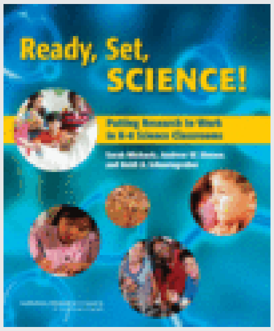


# Ready, Set, SCIENCE!: Putting Research to Work in K-8 Science Classrooms

## DETAILS

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## OVERSIGHT GROUP ON SCIENCE LEARNING, KINDERGARTEN THROUGH EIGHTH GRADE PRACTITIONER VOLUME



## BOARD ON SCIENCE EDUCATION

# Contents

# Foreword

*Ready, Set, Science!* makes the content of a major National Research Council study, *Taking Science to School: Learning and Teaching Science in Grades K-8,* accessible and useful to a very critical audience—science education practitioners who work with and support K-8 classroom teachers. It represents a collective commitment among the National Academies, its Board on Science Education, the Merck Institute for Science Education (this volume's sponsor), and the National Academies Press to make the products of the National Academies available in formats and language helpful to the work of practitioners.

In the context of this book, the term "science education practitioner" refers to a cross section of individuals who work closely with teachers on science content and assessments, with instructional materials, and with teacher professional learning experiences. Their titles may differ, depending on the districts in which they work. Generally they are called science specialist, curriculum developer, science instructional supervisor, teacher leader for science, or specialist in professional development and assessment. People in this collection of roles, while not in the same classroom on a daily basis, are pivotal when it comes to working with classroom teachers and administrators, and sometimes with parents and school board members, on science education matters.

While *Ready, Set, Science!* was written to honor the unique informational needs of these midlevel practitioners, it does not exclude the interests of classroom teachers, administrators, or even parents—quite the contrary. All school- and district-based science education roles as well as committed parents, extended family, and caretakers are part of a system that determines how students engage with the ideas of science. It is in the spirit of shaping that system around a common base of well-researched knowledge about learning and teaching science that *Ready, Set, Science!* makes a singularly important contribution to science education writ large.

*Taking Science to School,* the report on which *Ready, Set, Science!* is based, brought together current research literatures from cognitive and developmental psychology, science education, and the history and philosophy of science to synthesize what is known about how children in grades K through 8 learn the ideas and practices of science. The Foreword to that volume states that this research synthesis "has the potential to change science education in fundamental ways." We believe this statement to be even truer today, almost a year since the release of *Taking Science to School*.

The response to *Taking Science to School* from the science education community (locally as well as at the state and national levels), policy makers, and education researchers has been remarkable. The report provides a synthesis of research on learning and teaching too long absent from science education. As such, it offers a redefinition of and a framework for what it means to be proficient in science. It is this framework and its potential to reshape science education classrooms and the system of roles and actions that support those classrooms that is at the heart of *Ready, Set, Science!*

This book will not answer every question about how to implement the ideas of *Taking Science to School* in a classroom or school system, but it will answer many. Cases of teaching and learning in science classrooms are presented to engage readers with the major conclusions and recommendations made in *Taking Science to School,* as well as the research base on which those conclusions and recommendations rest. We often hear the expression about moving research into practice, and the classroom cases developed for *Ready, Set, Science!* seek that result.

Dissemination of the knowledge that results from studies, workshops, or other activities undertaken by the Board on Science Education is a high priority for board members and board staff. Effective dissemination strategies for its products are essential to fulfilling the founding mission of the National Academies—to advise the nation, with an independent and evidence-based voice, on matters critical to science, engineering, and medicine. Science educators are essential to the overall enterprise of science in this country. *Ready, Set, Science!* both acknowledges and honors their critical contribution to the whole of the scientific enterprise. As a board with a clear link to the work of teachers, practitioners, teacher educators, teaching faculty, administrators, and caregivers, we expect to produce other field-oriented books based on our synthesis studies and workshop reports.

We want to recognize and express our gratitude to Carlo Parravano as the individual with the founding idea for this volume. Given his many years of leadership as director of the Merck Institute for Science Education, he understands the work and information needs of science education practitioners. Similarly, he understands the potential contributions to that work of the National Academies through its National Research Council. The Board on Science Education is grateful to the Merck Institute for Science Education for sponsoring *Ready, Set, Science!* and for helping us take a very important dissemination step. Our goal is for this to be the first of many translations of major studies for educator audiences.

Carl E. Wieman, *Chair*
C. Jean Moon, *Director*
Board on Science Education

# Preface

Science education has risen to the top of the national and international agendas. International networks of scientists pursue basic questions about the natural world and build powerful technologies to improve health and standards of living. Meanwhile the United States and other nations are scrambling to figure out how to feed and support the scientific enterprise. In the United States this means that policy makers are calling on educators to vastly improve mathematics and science education. Scores on international tests of scientific proficiency are cited as evidence that the United States risks falling behind other countries, even those in the developing world. The requirement, under the No Child Left Behind Act, that states assess science learning beginning in the 2007-2008 school year testifies to the nation's sense of urgency about science education.

All of this sounds very familiar to science educators. After the launch of Sputnik in 1958, Americans worried that they were being overtaken in science and technology by the Soviet Union. In 1982 the National Commission for Excellence in Education warned of a "rising tide of mediocrity" and called for "more rigorous and measurable standards" in science and mathematics. In response to these and other calls to improve science education, new curricula were developed, state and local initiatives led to changes in the classroom, and new standards and benchmarks focused attention on what students need to learn in science.

These reforms have had an important impact. Scores on tests of scientific achievement have risen in recent decades, especially for disadvantaged minority groups. Scientific research and other technical fields have become more diverse as more women and members of minority groups underrepresented in science have received the education they need to work in these fields. Continuing shortfalls in U.S. students' scientific proficiency show that there is still a long way to go.

Why has science education been a topic of concern for so long? Simply stated, teaching and learning science are challenging tasks, for a variety of reasons. Unlike many countries that have a national curriculum, the United States has a highly decentralized education system. Across states and even within individual districts, many schools do things differently and independently. As a result, there is great variability from classroom to classroom, school to school, and state to state, which makes it difficult to replicate and disseminate successful initiatives.

Furthermore, many elementary school teachers and science teachers in middle schools and high schools have not received the preparation and support they need to do the job they're being asked to do. Many teachers aren't familiar with all the areas of science they are expected to teach. In spite of the national investment in the development of new curricula, not all teachers have the high-quality materials they need. Moreover, teachers rarely get all the time and professional development they need to use new curricula well and to teach to new standards.

Teachers, in short, have not been well supported to do the job they are being asked to do. Despite the important progress that has been made in science education, much more can be done to honor what teachers know and do and to support them with the tools, knowledge, and resources they need. Teachers, after all, are society's most valuable resource for improving science education and the most important agents of change in education.

This book is designed to acknowledge and support the work of teachers while explaining the implications of new knowledge for classroom practice. *Ready, Set, Science!* is an account of groundbreaking recent research into teaching and learning science. It is designed to help practitioners make sense of new research and use this research to inform their classroom practice.

This book is based on a report published in December 2006 from a 14-person committee of the National Research Council, entitled *Taking Science to School: Learning and Teaching Science in Grades K-8*. Over a period of two years, the committee made a comprehensive review of recent research on teaching and learning from a variety of academic disciplines. These disciplines include cognitive science, developmental psychology, education research, the design of effective learning environments, the history and philosophy of science, and new interdisciplinary fields, such as neurobiology and sociocultural studies of the mind. It deliberated on the information it had gathered, identified gaps and questions, and gathered more information to fill these gaps. It held three public fact-finding meetings, reviewed unpublished research, and commissioned experts to prepare and present papers.

At its fourth and fifth meetings, the committee intensely analyzed and discussed its findings and conclusions in the process of writing its report.

Even before the committee's first meeting, the leadership of the Merck Institute for Science Education realized that the committee's report would contain information that would be extremely useful for everyone involved, directly or indirectly, in the teaching of science. The executive director of the Merck Institute, Carlo Parravano, asked the director of the Board on Science Education about the possibility of producing a book based on the committee's report that would be focused directly on the needs of science education practitioners. The Board on Science Education and the leadership of the National Research Council agreed that such a book would have tremendous value, and the Merck Institute generously agreed to support the project.

This book has been written for individuals who influence what happens in K-8 classrooms. That group includes teachers, of course, and it includes many other people as well. Science specialists who work with classroom teachers are a particularly important target audience. These individuals are in an ideal position to implement the ideas in this book through their work both with teachers and with school administrators. Other major audiences include curriculum supervisors, staff development experts, teacher educators, curriculum and assessment developers, and school principals. All of these individuals work in a system that determines what happens in the classroom. This book is intended to help everyone in this system work together toward common objectives.

Just as the intended audiences for this book include a variety of groups, so it can be used in a variety of ways. Its primary purpose is to help K-8 science educators grapple with a burgeoning body of research on teaching and learning science and to consider its implications for practice. To that end, individual teachers can use it to shape and reflect on what occurs in their classrooms. Teacher study groups and teacher leaders can use it as a guide for discussions and learning. Professional developers and university-based teacher educators can use it to shape the experiences and knowledge that teachers bring to their classrooms. School administrators and policy makers can use it to determine the kinds of support that teachers and other educators need to do their jobs well. Parents also will find much that is of interest in this book, since they are their children's first teachers and have an important influence on science education in elementary and middle schools. This is not a how-to book, but rather a way to bring the best of research to practitioners and to contextualize research in familiar classroom settings. Those interested in using this book in professional education (e.g., science teacher education, teacher work groups, curriculum and assessment development, staff meetings) may draw on the accompanying questions in Appendix A and extended examples in Appendixes B and C.

This book contains the major observations and conclusions made in *Taking Science to School: Learning and Teaching Science in Grades K-8*. The committee's work has been reorganized and reshaped specifically for a practitioner audience. In addition, the book contains a number of elements that have been designed to make the committee's conclusions as useful as possible in a classroom setting. Most noticeably, most of the chapters feature stories that are designed to make the research findings described in this book more concrete. Most of these stories are based on real classroom experiences (although in some cases the names of the students and teachers and some of the details of the events have been changed). As a result, they illustrate the complexities that teachers grapple with every day. They show how teachers work to select and design rigorous and engaging instructional tasks, manage classrooms, orchestrate productive discussions with culturally and linguistically diverse groups of students, and help students make their thinking visible using a variety of representational tools.

In writing its report, the Committee on Science Learning, Kindergarten Through Eighth Grade made an important point that applies to this book as well. In some areas, current research is not robust enough to offer a detailed, step-by-step road map for improving science education. But the need for improvement is urgent, and enough is known to move forward. As a result, the committee offered what it called "best bets" for improving science education. These best bets are based on well-substantiated research, but additional documentation is needed through continued research and careful evaluations of changing practices. By evaluating school, district, and state initiatives, these best bets can be transformed into well-researched alternatives for policy and practice.

The world is changing much faster now than it was just a couple of decades ago. Countries with scientifically proficient workers are likely to fare much better than those without them. Good decisions on such issues as stem cell research, climate change, and energy policy require that people have a sound education in science. The underrepresentation of women and many minority groups in U.S. science remains a serious problem, especially as those groups become a larger percentage of the population. The gap between disadvantaged students and mainstream students in science learning continues to be an affront to American ideals of fairness and opportunity.

Recent research can help teachers and other educators meet the many demands being made on them. This research points toward a kind of science education that differs substantially from what occurs in most science classrooms today. It's time to ready science education for the 21st century.

# Ready, Set, SCIENCE!

# 1 A New Vision of Science in Education

Joanna Fredericks feared that she was becoming the teacher she'd vowed never to be. She'd arrived at Tubman Middle School a year and a half earlier to teach science after a successful career in geographical information systems. While she'd enjoyed her previous job, she wanted to do something that would make a real difference in the lives of children. So she enrolled in a highly regarded university teaching master's program, became certified in middle school science, and took a job in the city near her home.

Her colleagues at Tubman Middle School considered her a smart, energetic, and passionate teacher. But her new job was turning out to be much harder than Ms. Fredericks had expected. Her school district, one of the largest, most diverse, and poorest in the state, had adopted a textbook that covered far too many topics. The resulting curriculum was, as many of the national reports on science have observed, "a mile wide and an inch deep." There was simply no way for her to cover all the lessons, vocabulary, and experiments described in the book in enough depth that the students would really understand the concepts being presented.

While students were interested in the demonstrations suggested by the textbook and in the experiments Ms. Fredericks had them do, there was rarely enough time to follow up on the results, so the students had difficulty understanding them. Also, Ms. Fredericks knew that her students needed to do well on the state tests given in science at the end of eighth grade, but 80 to 90 percent of them were failing the end-of-chapter tests in the textbook.

As the year went on, her students became increasingly disrespectful to each other. Part of the problem, she knew, was that they were bored, but she didn't know how to make her lessons more interesting while still following the curriculum. The more she asked her students to sit quietly and do their worksheets, the more they acted out.

Well into her second year, Ms. Fredericks felt her worst nightmare was coming true. She was becoming one of those science teachers who taught her students only two things: that they didn't like science and that they weren't any good at it.

## The Importance of Teaching Science Well

Science has become a cornerstone of 21st-century education. This is evident in the provision that the No Child Left Behind Act calls for assessments in science, along with reading and mathematics, starting in the 2007-2008 school year. Apart from the law, there are many other reasons why it is important to teach science well in schools.

Science is a powerful enterprise that can improve people's lives in fundamental ways. Teams of scientists participate in developing treatments for diseases, technologies for distributing clean water in arid environments, building systems for enhancing national security, and building computer models that help track the impact of human behavior on the environment. These issues, and many others of equal importance, will continue to require attention now and far into the future. Generating scientific productivity requires a workforce, not only of scientists, engineers, medical and health care professionals, but also of journalists, teachers, policy makers, and the broader network of people who make critical contributions to science and the scientific enterprise. It is imperative that we teach science well to all children, as science is a critical factor in maintaining and improving the quality of life.

Science can also provide a foundation for continued science learning, as well as for the study of other academic subjects. Students who learn to talk with peers in scientific ways, for example, tracing logical connections among ideas and evidence and criticizing ideas constructively, may employ those skills in other subject areas.

Science is important for another, often overlooked reason. To the degree that we actually know science, we have knowledge and strategies with which to examine evidence systematically, interpret, and control our surroundings. Knowledge of science can enable us to think critically and frame productive questions. Without scientific knowledge, we are wholly dependent on others as "experts." With scientific knowledge, we are empowered to become participants rather than merely observers. Science, in this sense, is more than a means for getting ahead in the world of work. It is a resource for becoming a critical and engaged citizen in a democracy.

The growing importance of science in the modern world has focused increased attention on K-12 science education. The development in the 1990s of national standards and benchmarks catalyzed a nationwide conversation about what students need to learn in science and how the education system can support student learning. Standards and benchmarks at the national level provided the basis for state standards and curriculum frameworks that have had a significant impact on what students learn in science classes.

These changes have taken us only partway to where we need to go. Research on learning and teaching has now progressed significantly beyond where it was when the standards were being written. Enough is now known for educators, administrators, and policy makers to rethink key aspects of science education. We've also come to understand the ways in which standards are used that have implications for how they are designed. As originally developed, the national standards provide very broad guidelines for the content that should be covered in science classes and for instructional practice. But they don't provide much guidance on which topics are most important. They offer a few instructional exemplars, but they fall short of providing a model of successful instruction.

***Four Reasons to Teach Science Well***

1. **Science is an enterprise that can be harnessed to improve quality of life on a global scale.**
2. **Science may provide a foundation for the development of language, logic, and problem-solving skills in the classroom.**
3. **A democracy demands that its citizens make personal, community-based, and national decisions that involve scientific information.**
4. **For some students, science will become a lifelong vocation or avocation.**

New research points toward a kind of science education that differs substantially from what occurs in most science classrooms today. This new vision of science education embraces different ways of thinking about science, different ways of thinking about students, and different ways of thinking about science education.

## What Scientists Really Do

Over the past few decades, historians, philosophers of science, and sociologists have taken a much closer look at what scientists actually do—with often surprising results. In the conventional view, the lone scientist, usually male and usually white, struggles heroically with nature in order to understand the natural world. Sometimes scientists are seen as applying a "scientific method" to get their results. They are perceived as removed from the real world, operating in an airy realm of abstraction.

Studies of what scientists actually do belie these stereotypes. They approach problems in many different ways and with many different preconceptions. There is no single "scientific method" universally employed by all. Scientists use a wide array of methods to develop hypotheses, models, and formal and informal theories. They also use different methods to assess the fruitfulness of their theories and to refine their models, explanations, and theories. They use a range of techniques to collect data systematically and a variety of tools to enhance their observations, measurements, and data analyses and representations.

Studies also show that science is fundamentally a social enterprise. Scientists talk frequently with their colleagues, both formally and informally. Science is mainly conducted by large groups or widespread networks of scientists. An increasing number of women and minorities are scientists—although still not enough to match their representation in the population. They exchange e-mails, engage in discussions at conferences, and present and respond to ideas via publication in journals and books. Scientists also make use of a wide variety of cultural tools, including technological devices, mathematical representations, and methods of communication. These tools not only determine what scientists see but also shape the kinds of observations they make.

Although different domains of science rely on different processes to develop scientific theories, all domains of science share certain features. Data and evidence hold a primary position in deciding any issue. When well-established data, from experiments or observations, conflict with a hypothesis or theory, that idea must be modified or abandoned and other explanations must be sought that can incorporate or take account of the new evidence. Theories, models, and hypotheses are rooted in empirical evidence and therefore can be tested and revised or expanded if necessary. Scientists develop and modify models, hypotheses, and theories to account for the broadest range of observations possible.

## The Language of Science

In science, words are often given specific meanings that may be different from or more precise than their everyday meanings. It is important for educators to be clear about specific scientific usage to avoid confusion.

A scientific theory—particularly one that is referred to as "the theory of . . . ," as in the theory of electromagnetism or the theory of thermodynamics or the theory of Newtonian mechanics—is an explanation that has undergone significant testing.

Through those tests and the resulting refinement, it takes a form that is a well-established description of, and predictor for, phenomena in a particular domain. A theory is so well established that it is unlikely that new data within that domain will totally discredit it; instead, the theory may be modified and revised to take new evidence into account. There may be domains in which the theory can be applied but has yet to be tested; in those domains the theory is called a working hypothesis. Indeed, the term "hypothesis" is used by scientists for an idea that may contribute important explanations to the development of a scientific theory. Scientists use and test hypotheses in the development and refinement of models and scenarios that collectively serve as tools in the development of a theory.

Outside science, the term "theory" has additional meanings, and these other meanings differ in important ways from the above use of the term. One alternative use comes from everyday language, in which "theory" is often indistinguishable in its use from "guess," "conjecture," "speculation," "prediction," or even "belief" (e.g., "My theory is that indoor polo will become very popular" or "My theory is that it will rain tomorrow"). Such "theories" are typically very particular and unlike scientific theories have no broader conceptual scope.

A datum—or "data" in plural form—is an observation or measurement recorded for subsequent analysis. The observation or measurement may be of a natural system or of a designed and constructed experimental situation. Observation, even in the elementary and middle school classroom, may be direct or may involve inference or technological assistance. For example, students may begin by conducting unaided observations of natural phenomena and then progress to using simple measurement tools or instruments, such as microscopes.

Evidence is the cumulative body of data or observations of a phenomenon. When the evidence base provides very persistent patterns for a well-established property, correlation, or occurrence, this becomes the basis for a scientific claim. Scientific claims, always based on evidence, may or may not stand the test of time. Some will eventually be shown to be false. Some are demonstrated to occur forever and always in any context, and scientists refer to these claims as factual (e.g., the sun rises in the east). Facts are best seen as evidence and claims of phenomena that come together to develop and refine or to challenge explanations. For example, the fact that earthquakes occur has been long known, but the explanation for the fact that earthquakes occur takes on a different meaning if one adopts plate tectonics as a theoretical framework. The fact that there are different types of earthquakes (shallow and deep focus) helps deepen and expand the explanatory power of the theory of plate tectonics.

The way that scientists operate in the real world is remarkably similar to how students operate in effective science classrooms. Throughout this book we examine different science classrooms in which educators strive to structure students' scientific practice so that it resembles that of scientists. In these classrooms, students engage in a process of logical reasoning about evidence. They work cooperatively to explore ideas. They use mathematical or mechanical models, develop representations of phenomena, and work with various technological and intellectual tools. Students participate in active and rigorous discussion—of predictions, of evidence, of explanations, and of the relationships between hypotheses and data. They examine, review, and evaluate their own knowledge. This ability to evaluate knowledge in relation to new information or alternative frameworks and to alter ideas accordingly is a key scientific practice.

Of course, students can't behave exactly like scientists. They don't yet know enough and haven't had enough experience with the practices of science. But students who understand science as a process of building theories from evidence develop many of the skills and practices that scientists demonstrate. They can be taught to apply their existing knowledge to new problems or in new or different contexts. They can make connections between different representations of a concept. They can ask themselves why they believe something and how certain they are in their beliefs. They can become aware that their ideas change over time as they confront new evidence or use new tools or models to examine data. They can learn how to ask fruitful and researchable questions, how to challenge a claim, and where to go to learn more.

## Rethinking Children's Capacity for Scientific Understanding

Just as studies have revealed a radically different picture of what scientists do, they have also revealed a radically different picture of what young children are capable of doing. Cognitive researchers have become much more sophisticated in probing children's capabilities. In the process, they have uncovered much richer stores of knowledge and reasoning skills than they expected to find in young children. Studies show that even children in kindergarten have surprisingly sophisticated ways of thinking about the natural world based on direct experiences with the physical environment, such as watching objects fall or collide, and observing animals and plants. Children also learn about the world by talking with their families, watching television, going to parks, or playing outside. Children apply their understanding when they try to describe their experiences or persuade other people about what's right or what's wrong. In trying to understand and influence the world around them, they develop ideas about how the world works and their role in it.

Experiences outside school influence and shape the knowledge and skills that children bring with them to the classroom. These experiences vary from child to child and often result in knowledge, skills, and interests that vary from child to child as well. Children who go to science museums or summer camps may have extensive experience investigating nature or topics in science. Children whose parents talk to them often about science are likely to be more knowledgeable about science. Research has shown that even raising goldfish at home can accelerate children's understanding of some biological processes! The variability in student knowledge and skill that these nonschool experiences can produce can be drawn on in a constructive way in a well-structured science classroom.

The capacity of very young children to reason scientifically is also much greater than has previously been assumed. Children from all backgrounds and all socioeconomic levels show evidence of sophisticated reasoning skills. Although they may lack knowledge and experience, they can and do engage in a wide range of subtle and complex reasoning processes. These processes can form the underpinnings of scientific thinking. Thus, children begin school with a set of ideas about the physical, biological, and social worlds. By paying more attention to their thinking, listening to and taking their ideas seriously, and trying to understand their thinking, educators can build on what children already know and can do. Their ideas may be more or less cohesive, and certainly in very young children they may be underdeveloped. But these initial ideas can be used as a foundation to build remarkable understanding, even in the earliest grades.

This is a marked departure from previously accepted ways of looking at children's capabilities or knowledge. Much of current science education is based on the idea that younger children have specific cognitive deficiencies that cannot be overcome. One widely accepted view has been that children pass through cognitive stages naturally and with little direct intervention from adults, gradually developing new capabilities as they get older. As a result, educators have often assumed they must wait until a child reaches a certain stage and is ready to grasp specific ideas or activities, rather than building on a child's existing knowledge and skills. The reality, as the following case studies demonstrate, is that children as young as kindergarten age have the ability to think in ways that can serve as a foundation for later, more sophisticated scientific reasoning. Although we focus on measurement here, this is just one of many important areas in which children have strong skills and experiences to build on but need structured learning opportunities to make progress. Kindergartners enter school with little understanding of the deeper reasons for using instruments or of how to judge what makes a good measurement. Measurement introduces students to the importance of generating data that can be described in reproducible ways (so they can be verified) and that can be plugged into mathematical representations and manipulated. Measurement also helps children find patterns in data—patterns that would be obscured if they always rely on commonsense impressions.

These cases are meant to illustrate what it looks like when young children engage in scientific practice—what happens when they are challenged to reason about a problem, when they examine a problem in light of what they already know or have experienced, and when they work toward a collective understanding of a problem. The instructional practice depicted here is built on the teachers' knowledge of the subject, their understanding of the skills and knowledge their students have, and their ability to orchestrate complex, unscripted classroom discussions.

Laying a foundation through work on measurement in kindergarten and first grade will have important payoffs in later grades, when students are able to reason about measuring and use the results of measurements in more sophisticated ways.

# Science Class

## SEEING OURSELVES IN MEASUREMENT[1]

As part of a unit called "Seeing Ourselves in Measurement," Julia Martinez's kindergartners were about to measure themselves to create a full-size height chart. Each student had a small photograph of himself or herself, and a tape measure was attached to the wall. Before they got started, Ms. Martinez said she had an important measurement question to ask the students, and they had to come to a decision as an entire group.

"Should we measure your height with or without your shoes on?" Ms. Martinez asked. "Sit down in your circle time spots, and let's discuss this as scientists. Think about it first by yourself for a minute, and then let's talk."

Hands went up.

"I have an idea!"

"I know!"

Ms. Martinez waited until many hands were up. Then she said, "You're all going to get a chance to give your ideas. But first you have to listen really, really hard to what everyone has to say, so we can come up with a good decision together."

Ms. Martinez called on Alexandra.

"I think we should do it with our shoes off because some of our shoes are little and some are big or like high up. That wouldn't be fair," said Alexandra.

"What do you mean by fair? Can you say a bit more about that?"

"You know. Someone might be taller because of their shoes but not really taller. That wouldn't be fair."

"Does anyone want to add on to what Alexandra said? Does anyone disagree?"

"I no agree," said Ramon, who spoke Spanish at home and was just beginning to learn English. "Shoes all the same. All like this big." He measured the bottom of his shoe and held up two fingers. "It no make no difference."

"So let me see if I've got your idea right," Ms. Martinez said. "Are you saying that since we all have shoes on and they're all about the same size, it adds the same amount to everyone's height and so it would be fair? Is that what you're thinking?"

Ramon nodded.

"I think we should take our shoes off because some shoes are taller," said Damani. "Look at your shoes! They're way taller." He pointed to Ms. Martinez's shoes, which had 2-inch heels. "And mine are short, and Lexi's are tall." By now several kids had their legs in the air, showing off their shoes.

"Okay, friends, we have a disagreement here," said Ms. Martinez. "Alexandra's saying that it wouldn't be fair, and Ramon is saying that it wouldn't make any difference. Damani says it would make a difference. How should we decide?"

Kataisha raised her hand. "We could line up our shoes and measure them and see if they're all the same height. But you can tell that they aren't, so I don't think we really need to measure them all. Lexi's are really big, and mine are not so big. That wouldn't be fair."

Ramon said that he had changed his mind. Now he agreed that no shoes would be better. The other students agreed. After 10 minutes of discussion, the group had arrived at a consensus.

At first, Ms. Martinez had thought that a vote might settle things, but instead her students used evidence and a shared sense of fairness to make a decision. They were able to explain their reasons with evidence (the different heights of the shoes) and challenge someone else's evidence with counterevidence. They were able to propose a simple experiment to evaluate a particular claim (measure all the shoes). They listened respectfully to each other's opinions, agreed and disagreed, and even changed their minds as new evidence was introduced. They were able to reason about the idea of a "fair test," which in later years they might extend and apply to the more sophisticated idea of holding variables constant.

Young children still need assistance as they build on and add to their knowledge of science. In Ms. Martinez's class, the children arrived with some sense of measure but little understanding of the methods of standard measure, the purposes for developing standard measure, or the ways of checking the quality of a measurement (e.g., developing reproducible results). In science, adults play a central role in "promoting children's curiosity and persistence by directing their attention, structuring their experiences, supporting their learning attempts, and regulating the complexity and difficulty of levels of information for them."[2] Ms. Martinez challenged her students with an interesting problem. She used several good instructional techniques to help the children listen to one another and take each other's ideas seriously. By helping them clarify and explicate their reasoning, she built on their existing experiences with measurement and guided them toward effective scientific practices.

Ms. Martinez also helped the students engage in collective reasoning much in the same way that a community of scientists does. She facilitated the discussion so that a variety of observations were considered. By making sure that everyone had access to the conversation, including students who were English language learners, she helped the children benefit from the more complex reasoning as a group than any single child could have alone. In the end, Ms. Martinez's class was able to accomplish far more by investigating the measurement question than they would have if they had simply resolved the question with a vote. Often, teachers mistakenly believe that a vote is a good way to make scientific decisions. In Ms. Martinez's class, the students went beyond simply offering opinions. They gave reasons for their opinions, and then they explained their reasons with evidence.

Science Class

## MEASURING AND GRAPHING HEIGHT[3]

Robert Dolens's first graders were engaged in a science activity similar to Ms. Martinez's kindergarten class. They too were measuring and graphing height, although they were taking the activity a step further. They were planning to measure the height of all the first graders in the school and then examine their data both within individual classrooms and across the entire first grade.

Mr. Dolens wanted to emphasize with his students the importance of explaining their reasons and supporting their ideas with evidence. He also wanted them to find ways to make their evidence visible to their classmates, even before they became accomplished writers, so they could discuss it together. As a possible extension activity, Mr. Dolens, who had a friend who taught first grade in Anchorage, Alaska, hoped to exchange height charts with his friend's class as a way of demonstrating the importance of sharing scientific data.

Mr. Dolens began the activity by calling his 25 students to the meeting area. He explained that they were going to gather information on their own heights as well as the heights of all the first graders in the school. But first, he told them, they would have to make decisions about how to measure, how careful to be, what measuring tools to use, and how to keep track of their data. He began by asking the same question as Ms. Martinez: "Should we measure our heights with or without our shoes on?"

Before his students could respond, Mr. Dolens said, "Don't answer yet. Just think for a moment. While you're thinking, I'm going to call up a few of you and measure your heights."

Mr. Dolens called on three girls and asked them to take their shoes off. He quickly measured them with a tape measure and recorded their heights on one side of a large sheet of one-inch graph paper (see Figure 1-1). Then he called on three boys and measured their heights with their shoes on.

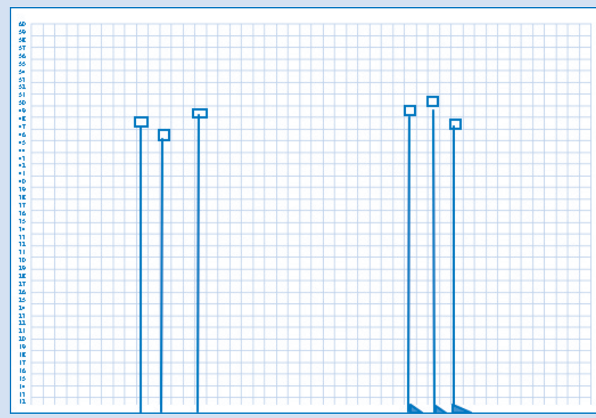

**FIGURE 1-1**
*Student heights recorded on graph paper.*

Immediately, his students began to call out.

"No fair!"

"They have to take their shoes off!"

Mr. Dolens reminded them that this was thinking and observing time with no talking yet.

Finally, Mr. Dolens organized the students into groups of four. He said that each group would have to come up with an answer to his original question. And they had to follow a few rules in finding their answers: they had to use data to support their arguments, and they had to base their decisions on evidence, either drawing on data from the chart or supplementing the chart with other data. Once they had come to a decision, they were to make a recommendation and record their decision and the evidence that supported it on paper. He assigned each member of the group the role of reporter, scribe, or facilitator. (His class had done a number of activities using these roles on a rotating basis, and they frequently reflected on how the roles were working, so that everyone participated actively.)

"Get started, scientists," Mr. Dolens said. The class went right to work.

Over the next two days, during science time, the class worked on answering the measurement question. Many times they sent a member of their group back to the wall chart to look at the data and take notes. Two groups asked Mr. Dolens for permission to borrow his tape measure, and they remeasured the girls with their shoes on. Another group carefully measured the height of the heels of the three boys' shoes. There was a good deal of talk about whether to measure in inches or centimeters, something the students had been doing a lot of in math class. Each group ended up deciding to use inches (probably because this was what Mr. Dolens had used). One group noticed that one of the boys was wearing a different pair of shoes and had him stand next to the chart. He was slightly taller now, although not by much.

At last it was time for the "Measurement Congress," as Mr. Dolens called it. He explained to his students how scientists come together to explain their processes and their findings and take questions from the audience.

Each group arrived at the rug with documents, a poster, or chart paper. One by one, they presented their decision and their reasons. The first group to present included two reporters, Shandra and Coral. Shandra spoke first.

"At first we couldn't decide, based on the chart. We figured you couldn't do it both ways—measure some kids with shoes on and some kids with shoes off, because that wouldn't be fair."

**Both Ms. Martinez and Mr. Dolens knew that if their students were simply told to measure length in a unit such as a centimeter or an inch, they would develop very little understanding of the principles of measurement. Even children who appear to use rulers and scales appropriately often do not understand core ideas like the zero point, iteration, constant units, and tiling, for example. What is important for success in science, in contrast, is having a solid theory of measure that encompasses several kinds of measurement and units. This involves much more than understanding how to measure things.**

**Over the course of many different measurement activities, Ms. Martinez and Mr. Dolens guided their students in discovering and exploring a number of key principles about measurement, including:**

1. ***Appropriate units***
   **Use units of measure appropriate to the thing being measured. Units that work for measuring the length of your driveway may not work for measuring the length of your notebook.**

2. ***Identical units***
   **To say that a candy bar is 5 inches long means that every inch is exactly the same.**

3. ***Measurement conventions***
   **Standard units like centimeters or inches exist as the result of discussions and agreements among people about measurement problems. Because children will invariably encounter conventions in science, they need opportunities to learn why and how such conventions are established. When children participate in the process of forming conventions, they come to see their utility.**

4. ***Iteration***
   **Measurement means repeated applications of identical units.**

"We noticed on the chart that Shandra and Jeremy ended up being the same height, but they weren't really," Coral said. "We had them go back to back without their shoes on and Shandra was taller. So that was proof, I mean, evidence. So we decided that you couldn't do both."

"But we couldn't tell from the chart which was better," Shandra added. "We couldn't really tell if it made a difference on the boys. They were all different heights, but maybe their shoes didn't matter."

Mr. Dolens said it wasn't completely clear what they meant by "their shoes didn't matter" and asked if anyone in the group could clarify. Gabby, another group member said, "She means that maybe keeping shoes on, if everyone did it, wouldn't matter. We couldn't really tell from the chart." She pointed to the chart Mr. Dolens had made, indicating that the boys were three different heights.

Shandra spoke again. "Oh yeah, and we found a problem. Dorian was wearing different shoes today, and when we stood him next to his height on the chart he was just a teeny bit taller, so we figured that was a problem. We think you should measure without shoes on, even though it might be sort of hard to measure everyone in every class without their shoes on."

The next group stepped forward to present their findings. They had measured the heels of the boys and found that they were practically identical. They showed the evidence on their poster. They had drawn the shoes of each boy and recorded their measurements. They measured the entire back of the shoe, the height from the heel to the top edge of the shoe, and then from the heel padding inside the shoe to the bottom of the sole. According to their measurements, the heel was about one inch for all three boys, so they decided it would be much the same for everyone.

Under questioning, they admitted that it had been difficult to measure from the inside of the shoe to the bottom, so they had measured with their fingers and estimated. They also hadn't realized that

Dorian had worn different shoes and was no longer the same height against the chart.

After each group had presented, all but one recommended measuring with shoes off. Mr. Dolens asked his students to make a group decision, taking into account the issue of getting all of the first graders in the school to take their shoes off and what they would do if some didn't want to.

Finally, one student proposed that they measure with shoes off, and if someone didn't want to take their shoes off, they could subtract one inch from that person's height. Everyone agreed with this idea.

The entire decision-making process had taken Mr. Dolens's class three days compared with the 10 minutes it had taken Ms. Martinez's class. But Mr. Dolens's class had considered several different issues, and students had supported their ideas with carefully collected evidence and thoughtful public debate.

Several months later, Mr. Dolens's class exchanged their height data with the first grade students from Anchorage, Alaska. There was tremendous excitement the day the Alaskan height data arrived in the mail. It turned out that the Alaskan students were almost an inch taller, on average, than the students in Mr. Dolens's class! The results surprised everyone and prompted several ideas about what might have caused the Alaskan students to be taller. Some thought it might be the colder weather, while others theorized that it might be the different food. At least one student thought that the Alaskan kids might have taken their measurements with their shoes on!

## Building on Knowledge, Interest, and Experience

Both of these cases show ways that teachers build on the knowledge, interest, and experience students bring to school. The activities allowed Mr. Dolens's and Ms. Martinez's students to build knowledge and skill with measurement. In later years, these same students will draw upon this knowledge and skill when interpreting growth patterns in individual plants and when tracking growth in populations.

In both Ms. Martinez's and Mr. Dolens's classrooms, students were proposing and designing empirical investigations to make arguments and claims about appropriate measurement techniques. In Mr. Dolens's class, students had to generate and present evidence for their positions, collect data (on children's heights or shoe heights), structure the data in posters, and explain their positions to their peers. Students in the audience were involved in evaluating their peers' claims, challenging assumptions, critiquing their conclusions, and coming to a classroom consensus based on weighing all of the evidence and claims.

The students came to appreciate that in scientific practice how you measure and observe impacts the data you collect and analyze and your ultimate findings. The students explored the reasons for conducting measurement in consistent ways. They explored the implications of inconsistent measurement practice. In both classrooms, students presented evidence to each other, and sometimes they changed their minds based on new evidence or arguments that undermined previous claims. Mr. Dolens pointed out to his students that in generating evidence for their claims, examining others' evidence carefully, and presenting their work to colleagues they were behaving like real scientists. He used charts and posters to help students consolidate their ideas and make them visible to one another. These public representations of ideas can be revisited later, and students can be asked to reflect on how their ideas have remained the same and how they have changed over time. This helps build the classroom norm that, in science, ideas are constantly evolving based on new evidence. It is important that students step back from evidence-based explanations and consider the plausibility of other interpretations.

Just as scientists do, the students in these classrooms worked within a community on a common problem, striving to account for a wide range of observations or interpretations. Both Ms. Martinez and Mr. Dolens engaged their students in a problem that was compelling and accessible. Every student was able to participate because each had relevant knowledge and experiences to bring to the discussion. Unlike scientists, the students had not yet mastered scientific discourse.

Accordingly, teachers supported the students in making their ideas clear and accessible to others, through spoken language and visual aids. This made it possible for the students to engage in discussion, conjecture, decision making, and argumentation, with evidence.

In important but subtle ways, both teachers carefully tracked students' thinking, including their occasional frustrations. They used particular "talk moves" to ensure that their students explicated their ideas fully and listened well to each other. Ms. Martinez and Mr. Dolens both asked for explanations of specific comments or conclusions made by students when they felt further clarification was needed.

Helping the students explicate and make public their thinking also served both Ms. Martinez and Mr. Dolens as teachers. They were better able to understand their students' thinking about measurement and data display and guide it in productive ways.

To do this effectively, both teachers had to carefully establish norms for discussion, group work, and group presentations. Over a period of months, they emphasized and modeled the importance of listening well, working hard to make their ideas clear to others, and respectfully challenging ideas, not people, with evidence. Over time, their students developed a shared understanding of the norms of participation in science. They learned how to construct and present a scientific argument and how to engage in scientific debates.

This chapter introduces several major themes that we'll revisit throughout this book. One such theme is that children are more competent and capable science learners than we once thought. Their capabilities and knowledge are a resource that can and should be accessed and built upon during science instruction.

Another theme is that science learning can be modeled in important ways on how real scientists do science. Children offer amazing promise for science learning when we compare their knowledge and skills to what scientists do in the course of their work.

Effectively changing science teaching and learning will require dramatic change on the part of those involved in the education system. This book urges the many educators who shape K-8 science learning to reexamine their work in light of current thinking about teaching and learning science. In order to be effective, science learning must be supported by a broad, complex education system that supports and guides good teaching.

In addition to encouraging and supporting instructional practices that are complex and require a high degree of skill and knowledge on the part of teachers, we draw in science assessment, professional development, and school administration as essential pieces to meaningful improvement in science education. The many teachers who are struggling to do their work well, but in isolation, should interpret their struggles in light of this. For teachers like Ms. Fredericks and her contemporaries, who often work without sufficient systems of support, this book will not solve every problem but may offer some help in the science classroom, both in the short term and for the future.

## For Further Reading


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# 2 Four Strands of Science Learning

By looking much more deeply at how students learn science, recent research has produced new ways of thinking about what happens in science classrooms.

