. Thus Michael Matthews has argued that "constructivism is basically, and at best, a warmed up version of old-style empiricism" (Matthews, 1992, p. 5). One might question whether adherents to such an empiricist view of constructivism actually exist.

Central to the social constructivist response to charges of empiricism is the fundamental epistemological tenet that areas of knowledge such as science are developed within specific social communities. Thus, Driver et al. (1994) stated:

> [I]f knowledge construction is seen solely as an individual process, then this is similar to what has traditionally been identified as discovery learning. If, however, learners are to be given access to the knowledge systems of science, the process of knowledge construction must go beyond personal empirical enquiry. Learners need to be given access not only to physical experiences but also to the concepts and models of conventional science. (p. 7)

The implications of this point are fundamental. The understandings of an individual, acquired, on the one hand, through the individual's interactions with the material world, and, on the other, through being introduced to the concepts and models of conventional science, are ontologically different. The concepts and models of conventional science embody practices, conventions, and modes of expression that are socially and institutionally agreed upon. Because scientific knowledge is the product of the scientific community, it cannot be learned through interactions with the material world alone. Such differences between empiricist interpretations of personal constructivism and social constructivist accounts of learning were discussed by Leach and Scott (2003).

Following the ideas set out in the preceding sections, social constructivist accounts of learning can be deemed to be "social" in nature on two counts: first, in the sense of specifying the social origins of learning, through the interactions of the social plane, and second in recognizing the social context of the scientific community for the development of scientific knowledge.

Learning Science as Learning the Social Language of Science

The view of scientific knowledge as a product of the scientific community maps onto Bakhtin's notion of *social languages*. For Bakhtin, a social language is "a discourse peculiar to a specific stratum of society (professional, age group etc.) within a given system at a given time" (Bakhtin, 1934/1981, p. 430). Thus science can be construed as the social language that has been developed within the scientific community. It is based on specific concepts such as energy, mass, and entropy; it involves the development of models that provide a simplified account of phenomena in the natural world; and it is characterized by key epistemological features such as the development of theories, which can be generally applied to a whole range of phenomena and situations. The social language of science is clearly different from that of geography or economics or literary criticism. Furthermore, the science that is taught in school focuses on particular concepts and models and is subject to social and political pressures, which are quite different from those of professional science (Tiberghien, 2000). From this point of view, learning science involves learning the social language of "school science" (Leach & Scott, 2002; Mortimer & Scott, 2003; see also Chapter 3, this volume).

James Wertsch (1991) suggested that the different social languages that we learn constitute the "tools" of a "mediational tool kit," which can be called upon for talking and thinking as the context demands. Furthermore, Wertsch suggested that "children do not stop using perspectives grounded in everyday concepts and questions after they master these [scientific] forms of discourse" (1991, p. 118). Thus, everyday, or spontaneous (Vygotsky, 1934/1987), ways of talking and thinking constitute an "everyday social language." Wertsch saw the learner developing disciplinary social languages alongside these everyday ways of talking and thinking. As such, this sociocultural perspective on learning clearly involves a process of conceptual *addition* (as introduced in the earlier section on cognitive science approaches) rather than replacement.

Learning as Conceptual Addition/Replacement

This formulation of learning in terms of conceptual addition and replacement is rather more complex than these simple labels might suggest. For example, can it be the case that, in conceptual addition, everyday knowledge is left intact as the learner develops a new point of view based on a particular social language, such as school science?

There is a certain ambiguity in Vygotsky's (1987) views on the possible outcome of the learning process. In some cases he seemed to suggest that scientific perspectives (Vygotsky actually uses the term *scientific* in referring to disciplinary knowledge, which includes the natural sciences) are likely to transform everyday views: "The formal discipline of studying scientific concepts is manifested in the complete restructuring of the child's spontaneous concepts. This is why the scientific concept is of such extraordinary importance for the history of the child's mental development" (p. 236).

Elsewhere, Vygotsky suggested that even with the emergence of scientific concepts, people continue to have access to everyday concepts, which they often employ:

> A child who has mastered the higher forms of thinking, a child who has mastered concepts, does not part with the more elementary forms of thinking. In quantitative terms these more elementary forms continue to predominate in many domains for a long time. As we noted earlier, even adults often fail to think in concepts. The adult's thinking is often carried out on the level of complexes, sometimes sinks to even more primitive levels. (p. 160)

So, we have a picture of scientific knowledge transforming everyday thinking on the one hand and everyday or elementary thinking being left behind on the other. It might be the case that the outcome of this meeting of social languages (everyday and school science) depends on the *context* of learning. For example, it might be argued that coming to understand a fundamental scientific principle such as the "conservation of substance" is likely to transform the thinking of the individual. It is difficult to believe that the learner will consciously revert to being a nonconserver and talk about simple everyday events in such a way (being prepared to accept, for example, that salt actually does disappear on dissolving in water). On the other hand, as one learns about air pressure, it is unlikely that air pressure explanations will replace everyday talk in terms of "sucking." Here it is likely that the individual will move between the two forms of explanation according to the perceived context of activity and application. Joan Solomon made a seminal contribution to the development of this perspective in science education with her work on "how children think in two domains" (see Solomon, 1983).

This general idea of a heterogeneity in ways of thinking (see Bachelard, 1940/1968; Berger & Luckmann, 1967; Tulviste, 1988/1991) has been developed in the context of science education in terms of a *conceptual profile* (Mortimer, 1995, 1998). The conceptual profile acknowledges the coexistence, for the individual, of different ways of conceptualizing physical phenomena in science. These different ways can range from approaches based on everyday knowledge (which might be informed by the immediate sense perception of the actual phenomenon) to sophisticated scientific ways (which might represent reality in purely symbolic models) and constitute different zones of an individual person's conceptual profile. As such, science learning can be characterized in terms of extending the zones of the individual learner's conceptual profile.

Alternative Conceptions and Everyday Social Language

The sociocultural view of learning offers an interesting perspective on the origins and status of alternative conceptions or misconceptions. From the sociocultural point of view, an alternative conception, such as the idea of a plant drawing its food from the soil, is representative of an everyday way of talking and thinking about plants. This is the way in which ordinary people talk about such things, and in this respect there is a very real sense in which the *scientific* point of view (based on the concept of photosynthesis) offers the *alternative* perspective. Viewed in this way, it is hardly surprising that the alternative conceptions or misconceptions identified by the science education community are "robust" and "difficult to change." These are not the ephemeral outcomes of the solitary musings of children trying to make sense of the natural world around them, but the tools of an everyday language that continuously acts to socially define, and reinforce, our ways of talking and thinking.

Social Constructivist Approaches: Summary and Implications

The following insights about science concept learning are common to social constructivist perspectives:

1. Learning scientific knowledge involves a passage from social to personal planes.
2. The process of learning is consequent upon individual sense-making by the learner.
3. Learning is mediated by various semiotic resources, the most important of which is language.
4. Learning science involves learning the social language of the scientific community, which must be introduced to the learner by a teacher or some other knowledgeable figure.

What perspective do these distinctive aspects of the social constructivist perspective take us to that is different from the interests and outcomes of the cognitive viewpoint? The most obvious development has been the increased attention, during the late 1980s and 1990s, to the role of the teacher and the ways in which teachers guide the discourse of the classroom to support the introduction of scientific knowledge and scientific ways of explaining (Edwards & Mercer, 1987; Mortimer & Scott, 2003; Ogborn, Kress, Martins, & McGillicuddy, 1996; Scott, 1998; van Zee & Minstrell, 1997). Through this kind of work, we have a much better grasp of the ways in which teachers make scientific knowledge available on the social plane of the classroom.

Whereas these approaches to *analyzing* teacher talk have been fruitful, we are less aware of work, informed by social constructivist perspectives, that addresses the issue of *designing* science instruction (see, for example, Hodson & Hodson, 1998; Leach & Scott, 2002). It also seems to be the case that the step of individual sense making, or internalization, has been given less attention, both theoretically and empirically in social constructivist studies.

And what about Alice and her learning the concept of energy? According to these views, Alice is learning a new social language, a new way of talking and thinking about the world. If some of the scientific ideas "that energy is not used up" appear implausible, it is because they *are* in relation to everyday ways of thinking. The obvious way to address this point is for the teacher to make clear that what is on offer is a new and powerful way of thinking and talking about the natural world—the scientific point of view. Furthermore, learning a scientific account of energy must involve an authoritative introduction of ideas by the teacher. Thereafter, Alice and her fellow students need the opportunity to talk and think with those conceptual tools for themselves.

SCIENCE CONCEPT LEARNING AS PARTICIPATION

In this final section of the review we take the step from approaches to conceptualizing science concept learning that are based on acquisition to those that entail some form of participation.

Situated Cognition

The metaphor of learning as participation has largely arisen through a perspective on learning known as *situated cognition* (see, for example, Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991; Rogoff, 1990).

The pioneering work in this field focused on the use of mathematics in the workplace and in day-to-day life. For example, Scribner (1984) analyzed the arithmetical practices of people as they worked in a dairy factory, and Lave (1988) focused on the use of arithmetic in everyday shopping. These studies and others (see Hennessy, 1993, for a comprehensive review) have identified forms of arithmetic that are radically different from those taught in school. The skilled users of these everyday forms of arithmetic vary their problem-solving approaches depending on the specific situation, and problems that appear to be structurally identical are solved with different strategies. In this sense, the strategies are seen to be directly linked to context and thereby *situated* in nature.

According to the situated cognition perspective, learning is seen as a process of enculturation, or participation in socially organized practices, through which specialized skills are developed by learners as they engage in an apprenticeship in thinking (Rogoff, 1990) or in legitimate peripheral participation (Lave & Wenger, 1991). According to Collins, Brown, and Newman (1989), the key components of the apprenticeship process include modeling, coaching, scaffolding, fading, and encouraging learners to reflect on their own problem-solving strategies. This apprenticeship leads to the learner becoming involved in the *authentic* practices of a "community of practice" (Lave and Wenger, 1991). Brown, Collins, and Duguid (1989) argued: "Unfortunately, students are too often asked to use the tools of a discipline without being able to adopt its culture. To learn to use tools as practitioners use them, a student, like an apprentice, must enter that community and its culture" (p. 33). Roth (1995a) suggested that authentic practices involve activities "which have a large degree of resemblance with the activities in which core members of a community actually engage" (p. 29).

In the context of education, situated cognition perspectives have received a lot of attention, particularly in North America and particularly in relation to mathematics education (see, for example, Cobb, Wood, & Yackel, 1991; Cobb & Yackel, 1996; Lampert, 1990). According to Cobb and Bowers (1999), "A situated perspective on the mathematics classroom sees individual students as participating in and contributing to the development of the mathematical practices established by the classroom community" (p. 5).

Situated perspectives on learning have also been drawn upon as part of a theoretical justification for "inquiry-based" approaches to science teaching and learning (see, for example, Metz, 1998; Roth, 1995b). Roth (1995a) suggested that "situated learning emphasizes learning through the engagement in authentic activities" (p. 29). He explained his use of the term "authentic" by suggesting that in classrooms focused on scientific activities, the students would (a) learn in contexts constituted in part by ill-defined problems; (b) experience uncertainties, ambiguities, and the social nature of scientific work and knowledge; (c) engage in learning (curriculum) that is predicated on, and driven by, their current knowledge state; (d) experience themselves as part of communities of inquiry in which knowledge, practices, resources, and discourse are shared; and (e) participate in classroom communities, in which they can draw on the expertise of more knowledgeable others (Roth, 1995a, p. 29; see also Wells, 1999).

Drawing explicitly upon these ideas, science instruction has been planned and implemented as the enculturation of students into practices such as field ecology (e.g., Roth & Bowen, 1995), environmental activism (e.g., Roth & Désautels, 2002), and basic scientific research (e.g., Ryder, Leach, & Driver, 1999). Although the practices described in these studies can be argued to be *authentic* in the sense that they refer to situations in which science is actually used, it is more difficult to argue that they are closely related to the everyday experience of most science learners. Furthermore, the authors' analyses of teaching focus more upon students' learning about various *practices* that involve science (the use of instrumentation and specific technical procedures, the construction of arguments, the social relationships of various communities) than upon the development of conceptual understanding by students.

Learning Science, Learning to Talk Science

Lemke (1990) offered a different perspective on learning science through participation in his book, *Talking Science: Language, Learning and Values*. This "social semiotic" approach has been highly influential in drawing attention to the fundamental importance of language in science learning. The basic thesis that Lemke proposed is that learning science involves learning to talk science: "it means learning to communicate in the language of science and act as a member of the community of people who do so" (p. 1). Lemke questioned the value of cognitive theories of concept use based on mental processes "which we know nothing about" and suggested that "we may as well cut out the 'middleman' of *mental* concepts, and simply analyse conceptual systems in terms of the thematic patterns of language use and other forms of meaningful human action" (p. 122). Consistent with this point of view, Lemke suggested that scientific reasoning is learned "by talking to other members of our community, we practice it by talking to others, and we use it in talking to them, in talking to ourselves, and in writing and other forms of more complex activity (e.g., problem-solving, experimenting)" (p. 122; see also Chapter 3, this volume, for more on language and science learning).

Multimodality: Extending Beyond Language

Although science classrooms are filled with the voices of teacher and students, it is clear that communication and learning in the classroom are achieved by more than just linguistic tools. Kress, Jewitt, Ogborn, and Tsatsarelis (2001) set out an approach to analyzing science teaching and learning, "in which the multiplicity of *modes of* *communication* that are active in the classroom are given equally serious attention" (p. 1). Through this "multimodal" approach, Kress et al. were able to demonstrate how the meaning of what is spoken or written does not reside purely in language, by focusing on the ways in which teacher and students use a variety of semiotic modes, "actional, visual and linguistic resources" (p. 33), to represent and communicate ideas. One of their examples offers a detailed and vivid illustration of how a teacher orchestrates a range of modes of communication to introduce the idea of blood circulation. The image that sticks in the mind is the teacher moving fluently between a diagram on the board, a model of the human body, and his own body, gesturing toward each as he develops the verbal scientific narrative (see also Scott & Jewitt, 2003).

This multimodal account of learning sits firmly in the participation camp. "We believe that 'acquisition' is an inappropriate metaphor to describe the processes of learning: it implies a stable system which is statically acquired by an individual" (Kress et al., 2001, p. 28). Rather, learning is presented as a *process* of transformation in which "students are involved in the active 'remaking' of teachers' (and others') signs" (p. 27). In other words, learning involves the students in making sense of (and thereby transforming) the multimodal events that are unfolding around them in the science classroom.

In his more recent work, Lemke has developed the social semiotics perspective introduced in *Talking Science*, along similar multimodal lines, to investigate "how we make meaning using the cultural resources of systems of words, images, symbols and actions" (Lemke, 2003, "Languages and Concepts in Science" section). As part of this analysis, Lemke made the important point not only that it is the communicative activities of teacher and students in the classroom that are multimodal in character, but that science itself also involves the use of multiple semiotic systems: "Science does not speak of the world in the language of words alone, and in many cases it simply cannot do so. The natural language of science is a synergistic integration of words, diagrams, pictures, graphs, maps, equations, tables, charts, and other forms of visual and mathematical expression" (p. 3).

Science thus consists of: "the languages of visual representation, the languages of mathematical symbolism, and the languages of experimental operations" (p. 3). Following this perspective, Lemke argued that learning science must involve developing the ability "to use all of these languages in meaningful and appropriate ways, and, above all, to be able to functionally integrate them in the conduct of scientific activity" (p. 3).

Participative Approaches: Summary and Implications

The following insights about learning are common to the participative approaches outlined above:

1. Learning is seen as a *process* of developing participation in the practices of a particular community.
2. The learner takes on the role of apprentice, whereas the teacher is seen as an expert participant.
3. That which is to be learned involves some aspect of practice or discourse.

Perhaps the biggest question to be raised in relation to the participative approaches concerns the issue of subject matter and the very aims of science education. For example, what does it mean to suggest that learning science should involve "participation in the practices of a scientific community"? What does it mean to suggest that students should "engage in the authentic practices of science"? To what extent is it possible to reconfigure the science classroom as a seat of authentic scientific practices? Is it reasonable to expect that the teacher can act as an expert practitioner within this scientific community of the classroom? What would be the aims of such an approach to science education? What would be learned?

Of course, we have already referred to examples of classroom practice where these kinds of questions have been addressed; it is clear that the kinds of investigative or inquiry-based activity suggested offer workable possibilities. But what about Alice and her quest to understand the scientific concept of energy? It stretches faith in participative methods to suggest that learning scientific concepts, the tools of science, might best be achieved through investigative methods. Here the social constructivist perspective seems to offer a more plausible and helpful way of framing possible instructional approaches.

WHAT CAN WE SAY ABOUT SCIENCE CONCEPT LEARNING IN CLASSROOM SETTINGS?

We began this chapter with a brief sketch of one student, Alice, and her learning of the scientific account of energy during science lessons in school. We return to that scenario, for a final time, to consider the ways in which the different approaches to viewing science concept learning might be drawn upon to illuminate such a teaching and learning event, addressing some of the questions listed in the introduction to the chapter. Our view is that, given the complexity of what goes on in classrooms as students learn science, it is unrealistic to expect that one "grand" theory might capture all of the activity. In this respect we follow the lead of Sfard (1998) and others (see, for example, Mayer, 2002) in drawing upon what might be regarded as complementary perspectives on learning.

As a starting point, we take the social constructivist perspective, which we believe constitutes a helpful framing or "orienting" (Green, Dixon, & Gomes, 2003) theory in bringing together the social context for learning with the individual student's response. Here the teacher occupies the pivotal role, between culture and students, in introducing the scientific social language. Given this overall framing, it is clear that learning scientific concepts is driven by teaching and that the students must engage in the act of personal sense-making during internalization.

Accepting the point of view that learning science involves learning the social language of "school science," a legitimate question to ask is, why can learning some parts of science prove to be so *difficult*? Why is it, for example, that Alice struggled to come to terms with the school science account of "energy." Why is it that the school science view often appears implausible to the learner, even if it is intelligible (Posner et al., 1982)? How can we develop and extend our *orienting* theoretical framework to address these questions?

One response relates to *differences* in social languages and is based on the idea that where there are significant differences between school science and everyday accounts of a particular phenomenon, greater "learning demands" (Leach & Scott, 2002) are created for the student. How might such learning demands be appraised? Three possible ways in which differences between everyday and school science perspectives might arise have been identified (Leach & Scott). These relate to differences in the *conceptual tools* used, differences in the *epistemological underpinning* of those conceptual tools, and differences in the *ontology* on which those conceptual tools are based.

For example, in relation to plant nutrition, students commonly draw upon everyday notions of food as something that is ingested, in contrast to scientific accounts, which describe the synthesis of complex organic molecules within plants, from simple, inorganic precursors. In the case of energy, the scientific concept is essentially a mathematical accounting device (which can be used to predict the limits of possible outcomes to physical events), whereas the everyday concept is likely to involve references to human activity and notions of energy as something that "makes things happen."

Other differences relate to the *epistemological underpinning* of the conceptual tools used. Thus, the ways of generating explanations using scientific models and theories that are taken for granted in school science are not part of the everyday social language of many learners (Driver, Leach, Millar, & Scott, 1996; Leach, Driver, Scott, & Wood-Robinson, 1996; Vosniadou, 1994). Whereas in scientific social languages, great importance is attached to developing a small number of models and theories, which can be generally applied to as broad a range of phenomena as possible, the same is not true for everyday social languages. Thus, in science, energy is an absolutely central concept, simply because it offers a generalizable way of thinking about virtually any phenomenon. In everyday contexts, where there is not the same attention to generalizability; the term *energy* might be used with different meanings in different contexts.

Learning demands may also result from differences in the *ontology* of the conceptual tools used (Chi, 1992; Chi, Slotta, & de Leeuw, 1994; Leach et al., 1996; Vosniadou, 1994). Thus, entities that are taken for granted as having a real existence in the realm of school science may not be similarly referred to in the everyday language of students. For example, there is evidence that many lower secondary school students learning about matter cycling in ecosystems do not think about atmospheric gases as a potential source of matter for the chemical processes of ecological systems (Leach et al.). There is a learning issue here that relates to the students' basic commitments about the nature of matter—initially they do not consider gases to be substantive. With regard to the energy example, in scientific social languages energy is regarded as an abstract mathematical device, whereas in everyday contexts it is often referred to as being substantial in nature: *Coal contains energy*; *I've run out of energy*.

From this point of view, learning science involves coming to terms with the conceptual tools and associated epistemology and ontology of the scientific social language. If the differences between scientific and everyday ways of reasoning are great, then the topic in question appears difficult to learn (and to teach). The key point here is that the concept of learning demand is framed in terms of the differences between social languages *and* draws on aspects of the "individual cognition" literature in identifying the epistemological and ontological aspects of learning demand.

In the cognitive literature, ontological recategorization (for example) is presented as a mental process, possibly as a psychological barrier to learning a specific science concept. The account of ontological barriers to successful learning presented here, however, begins by recognizing that ontological differences exist between the *social languages* of everyday talk and school science. Any ontological recategorization required of learners therefore has its origins in social language, and we can begin to address these through systematic teaching.

One might argue that all of this adds up to the same thing, and in a sense it does. The systematic teaching still requires individual cognitive effort by the student if learning is to take place. Nevertheless, it might be helpful in thinking about teaching and learning science in classroom settings, to cast the issue in terms of the aspects of learning demand to be worked on by teacher and students. In this way, there is greater clarity about what it is that needs to be taught and learned in any topic area of school science.

This realization of what it is is extended still further by Lemke's (2003) social semiotic analysis. As outlined earlier, Lemke emphasized that learning school science involves developing the ability to integrate and use all of the semiotic resources of science, pulling together the languages of visual representation, mathematical symbolism, and experimental operations. Lemke was absolutely clear in stating that it is the responsibility of the teacher to show students "how to move back and forth among the different mathematical, visual, and operational representations" (p. 5).

All of these preceding points relate to achieving greater clarity about what it is that needs to be taught if students are to come to understand and to be able to use the social language of science with its distinctive conceptual tools, epistemological and ontological framing, and range of semiotic resources. Within this account, there are also half-exposed hints about the kinds of instructional approaches that might be taken in addressing these learning targets. There is clearly a central role for the teacher in introducing these new conceptual tools and helping the students to make links to their existing ways of thinking. This communicative aspect of the teaching role, focusing on both language-based and broader multimodal approaches, has been developed in detail elsewhere (Kress et al., 2001; Lemke, 1990; Mortimer & Scott, 2003; Ogborn et al., 1996; Scott, 1998). It must also be a priority for the students to begin to use these ideas for themselves and to start talking and thinking with the scientific social language(s) if they are to engage with them meaningfully.

In these ways, we can see how Sfard's conclusion that "one metaphor is not enough" (p. 10) might be addressed, in the context of teaching and learning science contexts, as elements of theory are drawn on from the camps of both acquisition and participation.

LOOKING AHEAD: FUTURE RESEARCH DIRECTIONS

One measure of the extent to which science education research can be regarded as a progressive field of activity concerns the impact of that research on practice (see Fensham, 2004). The picture that is painted in this review points to areas of research on science concept learning where our knowledge is extensive. Thus, as a community, we are familiar with students' typical alternative conceptions in a wide range of science topic areas; we are able to identify the main barriers to conceptual learning as scientific ideas are introduced against a backdrop of everyday ways of talking and thinking; we are aware of the ways in which learning involves both engaging in the social contexts of the classroom and steps of personal meaning making. The list can be further developed and, given the relatively short history of research in science education, is impressive in its extent. This body of knowledge is both broad and reliable and is based upon aspects of theory along with extensive empirical studies.

What remains far more problematic concerns the instructional approaches that might be taken to *advance* that learning. Put briefly, science education researchers are currently in the position where we can point with confidence to the likely conceptual starting points and challenges for students in any area of science learning, but we have rather less to say about how to shape instruction in order to help students come to terms with the scientific point of view. The challenge remains one of crossing the bridge from our insights on learning to making the link to reliable approaches to instruction.

Some argue that teaching is an idiosyncratic, highly personalised activity such that the very notions of best practice or an optimal instructional approach do not make sense. Although it is clear that teaching is a responsive activity and that to an extent it must therefore depend upon the circumstances prevailing in specific contexts (this class of children, at this time of the week, in this particular school, with this teacher), it might still be argued that some instructional approaches are likely to be more effective than others in supporting student learning. Why should this be the case? Possibly because the particular instructional approach is tightly linked to clear teaching objectives, or involves a motivating activity for the students, or challenges students' thinking in an engaging way, or allows students the opportunity to articulate their developing understandings.

Following this line of argument, the central challenge for science education researchers remains one of building upon insights about learning to develop robust guidelines (both science domain specific and general) to support instructional design. If such research activity is to have an impact upon practice in schools, then it needs to engage with the professional knowledge and expertise of practicing teachers and their priorities for professional development. This is a substantial project that has as its ultimate aim the exciting prospect of allowing students such as Alice to develop deeper insights into the power and elegance of scientific knowledge.

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CHAPTER 3

Language and Science Learning

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In a 1998 contribution to the *International Handbook of Science Education*, Clive Sutton used the writings of Faraday, Boyle, Harvey, and others to compare the language found in historical documents with the ways in which science is represented in contemporary textbooks and classrooms. In Michael Faraday's letters to scientific contemporaries, Sutton found a voice that was personal and overtly persuasive, eschewing the third-person, "stick to the facts" register with which schoolchildren today are commonly taught to write laboratory reports. Drawing on science studies by Bazerman (1988), Lemke (1990), Medawar (1974), Shapin & Schaffer (1985), and others, Sutton (1998) recommended reduced emphasis in science education on language as a means of transmitting information and greater emphasis on language as an interpretive system of sense-making.

Only 5 years later, a survey of recent literature on language and science education demonstrates both the utility of Sutton's framework and the potential for its expansion. An overall healthy growth of that literature masks some interesting trends within that literature. Consider, for example, Figure 3.1, which plots the average annual publication rate of documents with keywords *Science Education*, *Language*, and either *Concept Formation* or *Culture*. Following a period of stability from about 1980 to 1995, publications related to *Concept Formation* have declined in number, while *Culture* has increased.[1] Trends like this reflect changes in the field regard-

1. For the sake of the narrative, I have simplified my description of the method in which the Figure 3.1 data were generated. The set described in the prose as (kw = "Science Education" AND "Language") is actually more accurately represented as ((kw = "Science Education" OR "Science Instruction") − (kw = "Programming" OR "Programing")) AND "Language". Use of the longer specification eliminated almost all of the numerous studies of computer programming (or ERIC's earlier spelling, "programing"), few of which were concerned with language as a means of oral or written communication between teachers and students engaged in science teaching and learning. My choice of keywords (and their linking algebra) followed a quantitative analysis of all ERIC citations in the aforementioned set from 1975–2002 (the most recent year that is reasonably completely indexed) and from study of the frequency distributions by date of the first 10 keyword descriptors of each of the citations. However, the data in Figure 3.1 are offered for heuristic purposes only; this is not a statistical argument!

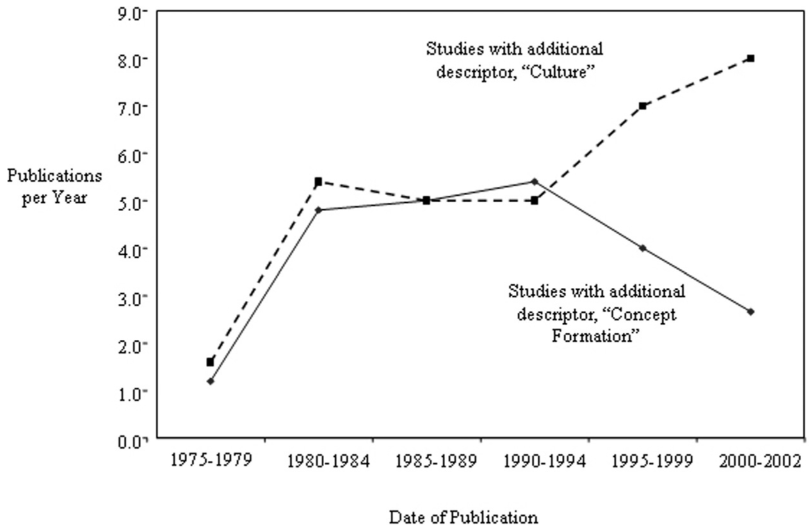

FIGURE 3–1. ERIC citation rates for publications with keywords *Science Education*, *Language*, and either *Culture* or *Concept Formation*, by date.

ing what it means to learn (and to teach) science. Following a shift in emphasis from learning as individual cognitive growth to learning as individual cognitive growth in social settings, research increasingly views language as more than just a social means to individual ends.

The first section of this chapter discusses the origins of much of this newer research, beginning with four schools of thought. The roots of these perspectives grow together in a number of ways, but they also emphasize different things. The second section of this chapter reviews recent research concerning language and science learning, building to a conceptual framework based on Sutton's earlier work. The reader should note that a detailed perspective on specific studies of spoken and written discourse in science classrooms is provided by Greg Kelly in Chapter 16. A comprehensive recent review of science literacy by Yore, Bisanz, and Hand (2003) deals more extensively than I do here with the important role of writing in science learning. My aim here is to propose a framework informed by theoretical issues that are historically significant or productively emerging in science education, without covering the same ground in the same way. To do this, I first identify some of the contributions of four productive contemporary approaches to studying the role of language in science learning: the Vygotskian perspective, conceptual change theory, sociolinguistics, and situated learning.

ORIGINS OF CONTEMPORARY RESEARCH ON LANGUAGE AND LEARNING

Vygotsky

Lev Vygotsky was a contemporary of the young Piaget and closely followed his work. He concurred with many, but not all, of Piaget's conclusions. Vygotsky's most compelling contribution to science education is probably *Thought and Language* (1934/1986). Although the book says practically nothing about pedagogy, it has been productively probed for its educational implications, which are significant (Howe, 1996; Wertsch, 1985, 1991). Vygotsky distinguished between spontaneous and scientific thinking. Spontaneous concepts arise in a child's everyday experience and begin with egocentric speech, often in the company of others. Eventually, vocalized speech is internalized, evolving into inner speech. According to this view, spoken language precedes conceptualization in everyday life. Meaning actually follows speech.

According to Vygotsky, scientific thinking is special because new scientific concepts generally arise from work within a formal conceptual structure (which may be explicitly taught). Consequently, science learning is a process of moving from the linguistically abstract to the concrete, not vice versa. Children learn spontaneous concepts (e.g., what a bowl is) from their everyday experiences. Scientific concepts (e.g., what photosynthesis is) are often invisible, abstract, or otherwise inaccessible. One oft-overlooked instructional implication of this perspective is that some scientific concepts may never arise from hands-on experience, no matter how creative or time-consuming that experience may be.

Vygotsky's "zone of proximal development" (ZPD) has been used extensively by researchers and educators. The idea is appealing: The trajectory of future learning can be predicted by comparing a child's work alone with his or her work in the company of a more knowledgeable teacher or peer. Numerous studies have translated the ZPD concept into a pedagogical agenda: Engage learners in group tasks with others, on the grounds that the social setting will allow many students to stretch beyond the limits of their abilities, working alone.

Finally, in *Thought and Language*, Vygotsky noted that writing is linguistically distinct from and more demanding than speech. The developmental path of writing is more abstract, symbolic, and less likely to elicit (and be shaped by) feedback from others. A number of research and instructional projects have been built upon Vygotskian ideas, such as the Cognitive Acceleration through Science Education (CASE) project in Britain (Adey, 1999), research on elementary science instruction in Mexico (Candela, 1995), and the effects of computer-mediated communication in American science and math instruction (Charnitski & Harvey, 1999).

Some critics have charged that Vygotsky has been misappropriated for nefarious purposes like promoting sociocultural relativism, replacing formal instruction with useless hands-on experiences, and misinterpreting the ZPD as a bridge between everyday experience and scientific concepts. Vygotsky, argued Stuart Rowlands (2000), was an "out-and-out objectivist" who believed that theory precedes practice in science. Everyday experiences may be necessary for scientific concepts to develop, but they do not cause that development. Scientific ideas ascend from the abstract to the concrete (Rowlands, 2000; Rowlands, Graham, & Berry, 1999). In science there is always a critical need for formal instruction.

Conceptual Change Theory

Conceptual change theory (CCT) has long been an important paradigm in science education research. Building from work by Piaget (1929/1969) and Thomas Kuhn

(1970), the team of Posner, Strike, Hewson, and Gertzog (1982) outlined a model of science learning that accounts for the resistance of misconceptions to change and that foregrounds the interaction between individuals and the scientific communities (and theoretical perspectives) to which they are acculturated. From a sociolinguistic perspective, CCT is itself a fruitful research program; that is, it stimulates the generation of interesting questions. For example, Lavoie (1999) documented the positive effects of adding a prediction/discussion phase to the beginning of a learning cycle in secondary biology. Among the features of his experimental treatment was an insistence that students make their predictions explicit and that they publicly debate, modify, and reevaluate those predictions. The genesis of these steps from CCT is clear.

Constructivism has largely supplanted CCT in the science education research vernacular, despite the problem of its many different meanings. Nevertheless, CCT remains a viable theory and may prove—for social, philosophical, and methodological reasons—to be more long-lived. Fundamentally, constructivism is about individuals creating individual meanings, sometimes in social settings. Conceptual change theory emphasizes the congruence of individual understandings with public, often established, knowledge (see also Chapter 2, this volume). CCT also foregrounds the importance of epistemic communities (Kelly, 1997).

As Vygotsky's work is becoming more widely known, researchers and educators are seeking ways to extend CCT from the intramental to the intermental plane. Using an analysis of a chemistry lesson, Mortimer and Machado (2000), for example, discussed the evolution of their understandings of cognitive conflict (an individual, Piagetian construct) to one of public, discursive conflict, resolved dialogically. In recent years, the emphasis of many studies of conceptual development in science education has shifted from the investigation of individuals' cognitive schemata to studies of interactive discourse and the co-construction of concepts in natural language. This has required finding tools and methods better suited for documenting and analyzing the dynamics of spoken language in classrooms. This brings us to a third major approach to studying how language and learning are related: the sociolinguistic perspective.

Social Semiotics and Sociocultural Considerations

Lemke's *Talking Science* (1990), a field guide to analyzing the content of classroom discourse, clearly demonstrates the need to consider the context of spoken language. Although this principle is a sociolinguistic fundamental, Lemke drew most directly on what he labeled "social semiotics." Here and in later works (e.g., Lemke, 2001), he argued that meaning is derived in part from the cultures in which talk takes place, and that meaning-making is impeded when culture clashes arise between disciplinary cultures, as well as between more conventional social/economic/political/ethnic cultures. In fact, the science classroom sits on the border between competing cultures, such as the scientific community, which values open inquiry and disagreement, and the formal school community, which generally prefers quiet obedience. Lemke and others found that sociologies of science also offer useful tools for understanding the social work of scientists, from which implications for classroom practice can be drawn (Kelly, Carlsen, & Cunningham, 1993; Roth, 1995a).

We learn to communicate in different ways in different settings. Children who begin school without having been socialized to conventional forms of school communication may experience communicative failures that are interpreted as lack of aptitude or intelligence (Heath, 1983). Studies of language minority students demonstrate how the routine communicative expectations of majority teachers can be misinterpreted because of lack of teachers' understanding of the cultural norms and practices in their students' out-of-school lives (Au & Mason, 1983; Erickson & Mohatt, 1982). Our *discourse* consists of the words, gestures, and other signs that we use; our *Discourse* consists of all of the other things that help us make sense of language: "Different ways of thinking, acting, interacting, valuing, feeling, believing, and using symbols, tools, and objects" (Gee, 1999, p. 13). Learning may be easier when teachers strive for instructional congruence between the academic culture and the culture(s) of their students, modifying subject matter by using students' language and cultural experiences (Lee & Fradd, 1998).

Provocative but less thoroughly explored, cultural practices and language may be exploitable in addressing students' scientific misconceptions. Hewson and Hamlyn (1984) discovered that southern African Sotho and Tswana teens speak languages that predispose them to kinetic (particulate) rather than caloric (substance) views of heat. Potentially, this linguistic and cultural resource might help them avoid common misconceptions. Although later studies of Sotho college entrants could not corroborate this phenomenon (Lubben, Netshisaulu, & Campbell, 1999), further studies of the interaction of nonmajority language and science learning opportunities would be worthwhile.

Hogan and Corey (2001) provided an excellent example of classroom research from a sociocultural perspective. In addition to *Talking Science*, Groisman, Shapiro, and Willinsky (1991) offer a gentle introduction to the use of semiotics in science education research.

Situated Learning and Communities of Practice

Clearly, the concepts of situated learning, legitimate peripherality, cognitive apprenticeships, and communities of practice are having an important impact on science education research. Studies by Lave, Wenger, and others have given educational researchers much to think about and work with, even though the bulk of their work has been done in nonschool settings (Chaiklin & Lave, 1993; Lave & Wenger, 1992; Wenger, 1998). Studies of cognition in situ—of craftwork, midwifery, and other jobs—reveal how novices learn complex skills through participation in real work, initially as peripheral participants. One of the most exciting aspects of this literature is its suggestions that learning is not a process of internalizing knowledge, that it is not promoted by social activity; learning is social activity.

Wenger (1998) portrayed a claims-processing office as an environment in which work, interaction, and learning are inextricably linked. "Issues about language," Lave and Wenger (1992) wrote, "may well have more to do with legitimacy of participation . . . than they do with knowledge transmission. . . . Learning to become a legitimate participant in a community involves learning how to talk (and be silent) in the manner of full participants" (p. 105).

In some cultures and for many crafts, conventional didactic instruction would be culturally inappropriate (Jordan, 1989) and less suitable than the traditional apprenticeship model.