Books on science education have often drawn a fairly sharp distinction between scientific content and scientific processes. Content has been seen as the accumulated results of science—the observations, facts, and theories that students are expected to learn. Processes have been seen as the scientific skills that students are expected to master—skills like designing an experiment, making measurements, or reporting results.

Underlying the arguments in this book, however, is a new way of thinking about what it means to be proficient in science and a new framework for moving toward and achieving proficiency. This framework rests on a view of science as both a body of knowledge and an evidence-based, model-building enterprise that continually extends, refines, and revises knowledge. This framework moves beyond a focus on the dichotomy between content or knowledge and process skills, recognizing instead that, in science, content and process are inextricably linked.

This link between content and process is vital because scientific processes almost always take place when students are considering specific scientific content. When children use their ideas about the natural world to design investigations or argue about evidence, it strengthens their understanding of both the phenomena and the means used to investigate those phenomena. Moreover, separating content and process is inconsistent with what is now known about the way scientists actually do science.

Instead of drawing a distinction between content and process, we'll define and describe four learning "strands" that encompass the knowledge and reasoning skills that students eventually must acquire to be considered proficient in science.

These learning strands also incorporate the scientific practices that students need to master in order to demonstrate their proficiency.

The strands of proficiency build on the helpful contributions of science standards documents such as the *Benchmarks for Science Literacy* and the *National Science Education Standards*. These documents set out to characterize the conceptual goals of science education and call for greater emphasis on science as inquiry. The strands of proficiency provide a framework for thinking about elements of scientific knowledge and practice. They can be useful to educators in their effort to plan and assess student learning in classrooms and across school systems. They can also be a helpful tool for identifying the science that is emphasized in a given curriculum guide, textbook, or assessment.

## The Four Strands

The strands offer a new perspective on what is learned during the study of science, and they embody the idea of knowledge in use—the idea that students' knowledge is not static. Instead, students bring certain capabilities to school and then build on those capabilities throughout their K-12 science education experiences, both inside and outside the classroom. Proficiency involves using all four strands to engage successfully in scientific practices.

Another important aspect of the strands is that they are intertwined, much like the strands of a rope.[1] Research suggests that each strand supports the others, so that progress along one strand promotes progress in the others. For example, there is evidence that students can make substantial gains in their conceptual knowledge of science when given opportunities to "do" science, and scientific reasoning tends to be strongest in domains in which a person is more knowledgeable. Students are more likely to make progress in science when classrooms provide opportunities to advance across all four strands.

Many science educators may want to interpret the strands in light of the current language and concepts of science education—for example, mapping the strands to the content, process, and nature of science, and participation, respectively. But it is important to note that the strands were developed because the Committee on Science Learning thought current assumptions about what constitutes the "content, process, and nature of science" are inadequate. In a sense, the first three strands revise and expand common ideas about the content, process, and nature of science to better reflect research and to include greater emphasis on the application of ideas.

## Strand 1: Understanding Scientific Explanations

To be proficient in science, students need to know, use, and interpret scientific explanations of the natural world. They must understand interrelations among central scientific concepts and use them to build and critique scientific arguments. This strand includes the things that are usually categorized as content, but it focuses on concepts and the links between them rather than on discrete facts. It also includes the ability to use this knowledge.

For example, rather than memorizing a definition of natural selection, a child who demonstrates proficiency with scientific explanations would be able to apply the concept in novel scenarios. Upon first encountering a species, the child could hypothesize about how naturally occurring variation led to the organism's suitability to its environment.

Part of this strand involves learning the facts, concepts, principles, laws, theories, and models of science. As the *National Science Education Standards* state: "Understanding science requires that an individual integrate a complex structure of many types of knowledge, including the ideas of science, relationship between ideas, reasons for these relationships, ways to use the ideas to explain and predict other natural phenomena, and ways to apply them to many events."[2]

## Strand 2: Generating Scientific Evidence

Evidence is at the heart of scientific practice. Proficiency in science entails generating and evaluating evidence as part of building and refining models and explanations of the natural world. This strand includes things that might typically be thought of as "process," but it shifts the notion to emphasize the theory and model-building aspects of science.

Strand 2 encompasses the knowledge and skills needed to build and refine models and explanations, design and analyze investigations, and construct and defend arguments with evidence. For example, this strand includes recognizing when there is insufficient evidence to draw a conclusion and determining what kind of additional data are needed.

This strand also involves mastering the conceptual, mathematical, physical, and computational tools that need to be applied in constructing and evaluating knowledge claims. Thus, it includes a wide range of practices involved in designing and carrying out a scientific investigation. These include asking questions, deciding what to measure, developing measures, collecting data from the measures, structuring the data, interpreting and evaluating the data, and using results to develop and refine arguments, models, and theories.

### *Strand 3: Reflecting on Scientific Knowledge*

Scientific knowledge builds on itself over time. Proficient science learners understand that scientific knowledge can be revised as new evidence emerges. They can also track and reflect on their own ideas as those ideas change over time. This strand includes ideas usually considered part of understanding the "nature of science," such as the history of scientific ideas. However, it focuses more on how scientific knowledge is constructed. That is, how evidence and arguments based on that evidence are generated. It also includes students' ability to reflect on the status of their own knowledge.

**Four Strands of Science Learning**

**Strand 1: Understanding Scientific Explanations**

**Strand 2: Generating Scientific Evidence**

**Strand 3: Reflecting on Scientific Knowledge**

**Strand 4: Participating Productively in Science**

Strand 3 brings the nature of science into practice, encouraging students to learn what it feels like to do science as well as to understand what the game of science is all about. Strand 3 focuses on students' understanding of science as a way of knowing. Scientific knowledge is a particular kind of knowledge with its own sources, justifications, and uncertainties. Students recognize that predictions or explanations can be revised on the basis of seeing new evidence, learning new facts, or developing a new model. In this way, students learn that they can subject their own knowledge to analysis.

When students understand the nature and development of scientific knowledge, they know that science entails searching for core explanations and the connections between them. Students recognize that there may be multiple interpretations of the same phenomenon. They understand that explanations are increasingly valuable as they account for the available evidence more completely. They also recognize the value of explanations in generating new and productive questions for research.

### Strand 4: Participating Productively in Science

Science is a social enterprise governed by a core set of values and norms for participation. Proficiency in science entails skillful participation in a scientific community in the classroom and mastery of productive ways of representing ideas, using scientific tools, and interacting with peers about science. This strand calls for students to understand the appropriate norms for presenting scientific arguments and evidence and to practice productive social interactions with peers in the context of classroom science investigations. It also includes the motivation and attitudes that provide a foundation for students to be actively and productively involved in science classrooms. Strand 4 puts science in motion and in social context, emphasizing the importance of doing science and doing it together in groups. Like scientists, science students benefit from sharing ideas with peers, building interpretive accounts of data, and working together to discern which accounts are most persuasive.

Strand 4 is often completely overlooked by educators, yet research indicates that it is a critical component of science learning, particularly for students from populations that are underrepresented in science. Students who see science as valuable and interesting tend to be good learners and participants in science. They believe that steady effort in understanding science pays off—not that some people understand science and other people never will.

The best way to begin thinking about the four strands of scientific proficiency and their interconnections is to see them at work in a classroom, as demonstrated in the following case study.

# Science Class

## BIODIVERSITY IN A CITY SCHOOLYARD[3]

Gregory Walker taught fifth grade in a predominantly low-income urban school in northwestern Massachusetts. It was his fourth year teaching, and he was still learning how to manage a classroom and how to plan and orchestrate rigorous learning activities with an extremely heterogeneous group of students. His school district was working hard to raise student achievement to meet the demands of the state tests. Over 75 percent of the students in his school were eligible for free or reduced-price lunches,

and his district was considered an "underperforming" district and was under close scrutiny by the state.

Despite these challenges, the teachers at Mr. Walker's school were collegial, energetic, willing to open their doors to colleagues and parents, and eager to share their successes with one another. For the past several years, the school had worked hard on improving literacy and mathematics achievement with solid results. Now the school was turning its attention to science.

The school district had appointed a committee of teachers and curriculum specialists to work together for a year to come up with a recommendation for a new science curriculum. In the meantime, teachers were asked to do the best they could to meet the state's science standards and prepare the students for the fifth-grade state test in science.

Mr. Walker's science class used an out-of-date textbook and several old science kits that were missing some key materials. He often stayed up late at night trying to come up with interesting science activities, but he never felt he knew enough to "invent" great science lessons. He was, however, very interested in teaching biodiversity, a topic emphasized in the national and state standards, even though the topic was not well developed in either his textbook or the available kits.

Mr. Walker's interest in biodiversity was not without foundation. He had taken a field biology course in college taught by a charismatic professor. She explained to her students that biodiversity demanded mastery of a world of details, while physics, chemistry, and the mechanistic aspects of biology more often required comprehension of core principles and the skills needed to apply them. The ability to teach biodiversity, she said, entailed knowledge of the characteristics and behaviors that distinguish individuals, species, genera, families, orders, and classes from each other. It required helping students acquire both the tools and propensities to see and characterize variation within and between species. It required a comprehensive knowledge of ecosystem types and functions. And it required an awareness of evolutionary, geological, and human history.

For these reasons, her class, even though it was offered through the biology department, was designed to teach students how to *teach* biodiversity. She hoped that they, in turn, would teach biodiversity to others.

Mr. Walker decided that he could apply many of the lessons he had learned during his college class to the fifth-grade science class he would be teaching that year. Because a major part of his college course on biodiversity had been preparing a local field guide based on weekend trips to a field station, he and a colleague, second-grade teacher Alicia Rivera, decided to work together to develop a yearlong project mapping the plants and animals in their schoolyard. To compensate for the lack of existing science materials, he and Ms. Rivera decided to combine fieldwork with some simple technology involving a computer and a scanner that Mr. Walker brought from home, as well as the school's website. They imagined that in the beginning the simple task of cataloging the species in their schoolyard would occupy much of the students' time. Once fewer new species were found, students could begin to focus on observing the behavior of different species and changes in the density and distribution of populations.

From the college course Mr. Walker had taken, he knew that selecting biodiversity as a theme afforded the opportunity to develop central biological principles important to evolutionary thinking, such as:

- Organisms can be described as collections of attributes and can be distinguished (classified) by variation among these attributes.
- Change in selected attributes of organisms (e.g., plant height) can be modeled mathematically, so that comparative study of patterns of change can be conducted at the organismic level, a level with great initial appeal to students who grow their own plant or care for their own insect.
- The "natural histories" of organisms (e.g., life cycles) could be described and compared.
- Growth can be aggregated at several levels (genotypic, phenotypic, population).
- Population growth can also be modeled mathematically. Heritability and selection transform distributions of selected attributes in populations, giving concrete meaning to differences in levels of analysis.

Moreover, in preparation, Mr. Walker and Ms. Rivera spent time discussing the science behind their schoolyard investigation. They sought out field guides and other text resources which helped them see that understanding behavior is central to both the social and the biological sciences and entails grasping a set of interrelated concepts, including:

- Descriptions of behavior vary in their level of detail (e.g., micro to macro) and in their scope of application (e.g., behaviors of individuals, groups, populations, and species).
- All organisms have repertoires of behavior that are species specific. One can often identify reliable patterns in behaviors. Some behaviors are automatic and relatively inflexible; others are under voluntary control and are relatively flexible.
- The form and/or functions of behaviors may change over the development of an organism. Sometimes a behavior maintains its form while its function changes; other times, organisms develop new behaviors to achieve a similar function.

Mr. Walker and Ms. Rivera spent time discussing the mathematical resources useful in modeling behavior, including representations of frequency, covariation, distribution, function, and classification models. Mr. Walker brought in notes from his college class about domain-specific models of behavior that could be developed with students, including rules, programs, ethograms, and information-processing models.

Ms. Rivera and Mr. Walker also had a large number of students who spoke Spanish at home and a few students who were just learning English. Their hope was that the project would get both English-speaking and Spanish-speaking students excited about producing an online bilingual field guide that would be continuously updatable.

Mr. Walker and Ms. Rivera began the project by arbitrarily dividing the schoolyard in half. The second graders took the west side, which included the grassy front of the school, a large shade tree, a parking lot, an outside play area, and a swampy woodlot where pools formed in the spring, providing a home for frogs.

The fifth graders took the east side, which abutted a street on one side and a sloping ravine that led down to a muddy, rocky stream.

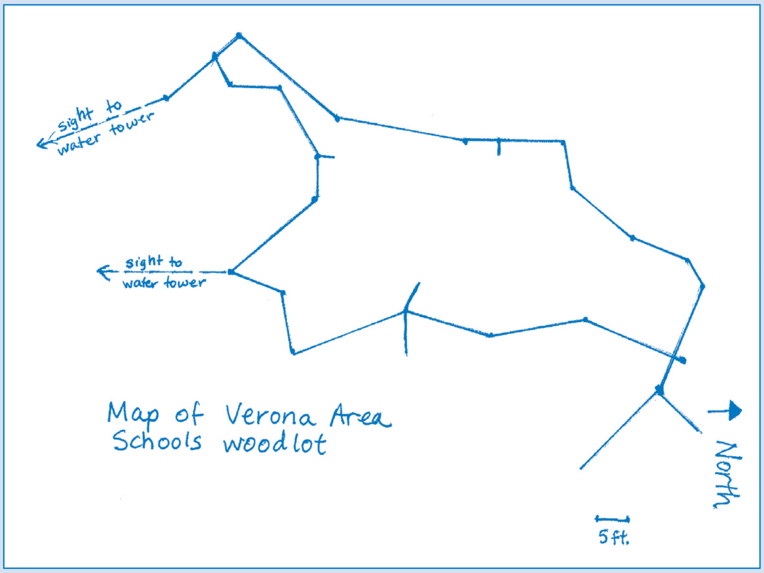


**FIGURE 2-1**

*This map shows a general depiction of the Verona Area Schools Woodlot Trail, before students developed a systematic plan for mapping the distribution and density of common species.*

Although the two classes worked separately, they agreed to follow a common plan: first identifying trees, then shrubs, and then flowers. The two groups met for an afternoon once a month to report to one another what they'd been doing and what they'd found. These monthly "biodiversity conferences" were popular with both classes. Mr. Walker and Ms. Rivera took turns providing snacks for the students, which they called "food for thought."

In preparation for the monthly meeting, both groups of students organized their ideas for presentation, typically in printed handouts, posters, or pictorial form, and they worked especially hard on communicating their ideas clearly. They developed PowerPoint slides of what they began to call "interim reports," "update posters," maps, and sometimes even drawings of the leaves or insects they'd found.

During the first several months, the two classes cataloged trees, shrubs, and flowers. They found that identifying trees was fairly easy, but the students, especially the second graders, had more difficulty identifying shrubs and flowers. Mr. Walker and Ms. Rivera, in private conversations, grappled with whether they should or should not require the students to develop an explicit sampling plan. They suggested that students be organized in mapping their sections of the yard, providing them with graph paper for a grid, but they did not insist on this (see Figure 2-1 for an example of the initial map). They hoped that the need for a more systematic plan would emerge from the students' own questions.

In addition to trees and plants, they identified a few different kinds of animals, including two species of squirrels, one species of chipmunk, several species of birds, and many different insects. They borrowed a number of field guides from the local library (*Peterson's Field Guides* were the favorite), which they used to identify different plants. Shrubs were difficult to distinguish from small trees, and flowers were hard to identify when they weren't flowering. These became topics of intense conversation.

As they cataloged plant and animal species, the students faced several challenges. Using field guides as references was sometimes confusing, as the actual plants they found often looked different from the pictures in the guidebook. Mr. Walker and Ms. Rivera used this as an opportunity to steer students toward the reading of expository texts. When it wasn't clear whether a plant was the same as the one shown in the guidebook, students found other books or materials with information on the same plant. This, in turn, prompted the students to find additional information as they assembled clues: Where is the plant usually found? When does it typically bloom? How tall is it?

Cataloging the animals in the schoolyard was particularly challenging. How could they tell whether they were seeing two different squirrels or the same squirrel twice? Long discussions ensued. Mr. Walker explained that what practicing biologists do to identify particular animals is to put some kind of identifying device on them. This might entail capturing and perhaps even anesthetizing the animal. They might put a colored band on a leg or sometimes a spot of indelible paint (e.g., a green dot on the left rear foot for one squirrel and a red dot on the left rear foot for another squirrel). This, of course, would not be possible in their schoolyard. But, he told them, not all identification requires intervention. Whale biologists, for example, rely on photographs of whales, identifying individuals by the visible pattern of whale lice on their rear flukes.

After much discussion, during which different proposals were considered, the students decided that they could do something similar to what whale biologists do. After a period of observation, they asked if anyone had noticed squirrels with different characteristics—scraggly tails or bushy tails, squirrels with tails that are darker or lighter than their body fur, black versus brown fur, scars or bare patches, etc. The students made drawings, took photographs, and then attempted to record observations of particular individuals or species, according to these characteristics. From there, the students were able to develop reasonably reliable category systems, based on which features were most diagnostic in telling one squirrel from another.

From their initial observations, readings, and collections, the students decided to map their areas more carefully. This interest in more systematic sampling grew out of a lengthy discussion in one of the monthly biodiversity conferences. Although both teachers had encouraged making a grid of the yard to guide their observations, the students initially did not see the need to map or develop a systematic plan. The students had begun with an "Energizer bunny" strategy: look around, write down novel species, and keep doing that until you don't see any more. In comparing results between the two classes—and hence comparing the east and west sides of the schoolyard—the students realized that they needed to be more systematic in figuring out the distribution or density of common species. In order to do this, they shared mapping techniques and some strategies for sampling to characterize the woodlot and ravine areas (using compasses and pacing) and made explicit decisions about where, how, and what to sample (see Figure 2-2).

With more accurate maps, they began to speculate about the causes of variation in plant and animal life. They wondered if a species often grew in one place rather than another because of the other things growing around it. Careful observations that included shade, position on a slope, and distance from a path where the soil is disturbed took on new significance. They noticed that there were more trees and larger trees on one side of the schoolyard than there were on the other, which prompted a great deal of theorizing about the cause: Was it sunlight, soil quality, or amount of water? This, in turn, led to more systematic measurements of tree circumference and height. Mr. Walker and Ms. Rivera realized that the students' decision to use systematic measurement had to be motivated by their own theories and investigations in order to be seen as a necessary and useful technique.

After several months, a number of the students in each class emerged as highly skilled draftsmen

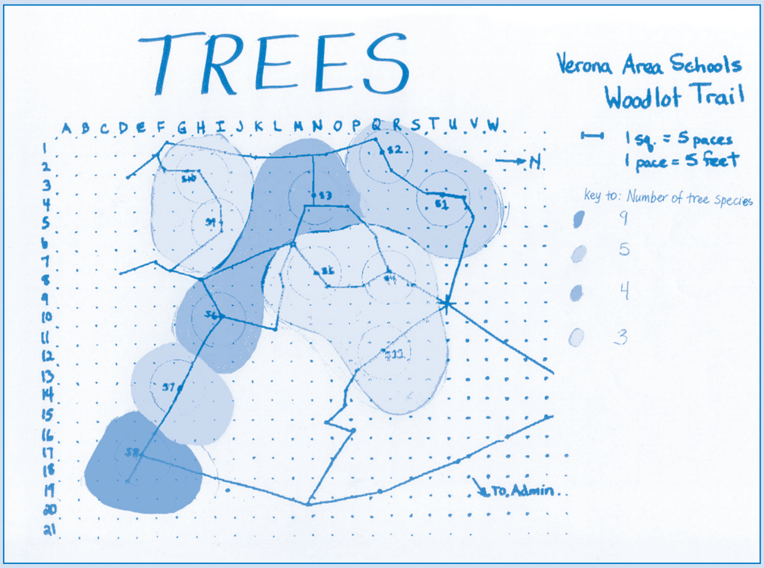


**FIGURE 2-2**

*This map shows a more detailed depiction of the Verona Area Schools Woodlot Trail, with shaded areas showing the number of different tree species in each area of the schoolyard.*

and artists, depicting the details on plant leaves, woody stems, and bark. The second graders created elaborate scrapbooks of pressed plants, and a group of four boys assembled a pinned insect collection. In the spring, the students discovered tadpoles in the pools that had formed by the marsh, and they watched, fascinated, as the tadpoles became frogs.

Several children who didn't speak English emerged as keen observers and were highly valued for their artistic contributions. Others were interested in annotating drawings and making sure that all captions and commentary were done in both English and Spanish. Ms. Rivera, who spoke both languages, was helpful in this as well.

Gradually, interest groups emerged. One group was interested primarily in trees, estimating their age by measuring their circumference and height. In order to overcome the challenge of measuring the heights of tall trees, Mr. Walker built on the children's understanding of the mathematics of triangles. He showed them how to make a simple altimeter, which, along with the Pythagorean theory, the children used to measure the heights of all of the trees in the yard. This gave the tree group an opportunity to discuss variability of measures and sources of measurement error, which they shared with their classmates.

Another group was primarily interested in weeds, which turned out to be much harder to categorize than trees and shrubs. After weeks of debate and discussion, the group realized that the term "weed" could be used to describe any unwanted plant. The students came up with a saying that they displayed on a wall banner in both classrooms: "One person's weed may be another person's flower and another person's dinner." This helped the students realize that how one views the world influences the way one describes it and to press themselves to clarify their assumptions and work to strive for common language and meaning in their scientific work.

Students' interests in the project varied widely, and not all of them were easily drawn into the course. Ms. Rivera and Mr. Walker worked hard to make the children aware of different aspects of the investigation in order to help them identify their own interests in the unit. Some were interested in such areas of study as sustainability, collecting and studying insects (both alive and dead). Some were interested in developing and using such tools as Excel databases and other software packages to aid in drawing. The students who collected and studied the insects pursued their interest over time and eventually focused on investigating insect movement. They focused primarily on the area by the stream, as it seemed less affected by people than other areas of the yard and had more insects. The students compared the locomotion of insects in water with their locomotion on different ground surfaces, such as grass, mud, and pavement.

The students in the insect group at first wanted to classify insects by salient attributes like color or size.

Mr. Walker and Ms. Rivera found it helpful to refocus their attention on more important features like mouth parts, by presenting "tools" analogous to mouth parts (picks, straws, tongs, etc.) along with different kinds of food and asking the children to investigate which types of food can be most easily picked up with which types of "tools." This led to an interesting investigation of the "tools" that different insects had.

A number of students in the fifth grade began to explore the history of different plantings in the yard, interviewing older residents who lived nearby and visiting the local history museum. After extensive investigation, they determined that the largest and tallest of the trees in the front yard was probably older than the school building itself.

By the end of the school year, the two groups had assembled an electronic field guide, with detailed drawings, annotated commentary in both English and Spanish, and a map of flora and fauna organized both by quadrants and by a much finer-grained grid of square meters.

In all, the children had identified 9 species of trees, 12 types of woody shrubs, and 14 species of planted flowers. The field guide contained 47 detailed drawings, with separate chapters on trees, shrubs, flowering plants, weeds, animals, and insects. The two classes presented a print version of their completed field guide to the school, to be placed on reserve in the library. They presented their work via PowerPoint presentation at an all-school assembly.

While Mr. Walker and Ms. Rivera were pleased with the results of the biodiversity project, they knew it was just the beginning. A friend of Mr. Walker who worked in landscaping examined the field guide and pointed out several errors in classification. Moreover, despite the polished presentation for the school and all the information they had gathered, the students had ended up with many unanswered questions. They were still unsure what accounted for the variation in the heights of the trees. They had ruled out differences in soil quality, but not whether the cause had to do with age or sunlight conditions or the species itself.

The following September, Ms. Rivera and Mr. Walker decided to continue their curriculum, which they were now calling "Biodiversity in a City Schoolyard." The students from the previous year wanted to continue their work. In response, the third- and sixth-grade teachers asked to join the project with Mr. Walker and Ms. Rivera.

The second year of the project began with presentations from the students who had developed the field guide the year before. The launching point was the unfinished work and unanswered questions generated by the previous year's second and fifth graders. The introductory session for all of the students included these "hanging questions," as well as a number of new ones. One student wanted to know how many trees over 60 feet tall there were in the neighborhood. Another wanted to map big trees throughout the entire city using global positioning system technology.

The two teachers were simultaneously excited about their past success and nervous about their lack of subject matter expertise. This provided a learning opportunity for everyone. Mr. Walker decided to ask for help from members of the biology department at the local college. He was amazed at the response. Several faculty and advanced undergraduates were interested in visiting the school to discuss the project. When the guest speakers came, the teachers had as many questions as the students, asking about methods for pursuing the students' questions, as well as soliciting factual information.

Despite their concerns about being able to oversee all of these activities adequately, Mr. Walker and Ms. Rivera still felt they were doing many things right. And their concern with the success of the project led them to reach out and find resources they might never have otherwise.

Mr. Walker and Ms. Rivera's study of biodiversity had become a keystone for teaching science in their school. It posed questions of civic and global importance. It integrated diverse modes of inquiry. It called on mathematical, historical, literary, and artistic skills and tools. It provided students not only with a deep and personal relationship with their subject but also with an understanding that learning science is based on continuous and creative investigation: questioning, mapping, reflection, systematic observation, data analysis, presentation, discussion, modeling, theorizing, and explaining. The most exciting part was that their continued investigations inevitably led to more questions. The study of biodiversity offered endless opportunities for learning.

## Examining the Four Strands in Instruction

The "Biodiversity in a City Schoolyard" case provides an example of how the four strands of science learning can be intertwined in instruction and how skills and knowledge are built over time.

### *Strand 1: Understanding Scientific Explanations*

The young students in Mr. Walker's and Ms. Rivera's classes were not starting their study of biodiversity completely from scratch. They all came with some foundation of prior understanding, the result of personal interests and previous experience or interaction with nature. They also had a well-developed sense of the causal regularities, mechanisms, and principles of the biological world, and Mr. Walker and Ms. Rivera were able to activate and build on that knowledge.

Research shows that very young children—even infants—are able to distinguish animals (birds) from artifacts (stuffed animals), even when they have strikingly similar appearances. This may be related to their ability to distinguish intentional agents from inanimate objects, in that animals are distinctive because they are social creatures with desires, goals, and other cognitive and emotional states that help explain their actions.

Young children tend not to know much about the mechanisms that underlie biological processes, such as digestion, movement, and reproduction. However, they have a remarkable ability to track various patterns in the biological world. For example, they understand that food is transformed in a manner that gives organisms the ability to grow and move and that an organism will physically deteriorate if it does not eat. So they understand some of the distinctive processes that are essential to digestion.

Children are also able to recognize particular aspects of or patterns related to living things: that they have an underlying nature and that they are embedded in an ordered system of groups and categories. Indeed, some aspects of children's beliefs about biology are common across cultures, suggesting that ways of organizing the living world are deeply embedded in human thinking.

With opportunities such as the "Biodiversity in a City Schoolyard" course of study, children's ideas about the living world undergo a dramatic change during elementary school. They move from seeing plants and animals as special because they possess a "vital force" to seeing them as animated by metabolic activities. They are able to explore, map, and model habitats and ecosystems. In the process, their conceptual understanding of living things undergoes significant changes: they begin to see interconnections among living things in a dynamic system.

### *Strand 2: Generating Scientific Evidence*

Even though the children were young and many spoke English as a second language, much of what the students in Mr. Walker's and Ms. Rivera's classes were

doing involved generating scientific data. They mapped the schoolyard and developed systematic ways of sampling the number and kind of plants and animals. They collected samples of plants and insects, took careful measurements, and plotted the kind and density of different plant and animal species. They drew careful pictures of stems, leaves, and buds and often cut them open to explore their insides. They also brought specimens inside and carried out sustainability studies of plants in jars, with different kinds of soil, food and sunlight. They created a laboratory to examine the life cycle of butterflies from the caterpillars they found on leaves. They recorded these changes in notebooks, Post-it notes, and wall charts and used these documents to graph changes over time.

All of this documentation became "data" to think about, question, and argue with. Using these data, they could describe and discuss patterns of vegetation and the relationships among vegetation and animal life. With their maps, charts, and evolving field guide, they could raise questions about the evidence they'd gathered and what it meant. If they needed more evidence, they could design investigations to answer specific questions. When their maps of the schoolyard showed a different density of fall woody plants on one side, they collected more systematic evidence of the height of the trees, using handmade altimeters. They found, to their surprise, that the trees on one side of the yard were taller on average. With careful documentation of the height of the trees, the students generated questions about the causes of differential tree height. Was it due to differences in exposure to sunlight or water? Was it because there were different species of trees present? Or was it due to the age of the trees? These questions led to a detailed cataloging of species as well as an investigation of sunlight, ground temperature, and ground moisture. Good evidence led to more questions, which in turn led the students to generate more evidence.

### *Strand 3: Reflecting on Scientific Knowledge*

The students in the two classes had many opportunities to reflect on their increasing knowledge as well as on the puzzles they encountered. In exploring the answer to the question of why the trees on one side of the yard were taller, the students were aware of the limitations of their evidence with respect to the age of the trees. When reporting on their findings after a fieldwork activity, they asked each other questions about the quality and reliability of the data they were collecting. Increasingly, they asked for evidence from one another when causal explanations were proposed.

As the field guide developed over the year, there were disagreements about classifications that needed to be resolved. The students became aware of occasional mistakes and paid attention to how these mistakes were corrected, as well as to how their ideas changed over time. The most obvious example of this was the shift in students' thinking about the differences between weeds and flowers. The field guide became a "collective memory" for the group. Updates to the guide reminded everyone of how thinking can undergo significant change.

### *Strand 4: Participating Productively in Science*

The scientific practices at the heart of the biodiversity work took place both outside and inside the classroom. In addition to fieldwork in the schoolyard (mapping, observing, drawing, plotting frequency), the students actively participated in discussions about their data, their questions, and their emerging conjectures and plans for systematically following up on these ideas. Students worked in small groups and regularly engaged in "cross-talk" sessions in which they exchanged information with other interest groups. And of course there were the monthly biodiversity conferences, moderated by Mr. Walker and Ms. Rivera. On the basis


of both fieldwork and class work, the groups spent a great deal of time refining, revising, and publishing their work so that they could share it with others—other classes in the school, local experts, and members of the community.

The monthly meetings of the two groups were designed to be like scientific conferences, and the students treated them with appropriate seriousness and respect. Attendance was nearly 100 percent on these days in both classrooms, and the students rarely misbehaved. They spent a great deal of time and effort preparing their presentations.

A major point of controversy that played out in the biodiversity conferences involved the question of what defines a "weed." The conclusion that defining a weed was more a matter of interpretation and perspective, as opposed to scientific fact, emerged over a long period of time. Change came about as the result of disagreement, the marshaling of systematic evidence, sustained investigation (which involved some surveying of students, adults, and local gardeners), and even the help of outside experts. Early on, some students proposed surveying the school and taking a vote, while others argued that there might well be scientific evidence they could find to establish a definitive answer. This turned out to be one of the most exciting periods of investigation during the year. Issues of confidence in one's data, the reasonableness and persuasiveness of arguments, and the fruitfulness of certain lines of investigation became the primary focus of the later biodiversity conferences.

## The Interrelated Nature of the Four Strands

While it is possible to separate the strands for the purpose of analysis, in practice the strands overlap. A specific task might function in multiple ways and be a part of multiple strands at once.

For example, in one of the monthly biodiversity conferences, a fifth-grade student, Cara, presented a chart showing plots of trees and calculations of tree heights on two different sides of the school. In showing the chart, Cara said that the tree group had determined how to measure the height of the trees using triangles and the Pythagorean theorem. But their calculations of tree height puzzled them and made them wonder if their data were accurate. A student from the audience asked if the difference might be related to sunlight because he had found in his experiment with wildflowers (growing under different conditions) that a certain wildflower grew faster and taller with more sunlight. In this brief exchange, the students were marshaling scientific explanations, using their own data as evidence, reflecting on their current understanding, and participating in authentic scientific practices as presenters and audience members. All four strands were actively in play.

It is important to emphasize that the different strands inform and enhance one another. They are mutually supportive so that students' advances in one strand tend to leverage or promote advances in other strands. In the case of "Biodiversity in a City Schoolyard," one can see this kind of synergy growing over the course of the investigation. Prior knowledge and understanding help the students as they begin observing and recording. Their different interests lead them in different directions in the early stages of fieldwork. The collection of data (Strand 2) becomes evidence that they use to reflect on and reason with (Strand 3). That, in turn, prompts them to ask more questions and search for information from a number of different sources, which leads them to a deeper understanding of the biological processes at work (Strand 1). As their understanding of biological explanations increases, their questions and their search for evidence grow more complex and focused (Strand 2). For example, as the students come to understand the relationship between food sources and population density, they seek out better techniques for mapping populations and population density in different parts of the yard. They seek out more sophisticated tools for mapping and graphing the density of certain plants and measuring the height of woody plants (Strand 2).

As the sophistication of their tools increases, their evidence grows richer and their techniques more systematic (Strand 2). This also leads to more disagreements about measurements and more discussions about the quality and reliability of data (Strand 3). Over time, the students' reasoning about and understanding of trends and patterns grows more sophisticated (Strand 1) and their questions evolve further. They have more critical discussions about trade-offs among different methods of data collection and the fruitfulness of particular lines of investigation (Strands 3 and 4). As their questions grow more complex and their understanding of what counts as evidence grows more sophisticated, the design of their investigations becomes more nuanced and appropriate (Strands 1, 2, 3, and 4).

The techniques that Mr. Walker and Ms. Rivera used to promote cross-talk and whole-group discussion allowed everyone to have access to the thinking, data, and discoveries of others (Strand 4). At monthly biodiversity conferences, they were able to critique one another's proposals and designs with counterevidence and make constructive suggestions based on previous efforts (Strands 3 and 4).

These investigations led to greater understanding of their schoolyard and of the ways that biologists and botanists understand the world (Strands 1 and 3).

While different classroom activities will emphasize different strands at different times, the goal is to try to bring all four strands into play on a regular basis.

## Science as Practice: Doing and Learning Together

Throughout this book, we talk about "scientific practices" and refer to the kind of teaching that integrates the four strands as "science as practice." Why not use the term "inquiry" instead? Science as practice involves doing something and learning something in such a way that the doing and the learning cannot really be separated. Thus, "practice," as used in this book, encompasses several of the different dictionary definitions of the term. It refers to doing something repeatedly in order to become proficient (as in practicing the trumpet). It refers to learning something so thoroughly that it becomes second nature (as in practicing thrift). And it refers to using one's knowledge to meet an objective (as in practicing law or practicing teaching).

A particularly important form of scientific practice is scientific inquiry. The term "inquiry" has come to have different meanings as the concept has been implemented in curriculum frameworks, textbooks, and individual classrooms in recent years. To reflect this diversity and to broaden the discussion of effective science teaching and learning, the Committee on Science Learning, Kindergarten Through Eighth Grade chose to emphasize scientific practices rather than the specific practice of inquiry. This decision has several benefits. What we say about scientific practice applies to inquiry as well as to many other activities that take place in science classrooms. Focusing on practices also places inquiry in a broader context that can reveal when and why inquiry is effective.

When students engage in scientific practice they are embedded in a social framework, they use the discourse of science, and they work with scientific representations and tools. In this way, conceptual understanding of natural systems is linked to the ability to develop or evaluate knowledge claims, carry out empirical investigations, and develop explanations.

This perspective is a far better characterization of what constitutes science and effective science instruction than the common tendency to teach content and process separately. When students engage in science as practice, they develop knowledge and explanations of the natural world as they generate and interpret evidence. At the same time, they come to understand the nature and development of scientific knowledge while participating in science as a social process.

The diverse group of professionals who collectively build and support children's science learning can draw from the strands in important ways. At the classroom level the individual teacher can analyze the resources at her disposal—the textbooks, trade books, science kits, and assessment instruments—and begin to consider how they support the strands. It is likely that many of these resources will provide uneven or incomplete support for some important aspects of the strands. Some teachers may be well positioned to enhance the available resources by consulting the literature or connecting with local professional development opportunities. For many others, though, it won't be that easy. Despite her strong science background, Ms. Fredericks struggled in the classroom and ultimately found support through an informal network of colleagues who invested time and energy in helping her learn to teach science.

While teacher-initiated activity like that of Ms. Fredericks and her colleagues is essential to meaningful change in K-8 science, it is not enough. School- and district-level science curriculum professionals, as well as professional development opportunities, instructional supervision, and assessment, must all play a part if meaningful change is to occur. Like the classroom teacher, educators at the school and district levels must examine the resources at their disposal, including teacher training materials, district curriculum guides, and materials adoption processes. They can examine, critique, and refine these resources to reflect the strands. They can scrutinize the professional learning opportunities available to teachers through the school system, local universities, science centers, and other vendors to identify ways to advance teachers' understanding of the strands.

The strands offer a common basis for planning, reflecting on, and improving science education. The coming chapters will show that the educator who hopes to integrate the strands into his science curriculum has a lot in common with his students. Educators, researchers, administrators, and policy makers will all have to find ways to advance their own understanding and provide support to one another as they explore and integrate this new model of what it means for children to understand and participate in science.

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# 3 Foundational Knowledge and Conceptual Change

Recent research has revolutionized views of how children's minds develop from infancy through adolescence.

The past 20 to 30 years of research have shown that children come to school with a great capacity for learning in general and learning science in particular. Even preschool children have a rich set of ideas, conceptual frameworks, and reasoning skills. They bring to school rudimentary "theories,"[1] rules of thumb, and general principles that help them separate the world into different domains and organize their expectations about how things ought to behave. Their understanding of the world helps them explain phenomena and solve problems. They are able to engage in surprisingly sophisticated scientific thinking in the early grades and can appreciate deep points about the nature of science.

This is good news for educators committed to improving science learning for students. It also raises a number of questions that are explored throughout this book:

- How does one recognize the knowledge that children bring to school?
- How does one build on this knowledge in ways that specifically support science learning?
- How does one make diversity (in culture, language, or prior experience) a resource rather than an obstacle?
- How does one integrate the four strands of science learning so that each informs and enhances the others?

Elements of all four strands of science learning can be seen in the capabilities and knowledge that children bring with them to school. This means that the four-strand framework described in Chapter 2 can and should begin as soon as children enter school. In this chapter, we focus on the first strand, understanding scientific explanations, by looking at the concepts (and alternate conceptions) that students bring to school.

These concepts evolve as students move from kindergarten through eighth grade as a result of instruction, experience, and maturation. A key challenge for teachers is to build on students' embodied knowledge and understanding of the world and to help them confront their misconceptions productively in order to develop new understanding.

## Identifying a Shared Base of Understanding in Young Children

Children in all cultures encounter and learn about a common set of natural systems or science "domains." Four domains have been extensively studied in infants and young children, and these domains loosely connect to scientific disciplines: simple mechanics of solid bounded objects (naïve physics), behaviors of psychological agents (naïve psychology), actions and organization of living things (naïve biology), and makeup and substance of materials (naïve chemistry). These domains provide solid foundations on which children can build scientific knowledge and skill.

Young children tend to think about their experiences in regard to each domain in similar ways, regardless of their culture, so one can expect that nearly all children will share basic ideas and expectations about these domains. In biology, for example, they correctly identify living and nonliving things and understand that species "fit" biological niches that serve their survival needs. These are just a few examples of the fairly broad basic understanding that young children derive from their experience in the world even before formal instruction begins.

### *Four Domains of Knowledge*

1. Simple mechanics of solid bounded objects
2. Behaviors of psychological agents
3. Actions and organization of living things
4. Makeup and substance of materials

Interestingly, while all children tend to reason in a given domain in similar ways, the type of reasoning they do varies by domain, depending on how the domain functions. That is, their reasoning is domain specific. For example, in physics, children observing a rolling ball understand that the ball has no "desire" to roll down a ramp and that when it hits a wall it doesn't "want" to hit the wall. In contrast, in the psychological domain, children do think a person or animal might have the desire to go down a ramp in order to find food at the bottom or that a person might want to hit a wall because she is angry. Children understand that the causes of physical events are fundamentally different from the causes of psychological events.

Another example of this domain-specific reasoning can be observed in the questions children often ask about living things, in contrast to the questions they ask about manufactured objects. In studies, the questions they ask vary systematically. Children know to ask what a tool, such as a wrench, is used for. They recognize that tools, like many other manufactured objects, often have a purpose. They also recognize that living things, such as tigers, don't have the same practical purpose as tools. Their questions about living things therefore do not usually focus on what the living thing is used for or what its purpose is.

This pattern of thinking or applying reasoning in a consistent way *within* a domain of knowledge but in different ways *across* domains of knowledge seems to hold true regardless of a child's culture or language. Recognizing that virtually all children arrive at school with these types of sophisticated reasoning skills and knowledge is the first step toward building on and supporting effective, ongoing science learning.

Besides their conceptual understanding of the world, children bring to school a variety of general reasoning abilities that can form the underpinnings of scientific reasoning. Preschoolers can be exquisitely sensitive to abstract patterns in the world, and they can use this sensitivity to guide how they think about the behaviors of objects, the nature of living things, the layout of things in space, and many other ideas. For example, young children and even preverbal infants seem to have a strong sense of the principles of cause and effect that goes beyond merely noticing that two things happen together. They have reasonable expectations about how causes precede effects and how certain kinds of causes are linked to specific kinds of effects. Categorization, induction, and many other forms of reasoning seem to be guided by such abstract forms of information.

The foundations of modeling are also evident in young children. Long before they arrive at school, children have some appreciation of the representational qualities of toys, pictures, scale models, and video representations. In pretend play, children may treat one object as a stand-in for another (a block for a teacup; a banana for a telephone), yet they still understand that the object has not really changed its original identity, character, or function. Later in school, they build on similar understanding to use counters to solve simple early arithmetic problems.

Young children's use of models has been validated in a series of laboratory-based studies. In studies by Deloache and colleagues, children as young as three years old are presented with both an actual room and a scale model of that room. They are shown where an object resides in the scale model room and then asked to find the object in the actual room. To be successful in this task children must understand that the model is an object in its own right and that it represents something about the larger room. This suggests that children have rudimentary skills for modeling—a fundamental aspect of contemporary scientific practice—even before kindergarten.

In addition, children are able to understand their own and others' ideas, beliefs, and knowledge, and they have the ability to assess sources of knowledge. The ability to consider ideas and beliefs as separate from the material world is essential for children to engage in debates about the interpretation of evidence. Children also understand that knowledge is distributed unevenly in the world. Before they arrive at school they already have a sense of who has expertise in areas they care about and who does not. This too is critical to scientific practice, as much of science is done in groups, and both scientists and science learners have varying levels of expertise.

Finally, children are eager participants in the quest for knowledge. One of the great pleasures of working with young children is their enthusiasm and lack of inhibition in generating and considering new ideas. They discuss ideas and debate positions with a sophistication that is often surprising.

***Young children begin school with...***

- **rich knowledge of the natural world.**
- **the ability to reason.**
- **an understanding of the principles of cause and effect.**
- **foundations for modeling.**
- **the ability to consider ideas and beliefs.**
- **an eagerness to participate in learning.**

Even very young children can engage in all four strands of scientific proficiency. They typically have significant gaps in their understanding (as do many adults), and their unschooled reasoning abilities may lead them to draw erroneous conclusions. But young children are not the bundles of misconceptions they are sometimes portrayed as being. They are active explorers who have successfully learned about regularities in particular domains of experience in ways that help them interpret, anticipate, and explain their worlds.

Over time and with different experiences, children's common sets of understanding may diverge to some extent, and this diversity can be seen both within a single classroom and across cultures. Nevertheless, children continue to retain a shared base of understanding that can be a valuable foundation for the learning and teaching of science.

## Seeing Nature in New Ways

Science education is sometimes seen as a straightforward process of filling students up with facts. According to this line of reasoning, if students learn enough concepts, definitions, and discrete facts, they'll understand science.

Learning new facts *is* important in science education. Young children won't deepen their understanding of living things, for example, without learning about a variety of living things and their characteristics. But learning facts alone is not enough. To understand science, children also need to view facts in broader contexts of meaning. They need to reposition the ideas they bring with them to school within a larger network of ideas. They need to learn how to think about scientific explanations. Researchers group all of these kinds of changes in thinking into the general category of conceptual change.

The elementary and middle school years can include impressive periods of conceptual change. Children can have dramatic new insights that change the way they understand a whole domain. They can come to new understandings that literally change their lives.

Conceptual change of the kind that is needed in K-8 science instruction can be difficult to engineer. Many teachers have their students do experiments or make observations with the hope that scientific understanding will miraculously emerge from the data. Being exposed to new information, however, is not the same as understanding or integrating that information into what one already knows. Real conceptual change requires that deeper reorganizations of knowledge occur.

Students who are proficient in science know more than mere facts. Their proficiency arises from the organization of their knowledge. Developing expertise in science means developing a rich, interconnected set of concepts—a knowledge structure—that comes closer and closer to resembling the structure of knowledge in a scientific discipline. When students understand the organizing principles of science, they can learn new and related material more effectively, and they are more likely to be able to apply their knowledge to new problems.

## Types of Conceptual Change

There are several different types of conceptual change, some of which are more difficult to achieve than others. Many educators aren't aware of the different levels of difficulty, so they don't adjust their instruction when confronting different cases. It isn't always easy to know which kind of change is needed, and some change will require more time and effort on the part of both teachers and learners. Here we consider three broad types of conceptual change, beginning with the easiest and progressing toward the most challenging.

### *Elaborating on a Preexisting Concept*

The easiest kind of conceptual change involves elaborating on an already existing conceptual structure. In biology, for example, students may learn how species' anatomical features (e.g., teeth) convey information about the animal's lifestyle (e.g., diet). Later they might investigate other body parts (e.g., claws, reproductive system) and extrapolate other behaviors (e.g., hunting, mating, cooperating). As students build a foundation of conceptual understanding, extending it with new evidence, knowledge, or experiences that fit well with their current thinking can be relatively easy to accomplish.

### *Restructuring a Network of Concepts*

A more challenging type of conceptual change involves thinking about a preexisting set of concepts in new ways. Grasping the idea of air as matter, for example, requires a change in understanding of the concepts of both air and matter. Once this new understanding of air is fully integrated, the old idea that "air is nothing" is no longer relevant and can be discarded.

Restructuring a network of concepts can also involve uniting concepts previously thought to be fundamentally different or separate. For example, children may initially see liquids and solids as fundamentally different from air. Later they may come to see that all matter is made up of tiny particles and can exist in different "phases." This requires a shift from thinking of matter as something that can be directly perceived (as something you can see, feel, or touch) to something that takes up space and has mass. Similarly, they must shift from seeing weight as something that is defined and assessed perceptually (how heavy something feels) to a magnitude that is measured and quantified. These steps are necessary if students eventually are to differentiate between weight and density. This type of conceptual change can be difficult and may require extensive and repeated opportunities to reexamine and think about the concepts in question.

### *Achieving New Levels of Explanation*

Perhaps the most challenging type of conceptual change involves achieving new levels of explanation for particular phenomena; this type of conceptual change is necessary for the advance of students' scientific understanding. To understand atomic-molecular theory, for example, they need to understand that materials consist of atoms and molecules, and they need to understand the behaviors and interactions of these microscopic constituents of matter. These new levels of understanding provide for a much deeper understanding of many other phenomena, and they connect explanations in one area of science to explanations in other areas of science. For example, once students understand atomic-molecular theory, they are in a position to understand the basic biological processes of living things.

Developing new levels of explanation can be challenging because fundamental conceptual change requires that existing concepts be reorganized and placed within a larger explanatory structure. Learners have to break out of their familiar frame and reorganize a body of knowledge, often in ways that draw on unfamiliar ideas. Because of the complexity of this process, students are likely to require extensive and well-supported opportunities to work on the development of these new levels of explanation.

**Types of Conceptual Change**

1. Elaborating on a preexisting concept
2. Restructuring a network of concepts
3. Achieving new levels of explanation

## Using Prior Knowledge to Make Sense of the World

One common approach to science education in the past has been to focus on students' "misconceptions." Children often use their observations and common sense to arrive at conclusions about the world that are incomplete or incorrect. The extreme version of this view is that a kindergartner arrives at school with a bundle of mistaken ideas that need to be corrected.

A more productive way to look at these misconceptions is to see them as children's attempts to make sense of the world around them. It is true that science instruction should ultimately aim to have children understand scientific explanations of natural phenomena, but if one jumps to scientific explanations too fast, students will fail to master science in meaningful ways. Often their ideas are parts of larger systems of thought that make sense to them, even though they may be wholly or partially incorrect.

Consider, for example, that many children (and adults) believe that temperatures in the summer are warmer than those in the winter due to the distance between the sun and earth. This is incorrect. Scientific accounts would point to the length of the day and the tilt of the earth as factors that account for seasonal temperature change. However, underneath the child's reasoning is a way of thinking that works. The child knows, for example, that when she moves her hand closer to a radiator, it feels hotter. She can use this knowledge to navigate the world. The child who follows this kind of reasoning is linking her own experience with radiators and other hot objects, to the seasons, a new problem that she cannot experience physically. She is essentially testing a "theory" against a new observation.

What we call misconceptions may be necessary stepping-stones on a path toward more accurate knowledge. They may coexist with some accurate ideas about the natural world. Mistaken ideas may be the only plausible way for a child to progress toward a more accurate understanding of scientific concepts. And not all errors necessarily require instructional intervention. For example, very young children often believe that individuals can become giants by eating heartily, that death can be reversed, or that if you break material into successively smaller pieces will make it disappear. While all of these views are obviously incorrect, they will generally self-correct without instruction as children go about their lives.

Some aspects of modern scientific understanding are so counterintuitive and "unnatural" that a child is highly unlikely to arrive at that understanding without explicit instruction. Understanding atomic-molecular theory, for example, calls for children to imagine matter at a scale far removed from their everyday experiences. Their view that the kinds of materials in the world are infinitely varied is not easily reconciled with the notion that there are only about 100 different kinds of atoms on earth.

While young children generally have many misconceptions about air, in the later years of elementary school they can begin to develop an initial macroscopic understanding of matter. They can begin to determine whether all material entities have some properties in common and what those properties are. In this way, they can start articulating a general concept of matter that was initially implicit in their notions of kinds of materials. They can develop the idea that objects of different materials are made of something that continues to exist, takes up space, and has weight across a broad range of transformations.

Science Class

# MOLECULES IN MOTION[2]

**The following case study involves a classroom of seventh graders struggling to understand a set of new and difficult concepts. It focuses on a specific domain of scientific knowledge—the nature and properties of matter, including gases. At least some of this material will be unfamiliar to most educators—in fact, most adults struggle with the properties of gases and air pressure. Focusing on a specific example of teaching that incorporates all four strands demonstrates the power of using the strands together to engage kids in actively doing science. It also makes it possible to dig deeper into some of the new perspectives on conceptual understanding and scientific proficiency that offer so much potential for science education.**

Michelle Faulkner, a seventh-grade science teacher, was beginning a unit on air, called "Molecules in Motion," as an introduction to the atomic-molecular theory of matter.

## THE ATOMIC-MOLECULAR THEORY OF MATTER

**The atomic-molecular theory is a well-established body of scientific thought that helps make clear the properties of substances, what things are made of, and how things change (and do not change) under varied environmental conditions, such as heat and pressure. The atomic-molecular theory accounts for visible as well as invisible (microscopic) aspects of substances.**

Ms. Faulkner had two reasons for starting with air pressure demonstrations at the outset of this unit. The first was that the textbook she used in class introduced the atomic-molecular theory with dramatic air pressure demonstrations. Her second reason was that she knew these demonstrations would produce surprising and unexpected outcomes that would elicit students' thinking about experiences they've had with air pressure. The students were likely to think they knew what was happening in the demonstrations, because they would be observing and working with everyday objects and situations familiar from their own lives. This familiarity and assumed knowledge would elicit a number of predictions and theories from them. Ms. Faulkner knew, however, that her students would quickly discover that their usual explanations or assumptions did not, in fact, work well to explain what was going on. This, in turn, would encourage them to be more open to exploring new tools and models and to developing new explanations.

The air pressure demonstrations were dramatic because, although air is invisible, air *pressure* pushes in every direction with 14.7 pounds per square inch at sea level—a huge amount of force. Once students began to discover how air pressure works, Ms. Faulkner hoped they would be motivated to greater exploration and mastery of other related scientific phenomena, such as the nature of molecular motion and the effects of heat.

Ms. Faulkner's seventh graders loved to see chemical reactions, and the grander the better. The problem with many of the demonstrations in their science textbook was that they never really understood the concepts behind the outcomes they produced. They predicted what would happen, invariably found the results surprising and interesting, but due to time constraints were forced to move on too quickly to other demonstrations, memorizing vocabulary, and completing worksheets. The demonstrations also often overestimated the students' knowledge and experience, subtly communicating the message that, if only they were smarter, they would be able to understand the outcomes better. This time, Ms. Faulkner was determined to make sure that her students saw themselves as "doing science," not just seeing cool effects or memorizing vocabulary for tests.

The day she began the new unit Ms. Faulkner arranged in front of the class an empty 10-gallon aquarium, several different-sized drinking glasses, and an empty glass milk bottle. She asked two students to fill the aquarium with water. Then she added some blue food coloring so they could better see the contrast between the water and the air.

Ms. Faulkner had chosen this particular demonstration because she believed it made sense to start with something her students had probably seen before and could demonstrate to their parents later at home. As her science students entered the classroom, she called for them to join her around a central work area with the aquarium on a table in the middle.

"You've probably had this happen to you while doing the dishes," she said. "And it's very strange." She chose a small drinking glass from the several she had gathered and put it into the aquarium, turning it sideways so that all the air bubbled out. When the glass was fully immersed in the tank, she turned it upside down and slowly raised the bottom, bringing the glass almost completely out of the water (see Figure 3-1).

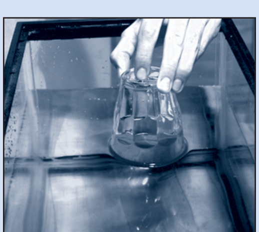

**FIGURE 3-1**
*Small inverted glass being submerged in water.*

The students watched as the water stayed in the glass above the tank, as if by magic. Someone said, "Cool, it's like the water's stuck in the glass." At that moment, the rim of the glass broke the surface and the water flowed out in a rush. Everyone laughed.

"Do it again," someone called.

"Do it with the taller glass," Alliyah said, "and see if that works."

"That's a great idea," Ms. Faulkner said. She was thrilled that the kids were proposing their own ideas for demonstrations, and she was happy to follow their lead. She asked Alliyah to try the experiment with the bigger glass, since it was her idea.

Alliyah placed the glass in the aquarium, turned it upside down, and filled it with water. As she lifted the bottom of the glass slowly from the water in the tank, the water came with it (see Figure 3-2).

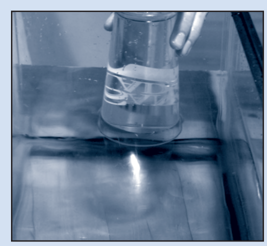

**FIGURE 3-2**
*Large inverted glass being lifted out of the water.*

"Could we try it with an even taller glass?" asked Eriziah. "Or how about that graduated cylinder?"

"Go ahead and try it, Eriziah," said Ms. Faulkner. As with the other two glasses before, the water stayed in the graduated cylinder as Eriziah lifted it out of the tank (see Figure 3-3).

"So what's going on here? What's *making* the water stay in the glass?" Ms. Faulkner asked. No one answered. Then Damian called out, "Suction! The water gets sucked up into the glass like a vacuum!"

"You know what, Damien?" Ms. Faulkner responded. "A lot of adults would guess the same thing. They would say, 'A vacuum sucks the water up into the glass.' But I'll tell you a saying that I learned in my physics class in college: 'Science never sucks!'" The group erupted in laughter.

Ms. Faulkner had expected that one of her students would suggest suction or a vacuum as the cause. This happened every time she taught students about

**FIGURE 3-3**
*Graduated cylinder being lifted out of the water.*

air pressure. Suction as an explanation made sense to students because they'd had actual experience with it. Drinking a milkshake through a straw, for instance, felt like "sucking" liquid into your mouth.

Ms. Faulkner wanted to give her students some time to think about this explanation, rather than simply telling them it was not valid. She also wanted them to question their assumptions and move beyond the idea of suction just because it sounded scientific. She told them that they would explore the issue in depth, amazing themselves and their parents by the end of the unit by knowing more about the physics of air pressure than most college graduates do.

Then she briefly set out the plan of action. She would do one more group demonstration. Then they would work at different stations around the room, called "situation stations," in groups of four, exploring different activities with air and water. They would have a short amount of time to rotate through all of the different stations, after which they would choose one station to focus on. Each group would put together a report for the rest of the class, trying to explain what was going on at their particular station.

After explaining the plan of action, Ms. Faulkner took the top off a clean mayonnaise jar and passed the jar around, asking the students to tell her what was in it. They turned it upside down, examining it closely. One student sniffed it and said, "Nothing." Another said doubtfully, "Air?"

"So we have two different ideas on the table," Ms. Faulkner said to the class. "What do the rest of you think?" Surprisingly, the students had a lot of different ideas about this. Some thought both ideas were possible, because, as Jessa said, "air sort of is nothing, except if the wind is blowing."

As the students shared their ideas, Ms. Faulkner recorded them on a large piece of chart paper. She titled the chart "What We THINK We Know About Air," reminding them that this was just the beginning of the investigation and their ideas were sure to change. She explained that it was important for them to record their ideas now so they could look critically at them later and see how they had changed over time, as more evidence was gathered.

Finally, Ms. Faulkner said, "Let me do one more demonstration that will add a little more data and help us think about air."

The demonstration was designed to show the students that air took up space even though it was invisible. Ms. Faulkner balled up a paper towel and stuck it in the bottom of a large glass in such a way that it would stay there and not fall out when turned. She turned the glass upside down so the opening was facing the water in the tank (see Figure 3-4).

"I'm going to push the glass down into the water. What do you think will happen? Will the paper get wet?"

Everyone wanted to talk at once. Ms. Faulkner told each student to turn to the person next to them and discuss their ideas. The room filled

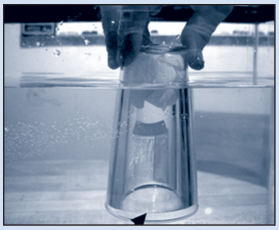

**FIGURE 3-4**
*Partially submerged upside-down glass with balled-up paper towel. Will the paper get wet?*

with talk as the students discussed with their partners the experiment they were about to try. Ms. Faulkner

circulated around the room and listened in on different conversations, noting a range of predictions.

After a few minutes, she brought the students' attention back to the front of the room and asked different partners to share their predictions, which she wrote on the whiteboard. There were four different predictions:

1. The glass will be filled with water and the paper will get wet.

2. A lot of water will go in the glass but the paper will not get wet.

3. A little water will go in the glass but the paper will not get wet.

4. No water will go in the glass and the paper will not get wet.

Ms. Faulkner asked the students to vote, by a show of hands, for the prediction they agreed with. She explained that the voting was intended not as a basis for determining correctness but to let everyone get a sense of each other's views of the most likely outcome.

Most of the students voted for Prediction 1, several for Prediction 2, and a few for Predictions 3 and 4. Then Ms. Faulkner asked the students to explain the reasons for their predictions, telling them they were free to change their minds at any point if they heard something that convinced them to rethink their position. April went first because she and her partner had proposed Prediction 1.

"At first we thought the water would just go into the glass, because, you know, it seems like there's nothing in there," April said. "But then I heard someone else saying they'd done it and no water went in, and I changed my mind. I guess, like Joanna said, there's air in the glass and the air won't let the water in."

Phuong spoke next. She was from Vietnam and had lived in the United States for only two years, but she was fascinated by science.

"I say 4. I don't think the water will go in because air is everywhere in the glass but not where the paper is."

Ms. Faulkner said, "So are you agreeing with April? You're both saying no water at all will go in the glass and the paper will be dry?" Both girls nodded.

Phuong continued, "I know air is real. It takes up space and keeps water away from the paper."

Ms. Faulkner asked for someone who had voted for Prediction 3—predicting that a little water would go into the glass—to explain their reasoning. Joanna volunteered.

"Well, actually, I think this is probably wrong, but me and Tanika were thinking that water is heavier and has more force than air, and it might force the air into a smaller and smaller space, and even squish up the paper. But we agree with Juanita and April. We're pretty sure the paper won't get wet."

Finally Ms. Faulkner did the demonstration. The students watched, craning their necks and getting out of their seats to see the aquarium, as she pressed the upside-down glass slowly into the water (see Figure 3-5).

It was difficult to see what was happening because everything looked blue. One of the students pointed out that the paper wasn't getting wet, and the water went only a little way up into the glass. Someone else noticed that the farther down into the water the glass was pushed, the more water went into it.

**FIGURE 3-5**
*Fully submerged glass: only a small amount of water gets in.*

Ms. Faulkner pulled the glass out of the water, took out the paper, and showed it to everyone. It was completely dry! To prove it, she passed the paper around to each student.

"So what have we figured out with this experiment?" Ms. Faulkner asked. "Which prediction fits the results the best, and why didn't the paper get wet? Go back to your seats and let's talk about this."

As soon as he sat down, Jeremy waved his hand excitedly. Ms. Faulkner waited patiently for more hands to go up. After about 10 seconds she called on Tanika, who didn't typically volunteer to speak.

"I think what we figured out is that the glass has air in it and that the air keeps the water out," said Tanika. "Even though you can't see it, it's there. And the reason the water went in a little, is like what Joanna and I were saying, that the water is maybe stronger than the air and kind of forces it into a smaller space."

"Can you say more about that?" asked Ms. Faulkner.

"Maybe it's like forcing a suitcase closed. You press all the clothes down and even though it's the same amount of clothes, they take up less space."

"That's a really interesting way of thinking about the same amount of stuff taking up less space," said Ms. Faulkner. "Let me see if I understand what you're saying. Are you saying that the air is getting pressed up by the water, or compressed?"

Tanika nodded. "It's like the air is getting squished."

Ms. Faulkner added the words "air is squishable or compressible" to the "What We THINK We Know" chart.

"Are there any other things we think we know about air? Turn to the person sitting next to you and talk for a minute about both of the demos we've done. I want you to think about anything you think you know about air. And talk about what the bases for your claims about air are and how certain you are about your ideas."

Ms. Faulkner circulated among the students. Everyone seemed to be talking, even students who were usually reluctant to speak in a large group.

After calling the group back into session, she decided to start with Jorge and Salizar, who felt certain that air was everywhere. She'd overheard them speaking both in English and Spanish, and she'd heard the word *moléculas.* She called on Jorge, the quieter of the two, to explain what he and his partner had come up with. Ms. Faulkner stood poised to write on the "What We THINK We Know" chart, and she reminded them again that these were just "first draft" ideas, as she called them, that would probably change a lot over the course of the unit.

Jorge spoke first. "Me and Salizar, we think air is everywhere. *Pequeñitos, moléculas.*"

"I read in a book that molecules are really, really small, too small to see without a microscope," Salizar said.

Ms. Faulkner wrote, "Air is everywhere, made up of tiny molecules."

Other students shared their ideas. Joanna spoke for herself and Sherrie.

"Well, we sort of agree and sort of disagree. We don't think there's air in space. Maybe there's air everywhere on earth, but not really *everywhere.* We're not completely sure if there's air on the moon, but we're pretty sure there's no air in space. That's why astronauts have to wear spacesuits." Everyone laughed.

Ms. Faulkner said, "Do you want me to change our 'What We THINK We Know' chart?"

Jorge suggested adding "on earth" to "air is everywhere."

Shanita went next. "Air is a gas, right? Not a liquid or a solid. The molecules are moving around really, really fast. We learned this in sixth grade, but I can't remember the difference between molecules and atoms."

Ms. Faulkner recorded these ideas, with question marks next to "moon" and "atoms." She felt the class had made a great start. She directed them to a much smaller wall chart, which showed their eight assigned groups and the stations they'd specialize in. Around the room were four very different set-ups, each involving air and water, making use of soda bottles, cups and paper, straws, and large and small graduated cylinders. She told her students they would have 5 minutes to spend at each of the four different stations. They would then have 15 additional minutes to spend at the station they would specialize in, and they would continue the next day as well. Because there were two different versions of each station, each of the eight groups had its own set-up to explore in depth.

For the next 20 minutes, the students moved from station to station in 5-minute blocks, reluctant to leave each station when Ms. Faulkner's timer rang. When it was time to specialize, the students settled around their designated stations and began working. They took notes and drew pictures in their lab notebooks, talking excitedly.

After 15 minutes, the bell rang. The students were so engrossed in their stations they didn't want to stop. Ms. Faulkner was pleased and told them they'd have more time the next day.

Over the next several days, each of the groups attempted to explain what was happening at their specific station. Each group developed a poster that showed the demonstration in action and


tried to explain what was pushing what. Groups presented to the class, and the students in the audience responded with questions, challenges, comments, and suggestions based on what they had discovered at their own stations. Ms. Faulkner made sure that the discussion stayed focused on what was pushing what, in what direction, and on what was causing change to occur.

After the last group presented, Ms. Faulkner told the students she wanted to try to consolidate their findings. The "What We THINK We Know" chart was now full of new notes that the students had added on their own, such as "air pushes up and down and sideways," "air has more force than water," and "air is squishable and can be made smaller." There were still, not surprisingly, several explanations that used the notion of a vacuum or suction.

Ms. Faulkner told the class that she was going to start a chart called "Wall of Accepted Scientific Facts."

"These are ideas about air that are currently accepted as fact by the scientific community," she said. She pointed out that some of the facts were the same as the ideas the students themselves had come up with, while others had taken scientists hundreds of years to figure out. Some ideas, she explained, might be hard for them to believe.

"I'm going to put up these facts, and we're going to see if we understand and accept them or if we still have questions." She told the class that 100 years ago a wall of facts about air would have looked different, and it might look a bit different 100 years from now. "We still might want to add to these, or rephrase them a bit as we continue our unit, but these have a different status than the ideas in our "What We THINK We Know" chart."

Of the facts she put on the "Accepted Facts" chart was one they'd already proposed—that air was all around them, even though they couldn't see it. She confirmed that it was made up of tiny, tiny particles—air molecules—so small they couldn't be seen with a regular microscope. As Shanita had said, air molecules are constantly moving, very fast, in *every* direction.

Ms. Faulkner demonstrated this fact, pointing up under her chin, pressing on the outside of her nose, even on the inside of her nostril. She explained that the air was pressing equally everywhere, on the front and back of her ear lobe and on the outside of their noses as well as the inside. "Otherwise your nostrils would collapse (she pressed her nostrils closed) and you wouldn't be able to breathe! So there's just as much air pressure on the inside of your nostril as on the outside. If something is not moving, it doesn't mean that there's no air pressure. It means the forces of the air are balanced—pushing equally in all directions. So air molecules are bouncing every which way—down, sideways, up—on every square inch of my body. But here's something really important. Scientists don't say that the air molecules *want* to move or *decide* to move. They just move. They don't want or try or desire to move. There's no intention or knowledge. It's not like they *know* there's a door open and decide to go out the door. Instead, they get pushed by another molecule and hit a wall, bounce off, and by chance, they bop out the door." She wrote on the "Accepted Facts" chart:

- Air molecules are constantly moving, but without intention or knowledge.
- Air molecules are moving very fast in every direction, and they don't stick to one another, so they can't pull; they only push.

Then Ms. Faulkner added some more "surprising facts," as she called them. She told the kids that scientists often say we live at the bottom of an ocean of air. "Scientists think of both air and water as fluids. Fluids push in every direction—up, down, and sideways—just like you saw in your stations. And with both air and water, there's more push, more force, the deeper down you go. Remember when you found that it got harder and harder to push the drinking glass into the aquarium?" The students nodded.

Shanita said, "Oh yeah, and remember how we pushed an empty, upside-down glass into the aquarium and the further down we pushed it, the more the air got squished, or um, compressed? It seemed like the water had more force the deeper in the tank we went."

"That's another demonstration of the way that the pressure in a fluid is greater the deeper down you go," Ms. Faulkner said. "And air is also a fluid. The air molecules at the bottom of the 'ocean of air' are more squished together, or compressed, at sea level because of the weight of all the air molecules above them. In fact, at sea level, there's 14.7 pounds of air pushing on every square inch of your body! Who can think of something that weighs that much, almost 15 pounds?"

Eriziah said, "I have a 15-pound dumbbell at home, and man that thing is heavy!" "Maybe two gallon jugs of water one on top of another?" Shanita volunteered.

"Yes, but I'm talking about 14.7 pounds per square inch, don't forget," said Ms. Faulkner. An adult man has about 100,000 pounds of air, pushing in every direction, on his body, up, down, sideways." She drew a square inch on her arm in blue magic marker. "There's 14.7 pounds, almost 15 pounds, of air pressing down right here."

"How come we can't feel it?" Eriziah asked.

"Great question." Ms. Faulkner said. "We can't feel it because we're used to it. Our bodies—and every living thing on earth—have evolved to live under these conditions. So it's normal for us. But the change in air pressure is why your ears pop when you hike up a mountain or fly in a plane. If you took an inflated balloon that you blew up here, where we're close to sea level, and carried it all the way to Denver, which is a mile above sea level, the balloon would be larger in Denver because there'd be fewer air molecules hitting the balloon on the outside, so there would be less resistance against the molecules inside the balloon."

A few of the students were beginning to think about the first demonstration again, which many still explained as having to do with suction.

"Wait a second," Damian said. "You're saying the water is *pushed* into the glass, not sucked in?"

Ms. Faulkner asked if anyone could put into their own words what Damian had said. Eriziah wanted to try.

"Damian said the air wasn't sucked into the glass like with a vacuum, like he first thought it was."

Ms. Faulkner nodded. "But why can't the water get sucked into the glass? Why can't the air in the glass suck up the water?"

Ms. Faulkner used her trick of silently counting to 10 before speaking, in order to give her students time to think.

Finally, Tanika raised her hand. "Is it because the air molecules are moving so fast, like it says on the wall of facts, they can't pull, they can only push?" She paused. "So air can't pull or suck? It can only push?"

"I'm getting it, I think," said Damian. "The water is *pushed* into the glass by the air pressing down on the surface of the water in the aquarium? It's like the air is forcing or squirting the water up into the glass. Like if you slap your hand down on water, it sort of splashes up?"

"Can anyone remember how much pressure there is, how much force there is on every square inch of the water in the fish tank?"

Jorge looked up at the wall of facts and said, "14.7 pounds per square inch of air pressing on the water."

Then Ms. Faulkner gave them an example, which she sketched on the board (replicated in Figure 3-6). If instead of using a regular glass, upside down, to pull out of the aquarium, they used a glass that had a one-square-inch opening, like a rectangular bud vase, the water in the vase would weigh however much a column of water one inch by one inch weighs. That depends, of course, on the height of the column of water, because the more water in the column, the more it would weigh. Still, there was no way that the water in a column of 5 inches would weigh 14.7 pounds. As a result, the air pressure on the surface of the water would keep the water in the glass.

Ms. Faulkner's diagram looked something like this:

Phuong asked a question that Ms. Faulkner wasn't anticipating. "How much *would* the water weigh in that bud vase if it was like 5 inches high?" Ms.

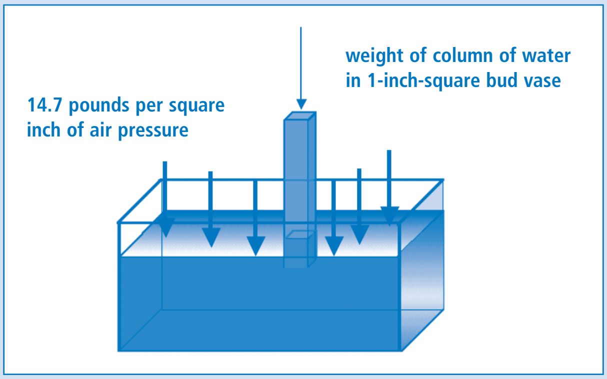


**FIGURE 3-6**
*Ms. Faulkner's diagram of air pressure.*

Faulkner decided she would follow Phuong's lead and take a bit of a detour to explore her question. She sensed that figuring out the weight of a column of water that was one inch by one inch might help her students, down the road, in thinking about pressure more generally as a ratio of force per area.

She asked the students to propose ways they could investigate the answer to Phuong's question. Again she wrote proposals, figuring someone might come up with a solution that the class could work on as homework. A number of suggestions were proposed:

- Get a hollow one-cubic-inch container and weigh it before and after you fill it with water and subtract the weight of the container. Then multiply that by 5, for the 5-inch height.
- Measure the aquarium carefully to find out how many cubic inches it holds, and then weigh it both empty and filled with water. Then subtract the container and divide the total by the number of cubic inches. Multiply that by 5.
- Ask a scientist!
- Get a syringe and fill it with the number of milliliters of water that would equal a cubic inch of water and weigh the syringe with and without water.

Finally, much to Ms. Faulkner's surprise, Salizar called out, "Just Google it!" He walked over to the computer and "Googled" *weight of cubic inch of water* and less than 5 seconds later said, "I've got it! Water weighs 0.036 pounds per cubic inch or 8.33 pounds per gallon." Ms. Faulkner wrote down the results. Shanita added, "That's way less than the 14.7 pounds per square inch that the air is pressing down with."

Ms. Faulkner directed the students back to Phuong's original question. "How much would the water in this 5-inch-high bud vase weigh? Everyone take a minute to figure it out and then talk to the person sitting next to you."

There was silence for a few moments as students worked alone, and then partner talk took off. Two students showed their work—drawing 5 cubic inches on top of one another and multiplying Phuong's results of 0.036 pounds per cubic inch by 5 inches, with the answer of 0.18 pounds of water. There was uniform agreement that this was how much the 5-inch column of water would weigh.

Jason asked if there would be more force pushing the water into the glass in a larger aquarium because there would be more total pounds of air on the surface of the water. "Or what if it was like a huge swimming pool full of water?"

"Jason has asked a really important question," Ms. Faulkner said. "He asked if there would be more air pressure pushing down on the water in a bigger tank, or a swimming pool, or an ocean? The answer that the science community would give is that the pressure would be the same on every square inch, so the amount of water doesn't matter. It's the weight of the air per unit area." She reminded them that pressure is always a ratio, a relationship between two things—force per area.

The concept of a ratio, Ms. Faulkner knew, was an important one in science, and the class had spent a great deal of time learning about ratios and using different analogies to understand them.

This time, Ms. Faulkner used an analogy that related directly to pressure. She asked her students to imagine all of the girls in the class walking across a lawn in high heels versus flat-soled running shoes. Everyone could imagine right away that the girls would make a deeper indentation in the dirt if they were walking in high heels.

"You weigh the same, but the pressure on the high heel is pressing on a much smaller area. Pressure is a ratio: how much force there is in relationship to how much area there is." Then Ms. Faulkner brought them back to the situation in the aquarium. "So even if the surface area of the water is huge, what matters is how many and with how much force the air molecules pound each square inch of the surface of the water. Wherever you are, at sea level or in the mountains, you don't have to calculate the surface area in a container, or in a swimming pool, or in a huge lake, because at the same elevation, every single square inch has exactly the same amount of air pressure on it."

After a moment, Monica asked, "How tall a glass could we pull out of the aquarium? How far could the column of water be pushed up, by air?"

"Could it go all the way up into space?" someone else asked.

Salizar quickly responded, "It couldn't go that far up because there's only 14.7 pounds per square inch pushing down. If the water weighed more than 14.7 pounds per square inch, it wouldn't stay up. The water would win in the battle of the forces!"

"So how far can the air push the water up?" Monica asked again.

"I don't know the answer to that question," Ms. Faulkner admitted. "But I'm sure we can figure it out. Any ideas about how to get started? What would we need to know?"

There was silence. Finally, Tanika said, "How many cubic inches of water does it take . . . um, to weigh more than the air pressure—like 14.7 pounds?"

As if finishing Tanika's sentence, Monica continued, "Like how many cubic inches of water can push down on that spot to outweigh the air pressure that's forcing the water up?"

Phuong said, "I think I get it. It's like the air pressure is pressing down on the surface of the aquarium, everywhere, like a piece of plywood pressing down with a lot of force, like a *lot* of force. And then we cut a hole in the plywood, like a one-square-inch hole. And right there, on that square inch, there's no air, no nothing, I mean no pressure pushing the water down. So the water would squirt up through the hole! If we had the one-inch glass there, the bud vase thingy, then the water would squirt up into it. When the water column goes higher and higher it gets heavier and heavier, and at some point, eventually, the water will weigh as much—down—as the air is pushing up. That's as far as it could go." After a long pause he said, "So how many of Salizar's little cubic inches could we pile up on top of one another? How many would equal up to 14.7 pounds?"

"Phuong's on the right track when she asks how many of Salizar's little cubic inches could we pile up on top of one another to equal the air pressure at 14.7 pounds per square inch," Ms. Faulkner said. "It's really a question of balancing forces. It's like a seesaw. We've got someone on one side who weighs 14.7 pounds. That's the air pressure. On the other side, we've got a one-inch-square column of water. With what we've figured out already, see if you can figure out how tall that column of water could be. And, even more interesting, see if you can figure out a way we could test it to see if our calculations are right. Think about it tonight, and we'll talk about it tomorrow."

By the next day, the class had calculated that the air could hold up a column of water 34 feet tall. They had come up with many different methods, but the simplest was building on Salizar's fact that a cubic inch of water weighs 0.036 pounds. They divided 14.7 pounds by 0.036 pounds (per cubic inch) and came up with 408.3 cubic inches. That's how many cubic inches of water could be piled on top of each other to equal 14.7 pounds. They then divided that by 12 to determine the feet and got 34.03 feet.

Ms. Faulkner applauded her students' hard work and amazing results—they had truly changed their conceptual thinking in many ways.

## Examining Conceptual Change in *Molecules in Motion*

In the "Molecules in Motion" unit, students began with many ideas about air based on their personal experience. For example, some students began the unit thinking that air was nothing, except when you could feel it as wind. For most of the students, the investigations with air pressure entailed building on their preexisting concepts of air and elaborating on them—the first type of conceptual change described earlier in this chapter.

After eliciting ideas from the students for the "What We THINK We Know About Air" chart, Ms. Faulkner introduced some new facts about air molecules. The students grappled with these facts as they attempted to understand and explain why water stayed in a glass as it was pulled, upside down, out of an aquarium full of water. After the first group discussion and demonstration, all of the students were certain that air was something—something that took up space in an "empty" glass. "Something" is a concept that the students entered with and that they elaborated on to include air once they were persuaded that air qualified as *something*. This was an important development for their continued learning and understanding of matter. Helping students elaborate the concept that air is something took only a modest instructional intervention.

At this point, the students were beginning to rethink and restructure the network of existing concepts about air, molecules, forces, and pressure—the second type of conceptual change we discussed above. Many questions, conjectures, and divergent ideas were made public. Over several days of investigation and discussion, students learned to embrace and apply the notion that air pressure pushed the water up into the glass, and that asymmetrical levels of air pressure within a system would predictably result in such movement. This entailed developments in their thinking about air, the way it pushes in all directions, and the magnitude of force with which it pushes.

Ultimately, the students would go on to build new levels of explanation, the third type of conceptual change, either in Ms. Faulkner's class or in subsequent grades. That is, they will come to understand atomic-molecular theory and use it to explain phenomena like air pressure. The students will also learn to understand increasingly more complex material explanations. Once they master macroscopic explanations, they will go deeper into atomic-molecular theory and develop an explanation of phase change and motion at the molecular level. They will learn that molecular theory is a basic and broadly applied idea that can help them make sense of processes in other domains. The foundation built in Ms. Faulkner's classroom will be critical for their success in subsequent years.

What specific classroom activities and forms of instruction supported the students' conceptual reorganization?  First, it's important to note that Ms. Faulkner began the unit by recognizing and honoring students' everyday knowledge in order to transform and build on it.  She convinced her students that air is matter and takes up space, not by telling them but by letting them observe the empty glass being pushed into the water while not letting any water in.  They could not see the air, but they could see its force on the water.

They could also see that air is compressible or, as they described it, "squishable."  They saw that the water entered the glass a little bit—evidence that the water was forcing the air into a smaller space.  They couldn't see molecules, but the idea of air pressure allowed them to make sense of the idea of air getting squished into a smaller space.

In their situation stations, the students experienced multiple demonstrations and activities that helped them explore—and revisit in new forms—some of the ways in which air and water act.  These experiences provided them with specific and shared experiences to integrate, think with, and generalize from.

The demonstrations were designed to enable the students to recognize evidence that air presses up, down, and sideways and has fluid-like properties.  They experienced the phenomenon of differential pressure in a gravitational field—the deeper down, the more pressure—in a column of air or water.  These demonstrations also provided students with opportunities to work with and clarify their ideas.  Working in small groups gave everyone time to try out their own ideas and hear the ideas of their teammates. This helped them prepare a presentation about their particular demonstration to share with the rest of the class.  Work at the stations gave the students time to manipulate the materials, think about their counterintuitive outcomes, and prepare to present their ideas to others.  Time for thinking, doing, and talking is essential for understanding complex ideas, especially ideas that require a transformation in one's everyday thinking.