Roth (1995b) applied many of these ideas in his analysis of science classroom practices. Of particular interest are his demonstrations of the transformation of gestures, inscriptions, and other phenomena in shaping concepts in the public sphere, a paralinguistic process evocative of Vygotsky. In the laboratory setting, gestures, for example, may function less as evidence of conceptual understanding than as a tool for co-constructing concepts with one's laboratory partners (Roth, 2001). The utility of viewing science learning in a social fashion has also been demonstrated in studies of adult learners. For example, in an ethnographic study that took place over several years, Bowen and Roth (2002) identified the different contributions to the education of ecologists that take place in formal and informal settings, and demonstrated the importance of stories and other informal communications in shaping novices' understandings. They also argued that storytelling contributes to social cohesion in scientific communities. In other words, not only do communities of practice provide a context and a means for learning science through language, but informal language—often superficially off-task—functions to help create functioning communities. The model of apprenticeship embedded in Lave's work can also be used productively to study the learning of novice teachers in settings where they coteach, and studies conducted with this lens have the potential to inform teacher education, viewing the learning of novice and experts as reciprocal (Roth & Tobin, 2001).

TOWARD A REVISED FRAMEWORK FOR THE ROLE OF LANGUAGE IN SCIENCE EDUCATION

My goal in this section is to extend and update Sutton's 1998 framework concerning the role and function of language in science teaching and learning, focusing on four features: (a) what a speaker appears to be doing, (b) what listeners think that they are doing, (c) how language is thought to work in learning, and (d) how language is thought to work in scientific discovery.

What a Speaker Appears to Be Doing

Controlling discourse. Although of course students often speak and write, traditional teaching is characterized by an asymmetry of conversational rights that favors the teacher. Teacher questions, for example, both reflect a teacher's authority and reinforce it (Carlsen, 1991a). Questions assert sociolinguistic power (Mishler, 1978), and when teachers find themselves discussing unfamiliar subject matter, they may rely upon questioning to prevent the topic of discussion from wandering into uncomfortable territory (Carlsen, 1991b). This creates what Driver (1983) labeled as the science teachers' dilemma: teaching science as a process of inquiry and as an accepted body of knowledge poses a constant linguistic challenge. Driver wrote, "On the one hand pupils are expected to explore a phenomenon for themselves, collect data and make inferences based upon it; on the other hand this process is intended to lead to the currently accepted law or principle" (p. 3). We expect teachers to invite students to construct meaning, but we hold them accountable for the construction of the right meaning.

Fortunately, most students cooperate in the most common patterns of classroom discourse, such as variations on the Initiation-Response-Evaluation (IRE) triad that have been described by Mehan (1979), Lemke, and many others. Viewed as a language game (Wittgenstein, 1967), the IRE is both a mechanism of control and a cultural tool (Wertsch, 1991). Unfortunately, even well-intentioned control of the direction of science talk may result in a conflation of the teacher's authority as an expert with her authority as the person in charge (Carlsen, 1997; Russell, 1983; Toulmin, 1958). The resulting discourse may suggest to students that the nature of science is more certain and less susceptible to challenge than it really is. There are other cognitive hazards. Wilson (1999) cautioned: "[If] engagement in epistemic tasks in discourse is important in the construction of abstract declarative knowledge and conceptual understanding, then students may face disadvantages in classrooms in which discursive practices are teacher controlled and dominated by extensive triadic dialogue about knowledge claims provided for students by the teacher or the text" (p. 1080).

In more open-ended project-based science work, students may not understand the rules, and both order and learning may suffer. There are hazards to unguided discovery (Rogoff, 1994), but teachers who know how to play language games can transform original student moves and open them to extension, elaboration, or critique (Polman & Pea, 2001). But it is a balancing act. Hogan, Nastasi, and Pressley (1999) found that teacher-directed discourse was most effective in promoting higher-order reasoning and higher-quality explanations, but discussions among students were more generative and exploratory. Other work on the balance between restricting or expanding control has been informed by Vygotsky's ZPD concept (e.g., Blanton, Westbrook, & Carter, 2001).

Creating opportunities for meaning-making. On a more constructive note, teachers facilitate linguistic meaning-making in many ways. Kelly and his collaborators documented the work of a science non-expert teaching science to third graders. Instead of closing down the conversation, the teacher successfully modeled and directed scientific discourse, leading her students to define science in their local context (Crawford, Kelly, & Brown, 2000).

> To become a member of a community (e.g., science classroom or research laboratory) who acts in socially appropriate ways (e.g., one who adheres to genre conventions when speaking and writeing), one must first understand the social practices of a community, that is, what counts as a valid description, explanation, inference, etc. (p. 626).

The research group found similar practices in a high school physics classroom: a teacher framing activities and coordinating sociocultural practices, thus leading his students to appropriate scientific discourse (Kelly & Chen, 1999). Coherent and jointly constructed discourse resulted in the creation of public, sociolinguistic meaning.

Of course, local meaning is not the same as scientific fact: Gravity cannot be dismissed through a classroom conversation. Science is epistemologically distinct in its empirical approaches, its forms of argument, and the demonstrable productivity of concepts and theories that would never arise spontaneously in a school setting (quantum physics, for example). Recalling Vygotsky, scientific concepts often grow from the abstract to the concrete. They are useful because they are decontextualized (Rowlands, 2000). Approached from a different direction, scientific experiments yield facts through social processes of inscription, translation, and the ultimate removal of "weasel words" that relate the empirical *who, what, when, where*, and *how* (Latour & Woolgar, 1986). The approaches are different, but the outcomes are the same: useful facts stripped from the particulars of their construction.

What Listeners Think They Are Doing

In inquiry-oriented classrooms, students often work in groups, and their work can be viewed as contributing to the solution of shared problems. Students can learn science and *about* science when their communication takes place through online discussions (Hoadley & Linn, 2000), computer-mediated peer review (Trautmann et al., 2003), and other modalities, but group work usually takes place face to face. Without the teacher present, the rules of the language game are altered, and the new rules must be understood by all in order to make progress. Communicative competence entails knowing how to take turns without the teacher's direction, how to hold (and yield) the floor, and how to make sense to (and of) others. These tasks are inevitably complicated by speaker differences of gender, culture, ethnicity, and so on (Philips, 1972).

The substance of science talk can be evaluated in a number of ways. Geddis (1998), for example, developed a multidimensional method for gauging the quality of discourse. High-quality discourse includes practices like giving reasons for assertions and demonstrating intellectual independence from the teacher's authority. Hogan (1999) identified metacognition as an essential element in group inquiry and conducted a study in which students in experimental classes received training in metacognition and cognitive strategies for group work. The intervention resulted in improvements in students' knowledge about metacognition and collaborative reasoning, but no difference was found in the experimental and control groups' actual collaborative behaviors. Nevertheless, the success of metacognitive strategies in individual students' learning suggests that further work along these lines may be valuable.

Epistemological beliefs may not change easily. In one study, 4 weeks of substantive inquiry about evolution produced little shift in students' epistemological frameworks, which were found to be unstable and ill-defined. The investigators in that study advocated explicit epistemic discourse coupled with inquiry (Sandoval & Morrison, 2003).

In a study of college engineering students, Kittleson and Southerland (2004) found that concept negotiation was rare, even when the instructor structured the task to promote that process. Clearly, success in channeling student discourse into productive knowledge construction is a pedagogical goal that demands much more work.

How Language Works in Learning

Making meaning. The Sapir-Whorf hypothesis (Whorf, 1956), now largely discredited, proposed that language shapes human cognition in profound ways, so that a person's native language would shape how she perceived the world. Today it is commonly assumed by linguists that our brains are wired for language (although the details remain in dispute, such as Chomsky's (1972) theory of a universal grammar). Why then is culture—and the signifying systems that culture embodies—so important in meaning-making? From a sociocultural perspective, learning involves appropriating and using intellectual and practical tools. Much of what a student learns comes not from direct experience, but from texts that are organized to tell a disciplinary story. "From a sociocultural perspective, the use of texts as the prime vehicle for communicating knowledge can be seen as a further step in the adoption of experience-distant accounting practices for understanding the world" (Säljö, 1998, p. 49). Human knowledge is discursive in nature, reproduced through language and artifacts in social institutions like schools.

> The knowledge produced within these discourses does not remain inside the heads of individuals. . . . Rather, knowledge emerges as properties of tools and socially organized practices in which individuals participate, and which by necessity are ideological in nature—without values there can be no knowledge. . . . Knowledge is fundamentally argumentative in nature; it moves the world rather than reflects it. (Säljö, p. 53)

Wong and Pugh (2001) observed that we promote the teaching of concepts rather than facts because concepts are more integrative and thus more powerful in science. Cognitive perspectives emphasize thinking; sociocognitive perspectives highlight the role of language in stimulating and supporting thinking. John Dewey emphasized ideas rather than concepts, and being, the combination of cognition and action:

> Dewey's emphasis on being, rather than cognition, reveals an epistemological stance that locates meaning neither in the mind of the learner nor in the surrounding environment. Instead, meaning is a transactive phenomenon: it exists only in the situation created in interaction between person and world. . . . To some readers, ideas and concepts may seem synonymous and we admit that Dewey's use of the term *idea* (along with other terms), although precise, is often confusing. To begin, concepts are something that students learn: To understand is to have an accurate representation of it and to be able to apply it appropriately. The goal of conceptually oriented teaching is the construction of accurate, meaningful representations. By contrast, ideas are something that seizes students and transforms them. The goal of ideas-based teaching is to help students to be taken by an idea and to live with it, to be with it in their world. (Wong & Pugh, pp. 324–325)

Of course, meaning-making is not the only function of language in the classroom. Discourse has two distinct functions in science education: generating meaning (its generative function) and conveying meaning (its authoritative function) (McDonald & Abell, 2002; Mortimer & Machado, 2000).

Representing knowledge. A number of researchers have studied how knowledge is represented in science education settings and have developed tools that provide insights into how language functions in learning. For example, in a cross-cultural study of English and Asian-speaking children, Curtis and Millar (1988) developed a method for representing students' knowledge about scientific concepts by classifying ideas generated in a writing task. Concept mapping in diverse forms remains a popular tool for representing the relationships among concepts (Fisher, Wandersee, & Moody, 2000), and the use of concept maps has been facilitated by several different computer tools. Semantic networks, ideational networks, and other graphical diagrams have been found to be useful diagnostically and to stimulate science talk with language minority students (Anderson, Randle, & Covotsos, 2001; Duran, Dugan, & Weffer, 1998).

Building upon work on situated learning and the sociology of science, Roth (1995a) described a number of cases of both individual and collaborative knowledge construction. The assignment of group work and the use of conscription devices such as concept maps helped create conditions in which "students had to negotiate the meanings of concept labels or future courses of action. During these negotiations they externalized and objectivized their understandings so that they were open not only to public scrutiny but also to critical self-reflection. In this process, students negotiated prior understandings and invented new and not-yet experienced connections between concepts" (p. 267).

In related studies, Roth and his colleagues described the semiotic significance of graphs as signs representing objects and processes (Roth, Bowen, & Masciotra, 2002), as well as the role of gestures and rough-draft talk, which they believe support the subsequent evolution of more structured talk, iconic objects, and eventually abstract communication tools, including symbols and writing (Roth & Lawless, 2002). "Gestures are a medium on which language can piggyback in its development" (Roth & Welzel, 2001). The authors suggested that, because gestures frequently are used to refer to materials in the laboratory, students should not be sent home to write laboratory reports until they have had the opportunity to discuss the complex conceptual issues explored in the teaching laboratory.

Cultural Considerations

The interaction of culture, language, and schooling has been a productive focus of research in a number of disciplines. A great deal is known, for example, about how and why differences between the cultures and languages of school and home can be problematic for students (Au & Mason, 1983; Shultz, Erickson, & Florio, 1982). Even among speakers of the same language, problems may arise if the home register does not match the privileged formal register of schools (Bernstein, 1961). The dynamics of communication between linguistic and ethnic minority and majority speakers continues to be an active and interesting area of work (see, e.g., Moje, Collazo, Carrillo, & Marx, 2001; Stoddart, Pinal, Latzke, & Canaday, 2002). Lee's (1999) study of south Florida children's attributions of Hurricane Andrew demonstrated gender, socioeconomic, and ethnicity effects, not only with respect to what the children knew, but also where they got their information. Lee and Fradd (1996) emphasized that although culture may sometimes contribute to misconceptions, and that scientific practices like questioning and public skepticism may clash with some cultural norms, culture also provides metaphors and other linguistic resources that we are only beginning to understand.

Writing

Although my comments have focused primarily on spoken language, there is a growing literature on how writing functions in the development of knowledge. For example, Keys has shown how collaborative writing can enhance students' constructions of scientific concepts (Keys, 1994, 1999) and the quality of their reasoning (Keys, 1995). She and her colleagues developed a Science Writing Heuristic as an alternative to the traditional laboratory report and reported that it promotes students' generation of assertions from data; making connections among procedures, data, evidence, and claims; and metacognition (Keys, Hand, Prain, & Collins, 1999). Positive outcomes from interventions using diverse types of writing tasks have been reported, although the students themselves may not see writing as a tool for knowledge development (Prain & Hand, 1999).

Talking and writing yield different outcomes because of their different natures. Rivard and Straw (2000) noted:

> Talk is important for sharing, clarifying, and distributing scientific ideas among peers, while asking questions, hypothesizing, explaining, and formulating ideas together all appear to be important mechanisms during discussions. The use of writing appears to be important for refining and consolidating new ideas with prior knowledge. These two modalities appear to be dialectical: talk is social, divergent, and generative, whereas writing is personal, convergent, and reflective. (p. 588)

Both are important for doing science in classrooms: just as it is through the public processes of formal science that objectivity is pursued, via intersubjective means.

How Language Works in Science

Language is central to science. It is the medium through which claims are made and challenged, empirical methods and data are recorded, and the story of inquiry unfolds. Language is not just a vehicle for transmitting scientific information; the history of science reveals that analogies, for example, are a powerful conceptual resource for scientific discovery and understanding (Dörries, 2002). Scientific language is rich with specialized terms that have metaphorical origins (Sutton, 1992).

Compared with students, scientists, not surprisingly, hold much more sophisticated understandings about how to make knowledge claims from data. They are more likely to prioritize rhetorically the relationship between empirical evidence and conclusions, and they attribute this ability to their earlier socialization to science. In contrast, middle-school science students rely more upon their personal views to evaluate claims (Hogan & Maglienti, 2001). Nevertheless, scientists generally believe that the writing process involves knowledge telling, not knowledge building. Their writing tends to be narrowly focused on a specific genre, target audience, and approach (Yore, Hand, & Prain, 2002).

The experimental article is a specialized genre with an interesting history. For example, the detachment and emotionlessness of the form may have helped to reduce factionalism in science (Bazerman, 1988). Scientific writing is lexically dense because it is replete with colorful, invented words that reduce complex processes to singular identities (Halliday & Martin, 1993) (e.g., *photosynthesis* or *cellular automaton*). Also commonly invented are scientific discoveries, which are often reconstructed after the dust settles, fixed in time retrospectively by a scientific community (Brannigan, 1981; Woolgar, 1976). But the more startling the claim, the more likely it is that there will be dust to settle. Discursive consensus in science is not as clean or as common as is generally believed. Intellectual divergence is normal, and the interpretations of scientists may vary with their own sociocultural context (Mulkay, 1991).

Nevertheless, it would be an unusual scientific research manuscript that began with a personal statement about the investigator's gender, race, religion, or ethnicity. The official registers of science do not document an investigator's personal and social values, beliefs, and commitments, because, after all, facts speak for themselves. The status of science is attributable in part to persistent myths. As Helen Longino (1990) noted, science achieves objectivity through social means. We ought to be willing to talk about it. Furthermore, students of science need those opportunities as well. Longino (2002) offered four criteria for effective scientific discourse: (a) public venues for the critical review of methods, facts, and the interpretation of data; (b) an expectation of uptake—that investigators will respond to the substance of public criticism; (c) the existence of public standards for evaluating claims, such as the criterion that claims refer specifically to data in ways that can be generally understood; and (d) that discourse occurs in a context of tempered intellectual equality—one that recognizes inevitable differences in participants' knowledge without denying the less knowledgeable opportunities to challenge.

CONCLUSION AND IMPLICATIONS

Table 3.1 updates and extends Sutton's (1998) framework. To his two articulations of the role of language—1. a system for transmitting information, and 2. an interpretive system for making sense of experience—I have added a third column: a tool for participation in communities of practice. This third perspective reflects a contemporary emphasis on learning as a social accomplishment. Formal science is much more than Scientist A convincing Scientist B that X is true. Scientist A's conception of X is almost always the product of extensive work in a local community of practice (such as a lab group), and the proposed definition of X may have emerged there from a complex iteration of experiments, inscriptions, translations, conversations, arguments, informal talks, feedback from peers outside the group, methodological training, new experiments, etc. (see Knorr-Cetina, 1983). At the broader disciplinary level, Scientist A and Scientist B probably share assumptions and understandings that are not recognized by others. Scientist C (and her group) may be exploring the same scientific terrain with very different tools and assumptions, leading to very different conclusions. Eventually, an agonistic struggle is likely, but as Longino (1990) notes, that is the point of science. It is in the expectation and practice of public argument that science progresses. Conflict is not only permissible, it is necessary. This does not mean that science is nothing more than mob psychology. Usually arguments must be based on observable phenomena, but what counts as an observation is something we agree to agree about.

An important problem for researchers using sociocultural tools—at least in the United States—is that we are working in an era of accountability, and political forces demand "objective" measures of student learning and educational productivity. Today's emphasis on individual standardized testing is based on an assumption that learning is an individual accomplishment. One implication of a sociocultural perspective is that we need to develop better tools for evaluating learning in complex social environments. Affordable new tools for video recording and analysis

TABLE 3.1.
Changing Perspectives on the Role of Language in Science and Science Teaching

*Characteristic**		*Role of Language*		
		A system for transmitting information (Sutton, 1998)	*An interpretive system for making sense of experience (Sutton, 1998)*	*A tool for participation in communities of practice*
1	What the speaker or writer appears to be doing.	Describing, telling, reporting.	Persuading, suggesting, ex-ploring, figuring.	Contributing to the solution of a shared problem.
2	What listeners or readers think that they are doing.	Receiving, noting, accumulating.	Making sense of another person's intended meaning.	Contributing to the solution of a shared problem.
3	How language is thought to work in learning.	Clear transmission from teacher to learner; importance of teacher's speech.	Re-expression of ideas by learner; importance of learner's speech.	Achievement of a shared understanding. Learning and language as social accomplishments.
4	How language is thought to work in scientific discovery.	We find a fact, label it, and report it to others. Words stand for things.	Our choices of words influence how we and others see things: highlighting some features and ignoring others.	Language is used to persuade, and "discovery" is often constructed only retrospectively.

**Note.* "Characteristic" labels and the next two columns are based on Sutton (1998).

offer great potential for helping researchers study language as an educational outcome, not just a means. However, few science education researchers have had formal training in sociolinguistics; after all, their undergraduate training tends to occur in the sciences. It would benefit our community to support the development of graduate training programs that teach future researchers skills to work with linguistic data.

A related implication is that we need to publicly challenge the prevailing view of learning as an individual accomplishment. We must challenge that view with policymakers and parents as well as within our own research community. Strategically, support for the development of social methods of assessment is likely to require convincing the public of the social nature of real science and demonstrating that the attrition of talent from the scientific work force is in part the result of practices that represent science as the individual accomplishment of unambiguous understandings.

New tools notwithstanding, collecting data in the form of natural language is extraordinarily time-consuming and expensive. Because our community lacks useful standards for the collection, transcription, analysis, cataloging, and use of sociolinguistic data, data collected in one study are unlikely to be used again. Compounding this problem, university institutional review boards today often seek assurances that the use of video recording in precollege classrooms is minimized and that recordings are locked away or destroyed after research is conducted. The development of standards for sociolinguistic analysis in science education would be a useful effort. These standards should certainly be informed by standards in related fields. However, our needs are likely to be unique, given the gestures and other signs, texts and inscriptions, specialized tools, and shifting group composition that characterize science learning environments. We are likely to be best served by systems that could be used responsibly by researchers who have not had extensive training in linguistics. As part of such an initiative, it would be useful to develop conventions for metadata production and cataloging (e.g., through the Open Archives Initiative, www.openarchives.org), as well as mechanisms for protecting human subjects without the necessity of locking data away from other researchers. A corpus of such data would be useful in both future research and for training new researchers.

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CHAPTER 4

Attitudinal and Motivational Constructs in Science Learning

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This chapter examines the attitudinal and motivational constructs that are closely linked to science learning. First, we present a rationale for the study of attitudes and motivation in the context of science learning. We then discuss the history of attitude research in science education, define constructs prominent in this research, and review recent attitude research findings. We review research methods and instruments, students' attitudes toward science and factors that influence them, and interventions to change students' attitudes. Next, we focus on motivation, highlighting the historical background of theoretical orientations and discussing research on constructs of particular relevance to science education researchers. We conclude our chapter by offering recommendations for future research involving attitudinal and motivational constructs, noting implications for policy and practice.

At this point, we wish to acknowledge that it is impossible within the scope of this chapter to evaluate every significant study in the field of science education that addresses attitudinal or motivational constructs. Our goal is to provide the reader with an overview of the role these constructs play in science learning through strategic sampling of the relevant research.

Throughout this chapter we use the term *construct* to mean a scientific concept that represents a hypothesized psychological function (Snow, Corno, & Jackson, 1996). Attitudinal and motivational constructs are used to account for and infer patterns of science-related thinking, emotion, and action. They tend to be relatively enduring within a person, but have the potential to change. According to Snow et al. (1996), a construct identifies a unique dimension on which all persons differ by degree and should be represented by more than one kind of data.

Effective science instruction has the potential to improve attitudes toward science and heighten the motivation to learn science. Hands-on science activities, laboratory work, field study, and inquiry-oriented lessons tend to have these goals. Attitudinal and motivational constructs may also serve useful purposes in the context of science program evaluation and national comparisons. Of course, science instruction that is purposely developed to influence attitudes and motives may be construed as indoctrination (Koballa, 1992), raising ethical questions in some circumstances. In addition, there are attitudinal and motivational constructs that may be considered as both entry characteristics and outcomes of science instruction (Bloom, 1976). For example, motivation to enroll in elective science courses and positive attitudes toward chemistry are just as likely to be considered important instructional outcomes as they are determinants of whether a person will engage in certain science learning experiences.

An important reason for examining attitudinal and motivational constructs in science education is to understand the ways in which they affect student learning in the cognitive arena. Pintrich, Marx, and Boyle (1993) described attitudinal and motivational constructs as moderators of a learner's conceptual change and suggest that they may influence science learning in the short term and over longer periods of time. Researchers have studied these relationships intensively as individual learner differences and caution against forming expected "straightforward monotone relations" between such constructs and cognitive learning (Snow et al., 1996, p. 246). Furthermore, these relationships are influenced by contextual factors, including classroom organization, teacher authority, the nature of classroom academic tasks, and evaluation structure (Pintrich et al., 1993). These contextual factors may serve to strengthen the relations between attitudinal and motivational constructs and science learning as well as to weaken them.

Attitudinal and motivational constructs also are associated with students' actions that are considered precursors to science learning and achievement. Often, attitudes and motives are considered predictors of students' science-related decisions that affect learning, such as attending class, reading textbook assignments, and completing homework. However, the influence of attitudes and motives on science learning and achievement has tended to be difficult to document through research.

Finally, attitude and motivation are constructs of the affective domain. And although the affective dimensions of science learning have long been recognized as important, they have received much less attention by researchers than have the cognitive dimensions. Reasons for this imbalance include the "archetypal image of science itself," where reason is separated from feeling, and the "long-standing cognitive tradition" of science education research (Alsop & Watts, 2003, p. 1044). A contemporary view is that the "affective dimension is not just a simple catalyst, but a necessary condition for learning to occur" (Perrier & Nsengiyumva, 2003, p. 1124). Attitude and motivation are indeed the most critically important constructs of the affective domain in science education.

ATTITUDES

Attitudinal constructs have been part of the science education literature for more than a century; however, the interest in students' science-related attitudes among researchers and practitioners has waxed and waned over the years. According to Jones (1998), waxing interest in any research topic may result from factors ranging from convenient research paradigms and new measurement instruments to prestige of the investigator, funding priorities, and theoretical power. Waning interest, on the other hand, may result from redirection to other emerging research areas, achieving solutions to previous research problems, and research activity reaching an empirical plateau. Factors such as these have caused research on students' science-related attitudes to wax and wane.

Historical Background and Theoretical Orientations

John Dewey's philosophy served as an early inspiration for attitude research in science education. Dewey (1916) underscored the need for teaching scientific attitudes as an important aspect of educating reflective thinkers in the inaugural issue of the journal *General Science Quarterly*, which later became *Science Education*. He believed that science instruction should foster such mental attitudes as intellectual integrity, interest in testing opinions and beliefs, and open-mindedness rather than communicate a fixed body of information (Dewey, 1934). Many agreed with Dewey's thinking about scientific attitudes and translated it into practice. An early effort by Weller (1933) involved the development and use of a true-false scale to determine whether scientific attitudes could be taught. Others developed scales to measure elements of scientific attitude (Koslow & Nay, 1976) and sought to determine whether scientific attitudes can be changed by instruction (Charen, 1966).

Pioneering work on attitude measurement (Likert, 1932; Thurstone, 1928) and theoretical ideas about attitude and its relationship to behavior (Sherif, Sherif, & Nebergall, 1965) were major influences on science attitude research. In the 1960s, research on students' attitudes toward science, scientists, and science learning appeared regularly in the science education literature (e.g., Weinstock, 1967). Science educators began to distinguish "attitudes toward science" from "scientific attitudes," also called *scientific attributes*. This new label stems from the notion that scientific attitudes, such as open-mindedness, embody the attributes of scientists that are considered desirable in students (Koballa & Crawley, 1985).

The 1970s and 1980s saw a proliferation of research on students' attitudes toward science; however, research interest in scientific attitudes waned. This shift in interest from scientific attitudes to attitudes toward science was attributed to the understanding that learning about the modes of thinking associated with scientific attitudes does not mean that students will adopt them as their own (Schibeci, 1984). In other words, students may hold favorable or unfavorable attitudes toward these scientific attitudes. Attitudes came to be viewed as both the facilitators and products of science learning and research efforts focused on documenting student attitudes and their relationship to science achievement. Highlighting the research of this period was the learning theory-based program led by Shrigley (1983) that addressed the influence of persuasive messages on science attitudes and the development of Likert-type attitude scales.

Attitude research in science education began to wane in the 1990s, in part because attitude researchers seemed to reach an empirical plateau. Many studies produced results that provided little direction for improving classroom practice or advancing research in the field. For example, some studies showed favorable effects of activity-oriented instruction on students' attitudes toward science, whereas others did not (see Simpson, Koballa, Oliver, & Crawley, 1994). A second reason for the decline is that the research paradigms in social psychology and educational psychology that had influenced attitude research in science education shifted from a behavioral to a more cognitive orientation (Richardson, 1996). This shift in theoretical orientation saw attitudes aligned with affect, or feeling and belief with cognition, as exemplified in studies based on Ajzen & Fishbein's (1980) theory of reasoned action (see Crawley & Koballa, 1994). With the separation of attitudes from cognition, and the emergence of beliefs as a construct thought to explain the actions of learners, attitudes became less important.

Research on students' science-related attitudes is again receiving increased attention. The disturbing decreases in science course enrollments at the secondary and post-secondary levels, particularly in Western countries, the disdain expressed by many students for school science, and the promise of new research methods have prompted renewed interest in attitude research (Osborne, Simon, & Collins, 2003). Exemplifying this renewed interest is the special issue on affect edited by Alsop and Watts (2003) in the *International Journal of Science Education*, which included three articles that address aspects of students' attitudes.

Attitudinal Constructs

Unfortunately, issues of definition and meaning have hampered the advancement of attitude research in science education. School science is typically the focus of investigations, but often this is not made clear in reports of science attitude research. Osborne, Driver, and Simon (1998) contend that attitude researchers should consider the elements of science in society, school science, and scientific careers separately, defining them carefully. But attitude has been defined in many ways and has, unfortunately, often been used interchangeably with terms such as *interest, value, motivation*, and *opinion*. This confusion is unnecessary because quite specific definitions appear in the attitude literature (e.g., Ramsden, 1998; Schibeci, 1984; Shrigley, Koballa, & Simpson, 1988).

An attitude is "a general and enduring positive or negative feeling about some person, object, or issue" (Petty & Cacioppo, 1981, p. 7). *I love science, I hate my science teacher*, and *Science experiments are wonderful!* reflect attitudes because they express general positive or negative feelings about something. This definition distinguishes attitude from related terms such as *value, belief*, and *opinion*. Values are more complex and broader than attitudes and are more enduring (Trenholm, 1989). Examples of values are equality, justice, and symmetry in nature. Beliefs are often described as the cognitive basis for attitudes (Ajzen & Fishbein, 1980); they provide information about a person, object, or issue that may be used in forming an attitude. *Science is fun, My science teacher is smart*, and *Animal dissection should be banned* all reflect beliefs. Opinions are cast as verbal expressions of attitudes and historically have been used to represent not only attitudes but also the constructs of cognition, evaluation, and behavior (Shrigley, Koballa, & Simpson, 1988). When considered in relation to one another, a person will have far fewer values than attitudes or beliefs and many more beliefs than attitudes.

The relationship between attitude, belief, and behavior was presented in a causal model in research based on the theory of reasoned action (e.g., Crawley & Black, 1992). Attitude is the overall evaluation of a highly specific behavior that is defined in terms of action, target, context, and time. The overall evaluation of the behavior, called *attitude toward the behavior* (AB), is the affective component of the model. Attitude toward the behavior is a significant determinant of intention to engage in the behavior, the conative component of the model, called *behavioral intention* (BI). Personal beliefs, the cognitive element of the model, are the determinants of attitude. According to Simpson et al. (1994): "Each belief about the behavior links the behavior with a specific attribute (a characteristic, outcome, or event). The strength of the link between an attribute and the object (called behavioral belief, b) is weighted by the attribute's subjective evaluation (called outcome evaluation, e) through the expectancy value theorem" (p. 222). The summed product of each salient belief by its associated evaluation is the cognitive or belief-based estimate of attitude, called attitude toward the behavior (AB).

Feeling and emotion are other constructs considered in science education attitude research. According to Teixeira dos Santos and Mortimer (2003), "the word *feeling* is used to characterize the mental experience of an emotion, and the word *emotion* is used to describe the organic reactions to external stimuli" (p. 1197). Basing their definitions of these terms in the work of Damasio (1994), these researchers explain that while feelings cannot be observed, the emotions that prompt feeling are observable. The emotional states of science students and teachers that are detectable through observation of body posture, body movement, and contraction of facial musculature include anger, annoyance, joy, and satisfaction. *Mood* is the term used to describe a long-term emotional climate (Damasio, 1994; Teixeira dos Santos & Mortimer, 2003).

Reaching a universal agreement on definitions of attitude and its related terms is unlikely to occur in the near future and may even be undesirable. It is for this reason that Snow et al. (1996) recommended that it is "important not to belabor definitions unduly, even while seeking common agreement on some convenient and useful terminology" (p. 247). We suggest that science educators heed this recommendation when conducting and interpreting attitude research.

Research Methods and Instruments

The methodological approaches used in studying students' science-related attitudes are increasing in their variety. While most studies continue to make use of self-report instruments that provide quantitative measures of attitude, investigators are also employing student drawings, personal interviews, and physiological expression as indicators of attitudes. Furthermore, the research methods reveal different levels of emotiveness, ranging from "the detached, statistical analysis of attitudes to the personalized, emotionally charged account[s] of teaching and learning" (Alsop & Watts, 2003, p. 1044). In this regard, it comes as no surprise that the various methodological approaches employed in the research reflect, and in a sense are limited by, the strategies used to collect and interpret attitudinal data. For example, Siegel and Ranney (2003) used quantitative modeling and Rasch analysis to develop and test the usefulness of the *Changes in Attitudes about the Relevance of Science* (CARS) questionnaire. In contrast, the ethnographic approaches highlighted in the research of Palmer (1997) and Pilburn and Baker (1993) used interviews and researchers' field notes. In the study by Teixeira dos Santos and Mortimer (2003), which is anchored in work of Damasio (1994) on emotions and feelings, videotapes of lessons were used to attend to such details as personal posture, gestures, and facial expressions in constructing understandings of emotion and attitudes. Stretching the methodological envelope of science attitude research are studies like that reported by Perrier and Nsengiyumva (2003). Basing their work on trauma recovery therapy, these researchers used data gleaned from photographs and the contents of personal diaries to construct a vivid description of the influence of inquiry-based science activities on the attitudes of orphans in war-ravaged Rwanda.

Attitude Instruments

The self-report instruments used in much of the research address one or more dimensions of attitude. An example of a unidimensional instrument is the *Attitude Toward Science Scale* (Francis & Greer, 1999), which has only 20 items and purports to measure secondary students' attitude toward science. A second example is the *Changes in Attitudes about the Relevance of Scienc*e questionnaire (Siegel & Ranney, 2003), which includes three equally balanced versions to overcome problems associated with assessing students' attitudes over multiple intervals. In comparison, the scale developed by Pell and Jarvis (2001) includes subscales that measure the five dimensions of *liking science*, *independent investigator*, *science enthusiasm*, *the social context of science*, and *science as a difficult subject*. Excluding instrument development influenced by the theoretical work of Ajzen and Fishbein (1980), science attitude instruments typically address the evaluative or affective component of attitude and do not distinguish among the cognitive, affective, and conative components that constitute the attitude trilogy. Some of these instruments (e.g., West, Hailes, & Sammons, 1997) that have been designed for young children make use of smiley faces rather than words, in an effort to better capture the children's expressions of attitude. We present summary data for a sampling of recently developed attitude instruments in Table 4.1.

Instrument reliability and validity are important qualities of attitude scales. Content analysis, exploratory factor analyses, item analyses, correlations between subscales, correlations between attitude scale scores and the number of science-related subjects studied, and student interviews are among the tests and procedures used by researchers to explain the reliability and validity of their instruments (Francis & Greer, 1999; Pell & Jarvis, 2001; Siegel & Ranney, 2003). It is recognized that attitude scale construction is a multistep process that may take more than a year to complete (Bennett, Rollnick, Green, & White, 2001). In addition, instrument reliability and validity need to be reestablished when an instrument is modified or used with a population that is different from the one for which it was originally developed. Unfortunately, attitude instruments are sometimes selected for use without adequate attention to reliability and validity (e.g., Terry & Baird, 1997).

There are two limitations commonly associated with science attitude scales: (a) the limited amount of information yielded about the respondents' attitudes and (b) the inclusion of items generated by researchers who do not share the mindset of the respondents (Pilburn & Baker, 1993). These limitations have been addressed in several ways by science education researchers. One strategy involves scale

TABLE 4.1.
Summary Data for Sample Attitude Instruments

Developers and instrument focus	*Instrument format*	*Sample items*
Thompson and Mintzes's (2002) Shark Attitude Inventory measures the attitudes toward sharks of fifth-grade students through senior citizens.	Five-point Likert scale, with response options ranging from *strongly agree* to *strongly disagree* across four subscales.	I would like to touch a shark. Sharks should not be protected if protecting them makes shark fishermen lose money.
Francis and Greer (1999) developed an instrument to measure secondary school students' attitudes towards science.	A 20-item unidimensional instrument arranged for scoring on a 3-point Likert scale, with *not certain* as the midpoint response.	Science has ruined the environment. Studying science gives me great pleasure.
Pell and Jarvis's (2001) instrument assesses the attitudes to science of 5- to 11-year-old children.	Five-point "smiley" face Likert scoring scheme across five attitude subscales that include only positively worded items.	How do you feel about . . . Doing science experiments. Watching the teacher do an experiment.
Bennett, Rollnick, Green, and White's (2001) instrument measures university students' attitudes toward the study of chemistry.	Patterned after Aikenhead and Ryan's VOSTS, the multiple-choice items include response options that combine evaluation and explanation.	I like it when the lecturer gives us small tasks to do in lecture. A. I AGREE with this statement because it improves my understanding. E. I DISAGREE with this statement because it increases the noise and wastes time. X. None of the above statements reflect my view, which is . . .
The Parkinson, Hendley, Tanner, and Stable (1998) questionnaire was developed to assess the attitudes toward science of age 13 pupils in England and Wales.	Statements generated by pupils were selected for inclusion on the 34-item scale. Scoring is based on a 4-point Likert scale.	I like doing experiments in science lessons. More time should be spent on science at school.
Siegel and Ranney's (2003) Changes in Attitude about the Relevance of Science (CARS) questionnaire was designed for use with adolescents.	Three versions for repeated measures were developed. Scoring for each 20-item version is based on a 5-point Likert scale with an additional *don't understand* response option.	Science helps me to make sensible decisions. The things I do in science have nothing to do with the real world.

construction in which researchers solicit input from a sample of respondents. Crawley and Koballa (1992) questioned a representative sample of Hispanic-American students and used the students' responses to construct a scale to assess attitudes toward chemistry enrollment. Along similar lines, Bennett et al. (2001) and Ellis, Killip, and Bennett (2000) solicited student input in developing multiple-choice attitude scale items. Guided by work on the *Views on Science-Technology-Society* instrument (Aikenhead & Ryan, 1992), they used data from students to construct four or more statements for each scale item that are expressions of agreement or disagreement with the item and reasons for agreeing or disagreeing. For example, for the scale item *Scientists do a wide variety of jobs*, sample statements are: "I AGREE because they do jobs ranging from designing new medicines to being astronauts," and "I DISAGREE because scientists tend to concentrate on one thing" (Ellis et al., 2000, p. 25).