## Building Understanding Over Multiple Years

Of course, the capabilities of young children along each of the four strands are also limited in important ways.  They have only limited understanding of different materials, of physical quantities such as weight or volume, and of how to construct knowledge in science. They might know something about the objects they encounter in their everyday lives, but their experience with other materials or the transformation of materials is still limited. For example, they may deny that an object broken into tiny pieces is still the same kind of stuff because it no longer "looks like" the same stuff. Many of the most enduring and essential characteristics of materials (such as density, boiling and melting points, thermal and electrical conductivity, and solubility) are unknown to them.

Also, young children's understanding of the material world is based on their perceptual experiences—on what they can see, feel, or touch. For example, they think of weight as something that they can feel with their hand. They may think, for example, that a piece of Styrofoam weighs "nothing at all" because it seems to exert no force on their hand. They rely on how heavy something feels because they have not yet differentiated weight and density.

While children may have amazing skills and capabilities to learn science, people do not spontaneously generate scientific understanding. The development of early ideas about matter, in which neither mass nor volume is considered a defining property, into a sophisticated understanding of atomic theory clearly requires formal academic instruction. Nor do people spontaneously generate deep scientific understanding of other core domains. The theory of evolution, for example, although fundamental to modern science, can be quite difficult to understand. Many children and adults embrace erroneous beliefs about evolution.

The complexities of science and science learning are real. To acknowledge this is to also concede that good science teaching requires extensive teacher knowledge, excellent curriculum, effective systems of support and assessment, and much more time and attention than are currently devoted to it. This can be daunting.

While the complexity of science poses significant instructional challenges, the interrelatedness of science makes it possible to focus and simplify curriculum and instruction in another important way. Science can be organized instruction around a small number of concepts. These "core concepts" have great explanatory power and can be built on in increasingly complex ways from year to year. In the next chapter, we'll see how this process can work, not only for atomic-molecular theory but also throughout the disciplines of science.

## For Further Reading


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# 4 Organizing Science Education Around Core Concepts

In order to develop a deep understanding of scientific explanations of the natural world, students need sustained opportunities to work with and build on the concepts that support these explanations and to understand the connections between concepts. Yet many science curricula consist of disconnected topics, with each given equal priority. Too little attention is paid to how students' understanding of a concept can be built on from grade to grade. While students are continually introduced to new concepts, unless those concepts connect to other related ideas, they will not build conceptual understanding in a meaningful way.

Research strongly suggests that a more effective approach to science learning and teaching is to teach and build on core concepts of science over a period of years rather than weeks or months. These core concepts offer an organizational structure for the learning of new facts, practices, and explanations, and they prepare students for deeper levels of scientific investigation and understanding in high school, college, and beyond.

Other ways have been proposed to organize science curriculum and instruction over extended periods of time, and it is important to distinguish between these other proposals and the teaching and building of core concepts. For example, the American Association for the Advancement of Science has proposed a set of themes—constancy and change, models, systems, and scale—that would extend across science curricula. These themes are much broader in scope than the core ideas, and they are not clearly rooted in science. The core concepts are science ideas that have been well tested and validated and are central to the disciplines. Examples of core concepts in science are the atomic-molecular theory of matter, evolutionary theory, cell theory, and Newtonian laws of force and motion—all of which are considered foundational ideas in science. Each integrates many different findings and is the source of coherence for many key concepts, principles, and even other theories in the discipline. Each guides new research and can be understood in progressively more complicated ways. Each enables creative links to be made between disciplines. For example, atomic-molecular analyses are important in physics, chemistry, biology, and geology. Biologists work with DNA molecules to understand patterns in genetic code and unravel the interrelations of species. Chemists seek to articulate the laws that govern interactions between molecules that result in newly formed or broken chemical bonds. And teams of multidisciplinary experts—including chemists and biologists—draw heavily on molecular science to develop drugs that attack unhealthy molecules (or cells) and leave others undisturbed.

***Examples of Core Science Concepts***

- **Atomic-molecular theory of matter**
- **Evolutionary theory**
- **Cell theory**
- **Newtonian laws of force and motion**

The proposed use of core concepts and learning progressions still requires significant additional research and development on the part of science educators, scientists, and education researchers. The science education community will need to identify core ideas, and specific learning progressions will need to be developed and tested extensively in classrooms.

Here we define learning progressions and offer an example of how learning progressions might be structured over the course of the K-8 school years. This is a dramatic departure from current classroom practice. Many educators and school systems are not in a position to pursue an immediate wholesale change to their science curricula. Accordingly, later in the chapter we reflect on the incremental steps that can be made right away at the classroom and the school levels.

## Building on Core Concepts Over Time

Organizing science education around core concepts that provide a specific context for learning is a significant departure from typical classroom practice. Science educators must work cooperatively to define long-term goals for students that take into account the reality that students need opportunities to learn over multiple years to deepen their understanding of scientific concepts. Much thought will need to be given to how specific experiences along the K-8 grade span will accumulate and contribute to student learning and how to provide the kinds of support that teachers will need to accomplish this.

The core concepts used in this practice would be dramatically fewer in number than those currently focused on or included in standards and curriculum documents. This would allow teachers and teacher educators to focus on building and deepening their own knowledge of a smaller number of critical science concepts. At the same time, a grade-level teacher would need to be concerned not only with the relevant "slice" of a given core idea taught in her particular grade, but also with the longer continuum of learning that K-8 students experience. Thus, teachers and science teacher educators (at the district, school, and college levels) would need to build structures and social processes to support the exchange of knowledge and information related to core concepts across grade levels.

Because core ideas are bound up in the practices of science, teachers would also need a solid foundation in science and excellent classroom skills to guide and extend students' experiences. Again, a network of science educators would need to work together to ensure that the complex instructional practices described here are supported with systematic, sustained professional learning throughout teachers' careers. An excellent curriculum built on core ideas is but one of many major shifts required.

At the same time that science teachers are identifying and promoting long-term goals and connections related to core concepts, they must also define shorter term goals for students that involve more immediate understanding. At each grade level, teachers will need to aim for teaching specific intermediate ideas, with an eye to how these will connect with and inform the more sophisticated concepts that students are building toward understanding. For example, later in this chapter we describe a K-2 level intermediate understanding of atomic-molecular theory that does not employ the language of "atoms," "molecules," or "theory." Instead, it builds essential conceptual bases for students to learn atomic-molecular theory in progressively more complex ways over the years.

Although most schools and school systems maintain control over the science curriculum, in the short term, individuals and small groups of science educators may find that they have opportunities to organize instruction in their own classrooms in a way that will build students' understanding of core ideas across the year. Gradually, as this approach is implemented in schools and districts, science curricula can be organized around a limited number of key scientific concepts that are linked over successive grades.

## Core Concepts in Relation to Standards and Benchmarks

In the 1990s, the K-12 subject matter communities, comprised of education researchers, curriculum developers, scientists, teacher educators, and teachers, developed frameworks to guide state and local authorities with curriculum development. These became the *National Science Education Standards (NSES)*[1] and the *Benchmarks for Science Literacy.*[2] In turn, local and state authorities developed standards, curricula, and assessments that were meant to align with the national standards.

The development of standards and benchmarks was an important step toward building and expressing shared values for K-12 science education. These standards succeeded in building common frameworks. While standards were marginally rooted in research on children's learning and analyses of scientific practice, we now have a richer research base to inform science education and a better sense of the critical role this research should play.

Current national, state, and district standards do not provide an adequate basis for designing effective curriculum sequences, for several reasons. First, they contain too many topics. When the *NSES* were compared with curricula in countries that participated in the Third International Mathematics and Science Study, the *NSES* were found to call for much broader coverage of topics than those in high-achieving countries.[3]

Second, the *NSES* and benchmarks do not identify the most important topics in science learning. Comparisons of the *NSES* with curricula in other countries show that they provide comparatively little guidance for sequencing across grades. As we pursue a course of organizing curricula around core ideas, we need to ask ourselves questions that were not central to the development of the current standards. What areas of study are critical for students' future learning? Which of these critical areas of scientific study can students explore in meaningful and increasingly complex ways across the K-8 grade span and beyond? Which areas of science can safely be deferred until high school or college? These are not easy questions, and answering them will require collective, sustained attention and focus among a number of stakeholders.

Finally, the *NSES* and benchmarks provide limited insight into how students' participation in science practices can be integrated with their learning about scientific concepts; that is, they do not describe how an understanding of scientific concepts needs to be grounded in scientific practice. In addition, although the

*NSES* and benchmarks recognize the importance of the first three strands of science learning, each strand is described separately, so the crucial issue of how the strands are interwoven and how they support each other is not addressed.

Although there is a solid research base that supports the premises of organizing science around core concepts, one should be mindful that few studies have examined children's learning of core concepts over multiple years. So questions about what the optimal set of core concepts are, how they should be distributed and organized over the grades, and how to link together instruction across the grades are as yet unanswered. It is, however, very clear that future revisions to the national science standards—and the subsequent interpretation of those standards at the state and local levels and by curriculum developers—should dramatically reduce the number of topics of study and provide clear explanations of the knowledge and practices that can be developed from kindergarten through eighth grade.

## Using Core Concepts to Build Learning Progressions

Research indicates that one of the best ways for students to learn the core concepts of science is to learn successively more sophisticated ways of thinking about these ideas over multiple years. These are known as "learning progressions." Learning progressions can extend all the way from preschool to twelfth grade and beyond—indeed, people can continue learning about core science concepts their whole lives. If mastery of a core concept in science is the ultimate educational destination, learning progressions are the routes that can be taken to reach that destination.

Learning progressions for K-8 science are anchored at one end by the concepts and reasoning abilities that young children bring with them to school and at the other end by what eighth graders are expected to know about science. The most effective and appropriate concepts on which to build learning progressions are those that are central to a discipline of science, that are accessible to students in some form starting in kindergarten, and that have potential for sustained exploration across grades K-8. A well-designed learning progression will include the essential underlying ideas and principles necessary to understand a core science concept. Because learning progressions extend over multiple years, they prompt educators to think about how topics are presented at each grade level so that they build on and support each other.

Learning progressions have many other potential benefits. They can draw on research about children's learning in determining the scope and sequence of a curriculum. They can incorporate all four strands of scientific proficiency. Since they are organized around core concepts, they engage students with meaningful questions and investigations of the natural world. They suggest the most appropriate ages for introduction of core concepts. And they can suggest the most important tools and practices to assess understanding.

**Some Benefits of Learning Progressions**

- They require serious thinking about the underlying concepts that need to be developed before a student can master a particular area of science.
- They prompt educators to think about how topics are presented at each grade level so that they build on and support each other.
- They can draw on research about children's learning in determining the scope and sequence of a curriculum.
- They can incorporate all four strands of scientific proficiency.
- They engage students with meaningful questions and investigations of the natural world.
- They suggest the most appropriate ages for introduction of core concepts.
- They can suggest the most important tools and practices to assess understanding.

In this chapter, we'll be examining a learning progression based on the atomic-molecular theory of matter. The idea that all matter is composed of atoms and molecules is a core scientific concept that all students should master. It allows for the integration of many different scientific findings and explains otherwise puzzling aspects of the physical world. It allows for links to be made between various scientific disciplines, including physics, chemistry, biology, and geology. We explore this learning progression to illustrate the intermediate levels of understanding achieved at various points throughout the K-8 curriculum and how this understanding is rooted in science and learning research. We intend for this to serve as an example that can be further elaborated, tested, and emulated in the service of developing learning progressions in other areas of study.

The learning progression in this chapter is divided into three grade bands—grades K-2, grades 3-5, and grades 6-8[4]—with a case study at each grade band that focuses on one or more of the concepts covered as part of atomic-molecular theory. This learning progression was designed so that students can give progressively more sophisticated answers to the following questions:

1. What are things made of, and how can we explain their properties?

2. What changes, and what remains the same, when things are transformed?

3. How do we know?

A well-designed learning progression on atomic-molecular theory won't mention atoms and molecules in the earliest grades. The notion of atoms, chemical substances, and chemical change are complex ideas that take time to develop, test, expand, and revise. These ideas are too advanced for most young children, although some may have heard about atoms and molecules and may use these terms or ask questions about them. The point is to emphasize the goal of understanding concepts, which is very different than merely memorizing vocabulary or definitions. By not emphasizing technical terms in the early grades, the teacher avoids sending the counterproductive message to students that science is about memorizing terms and definitions for phenomena that they fundamentally don't understand.

Even in the later years of elementary school, students may not be ready for the idea that all matter is composed of atoms and molecules. They first need to develop a sound macroscopic understanding of matter. In general, one of the most difficult transitions children must make during the K-8 years is linking macro-level processes with micro-level phenomena. For example, elementary school students may think that, at a molecular level, wood will look like tiny pieces of wood, rather than consisting of molecules. It takes several years for students to work out the subtleties of understanding the basic constituents of matter (atoms and molecules) and how they combine to create larger units.

It is important to keep in mind that a learning progression is not a lock-step sequence. Different classrooms, and even different students within the same classroom, can follow different pathways in coming to understand core science concepts. There are many ways to learn that all matter is composed of atoms and molecules.

The following case study involves a classroom of kindergartners who are investigating the idea that different objects are made out of different materials, that there is a difference between what an object is used for (its function) and what it is made of (its material kind), and that these different materials have properties that can be discussed, examined, and described.

## THE MYSTERY BOX (GRADES K-2)[5]

**FIGURE 4-1**
*The Mystery Box.*

**FIGURE 4-2**
*Eating utensils used with the Mystery Box.*

"Are you ready to run a Mystery Box investigation with me?" Shawna Winter asked as her 22 kindergartners gathered around her. The classroom erupted into cheers. "Look at all these different eating utensils I've brought from home." She pointed to two identical sets of spoons and forks made of three different materials. Each set was lined up in a row in front of a wooden chest a little bigger than a toaster. The box was latched shut with a heavy lock, and next to the box was a key tied to a long ribbon (see Figures 4-1 and 4-2).

"One set of these utensils is going to be mine, and the other set is going to be yours," Ms. Winter said. She quickly established with the children the names of each of the utensils and the material it was made of. "So," she summed up, "we have a plastic spoon, a wooden spoon, and a metal spoon, as well as a plastic fork, a wooden fork, a metal fork."

"Now I'm going to take my whole set away," she said, scooping up one row of the spoons and forks and tossing them into a bag. "Then I'm going to take one item—just one—from my set and put it into the Mystery Box. Close your eyes. No peeking!" All 22 kindergartners gleefully covered their eyes.

Ms. Winter turned her back to the kids, unlocked the Mystery Box, selected an item from her bag of utensils, and locked it inside the box with the key. The students' set of six items—forks and spoons—remained lined up in front of the Mystery Box.

"Now open your eyes," she said. "Inside the Mystery Box is one thing taken from my set of objects, which is just like your set. And here's the amazing thing. You're going to figure out what is inside the Mystery Box just by asking me questions." Then, very dramatically, Ms. Winter uttered the words she always used to start the Mystery Box game. "If you ask me a question about what's inside the Mystery Box, I will tell you the truth."

"I know," said Maya. "Is it the plastic spoon?"

"That is a very good question, Maya. Do you know why it's a good question? It's a good question because . . . it's *not* the plastic spoon." Several kids giggled; a few sighed with disappointment.

"So Maya's question has taught us something important," Ms. Winter said. "Whatever is inside the box, it is not a plastic spoon. So that means we don't need this one here anymore." She picked up the plastic spoon from the students' set of utensils and put it on the table, out of sight.

Ms. Winter reached into a cup of Popsicle sticks that had all of the children's names written on them, which she used to ensure that each child had an equal chance of getting a turn. The stick she pulled from the cup had "Carlos" written on it.

"Carlos, what question do you want to ask?" Carlos was new to the classroom, having moved to the United States from Central America just a few weeks before. Carlos said nothing for several seconds. Ms. Winter and the children waited. Then Carlos said, “Tenedor, um, fork!”

Marisa, who was sitting next to Carlos, piped up. “He’s supposed to ask it as a question, right?”

“Marisa’s right,” said Ms. Winter. “You’re asking if there’s a fork inside our Mystery Box, Carlos, is that right?” Carlos nodded. “Can you say it as a question?”

“Is it a fork?” Carlos asked.

“Is it a fork?, Carlos wants to know,” said Ms. Winter. “That’s another good question, because what is in the Mystery Box . . . is *not* a fork.” The children laughed and clapped. “And because it’s not a fork, what have we learned?” Ms. Winter picked up the plastic fork, the wooden fork, and the metal fork.

“We don’t need them,” two children said.

“Right. Because we know it’s not a fork in our box, we can get rid of every single fork. It can’t be one of these.” Ms. Winter put the three forks out of sight.

“Hey, I just noticed something interesting,” said Ms. Winter. “With Maya’s question we got rid of one thing, the plastic spoon. With Carlos’s question, we got rid of *three* things, all three forks. Can anyone figure out why that is?” No one said anything. Ms. Winter waited.

Finally, Kelly, who tended not to talk much in the large group, raised her hand. “Carlos asked about all of the forks, and Maya just asked about the plastic one, just the plastic spoon.”

“Wow! Did anyone hear what Kelly said?”

Lots of hands went up.

“Does anyone think they can put what Kelly said in their own words? Yes, James?”

“She said Carlos asked his question about *all* the forks. Maya asked about only one spoon—the plastic spoon. It’s like we got three answers with one question.”

“Is that what you were saying, Kelly?”

Kelly nodded.

“Wow, you guys are really thinking today. I can see smoke coming out of your ears. Let’s see who’s next. Lassandra?”

“It has to be a spoon,” several children called out.

“Ah, but which spoon? What is the spoon made of?” Ms. Winter asked. “Lassandra?”

“Is it the wooden spoon?”

“That’s a very good question. Do you know why? Because, I’m telling you the truth, it *is* the wooden spoon.” The kids squealed with delight. Ms. Winter reached for the key. “So you think there’s going to be a wooden spoon in there? How certain are you?”

“A billion percent,” called out Jason. Slowly and dramatically Ms. Winter removed the lock and opened the doors of the Mystery Box, revealing—“Ta dah!”—the wooden spoon inside. “Congratulations,” Ms. Winter said. “Just by asking questions, without being able to see inside, you’ve discovered what’s in the Mystery Box.” Ms. Winter’s 22 kindergartners broke into applause.

The Mystery Box activity may seem a long way from the kinds of scientific investigations children will do in later grades relating to the atomic-molecular structure of matter, but it actually has some important similarities. Students are using their reasoning abilities to draw inferences about something they can't see. They are thinking about how to ask questions and how to learn from other people's questions. They are learning that different kinds of questions can produce different amounts of information. Perhaps most importantly, they are learning that getting the right answer isn't the only thing that matters in a scientific investigation. Negative evidence can be very useful.

While the Mystery Box activity doesn't directly address the atomic structure of matter, it enables Ms. Winter's kindergartners to practice making a distinction that will be essential in their understanding of matter. They are separating the use or type of an object (spoon or fork) from what it's made of, or its "material kind" (plastic, wood, or metal). This may seem to be a simple task—indeed, it's something that children generally master before they begin school. But they have to make this distinction clearly before they can learn about the detailed properties and microscopic composition of matter.

Science learning can be very effective when it is grounded in a task that supports multiple predictions, explanations, or positions. In such a setting, children have reasons to "argue" (to agree and disagree) and to back up their positions with evidence. These rich tasks involve the students in actual scientific investigations but require support and guidance from the teacher.

For example, the Mystery Box activity is a focused, teacher-guided activity, but the children are playing active roles, reasoning and theorizing. They are listening hard to one another and building on one another's ideas. Ms. Winter is also actively involved, pressing them to clarify and explain their ideas to one another. The activity involves a whole-group discussion in which everyone takes part and has equal access to everyone else's thinking, with help from Ms. Winter to keep the discussion on track. In addition, the Mystery Box activity can be played in many different ways and can be used to classify many different kinds of objects over the course of the school year. This activity can help students become thoughtful and logical questioners and data analysts.

The Mystery Box is an activity that supports logical or deductive reasoning practices. The implicit reasoning of the students as they play is as follows: We know that what's in the Mystery Box is *not* a plastic spoon. We also know it's *not* the plastic fork, the metal fork, or the wooden fork. Therefore, we have figured out that what's in the Mystery Box *must* be a metal spoon or a wooden spoon, because they're the only choices left.

In contrast, the proposed measurement activity in Ms. Martinez's kindergarten class (Chapter 1) would be considered an "empirical investigation." In that case, the students tested a prediction: "Measuring with shoes on would make a difference in measurement." They would need to examine evidence to suggest a pattern and then interpret the pattern to decide if their prediction was correct or

not. They would thus be arranging the world (selecting, lining up, and measuring shoes) in order to learn something about it. They would have to collect measurement data, organize the data in some way, and then decide, based on their evidence, whether wearing shoes made a difference or not. The data might prove difficult to interpret (most shoes are the same but a few are different), and the students might never be as certain of the right answer as they are with the Mystery Box activity. Generalizations about the empirical world are never certain. You cannot "prove" generalized conclusions via observation. Moderating uncertainty is central to scientific thinking. Unlike proof in mathematics, there is no absolute certainty in science.

The skills the students are learning in the Mystery Box activity—making sense of, categorizing, and reasoning with available information—are key to asking good questions and formulating good hypotheses. And of course the students are also learning to participate in discussions with peers. That is, they are learning the norms of participation in science and how to handle uncertainty together.

## Extending Scientific Discussion

This chapter emphasizes the importance of building on learning progressions as they unfold over the course of several school years. Learning progressions can also take place in the short term as the ideas and concepts related to specific science activities are extended and deepened.

For example, in Ms. Winter's classroom, the Mystery Box activity eventually led to an investigation of the different objects in the classroom that were made of wood, plastic, or metal. The students, working in pairs, focused on each type of material and attempted to catalog, using pictures or words, all of the objects they could identify that were made of that material. When two or more of the same objects were identified, such as chairs, the students counted and recorded the total number of those objects.

At group meeting time, for a period of several days, the students reported on their findings. Questions arose that led to further investigation. Had each student pair identified the same items? Was there agreement or disagreement about some items? What did all of the wooden items have in common, and in what ways did they differ? How could the students tell, for sure, if something was made of wood?

The students requested magnifying glasses in order to see the grain of certain items better, and Ms. Winter introduced a set of "density blocks," which were same-sized cubes and triangular prisms made out of different materials (wood, plastic, metal). This led to several weighing and measuring activities that involved using a pan balance and a water displacement cup (sometimes called a "Eureka can"). This allowed the students to begin the transition away from reliance on sensory observations (felt weight) and to see the need for standard measurement—critical developments that are frequently overlooked or underestimated in science curricula and instruction. The students explored weight versus volume, and they made predictions about whether the weight of the triangular prisms would match the rank ordering of weight of the cubes—that is, whether the metal triangular prism would be heavier than both the wooden and plastic ones, and why that might be.

This is an example of just one of many ways the Mystery Box activity could be extended to allow students more time to work with complex ideas across different contexts—an integral and essential part of learning progressions. Students themselves might generate questions about the materials that would be worthy of investigation. The teacher might engage the students in a discussion about the materials and chart their questions. For example, students might ask the following questions:

- Which is heavier: wood, metal, or plastic?
- Why does metal shine?
- Which of those objects would float?
- Would plastic spoons that are the same size but different colors all weigh the same?

Any of these questions would work well for generating a brainstorming discussion. Some of them could be investigated empirically—for example, weighing same-sized objects made of different materials to see which float or sink, or weighing similar spoons of different colors—once students' theories and predictions were made public.

Note that any of these follow-up activities will raise new pedagogical challenges. For example, if multiple students weigh same-sized objects, there is likely to be variation in their results. That will present interesting problems and rich material for discussion, and the teacher must be prepared to take this on. How will students show their results? How will they show the variations in their results? How will they figure out how to explain the variation and decide what to do about it? These questions are important to consider as they reflect the kinds of thinking that underlie purposeful scientific work. They can also be effectively and productively pursued with young children. Doing so, however, demands a solid base of teacher knowledge—about science, about children's capabilities and how to assess their capabilities, and about structuring constructive classroom tasks. We return to the subject of teacher knowledge and support for teacher learning in subsequent chapters.

Science Class

# THE PROPERTIES OF AIR (GRADES 3-5)[6]

**In grades 3-5, the core concepts in atomic-molecular theory become more sophisticated. Some of the core concepts important to develop in these grades include understanding that:**

- **Objects are made of matter that takes up space and has weight.**
- **Solids, liquids, and gases are forms of matter and share these general properties.**
- **There can be invisible pieces of matter (that is, too small to see with the naked eye).**
- **Matter continues to exist when broken into pieces too tiny to be visible.**
- **Matter and mass are conserved across a range of transformations, including melting, freezing, and dissolving.**

**Although these concise statements summarize key aspects of the science, they do not reflect the ways in which students express understanding of atomic-molecular theory. In fact, the student who simply memorizes or repeats these statements verbatim may very well understand little about the actual science behind them. Students should be able to describe these concepts in their own words in order to show their understanding, as the goal is for students to understand the core concepts behind the words.**

**Students in grades 3-5 continue to engage in a wide variety of scientific practices. They pose questions, make predictions, design and conduct investigations, represent and interpret data, design models, and make arguments that support conclusions. Furthermore, the scientific practices of older elementary school children become more complex in several ways. No longer reliant on mere sensory measures, and having established a theory of measure, they can now engage in more complicated forms of measuring and graphical representation. Thus, students build on their understanding of area to explore the volume of rectangular solids, develop greater precision in measurement through more general understanding of fractional units, and construct graphs that show the relation between volume and mass instead of displaying each property separately.**

**We'll see several of these practices at work as we look at a third-grade classroom that is investigating the properties of air.**

Reggie Figueroa's third graders were carrying out a scientific investigation that involved weighing air.[7] In the previous weeks, they had weighed and measured different kinds of objects and materials, had predicted which objects would be heavier, and had graphed their results. Now the children were investigating whether or not air could be weighed. Some of the students were sure that air couldn't be weighed because "you can't weigh something that's nothing." Others disagreed and thought that air was definitely something.

One student, Jeremiah, reminded the others about the time each one of them had measured their own lung capacity by blowing through a tube into an upside-down jar full of water which was immersed in a fish tank. Pointing to a wall graph that showed lung capacity, height, and resting pulse rate for each student, he reminded them that he'd had the biggest lung capacity in the class, proving that air was present.

Marisa agreed. She'd been able to see her breath push the water out of the upside-down jar. "Air is something. You could see the air bubbles coming from my lungs."

"And you can see air in the winter when you go outside and blow." Jenna said. She blew hard on her hand. "It's like wind. You can't see it, but you can feel it."

To investigate the properties of air, Mr. Figueroa had brought in two volleyballs and a bicycle pump.[8] While his students were at gym, he put the volleyballs on the Harvard pan balance and adjusted the scale so they balanced perfectly, then he took them off. When the kids returned from gym, Mr. Figueroa called them over to the rug for "Circle Time."

"Look at these two balls. They're both volleyballs, and they're both the same size, but one is dark and one is light colored. When I put them on our pan balance, one on each side, what do you think will happen?"

"They'll balance," called out Jocelyn. Others chimed in: "Balance." Someone else said, "They'll be the same."

"Why do you think that?" asked Mr. Figueroa. Gemma waved her hand. "Because they're the same everything. Same size, same, um, leather covering, just like when we weighed and graphed our density blocks. If it was the same size and same material, they weighed the same."

Everyone seemed to agree, so Mr. Figueroa put the two volleyballs on the pan balance (Figure 4-3). The balance arm wobbled a bit for a moment and then came to rest in a balanced position.

"They balance. I was right," said Gemma.

"Okay," said Mr. Figueroa, "but here's the investigation for today. I brought a bicycle pump from home that lets me pump air into things. I'm going to pump air into the light-colored volleyball—15

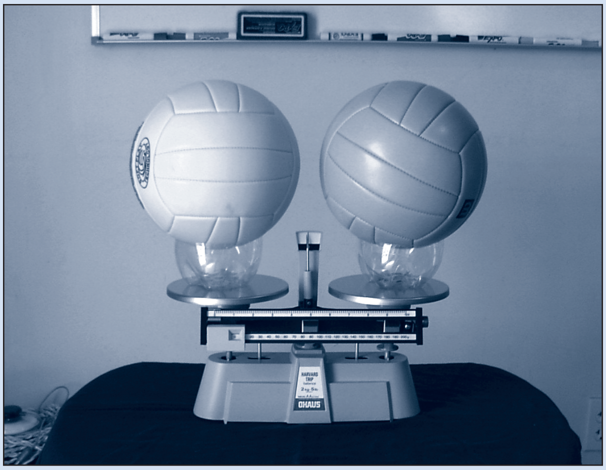


**FIGURE 4-3**
*Light- and dark-colored volleyballs on balance.*

pumps." He inserted the needle of the bicycle pump into the volleyball. He pumped 15 times while the kids counted, "One, two, three, . . . thirteen, fourteen, fifteen." (See Figure 4-4.)

"Okay, so now our light-colored volleyball has 15 pumps more air in it. So did that make it heavier? Lighter? Or still the same weight? When we put this volleyball back on the pan balance, is it going to go down?" He tipped his body to the left. "Is it going to go up?" He tipped his body to the right. "Or is it going to stay balanced?"

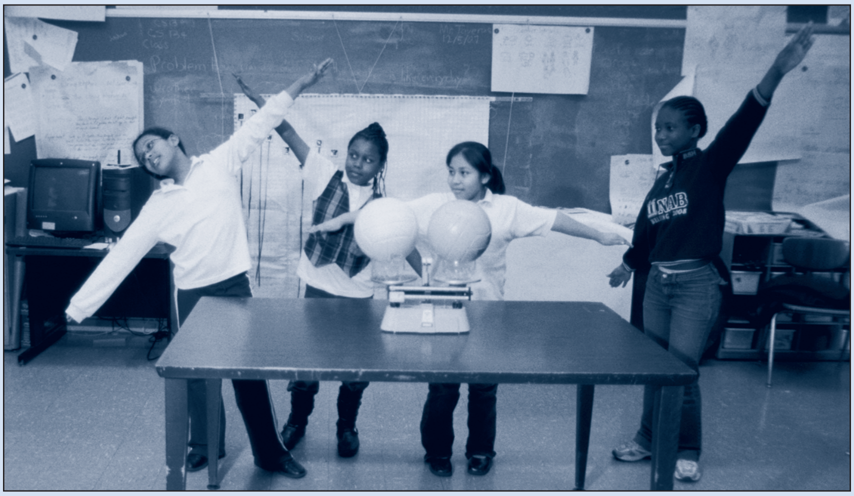
Several students called out answers.

"Don't say anything yet," Mr. Figueroa said. "Just think for a minute." Then he said, "Okay

**FIGURE 4-4**
*Air being pumped into light-colored volleyball.*

scientists, stand up for your predictions! Let's see which side you're on!"

Each student stood up and spread out his or her arms, some tipping to the right, some tipping to the left, and some standing with their arms stretched straight out on either side.



Once they'd made their predictions, they sat back down. Mr. Figueroa said, "Who wants to start off?" He waited patiently as more and more hands went up. He finally picked Megan because he knew she would have something to say that would be likely to spark further discussion.

"I think it will go up, I mean the light-colored volleyball, the one you pumped, will go up," said Megan.

"And why do you think that?"

"Because doesn't air make things lighter? Like when you blow up a balloon with air, it gets light. It sort of floats."

Several students began to talk at once. Mr. Figueroa reminded them that in order for everyone to hear, only one person could talk at a time. "Let's use this volleyball as our talk ball," he suggested. Mr. Figueroa's class often used a talk ball during Circle Time. Only the person holding the ball was allowed to speak.

Mr. Figueroa handed the ball to Marisa.

"I'm pretty sure it will balance because air is nothing. I mean it's invisible. It's like nothing," said Marisa. Several other students nodded and agreed.

Eduardo had his hand up and Mr. Figueroa called on him. Eduardo was born in Puerto Rico and had lived there most of his life. His English was improving, but he still mainly spoke Spanish and often struggled when speaking English aloud.

"*Más,* more, um, more heavy? *Tiene más* air, *más* material," Eduardo said.

"Let me see if I've got your idea right, Eduardo," Mr. Figueroa said. "Are you saying you think the volleyball will be heavier, that it will go down on our pan balance, because it has more air, more matter, in it?" Eduardo nodded.

"Can you say a bit more about that?" Mr. Figueroa asked.

Eduardo spoke slowly and paused often to find the correct words. He had some difficulty with pronunciation, but the other students waited respectfully while he spoke, and some of the other Spanish-speaking students volunteered words or phrases when he seemed stuck.

"Once my papi had a flat tire and he use a pump like this. He pump the tire and his truck went up. The air make it to go up. The truck is heavy."

"Wow! What an interesting observation," Mr. Figueroa said. "Does anyone think they understood Eduardo's observation well enough to put it into their own words? Can anyone repeat what Eduardo has told us?"

Keisha said, "I think I understand, because the same thing happened to me. I think Eduardo is talking about when his dad got a flat tire. And when they pumped the tire up, the whole car went up. It's like blowing up a balloon. The air pushed inside the tire and lifted the truck up."

Mr. Figueroa turned back to Eduardo. "Is that what you were saying, Eduardo?"

Eduardo nodded.

Billy went next. "I sort of agree with Eduardo that you're putting more stuff in the ball and so it should get heavier. Like, if you added sand or water, it would definitely get heavier. But I don't think you can weigh air. It's like too light, too small. So I think it will still balance, or maybe get lighter. Can I vote for two predictions?" Everyone laughed.

"We have lots of different theories on the table, and they're all interesting. Does anyone want to agree or disagree with any of these predictions?" More hands went up. One student said, "Just do it!" Then several said, "Yeah, let's find out."

"I still want to hear what more of you think," Mr. Figueroa said. "Let's go around so everyone gets a chance to explain their predictions."

The discussion continued for about 10 more minutes, with students arguing for each of the different alternatives.

Finally, Mr. Figueroa said, "Okay, let's do it and find out." He walked to the pan balance, which still had the dark-colored volleyball on the right-hand side. As he was about to place the light-colored volleyball on the left pan, he looked back at the students and said, "Has anyone changed their minds? You know, scientists often change their minds after discussing things with other scientists. So, stand up for your prediction one more time. Do you think the yellow volleyball with 15 pumps of air will be heavier and tip to the left, lighter and tip to the right, or stay balanced?"

Once again the students stood up and tilted their bodies, but this time several more voted that the light-colored ball would be heavier. When Mr. Figueroa put it on the pan, it tilted to the left. The students cheered.

"So what have we learned?" Mr. Figueroa asked.

"You can weigh air!" Marisa said. Then after a pause, she added, "Does that mean that if I take a big breath of air when I get on the scale at the doctor's I'll weigh more?"

**Weighing volleyballs may seem a long way from the kinds of science experiments students will do in later grades, but it is actually a prototypical scientific investigation. Students are making predictions based on working theories about the way air behaves, using evidence from their own observations and experience (with balloons, tires, sand) to support their positions. They are using their reasoning abilities to draw inferences about something they can't see. They are organizing the world in very specific ways to test their predictions, and they are taking careful note of the resulting evidence. Then, they attempt to reason about what they have learned and think about other situations in which their new understanding might be relevant.**

**Behind the volleyball activity are two important ideas that will lead to an understanding of the atomic-molecular structure of matter: air is something, even though you can't see it, and air has mass and can be weighed. Later, students will learn that air is made up of tiny air molecules that are moving around very quickly. That might cause confusion when thinking about the air in a volleyball being weighed, since the molecules are bouncing around constantly in all directions. However, the molecules that are bouncing side to side balance each other out, so the ball doesn't move sideways. But the molecules in the ball are being pulled down by gravity, so the ones hitting the bottom of the ball exert more force than the ones hitting the top of the ball. Therefore, when more air is added to the volleyball, more molecules hit the bottom of the ball with more force than before, and this force registers on the scale.**

## Teaching the Atomic-Molecular Theory at the Middle School Level

In grades 6-8, building on robust learning experiences in the lower grades, students are ready to make a fundamental conceptual leap. They are ready to explain a host of new phenomena, and to reexplain phenomena they are already familiar with, using a new understanding of atoms and molecules. This new understanding will enable them to distinguish between elements and compounds. They can begin to recognize other considerations in tracking the identity of materials over time, including the possibility of chemical change. Some transformations involve chemical change (e.g., burning, rusting) in which new substances, as indicated by their different properties, are created. In other changes (e.g., changes of state, thermal expansion), materials may change appearance but the substances in them stay the same. Students can describe and explain the behavior of air or other gases. In general, they come to appreciate the explanatory power of assuming that matter is particulate in nature rather than continuous.

The learning progression proposes that, during these grades, students can be introduced to the following core tenets of atomic-molecular theory:

- Matter exists in three general phases—solid, liquid, and gas—that vary in their properties.
- Materials have characteristic properties, such as density, boiling point, and melting point.
- Density is quantified as mass/volume.

At the microscopic level:

- There are more than 100 different kinds of atoms; each kind has distinctive properties, including its mass and the ways it combines with other atoms or molecules.
- Each atom takes up space, has mass, and is in constant motion.
- Atoms can be joined (in different proportions) to form molecules or networks—a process that involves forming chemical bonds between atoms.
- Molecules have characteristic properties different from the atoms of which they are composed.

These are not simply facts to be memorized. These are complex concepts that students need to develop through engagement with the natural world, through drawing on their previous experiences and existing knowledge, and through the use of models and representations as thinking tools. Students should practice using these ideas in cycles of building and testing models in a wide range of specific situations.

At this grade band, students can begin to ask the questions: What is the nature of matter and the properties of matter on a very small scale? Is there some fundamental set of materials from which other materials are composed? How can the macroscopically observable properties of objects and materials be explained in terms of these assumptions?

In addition, armed with new insight provided by their knowledge of the existence of atoms and molecules, they can conceptually distinguish between elements (substances composed of just one kind of atom) and compounds (substances composed of clusters of different atoms bonded together in molecules). They can also begin to imagine more possibilities that need to be considered in tracking the identity of materials over time, including the possibility of chemical change.

Students have to be able to grasp the concept that if matter were repeatedly divided in half until it was too small to see, some matter would still exist—it wouldn't cease to exist simply because it was no longer visible. Research has shown that as students move from thinking about matter in terms of commonsense perceptual properties (something one can see, feel, or touch) to defining it as something that takes up space and has weight, they are increasingly comfortable making these kinds of assumptions.

This is one example of the ways in which the framework that students developed in the earlier primary and elementary grades prepares them for more advanced theorizing at the middle school level. Middle school science students must conjecture about and represent what matter is like at a level that they can't see, make inferences about what follows from different assumptions, and evaluate the conjecture based on how well it fits with a pattern of results.

Research has shown that middle school students are able to discuss these issues with enthusiasm, especially when different models for puzzling phenomena are implemented on a computer and they must judge which models embody the facts. This approach led students who had relevant macroscopic understanding of matter to see the discretely spaced particle model as a better explanation than alternatives (e.g., continuous models and tightly packed particle models). Class discussions allowed students to establish more explicit rules for evaluating models: models were evaluated on the basis of their consistency with an entire pattern of results and their capacity to explain how the results occurred, rather than on the basis of a match with surface appearance. In this way, discussions of these simulations were used to help them build important metacognitive understanding of an explanatory model.

Describing and explaining the behavior of air or other gases provide still more fertile ground for demonstrating the concept that matter is fundamentally particulate rather than continuous. Of course, these investigations are effective only if students understand that gases are material, an idea that the proposed learning progression recommends they begin to investigate at the grades 3-5 level.

At the same time, coming to understand the behavior of gases in particulate terms should help consolidate student understanding that gas is matter and enable them to visualize the unseen behavior of gases. In other words, developing macroscopic and atomic-molecular conceptions can be mutually supportive. Direct support for this assumption was provided in a large-scale teaching study with urban sixth-grade students that compared the effectiveness of two curriculum units.[9] One unit focused more exclusively on teaching core elements of the atomic-molecular theory, without addressing student misconceptions about matter at a macroscopic level. The other included more direct teaching of relevant macroscopic and microscopic concepts and talked more thoroughly about how properties of invisible molecules are associated with properties of observable substances and physical changes. The latter unit led to a much greater change in understanding phenomena at both macroscopic and molecular levels. Thus, sequencing instructional goals to reflect findings on student learning has important implications for how children make sense of science instruction.

Instruction that is focused on building core ideas is especially effective when students are regularly involved in classroom debates and discussion about essential ideas and alternative theories. Classroom debate and discussion make scientific experiments more meaningful and informative. Thus, building an understanding of atomic-molecular theory must also involve engaging students in cycles of modeling, testing, and revising models that describe a wide range of situations, such as explaining the different properties of solids, liquids, and gases, the thermal expansion of solids, liquids, or gases, changes of state, dissolving, and the transmission of smells.

Students engage in these types of discussions and investigations in the following case study.

Science Class

# THE NATURE OF GASES (GRADES 6-8)

**Over the past 10 years, the Investigators Club (I-Club) has sought to bridge what students already know about science and what they learn about science in school. The I-Club has been used in a variety of after-school and in-school settings. In its original design, the I-Club is an after-school program, meeting three times a week with students from a wide range of cultural and linguistic backgrounds, predominantly students from low-income families who are struggling or failing in school. It has since been expanded to include an in-school program in middle schools, as well as a prekindergarten curriculum. The following case involves 25 seventh- and eighth-grade students participating in an I-Club after-school program.**

Richard Sohmer directs the Investigators Club program, which meets for 15 weeks each school term. There are no special tests or grade requirements for participating in the program, but students in the program have to commit to attending regularly, be respectful of one another, and work hard "to discover, practice, and acquire the skills of scientific investigation."

Mr. Sohmer's students were investigating air pressure and the nature of gases and were about midway through their investigation. Prior to this time, the students had begun learning about balanced and unbalanced forces.

In order to demonstrate concepts related to balanced and unbalanced forces, Mr. Sohmer had had two students stand on either side of him and push him hard but with equal force. Despite their efforts, he hadn't moved. He had then instructed the student on his left, at the count of three, to take a step back, while the student on his right kept pushing. The result was that Mr. Sohmer had stumbled to the left, nearly falling down.

The demonstration had generated a discussion about how objects that were stationary had forces acting on them, but that these were balanced forces. The students had also explored the difference among the three phases of matter: solid, liquid, and gas. They had investigated how phases of matter stem from the interaction of molecular speed and intermolecular attraction.

It was at this point in their investigation that Mr. Sohmer introduced the students to a number of demonstrations, all of which involved everyday materials that the students were familiar with and which they could take home and share with their families. With each demonstration, the students predicted what would happen or attempted to explain what had caused the demonstration to work the way it did.

Over the years, he had found it difficult to disabuse his students of the notion of suction and vacuums as useful explanatory devices. Even though his students knew that air molecules don't stick together and can't hook onto anything and therefore can't pull anything, they routinely invoked the idea of suction. To help his students adjust their view of how air pressure worked, Mr. Sohmer came up with an analogy, a narrative form of the ideal gas law, that he called the "Air Puppies" story.

Mr. Sohmer drew a large rectangle on the blackboard. He told his students to pretend that they were looking down at a large room.

"In this room is a special wall that divides the room into two parts. The wall is on roller blades, the kind with really good wheels, so it's practically frictionless."

Mr. Sohmer drew a line down the middle and showed the roller blades in red. He said: "The wall can move easily, to the right or left, if something touches it. So if I were standing on the left side of

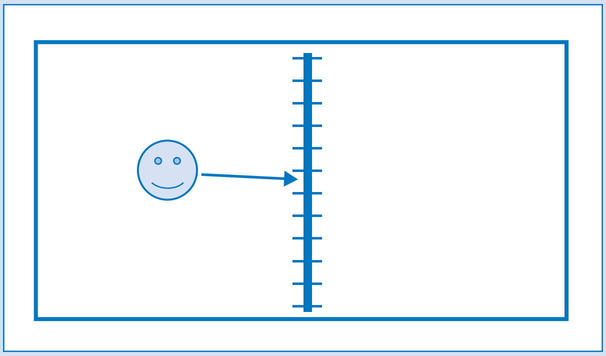


**FIGURE 4-5**
*Mr. Sohmer's wall-on-wheels.*

the wall, and—by accident—I leaned against it, what would happen to the wall?" (See Figure 4-5.)

"It'll move over there—it's gonna move to the right!"

"True. And it's going to keep on moving to the right until—remember, these are frictionless wheels—until it bounces off the end of the room, and comes back the other way."

Then Mr. Sohmer told the story of the Air Puppies.

"Imagine that Air Puppies represent air molecules. Think about how newborn puppies bumble around constantly, mindlessly, with no intentions at all. They move around constantly, in every direction, like air molecules, without thinking, wanting, planning, or choosing to do anything."

"Do Air Puppies breathe air like real puppies?" one of the students asked.

Mr. Sohmer responded by introducing a discussion about models and how they are never exactly the same as the thing they represent. Students volunteered examples: Model airplanes don't fly. Maps don't include the potholes that are on some roads. A menu doesn't taste like the food it describes.

"Different models highlight different things," he explained. "They're useful in different ways. They make some things visible and other things invisible."

This kind of discussion about the advantages and limitations of different models helped the students understand how scientific knowledge is constructed and how central models are in the construction of that knowledge. The Air Puppies are the bumbling (mindless) agents in a modifiable drama with a particular setting (always including two rooms separated by a moveable wall-on-wheels). The necessary result of the Air Puppies' incessant, unintentional bumbling is a completely understandable, completely predictable, and thoroughly lawful effect—that is, the wall moves as it must, given the Air Puppies' opposing impacts on both sides.

Mr. Sohmer continued the Air Puppies story. In his first version, the two rooms on either side of the wall-on-wheels each contain an equal number of identical Air Puppies mindlessly bumbling around and bumping into the walls and each other. The wall-on-wheels moves whenever a puppy bumps into it (see Figure 4-6).

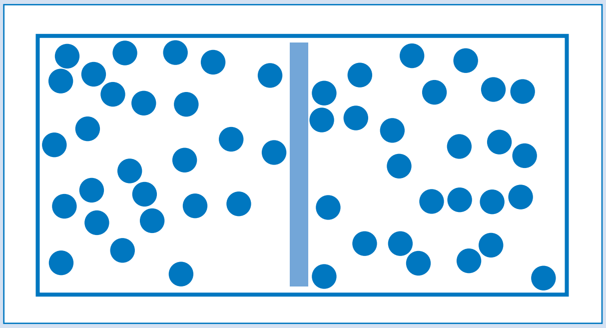


**FIGURE 4-6**
*The view from above at the beginning of the Air Puppies story showing an equal number and kind of Air Puppies on each side of the wall.*

"So what will happen to the wall?"

"It'll stay in the same place," a number of students called out. With the aid of a QuickTime movie of an interactive physics animation, Mr. Sohmer demonstrated how the scenario in Figure 4-7 was set in motion. The wall stayed in approximately the same place, oscillating about the centerline (Figure 4-7).

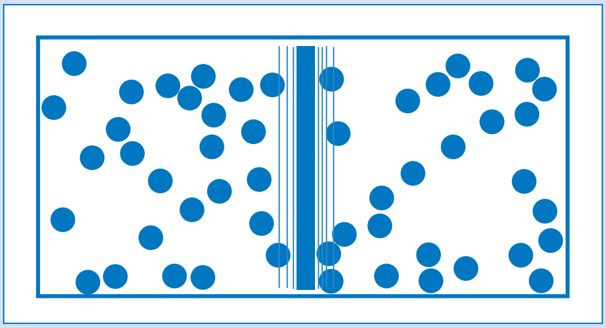


**FIGURE 4-7**

*With an equal number and kind of Air Puppies on each side, the wall-on-wheels is continually bumped from side to side.*

Mr. Sohmer continued with a variation on this basic story:

"What will happen to the wall if we have 25 Air Puppies on the left side and 10 Air Puppies on the right side?" Mr. Sohmer asked. He drew a diagram on the board (Figure 4-8).

"Point which way the wall will go."

Everyone pointed to the right. "But it wouldn't go all the way over," Jennifer noted. "It would go about three-quarters of the way and then the puppies on the other side would be getting squished."

"Wouldn't the wall keep moving back and forth, just a bit, because the puppies on the right side would still be moving and hitting the wall?" Raul asked.

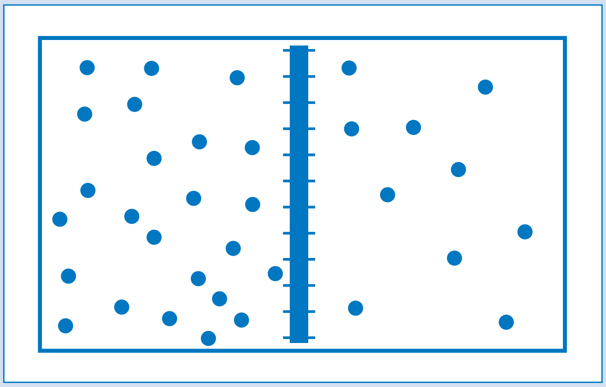


**FIGURE 4-8**

*Divided room with 25 Air Puppies on the left side and 10 on the right side.*

"Great! You're starting to see how this model works!" Mr. Sohmer said. "As the 10 puppies on the right get more and more squished into less and less space, they're going to get bounced more, and move faster and faster, and hit the wall more and more times. At the same time, the 25 puppies on the other side will still be bumbling around—but as their room expands each of the 25 puppies has, on average, farther to go before running into and bouncing off something. There will be more and more time between hits against the wall—they'll be hitting the wall less often. The wall will move pretty far over to the right, then get pushed back some, to the left, and so on, ending up by shimmying back and forth around a point well to the right of the original centerline."

Mr. Sohmer had another QuickTime video that showed exactly what would happen in this 25-to-10 situation. When he projected it from his computer onto the wall, the students watched the wall be driven to the right until a new equilibrium of puppy hits was established.

"Let me ask you one more thing," said Mr. Sohmer. "When the wall moved over to the right, how did that happen? Was it due to suction?"

A chorus of voices called out, "No, the puppies on the other side *pushed* it over!"

Mr. Sohmer continued the discussion with another variation.

"What if we start out with the same number of Air Puppies on both sides of the wall, but the puppies on the left, the red puppies, are more active. They are excited and running fast, fast, fast, while the puppies on the right, the blue puppies, are just moving around at a normal, unexcited pace. What do you think is going to happen to the wall?"

"The fast puppies are gonna bump into the wall faster and more times and harder, so it's gonna be pushed away, towards the slow puppies," Sandra answered.

Mr. Sohmer showed another QuickTime video, with the red Air Puppies moving much faster than the blue Air Puppies.

"This is a nifty picture definition of what heat is. The red Air Puppies are pounding on everything much more than the blue Air Puppies are—so we could say they are hot, and the blue puppies are cold. But as long as the blue puppies are moving at all—and they always will be—they will have heat energy. Even ice has heat!"

Mr. Sohmer added another variation to the story. "How about if we had our regular situation, with 100 puppies on one side and 100 puppies on the other, the same amount of excitement activity on both sides, but we make the room on the right bigger. What would happen to the wall then?"

"The wall's going to move to the right," Pedro said.

"Why do you think that?" asked Mr. Sohmer. "What's making the wall move? Is it getting sucked over?"

"No, it's getting pushed. There's more space on the right, so the puppies bop around the same, but they don't hit the wall as often."

Mr. Sohmer then added another aspect to the problem by asking students to imagine what would happen when each room had an equal number of Air Puppies, but the room on the right had an open door (see Figure 4-9). The students reasoned that as Air Puppies escaped from the open door on the right, the wall would move to the right, resulting in the room on the right getting smaller and the room on the left getting bigger.

"What if you close the door after a lot of Air Puppies have already escaped from the right side?" Gina asked. "There's going to be lots of space, and lots of puppies, on the left side, and then the wall between them, and then only a little teeny space over on the right side with hardly any puppies. But can the wall just destroy the puppies on the right?"

"No, they won't be destroyed," Mr. Sohmer said. "They'll still be there, still be bumbling and bouncing around."

"Then it seems like at some point, after a long time, the wall is going to come to some kind of balance point. It's going to be somewhere way over on the right side, but it's gonna eventually stop."

"If the wall stops moving, does that mean there's no more pressure, no more puppy hits per area?" asked Mr. Sohmer.

"No," Gina said. "I think I get it. If the wall's not moving, it just means that there's the same number of hits on both sides, or equal pushes, or equal forces. Like when you had two guys pushing you the same on both sides and you didn't move. So I guess you were like the wall!"

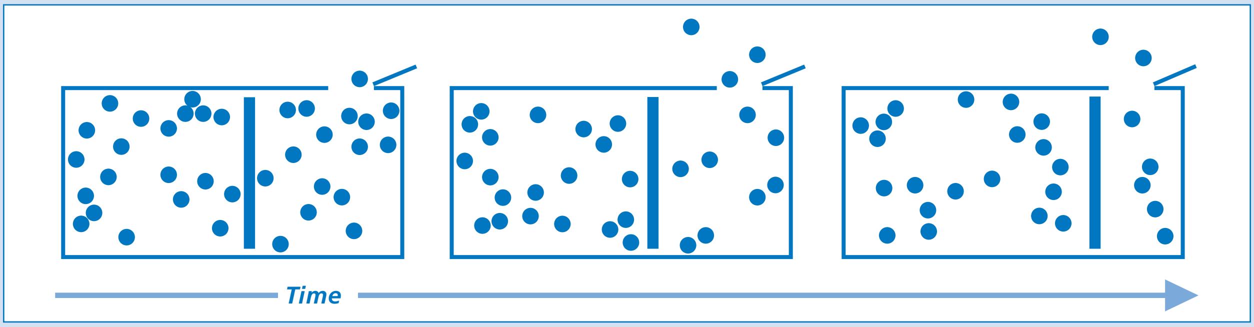



**FIGURE 4-9**

*As Air Puppies in the right room bumble randomly out the open door, there are fewer and fewer Air Puppy impacts on the wall from the right. Increasingly unopposed Air Puppy impacts from the left push the wall to the right.*

"Truth!" Mr. Sohmer declaimed. Laughter and a buzz of speculation ensued about the other air pressure demonstrations the class had done.

"Okay all, so that's the Air Puppies story," Mr. Sohmer said. "With that story, you can see into a ton of interesting phenomena, explain to your parents how vacuum cleaners really work! But in order to know that you really understand the story, you have to be able to explain it to someone else. So I'd like you all to go home and explain it to someone there—a brother, a sister, a parent, a grandparent whoever is at home. And also explain one of the demos we did in class."

Mr. Sohmer reminded the class that the Air Puppies story was a new tool, and that it was often difficult at first to use any new tool. He had his students each choose one of the air pressure demonstrations they had done and explain it to the group. The goal, Mr. Sohmer said, was to explain things clearly enough so that even a person who could only hear and not see them presenting could still understand what they were saying. The students in the audience listened to the explanations and made suggestions for how they could be explained more clearly or completely. Each presenter had as many chances as needed to revise their presentation, until everyone in the group was satisfied.

After a few weeks of practice in small groups using the Air Puppies model in many different situations, each group selected a demonstration and worked hard to develop a thorough, compelling, and cogent explanation of all the causal forces at work. These were eventually put on posters and presented in a schoolwide after-school celebration. The I-Club students also published a bimonthly Investigators Club newsletter, detailing their work and describing interesting physics demonstrations that could be done at home. Discussions of the demonstrations were written up in an issue. I-Club students developed teaching texts that were used to teach younger students and archived in the school library. They presented their work to adults in the community and participated in science fairs.

Many of the I-Club students were reluctant, struggling writers in school, and most read far below grade level. Nonetheless, every one of them decided that they wanted to prepare teaching texts. Of the 25 students, 23 voluntarily entered their school science fair, most of them doing physics projects that revolved around the power of air pressure. And 13 students were among their school winners and went on to the citywide competition.

In spite of the fact that they said they "hated to write in school," the I-Club kids put an enormous effort into preparing science fair or teaching texts, writing as "experts" rather than as students. They worked in teams of four, adding elaborate photographs and diagrams, formatting their texts on the computer, soliciting comments from other groups, and drafting and revising.

These tasks motivated the students to take their thinking and their presentation of their ideas (in writing and orally) to a higher level. Sandra, one of the I-Club students, put it well when she said, "In school, they just give you a book. It's boring. But in the I-Club, we really get to explain things, down to the very core of the problem. That's why we did so well in the science fair."

## The Benefits of Focusing on Core Concepts and Learning Progressions

As the cases in this chapter suggest, it takes considerable time and effort to introduce students to ideas about atomic-molecular theory in a meaningful manner. It is important to take that time at the middle school level for several reasons.

First, understanding atomic-molecular theory opens up many productive new avenues for investigating matter. For example, it introduces the concept of chemical change, which research suggests is not really accessible to students with only macroscopic criteria for identifying substances.

Understanding atomic-molecular theory also helps students more clearly understand what substances stay the same and what substances change during the water cycle. In addition, many important topics across the sciences—osmosis and diffusion, photosynthesis, digestion, decay, ecological matter cycling, the water cycle, the rock cycle—depend on an understanding of atomic-molecular theory.

Finally, atomic-molecular theory gives students an opportunity to begin developing an understanding of and respect for the intellectual work and experimentation needed to formulate successful scientific theories.

In current practice, atomic-molecular theory is often presented to students without careful attention to how their ideas develop through instruction or how to help them link science with their emergent ideas and relevant everyday experiences. As a result, as research makes clear, the majority of students fail to internalize the core assumptions of atomic-molecular theory, and they are unable to understand such important ideas as chemical change. Perhaps more importantly, students are not given the opportunity to recognize the standards that a scientific theory is built on, how it is formed, and why it cannot be challenged by other theories that do not meet the same rigorous epistemological standards. Without an understanding of those epistemological standards, students will not know the grounds on which they should test and believe scientific arguments.

Learning progressions are a promising way to design and organize science learning. Recognizing this, teams of educators and researchers are actively developing learning progressions with support from the National Science Foundation and other sponsors. For now, fully developed, well-tested learning progressions that are ready for broad application will have to wait. But that does not mean that science educators can't use aspects of this work now. In fact, it is important for science educators to begin to consider how learning progressions might be used in their own schools and classrooms and how learning progressions might affect their current teaching practices. The effectiveness of learning progressions is dependent on committed and capable implementation, and they will benefit from the experience and feedback of early adopters who can also play an active role in refining the practice.

In order for productive science learning to take place, students and teachers need to have a clear idea of major conceptual goals. We've proposed a frame for thinking about K-8 goals, but shorter term goals can also be set for a four- to six-week unit or over a year of instruction. Science educators can begin to reflect on their curricular goals, identifying and focusing on those that are most scientifically powerful and fundamental.

Meaningful science learning takes time, and learners need repeated, varied opportunities to encounter and grapple with ideas. Identifying core ideas means making hard decisions about "coverage" and will require that a curriculum be pared down and significantly focused. For this reason, it is advisable to begin on a small scale. A group of teachers at a given grade level, for example, might begin with a single unit of study, one that they feel comfortable with; perhaps the unit they feel is the strongest at their grade. They will need to give themselves ample time to identify meaningful problems, figure out how best to sequence the unit, and plan lessons that will provide students with the skills they need to do the science involved. Beginning this effort a year in advance of trying to enact changes to the curriculum should allow time for adequate teacher learning and planning.

Whether at the state, district, school, or individual classroom level, as educators take up learning progressions, it is important to treat them as a research and development initiative. As such, educators will require support in order to break from current practice and embrace new ideas. They will require feedback on the quality of the changes they enact as well as student learning outcomes.

## For Further Reading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# 5 Making Thinking Visible: Talk and Argument

As we noted in Chapter 1, science requires careful communication and representation of ideas. Scientists frequently share formulas, theories, laboratory techniques, and scientific instruments, and require effective means by which to understand and disseminate these types of information. They share their ideas and observations in myriad ways, including the use of text, drawings, diagrams, formulas, and photographs. They communicate via PowerPoint slides, e-mail exchanges, peer-reviewed research articles, books, lectures, and TV programs or documentaries. They participate in research groups, academic departments, scientific societies, and interdisciplinary collaborations.

Often, scientific collaboration takes the form of disagreement and argument about evidence. In this way, communities of scientists challenge and validate one another's ideas in order to advance knowledge.

These practices have analogues in science classrooms.[1] Effective science teaching can employ some of the same methods of communication and representation that are used by scientists in the real world. This chapter and the subsequent one focus, respectively, on the ways in which students can use language and argument, as well as other forms of representation, to communicate and further develop their ideas. As the case studies in previous chapters make clear, science teaching and learning involve more than just conducting interesting demonstrations in the hope that students will somehow, on their own, discover the underlying concepts behind the outcomes. Effective science teaching and learning must also include communication and collaboration, which require both spoken and written representations of the world.

In this chapter, we explore how talk and argument work in science and the role they play in good science teaching. We focus on language, both oral and written, as the primary tool for communication in science and the primary mechanism for making thinking public. Science provides unique opportunities for students to adopt and use new forms of argument and new representational tools. Because so much of what happens in classrooms is communicated and processed through speaking and writing, language plays a particularly important role in teaching and learning science. It is one of the most important ways for the teacher to understand and assess how students are thinking.

Language also provides students with a way to reflect on and develop their own scientific thinking, alone or with others. Teachers play a critical role in supporting students' use of language, guiding them toward a greater understanding of the language of science.

## Learning Through Talk and Argument

In order to process, make sense of, and learn from their ideas, observations, and experiences, students must talk about them. Talk, in general, is an important and integral part of learning, and students should have regular opportunities to talk through their ideas, collectively, in all subject areas. Talk forces students to think about and articulate their ideas. Talk can also provide an impetus for students to reflect on what they do—and do not—understand. This is why many seasoned teachers commonly ask students to describe terms, concepts, and observations in their own words.

Two additional ways to think about talk in learning have specific applications in science. First, the language of science can be very particular. Certain words have precise, specialized definitions. It is quite common, however, for children and adults alike to confuse specialized science definitions with the more familiar definitions commonly associated with those words. An example of this, as mentioned earlier, relates to the word "theory," which in science is understood to mean "a well-elaborated body of scientific knowledge that explains a large group of phenomena." In common parlance, the word "theory" is often used to refer to a guess or a hunch. By having students read and discuss instances in which different definitions of a word are used and then explain how they've come to understand it, teachers can help students distinguish between science-specific and more common meanings of a word.

Another form of talk that has unique applications in science is argumentation. Like the language of science, it too needs to be distinguished from nonscientific interpretations in both definition and practice.

Argumentation can take several different forms. It is important that educators and students recognize and understand the science-specific forms of argumentation and how they differ from the common forms of argumentation in which people engage in daily life. For example, the kinds of arguments in which a person may participate with family members, friends, or acquaintances are often acrimonious or focused on the desire to make one's point and "win" the argument. Or in the case of more formal debate, such as the kind politicians engage in, contestants are scored on their ability to "sell" an argument that favors a particular position.

Both of these forms of argumentation differ from scientific argumentation in important ways. In science, the goals of argumentation are to promote as much understanding of a situation as possible and to persuade colleagues of the validity of a specific idea. Rather than trying to win an argument, as people often do in nonscience contexts, scientific argumentation is ideally about sharing, processing, and learning about ideas.

Scientific argumentation is also governed by shared norms of participation. Scientific argumentation focuses on ideas, and any resulting criticism targets those ideas and observations, not the individuals who express them. Scientists understand that, ultimately, building scientific knowledge requires building theories that incorporate the largest number of valid observations possible. Thus, while scientists may strongly defend a particular theory, when presented with a persuasive claim that does not support their position, they know they must try to integrate it into their thinking.

## Encouraging Talk and Argument in the Classroom

In spite of the importance of talk and argument in science and in the learning process in general, K-8 science classrooms are typically not rich with opportunities for students to engage in these more productive forms of communication. Analysis of typical classroom practice suggests that patterns of discourse in classrooms typically adhere to a turn-taking format, often characterized as "recitation." A teacher asks a question with a known answer and a student is called on and responds. The teacher then follows up with a comment that evaluates the student's response.

This talk format is sometimes referred to as the I-R-E sequence, for teacher *I*nitiation, student *R*esponse, and teacher *E*valuation. Researchers have found it to be the dominant, or at least the default, pattern of discourse in classrooms. As such, students come to expect and accept it, and after a few years of using the I-R-E sequence, it's often difficult to get them to use a different pattern.

While I-R-E recitation can be helpful in reviewing prior knowledge or assessing what students know, it does not work well to support complex reasoning, to elicit claims with evidence, to get students to justify or debate a point, or to offer a novel interpretation. I-R-E patterns are likely to support only some of the strands of science learning (e.g., Strand 1) but not others (Strands 2-4). The I-R-E discourse pattern is not a particularly good one if the goal is to encourage and support argumentation. But changing long-standing discourse patterns in the classroom is not a simple undertaking. Students and teachers will require extensive modeling and ongoing support to become comfortable and competent with more effective talk formats.

The kind of discourse that encourages scientific talk and argument is different—in subtle and not so subtle ways—from the I-R-E pattern of discourse. To begin with, teachers ask questions that do not have "right" or "wrong" answers or to which they themselves don't know the answers. For example, a teacher might ask, "What outcome do you predict?" and follow up the initial question with comments such as, "Say more about that." They may ask other students to respond, saying, "Does anyone agree or disagree with what Janine just said?" or "Does anyone want to add or build on to the idea Jamal is developing?"

Teachers may also ask students to use visual representations, such as posters or charts, to make their thinking more accessible to the rest of the class. They may follow questions with "thinking" or "wait" time, so that students have a chance to develop more complex ideas and so that a greater number of students have a chance to contribute, not just those who raise their hands first.

Teacher-initiated questions might also ask for clarification, for example, "Does anyone think they understand Sarah's idea? Can you put it into your own words?" They might pose alternate examples or theories, or "revoice" a student's contribution, saying, for example, "Let me see if I've got your idea right. Are you saying that our measurements will be less accurate with shoes on?" This strategy helps make the student's idea, restated by the teacher, more understandable to the rest of the class. These "talk moves" implicitly communicate that it takes effort, time, and patience to explicate one's reasoning and that building arguments with evidence is challenging intellectual work.

The table on the next page shows six productive classroom talk moves[2] and examples of each, which teachers can use to help students clarify and

| *Talk Move* | *Example* |
| --- | --- |
| Revoicing | "So let me see if I've got your thinking right. You're saying _________?" (with space for student to follow up) |
| Asking students to restate someone else's reasoning | "Can you repeat what he just said in your own words?" |
| Asking students to apply their own reasoning to someone else's reasoning | "Do you agree or disagree and why?" |
| Prompting students for further participation | "Would someone like to add on?" |
| Asking students to explicate their reasoning | "Why do you think that?" or "What evidence helped you arrive at that answer?" or "Say more about that." |
| Using wait time | "Take your time. . . . We'll wait." |

expand their reasoning and arguments. These talk moves are illustrated throughout this book in the different case studies.

In addition to talk moves, teachers can engage students in a number of talk formats, each of which has a particular norm for participation and taking turns. Examples include partner talk, whole-group discussion, student presentations, and small-group work. A number of studies have suggested that productive classroom talk has many benefits in the classroom. It can lead to a deeper engagement with the content under discussion, eliciting surprisingly complex and subject matter–specific reasoning by students who might not ordinarily be considered academically successful.

Some of the reasons why productive classroom talk is so important, and why it may be effective, include the following:

- It allows students' prior ideas to surface, which in turn helps the teacher assess their understanding.
- Discourse formats such as extended-group discussion might play a part in helping students improve their ability to build scientific arguments and reason logically.
- Allowing students to talk about their thinking gives them more opportunities to reflect on, participate in, and build on scientific thinking.
- It may make students more aware of discrepancies between their own thinking and that of others (including the scientific community).
- It provides a context in which students can develop mature scientific reasoning.
- It may provide motivation by enabling students to become affiliated with their peers' claims and positions.

Many educators reading the classroom case studies in this book might doubt whether this kind of productive talk can really take place in science classrooms. They might think, "It looks easy for them, but the students in our district couldn't do this." Or, "Maybe my students would like this, but I don't know if I can bring it off successfully. What if no one talks? What if I can't understand what they're trying to say? What if they make fun of each other?"

These are reasonable concerns. Instruction that supports productive scientific discussion is difficult to enact, even for seasoned veterans. The kinds of discussions described in the case studies are largely improvisational, and students' contributions can be unpredictable. The improvisational and unpredictable nature of these discussions can be intimidating for teachers, school administrators, science specialists, and teacher educators who share responsibility for creating safe, orderly, and productive science learning environments. In addition, some educators are uncomfortable encouraging or condoning any kind of argument in the classroom. That's understandable, given how much time is spent in schools mediating conflict and persuading students of the value of civil exchange.

Teachers need support, skill, and persistence to help students grasp the difference between respectful scientific argument and the kind of confrontational, competitive argument they may be used to. The success of the former is dependent on students having the shared understanding that the goal of the argument is to reach a point of mutual understanding or consensus. The latter relies on the assumption that the goal of an argument is winning. Students of any age, from kindergarten through middle school, will need help to recognize the distinction between disagreeing with an idea and disagreeing with a person.

Mediating effective scientific argument also requires the teacher to have sufficient knowledge to perceive—on the fly—what is scientifically productive in students' talk and what is not. Younger students, English language learners, or students exploring a new topic will tend to use language that is ambiguous, fragmentary, or even contradictory—especially in a heated conversation. In these moments, the content and structure of students' arguments can be difficult to follow. Yet if the educational goal is to help students understand not only scientific outcomes and the concepts that support them but also *how* one knows and *why* one believes, then students need to talk about evidence, models, and theories.

## Position-Driven Discussion

In Chapter 4, we saw a class engage in a collective discussion about whether adding air to a volleyball would increase its measured weight. This discussion and the ensuing activity involved all of the students in a teacher-guided, whole-group discussion. This was a discussion of a very specific kind—what might be called a "position-driven" discussion. It involved a demonstration that was poised to run but was not run until after students exchanged predictions, arguments, and evidence. The proposed problem had more than one imaginable outcome, so the students could predict and argue for different outcomes. In addition, it featured materials and scenarios familiar to the students, so that each student believed that they could anticipate the outcome. By using familiar materials and phenomena, students can more readily conjure up their own ideas and experiences and tap into these as they build explanations. This makes it possible for every student to participate in a more meaningful way.

A position-driven discussion generally forces the student to choose from two or three different but reasonable answers. In the case of the students in Mr. Figueroa's class in Chapter 4, the students had to decide whether the volleyball with 15 extra pumps of air would be (1) heavier, (2) lighter, or (3) weigh the same. This kind of discussion generates productive and lively talk. It also calls on students to actively participate in reasoning, theorizing, and predicting. Students take positions and attempt to formulate the best arguments and evidence they can in support of their position. Sometimes, informal votes are taken to see where the students stand with respect to one another, followed by more opportunities for students to change their minds, argue, and revote. In position-driven discussions, everyone is focused on the same phenomenon but is required to commit to one position or another and to argue for their respective predictions or theories. Everyone is also free to change positions on the basis of another person's evidence or arguments—typically with the proviso that one says, as specifically as possible, what it is in the other's position that one finds useful or persuasive.

Position-driven discussions are designed to push for divergence in predictions and theories. They also capitalize on the wide variety of life experiences and resources inherent in an ethnically and linguistically diverse group of students. Such discussions are a powerful form of "shared inquiry" that mirror the discourse and discipline of scientific investigation.

In position-driven discussions, as in most effective classroom talk and argument formats, the teacher's role is to help students explicate their positions as clearly and cogently as possible, not indicating, even subtly, how close to the "right" answer they may be. The teacher does not evaluate student contributions as correct or incorrect, as is often common in traditional teacher-guided discussion or recitation. Instead, the teacher typically supports students by revoicing their contributions and pushing for clarification. This helps both the speaker and the rest of the class move toward a greater understanding of their own and everyone else's reasoning.

This emphasis on having a clearly explained theory or position over having a correct theory or position continues until the demonstration is run and students see the actual outcome. This focuses students on finding explanations or answers in the outcomes of evidence, not merely in authoritative sources like textbooks and teachers.

One important aspect of a position-driven discussion is the framing of the question with which the discussion is launched. This is not always an easy task. It requires that the teacher produce a clear, easily understood question that will provoke a range of reasonable responses and positions, none of which can appear obviously correct. In addition, the question must be carefully selected and sequenced among other science-related tasks so as to advance the thinking of the group as a whole. It is unreasonable to expect a teacher to develop such framing questions without the support of a rigorous, coherent curriculum, colleagues, or an instructional coach.

Science Class

# ESTABLISHING CLASSROOM NORMS FOR DISCUSSION[3]

**It takes time to get students to understand that more than one explanation for a scientific event is possible and that alternative explanations should always be examined. One way to encourage this thinking is for teachers to frequently introduce and discuss alternative beliefs and explanations or describe the ways scientists disagree and resolve their disagreements.**

**Some researchers, in collaboration with science teachers, have found that argumentation in classrooms is more likely to occur when students are permitted and encouraged to talk directly with each other, rather than having their discussions mediated by the teacher. Other researchers have found that teacher-mediated whole-group discussion is more productive. Most successful teachers use a combination of talk formats to provide opportunities for both of these types of discourse. No matter what the format, teachers need to work actively to support classroom norms that emphasize responsibility, respect, and the construction of arguments based on theory and evidence.**

**As we described earlier, the most productive classroom environments, in all subject areas, are those that are enriched by talk and argument. But many students and teachers are not accustomed to or comfortable with extensive student talk in the classroom, so it is important to understand how to define and establish effective, acceptable classroom norms for discussion. Following is a case study that illustrates some methods for establishing and using norms for discussion.**

Gretchen Carter's 28 sixth-grade students are a diverse and challenging group, with over 70 percent of them eligible for free or reduced-price lunches. Among her students are six children who recently immigrated to the United States and who leave the room each day for intensive English language instruction. In addition, she has four students using individualized education plans (IEPs), including one student, Lucy, who has been diagnosed with autism. Lucy rarely speaks in class but is treated by her teacher and peers as a full participant in classroom activities.

Ms. Carter works hard to establish an environment of cooperation and respect in her classroom. Her mottos are "No single student is as smart as all of us put together" and "You have the right to ask for help, and the duty to provide it to others." She has also established norms for her students for respectful participation in small-group work and whole-group discussion. Each student has a set of rights and obligations printed on green paper and pasted into the first page of their science notebooks. The students and Ms. Carter refer to these rights and obligations as the "Green Sheet." The Green Sheet outlines the rules for talk in Ms. Carter's class. She developed the rules over a number of years, so she no longer negotiates them with her students at the beginning of each year. Instead, she hands out the Green Sheet and discusses it with her students, asking them to describe the rules in their own words and to give reasons why the rules are appropriate and effective. The Green Sheet rights and obligations are as follows:

Student Rights:

1. You have the right to make a contribution to an attentive, responsive audience.
2. You have the right to ask questions.
3. You have the right to be treated civilly.
4. You have the right to have your ideas discussed, not you, personally.

Student Obligations:

1. You are obligated to speak loudly enough for others to hear.
2. You are obligated to listen for understanding.
3. You are obligated to agree or disagree (and explain why) in response to other people's ideas.

Once the rules have been discussed, Ms. Carter consistently reminds her students of them, pointing out any infractions. Ms. Carter uses a color-coded discipline system in conjunction with these rights and obligations. Each student starts the day on green. A warning is given for misbehavior, and a further infraction results in a change to yellow. After one more warning, another infraction puts a student on red and the parent is called after school. If there is a serious infraction, she stops the class and has everyone turn to their Green Sheets to find the right or obligation that relates to that particular infraction. She then discusses that right or obligation at length with her students. Disrespectful comments get a warning. Repeat offenses get the offender a color change. Over a period of weeks, the rules become thoroughly internalized by her students and Ms. Carter rarely needs to refer to the Green Sheet. It remains a resource, however, available for review if discussions get off track.

Students know that she will keep enforcing the norms consistently, week in and week out. As a result, Ms. Carter's class is known for its good behavior. In

addition, her students appear to be willing to ask questions, put forward their ideas, and respond fully and respectfully to each other's questions. These are all signs that Ms. Carter has succeeded in making her classroom a safe place for students to engage in challenging academic thinking, problem posing, theorizing, and problem solving—by making their thinking visible to one another and to themselves.

## Appreciating Cultural, Linguistic, and Experiential Differences[4]

In efforts to support effective use of talk and argument in the classroom, it is important to remember that scientific language is, to some extent, foreign for *all* students. There are no native speakers of science. In addition, all students are shaped by their cultural backgrounds, and those backgrounds affect how they learn science and communicate in the science classroom. Today's students come from a variety of cultural backgrounds and have different ways of behaving, thinking, and interpreting the world, and they interact differently with the communities and institutions that they encounter in their everyday lives. Children both shape and are shaped by their cultural practices and traditions, so that the relationships between culture and personal belief are fluid and complex.

In addition, people's experiences and histories vary, and a person's ability to negotiate change across cultures and settings may be affected by their history. Thus, teachers' and students' personal cultural experiences have implications for how they learn to talk and act in classrooms generally, and this will have implications for how they experience scientific talk and argumentation. Cultural diversity is important to recognize, because classrooms are not neutral settings. They too are imbued with social and cultural norms and expectations. These norms and expectations are often unstated, which can make it difficult for some students to understand what those norms and expectations are. This observation will become even more relevant over time, as the demographics of the United States continue to shift, and classrooms become even more diverse than they are today.

How does a teacher create the conditions that allow all children—despite their cultural, linguistic, or experiential differences—the same access to classroom conversations and to be held accountable to the same high levels of academic rigor in their talk, reasoning, and representations?

A good place to start is with some important principles and ideas that research in a variety of fields has shown to be true. Regardless of their race, culture, or socioeconomic status, all children, unless they have severe mental disabilities, have well-developed ways of telling stories, giving accounts, providing reasons, making arguments, and providing evidence. Similarly, all children have the capability to think abstractly about situations, concepts, and even about language itself.

With very few exceptions, children come to school as adept language learners and language users. Linguists have shown definitively that all such children are grammatical speakers of their home language—that is, they use language in consistent and rule-governed ways. While their dialects may be different from standard English, all children speak their home dialects with fluency and accuracy. Some children even bring a second language to the classroom at a level of sophistication and fluency that few of their teachers are able to match.

If all children have linguistic abilities, why does it sometimes seem that certain students are not adept language users? Why does it seem that some students don't bring much, if any, language from home or aren't able to speak about academic subjects? Why does it seem that certain students are good at talking about science and others are not?

The primary reason for this is that speakers of all languages have a tendency to perceive differences in the way other people speak and identify these differences as "inadequacies" or "deficits." For teachers, this tendency can create problems in the classroom. A focus on deficits in students' language makes it harder for the teacher to connect with students, harder to build on their strengths, and harder to create the conditions for rigorous and productive discussion, reasoning, and presentations in science.

Every child in this society learns culturally appropriate ways of using language and of taking meaning from written texts in the early years at home. Every cultural group in this society has sophisticated ways of integrating the oral and written language around them into daily life. However, ways of using oral and written language are closely tied to culture and the different ways members of a culture have of interacting with others. In some cultures, the use of language in the home is closely related to the ways in which language is typically used in schools, while in other cultures it is not as closely related.

For example, Yup'ik children in Alaska typically learn by observing experienced adults and participating as helpers in adult work and other activities. Verbal interaction is not central to their learning process; observation and participation are considered more important.[5] Because of this, a reliance on explicit verbal instruction may be less effective or even disconcerting to children from this cultural background.

As another example, researchers in Hawaii, part of the Kamehameha Early Education Project, have shown that part-Polynesian children perform much better in small-group reading instruction if they are allowed to talk without waiting to be called on. Effective teachers allow these students to "overlap" their talk with one another in much the same way they do when talking or storytelling outside of school.[6]

Carol Lee has found, in her research with predominantly African American high school students in Chicago, that at times in a lesson, students would break into animated discussion, all seeming to talk at once, speaking over or interrupting one another.[7] On the surface, the discussion might have appeared chaotic. However, Lee showed that this kind of discussion could be highly productive in advancing the academic purpose of a lesson. She found that the students' talk, when analyzed closely, showed evidence of rigorous thinking and of students hearing and building on one another's contributions.

In addition to coming to school with different discourse experiences and styles, some children have had far less exposure than others to many of the kinds of practices that form the basis of scientific activities and investigations, including providing explanations, analyzing data, making arguments, providing evidence for their claims, and interpreting texts. An extensive body of research suggests that such cultural differences often lead to negative judgments about a student's intelligence or the quality of their thinking. These judgments can affect a teacher's expectations of how a student should contribute or participate in classroom discussion. Research also shows that it is hard for teachers to recognize and build on the reasoning of a student whose methods of communication may not be the same as their own. These subtle and not so subtle miscommunications with respect to language and culture in the classroom can lead to serious problems of equity and access, creating barriers to communication, student-teacher trust, and the conditions that nurture active participation and effort. This, in the end, can result in significant decreases in student motivation, participation, and learning, which can have far-reaching, real-life consequences in regard to knowledge and performance.