Drawing

Finson (2002) reviewed efforts since 1957 to use drawings to gather information about one aspect of students' attitudes toward science, perceptions of scientists. The image that school students hold of scientists tends to be stereotypical and rather negative, with scientists most often depicted as men with unkempt hair, wearing glasses and white lab coats, and working alone in laboratories. He concluded that Chamber's *Draw-a-Scientist Test* and the more recently developed *Draw-a-Scientist Checklist* are reliable and valid instruments for gathering data about students' perceptions of scientists and recommends that interviewing students about their drawings can enhance researchers' interpretations of students' perceptions. Finson also cautioned researchers about assuming that a student's drawing provides the definitive image of his or her perception of a scientist because students may hold multiple images of scientists that differ depending on context and recent exposure.

Interview

Other researchers have turned to student interviews as a way to overcome the limitations associated with attitude scales and to augment the data provided by the scales. In an effort to determine more about the meaning associated with students' images of scientists, Palmer (1997) interviewed upper elementary and high school students about their understandings of scientists and their work in an environmental context. From an analysis of 125 interviews, he concluded that students hold both private perceptions and stereotyped images of scientists and their work. The findings of Palmer's study suggest that drawings may not encourage students to express the full range of their perceptions about scientists. Pilburn and Baker (1993) also interviewed students with the use of a semi-structured protocol and employed a qualitative data analysis approach to gauge students' attitudes. Students were questioned about their attitudes toward science and school, academic and career goals, and what improvements they would make to science class if they were the teacher. By changing the wording of questions to suit the age of their student participants and following initial student responses with additional probing questions, Pilburn and Baker gathered attitude data from students in kindergarten through grade 12. They concluded from their work that student interviews provide useful information about students' attitudes toward science.

Attitudes and What Influences Them

Despite the limitations associated with attitude scales and other techniques used to gather attitudinal data, what they reveal provides valuable insight into students' science attitudes. A number of studies reported that although children at the primary level hold positive feelings about science, attitude scores decline as students progress through the grades (George, 2000; Jurd, 2001; Osborne et al., 1998; Reid & Skryabina, 2002). This decline, which is particularly evident in the middle school and high school years, is likely related in some way to the types of science courses in which the students are enrolled and the science self-concept that they develop as a result of these courses (George, 2000). However, it is also possible that the decline is a result of students' inability to separate their attitudes toward science from their attitudes toward school. Morrell and Lederman's (1998) investigation of the relationship between students' attitudes toward school and attitudes toward classroom science revealed a weak relationship between the two attitudes. Their findings led them to conclude that students' less-than-favorable attitudes toward science are not part of a bigger school-related attitude problem and that attitudes toward science could not be improved by addressing students' attitudes toward school. Also, in contrast to the findings of the other studies previously discussed, Morrell and Lederman found no evidence of declining attitudes toward science for older students.

Gender

Despite more than two decades of attention to issues of gender equity in science education, differences between girls and boys still persist regarding attitudes toward science. The findings of several recent studies indicate that the differences develop during the elementary school years (Andre, Whigham, Hendrickson, & Chambers, 1999; Jones, Howe, & Rua, 2000). Consistent with previous findings (e.g., Weinburgh, 1995), these studies report that girls tend to have less favorable attitudes toward science than boys, and that girls' science-related interests are more focused on the biological than physical sciences. Dawson (2000) reported similar trends in a study of primary-age boys and girls in Australia and concluded that little has changed in two decades. In contrast, Andre et al. (1999) found no differences between girls and boys in their liking of life science or physical science. However, their comparison of students' preferences for school subjects revealed that, in the elementary grades, girls prefer reading and language arts over physical science. Their findings led them to speculate that the attitudinal differences often detected between boys and girls are not a result of girls liking physical science less than boys, but their liking reading more.

Differences between boys and girls also extend to the stereotypic images that they hold of science and scientists. Boys and girls view science as a male-dominated school subject and consider science to be a male profession (Andre et al., 1999). Students in Taiwan, as is the case in other countries, are influenced by the stereotypic images of science and scientists that are often depicted in the popular media. However, the impact of these stereotypes on students' interest in a science career seems to decline as students advance in school, with girls more so than boys open to the idea of women working as scientists (She, 1998). One possible interpretation of this finding is that students hold both private perceptions of scientists and their work in addition to the public stereotypes (Palmer, 1997).

Explanations for these gender differences include both physiological and sociological functions. More credence is given to sociological factors, as indicated by the widespread support for broad-based intervention programs such as EQUALS and *Family Science* that target the science attitudes and experiences of girls. The most frequently given sociological reasons for why girls have less positive attitudes toward science than do boys include the differential cultural expectations placed on girls and boys by parents, teachers, and peers, and the different experiences in science, both in school and out of it, provided to boys and girls (Jones et al., 2000; She, 1998).

Achievement and Science-Related Decisions

A study of Australian students using data collected as part of the Third International Mathematics and Science Study (TIMSS) revealed that attitudes toward science have a strong effect on achievement (Webster & Fisher, 2000). Attitudes were found not to predict physics achievement (Willson, Ackerman, & Malave, 2000) and to be related directly to the science achievement of American students (Singh, Granville, & Dika, 2002). The narrow interpretation of attitude applied in many studies might explain the weak relationships found between attitude and achievement (Rennie & Punch, 1991), as might the narrow definitions of achievement. Research in this area still tends to corroborate Fraser's (1982) position that improving science attitudes will not necessarily lead to science achievement gains.

The influence of attitudes on students' decisions such as enrolling in elective science courses and pursuing careers in science was also examined in recent studies. The attractiveness of careers in science and higher education courses, the relevance of courses for future study and careers, self-confidence in science, and science interests are among the factors found to influence students' science course-taking and career decisions (Robertson, 2000; Woolnough & Guo, 1997). Based on a review of earlier studies that produced similar findings, Shrigley (1990) concluded that only under certain conditions should attitudes be expected to predict learners' science-related decisions. These conditions include: (a) when attitude and the decision are measured at the same level of specificity; (b) when social context and individual differences, including cognitive ones, are considered; and (c) when the person's intentions regarding the decision are known. Each of Shrigley's conditions was addressed in Butler's (1999) study, in which he sought to identify the determinants of students' intentions to perform both laboratory and non-laboratory science learning tasks in grades 4 through 8. Butler found that the students' attitudes toward the behavior were better predictors of their intentions to perform both laboratory and non-laboratory science learning tasks than either attitudes toward science or subjective norm, the element of Ajzen and Fishbein's (1980) model that measures social support for engaging in the behavior. A limitation of Butler's study was that the students' actual behaviors were not observed.

Attitude Change Interventions

Activity-based practical work (Thompson & Soyibo, 2002), learning cycle classes (Cavallo & Laubach, 2001), formally teaching ethical issues (Choi & Cho, 2002), jigsaw cooperative learning groups (De Baz, 2001), student- and teacher-constructed self-teaching resources (McManus, Dunn, & Denig, 2003), video technologies (Escalada & Zollman, 1998; Harwood & McMahon, 1997), inquiry-based summer camps (Gibson & Chase, 2002), and computer-assisted instruction (Soyibo & Hudson, 2000) are among the attitude change interventions evaluated in recent years. Other interventions targeted the attitudes toward sciences of girls and minorities and their continuation in the science pipeline. These included after-school science programs and residential summer science camps as well as year-long science courses that emphasize hands-on and performance-based learning experiences (Ferreira, 2002; Freedman, 2002; Haussler & Hoffmann, 2002; Jayaratne, Thomas, & Trautmann, 2003; Jovanovic & Dreves, 1998; Phillips, Barrow, & Chandrasekhar, 2002).

Overall, the interventions were well planned and quite complex and incorporated a host of activities believed to enhance attitudes toward science and commitment to the study of science. The results of these studies point to the success of some interventions, particularly those that engage learners in hands-on science activities and that stress the relevance of science through issue-based experiences (e.g., Haussler & Hoffman, 2002; Perrier & Nsengiyumva, 2003; Siegel & Ranney, 2003).

MOTIVATION

As we turn to a discussion of the role of motivation in learning science, it is important to recognize that attitudes influence motivation, which in turn influences learning, and ultimately behavior. This sequence is relevant to investigating learning in many science contexts, although the relationships among these variables can be more complex and interactive than this basic sequence suggests.

It is also important to recognize that motivation has not been manipulated or assessed as frequently as attitudes by science education researchers, although historically science education research on learning has been significantly influenced by the theoretical orientations that researchers have adopted toward motivation. As science education researchers respond to current national initiatives to foster students' science achievement, the emphasis placed on motivation has been increasing, as reflected in recent articles with titles such as "Skill and will: The role of motivation and cognition in the learning of college chemistry" (Zusho & Pintrich, 2003, p. 1081). Ten years ago, in the *Handbook of Research on Science Teaching and Learning* (Gabel, 1994), the word *attitude* appeared in more than 45 subject index listings and sub-listings, whereas the word *motivation* appeared only three times. The inclusion of *motivation* in the present *Handbook* in a chapter with attitudes attests to greater value being placed on the role that motivation plays in science learning.

A discussion of motivation should begin with a definition. Motivation is an internal state that arouses, directs, and sustains students' behavior. The study of motivation by science education researchers attempts to explain why students strive for particular goals when learning science, how intensively they strive, how long they strive, and what feelings and emotions characterize them in this process.

In this section, we discuss the research orientations and constructs that play important roles in learning science. One feature of motivation research has been the creation of many motivational constructs. Unfortunately, the constructs are often unclear in their definitions and functions, as Schunk (2000) observed:

> The field of motivation is beset with a lack of clear definition of motivational constructs and specification of their operation within larger theoretical frameworks. These problems have implications for interpretation of research results and applications to practice. . . . At times educational researchers—perhaps unwittingly—have behaved like Humpty Dumpty by renaming or defining motivational constructs to fit their theoretical models and research methodologies with insufficient attention paid to extant conceptualizations. (p. 116)

Our goal is to provide an overview of current motivation research in learning science that stresses the most widely accepted and empirically supported findings about student motivation. Cognizant of the conceptual clarity issue raised by Schunk and others (e.g., Pintrich, 2003), we have endeavored to describe, in as straightforward a fashion as possible, the orientations and constructs that are of particular relevance to science education researchers. The broad theoretical orientations that researchers adopt, either explicitly or implicitly, influence the assumptions they make about the more specific constructs they study. This point is important because researchers with different theoretical orientations often study the same constructs. They may even define them similarly but interpret them differently.

Historical Background and Theoretical Orientations

Historically, science education researchers have adopted four orientations to motivation when studying learning. We refer to these orientations as *behavioral*, *humanistic*, *cognitive*, and *social*. Although these orientations are described separately, it should be kept in mind that many science education researchers adopt aspects of more than one orientation when studying learning, with hybrids resulting, such as a *cognitive-social* orientation (Pintrich, 2003). In addition, the orientations researchers adopt often are determined by the particular topic they are studying.

Science education researchers with a behavioral orientation to motivation focus on concepts such as *incentive* and *reinforcement.* An incentive is something that makes a behavior more or less likely to occur. For example, the promise of a field trip to a quarry to study rock strata could serve as an incentive for students to perform well on a geology test. Participation in the trip itself could be the reinforcement.

Researchers have identified potential problems associated with the use of incentives and reinforcements to shape behavior in a science classroom. One major problem is that the students may not develop *intrinsic motivation* to learn. In some conditions, when students are offered incentives for doing tasks they naturally find motivating, their desire to perform the tasks can decrease (Cameron & Pierce, 2002; Deci, Koestner, & Ryan, 1999). External incentives also can focus students' attention on the incentives as ends in themselves, rather than serve as a kind of feedback on the progress students are making.

Science education researchers with a humanistic orientation to motivation emphasize students' capacity for personal growth, their freedom to choose their destiny, and their desire to achieve and excel. Humanists have used various constructs to express students' need to reach their potential. Maslow (1968, 1970) described this need as *self-actualization*. Maslow proposed that everyone has a hierarchy of needs: physiological, safety, love and belongingness, esteem, intellectual achievement, aesthetic appreciation, and self-actualization. When basic needs are satisfied, the motivation to fulfill them decreases and the motivation to fulfill the higher-level ones increases. Building upon Maslow's theory, humanists currently investigate students' *actualizing tendency* (Rogers & Freiberg, 1994) and *self-determination* (Deci, Vallerand, Pelletier, & Ryan, 1991).

When science education researchers adopt a cognitive orientation to motivation, they emphasize students' goals, plans, expectations, and attributions (Glynn & Duit, 1995; Glynn, Yeany, & Britton, 1991; Schunk, 1996). An *attribution* is an explanation for the cause of a particular behavior (Weiner, 1986, 1990, 1992). When students respond to instructional events, they are viewed as responding to their attributions about these events. For example, students' motivation to achieve in a particular college biology class could be undermined by the students' attribution (true or false) that all students are receiving high grades because the instructor's grading criteria are lax.

Science education researchers with a social orientation to motivation emphasize students' identities and their interpersonal relationships in the communities that exist inside and outside of school. Students' identities are formed in their communities, and a great deal of science can be learned, both intentionally and incidentally, in them. To maintain their membership in their communities, students are motivated to learn the attitudes, values, and behaviors of those communities (Lave & Wenger, 1991). The process of *modeling* is central to the learning that takes place in those communities (Greeno, Collins, & Resnick, 1996). Science classrooms, museums, nature centers, aquariums, and even websites are being conceptualized as *learning* communities. One template for conceptualizing a science-learning community was developed by Scardamalia and Bereiter (1996), who used a computer system called *Computer-Supported Intentional Learning Environment* (CSILE) to prompt students to collaborate by posing questions and hypotheses and discussing findings. Brown and Campione (1996) developed another template that made innovative science research projects central to a classroom community.

Motivational Constructs

According to Brophy (1987), *motivation to learn* is "a student tendency to find academic activities meaningful and worthwhile and to try to derive the intended academic benefits from them" (pp. 205–206). What motivates students to learn science? We answered this question by closely examining the disparate body of research that Schunk (2000) alluded to, integrating the findings, and identifying relevant methods and instruments for the constructs. We noted that the constructs of *arousal*, *anxiety*, *interest*, and *curiosity* all have been found to play important roles, particularly in the creation of *intrinsic motivation*. We also noted that the extent to which science students are intrinsically motivated was found to be influenced by how *self-determined* they are, by their *goal-directed behavior*, by their *self-regulation*, by their *self-efficacy*, and by the *expectations* that teachers have of them.

Arousal and Anxiety

Arousal, defined as a student's level of alertness and activation (Anderson, 1990), plays an important role in initiating and regulating motivation. Arousal is a state of physical and psychological readiness for action. Too little arousal in students leads to inactivity, boredom, daydreaming, and even sleeping, and too much of it leads to *anxiety*, defined as a "general uneasiness, a sense of foreboding, a feeling of tension" (Hansen, 1977, p. 91). All students experience anxiety from time to time. Some anxiety is good in that it helps motivate science learning. Too little, however, debilitates performance, and so does too much (Cassady & Johnson, 2002).

Most researchers conceptualize anxiety as both a *state*, temporarily associated with a situation such as a science test, and a *trait*, enduringly associated with the individual. As measured by the *State-Trait Anxiety Inventory* (Spielberger, 1983), state anxiety is defined as an unpleasant emotional arousal in response to situations that are perceived as threatening. Trait anxiety, on the other hand, implies the existence of stable individual differences in the tendency to respond with state anxiety in the anticipation of threatening situations.

Interest and Curiosity

The terms *interest* and *curiosity* are often used interchangeably in the science education literature. A student who is interested or curious about a science topic has a readiness to pursue it. A student's interest in a science topic or activity is "specific, develops over time, is relatively stable, and is associated with personal significance, positive emotions, high value, and increased knowledge" (Wade, 2001, p. 245). This particular kind of interest is known as *individual* or *personal*; it should be distinguished from *situational* interest that is evoked by things in the environment that create a momentary interest. When students do poorly in science and other areas, what is the most common reason? "Lack of interest" was rated highest by more than 200 middle school students studied by Vispoel and Austin (1995). In some cases, ratings of low interest can be ego-protective—students wish to attribute their poor performance to an external, uncontrollable variable. When students do well, what is the reason? Vispoel and Austin found that middle school students rated effort highest, but interest next highest, in explaining successes. These findings indicate that students perceive interest to be a very important factor in their achievement.

According to Pintrich and Schunk (1996), interest or curiosity is "elicited by activities that present students with information or ideas that are discrepant from their present knowledge or beliefs and that appear surprising or incongruous" (p. 277). This does not mean, however, that the more discrepant the better. Researchers have found that students are most interested in science concepts and phenomena that are moderately novel to them and moderately complex (Berlyne, 1966). When students are very familiar with something, they may ignore it, and when they are unfamiliar with something, particularly if it is complex, they may not find it relevant or meaningful.

One of the most effective means of making science concepts relevant and meaningful to students is the use of analogies during instruction (Glynn & Takahashi, 1998). For example, Paris and Glynn (2004) found that elaborate analogies increased students' interest in the concepts covered in science texts, as well as their understanding of those concepts. This finding suggests that elaborate analogies can play an important role in strategically regulating students' motivation. The analogies likely do this by establishing in students a sense of self-relevancy, or personal involvement. In the Paris and Glynn study, most of the students indicated that a text with analogies was interesting because it compared an abstract science concept to something more familiar to them. A typical comment was: "I know about photography, so it was more interesting when the eye was compared to a camera."

Intrinsic and Extrinsic Motivation

Motivation to perform an activity for its own sake is intrinsic, whereas motivation to perform it as a means to an end is extrinsic (Pintrich & Schunk, 1996). Intrinsic motivation derives from arousal, interest, and curiosity. Intrinsic motivation taps into the natural human tendency to pursue interests and exercise capabilities (Deci, 1996; Reeve, 1996; Ryan & Deci, 2000). Typically, students who are intrinsically motivated to learn a science concept do not require physical rewards, because the process itself is inherently motivating. On the other hand, when students learn concepts only to earn grades or avoid detention, their motivation is primarily external (Mazlo et al., 2002). Students who are intrinsically motivated to perform a task often experience *flow*, a feeling of enjoyment that occurs when they have developed a sense of mastery and are concentrating intensely on the task at hand (Csikszentmihalyi, 2000). For example, *flow* describes the preoccupation that some students develop with a science fair project to the exclusion of other activities in their lives.

The distinction between intrinsic and extrinsic motivation is difficult to make in some instances. When studying motivational patterns in sixth-grade science classrooms, Lee and Brophy (1996) found it useful to distinguish among students' motives in multiple ways. Students are often motivated to perform tasks for both intrinsic and extrinsic reasons. The student who constructs the science fair project may enjoy the process, particularly because the student selected the topic, but may also be motivated by the prospect of receiving a prize, an award ribbon, or entry into a higher-level science fair.

Self-Determination

Self-determination is the ability to have choices and some degree of control in what we do and how we do it (Deci et al., 1991; Reeve, Hamm, & Nix, 2003). Most people strive to be in charge of their own behavior—to be captains of their own ships. Most people are unhappy when they feel they have lost control, either to another person or to the environment. Deci (1996), in his theory of self-determination, suggested that students in particular need to feel competent and independent. He explained that intrinsically motivated activities promote feelings of competence and independence, whereas extrinsically motivated activities can undermine these feelings. Deci has found that students with self-determined motivation are more likely to achieve at a high level and to be well adjusted emotionally.