One way for teachers to overcome cultural and linguistic differences in students is to treat them as if they were highly intelligent foreign diplomats. This simple strategy is reliant on common sense. People recognize that foreign diplomats think and communicate in ways that they cannot always immediately understand or relate to, but they assume, nonetheless, that foreign diplomats are intelligent and possess unique talents and skills. Similarly, in a fast-paced classroom conversation, it may be difficult to immediately understand a student's unique intelligence, wit, insight, and analytic skills. But the teacher can assume that they have an innate capacity to think deeply, to reason abstractly, to coordinate theory and evidence, and to develop sound arguments. An assumption of competence makes it easier to build on and promote students' contributions, even if those contributions are incomplete, not entirely explicit, or are expressed in a nonstandard dialect. Once students are invited into the conversation, are given opportunities to engage in coherent instructional tasks, are able to hear and build on the contributions of their peers, and have scientific reasoning modeled for them by teachers and peers, they gradually take on the language and forms of competence that are valued in science.

## Strategies for Inclusiveness

But how does one listen through cultural differences? How does one ensure that every student participates in the conversation and is held to the same rigorous standards in providing evidence, justifying claims, and representing ideas in ways that others can understand? How does one promote equity and access in the face of tremendous sociolinguistic diversity? How can teachers create the conditions for rigorous science talk simultaneously with children from many different cultures and language backgrounds?

According to researchers, there are two effective strategies that teachers can use. First, they need to make the rules of participation visible in the science classroom, instead of assuming that students implicitly know what the rules are. When engaging in new or unfamiliar scientific activities, teachers may need to provide explicit, detailed accounts of expectations, including, if necessary, structured or scripted roles to play in discussions.

The goal should be to establish and maintain what Okhee Lee has described as *instructional congruence*.[8] With instructional congruence, the nature of an academic discipline is meshed with students' language and cultural experiences to make science accessible, meaningful, and relevant. Students are given opportunities to master new ways of thinking and participating, while teachers ensure that students know that their existing norms and practices are valued.

The work of establishing, understanding, and modifying classroom norms for scientific thinking must be ongoing. Students themselves can help create these norms by proposing, debating, and establishing criteria for what counts as a good scientific question or what counts as persuasive evidence. For example, in one particular classroom, criteria for judging good questions and persuasive evidence were adopted by the students as the norm. Then, midyear, new ideas about questions and evidence surfaced as students evaluated their work. Some students argued that they should amend their criteria of what qualified as a good question by adding that a good question should encourage "piggybacking" (good questions are inspired by the findings of others and in turn inspire related additional questions). They changed their criteria to reflect their new understanding that knowledge in the scientific community depends on the sharing of information and evidence, and that new knowledge is often built on the contributions of fellow scientists.

Research shows that children are adept at learning how to participate in public speaking activities in the classroom. They quickly learn what the implicit norms, rights, and obligations for speaking are. When students resist taking on the roles or norms of classroom activities, it is not because they're not smart enough to know what the norms are. Rather, it often means that students resist assuming these roles because it means taking on a social or academic identity with which they feel uncomfortable. Students must feel that they belong, and they must *want* to belong. When classroom discourse is successful, every student is treated as a full member of the group, with all of the rights and status of membership, even before they have fully mastered the discourse.

The second strategy for effectively promoting equality in discourse is making evident the connections between students' everyday thinking, knowledge, and resources and those of practicing scientists. In the Chèche Konnen research program, researchers conducted studies with Haitian Creole students and their teachers over 15 years to identify key points of contact between students' ways of knowing and scientific ways of knowing. For example, they observed that the students visualized themselves in problems, regularly evoking analogies, arguments, and narratives as a means of making sense of phenomena—all common strategies among scientists.

One student who was investigating animal behavior—in this case, the preference of ants for different kinds of habitats—imagined himself in the different habitats. His original intention had been to set up an experiment to establish whether ants prefer an environment that is dark to one that is brightly lit. But as this student imagined himself as an ant crawling through the soil, he began to wonder how either side of the chamber—lit or unlit—could possibly appear light to an ant underground.[9] The Chèche Konnen research program demonstrates how the cultural practices of urban, language-minority students can be drawn on to support high-level scientific reasoning and problem solving.[10]

Some of the strategies discussed earlier in this chapter, such as student and teacher revoicing, the modeling of scientific argument, and the use of wait time, are especially helpful in classrooms in which there is great linguistic diversity among students. These strategies help slow the pace of the discussion, allowing time for complex ideas to be expressed, listened to, repeated, revoiced, and responded to at length. This facilitates the acquisition and use of scientific language and of discourse structures. It exposes students to complex scientific reasoning, allows them to practice it with support and guidance from their teacher and peers, and gives them opportunities to become confident and competent in presenting their claims, models, and explanations as well as at challenging evidence and asking questions.

In establishing norms for inclusion so that students of different cultural backgrounds and experience can understand and build on one another's ideas, teachers must also find ways to ensure equitable access for all students to participate in the talk that surrounds scientific investigations. Equitable participation does *not* mean that every student must participate in every conversation. Rather, it means that *access* to every conversation must be equal. In discussing equitable participation, one must assume that there is a structured, robust scientific conversation being held, not merely a turn-taking event in which the goal is for everyone to offer an opinion or idea. Assuming this to be the case, equitable participation requires that everyone hear what is being said and that everyone have equal time to develop their ideas and be heard, respectfully, by all. Participation is not equitable if some students routinely dominate the conversation while others are routinely excluded. Again, the goal is not to allow every student to say something. The goal is to ensure that the conversation stays focused, that each student can hear what is being said, and that each student has opportunities to contribute relevant ideas if they so choose.

In order to develop their ideas and arguments, students must be able to think aloud, practicing what some teachers and researchers call "first draft thinking" or "exploratory talk." During this sort of initial exploratory talk, students' communication is sometimes halting, with pauses, repetitions, hesitations, and false starts. It can be difficult to follow. Their ideas may be flawed in some way. But the goal is for students to have an opportunity to clarify their initial ideas and for others to listen, attempt to build on those ideas, and adjust or improve on them.

For students there is often much at stake beyond their success or failure at learning science, so getting them to express thoughts about which they are not certain can be particularly challenging. Some students may fear being seen as bookish and may shy away from expressing their thoughts. Others may worry about expressing ideas that are not fully formed. Still others may take every opportunity to insert their voice and dominate classroom discussions. This makes for a complex social dynamic that is critical for teachers and students to learn to monitor.

In creating an environment that supports equitable participation in classroom discourse, it is critical to pay special attention to English language learners. In science, in which vocabulary and discourse are so important, limited proficiency in English can make it difficult for teachers to recognize or gauge the depth of a student's understanding of scientific concepts, which in turn makes it difficult to build on what the student already knows.

Many teachers assume that English language learners must become fairly proficient in English before they can learn much about science. This is not the case. Research suggests that the science classroom is a good environment in which to teach diverse language populations, because talk in the science classroom is often about materials and events that all of the students see and experience together. This provides a basis for the development of vocabulary and discourse practice. It also motivates the reading of associated texts.

There is evidence that with good instruction children from all cultural and language backgrounds can learn science. However, research is not yet clear as to which methods work best under which circumstances. One clear objective for the future must be to build on the unique strengths and needs that students of diverse backgrounds bring to the classroom. This should be a central focus of teacher preparation courses and of ongoing professional development in regard to making science teaching and learning equitable and accessible to all students.

The following case study demonstrates how students' culturally diverse ways of speaking and thinking interact with school tasks and curricula.

Science Class

## SUCCESSFULLY SUPPORTING DIVERSITY[11]

Jocelyn Wright taught a combined third- and fourth-grade multiethnic class in a large city in Massachusetts. There were a large number of Haitian Creole–speaking children in her school, as well as a transitional Haitian Creole bilingual program. Ms. Wright spoke quite a bit of Haitian Creole herself, and she valued the linguistic and cultural resources her diverse group of children brought from home.

The class was doing a science activity on the topic of balance, using a balance scale with small metal weights placed at different points of the scale on both sides. In this science unit, over the course of several weeks, the students worked on a series of balance problems.

After a particular problem was posed, students were asked to predict, by a class vote, whether the weights would balance or whether they would tip to the right or to the left. Once the students voted for their choice, they debated or discussed their predictions and their reasons for those predictions with each other as a group. After the discussion, they had a chance to vote again in case they had changed their minds on the basis of someone else's explanation or argument. Finally, the teacher performed the demonstration, and the students went to their seats to fill out a worksheet explaining their reasoning.

Approximately four weeks into the unit, the students had progressed through a series of balance problems, predicting, debating, and changing their minds. At this point, the students had been introduced to the formula "multiply weight times distance," to help them figure out how the balance would behave. They had already practiced solving balance problems of this type, but there was still some confusion among the students as to when to multiply and when to add.

Sabrina, a fourth grader, argued that the configuration shown below would balance (see Figure 5-1). She demonstrated her reasoning to the group by writing on the small whiteboard easel:

| | | |
|---|---|---|
| **2 x 5 = 10** | ‖ | **1 x 1 = 1**   **3 x 3 = 9** |
| | ‖ | **1 + 9 = 10** |

Sabrina said, "Three weights on the 'three point' equal nine, the single weight on the 'one point' equals one, so the total force on the right side of the scale is ten. Then, on the other side, two times five equals ten, so since both sides equal ten, it will balance."

Josianne asked to report next. Josianne, a native speaker of Haitian Creole, had moved to Ms. Wright's class two months earlier from a transitional Haitian bilingual classroom.

Ms. Wright used a "handing off" procedure for turn-taking during science discussions, which

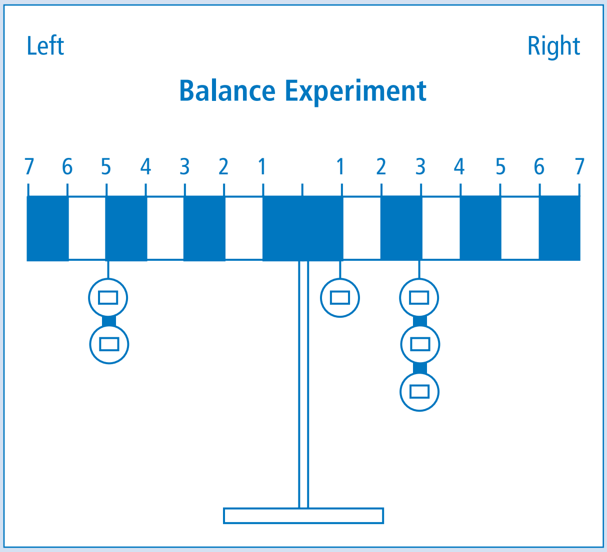


**FIGURE 5-1**
*Balance with weights.*

required that the current speaker nominate the next speaker, so Sabrina called on Josianne.

Josianne: "I agree with you [referring to Sabrina] because I was thinking it will balance."

Ms. Wright: "And what made you think that?"

Josianne: "Because, I think it will be balanced, because, I was thinking. I think it will be balanced."

Ms. Wright probed further to try to get Josianne to reveal some of the reasoning behind her conclusion.

Ms. Wright: "So, do you remember what made you think that? Were you just persuaded by what other children were able to say?"

Josianne: [shaking her head no] "Uh-uh."

Ms. Wright: "Can you give us some words for your thinking?"

Again, Ms. Wright tried to encourage Josianne to explain her reasoning, but Josianne seemed to struggle.

At this point, Ms. Wright asked Josianne if she would like to bring the next speaker into the conversation. After more students explained their mathematical reasoning, the class held a second vote. Ms. Wright performed the demonstration, which showed that the scale did, in fact, balance. She then asked the students to return to their seats and put down in writing their reasoning for why it balanced. Josianne returned to her seat and wrote the following:

"Because I was thinking it have to be balance, and I vote for balance."

Ms. Wright thought that Josianne's answer might reflect her limited proficiency with English. She asked a colleague to work one on one with Josianne to try to determine whether she could explain her reasoning. All of Josianne's answers were given first in Creole and then in English.

Teacher: "Can you tell me why you thought it would balance or why you now think it would balance?"

Josianne: "I say because I was thinking in my brain. And my brain think it will be balance."

Teacher: "Okay. Can you say more about why?"

Josianne: [puzzled] "Say more about why?"

Teacher: "Why do you think it will be balanced? What did your brain think to get you to think it would be balanced?"

Josianne: [grinning] "I don't know because I didn't ask my brain."

Teacher: "*Ask* your brain about the weights and where they are and why you think it would be balanced or why you think it did balance. Why does it have to balance? Why doesn't it tip to the right or to the left?"

Josianne: [impatient] "Because I make multiplication in my head! I say, here it's two, and this five, two times five here and three time three is nine plus the one point is ten."

Josianne had clearly known the reasoning behind her answer all along but had not understood what the teacher was asking her to explain. When Ms. Wright's colleague asked her why she didn't explain "all that multiplication stuff" in the first place, Josianne responded, "I didn't understand your question."

Josianne knew her multiplication facts and how to apply them to the problem. But she did not understand the discourse of school science. She interpreted Ms. Wright's questions and those of her colleagues as asking her about the status of her knowledge and how she came by it. Did she guess? Was she persuaded by her classmates? Or did she figure it out for herself?

In as many different ways as she could, Josianne was trying to explain that she had figured it out for herself. However, in the discourse of school science, reasoning the proof, the theory, the model, or the mathematical reasoning has to be made explicit. This might have been obvious to the other students in the class who participated in the discussion. But as this example illustrates, "why" questions can be interpreted by students in many different ways. They can be interpreted as asking for an explanation, a demonstration of one's reasoning, a motive, evidence, and so on, depending on the discourse conventions particular to a given domain.

What's instructive in this example is that Ms. Wright did not give up on Josianne. During the group discussion, she tried asking the same question of Josianne in several different ways, and eventually she moved on to another student so Josianne wouldn't feel uncomfortable. Ms. Wright sensed that the problem lay in her own inability to tap into Josianne's understanding. In the end, it wasn't specifically language that made the difference for Josianne. It more likely was the reframing of the "why" question that helped Josianne to understand. The newly framed question did not ask *how* Josianne knew, but *what about* the configuration of the weights made the balance arm tip.

In the fast pace of classroom life, it takes a careful eye (or just as likely, ear) and a stock of good questions and tasks to successfully gauge students' understanding. It helps if teachers presume that their students have ability, reasons, and complex ideas, even if this is not at first apparent, and then work hard to help them demonstrate these abilities.

Representing ideas through talk and argument plays an essential role in learning in general and a more specialized role in the learning and practicing of science. In the science classroom, students need opportunities to talk through their own ideas and hear and respond to those of their peers. When discussion is conducted only through the filter of the teacher or the textbook, students have fewer opportunities to formulate and develop their own understanding and ideas or to practice listening to peers and building arguments collectively. In many classrooms, students are given scant opportunities to think aloud, let alone engage in argumentation that is uniquely scientific. In order to engage in effective scientific argumentation, students must embrace norms and habits that focus on data, analysis, and the building of ideas in a collective, cumulative fashion.

Building classroom environments like those of Mr. Figueroa, Ms. Carter, and Ms. Wright can be challenging. The ways in which these teachers structure and elicit student talk and argumentation is an ongoing and often complex process. The methods described in this chapter can serve as entry points for improving the practice of classroom discourse and for adjusting the ways teachers may structure student interactions related to science.

In order to do this, teachers will need opportunities to observe science classrooms like the ones described in this chapter. They'll need to experience firsthand what it is like to be members of a community governed by scientific norms for talk and argumentation. And they'll need help reflecting on those experiences and planning appropriate ways to create scientific talk and argumentation structures in their own classrooms. They'll need access to resources that illustrate these practices and provide additional explanations for how to implement them.

In asking teachers to move away from the well-established patterns of classroom interaction to embrace student talk and argumentation as a central feature of the science classroom, we must recognize that they will require support. Typical patterns of discourse in schools, such as the I-R-E pattern described earlier, are so pervasive in U.S. culture that they can even be observed in young children as they play school. School system administrators, curriculum developers, and science teachers and educators will all need to understand and participate in the challenge of moving to more effective methods of promoting talk and argumentation in the science classroom.

## For Further Reading

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# 6 Making Thinking Visible: Modeling and Representation

Scientists develop models and representations as ways to think about the natural world. The kinds of models that scientists construct vary widely, both within and across disciplines. Nevertheless, in building and testing theories, the practice of science is governed by efforts to invent, revise, and contest models. Using models is another important way that scientists make their thinking visible.

Representation is a predecessor to full-fledged modeling. Even very young children can use one object to stand in for, or represent, another. But they typically do not recognize or account for the relationships and separations between the real world and models: the features of a phenomenon that a representation accounts for or fails to account for. The use of all forms of symbolic representation, such as graphs, tables, mathematical expressions, and diagrams, can be developed in young children and lead to more sophisticated modeling in later years. In "Science Class: The Nature of Gases" (Chapter 4), we described students in an after-school science program who were attempting to understand air pressure. The students used "Air Puppies" as a model to represent air molecules. They depicted Air Puppies as dots in some scenarios and as numbers in others (see Figures 6-1 and 6-2).

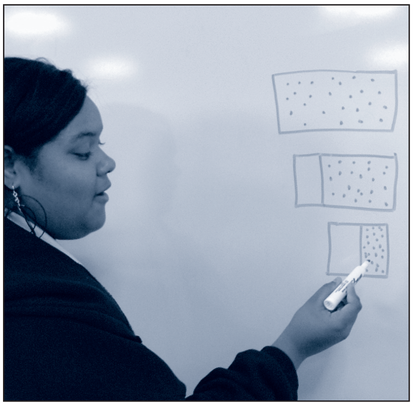


**FIGURE 6-1**
*Taylor explaining the movement of the wall-on-wheels with Air Puppies represented as dots.*

Modeling involves the construction and testing of representations that are analogous to systems in the real world. These representations can take many forms, including physical models, computer programs, diagrams, mathematical equations, and propositions. The objects depicted in a model, as well as their behavior and relationships to each other, represent theoretically important objects, behavior, and relationships in the natural world. Models allow scientists to summarize and depict the known features of a physical system and predict outcomes using these depictions. Thus, they are often important tools in the development of scientific theories.

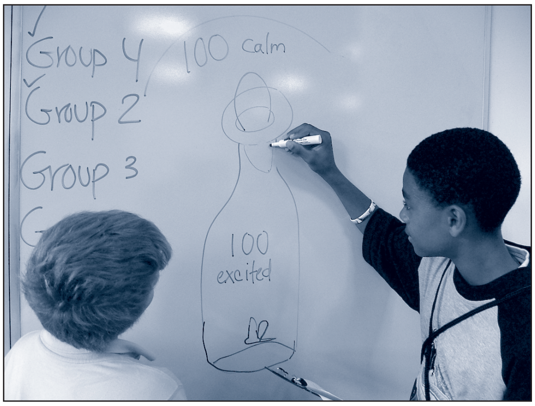



**FIGURE 6-2**
*Mitchell and Antwaune show Air Puppies in and outside a bottle as numbers (100 calm and 100 excited puppies).*

A key concept for students to understand is that models are not meant to be exact copies. Instead, they are deliberate simplifications of more complex systems. This means that no model is completely accurate. For example, in modeling air molecules with Air Puppies, certain characteristics of molecules are represented, such as the fact that they move constantly without intention, and other characteristics are not, such as their being composed of hydrogen and oxygen atoms. Students need guidance in recognizing what characteristics are included in a model and how this helps further their understanding of how a system works. When first introduced to the Air Puppies model, students often ask, “Do Air Puppies breathe air? Do they sleep? Do they die?” They need to figure out which aspects of Air Puppies are useful for understanding how air molecules work.

## Mathematics

For the past 200 years, science has moved toward increasing quantification, visualization, and precision. Mathematics provides scientists with another system for sharing, communicating, and understanding science concepts. Often, expressing an idea mathematically results in the discovery of new patterns or relationships that otherwise might not be seen.

In the grade-level representation activities that follow, third-grade children investigating the growth of plants wondered whether the shoots (the part of the plant growing above the ground) and the roots grow at the same rate. When they plotted the growth on a coordinate graph that displayed millimeters of growth per day, students noticed immediately that the rates of growth were not the same. However, one student pointed out that the curves for both the roots and the shoots showed the same S-shape. This S-shape appeared again on graphs describing the growth of tobacco hornworms and populations of bacteria on a plate. Students came to recognize this shape as a standard graph pattern that indicated growth. This similarity in patterns would not have been noticeable without the mathematical representation afforded by the graph.

Given the importance of mathematics in understanding science, elementary school mathematics needs to go beyond arithmetic to include ideas regarding space and geometry, measurement, and data and uncertainty. Measurement, for example, is a ubiquitous part of the scientific enterprise, although its subtleties are almost always overlooked. Students are usually taught procedures for measuring but are rarely taught a theory of measure. Educators often overestimate children's understanding of measurement, because measuring tools—like rulers and scales—resolve many of the conceptual challenges of measurement for children. As a result, students may fail to understand that measurement entails the use of repeated constant units and that these units can be partitioned. Even upper elementary students who seem proficient at measuring lengths with rulers may believe that measuring merely entails counting the units between boundaries. If these students are given unconnected units (say, tiles of a constant length) and asked to demonstrate how to measure a length, some of them almost always place the units against the object being measured in such a way that the first and last tiles are lined up flush with the end of the object measured, leaving spaces among the units in between. These spaces do not trouble a student who holds this "boundary-filling" conception of measurement.

## Data

Data modeling is central to a variety of scientific enterprises, including engineering, medicine, and natural science. Scientists build models with an acute awareness of the data that are required, and data are structured and recorded as a way of making progress in articulating a scientific model or deciding among rival models.

Students are better able to understand data if as much attention is devoted to how they are generated as to their analysis. First and foremost, students need to understand that data are constructed to answer questions, not provided in a finished form by nature. Questions are what determine the types of information that will be gathered, and many aspects of data coding and structuring also depend on the questions asked.

Data are inherently abstract, as they are observations that stand for concrete events. Data may take many forms: a linear distance may be represented by a number of standard units, a video recording can stand in for an observation of human interaction, or a reading on a thermometer may represent a sensation of heat.

Collection of data often requires the use of tools, and students often have a fragile grasp of the relationship between an event of interest and the operation or output of a tool used to capture data about the event. Whether that tool is a microscope, a pan balance, or a simple ruler, students often need help understanding the purpose of the tool and of measurement. Some students, for example, accustomed to relying on sensory observations of "felt weight," may find a pan balance confusing, because they do not, at first, understand the value of using one object to determine the weight of another.

Data do not come with an inherent structure. Rather, a structure must be imposed on data. Scientists and students impose structure by selecting categories with which to describe and organize the data. However, young learners often fail to grasp this as evidenced in their tendency to believe that new questions can be addressed only with new data. They rarely think of querying existing data sets to explore questions that were not initially conceived when the data were collected. For example, earlier we described a biodiversity unit in which children cataloged a number of species in a woodlot adjacent to their school. The data generated in this activity could later be queried to determine the spread of a given population or which species of plants and animals tend to cluster together in certain areas of the woodlot.

Finally, data are represented in various ways to see, understand, or communicate different aspects of the phenomenon being studied. For example, a bar graph of children's height may provide a quick visual sense of the range of heights. In contrast, a scatterplot of children's height by children's age would yield a linear relationship between height and age. An important goal for students—one that extends over several years—is to come to understand the conventions and properties of different kinds of data displays. There are many different kinds of representational displays, including tables, graphs of various kinds, and distributions. Not only should students understand the procedures for generating and reading displays, but they should also be able to critique them and to grasp the advantages and disadvantages of different displays for a given purpose.

Interpreting data often entails finding and confirming relationships in the data, and these relationships can have varying levels of complexity. Simple linear relationships are easier to spot than inverse relationships or interactions. Students may often fail to consider that more than one type of relationship may be present. For example, children investigating the health of a population of finches may wish to examine the weight of birds in the population. The weight of adult finches is likely to be a nonlinear relationship. That is, as both low weight and high weight are disadvantageous to survival, one would expect to find a number of weights in the middle, with fewer on both ends of the distribution.

The desire to interpret data may lead to the use of various statistical measures. These measures are a further step of abstraction beyond the objects and events originally observed. For example, understanding the mean requires an understanding of ratio. If students are merely taught to "average" data in a procedural way, without having a well-developed sense of ratio, their performance often degrades, mistakenly, into procedures for adding and dividing that make no sense. However, with good instruction, middle and upper elementary students can learn to simultaneously consider the center and the spread of the data.

Students also can generate various mathematical descriptions of error. This is particularly true in the case of measurement: they can readily grasp the relationships between their own participation in the act of measuring and the resulting variation in measures.

## Scale Models, Diagrams, and Maps

Scale models, diagrams, and maps are additional examples of modeling. Scale models, such as a model of the solar system, are widely used in science education so that students can visualize objects or processes that they cannot perceive or handle directly.

The ease with which students understand these models depends on the complexity of the relationship being communicated. Even preschoolers can understand scale models used to depict location in a room. Elementary school students can look beyond the appearance of a model to investigate the way it functions. However, extremely large and small-scale models often pose serious challenges for students. For example, middle school students may struggle to work out the positional relationships of the earth, the sun, and the moon, which involves not only reconciling different perspectives (what one sees standing on the earth, what one would see from a hypothetical point in space) but also visualizing how these perspectives would change over days and months.

Students are often expected to read or produce diagrams and integrate information from the diagram with accompanying text. Understanding diagrams seems to depend less on a student's problem-solving abilities than on the specific design and content of the diagram. Diagrams can be difficult to understand for many reasons. Sometimes the desired information is missing. Sometimes a diagram does not appear in a familiar or recognizable context. And sometimes features of a diagram can create confusion. For example, the common misconception that the earth is closer to the sun in the summer than in the winter may be due, in part, to the fact that two-dimensional representations of the three-dimensional orbit make it appear as if the earth is indeed closer to the sun at some points than at others.

Students' understanding of maps can be particularly challenging, because maps preserve some characteristics of the place being represented—for instance, relative position and distance—but may omit or alter features of the actual landscape. Recall the mapping done by Mr. Walker's class in the case study on biodiversity in Chapter 2, in which the students learned to develop a more systematic plan for mapping the distribution and density of common species. Young children especially have a much easier time representing objects than representing large-scale space. Students may also struggle with orientation, perspective (the traditional bird's eye view), and mathematical descriptions of space, such as polar coordinate representations.

## Modeling and Learning Progressions

In a study involving biological growth, Richard Lehrer and Leona Schauble observed characteristic shifts in the understanding of modeling over the span of the elementary school grades.[1] They developed a learning progression that emphasized different and increasingly complex ideas in different grade bands. Each had a different curriculum and tasks:

- Early elementary: Growth of flowering bulbs: A focus on difference
- Middle elementary: Growth of Wisconsin Fast Plants[2]: A focus on ratio
- Late elementary: Growth of population: A focus on distribution

They observed that primary grade students' initial representations of growth were typically focused on endpoints, for example: "How tall do plants grow?" Students' questions about plant height led to related concerns about identifying the attributes of a plant that could best represent height and how those attributes should be measured. As one might expect, students' resolutions to these problems varied by grade.

### First-Grade Representations

First graders represented the heights of plants grown from flowering bulbs, using green paper strips to depict the plant stems at different points in the growth cycle (see Figure 6-3). Consistent with the claim that young children try to create models that closely resemble real or known objects, the students at first insisted that the paper strips be adorned with flowers.

However, as the teacher repeatedly focused students' attention on successive differences in the lengths of the strips, students began to make the conceptual transition from thinking of the strips as "presenting" height to "representing" height (see Figure 6-4). Reasoning about changes in the height differences of the strips, students identified times when their plants grew "faster" and "slower." Their study of the plant heights was firmly grounded in prior discussions about what counted as "tall" and how to measure it reliably.

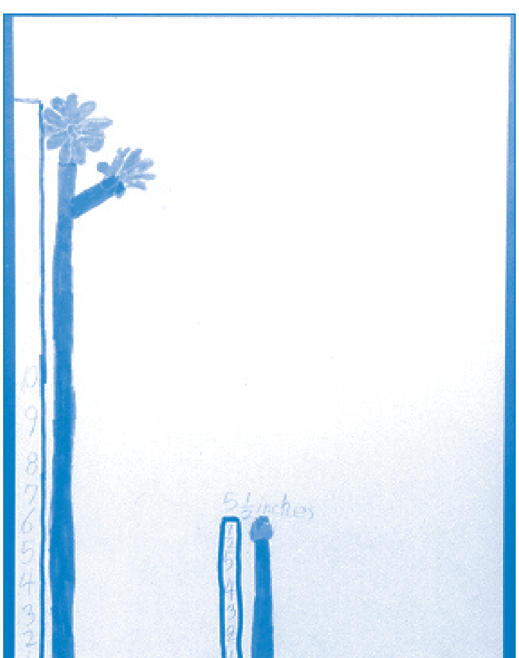


**FIGURE 6-3**
*A display with detailed drawings of individual plants that include flowers and colors.*

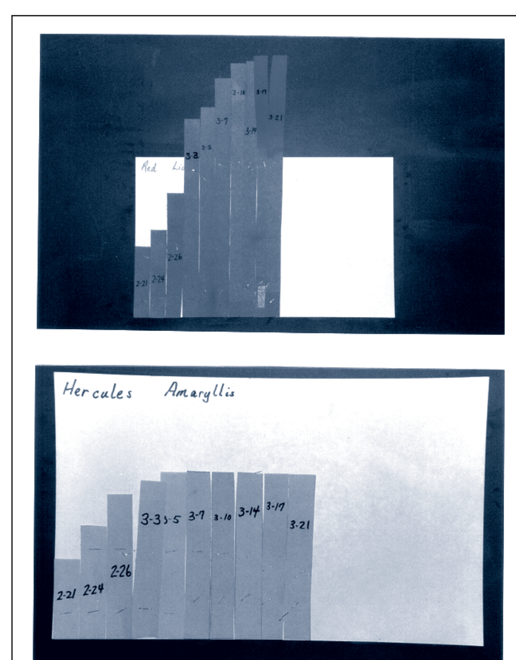



**FIGURE 6-4**
*Displays of plant height depicted in bar graphs.*

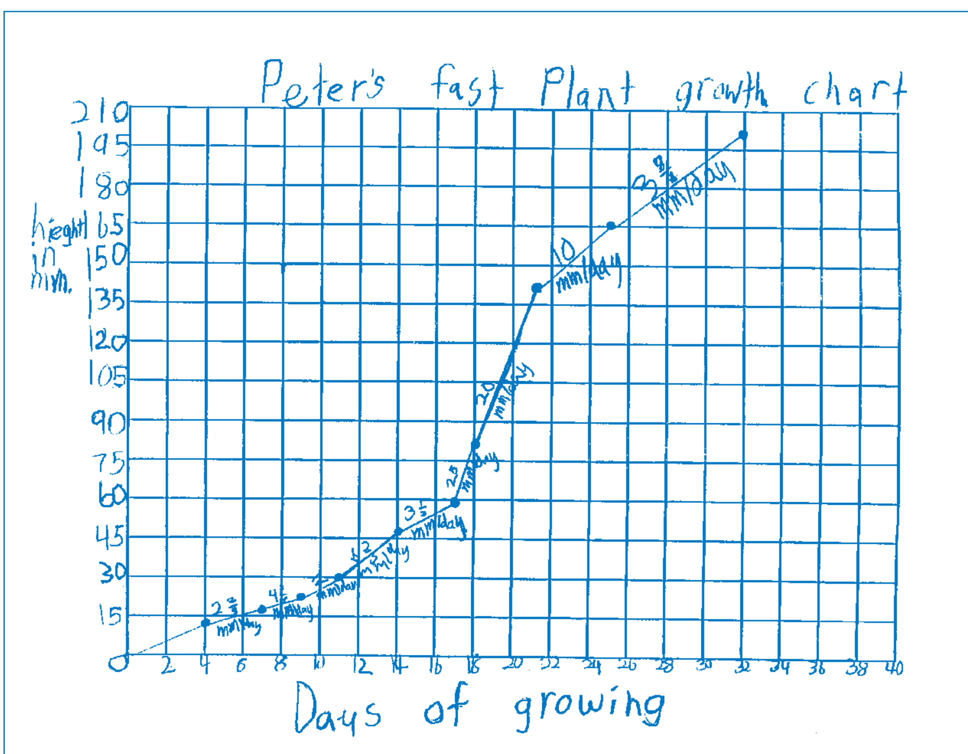
### *Third-Grade Representations*

In the third grade, children integrated math into their representations of Wisconsin Fast Plants in a variety of ways. They developed "pressed plant" silhouettes that recorded changes in plant morphology over time, coordinate graphs that related plant height and time, sequences of rectangles representing the relationship between plant height and canopy "width," and various three-dimensional forms to capture changes in plant volume.

As the diversity in types of students' representations increased, a new question emerged: Was the growth of roots and shoots the same or different? Comparing the height and depth of roots and shoots, students noticed that, at any point in a plant's life cycle, the differences in measurement were apparent. However, they also noted that graphs displaying the growth of roots and shoots were characterized by similar shapes: an S-shaped logistic curve (see Figure 6-5).

Finding similarities in the shape of data describing roots and shoots but not the measurements of roots and shoots, students began to wonder about the significance of the similarity they observed. Why would the growth of two different

**FIGURE 6-5**
*A display of plant height over time depicted in an S-shaped curve.*



plant parts take the same form on the graph? When was the growth of the roots and shoots the fastest, and what was the functional significance of those periods of rapid growth?

Students became competent at using a variety of representational forms as models. For example, students noted that growth over time *x*,*y*-coordinate graphs of two different plants looked similar in that they were equally "steep." Yet the graphs actually represented different rates of growth, because the students who generated the graphs used different scales to represent the height of their plants. The discovery that graphs might look the same and yet represent different rates of growth influenced the students' interpretations of other graphs in this and other contexts throughout the year.

### Fifth-Grade Representations

In the fifth grade, children again investigated growth, this time in tobacco hornworms (*Manduca*), but their mathematical resources now included ideas about distribution and sample. Students explored relationships between growth factors: for example, different food sources and the relative dispersion of characteristics in the population at different points in the life cycle of the hornworms.

Questions posed by the fifth graders focused on the diversity of characteristics within populations—for example, length, circumference, weight, and days to pupation—rather than simply shifts in central tendencies of attributes (see Figure 6-6 on page 120). As the students' ability to use different forms of representation grew, so, too, did their consideration of what might be worthy of investigation.

### Shifts in Understanding

In sum, over the span of the elementary school grades, these researchers observed characteristic shifts from an early emphasis on models that used literal depiction toward representations that were progressively more symbolic in character. Increased competence in using a wider range of representational types both accompanied and helped promote conceptual change.

As students developed and used new mathematical means for characterizing growth, they understood biological change in increasingly dynamic ways. For example, once students understood the mathematics of changing ratios, they began to conceive of growth not as a simple linear increase but as a patterned rate of change. These shifts in both conceptual understanding and forms of written or graphic representation appeared to support each other, opening up new paths of inquiry.

Students noticed similarities and differences among graphs and wondered whether plant growth was similar to animal growth and whether the growth of yeast and bacteria on a Petri dish was similar to that of a single plant. Students studying the growth of such organisms as plants, tobacco hornworms, and populations of bacteria noted that when they graphed changes in heights over a life span, all the organisms studied produced an S-shaped curve on the graph. However, making this connection required a prior understanding of a Cartesian coordinate system. In this case and in others, explanatory models and data models worked together to further conceptual development. At the same time, growing understanding of concepts led to increased sophistication and diversity of representational resources.

Current instruction often underestimates the difficulty of connecting representations with reasoning about the scientific phenomena they represent. Students need support in both interpreting and creating data representations that carry meaning. Students learn to use representations that are progressively more symbolic and mathematically powerful. Teachers need to encourage this process over multiple grades.

Let's take a closer look at how children develop scientific representations. In the following case, also taken from the work of Lehrer and Schauble, we examine a group of fifth graders working on an investigation of plant growth. They are challenged to develop representations of their data in order to reach particular goals in communicating.

# Science Class

## REPRESENTING DATA[3]

**Students need opportunities to build models and representations that suit particular explanatory and communicative purposes. They need experience refining and improving models and representations, experience that can be facilitated by critically examining the qualities of multiple models or representations for a given purpose.**

**In the following example we visit a fifth-grade classroom in which students are studying species variation. Having tracked the growth of Wisconsin Fast Plants over a period of 19 days, they are grappling with the best way to represent their data. Hubert Rohling, the teacher, has posted a list of unordered measures that the students had taken over the previous 18 days on chart paper at the front of the class. He has asked them to consider two questions: (1) how they might organize the data in a way that would help them consider typical height on the 19th day and (2) how to characterize how spread out the heights were on this day. He chose to have the students focus on these qualities of their representation in order to draw their attention to critical aspects of representing data sets.**

**Mr. Rohling understood that his students would need to grapple with how best to portray data and to practice doing so as a purposeful activity. Rather than assigning children particular data displays to use in capturing data, he asked them to invent displays. He introduced additional uncertainty into the assignment by asking students to identify typical values. Often the approach to learning about typical values is to teach children different measures of central tendency and to assign children to calculate means, or identify the modal or median values in a data set. Mr. Rohling's interest, however, was to push children to wrestle with the notion of typicality and articulate their understanding through creating and critiquing data displays.**

**In the process students would be forced to grapple with the value of maintaining regular intervals between data points (thus providing a visual cue as to the quantitative relationship among points) and sampling distribution. (What aspect of the data provides a fair sense of the overall shape of the data set?) Students would confront the same kinds of problems that scientists do in the course of their work. They must find meaningful ways to organize information to reveal particular characteristics of the data.**

**The students had previously been assigned to seven working teams of three to four students each. The students in each group worked to construct a data display that they believed would support answers to Mr. Rohling's two questions. Mr. Rohling encouraged each group to come up with its own way to arrange the data, explaining that it was important that the display, standing alone, make apparent the answer to the two questions about typicality and spread of heights.**

**The students' solutions were surprisingly varied. From the seven groups, five substantively different representational designs were produced. Over the next two days, students debated the advantages and trade-offs of their representational choices; their preferences shifted as the discussion unfolded. To encourage broad participation in critical discussion of displays, Mr. Rohling assigned pairs of students to present displays that their classmates had developed. And following this he facilitated discussions which drew in display authors, presenters, and other classmates. Despite the opportunity to exchange ideas with their peers, students did not easily or simply adopt conventions suggested by others. Instead, there was a long process of negotiation, tuning, and eventually convergence toward a shared way of inscribing what students came to refer to as the shape of the data.**

The first display discussed is shown in Figure 6-6. One of the students, Will, and his teammate presented this graph on large, easel-sized graph paper. As the figure shows, the authors first developed a scale (along the left side of the graph) to include all the observed heights of the plants. Then they simply drew lines to that scale, representing the height of each plant, ordered from the shortest to the tallest. As the class considered this display, Will tried to explain how this graph could be used to answer Question 1: "What is a typical height on Day 19?"

Will: "The tops of the lines represent height, and you have to see which lines stop and go along on one level. It's . . . it's the same number." [He points toward a space in the middle of the graph where all the lines appear to be about the same height.]

Mr. Rohling: "So you're looking for a flat line to tell you what typical is?"

Will: "Yes, then you can tell how many of those there are."

Mr. Rohling: "What about Question 2: How spread out are the plants on Day 19?"

Will: "You can look at the graph and see that it starts low down here on the left and goes up on the right."

Mr. Rohling: "If the data weren't spread out, what would it look like?"

Will: "One flat horizontal line."

This exchange shows that Will understood that "plateaus" on the graph denote clumps in the data. However, he went on to admit that the graph was

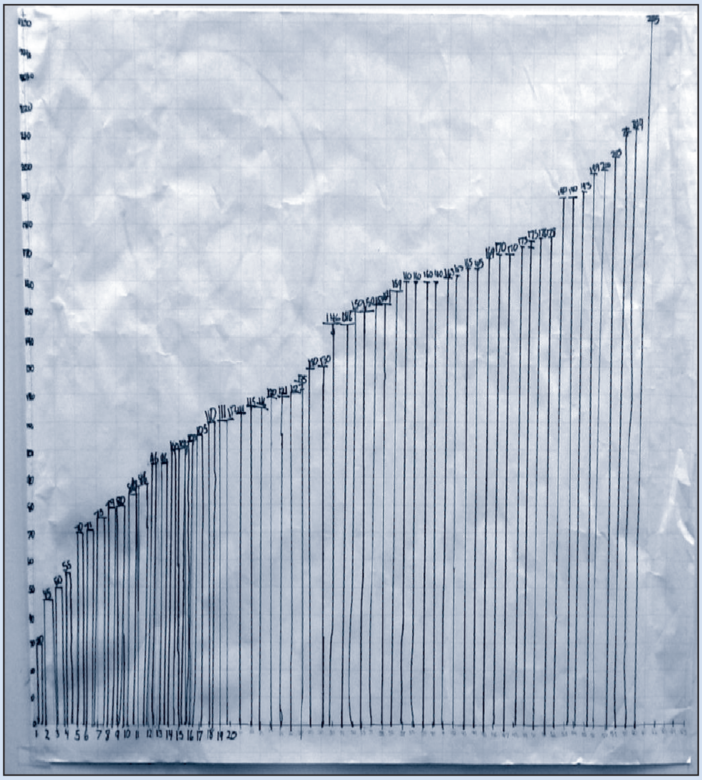


**FIGURE 6-6**
*A data display representing individual specimen height with a vertical line.*

difficult to read, especially from the back of the room. Will volunteered that the authors might consider alternating colors for different values, to make it easier to discern small changes in contiguous values.

The authors of the second display (Figure 6-7) simply ordered the values from lowest to highest and then wrote them along the bottom of the paper, stacking the values that occurred multiple times. The chart makers apparently ran out of room along the bottom of the page and, to avoid starting over, placed the remaining four values (200, 205, 212, 255) on the upper left, surrounded by a box. Although the values are separated by commas, this display, like the display previously discussed, fails to preserve interval. That is, the authors did not use spaces to indicate missing values. Therefore, linear distance does not accurately represent spread in the data. Keith and Matt interpreted this graph.

> Keith: "The typical number is, like, the one that goes higher than the others. You can just tell. The most common one is the highest column [the typical value.] The next question, for how spread out the data is . . . we just took the lowest number here . . . it was 30 . . . and subtracted it from 255. We got 225."

> Mr. Rohling: "So does the graph itself help you see that? Or do you have to do something with the numbers?"

> Keith: "You can tell the graph is pretty spread out from 30 to 255." [He sweeps his hand across the line.]

> Mr. Rohling: "What could you do to show typical and spread better?"

> Matt: "I think this part on the top shouldn't be there [pointing to the "leftover" numbers in the box]. It's kind of confusing. Those numbers on the top, they ran out of room."

The third display (Figure 6-8) presented values stacked in "bins" of 10. This display preserves each case value as well as the interval (the bin) as each plant height is written above its "bin" in ascending order. This form of display was used the previous year in a rocket investigation, and the students may have had at least a vague memory of its form.

Looking at the display, Julia and Angelique identified the mode as the "typical value," pointing out that most of the values were in the 160s column. However, one student found the graph confusing. She asked, "How come it's all grouped by tens?" Julia replied, "That's just how they did it."

Instead of letting this answer stand, Mr. Rohling pushed the discussion further. He wanted the students to think about why "binning" the values might produce different views (shapes of data) of typicality and spread. To raise these issues, he asked the class to think about a contrast, between the simple, ordered list (Figure 6-7) and the display currently under consideration (Figure 6-8). Of Figure 6-7, he asked, "How did this group bin them?"

A student replied, "One value per bin."

Another student asked, referring to Figure 6-8, "Why did you select bins of 10?" Tanner and Erica, the authors of the graph, explained their reasoning:

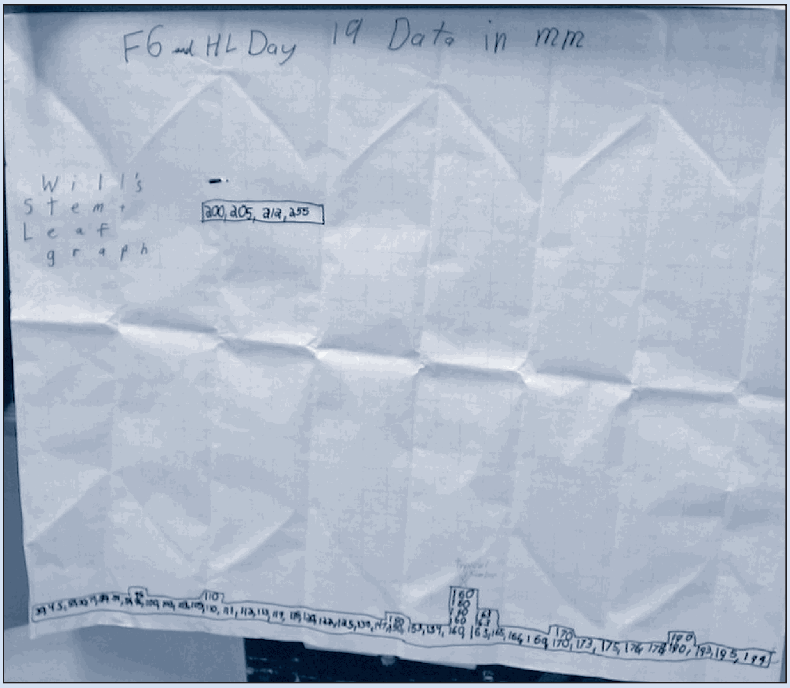



**FIGURE 6-7**
*A display featuring ordered values of plant heights.*

Tanner: "We wanted to make our numbers bigger and easier to see, so we didn't want to waste a bunch of room."

Erica: "We also thought it would be easier to answer the two questions this way."

Mr. Rohling: "So you're saying that binning them helps you see what's typical?"

Erica: "Yes, and how spread out they are."

Mr. Rohling: "How does binning help you do that?"

Tanner: "Typical is from 160 to 169. It's not that there is a typical *number*; it's the typical *group,* I would say.

This idea of a typical group or typical region would come to play an increasingly central role over the subsequent weeks of instruction, especially as the class began to discuss sampling. For the time being, Mr. Rohling decided to go on to the next display (Figure 6-9). This display listed values in ascending order from left to right, starting at the top left and moving down the page in rows, with repeated values stacked together. Katie and Greg, the presenters, noted that the authors had written their proposed typical value on the lower right of the display and that they had also marked out the 160s in their display, presumably to indicate that these were the values selected as typical. However, Katie and Greg

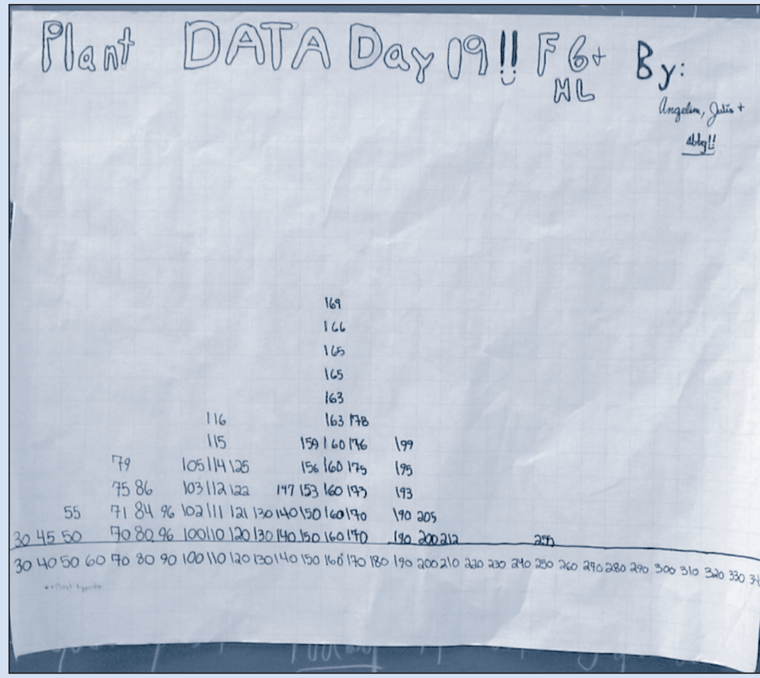



**FIGURE 6-8**
*A data display using "bins" of ten.*

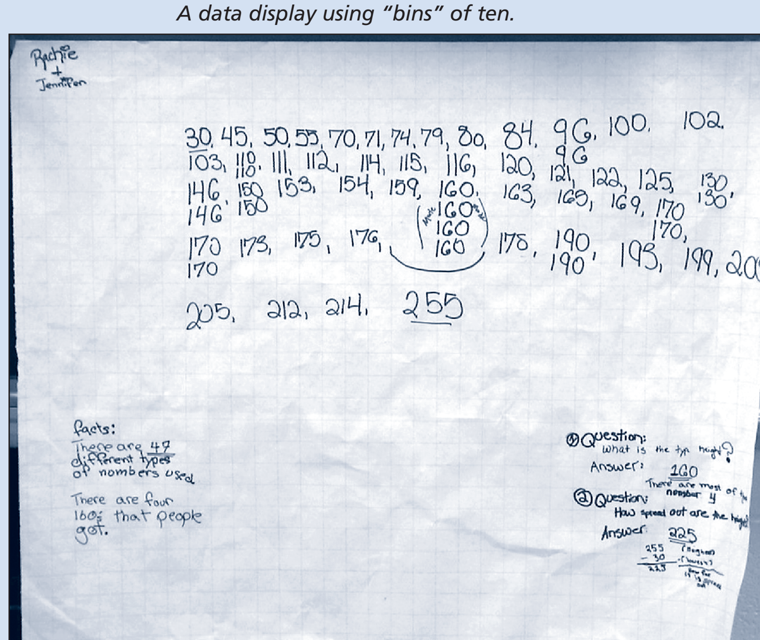



**FIGURE 6-9**
*A data display with rows of ascending values and repeated values stacked.*

thought that this graph made it difficult to answer the question about "spread."

> Katie: "This graph is a little more clumped up than the others (Figures 6-6 and 6-8 for example). It's not in a line, so it's a little harder to see. They were doing it in rows, but they did columns, too. That was kind of hard to figure out."

> Mr. Rohling: "So you're saying if you just had to use the graph data. . ."

> Keith: "We'd be way off."

Mr. Rohling then returned to the previous displays to juxtapose two different approaches to spread, one focusing on ordered cases (Figure 6-7) and the other on interval (Figure 6-8). He employed an imagined value (555) to highlight the difference between interval and order.

> Mr. Rohling: "I'm wondering which graph would show the spread better? Let's ignore 255 for a minute [the highest value on both graphs] and assume that the highest value is more like 555 [he opens his hands wider]. Does that feel quite a bit different than 255? If we include that number, that would become a much bigger spread. So let's pretend that the high value is 555. Which graph would help us see that it's more spread out? What about the one with the bins [Figure 6-8]? Is there a graph up there that would help?"

> Julia: "I think this one [Figure 6-9] might be harder to read from far away. They put the data in a square instead of a line."

At this point, one of the authors of that graph protested, "We wanted people to be able to see the numbers. If they're small, they're hard to read. If we had more paper, we'd have done it on a line."

> Mr. Rohling: "So, Julia, do you think if I wrote the number 555 right here [he appends the value 555 immediately at the end of the ordered list on Figure 6-7], it would be the easiest graph to see that this has a lot of spread?"

> Katie: "I think probably this graph [Figure 6-8] would probably be better for spread because they still leave the spaces there, even if there's nothing there. So you can really see how spread out it is. You can see how much space there is."

> Mr. Rohling: "You're saying if it was 555, we'd figure 555 would be out here? [He indicates a space way off the right edge of the graph.] Then the graph would actually look like it's spread? What helps you see the spread, then?"

> Isaac: "Not just the numbers that we *actually measured* that are in between, but empty spaces in *all* the numbers that are in between."

At this point, the students appeared to reach agreement that if a display is to show the spread in the data, it is necessary to scale the graph in a way that preserves intervals, even intervals for which no values have been observed. Although few of the original displays met this criterion, all of the displays made after the discussion did so.

Other displays were also presented (see Figures 6-10 and 6-11). And, as the discussion progressed, it was clear that there were two competing value systems in the air that were driving the students' display preferences. On one hand, students' own designs or those made by close friends were especially favored, and novelty and creativity were also highly prized. For example, as the presenters explained Figure 6-10, murmurs of "Oh, that's cool!" and "You guys are so cool!" were heard from about half the class. On the other hand, about half the students expressed concerns that the "cool" solution did not seem to provide an illustration of either typicality or spread. The display depicted in Figure 6-11 was deemed even "cooler" but, as more than one classmate noted, did not surrender its design logic readily. It took two full days of discussion before students finally surrendered their focus on novelty of design and gravitated instead toward criteria favoring clarity of the mathematical ideas.

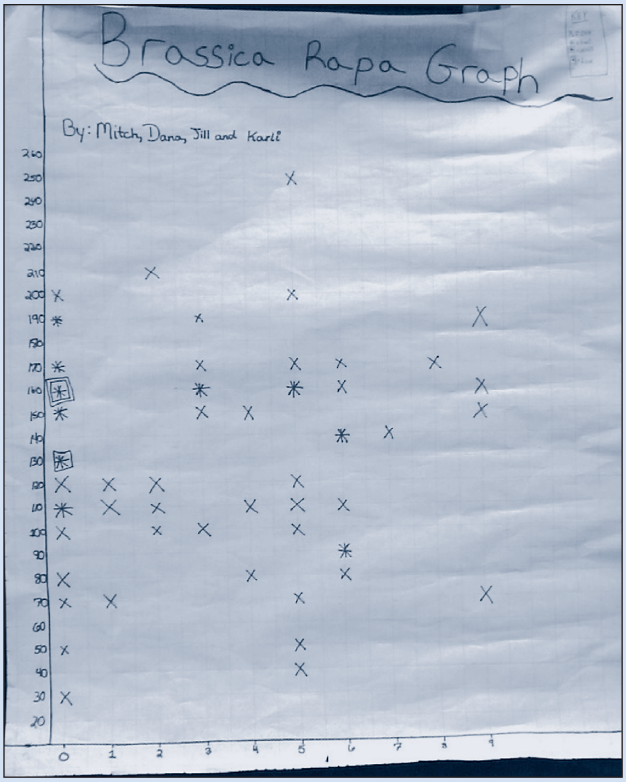



**FIGURE 6-10**
*A data display on a two-dimensional coordinate grid.*

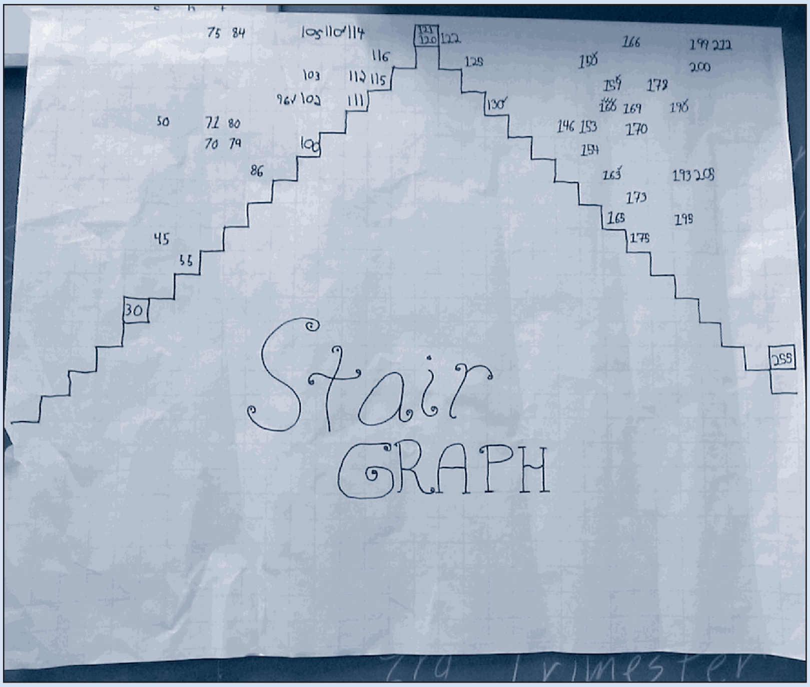



**FIGURE 6-11**
*A data display showing median at the apex of a pyramid.*

As this case illustrates, elementary school students can create representations that have clear communicative features. The representations themselves and the rich discussions they support offer an important window into how students are thinking about representation and about the phenomena being studied. Generating multiple representations and critiquing their utility for a particular goal can compel elementary school students to develop a clearer sense of the considerations that go into developing representations.

In addition to supporting students' skill at creating and using representation, modeling data through displays is fertile ground for advancing all four strands of science learning. In the case above, for example, children developed their substantive understanding of plant growth and population as they discussed and critiqued the data representations (Strand 1). They developed facility with graphing and making sense of data as they constructed representations of plant heights that conveyed information about the data spread and typical values (Strand 2). They embraced science as a dynamic undertaking and reflected on the adequacy of their representations. Over time their ideas changed—favoring "cool" displays slowly gave way to favoring displays that communicated clearly. Students whose previous displays did not retain intervals used intervals in subsequent displays, building on the cumulative insight of the group (Strand 3). Finally, their arguments and approaches to revising their models were governed by the goals and norms of science. As they analyzed and discussed the data displays, they practiced scientific norms by critically appraising each other's displays and explicitly reasoning about how well the displays accomplished the intended communicative goals (Strand 4).

Importantly, learning in each of the strands did not take place in isolation. Rather, advances in one strand supported and were catalyzed by advances in the other strands. This underscores a key point established in previous chapters: science is complex and learning science takes time and practice. The sophistication of students in the case above is the result of engaging in a rich investigative task, but also of many months and even years of science instruction that supported their knowledge and skill across all four strands.

Some important generalizations can be drawn from the examples of representation discussed in this chapter. Graphs, tables, computer-based tools, and mathematical expressions are examples of important symbolic and communication tools used in modeling. Scientists, as well as students of science, use representations to convey complex ideas, patterns, trends, or proposed explanations of phenomena in compressed, accessible formats. These tools require expertise to understand and use. Teachers can help students reflect on the features and purposes of representations by asking them to generate and critique their own representational solutions to problems, by encouraging them to interpret the representations developed by other students, and by asking them to consider what a representation shows and hides so that they come to understand representational choices as trade-offs. Although working with representations poses challenges for learners, it also can help bridge between the knowledge and skills they bring to the classroom and more sophisticated scientific practices.

## For Further Reading

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# 7 Learning from Science Investigations

In this book we have described how engaging children in scientific practice supports student learning in K-8 classrooms. The investigations in these classrooms typically unfold over several weeks or months. In pursuit of scientific answers, students engage in practices akin to those of real scientists, such as posing scientific questions, using data to examine complex phenomena, and generating explanations to account for their observations. These activities are often difficult even for professional scientists, who have access to complex social networks and well-resourced labs, let alone K-8 students. Yet there is compelling evidence that when classrooms function to support real scientific practice, students' understanding of science can flourish.

Supporting student learning in regard to scientific investigations requires deliberate and consistent instructional efforts. Research shows that simply "doing" science activities often leaves students with an inaccurate sense of what science is and how it works. To build their science knowledge and skill across the strands—learning scientific explanations, generating scientific evidence, reflecting on scientific knowledge, and participating in the social processes of science—requires intentional, sustained instruction and support. In this chapter, we focus on the kind of support that teachers can provide students to enable them to learn from their own scientific investigations. We examine several practices that effective teachers, in collaboration with researchers, have developed to help students do science in a "minds on" way.

## Creating Meaningful Problems

At the root of all science investigation are complex and compelling problems. In order for problems to be effective for supporting learning, they must be meaningful both from the standpoint of the discipline and from the standpoint of the learner. If a problem fails to connect to legitimate and fundamental scientific ideas, it cannot be used to promote science learning. And if students fail to see the problem as meaningful, there is little chance that they will engage in the range of productive scientific practices that result in science learning.

Scientifically meaningful problems are framed by core concepts, such as biodiversity, the atomic-molecular theory of matter, and evolutionary theory, and they typically focus on the smaller concepts within those core ideas. Scientifically meaningful problems may be theoretical or practical. Theoretical problems are framed in terms of basic scientific ideas: How can matter be transformed? Why do objects lie at rest on the earth's surface unless disturbed? Why are some species successful while others fail?

Practical or applied problems engage students in solving real problems in more immediate ways. For example, a unit on leverage and mechanical advantage might challenge students to think about and explore how a child could raise an adult off the ground using only a piece of 2 × 4 lumber as a lever and a cinder block as a fulcrum. Students might also engage in the application of science to broader societal issues. For example, they might explore the impact of an invasive species on a local woodlot and consider how to intervene to preserve the health of the local ecosystem. They might study the impact of a regional health problem, such as childhood obesity or asthma, and build a strategy for educating the community about risk prevention and treatment.

In addition to being scientifically meaningful, investigations must be meaningful to the person conducting the investigation. But what does it mean for a problem to be meaningful to a K-8 student? A meaningful problem must present an opportunity for something to be gained—practically or intellectually or both—from the investigation or outcome. In some cases, the benefits of solving a problem are easily recognized. For example, in the lever and fulcrum investigation, the problem posed and the resulting solution or outcome will be fairly easy for students to identify and appreciate. Students may also relate more easily to the curious phenomena they observe in their daily lives, such as what causes an empty juice box to crunch up when you suck continuously through a straw.

However, many concepts and problems worthy of investigation cannot be as easily linked to students' own experiences, their existing knowledge, or issues they are familiar with and care about. In these cases, students may be less motivated initially to find meaning in a problem, and they may need to know more about it in order to become motivated to find that meaning. For example, many students may not immediately recognize the problem of the impact of an invasive species on a local woodlot as one they should care about. They might require additional information about why this problem should matter to them, such as having the teacher illustrate the concept of interdependence in ecosystems—that is, showing that all species, including humans, are linked and therefore the impact of an invasive species has broad and important implications. In this way, a bridge is built between what students do know and do care about and the problem they are attempting to make a meaningful connection with. For example, a study of the motion of light (a common topic in the K-8 curriculum) might require that students first recognize that the motion of light is critical to understanding how telescopes, eyes, and cameras function. Subsequent lessons on such topics as describing and modeling light motion with vector diagrams may then be presented in an investigative context that students see as meaningful.

## Sequencing Meaningful Instruction

In order for problems to continue to be meaningful throughout an investigation, careful thought must be given at the outset to how to sequence instruction. Students will need to develop their ability to work on increasingly complex problems, including gradually acquiring knowledge of the concepts being studied and the specific skills needed to carry out a given investigation. A common but limited approach to sequencing investigations has been to teach the content related to the investigation first, and afterward to do the investigation in order to validate the content. This approach is counterproductive on a number of levels. First, it fails to give students a clear idea of why a particular investigative strategy is being used for that particular problem. It also emphasizes and promotes the false dichotomy between scientific content and process, leaving students with the misconception that scientific practice is algorithmic or procedural. Finally, it fails to recognize the critical aspects of science identified in Strand 3 and Strand 4, namely, the importance of reflecting on one's own scientific knowledge over the course of an investigation and the role of peers in building scientific arguments.

A more productive approach is to intentionally build the appropriate scientific knowledge and skills "just in time," at strategic points throughout the investigation. When presented at the point in the investigation at which they can be applied, new ideas, as well as new investigative skills and techniques, will be framed in a more meaningful context. In many cases, students will need quick access to some basic concepts in order to see a problem and investigation as meaningful. Over time, they will require additional skills as the investigation advances: they may need a method for collecting relevant data and then a method for analyzing the data. They will almost certainly need structured support in building the logical links that help move them from data to scientific explanation, as well as help them reflect on what they've learned in light of previous observations. Like the problems themselves, these and other skills need to be made meaningful to students, and presenting them in the context of a problem to which they can be readily applied helps students understand their utility.

Recently researchers have developed very promising results from building and testing science curriculum units that, from the outset, engage students with problems they will investigate over the course of several weeks or months. These units sequence lessons to gradually build students' knowledge and skill over time so that they arrive at each phase in an investigation prepared to engage in the necessary work.

"Struggle for Survival" is a six- to seven-week classroom science investigation that supports the learning of core evolutionary concepts. Developed as part of the Biology Guided Inquiry Learning Environments (BGuILE) project at Northwestern University, the unit is designed to support the learning of core concepts in evolutionary biology.[1] Using software that depicts a prolonged drought on the Galapagos Island Daphne Major, students investigate how the drought affects the animal and plant populations on the island. They learn background information about the island, read through the field notes of researchers, and examine quantitative data about the characteristics of the island's species at various times to look for changes in the populations.

The unit unfolds over four phases, which are sequenced to gradually increase the demands of the learning experiences and the sophistication of students' reasoning about core concepts. The students are presented with a problem at the beginning of the unit—the finch population on the island has declined precipitously. Their job is to examine a range of evidence to determine what has caused this decline. Within this framework, students engage in a study of the problem over a period of approximately six weeks to advance their understanding through reading, posing questions, data analysis, presentation, and debate.

The first phase (10 classes) sets the stage by probing students' existing knowledge of natural selection, by providing requisite background knowledge about ecosystems and the theory of natural selection, and by building student motivation. In the second phase (five classes), students learn about the Galapagos

Islands and the methods scientists use to study ecosystems. They generate initial hypotheses, work with a small data set, and learn about the computer system they will use in the major investigation. These first two phases of the investigation illustrate how foundational knowledge is built on in the context of an investigation. Although from the very beginning students are presented with the challenge of explaining a shift in finch population, they do not dive immediately into collecting and analyzing data. Instead, they begin by building their understanding of the specifics of the case and key principles of biological evolution.

Only after completing these initial 15 lessons do the students begin to work with the natural selection data set. Having immersed themselves in the problem and having built the theoretical knowledge and skills they will need to advance the investigation, they begin the third phase of the unit (10 classes). In this phase, students explore the data set, generate explanations for observed patterns of change in the finch populations, and critique the explanations of their classmates. In the fourth phase (six classes), student teams prepare reports, present findings, and analyze key points of agreement and disagreement across reports.

**Sequencing a Unit on Natural Selection**
*Four Phases of Learning*

**Phase 1 General Staging Activities**
Determine what students know, provide background knowledge, build student motivation (10 classes).

**Phase 2 Background for Investigations**
Gather information, generate initial hypotheses, work with small data set (five classes).

**Phase 3 Software Investigations**
Investigate data, generate and critique explanations for observations (10 classes).

**Phase 4 Presenting and Discussing Findings**
Prepare reports, present findings, analyze key points (six classes).

Carefully sequenced experiences such as these provide a road map for students, and they build just-in-time skills and knowledge that allow them to work through complex problems for which their knowledge and skill have immediate application. Students experience important elements of scientific practice as they wrestle with evidence, consider different ways of looking at phenomena and interpreting evidence, and work collectively to determine what they understand and which interpretations they find compelling. Students are not sent off on an unguided exploration of a phenomenon or question but are presented with intentionally sequenced and supported experiences framed in a sustained investigation of a central problem. This allows them to build knowledge about core aspects of biological evolution while building their skills and ability to work with data, learn with their peers, and present arguments using scientific language conventions.

## Constructing and Defending Explanations

The science curriculum in most school systems focuses narrowly on "final form science"—the collection of scientific findings that populate textbooks. When students are given opportunities to "do" science, these experiences are often presented as experiments with predetermined steps and findings. In other instances,

science investigations take the form of "activity mania" in which students complete activities that lack purpose and input from teachers.

Productive investigations are not sequentially scripted. Nor are they unguided. They do not simply unfold when students are given materials and opportunities to work on scientific problems. Rather, they are structured and regulated by the teacher, who plays an active role in the investigative experience. In order for investigations to be successful, teachers must work to make student activity purposeful, to build social interaction that supports cognitive processes, and to focus their efforts on pushing students' thinking about science toward increasingly sophisticated levels. Teachers and researchers have found ways to structure and script aspects of scientific investigations so that, over time, students gradually acquire scientific modes of thinking and interacting, drawing on these to learn science. They have also found promising ways to teach students fundamental practices for developing scientific explanations, as well as ways to integrate these practices into students' ongoing work.

We have discussed a science unit from the BGuILE project called Struggle for Survival. It is drawn from a research and design initiative called Investigating and Questioning Our World through Science and Technology (IQWST). The goal of IQWST is to design middle school science curricula that support the scientific practices of explanation and argument as learners engage in project-based investigations.[2] The IQWST units are designed to teach both scientific principles and the scientific practices of constructing and defending explanations by providing students and teachers with a framework that clearly defines this complex practice. The framework includes three components:

- **Claim:** What happened, and why did it happen?
- **Evidence:** What information or data support the claim?
- **Reasoning:** What justification shows why the data count as evidence to support the claim?

Thus, the curriculum helps students *make sense* of the phenomena under study (claim), *articulate* that understanding (evidence), and *defend* that understanding to their peers (reasoning).

As described earlier, part of the Struggle for Survival unit includes a two-week project in which students investigate a database holding information about the finch population on the Galapagos Islands. Students work in pairs in order to interpret the computer data and determine why so many finches died during the dry season of 1977 and why some were able to survive. The scientifically supported explanations for this question use data to identify which trait variations enabled birds to differentially survive the drought. For example, one response could state that the birds that survived the drought had longer beaks, which enabled them to crack the harder seeds that also survived the drought. Another plausible argument consistent with the data (but scientifically less accurate) could be that the birds that weighed more had fat stores that made them better able to survive the food shortage resulting from the drought.

Below is an excerpt from a student group presentation in which students use the claim-evidence-reasoning framework to reflect on their analysis and explain their current thinking about the investigation.

Evan: "Again, the question we had through this entire project, which does not have one simple answer, is: in 1977, why did 40 percent of the finch population die in Daphne Major in the Galapagos Islands, and why did the ones that survive, survive? This is our report. I'm Evan, this is Leona, and this is Nelly. Here we go."

Leona: [Reading from a poster] "We have a few theories. In concluding our research concerning the study of finches on the island, our focus is to find out why the population of finches on that island dropped dramatically in 1977. We believe the cause of the decrease in the population began with the change in the weather situation in Daphne Major. In 1977 we saw that there was an amazing lack of rainfall compared with the year before (1976). Here is the graph that shows the years and the different changes. [She points to the graph.] There were 167 centimeters of rainfall in the wet season of 1976, but there were only 20 centimeters of rainfall in the wet season of 1977. The lack of rainfall caused a decrease in plant life, because of the fact that all plant life, including cactus, lives off water or rainfall.

For example, in the dry season of 1976 there were 130 portulaca seeds on the island, but in the dry season of 1977, when there was absolutely no rain, there were no portulaca seeds whatsoever. This is the chart that shows that in the wet season in 1977 there were 20 portulaca seeds, in the dry season in 1977 there were none, and then it increased in the wet season of 1978 and went back up to 380 seeds."

Evan: "After I finish reading, I'm going to quickly explain a little bit about the chart we made. What we did next was, we circled all of the finches in both groups: the overweight group and the underweight group that survived. We determined that approximately 61 percent, or 14 out of 23, overweight finches survived the drought, while only 40 percent, or 9 out of 23, underweight finches survived the drought. Also, we noticed that the overweight finches tended to be male, and the underweight finches tended to be female."

Nelly: "Here are the groups; we circled the overweight ones, 14 that are circled, and these are all male. And these are all female, there's 9 circled, and they are underweight."

We can see the claim-evidence-reasoning framework in Leona's portion of the presentation. As she explains, the group *claims* that rainfall caused the finch population decline. They provide a record of annual rainfall as *evidence* of that claim. And they continue by *reasoning* that plants require rainfall to thrive and that finches require plants as a food source for their survival. At this point in the investigation, Leona and her peers have not yet hit on the most strongly supported explanation for the finch population decline. However, the unit is not yet complete, and they and their classmates have developed an informed scientific way of working on, representing, and analyzing the scientific problem. As they continue to examine the data and build their scientific skills, they are well prepared to continue to learn from the investigation.

## Scripting Student Roles

Another way that teachers can structure and focus students' thinking while they engage in scientific investigations is to define and assign particular roles for students to play during portions of the investigation. When scientists meet to discuss their work and exchange ideas, they work in a milieu of shared beliefs and goals that regulate participation. They ask questions of one another, critique ideas, and hold each other accountable according to a set of agreed on, but typically unspoken, cultural conventions. Classroom communities rely on a similar set of beliefs, goals, and modes of participation in order to learn from scientific investigations. However, without extensive scientific training and experience in scientific communities, students need more explicit guidance and structuring to interact in ways that are scientifically productive and support their learning from investigations.

The scientific community reaches consensus by proposing and arguing about ideas through both written and verbal communication. This allows scientists a means by which to test their ideas with other scientists, who in turn provide them with feedback. In this way, the scientific community reaches a consensual understanding of how some aspects of the natural world work. A very similar practice takes place in effective science classrooms. Students ask questions, talk and write about problems, argue about models, and eventually come to a more nuanced and scientifically accepted understanding of natural phenomena. This kind of interaction, which is both social and cognitive, not only supports learning but also communicates how scientific knowledge is created.

As we discussed in Chapter 5, talk in the classroom can be academically productive in a general way and also in a way specific to science and scientific ideas and practices. The learning that results from hands-on science investigations in particular is dramatically improved when students present their ideas and arguments to their peers. In these instances, verbal communication among students is conducive to learning in general, but it also gives them experience with a uniquely science-oriented practice. For example, when students debate the value of a given scientific observation, this is analogous to what scientists in the real world do regularly. Yet most students have very little experience talking and thinking with their peers in the manner in which they are expected to during investigations. In fact, typical classroom experiences suggest a different dynamic—one in which textbooks and teachers are consulted for answers, rather than peers and data. Argumentation among students is rarely a sanctioned activity and is often experienced as acrimonious.

To help students learn appropriate ways of interacting during science investigations, educators have developed methods for helping them acquire new social roles and collectively building norms for interaction in ways that emulate the interactions of scientists. Educators can establish such norms by intentionally mirroring the social interaction model of questioning, listening, reflecting, and responding that scientists use in their exchanges with each other, as well as by assigning roles based on basic elements of this interaction. This approach has its roots in the reciprocal teaching approach to reading comprehension, which makes the process of comprehension explicit for learners.[3] In reciprocal teaching of reading comprehension, teachers model the important elements of comprehension, such as predicting, summarizing, and questioning. Students then begin to take on the individual elements of the task. The task is essentially distributed among students, who share responsibility for its completion.

In the following case study, we look closely at a fifth-grade classroom in which learners are taught and assigned particular roles to play during an investigation. These roles are designed to emulate a range of intellectual and social practices that would seem more or less natural to the seasoned scientist. Note that in this case study the word "theory" is used to refer to students' explanations rather than to formal scientific theories, such as evolution or plate tectonics.

Science Class

# DIFFERENTIATING MASS AND DENSITY[4]

For the past month, Clarence Wilson, a fifth-grade teacher in a public school in the South Bronx, has been working with colleagues to develop a unit on mass and density. The unit combines exploration of the real-world phenomena related to sinking and floating with a conceptual model of density that was developed and implemented on a computer. They used a software program called Modeling with Dots, which introduced the students to a "dots-and-boxes" model of density (see Figure 7-1).

According to the model, each box represents a standard unit of volume (a size unit, or su), while each dot represented a mass unit (mu). The number of dots per box represented the density (mu/su). Thus, both of the objects shown were the same size: 8 boxes, or 8 su. The object on the left weighed 24 mass units, while the object on the right, at 40 mass units, was heavier. The density of the object on the right was greater (5 mu/su versus 3 mu/su).

Using another type of software called Archimedes, the students were able to perform simulated sinking and floating experiments, using the dots-and-boxes model of density (see Figure 7-2).

In carrying out simulated experiments such as these, Mr. Wilson's students were free to specify the material they wanted the object and liquid to be made of, and they could then gather data from their experiments. The size of the objects was held constant in these simulations to help students focus on density as the variable. Students were challenged to discover the rule the computer used to determine whether the object would float or sink in a given liquid—a rule, consistent with reality, that was based on the relative densities of the object and the liquid.

In Figure 7-2, the object floats. The relative densities of the material to the liquid are 1:3, and one-third of the object sinks into the liquid.

The unit was intended to last for about 15 classroom sessions. The students engaged in some preliminary baseline activities that involved making predictions about 16 everyday objects, including a plastic spoon, an apple, and a piece of graphite.

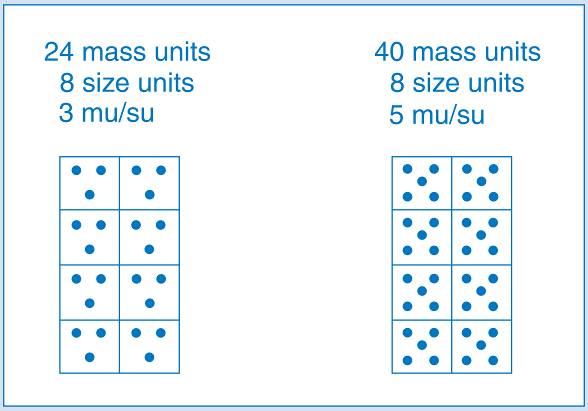


**FIGURE 7-1**
*Two objects represented by the grid-and-dots model with data display.*

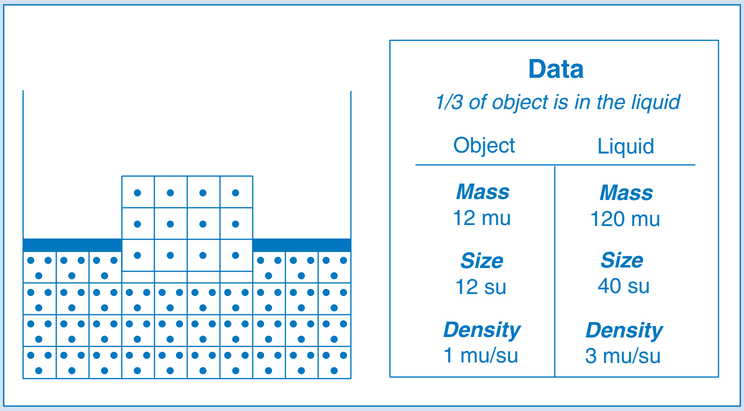


**FIGURE 7-2**
*Grid-and-dots representation of an object floating in a liquid with data display.*

They predicted whether the objects would sink or float, shared their predictions and rationale, tested their predictions, recorded the results, and wrote reports that they shared with the class.

The students were assigned rotating procedural roles, such as reporter, scribe, and poster designer. Working in small groups, they moved through a series of stations in which they were asked to order a set of objects, first by mass and then by volume, make predictions about sinking or floating, test their predictions, record the results, and prepare a report for the class. The objects used in the different stations were large and small cylinders, large and small cubes, and a set of spheres made of wood, Lucite, recycled plastic, and aluminum. A different subset of these items was used at each different station.

Following this period of exploration, predicting, and theorizing, the students were introduced to the dots-and-boxes model of mass, volume, and density. They worked on computers to explore and then apply a dots-and-boxes model of density to several different objects, some real and some imagined. They then revisited their earlier work, using the dots-and-boxes model, to explain their sinking and floating results with real objects. Finally, they applied the model (on and off the computer) in exploring thermal expansion—why it is that heated alcohol takes up more space but weighs the same and has decreased density. They also explored why certain objects sank in hot water but floated in cold water.

At the beginning of the investigation, Mr. Wilson decided to try something new—assigning roles for student audience members whenever a student group presented its findings. He hoped that this would help promote productive discussion and participation during student reports. This presentation time often had become more of a conversation between the presenting group members and Mr. Wilson, rather than involving the whole class as intended.

The students in the audience were assigned, on a rotating basis, one of three audience roles: checking predictions and theories, checking summaries of results, and assessing the relationship among predictions, theories, and results. These three roles were designed to help give guidance to the students as they explored, through talk, three important intellectual practices in science: predicting and theorizing, summarizing results, and relating predictions and theories to results (sometimes referred to as coordinating theory and evidence).

| | **STUDENT AUDIENCE** ROLES | **INTELLECTUAL PRACTICES** IN SCIENCE |
|---|---|---|
| **1.** | **Checking predictions and theories** | **Predicting and theorizing** |
| **2.** | **Checking summaries of results** | **Summarizing results** |
| **3.** | **Assessing the relation between predictions, theories, and results** | **Relating predictions and theories to results** |

Mr. Wilson suspected that playing audience roles effectively would be challenging for his students, so he created several strategies for providing support. After introducing the roles, the class made a "question chart" that provided appropriate sample questions for each of the student audience roles. For the first role, checking predictions and theories, the questions on the chart read:

**"What were some of your predictions?"**

**"Can you support your prediction with a theory?"**

**"Is your theory intelligible, plausible, and fruitful?"**

Intelligibility, plausibility, and fruitfulness were terms that Mr. Wilson had been working on with his students all year.