When science students have the opportunity to help design their educational activities, they are more likely to benefit from them. According to Garner (1998), "It is through this self determination, measured though it might be, that wise teachers allow each of their students to guide them to what the students find particularly enjoyable and worth learning" (p. 236). This advice is based on studies such as that by Rainey (1965), who found that high school science students who were allowed to organize their own experiments exhibited greater interest and diligence than students who were required to follow rote directions.

When students lack self-determination, it is difficult for them to feel intrinsically motivated. When they come to believe that their performance in science is mostly uncontrollable, they have developed a failure syndrome or *learned helplessness* (Seligman, 1975). Students who develop learned helplessness are reluctant to engage in science learning. They believe they will fail, so they do not even try. Because they believe they will fail, these students do not practice and improve their science skills and abilities, so they develop cognitive deficiencies. Students with learned helplessness also have emotional problems such as depression and anxiety.

Goal-Directed Behavior

A science objective or outcome that students pursue is a *goal*, and the process of pursuing it is referred to as *goal-directed behavior*, an important component of *goal theory* (Pintrich & Schunk, 1996). Goal theory builds upon an earlier *expectancy-value theory of achievement motivation* (Atkinson & Raynor, 1978), which posited that behavior is determined by how much students value a particular goal and their expectation of attaining that goal as a result of performing certain behaviors. When students endeavor to identify a substance as the objective of a chemistry lab, they are engaged in goal-directed behavior. Researchers have found that the very act of setting a goal is beneficial to students because it helps them to focus their attention, organize their efforts, persist longer, and develop new strategies (Covington, 2000; Linnenbrink & Pintrich, 2002; Locke & Latham, 1990, 2002; Midgley, Kaplan, & Middleton, 2001; Wentzel, 2000). In classrooms where students and teachers share the goals of student understanding and independent thinking, rather than the memorization and rote recall of science facts, students have higher motivation to learn (Glynn, Muth, & Britton, 1990; Nolen, 2003; Nolen & Haladyna, 1990). Recognizing this, Nicholls (1992) recommends that students be viewed as educational theorists who actively interpret and influence the classroom environment.

Science education researchers often distinguish between *learning goals* (also known as *mastery* goals or *task* goals) and *performance goals* (also known as *ego* goals). Students with learning goals focus on the challenge and mastery of a science task (Meece, Blumenfeld, & Hoyle, 1988). They are not concerned about how many mistakes they make or how they appear to others. These students are primarily interested in mastering the task and task-related strategies. They view mistakes as learning opportunities and do not hesitate to ask others for feedback and help. They are not afraid of failing, because failing does not threaten their sense of self-esteem. As a result, they set reasonably challenging goals, they take risks, and they respond to failure appropriately. When they succeed, they generally attribute it to their own effort. They assume responsibility for learning. They generally perform well in competitive situations, learn fast, and exhibit self-confidence and enthusiasm. They want to acquire mastery, often in an apprenticeship relationship. Students with learning goals are more likely to trust their teachers and adopt the goals set by their teachers as their own. They are also likely to work harder.

Meece et al. (1988) found that students with learning goals were more actively involved in science activities than students with performance goals because the latter were preoccupied with gaining social status, pleasing teachers, and avoiding extra work. Students with performance goals frequently compare their grades with others and choose tasks that are easy for them so they can maximize their grade. They work hard only on graded tasks and are often reluctant to help others achieve (Stipek, 1996). Their self-esteem is based on the external evaluation of their performance, so their esteem can be as fleeting as their last grade on a biology test. They take very few risks and restrict themselves to those skills with which they are most comfortable. If they do not receive positive external evaluations, they often develop ego-protective mechanisms such as procrastination or apathy.

In a study that examined more than 200 middle school students' motivation goals, Meece and Jones (1994) found students tended to feel greater confidence and mastery when science lessons were taught in small groups rather than in large ones. They also found that boys reported greater confidence in their science abilities than girls. More recent studies with middle school and high school students (Britner & Pajares, 2002; DeBacker & Nelson, 1999; Stake & Mares, 2001) suggest that the confidence of girls relative to that of boys is influenced by how science is being taught.

Self-Regulation

Goal setting is an important aspect of *self-regulated learning* (Schunk & Zimmerman, 1997). Students who are self-regulating know what they want to accomplish when they learn science—they bring appropriate strategies to bear and continually monitor their progress toward their goals. According to Neber and Schommer-Aikins (2002), self-regulated learning can be thought of as a cognitive activity consisting of two components, regulatory strategy use (for planning and monitoring) and cognitive strategy use (for organizing and elaborating). These components are often measured by subscales of the *Motivated Learning Strategies Questionnaire* (Pintrich & DeGroot, 1990), with items such as *In class, I ask myself questions to make sure I know what I have been studying* and *When I am studying a topic, I try to make the material fit together*.

Students' perceptions of *control* are relevant to their self-regulation and motivation to learn science. When students feel they are in control of their learning, they select more challenging tasks, they expend more effort, and they work longer on assignments (Anderman & Young, 1994; Schunk, 1996; Weiner, 1992). Students who feel they are in control are more likely to pick themselves up when they fail, attributing their failure to controllable, internal causes such as a lack of preparation. These students are adaptive and will adopt strategies to increase the likelihood of their success in the future. In contrast, students who typically feel that they are not in control of their learning focus increasingly on their own limitations and become apathetic about learning science.

Self-Efficacy

Before defining self-efficacy, it is easier to define what it is not. It is not self-concept, nor is it self-esteem (Bong & Clark, 1999). Self-concept is a more general construct that includes self-efficacy. Self-concept refers to global ideas about one's identity and one's role relations to others. According to Bong and Skaalvik (2003), "self-efficacy acts as an active precursor of self-concept development" and "self-concept is colloquially defined as a composite view of oneself" (pp. 1–2). Self-esteem is also a more general construct, and self-efficacy contributes to it. Self-esteem refers to the value one places on himself or herself. In contrast, self-efficacy is not a general personality trait or quality. It makes no sense to speak of a generally "self-efficacious" student.

Bandura (1997) defined self-efficacy as "beliefs in one's capabilities to organize and execute the courses of action required to produce given attainments" (p. 3). When science teachers use the term, they refer to the evaluation that a student makes about his or her personal competence to succeed in a field of science. For example, a student may have high self-efficacy with respect to knowledge and skills in biology, but low self-efficacy with respect to knowledge and skills in physics. In other words, self-efficacy is domain specific—and potentially task specific in a domain. Students' judgments of their self-efficacy in particular areas of science have been found to predict their performance in these areas. For example, Zusho and Pintrich (2003) found that students' self-efficacy was found to be the best predictor of grades in an introductory college chemistry course, even after controlling for prior achievement. Similarly, Joo, Bong, and Choi (2000) found that students' self-efficacy predicted their written test performance in a biology course. In their study, self-efficacy was assessed with questionnaire items similar to this one: "What grade (A through F) do you anticipate earning at the end of the term in biology?" Other questionnaires, such as the *Perceptions of Science Classes Survey* (Kardash & Wallace, 2001, p. 202), have been designed to assess self-efficacy for general science, with items such as "I have a good understanding of basic concepts in science." Given the domain-specific nature of self-efficacy, it may be that questionnaires that address a particular field of science will prove more useful than ones that address science in general.

According to Bandura (1997), a student's sense of self-efficacy is derived from sources such as mastery experiences, vicarious experiences, and social persuasion. Mastery experiences are students' actual experiences, and these have the greatest impact on their sense of efficacy in an area. Successes increase efficacy, and failures lower it. Vicarious experiences, according to Bandura, are those associated with the observation of others ("models") such as teachers, parents, peers, or characters in films (such as "Indiana Jones, archeologist"). The more that students identify with the model, the greater the model's influence on them. Social persuasion, particularly when it comes from a source that students respect, can also influence students and induce them to try harder in science. Social persuasion can reinforce students' self-efficacy in science when they have suffered a temporary setback.

Expectations and Strategies

The effect of teachers' expectations on student performance is called the *Pygmalion effect* (Rosenthal & Jacobson, 1968), named after a mythological king who created a statue and then made it come to life. Research findings on the Pygmalion effect have been mixed but generally support the view that the effect does occur and that teachers' expectations can influence student performance in science and other areas (Smith, Jussim, & Eccles, 1999). Science teachers' expectations of students, and the strategies based on these expectations, play an important role in increasing or reducing students' motivation. Researchers have found that teachers who have high expectations of students give cues and prompts that communicate to them their belief that the students can perform well (Good & Brophy, 1997; Rop, 2003). If teachers have high expectations of students, they are less likely to accept poor answers from them, and they are more likely to praise them for good answers. Teachers with low expectations of students are more likely to provide them with inconsistent feedback, sometimes praising inadequate answers, sometimes criticizing them, and sometimes ignoring them (Good & Brophy, 1997). Sometimes, if many teachers in a school adopt low expectations of the students there, a culture of low expectations can permeate the school (Weinstein, Madison, & Kuklinski, 1995).

RECOMMENDATIONS FOR FUTURE RESEARCH

The role of attitudes and motivation in learning science is a rich area for future research. As views of learning become increasingly constructivistic, it is more important than ever that researchers adopt a comprehensive view of learners that includes affective characteristics. The research reviewed in this chapter clearly shows that science learning cannot be explained solely by examination of cognitive factors. Learners' attitudes and motivation should be taken into account in explanations of science learning. Theoretical orientations and models describing meaningful relationships among affective constructs and cognition are becoming more evident in the research on science learning (Glynn & Koballa, 2007).

The research indicates that the principal means for assessing students' attitudes continues to be scales that produce quantitative scores. Instrument reliability and validity should be considered when one is choosing or modifying scales for use. We recommend that quantitative data gathered with the use of attitude scales be coupled with other forms of data, such as that collected via individual and group interviews, student drawings, log books, and photographs, to provide a more informed understanding of students' attitudes. Equally important, researchers should not be overly concerned with definitions of attitude and related constructs, but strive to seek common agreement for terms useful in their own studies. We found Teixeira dos Santos and Mortimer's (2003) use of personal posture, gesture, and voice intonation as evidence of emotion to be innovative and encourage further exploration of other physiological indicators of attitude. Building on this work, future research may include the examination of facial muscle patterns detectable through electromyographic recordings as evidence of learners' science-related attitudes (see Cacioppo & Petty, 1979).

Theoretical frameworks have not always guided attitude research in science education (Ramsden, 1998). Prominent in past research are the guiding frameworks of Hovland's learning theory approach and Fishbein and Ajzen's theories of reasoned action and planned behavior (Simpson et al., 1994). More recent attitude research has found theoretical grounding in Damasio's (1994) work on emotion and feeling and the psychotherapy of trauma recovery (Winnicott, 1970), which emphasizes the importance of play and community as elements of the learning process. These frameworks will provide guidance for continued research into the design of interventions to affect attitudes. In addition, psychologists' work on implicit attitudes (see Dovidio, Kawakami, & Beach, 2001) and the differentiated role of beliefs and attitudes in guiding behavior (called the mismatch model; see Millar & Tesser, 1992) may also contribute to the theoretical foundations for future attitude research in science education. It is clear from the research we have reviewed that diversity in theoretical orientation will lead to the use of more and different methodological approaches to investigate learners' science-related attitudes.

With respect to the role of motivation in learning science, a future direction for research is to investigate how different theoretical orientations and constructs relate to one another, rather than create new orientations and constructs simply to be innovative. *Synthesis* and *integration* should be the keywords of future motivational research in science learning (Pintrich, 2003). There is great need to clarify this area of research by examining the similar roles that orientations and constructs can play in fostering science learning (Glynn & Koballa, 2007).

We recommend that motivation researchers avoid simple categorizations such as high versus low anxiety, intrinsic versus extrinsic motivation, and learning versus performance goals. Instead, they should adopt broader perspectives that serve to synthesize orientations and constructs. For example, rather than conceptualize students as having either learning goals *or* performance, researchers should conceptualize students as having a variety of goals, depending upon the context, and endeavor to explain the relationship between students' goals and other motivational constructs such as self-determination and self-efficacy.

IMPLICATIONS FOR POLICY AND PRACTICE

Although there are certainly positive consequences of current federal initiatives designed to promote student achievement in science and other areas, there are negative ones as well. Because of an increased and often inappropriate emphasis on standardized testing, students are at increased risk of developing poor attitudes and low motivation in the area of science. Science education policy makers must come to understand that although high-stakes testing may serve to inspire some students to achieve at high levels, it serves as a deterrent to learning for many more. They are encouraged to adopt a view of learning in which "affect surrounds cognition," recognizing that "if children are not comfortable or joyful they will not learn, irrespective of how well pedagogical practices are designed" (Alsop & Watts, 2003, p. 1046). Acting from this informed view of science learning, policy makers should press state departments of education and local schools to specifically address affective elements of learning in their science curricula and associated assessment programs. Science learning experiences that are fun and personally fulfilling are likely to foster positive attitudes and heightened motivation toward science learning and lead to improved achievement. Attention to student attitudes and motivation in science curricula will prompt policy makers to become advocates for assessing affective outcomes of learning. Professional learning opportunities should be provided for teachers that will help prepare them to encourage unmotivated science students.

The research on science-related attitudes also has implications for professional practice. Teachers should consider strategies for improving students' attitudes as possible ways to increase enrollment in noncompulsory science courses and enhancing science achievement (Osborne, Simon, & Collins, 2003). Approaches to positively affecting student attitudes include instruction that emphasizes active learning and the relevance of science to daily life. When endeavoring to improve students' attitudes, teachers should consider their own cultural expectations. For example, teachers may unwittingly contribute to the persistent attitudinal differences between boys and girls. Teachers should recognize that students' enjoyment of science may be as important an outcome of school science in the long run as their scores on standardized tests.

Numerous instruments are available to assess the influence of instruction on students' science-related attitudes. When using an available measure, we recommend that teachers recognize that learners are not always willing and able to divulge their true feelings. We also encourage teachers to use interviews, photographs, and student drawings as alternatives to the use of scales and to supplement data gathered with the use of scales.

The research on motivational constructs also has many implications for practice in science education. Some of the most important of these involve the construct of self-determination, because science teachers wish to help students become independent, life-long learners. Science teachers can promote students' self-determination by providing them with appropriate challenges and feedback, by giving them leadership opportunities, by fostering students' relationships with peers and their parents, by creating a positive classroom environment, and by providing them with a role in classroom governance. The result will be greater student interest, sense of competence, creativity, learning, and preference for challenges (Matthews, 1991; Ryan & Grolnick, 1986; Williams, Wiener, Markakis, Reeve, & Deci, 1993).

Effective science teachers know students' self-determination leads to successful learning only when it is accompanied by high self-efficacy. If students have high self-efficacy in science, they will set higher goals, persist longer, expend greater effort, and endeavor to find increasingly better strategies. If students have low efficacy, they will tend to give up easily when science learning becomes difficult (Zimmerman, 2000). Students will increase their self-efficacy and improve their achievement if they adopt short-term goals to judge their progress, use specific learning strategies such as summarizing to help them focus their attention, and receive rewards based on their performance and not just their participation.

In conclusion, in this chapter we have examined the attitudinal and motivational constructs that influence science learning. We have reviewed the research conducted on these constructs, emphasizing the methods and instruments used, and the theoretical orientations in which the constructs are embedded. In addition, we have made specific recommendations for future research on these constructs and drawn implications for policy and practice.

We strongly encourage new and seasoned researchers to advance what is known about how attitudes influence motivation and how motivation influences science learning, and ultimately behavior. Ideally, all students of science should develop positive attitudes that motivate them to achieve at high levels. Their achievement should be reflected not only in their understanding of science and their development of scientific skills, but in their appreciation of the world around them. Ideally, students of science should learn to use their knowledge and skills to become caretakers of the world, preserving it and enhancing it for generations to come. We encourage science educators, who wish to help students achieve such goals, to embark on programs of research that focus upon how to best foster the growth of students' positive attitudes and their intrinsic motivation to learn science.

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CHAPTER 5

Classroom Learning Environments

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Because students spend approximately 20,000 hours in classrooms by the time that they graduate from university (Fraser, 2001), their reaction to their teaching-learning experiences are of considerable importance. However, despite the obvious importance of what goes on in school and university classrooms, teachers and researchers have relied heavily and sometimes exclusively on the assessment of academic achievement and other learning outcomes. Although no one would dispute the worth of achievement, it cannot give a complete picture of the educational process.

Although classroom environment is a subtle concept, it can be assessed and studied. A considerable amount of work has been undertaken in many countries in developing methods for investigating how teachers and students perceive the environments in which they work. Remarkable progress has been made over several decades in conceptualizing, assessing, and researching the classroom environment.

Researchers have carried out many dozens of studies of the relationship between student achievement and the quality of the classroom learning environment (Fraser, 1998a). These studies have been carried out in numerous different countries with tens of thousands of students. The consistent and overwhelming evidence from these studies is that the classroom environment strongly influences student outcomes. Therefore, teachers should not feel that it is a waste of time for them to devote time and energy to improving their classroom environments. The research shows that attention to the classroom environment is likely to pay off in terms of improving student outcomes.

A milestone in the historical development of the field of learning environments occurred over 30 years ago when Herbert Walberg and Rudolf Moos began seminal independent programs of research (Fraser, 1986; Fraser & Walberg, 1991; Moos, 1974). In turn, the pioneering work of Walberg and Moos built upon the ideas of Lewin (1936) and Murray (1938), presented several decades before. Lewin's field theory recognized that both the environment and its interaction with personal characteristics of the individual are potent determinants of human behavior. Lewin's formula, $B = f(P, E)$, stressed the need for new research strategies in which behavior is considered to be a function of the person and the environment.

Drawing on Murray's work, Stern (1970) formulated a theory of person-environment congruence in which complementary combinations of personal needs and environmental press enhance student outcomes. The Getzels and Thelen (1960) model for the class as a social system holds that, in school classes, personality needs, role expectations, and classroom climate interact to predict group behavior, including learning outcomes.

Psychosocial learning environment has been incorporated as one factor in a multifactor psychological model of educational productivity (Walberg, 1981). This theory, which is based on an economic model of agricultural, industrial, and national productivity, holds that learning is a multiplicative, diminishing-returns function of student age, ability, and motivation; of quality and quantity of instructions; and of the psychosocial environments of the home, the classroom, the peer group, and the mass media. Because the function is multiplicative, it can be argued in principle that any factor at a zero point will result in zero learning; thus either zero motivation or zero time for instruction will result in zero learning. Moreover, it will do less good to raise a factor that already is high than to improve a factor that currently is the main constraint to learning. Empirical probes of the educational productivity model were made by carrying out extensive research syntheses involving the correlations of learning with the factors in the model (Fraser, Walberg, Welch, & Hattie, 1987) and secondary analyses of large data bases collected as part of the National Assessment of Educational Progress (Walberg, Fraser, & Welch, 1986). Classroom and school environment was found to be a strong predictor of both achievement and attitudes even when a comprehensive set of other factors was held constant.

The field of learning environments has undergone remarkable growth, diversification, and internationalization during the past 30 years (Fraser, 1998a). A striking feature of this field is the availability of a variety of economical, valid, and widely applicable questionnaires that have been developed and used for assessing students' perceptions of classroom environment (Fraser, 1998b). Although learning environment research originated in Western countries, African (Fisher & Fraser, 2003) and especially Asian researchers (Fraser, 2002; Goh & Khine, 2002) have made many major and distinctive contributions in the last decade. For example, some of the main questionnaires that were developed in the West have been adapted (sometimes involving translation into another language) and cross-validated for use in numerous other countries.

This chapter provides access to past research on classroom learning environments and to instruments that have proved valid and useful in international contexts. The chapter begins by describing historically important learning environment questionnaires as well as contemporary instruments. In order to illustrate the application of learning environment assessments, another section is devoted to reviewing past research in six areas: (a) associations between student outcomes and environment; (b) evaluation of educational innovations; (c) differences between student and teacher perceptions of actual and preferred environment; (d) determinants of classroom environment; (e) use of qualitative research methods; and (f) cross-national studies. The chapter's concluding section provides a look forward to the next generation of learning environment research.

QUESTIONNAIRES FOR ASSESSING CLASSROOM ENVIRONMENT

Because few fields of educational research can boast the existence of such a rich array of validated and robust instruments, this section describes four contemporary instruments that have been used in both Western and non-Western countries: the Questionnaire on Teacher Interaction (QTI); the Science Laboratory Environment Inventory (SLEI); the Constructivist Learning Environment Survey (CLES); and the What Is Happening In this Class? (WIHIC) questionnaire. Before we discuss each of these instruments, some historically important questionnaires are briefly considered.

Historically Important Questionnaires

The Learning Environment Inventory (LEI) and Classroom Environment Scale (CES) were developed in the United States in the late 1960s. The initial development of the LEI began in conjunction with evaluation and research related to Harvard Project Physics (Walberg & Anderson, 1968). The CES (Moos & Trickett, 1987) grew out of a comprehensive program of research involving perceptual measures of a variety of human environments, including psychiatric hospitals, prisons, university residences, and work milieus (Moos, 1974).

The LEI was used in the Hindi language in a large study involving approximately 3,000 tenth-grade students in 83 science and 67 social studies classes (Walberg, Singh, & Rasher, 1977). Student perceptions on the LEI accounted for a significant increment in achievement variance beyond that attributable to general ability. In Indonesia, Paige (1979) used the CES and three scales selected from the LEI to reveal that individual modernity was enhanced in classrooms perceived as having greater task orientation, competition, and difficulty and less order and organization, whereas achievement was enhanced in classes higher in speed and lower in order and organization. Hirata and Sako (1998) used an instrument in the Japanese language that incorporated scales from the CES. Factor analysis of the responses of 635 students suggested a four-factor structure for this questionnaire (consisting of Teacher Control, Sense of Isolation, Order and Discipline, and Affiliation).

The My Class Inventory (MCI) is a simplified form of the LEI for use among children aged 8–12 years (Fisher & Fraser, 1981). In Singapore, Goh, Young, and Fraser (1995) changed the MCI's original Yes-No response format to a three-point response format (Seldom, Sometimes, and Most of the Time) in a modified version of the MCI that includes a Task Orientation scale. Goh et al. found the modified MCI to be valid and useful in research applications with 1,512 elementary-school students in 39 classes. In Brunei Darussalam, Majeed, Fraser, and Aldridge (2002) used the original version of the MCI with 1,565 middle-school students in 81 classes in 15 government secondary schools. When the Satisfaction scale was used as an attitudinal outcome variable instead of as a measure of classroom environment, Majeed et al. found strong support for a three-factor structure for the MCI consisting of three of the four *a priori* scales, namely, Cohesiveness, Difficulty, and Competitiveness.

Questionnaire on Teacher Interaction (QTI)

Research that originated in the Netherlands focused on the nature and quality of interpersonal relationships between teachers and students (Wubbels & Brekelmans, 1998; Wubbels & Levy, 1993). Drawing upon a theoretical model of proximity (co-operation-opposition) and influence (dominance-submission), the QTI was developed to assess student perceptions of the eight behavior aspects listed in Table 5.1. Research with the QTI has been completed at various grade levels in the United States (Wubbels & Levy) and Australia (Fisher, Henderson, & Fraser, 1995).

Goh pioneered the use of the QTI in a simplified form in Singapore with a sample of 1,512 elementary-school students in 13 schools (Goh & Fraser, 1996, 1998,

TABLE 5.1
Scale Names, Response Alternatives, and Sample Items for Four Commonly-Used Classroom Environment Instruments

Instrument	*Scale names*	*Response alternatives*	*Sample items*
Questionnaire on Teacher Interaction (QTI)	Leadership Helping/Friendly Understanding Student Responsibility/ Freedom Uncertain Dissatisfied Admonishing Strict Behaviour	Five point (Never-Always)	"She/he gives us a lot of free time." (Student Responsibility) "She/he gets angry." (Admonishing)
Science Laboratory Environment Inventory (SLEI)	Student Cohesiveness Open-Endedness Integration Rule Clarity Material Environment	Almost Never Seldom Sometimes Often Very Often	"I use the theory from my regular science class sessions during laboratory activities." (Integration) "We know the results that we are supposed to get before we commence a laboratory activity." (Open-Endedness)
Constructivist Learning Environments Survey (CLES)	Personal Relevance Uncertainty Critical Voice Shared Control Student Negotiation	Almost Never Seldom Sometimes Often Very Often	"I help the teacher to decide what activities I do." (Shared Control) "Other students ask me to explain my ideas." (Student Negotiation)
What Is Happening In this Class? (WIHIC)	Student Cohesiveness Teacher Support Involvement Investigation Task Orientation Cooperation Equity	Almost Never Seldom Sometimes Often Very Often	"I discuss ideas in class." (Involvement) "I work with other students on projects in this class." (Cooperation)

2000). This study cross-validated the QTI for use in a new country and found it to be useful in several research applications. Scott and Fisher (2004) translated the QTI into Standard Malay and cross-validated it with 3,104 elementary science students in 136 classes in Brunei Darussalam. An English version of the QTI was cross-validated for secondary schools in Brunei Darussalam for samples of 1188 science students (Khine & Fisher, 2002) and 644 chemistry students (Riah & Fraser, 1998). In Korea, Kim, Fisher, and Fraser (2000) validated a Korean-language version of the QTI among 543 Grade 8 students in 12 schools, and Lee and Fraser (2001a) provided further cross-validation information for the QTI with a sample of 440 Grade 10 and 11 science students. In Indonesia, Soerjaningsih, Fraser, and Aldridge (2001b) translated the QTI into the Indonesian language and cross-validated it with a sample of 422 university students in 12 classes. For example, Fisher, Fraser, and Rickards' (1997) study with a sample of 3,994 high school science and mathematics students revealed that the Cronbach alpha reliability ranged from 0.63 to 0.88 for different QTI scales at the student level of analysis.

Science Laboratory Environment Inventory (SLEI)

Because of the importance of laboratory settings in science education, an instrument specifically suited to assessing the environment of science laboratory classes at the senior high school or higher education levels was developed (Fraser, Giddings, & McRobbie, 1995; Fraser & McRobbie, 1995). The SLEI has the five seven-item scales in Table 5.1. The SLEI was field tested and validated simultaneously with a sample of 5,447 students in 269 classes in six different countries (United States, Canada, England, Israel, Australia, and Nigeria) and cross-validated with Australian students (Fisher, Henderson, & Fraser, 1997; Fraser & McRobbie). For example, based on a sample of 3,727 senior high school students from five countries, the Cronbach alpha reliability ranged from 0.70 to 0.83 for different scales when the student was used as the unit of analysis (Fraser et al., 1995).

The SLEI was further cross-validated and found to be useful in research involving both its original English form and translated versions. The validity of the English version of the SLEI was established in Singapore by A. F. L. Wong and Fraser's (1995, 1996) study of 1,592 Grade 10 chemistry students in 56 classes in 28 schools. Also, Riah and Fraser (1998) cross-validated the English version of the SLEI with 644 Grade 10 chemistry students in Brunei Darussalam.

A noteworthy program of research involving a Korean-language version of the SLEI was initiated by Kim and built upon by Lee (Kim & Kim, 1995, 1996; Kim & Lee, 1997; Lee & Fraser, 2001b; Lee, Fraser, & Fisher, 2003). For example, Lee and Fraser reported strong factorial validity for a Korean version of the SLEI and replicated several patterns from previous research in Western countries (e.g., low Open-Endedness scores and significant associations with students' attitudes).

Constructivist Learning Environment Survey (CLES)

The CLES (Taylor, Fraser, & Fisher, 1997) was developed to assist researchers and teachers to assess the degree to which a particular classroom's environment is consistent with a constructivist epistemology, and to help teachers to reflect on their epistemological assumptions and reshape their teaching practice. The CLES has 36 items, which fall into the five scales shown in Table 5.1.

In South Africa, Sebela, Fraser, and Aldridge (2003) cross-validated the CLES among 1,864 learners in 43 intermediate and senior classes, and they used it to provide feedback that successfully guided teachers in action research aimed at promoting constructivist teaching and learning. In Texas, Dryden and Fraser (1998) cross-validated the CLES among a sample of 1,600 students in 120 Grade 9–12 science classes, and they used it to evaluate the success of an urban systemic reform initiative aimed at promoting constructivist teaching and learning. Also in Texas, Nix, Fraser, and Ledbetter (2003) cross-validated the CLES among 1,079 students in 59 classes and used it to evaluate an integrated science learning environment that bridged traditionally separate classroom, field trip, and instructional technology milieus.

Kim, Fisher, and Fraser (1999) translated the CLES into the Korean language and administered it to 1,083 science students in 24 classes in 12 schools. The original five-factor structure was replicated for the Korean-language version of both an actual and a preferred form of the CLES. Similarly, Lee and Fraser (2001a) replicated the five-factor structure of a Korean-language version of the CLES among 440 Grade 10 and 11 science students in 13 classes. Furthermore, the CLES was translated into Chinese for use in Taiwan (Aldridge, Fraser, Taylor, & Chen, 2000). In this cross-national study, the original English version was administered to 1,081 science students in 50 classes in Australia, and the new Chinese version was administered to 1,879 science students in 50 classes in Taiwan. The same five-factor structure emerged for the CLES in the two countries. Scale reliabilities (Cronbach alpha coefficients) ranged from 0.87 to 0.97 for the Australian sample and from 0.79 to 0.98 for the Taiwanese sample, with the class mean as the unit of analysis.

What Is Happening In this Class? (WIHIC) Questionnaire

The WIHIC questionnaire combines modified versions of salient scales from a wide range of existing questionnaires with additional scales that accommodate contemporary educational concerns (e.g., equity and constructivism). The original 90-item nine-scale version was refined both by statistical analysis of data from 355 junior high school science students and by extensive interviewing of students about their views of their classroom environments in general, the wording and salience of individual items, and their questionnaire responses (Fraser, Fisher, & McRobbie, 1996). Analysis of data from an Australian sample of 1,081 students in 50 classes (Aldridge & Fraser, 2000) led to a final form of the WIHIC containing the seven eight-item scales in Table 5.1. The WIHIC items are listed in an article by Aldridge, Fraser, and Huang (1999).

Although the WIHIC is a relatively recent instrument, its adoption around the world has been frequent, and already it has been translated into several other languages and cross-validated:

1. Zandvliet and Fraser (2004) used the WIHIC among 81 classes of senior high school students in Canadian and Australian internet classes, whereas Lightburn and Fraser (2002) and Robinson and Fraser (2003) used the WIHIC in teacher-researcher studies in Florida.

2. An English version was cross-validated in Brunei Darussalam with samples of 644 Grade 10 chemistry students (Riah & Fraser, 1998) and 1,188 Form 5 science students (Khine & Fisher, 2001). In Singapore, Fraser and Chionh (2000) reported strong validity and reliability for both an actual and a preferred form of the WIHIC when it was responded to by a sample of 2,310 students in 75 senior high school classes.
3. A Chinese version of the WIHIC was developed for use in Taiwan and cross-validated with a sample of 1,879 junior high school students in 50 classes (Aldridge & Fraser, 2000; Aldridge et al., 1999).
4. The WIHIC was translated into the Korean language and validated with a sample of 543 Grade 8 students in 12 schools (Kim et al., 2000).
5. The WIHIC was translated into the Indonesian language and used with both high school and university students. The validity and usefulness of the WIHIC were established for samples of 594 high school students in 18 classes (Adolphe, Fraser, & Aldridge, 2003), 2,498 university students in 50 classes (Margianti, Fraser, & Aldridge, 2001a, 2001b), and 422 students in 12 classes (Soerjaningsih, Fraser, & Aldridge, 2001a).

Dorman (2003) used confirmatory factor analysis with data collected by administration of the WIHIC to 3980 high school students in Australia, Britain, and Canada. The *a priori* factor structure of the WIHIC was supported and was found to be invariant across country, grade level, and student gender. Alpha reliability coefficients for this sample ranged from 0.76 to 0.85 for different WIHIC scales at the student level of analysis.

The WIHIC has formed the foundation for the development of learning environment questionnaires that incorporate many of the WIHIC's dimensions, but encompass new dimensions that are of particular relevance to the specific study at hand. For example, in Canada, Raaflaub and Fraser (2002) used a modified version of the WIHIC in their investigation involving 1,173 science and mathematics students in 73 classrooms in which laptop computers were used. In Australia, Aldridge and Fraser (2003) added three new dimensions (Differentiation, Computer Usage, and Young Adult Ethos) to the WIHIC to form the Technology-Rich Outcomes-Focused Learning Environment Inventory (TROFLEI) in their study of 1,035 students in 80 classes in an innovative senior high school that provides a technology-rich and outcomes-focused learning environment. In South Africa, Seopa, Laugksch, Aldridge, and Fraser (2003) used the WIHIC as a basis for developing the Outcomes-Based Learning Environment Questionnaire (OBLEQ), which they used with 2,638 Grade 8 science students in 50 classes in 50 schools in Limpopo Province. In Texas, Sinclair and Fraser (2002) modified the WIHIC for use in a study aimed at changing classroom environments among a sample of 745 urban middle-school science students in 43 classes.

RESEARCH INVOLVING CLASSROOM ENVIRONMENT INSTRUMENTS

In order to illustrate some of the many and varied applications of classroom environment instruments in science education research, this section considers six types of past research which focused on: (a) associations between student outcomes and environment; (b) evaluation of educational innovations; (c) differences between student and teacher perceptions of actual and preferred environment; (d) determinants of classroom environment; (e) use of qualitative research methods; and (f) cross-national studies.

Associations between Student Outcomes and Environment

The strongest tradition in past classroom environment research has involved investigation of associations between students' cognitive and affective learning outcomes and their perceptions of psychosocial characteristics of their classrooms. Fraser's (1994) tabulation of 40 past studies in science education showed that associations between outcome measures and classroom environment perceptions have been replicated for a variety of cognitive and affective outcome measures, a variety of classroom environment instruments and a variety of samples (ranging across numerous countries and grade levels). For example, a meta-analysis encompassing 17,805 students from four nations revealed that student achievement was consistently higher in classes that were more organized, cohesive, and goal-directed and had less friction (Haertel, Walberg, & Haertel, 1981).

McRobbie and Fraser (1993) extended learning environment research to science laboratory class settings in an investigation of associations between student outcomes and classroom environment. The sample consisted of 1,594 senior high school chemistry students in 92 classes. The Science Laboratory Environment Inventory (SLEI) was used to assess Student Cohesiveness, Open-Endedness, Integration, Rule Clarity, and Material Environments in the laboratory class. Student outcomes encompassed two inquiry skills assessed with the Test of Enquiry Skills (TOES) (Fraser, 1979b) and four attitude measures based partly on the Test of Science Related Attitudes (TOSRA) (Fraser, 1981). Simple, multiple, and canonical analyses were conducted separately for two units of analysis (student scores and class means) and separately with and without control for general ability. Past research was replicated in that the nature of the science laboratory classroom environment accounted for appreciable proportions of the variance in both cognitive and affective outcomes beyond that attributable to general ability. Science educators wishing to enhance student outcomes in science laboratory settings are likely to find useful the result that both cognitive and attitude outcomes were enhanced in laboratory classes in which the laboratory activities were integrated with the work in non-laboratory classes.

Fraser (2002) noted that Asian researchers have undertaken a wide variety of valuable studies of associations between student outcomes and students' perceptions of their classroom learning environment. These studies also covered a wide range of environment instruments, student outcomes, school subjects, and grade levels. Whereas some studies involved English-language versions of questionnaires, other studies involved learning environment questionnaires translated into various Asian languages. These studies involved samples from Singapore (Goh & Fraser, 1998; Teh & Fraser, 1995; A. F. L. Wong & Fraser, 1996), Brunei (Majeed et al., 2002; Scott & Fisher, 2004), Korea (Kim et al., 1999, 2000; Lee et al., 2003), and Indonesia (Margianti et al., 2001a).

Many past learning environment studies have employed techniques such as multiple regression analysis, but few have used multilevel analysis (Bryk & Raudenbush, 1992), which takes cognizance of the hierarchical nature of classroom settings (i.e., students within intact classes are more homogeneous than a random sample of students). However, two studies in Singapore compared the results from multiple regression analysis with those from an analysis involving the hierarchical linear model. In a study by A. F. L. Wong, Young, and Fraser (1997) involving 1,592 Grade 10 students in 56 chemistry classes in Singapore, associations were investigated between three student attitude measures and a modified version of the SLEI. In Goh's study with 1,512 Grade 5 students in 39 classes in Singapore, scores on modified versions of the MCI and QTI were related to student achievement and attitudes. Most of the statistically significant results from the multiple regression analyses were replicated in the HLM analyses, as well as being consistent in direction (Goh & Fraser, 1998; Goh et al., 1995).

Some research into outcome-environment associations involved the use of more than one classroom environment questionnaire in the same study, so that commonality analysis could be used to ascertain the unique and joint contributions made by each questionnaire to the variance in student outcomes. In Singapore, Goh and Fraser (1998) used the MCI and QTI in a study involving the achievement and attitudes of 1,512 elementary-school students. The MCI and the QTI each uniquely accounted for an appreciable proportion of the variance in achievement, but not in attitudes. Much of the total variance in attitude scores was common to the two questionnaires. A conclusion from this study was that it is useful to include the MCI and QTI together in future studies of achievement, but not of attitudes. Similarly, when Korean-language versions of the SLEI, QTI, and CLES were used in a study of science students' attitudes in Korea, generally, each classroom environment instrument accounted for variance in student outcome measures independent of that accounted for by the other instrument (Lee & Fraser, 2001a, 2001b; Lee et al., 2003).

Evaluation of Educational Innovations

Classroom environment instruments can be used as a valuable source of process criteria in the evaluation of educational innovations. For example, in an early evaluation of the Australian Science Education Project (ASEP), ASEP students perceived their classrooms as being more satisfying and individualized and having a better material environment relative to a comparison group (Fraser, 1979a). In Singapore, Teh used his own classroom environment instrument as a source of dependent variables in evaluating computer-assisted learning (Fraser & Teh, 1994; Teh & Fraser, 1994). Compared with a control group, a group of students using micro-PROLOG-based computer-assisted learning had much higher scores for achievement (3.5 standard deviations), attitudes (1.4 standard deviations), and classroom environment (1.0–1.9 standard deviations).

Oh and Yager (2004) used the CLES with 136 Grade 11 earth science students involved in two longitudinal action research studies in Korea aimed at implementing constructivist instructional approaches. Not only was it found that students' perceptions on the CLES became more positive over time, but also that changes in the CLES scale of Personal Relevance were associated with improvements in student attitudes to science. In another study, the CLES was used among 70 Korean high school teachers who attended professional development programs at the University of Iowa to monitor changes in constructivist philosophies (Cho, Yager, Park, & Seo, 1997).

Classroom environment dimensions also have been used as criteria of effectiveness in evaluating the use of laptop computers in Canadian science and mathematics classrooms (Raaflaub & Fraser, 2002), a technology-rich and outcomes-focused school in Australia (Aldridge & Fraser, 2003), the use of anthropometric activities in science teaching in the United States (Lightburn & Fraser, 2002), and the success of outcomes-based education in South Africa (Aldridge, Laugksch, Fraser, & Seopa, 2005). For example, Aldridge and Fraser's (2003) longitudinal study revealed that, over time, the implementation of an outcomes-focused, technology-rich learning environment led to more positive student perceptions of Student Cohesiveness, Task Orientation, Investigation, Cooperation, and Young Adult Ethos, but less classroom Differentiation. Despite the potential value of evaluating educational innovations and new curricula in terms of their impact on transforming the classroom learning environment, only a relatively small number of such studies have been carried out around the world.

Differences between Student and Teacher Perceptions of Actual and Preferred Environment

An investigation of differences between students and teachers in their perceptions of the same actual classroom environment and of differences between the actual environment and that preferred by students or teachers was reported by Fisher and Fraser (1983). Students preferred a more positive classroom environment than was actually present for all five environment dimensions of Personalization, Participation, Independence, Investigation, and Differentiation. Also, teachers perceived a more positive classroom environment than did their students in the same classrooms on the four of the dimensions of Personalization, Participation, Investigation, and Differentiation. The pattern in which students prefer a more positive classroom learning environment than the one perceived as being currently present has been replicated with the use of the WIHIC and QTI among Singaporean high school students (Fraser & Chionh, 2000; A. F. L. Wong & Fraser, 1996) and the WIHIC among 2,498 university students in Indonesia (Margianti et al., 2001b).

Determinants of Classroom Environment

Classroom environment dimensions have been used as criterion variables in research aimed at identifying how the classroom environment varies with such factors as teacher personality, class size, grade level, subject matter, the nature of the school-level environment, and the type of school (Fraser, 1994). Hirata and Sako (1998) found differences between the classroom environment perceptions of at-risk students (delinquent and non-attendees) and normal students in Japan. In Brunei, Khine and Fisher (2002) reported cultural differences in students' classroom environment perceptions depending on whether the teacher was Asian or Western. In Korea, Lee and Fraser (2001a, 2001b) and Lee et al. (2003) reported the use of the SLEI, CLES, and QTI in the investigation of differences between streams (science-oriented, humanities-oriented) in the student-perceived learning environment. For the first four QTI scales, the clear pattern was that the humanities stream students had less favorable perceptions than did the other two streams. Science-oriented stream students perceived their classrooms more favorably than the humanities stream students did, but less favorably than the science-independent stream students did. Overall, cooperative behaviors were more frequently displayed in the science-independent stream than in the other two streams. In contrast, opposition behaviors were less frequently displayed in the science-independent streams than in the other two streams.

Undoubtedly, the determinant of classroom environment that has been most extensively researched is student gender. Generally within-class comparisons of students' perceptions reveal that females typically have more favorable views of their classroom learning environment than do males. These studies of gender differences have encompassed numerous countries, including Singapore (Fraser & Chionh, 2000; Goh & Fraser, 1998; Khoo & Fraser, 1998; Quek, Wong, & Fraser, 2005; A. F. L. Wong & Fraser, 1996), Brunei (Khine & Fisher, 2001, 2002; Riah & Fraser, 1998), Indonesia (Margianti et al., 2001a, 2001b), and Korea (Kim et al., 2000).

Use of Qualitative Research Methods

Significant progress has been made in using qualitative methods in learning environment research and in combining quantitative and qualitative methods within the same study of classroom environments (Fraser & Tobin, 1991; Tobin & Fraser, 1998). For example, Fraser's (1999) multilevel study of the learning environment incorporated a teacher-researcher perspective as well as the perspectives of six university-based researchers. The research commenced with an interpretive study of a Grade 10 teacher's classroom at a school, which provided a challenging learning environment in that many students were from working-class backgrounds, some were experiencing problems at home, and others spoke English as a second language. Qualitative methods included several of the researchers visiting this class each time that it met over five weeks, using student diaries, and interviewing the teacher-researcher, students, school administrators, and parents. A video camera recorded activities for later analysis. Field notes were written during and soon after each observation, and during team meetings that took place three times per week. The qualitative component of the study was complemented by a quantitative component involving the use of a classroom environment questionnaire.

The qualitative information helped the researchers to provide consistent and plausible accounts of the profile of this teacher's scores on a classroom environment instrument to which her students responded. For example, the high level of perceived Personal Relevance in this teacher's class was consistent with her practice of devoting one science period a week to things that were personally relevant to students. Relatively high scores on the Critical Voice scale were consistent with observations that this teacher encouraged students to voice their opinions and suggest alternatives (Tobin & Fraser, 1998).

One of the most salient aspects of the learning environment in this study was Teacher Support. This teacher's class perceived higher levels of Teacher Support than did students in other Grade 10 classes at this school. This teacher had several features in common with the types of students whom she was teaching. She had not been a motivated learner at school and knew that students' life histories often made it difficult for them to concentrate on learning as a high priority. She was aware that social problems afflicted many students, and she was determined to make a difference in their lives. Consequently, she planned to enact the curriculum to facilitate transformative goals. She had considerable empathy for her students, was concerned with their well-being as citizens, and perceived science as an opportunity to develop their life skills. Learning to be communicative and cooperative was a high-priority goal. Getting to know her students was a priority, and meeting them at the door seemed important because it permitted brief individual interactions with almost every student. For these reasons, it was quite plausible that Teacher Support scores were high (Tobin & Fraser, 1998).

Fraser (2002) noted that the use of quantitative methods has tended to dominate Asian research into learning environments. But there are some notable exceptions in which qualitative methods have been used to advantage. Quite a few Asian studies have used qualitative methods in a minor way, such as in interviews of a small group of students aimed at checking the suitability of a learning environment questionnaire and modifying it before its use in a large-scale study (e.g., Khine, 2001; Margianti et al., 2001a, 2001b; Soerjaningsih et al., 2001a, 2001b). Lee's study in Korea included a strong quantitative component involving the administration of the SLEI, CLES, and QTI to 439 students in 13 classes (four classes from the humanities stream, four classes from the science-oriented stream, and five classes from the science-independent stream; Lee & Fraser, 2001a, 2001b; Lee et al., 2003). However, two or three students from each class were selected for face-to-face interviews in the humanities stream and the science-oriented stream. In the case of students in the science-oriented stream, interviews were conducted via e-mail to overcome practical constraints. All of the face-to-face interviews were audiotaped and later transcribed in Korean and translated into English. When the Korean transcriptions were completed, they were shown to the students for member checking. Furthermore, one class from each stream was selected for observation. While the researcher was observing, whenever possible she wrote down any salient events that occurred in the classroom. Some photographs were also taken. Field notes were made and translated into English in order to transfer the images into English. Overall, the findings from interviews and observations replicated the findings obtained with the learning environment surveys.

During observations, the researcher noted that, in classes in the science-independent stream in Korea, teachers appeared more receptive to students' talking and the lessons involved mainly group activities. Students' cooperation was natural and did not require explicit intervention from the teacher. Interviews also indicated that students from the science-independent stream were more likely to interact actively with their teachers than were students from the other two streams. It would appear that the stream in which students study influences their perceptions of their science classes.

This Korean study suggested that teacher-student interactions in senior high school science classrooms reflect the general image of the youth-elder relationship in society of "directing teachers and obeying students." It is also noteworthy that each stream's unique nature in terms of teacher-student relationships did not go beyond this societal norm.

In Hong Kong, qualitative methods involving open-ended questions were used to explore students' perceptions of the learning environment in Grade 9 classrooms

(N. Y. Wong, 1993, 1996). This researcher found that many students identified the teacher as the most crucial element in a positive classroom learning environment. These teachers were found to keep order and discipline while creating an atmosphere that was not boring or solemn. They also interacted with students in ways that could be considered friendly and showed concern for the students.

Cross-National Studies

Educational research that crosses national boundaries offers much promise for generating new insights for at least two reasons (Fraser, 1997). First, there usually is greater variation in variables of interest (e.g., teaching methods, student attitudes) in a sample drawn from multiple countries than from a single country sample. Second, the taken-for-granted familiar educational practices, beliefs, and attitudes in one country can be exposed, made "strange," and questioned when research involves two countries. In a cross-national study, six Australian and seven Taiwanese researchers worked together on a study of learning environments (Aldridge, Fraser, & Huang, 1999; Aldridge, Fraser, Taylor, & Chen, 2000; She & Fisher, 2000). The WIHIC and CLES were administered to 50 junior high school science classes in Taiwan (1,879 students) and Australia (1,081 students). An English version of the questionnaires was translated into Chinese, followed by an independent back translation of the Chinese version into English again by team members who were not involved in the original translation (Aldridge et al., 2000).

Qualitative data, involving interviews with teachers and students and classroom observations, were collected to complement the quantitative information and to clarify reasons for patterns and differences in the means in each country. Data from the questionnaires guided the collection of qualitative data. Student responses to individual items were used to form an interview schedule to clarify whether items had been interpreted consistently by students and to help to explain differences in questionnaire scale means between countries. Classrooms were selected for observations on the basis of the questionnaire data, and specific scales formed the focus for observations in these classrooms. The qualitative data provided valuable insights into the perceptions of students in each of the countries, helped to explain some of the differences in the means between countries, and highlighted the need for caution in the interpretation of differences between the questionnaire results from two countries with cultural differences (Aldridge, Fraser, & Huang, 1999; Aldridge et al., 2000).

Another cross-national study of learning environments was conducted in the United States, Australia, the Netherlands, Slovakia, Singapore, and Brunei by den Brock et al. (2003). This study, involving 5,292 students in 243 classes, was intended only to test the cross-national validity of the QTI in terms of the two-dimensional circumplex model of interpersonal behavior on which the QTI is based. Researchers found that the empirical scale locations differed from the theoretical positions hypothesized by the model and that scale positions in the circumplex differed between countries. The authors concluded that the QTI cannot be compared between countries and that further research is needed to determine whether the QTI is cross-culturally valid.

In contrast to these findings in den Brok and colleagues' cross-national validation of the QTI, Dorman (2003) reported strong support for the cross-national validity of the WIHIC when used with a sample of 3,980 students in Australia, Britain, and Canada.

Researchers from Singapore and Australia also have carried out a cross-national study of secondary science classes (Fisher, Goh, Wong, & Rickards, 1997). The QTI was administered to students and teachers from a sample of 20 classes from 10 schools each in Australia and Singapore. Australian teachers were perceived as giving more responsibility and freedom to their students than was the case for the Singapore sample, whereas teachers in Singapore were perceived as being stricter than their Australian counterparts. These differences are not surprising, given the different cultural backgrounds and education systems in the two countries. Most recently, Adolphe et al. (2003) conducted a cross-national study of science classroom environments and student attitudes among 1,161 science students in 36 classes in private coeducational schools in Indonesia and Australia.

CONCLUSION

The history of the first two decades of learning environments research in Western countries shows a strong emphasis on the use of a variety of validated and robust questionnaires that assess students' perceptions of their classroom learning environment (Fraser, 1998a). The past decade of research into learning environments in non-Western countries shows a very similar pattern. Researchers have completed numerous impressive studies that have cross-validated the main contemporary classroom environment questionnaires that were originally developed in English (SLEI, CLES, WIHIC) and Dutch (QTI). Not only have these questionnaires been validated for use in English in countries such as Singapore and Brunei, but researchers also have undertaken painstaking translations and have validated these questionnaires in the African, Chinese, Indonesian, Korean, and Malay languages. These researchers have laid a solid foundation for future learning environment research internationally by making readily accessible a selection of valid, reliable, and widely applicable questionnaires for researchers and teachers to use in a range of languages for a variety of purposes.

On the basis on the research reviewed in this chapter, the following generalizations and implications for improving science education can be drawn:

1. Because measures of learning outcomes alone cannot provide a complete picture of the educational process, assessments of the learning environment should also be used to provide information about subtle but important aspects of classroom life.
2. Because teachers and students have systematically different perceptions of the learning environments of the same classrooms (the "rose-colored glasses" phenomenon), feedback from students about classrooms should be collected in the evaluation of preservice teachers during field experience and during investigation of professional development programs.
3. Science teachers should strive to create "productive" learning environments as identified by research. Cognitive and affective outcomes are likely to be enhanced in classroom environments characterized by greater organization, cohesiveness, and goal direction and by less friction. In laboratory classroom

environments specifically, greater integration between practical work and the theoretical components of a course tends to lead to improved student outcomes.

4. The evaluation of innovations and new curricula should include classroom environment instruments to provide economical, valid, and reliable process measures of effectiveness.
5. Teachers should use assessments of their students' perceptions of actual and preferred classroom environments to monitor and guide attempts to improve classrooms. The broad range of instruments available enables science teachers to select a questionnaire or particular scales to fit personal circumstances.

In the future, there will be scope for researchers to make internationally significant contributions to the field by developing new questionnaires that tap the nuances and uniqueness of classrooms in particular countries, and/or which focus on the various information technology-rich learning environments (e.g., web-based, online learning) that are currently sweeping education worldwide (Khine & Fisher, 2003). Similarly, there is scope to adapt currently widely used paper-and-pencil questionnaires to online formats.

The most common line of past learning environment research has involved investigating associations between students' outcomes and their classroom environment perceptions. This impressive series of studies has been carried out in many countries in a variety of subject areas (science, mathematics, geography, English, and computing), at various grade levels (elementary, secondary, and higher education), and using numerous student outcome measures (achievement, attitudes, self-efficacy) and different learning environment questionnaires. Overall, these studies provide consistent support for the existence of associations between the nature of the classroom environment and a variety of valued student outcomes. These findings hold hope for improving student outcomes through the creation of the types of classroom environments that are empirically linked to favorable student outcomes.

Feedback information based on student or teacher perceptions of actual and preferred environments has been employed in a five-step procedure as a basis for reflection upon, discussion of, and systematic attempts to improve classroom environments (Sinclair & Fraser, 2002; Thorp, Burden, & Fraser, 1994; Yarrow, Millwater, & Fraser, 1997). The five steps involve (a) *assessment* of actual and preferred classroom environments; (b) *feedback* of results, including identification of aspects of classroom environments for which there are large discrepancies between actual and preferred scores; (c) *reflection and discussion*; (d) *intervention*; and (e) *reassessment* of classroom environment. Surprisingly, this important practical benefit has not yet been widely realized in science education in any country.

Whereas the use of questionnaires in learning environment research has been prolific, studies that include qualitative methods such as interview and observation have been somewhat less common. Although studies demonstrate the benefits of combining qualitative and quantitative methods in learning environment research (Tobin & Fraser, 1998), it is desirable for future learning environment research to make greater use of qualitative methods. For example, qualitative data can help researchers to make more meaningful interpretations of questionnaire data that can take into account various background, cultural, and situational variables. Although learning environment questionnaires are valuable for illuminating particular constructs and patterns, their use can also obscure other important constructs and patterns that could be revealed through qualitative methods. Researchers can also use narrative stories to portray archetypes of science classroom environments.

There is scope for researchers to adopt, adapt, or create new theoretical frames to guide the next generation of learning environment studies. For example, this could build upon Roth's (1999) advice against conceptualizing the environment as being independent of the person, and on his use of life-world analysis as a new theoretical underpinning. Roth, Tobin, and Zimmermann (2002) broke with past traditions by taking researchers into the front lines of the daily work of schools, thereby assisting in bringing about change. They proposed co-teaching as an equitable inquiry into teaching and learning processes in which all members of a classroom community participate—including students, teachers, student teachers, researchers, and supervisors. Roth and colleagues articulate co-teaching in terms of activity theory and the associated first-person methodology for doing research on learning environments that is relevant to practice.

The next generation of learning environment studies also could benefit from advances in methods of data analysis. Rasch analysis has been used to permit valid comparison of different cohorts of over 8000 science and mathematics students who responded to learning environment scales during different years of a systemic reform effort in Ohio (Scantlebury, Boone, Butler Kahle, & Fraser, 2001). In research on systemic reform, there are several important measurement problems in need of solution. For example, if we are interested in improvements in achievement or attitudes at the same grade level over several years as reform is implemented, there is a potential problem: that our samples for different years are unlikely to be strictly comparable. Similarly, changes made to evaluation instruments during the lifetime of a reform initiative can make it difficult to attribute changes to the reform rather than simply to modifications in an instrument. Finally, because all students seldom answer all items on a test or questionnaire, we need a method of calculating a valid score for each student based on the subset of items answered. Item response theory, or the Rasch model, provides a solution to all of these measurement problems.

Dorman (2003), taking advantage of relatively recent advances in techniques for validating learning environment questionnaires, has demonstrated the value of using confirmatory factor analysis within a covariance matrix framework. Using a sample of 3,980 high-school students from Australia, Britain, and Canada, Dorman found strong support for the *a priori* structure of the WIHIC and demonstrated the factorial invariance of model parameters across three countries, three grade levels, and gender. In the first use of multitrait-multimethod methodology in learning environment research, a study by Aldridge, Dorman, and Fraser (2004) involving 1,249 students used the 10 scales of the Technology-Rich Outcomes-Focused Learning Environment Inventory (TROFLEI) as traits and the two forms of the instrument (actual and preferred) as methods. Findings supported the sound psychometric properties of the actual and preferred forms of the TROFLEI.

In investigating outcome-environment associations, Goh et al. (1995) have illustrated how multilevel analysis can take cognizance of the hierarchical nature of classroom environment data in their study involving over 1,500 Singaporean students. Because classroom environment data typically are derived from students in intact classes, they are inherently hierarchical. Ignoring this nested structure can give rise to problems of aggregation bias (within-group homogeneity) and imprecision.

This chapter encourages others to use learning environment assessments for a variety of research and practical purposes. Given the ready availability of questionnaires, the importance of the classroom environment, the influence of the classroom environment on student outcomes, and the value of environment assessments in guiding educational improvement, it seems very important that researchers and teachers more often include the classroom environment in evaluations of educational effectiveness. Although educators around the world pay much greater attention to student achievement than to the learning environment, research on the classroom environment should not be buried under a pile of achievement tests.

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