For the second role, checking summaries of results, the student might ask:

**"I'm not completely clear on what you found. Can you explain your evidence more clearly?"**

For the third role, relating predictions, theories, and results, the questions read:

**"Did you find what you originally predicted?"**

**"Did your results support your theory?"**

**"What evidence do you have that supports or challenges your theory?"**

At the beginning of the unit, the students relied heavily on the question chart in performing their audience roles. They also had a difficult time, at first, distinguishing between predictions and theories. To address this, Mr. Wilson created a public "theory chart" that kept track of the different theories posed over time, with periodic review of theories occurring when students decided that some theories could be ruled out on the basis of the results from different groups.

The point of the theory chart was to reinforce the notion that science involves a process of revising thinking over time as new evidence arises. Mr. Wilson had decided that this theory chart would also help him challenge the prevalent idea among his students (and many others) that the object of doing science is to "get the right answer." The theory chart helped make public the way in which the students' collective thinking was changing over time. What follows is an excerpt from one of Mr. Wilson's classes in which students use audience roles effectively.

Mr. Wilson: "Does anybody have a theory about the wood? For instance, why the wood floats? Why did you predict that the wood would float?"

Deana: "Because I've seen it float."

Mr. Wilson: "So are you saying that just having seen something do something before is a reason, an explanation of why something would sink or float?"

Deana: "I think it is."

Mr. Wilson: "You think it is? Can you say more about that?"

Deana: "Because if you've seen it before, then it's a theory."

Jody: "Wait, but didn't we sort of decide that our experience is a good way of helping us make predictions, but it doesn't explain why something happens?" [Christina waves her hand.]

Mr. Wilson: "Christina, do you have something to add?"

Christina: "Well, I sort of disagree with Deana, because a theory's kind of different from a prediction. A theory is *why* something happened. It's not just a guess or a prediction."

Caleb: "I know what a theory is. A theory is like 'all wood floats.' That means all wood has to float or else your theory is wrong."

Mr. Wilson: "Okay, so let me see if I've got what you're saying. You're saying that 'all wood floats' is a theory?"

Caleb: "Yep, a theory that's been proven right."

Mr. Wilson: "Does that tell me *why* wood floats though?"

Caleb: "Uh, not really."

Mr. Wilson: "Okay, so can you give me an example? Let's take wood. Some of us have seen in our experiments that wood floats. We have evidence that wood floats. But *why* does wood float? What *makes* it float? Can you give us a theory?"

Caleb: "My theory is that you can trap air underneath the wood."

[Mr. Wilson notes Caleb's theory on the theory chart.]

Elinor: "Your theory isn't really [she looks at the question chart] *intelligible* to me. I don't completely get what you mean by 'wood traps air underneath it.' [She looks at the question chart again.] Actually, it's not really plausible to me either. I mean how would wood trap air underneath it? It's not like a cup or anything, so how would wood do that? Do you have any evidence to support that theory? Did you see air bubbles? Or did you just come up with that theory from your mind?"

Caleb: [Smiling] "I just sort of flashed on it. But I like it. I mean it *might* have something to do with air."

This is an example of how teachers can intentionally structure student roles to focus student thinking and discussion on meaningful aspects of scientific investigation. Over a series of lessons these students practiced taking "roles" and learned to understand them in two ways. Initially, they learned to play procedural roles, which provided a framework for getting their group work done. (It is important to note that these were generic roles and not tied to specific scientific practices.) However, in addition to structuring their group tasks in a productive manner, the procedural roles gave the students some experience in playing assigned roles and engaging in interdependent tasks. Later, the students were assigned one of three audience roles. On a rotating basis, students would listen to their peers present and ask questions in order to check predictions and theories, check summaries of results, and assess the relation between predictions, theories, and results. In this case, the students played scientific roles. The science-specific audience roles were further defined—and students' efforts to enact them aided—by a public display identifying examples of appropriate role-specific questions.

In the case of Mr. Wilson's class, we saw students playing these roles in the context of a presentation. Christina pushed Deana to add an explanation to her prediction (Role 1, checking predictions and theories). Later, as Caleb asserted that "all wood floats," Elinor consulted the chart and found language to appropriately challenge his assertion, which she saw as implausible. With the support of a teacher who listens to their ideas and peers who understand how to play meaningful roles in scientific discussion, the students successfully work on clarifying, supporting, and refining their ideas.

Scripting roles and framing science in an explanatory framework are but two of many ways in which creative teachers can intentionally and explicitly teach and support students to enact and make meaning of scientific investigations. We've chosen to discuss these particular strategies because they've been studied more extensively than other approaches and suggest promising results. Other ways teachers may make particular talk moves explicit include posting "talk stems," such as, "I agree with X when he says Y, because [cite evidence]" or "I'd like to ask X to explain his thinking [evidence, model, theory, etc.] in more detail because I didn't completely understand it." They may also use methods such as position-driven discussions, in which students take particular positions (e.g., competing explanations for an observed phenomenon) and make a case for their position and build on peers' challenges to their position, all before a demonstration is run and an outcome determined. There are many ways to invite students to engage in scientific discourse as legitimate participants, even before they have become totally competent at scientific investigation.

# Science Class

## LOOKING AT OUR SCIENTIFIC THINKING

**Scientific investigations can take place over months and years in the K-8 grades, and when they are effective they can result in dramatic changes in the ways that students think about the topics they are studying, about their own thinking and learning, and about the enterprise of science. By actually looking at how their own thinking about a phenomenon has changed and developed, students see learning in action. In other words, they come to understand what it actually means to learn something—an understanding that is called for in Strand 3.**

**Like much of science learning, this kind of understanding will not evolve without intentional support from teachers and instructional materials. Reflecting on one's own scientific knowledge is critical to the enterprise of science and science learning. Scientists integrate new knowledge gained through investigations only when that knowledge is examined in relation to what they already know, tentatively believe, or previously doubted. Children, like scientists, must learn to examine the history of their own thinking and revise it if necessary, in light of subsequent investigations.**

**To examine how effective teachers can teach students to reflect on their changing knowledge in this way, we visit the classroom of Sister Mary Gertrude Hennessey, a science teacher for grades 1-6 in a small, rural elementary school.**

**Sr. Hennessey understands that in order to reflect on knowledge over time, children require extended opportunities to work on critical scientific concepts. She systematically focuses her lessons on core ideas built cumulatively across the grades. She enables her students to think deeply about knowledge in two important ways: she guides them in thinking and talking about how the scientific community structures and develops knowledge, and she helps her students think deeply about their own thinking, or how to be "metacognitive."**

**Research has shown that Sr. Hennessey's sixth-grade students have a much better understanding of the nature of science than sixth graders from a comparable school. The table below shows the way both her role and her students' roles change from first grade through sixth grade.**

Here's a look at Sr. Hennessey and her students in action:[5]

During a classroom demonstration in Sr. Hennessey's first-grade classroom, a large, transparent container of water is placed on an overhead projector. Students are asked to predict what they think will happen when various objects are placed in the water. The objects in question are two stones—a small (2-centimeter diameter) granite stone, and a large (10-centimeter diameter) pumice stone. The students did not have the opportunity to handle the stones prior to the demonstration.

One student, Brianna, is called on to explain her predictions.

Sr. Hennessey: "Would anyone like to predict what he or she thinks will happen to these stones? Yes, Brianna?"

Brianna: "I think both stones will sink, because I know stones sink. I've seen lots of stones sink, and every time I throw a stone into the water, it always sinks."

Sr. Hennessey: "You look like you want to say something else."

## INCREASINGLY SOPHISTICATED METACOGNITION FROM GRADES 1 THROUGH 6[6]

| GRADE | STUDENTS' ROLE | TEACHER'S ROLE |
|---|---|---|
| 1 | • Explicitly state their own views about the topic under consideration<br>• Begin to consider the reasoning used to support their views<br>• Begin to differentiate what they think from why they think it | • Finds a variety of ways in which students can externally represent their thinking about the topic<br>• Provides many experiences for students to begin to articulate the reasoning used to support ideas/beliefs |
| 2 | • Begin to address the necessity of understanding other (usually peer) positions before they can discuss or comment on those positions<br>• Toward the end of the year, begin to recognize inconsistency in the thoughts of others but not necessarily in their own thinking | • Continues to provide an educational environment in which students can safely express their thoughts without reproaches from others<br>• Introduces concept of consistency of thinking<br>• Models consistent and inconsistent thinking (students can readily point out when teacher is being inconsistent) |
| 3 | • Explore the idea that thoughts have consequences and that what one thinks may influence what one chooses to see<br>• Begin to *differentiate* *understanding* what a peer is saying from *believing* what a peer is saying<br>• Begin to comment on how their current ideas have changed from past ideas and to consider that current ideas may also need to be revised over time | • Fosters metacognitive discourse among learners in order to illuminate students' internal representations<br>• Provides lots of examples from their personal work (which is saved from year to year) of student ideas |
| 4-6 | • Begin to consider the implications and limitations of their personal thinking<br>• Begin to look for ways of revising their personal thinking<br>• Begin to evaluate their own/others' thinking in terms of intelligibility, plausibility, and fruitfulness of ideas<br>• Continue to articulate criteria for acceptance of ideas (i.e., consistency and generalizability)<br>• Continue to employ physical representations of their thinking<br>• Begin to employ analogies and metaphors, discuss their explicit use, and differentiate physical models from conceptual models<br>• Articulate and defend ideas about "what learning should be like" | • Provides historical examples of very important people changing their views and explanations over time<br>• Begins to use students' external representations of their thinking as a way of evaluating their ideas/beliefs (in terms of intelligibility, plausibility, and fruitfulness) in order to (a) create, when necessary, dissatisfaction in the mind of the learner to facilitate conceptual exchange or (b) look for ways of promoting conceptual change in the mind of the learner |

Brianna: "The water can't hold up stones like it holds up boats, so I know the stones will sink."

Sr. Hennessey: "You sound so sure, let me try another object."

Brianna: "No, you have to throw it in, you have to test my idea first."

[Sr. Hennessey places a small stone in the tank; it sinks.]

Brianna: "See, I told you it would sink."

[Sr. Hennessey puts aside a larger stone and picks up another object.]

Brianna: "No, you have to test the big one, too, because if the little one sunk, the big one's going to sink, too."

[Sr. Hennessey places the larger stone in the tank and it floats.]

Brianna: "No! No!" [Brianna shakes her head.] "That doesn't go with my mind. That just doesn't go with my mind."

During the activity described above, Brianna is involved in a form of introspection in which she is processing and interpreting both past and present experience. For example, when Brianna says, "I think both stones will sink. . . . I've seen lots of stones sink, and every time I throw a stone in the water . . . it always sinks," she reveals her current thinking about how that particular stone will behave in the water, based on her past experience with how stones have behaved in water.

As the discussion continues, Brianna reveals her beliefs about the nature of water. She uses her beliefs about water to support her current beliefs about stones. For example, she says, "The water can't hold up stones like it holds up boats. I know the stones will sink."

Brianna also insists on two separate occasions that Sr. Hennessey test her prediction by saying, "You have to test my ideas first," and "You have to test the big one, too, because if the little one sunk, the big one's going to sink, too." It is important to note that Brianna asks her teacher to test her prediction as opposed to asking her merely to test what happens with the stone; Brianna is consciously aware that understanding her own thinking is the object of the demonstration.

Brianna's reaction to having the larger stone float indicates that she is aware that the outcome is anomalous, and that this anomaly is inconsistent with her current view of both water and stones. "No! No!" she says. "That doesn't go with my mind." Her comment also shows that she is thinking about her own scientific thinking; she is being metacognitive.

The level of thinking about scientific thinking grows more sophisticated over time. Here's another scenario involving Sr. Hennessey and one of her sixth-grade students.

Jill wrote an essay as part of the assessment process in her physics class. Her assigned task was to focus on "the element of change" in her thinking. The following questions were posed:

- Do you think your ideas about force or forces acting on various objects have changed?
- If so, in what way have your ideas changed? Why do you think your ideas have changed?

Here's what Jill wrote:

*In the past I thought for instance the BOOK ON THE TABLE had only 1 force, and that force was gravity. I couldn't see that something that wasn't living could push back. I thought that this push back force wasn't a real force but just an in the way force or an outside influence on the book.*

*However, my ideas have changed since the beginning of this year. Sr. Hennessey helped me to see the difference between the macroscopic level and the microscopic level. That was last year. But I never really thought about the difference very much.*

*This year, I began to think about the book on the table differently than [last school year] I was thinking on the macroscopic level and not on the microscopic level. This year I wasn't looking at the table from the same perspective as last year. Last year I was looking at living beings as the important focus and now I am looking at the molecules as being the important focus. When I finally got my thoughts worked out, I could see things from a different perspective. I found out that I had no trouble thinking about two balanced forces instead of just gravity working on the book. It took me a whole YEAR to figure this concept out!!! Now I know it was worth THE YEAR to figure it out because now I can see balanced forces everywhere!*

*Balanced forces are needed to produce constant velocity. The book on the table has a velocity of zero; that means it has a steady pace of zero. Why, Sr. Hennessey asked, did my ideas change? I think my ideas changed because I have expanded my mind to more complicated ideas! Like molecules in a table can have an effect on a book, that balanced forces and unbalanced forces are a better way of explaining the cause of motion, and that constant velocity and changing velocity are important things to look at when describing motion.*

In her essay, Jill was able to examine both her past and current thinking. Moreover, she acknowledged that the construction of her thinking took a significant amount of time. The essay also reveals Jill's belief about the nature of molecules (they can cause an effect) and her belief about the nature of an explanation (some explanations are better and are more important than others). In the first sentence, Jill merely reveals her past understanding of the forces acting on a book on a table. In the next sentences, she reveals her beliefs about the nature of living and nonliving objects and to some extent the nature of forces. Jill explicitly states that she was aware that her ideas had changed over time, and she offered a causal explanation for the change in her thinking. She acknowledges that she was aware of a shift in the focus of her thinking as well as a change in her thinking. Jill illustrates that she can generalize and apply her current understanding to new situations.

Jill also displays an impressive understanding of what physicists call kinetics, a set of concepts dealing with the action of forces producing or changing the motion of a body. This understanding is critical. Students may be able to question and monitor their ideas, but if their knowledge is not thorough and well structured enough to evaluate those ideas, it won't do them any good. Metacognition, in and of itself, is not helpful without good cognition to be "meta" or reflective about.

What's notable in Sr. Hennessey's teaching is a strategic combination of support for students to think about the nature of scientific thinking (their own and others) linked to rigorous investigations that produce deep learning of scientific concepts.

Examples such as these shed light on the nature and range of students' abilities to think about scientific knowledge, how it is constructed, and how complex and certain it is. These abilities are not all or nothing; rather, they exist on a continuum of engagement and elaboration: Brianna is a beginner to the process, whereas Jill demonstrates a high level of engagement in thinking about scientific thinking.

How, one might ask, did Sr. Hennessey accomplish such remarkable results? What was it about her teaching and her classroom environment that contributed to the tremendous growth in her students' understanding of how knowledge is constructed in science? Here are some of the methods she uses. Notice all the different ways that talking about thinking and making thinking public play a role.

As Sr. Hennessey makes clear in her classroom, science is not only a body of knowledge but also a way of knowing. All science education practitioners, students, teachers, and even parents need to understand the nature and structure of scientific knowledge and the processes by which it is developed, not just the body of knowledge produced by science. They need to know *how we know* and *why*

## Strategies for Teaching How to Construct Scientific Knowledge

### FOCUS

1. **Teaching for conceptual change**
   - making students aware of their initial ideas
   - encouraging students to engage in metacognitive discourse about ideas
   - employing bridging analogies and anchors to help them consider and manipulate ideas
   - encouraging them to apply new understandings in different contexts
   - providing time for students to discuss the nature of learning and the nature of science
2. **Promoting metacognitive understanding**
3. **Engaging students with deep domain-specific core concepts**

### PEDAGOGICAL PRACTICES

- **Helping students understand, test, and revise ideas**
- **Establishing a classroom community that negotiates meaning and builds knowledge**
- **Increasing students' responsibility for directing important aspects of their own inquiry**

### STUDENT ROLES

- **Taking responsibility for representing ideas**
- **Working to develop ideas**
- **Monitoring the status of ideas**
- **Considering the reasoning underlying specific beliefs**
- **Deciding on ways to test specific beliefs**
- **Assessing the consistency among ideas**
- **Examining how well these ideas extend to new situations**

*we believe* scientific knowledge, not just *what we know.*

In science classrooms that include a strong component of metacognition, activities are introduced to make students aware of their initial ideas and to demonstrate that a conceptual problem may need to be solved. A variety of techniques may be useful in this regard. Students may be asked to make predictions about an event and give reasons for those predictions. Class discussion of the range of student predictions can emphasize alternative ways of thinking about a phenomenon, which can highlight the conceptual element of the analysis. In addition, gathering data that expose students to unexpected discrepancies or posing challenging problems that students may not immediately solve are ways of prompting students to stop and think, stepping outside their normal conceptual framework in order to understand what is happening.

Regular time for reflection, note taking, or public chart making to track ideas as they change over time is another critical component of metacognition. Researchers have documented that children often repeat experiments or interpret current results without connecting those results to prior hypotheses. Students need regular opportunities to reflect on science. Reflection helps students monitor their own understanding and track the progress of their investigations. It also helps them identify problems with their current plans, rethink plans, and keep track of pending goals.

Thus, multiple approaches are needed in order for students to develop the ability to think about scientific thinking.

Classroom investigations can be an exciting way for students to develop a strong grasp of science content, the practices of scientific work, and the nature of science itself. However, investigations in current practice are typically not well suited to support student learning.

An effective science education system must reflect a rich, practice-based notion of science. This means rethinking what counts as science in order to better incorporate the strands of science learning. Investigations need not and should not be sequentially scripted, superficial experiences with predetermined outcomes, nor should they be chaotic, unstructured explorations that yield little in the way of real understanding. Effective investigations should be organized, structured activities that guide students in using scientific methods to work on meaningful problems.

Investigations that support student learning require teachers who understand how scientific problems evolve, and teachers themselves will need to have first-hand experiences akin to those they create for their students. Schools, universities, foundations, science centers, museums, and government agencies must find ways for teachers to have these experiences, building their knowledge and comfort with science practice in order to create an effective environment for student learning.

## For Further Reading

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# 8 A System That Supports Science Learning

Understanding what it takes to teach and learn science effectively is very different today than it was 20 or 30 years ago. We now know that young children bring a strong foundation of knowledge and skills to school with them, including knowledge of the natural world, the ability to engage in complex reasoning about the natural world, a basic understanding of data sets, competing ideas about different science concepts, and the ability to apply their own thinking to a particular scientific domain as it evolves over time. They also have the ability to work collaboratively with classmates and teachers in ways that approximate practices in the scientific community: posing informed questions, representing ideas to one another using a range of methods, and critically appraising and incorporating diverse ideas and observations in order to build a common scientific understanding. With this foundation, young children entering school can begin to build and extend their science knowledge as they advance through the grades.

Good teaching is critical to students' understanding and mastery of scientific ideas and practices. Students need to work with scientific concepts presented through challenging, well-designed problems—problems that are meaningful from both a scientific standpoint and a personal standpoint. They need to be challenged to think about the natural world in new and different ways. They need guidance in adopting the practices of the scientific community, with its particular ways of seeing, building explanations, and supporting claims about knowledge.

Good science teaching and learning must draw from all four of the strands of scientific proficiency. With carefully structured classroom experiences, instructional support from teachers, and opportunities to explore and connect important science concepts over extended periods of weeks, months, and years, elementary and middle school students can make valuable gains in science learning.

The typical practices in today's science classrooms do not reflect the most recent findings regarding effective science teaching and learning. Current curricula tend to cover too many disparate topics in a superficial manner, and many are based on an outdated understanding of how children learn. They do not build on the core ideas of science in a progressive fashion from kindergarten through eighth grade.

The research outlined in this book carries immense implications for the education system as a whole, as well as for individual educators working in the system. The system includes standards, curricula, assessments, professional development, teacher preparation—all of which should be reexamined in light of current thinking about teaching and learning science. Systemic goals are, of course, large scale, and it will take years, as well as political will and investment, to realize them.

When the different parts of the education system are conceptualized, designed, and implemented in a coordinated fashion, there are positive effects on teachers, schools, and student learning.[1] For example, promising results have emerged from schools and districts participating in the local systemic change initiatives funded by the National Science Foundation, which were designed to support meaningful systemwide change.[2] In order to achieve this kind of success, clearly developed standards and goals for learning must be defined, and they must drive both the organization of the system and deployment of resources. This book supports a coordinated systems view, adding to it by sharpening the focus on *science learning*. We examine what it means to understand science, what children do when they learn science, and what educators can do to support and encourage children's science learning. Both the system itself and the individuals in it must reorient themselves to support current understanding of science learning.

New knowledge about science learning should form the foundation of such a system in the following ways:

- Standards should be revised to stress core scientific concepts. They should outline specific, coherent goals for curriculum and practice, organized around these core ideas.

- Curricula should enable these goals to be realized through sustained, progressive instruction over the K-8 years.

- Instruction should engage students in the four strands of scientific proficiency in challenging and stimulating ways.

- Assessments should provide teachers and students with timely feedback about students' thinking, and these assessments should support teachers' efforts to improve instruction.

- Professional development and teacher preparation should focus on effective methods for teaching science, understanding how students learn science, and helping teachers understand core scientific concepts and how they connect.

Although this new way of understanding science learning requires the involvement of many in the education system, it is the classroom science teacher who has the most frequent and direct impact on students' classroom experiences. In this chapter we focus on the particular knowledge and skill that teachers need in order to teach science well and the ways in which the system should shift to support teacher learning and development.

## Teachers as Learners

At the Rosa Parks Community School in the South Bronx, the teachers have been working together to change how they teach science, with support and guidance from their principal, Marianne Goldenada. The entire faculty, including the principal, assistant principal, and all pre-K through grade 8 instructional staff, have decided to make science learning a primary focus of their school improvement plan.

In order to do this, they decided to focus more attention on student learning, including exploring together how students learn, what supports student learning, and examining student work and performance. While they've made a commitment to follow the district's science standards, they've also decided to create what they call "grade by grade learning trajectories" that are built around a set of core science concepts that they will build on in each successive grade.

This year, all of the teachers in the school will be working together to deepen their knowledge and create linked instructional activities around a central topic in physics—the nature and structure of matter—and a central topic in the life sciences—biodiversity, biological variation, and change within and across populations. The teachers will work both in grade-level "study groups" that meet once a week and as an entire faculty meeting once a month, to plan units together, compare notes, read articles and curriculum reports, and present both problems and successes to each other.

School principal Goldenada inspires the teachers at Rosa Parks to learn right alongside their kids. She visits their classrooms, sits in on study group sessions, runs interference when teachers need extra materials or time, and circulates shared readings and examples of student work at the monthly faculty meetings. The teachers trust her and feel comfortable sharing problems with her.

As a former special-needs teacher and later a science coordinator for the school, Ms. Goldenada considers questioning, theorizing, modeling, collecting data, examining evidence, and changing one's mind (she calls it "revising") as important as getting the right answer. And she's a big believer in building on what learners already know. She helps students trust in their own ability to figure things out collectively, ask questions, and share their expertise, as well as their problems, with one another.

Ms. Goldenada wants to make teaching science both challenging and fun. But it's not easy creating a confident, fearless staff of teachers. None of the teachers at Rosa Parks majored in the sciences in college. Only a few took advanced science or mathematics courses as undergraduates, and those courses were of limited value for teaching science to elementary school students.

At the time Ms. Goldenada became principal at Rosa Parks, many of the teachers were wary of teaching science. The school was large (nearly 900 students in pre-K through grade 8) and more than 80 percent of the students received free or reduced-price lunches. More than 40 percent spoke a language other than English at home, and there was a fair amount of student attrition. Students' abilities in science varied widely—some had been doing science intensively since kindergarten, and some were completely new to inquiry-based science.

Ms. Goldenada is a believer in the value of teachers as investigators and learners, like their students, and with so many teachers representing so many different grade levels, she felt it made sense for them to try to master a few key concepts rather than covering many concepts superficially at a fast pace.

It was Ms. Goldenada who proposed the monthly faculty meetings, called "science breakfasts," which later evolved into monthly breakfasts plus one after-school "science symposium" per month. These meetings focused on a few central science concepts, and the idea was that the faculty would learn about science together, investigate common topics, focus their collective attention on what their students seemed to know about these topics, collect and share examples of student work, discuss ways of responding to that work or examining it for evidence of what the students understood, and track the students' deepening knowledge and expertise across the grades.

Under Ms. Goldenada's leadership, the entire faculty agreed to work on science curriculum planning and development, drawing on good materials that were available and adapting them to meet their own students' needs. They planned to build a coherent and increasingly sophisticated set of units around a central concept in science that they would all explore together, in grade-level teams, with one unit to be undertaken in the fall and another in the spring. That way they could compare notes across the grades, focusing on a multiweek unit, examining what their students know and can do in each successive grade, and building up concepts over years rather than weeks. They would track what worked and what didn't, sharing materials and techniques and maintaining an ongoing, schoolwide conversation.

The teachers and staff at Rosa Parks weren't starting entirely from scratch. In their preparation they drew on many excellent national reports, such as the *National Science Education Standards, Inquiry and the National Science Education Standards, Selecting Instructional Materials,* and *Benchmarks for Science Literacy.* Ms. Goldenada often started breakfast meetings by passing around a photocopied vignette from one of these reports. Everyone would read the vignette and discuss it in light of ongoing work and the school's science goals. That way the teachers would continue learning, from year to year, along with their kids.

Strong instructional leaders like Ms. Goldenada appreciate the complexity of teaching science well and create regular, recurring opportunities for their staff to build their knowledge and skill. There are many ways to build teachers' knowledge and skill in addition to the school-level efforts described above. Opportunities for teacher learning can also be organized in university- or museum-based courses, teacher study groups, and mentoring. However it is organized, it is important to note that teacher learning is focused on important conceptual goals and that it encompasses features of productive teacher learning environments.

To teach science well, teachers must draw on a body of knowledge that can be divided into three broad, partially overlapping categories: knowledge of science, knowledge of how students learn science, and knowledge of how to teach science effectively.

## Knowledge of Science

In order to teach effectively, the teacher must first understand the subject being taught. There is a growing body of evidence that what a teacher knows about science influences the quality of instruction and has a powerful effect on the success and type of discussions that teachers can engage in and sustain with students. It is important to pay close attention to the particular things teachers know about science, not only the "level" of knowledge (as indicated by number of science courses, degrees, certificates) teachers need to teach science. Without careful attention to what teachers need to know to teach science and how they can learn it, solutions are often limited to adding more courses to a given sequence, program, or credential requirement.

The strands of science learning, presented in Chapter 2, provide a useful rubric for analyzing the kinds of science that teachers currently learn and identifying the aspects of science proficiency that current professional development is unlikely to support. Two recurrent patterns in undergraduate science curricula emerge when considered in light of the strands. First, much like many current K-12 science curricula, undergraduate science curricula tend to emphasize, most heavily, conceptual and factual knowledge (Strand 1). There is some emphasis on doing investigations (Strand 2), although typically through contrived experiments in which both process and results are clearly spelled out for students. Undergraduate science rarely emphasizes reflection on scientific knowledge (Strand 3), and participation in science (Strand 4) is rarer still.

Not surprisingly, undergraduates' and prospective science teachers' views of science reflect these emphases. They often view science narrowly as a body of facts and scientific practice as nothing more than the application of a sequential scientific method. An example of this narrow view is discussed in Mark Windshitl's study of the views of preservice science teachers as they designed and conducted studies in the context of a secondary science methods course.[3] Study participants included 14 preservice teachers with earned bachelor's degrees in a science. The study tracked teachers' thinking about science through their regular journal entries for one semester and conducted interviews with them on their experiences in science from middle school forward. When researchers analyzed the teachers' efforts to develop inquiry projects (from formulating questions through presentations to peers), they found that they had a common "folk view" of science, meaning that they viewed hypotheses as guesses with little bearing on how problems should be framed and examined. Scientific theory assumes a peripheral role in this view of science, relegated to the end of a study as an optional tool one might use to help explain results.

Many elementary and middle school teachers, like many college-educated adults in this society, have only a superficial knowledge of science. Inadequate undergraduate courses, as well as inadequate teacher education or credentialing programs, and insufficient professional development opportunities all contribute to the problem.

What kind and level of scientific expertise are required to teach science effectively? Asking this question leads to still more questions: What does it mean to understand a concept well enough to *teach* it well? What do teachers need to know in order to design engaging and rigorous instruction, orchestrate activities so that students make their reasoning visible, build on what students already know, and create an environment in which *all* students are equal participants in the scientific conversation? What are the best ways for teachers to learn what they need to know? In order to work toward and achieve the new vision for K-8 science education described in this book, those involved in defining the content and practice of teacher education will have to wrestle with these questions.

## How Students Learn Science

Effective teaching requires that teachers understand what students do when they learn and what cognitive, linguistic, and emotional resources they bring to the table. While we often think about teaching from the perspective of the teacher, it is important to emphasize education as a process that is fundamentally concerned with the experience of learners. The strands of science learning characterize things that children do, both cognitively and behaviorally, when they learn science. Previous chapters have described the ways in which children use language and other representations of their thinking to communicate and build knowledge and how their out-of-school experiences influence their thinking about science.

In order to recognize and build on these capabilities, it is critical that science teachers not only be students of science but also that they be students of children's learning.

One of the implications of the new findings about how students learn is that everyone involved in the education system must rethink his or her assumptions about teaching and learning science. At the core of teacher professional development, we should focus on challenging conventional wisdom about learners and building a contemporary research-based view.

As we have argued previously in this book, several common beliefs about young science learners need to be challenged: (1) Young children are not able to reason abstractly and so should learn about science as observation (not theory building). (2) Science content and process should be isolated and taught discretely. (3) Immersing students in unstructured exploration and "investigation" will teach them scientific principles and concepts. (4) Children's ideas about the natural world are primarily misconceptions that teachers should aim to identify and correct or replace with canonical science.

These beliefs are reflected in standards, curriculum materials, and instructional practice. In order to make progress, we must find ways to challenge these beliefs and support the development of materials and instructional practice that reflect contemporary views of learning science.

## Knowing How to Teach Science Effectively

In order to teach science well, teachers need to understand science differently from the way that scientists do. A scientist understands scientific theory and its historical origins, the questions being investigated, and the ways in which questions are investigated in his or her field. But a scientist does not necessarily know how to convey scientific knowledge to children or other nonexperts, nor how to create appropriately structured opportunities for practicing science.

Teachers need to know science in ways that are particularly suited for instruction. In other words, they don't just need to know the subject matter—they need to know how to teach the subject matter. They need to understand the strands of science learning in a student-learning context. This "pedagogical content knowledge" combines the fundamental understanding of a discipline with an understanding of how students learn. A science teacher also needs to know how to create science learning opportunities; how to select appropriate instructional materials and problems; the appropriate points in an investigation to teach a new skill; and how to help students understand the unique qualities of scientific language and reasoning and how they relate to everyday forms.

We could create a long list of science-specific pedagogical considerations, but a concrete example may better illustrate the ways in which a teacher's knowledge of science intersects with a knowledge of pedagogy. Consider a teacher's challenges in teaching science investigations, as discussed in Chapter 7. To begin with, the teacher must select a problem to investigate that has meaning from the standpoint of science—that is, the activity has to be clearly connected to scientific concepts and methods. The activity also has to be meaningful from the standpoint of classroom learning—that is, it must provide opportunities for students to connect their knowledge, experience, and interests with the subject. Once students are involved in an investigation, the teacher must be prepared to field students' ideas and questions about the outcomes, and be prepared for the possibility that students may overlook key events in a demonstration or fail to interpret them correctly. The teacher must be prepared to subtly guide students toward certain insights through effective questioning.

Throughout instruction, teachers are challenged to assess which aspects of a problem students are understanding, how their current understanding can be advanced, and what types of experiences will move them incrementally closer to the ultimate instructional goal. This process requires teachers to engage in an internal dialogue between disciplinary science goals and the pedagogical means of determining what children know and how to move their understanding forward.

## Providing Teachers with Opportunities to Learn

Teachers learn continuously from their experiences in the classroom and their informal interactions with colleagues. These exchanges with students and colleagues can be productive when they are organized in a way similar to the experiences described earlier about the staff at Rosa Parks School. Through a combination of peer and administrative support, teachers developed knowledge of science, knowledge of student learning as it relates to science, and how to teach science effectively. The majority of elementary and middle schools, however, do not provide teachers either the time for peer study groups or practice-embedded professional development or the resources, materials, or pedagogical/content knowledge needed to learn science themselves and teach it well.

Resources such as effective professional development programs that are sustained over the long term and provide clear, consistent linkages to subject matter and the core tasks of teaching must be made available to teachers. Curriculum-based institutes, mentoring programs, study groups, and teacher coaching can also provide teachers with opportunities to deepen their subject matter expertise and reflect on classroom practice.

Thanks to recent studies about professional learning opportunities, we now know a great deal about what works best to support teachers.

These criteria emphasize purpose and rigor and suggest that teacher learning is serious business. They acknowledge that teacher learning is the by-product of thoughtful design and systemwide participation. Professional development programs often provide teachers with opportunities to analyze phenomena, think scientifically, represent and interpret data, build models, and engage in claim making

## Types of Support Teachers Need to Teach Science Well

- **High-quality curriculum or supplementary materials**
- **Means by which to have their questions answered (texts, colleagues, outside experts)**
- **Time and support to work through science tasks as learners**
- **Opportunity to explore a variety of materials and experience problems that students might have**
- **Time to think about and assess the knowledge their students bring to class**

and argumentation about data with peers. Teachers can gain experience with a broad range of scientific issues through such programs.

Professional development programs should also demonstrate how teachers can support their students' learning. Teachers need to learn how students think, have strategies for supporting their thinking as it develops, learn about teaching moves that serve particular functions in their students' learning, and use their own knowledge to respond strategically to student thinking. Good professional development programs give teachers opportunities to develop these skills.

But what does this look like in practice? In Lansing, Michigan, a National Science Foundation grant provides funding for a partnership between Michigan State University and the Lansing School District to provide research-based learning opportunities for teachers. In the PI-CRUST (Promoting Inquiry Communities for the Reform of Urban Science Teaching) project, K-8 teachers have been working in grade-level groups for the past five years. They have been focusing on the science that they teach at their grade level, on children's usual difficulties in understanding that science, on curriculum analysis and revisions of the inquiry-oriented, standards-based units they have adopted, and on the knowledge for teaching—including knowledge of representations, analogies, and models—that help children construct big ideas. Experienced facilitators from the university and the district lead these professional learning communities, which meet after school every two weeks and during the summer for an intensive study of the scientific concepts in one focus unit. Facilitators also observe and coach in classrooms, often coteaching with teachers and developing improved lessons, based on assessments of students' understanding.

During a recent summer session, the second-grade professional learning community worked on understanding essential concepts and models related to the study of sound. They performed investigations to deepen their understanding; tried multiple representations and materials that might help children understand how sound travels; analyzed the current curriculum unit; rewrote, added, deleted, or resequenced some lessons; read research reports about children's ideas about sound; and read excerpts from the National Science Teachers Association book *Sound: Stop Faking It! Finally Understanding Science So You Can Teach It* to enhance their own understanding. Teachers also designed pre-, embedded, and post-assessments to reveal children's thinking about what makes sounds, how sound travels, and how pitch and volume are changed. The following winter they taught the revised unit, focusing for nine weeks on children's learning and their own teaching, sharing children's work across the second-grade classrooms, videotaping and debriefing their lessons, and making modifications both individually and as a unit. The next summer, they met again to refine the unit, based on their documentation, and to share the revised unit with other second-grade teachers in the district.

The kindergarten professional learning community found that they already had a fairly successful unit on trash and recycling but lacked some of the resources needed to help students understand where the trash goes after they throw it away in their classroom. Teachers arranged to visit a local trash and recycling company to deepen their own understanding of the issue, and they videotaped their visit. They then enlisted a communications student to edit the videotape so they could show their students how garbage trucks take the classroom trash to a landfill site, where the trash is bulldozed, covered with earth, and layered in specially designed and sealed areas. The videotape also showed the sorting and recycling operation at the landfill site, including the composting of plant materials. Teachers planned to use the videotape to help their students understand the various ways that trash can be handled, recycled, and composted.

In both of these examples, teachers focused on understanding, representing, and teaching specific content to their students at specific grade levels. They analyzed the curriculum, revising and adjusting it to meet students' needs, documented what their students thought about and what they were learning, and shared their resources and experiences with other teachers in the district. Each project yielded teacher leaders who formed a particularly deep understanding of the content and curriculum at each grade level. Each project also yielded resources that other teachers, especially new teachers and teachers new to the district or to their grade level, could use. As one kindergarten teacher put it, "I didn't know what I didn't understand about trash and recycling before we took this field trip to the landfill. But now I feel like I can truly teach this unit to my kids, and understand the storyline and how it all fits together."

A small number of studies have examined the professional development opportunities available to science teachers who teach predominantly minority or low-income students in urban schools. As noted previously, there is little agreement in the field as to the most effective means of teaching diverse student populations, so these studies examined a range of teacher learning opportunities. Some focused on the unique qualities and challenges of working with diverse student groups, while others reflected approaches that were not solely related to teaching these groups. Despite the small number of studies, professional development for teachers of diverse student populations has shown promising results, including positive impact on students' science and literacy achievement and the narrowing of achievement gaps among demographic subgroups.

***Teacher learning opportunities should . . .***

1. **Reflect a clear focus on student learning in a specific content area**
2. **Focus on the strengths and needs of learners in that area and draw on evidence about what works from research**
3. **Include school-based and job-embedded support in which teachers may assess student work, design or refine units of study, or observe and reflect on colleagues lessons**
4. **Provide adequate time during the school day and throughout the year for both intensive work and regular reflection on practice. Professional development also needs to span multiple years**
5. **Emphasize the collective participation of groups of teachers, including teachers from the same school, department, or grade level**
6. **Provide teachers with a coherent view of the instructional system, from content and performance standards to instructional materials to local and state assessments to the development of a professional community**
7. **Receive the active support of school and district leaders**

Teachers of English language learners need to promote students' English language and literacy development as well as their academic achievement. A limited body of research indicates that professional development efforts have a positive impact on helping teachers integrate science with literacy development for these students. For example, one study that was part of a local systemic initiative sponsored by the National Science Foundation involved elementary school teachers of predominantly Latino English language learners.[4] After participating in a five-week summer professional development program, the majority of teachers had broadened their view of the connections between inquiry science instruction and second-language development to encompass a more elaborated perspective on the ways that the two could be integrated. Another study provided professional development opportunities to elementary school teachers serving students from diverse backgrounds.[5] Teachers' beliefs and practices in teaching science to language-minority students changed in a positive way. At the end of the school year, these students showed statistically significant gains in science and literacy (writing) achievement, enhanced abilities to conduct science inquiry, and a narrowing of achievement gaps.

Another group examined professional development in promoting science and literacy with predominantly Spanish-speaking elementary school students as part of a districtwide systemic reform initiative.[6] Over four years, the inquiry-based science program gradually became available to all teachers at all elementary schools in the school district. They were provided with professional development, in-classroom professional support from resource teachers, and complete materials and supplies for all the science units. Results indicated that the science and literacy achievement of language-minority students increased in direct relation to the number of years they participated in the program.

Another study examined the impact of standards-based teaching practices—including extended inquiry, problem solving, open-ended questioning, and cooperative learning—on the science achievement and attitudes of urban black middle school students.[7] The professional development programs consisted of six-week summer institutes and six seminars during the academic year, with support from the National Science Foundation. The results indicate that professional development designed to enhance teachers' content knowledge and use of standards-based teaching practices not only improved science achievement but also reduced inequities in achievement patterns for urban black students.

Researchers disagree on the specific qualities of science instruction that advance learning in diverse student populations. While the relative benefits of one approach over another are not clear, these studies suggest that, given opportunities to learn a range of new strategies for teaching these students, teachers can improve their practice and improve student learning.

The kinds of professional development opportunities described above are not the only option for school leaders. In conjunction with such programs, schools can invest in the resources of specialized science educators, such as science specialists, teacher leaders, coaches, mentors, demonstration teachers, and lead teachers.

Science specialists work in a wide variety of capacities in schools. They may work entirely with teachers. Or they may assume instructional duties for science for an entire K-5 school, for example, or for a certain grade level. This latter practice is not common in U.S. elementary schools. But some countries, including some that do better than the United States in international comparisons of student performance, typically rely on science specialists as early as the second grade.

Using science specialists may be a particularly useful strategy in schools and systems in which current K-5 teachers lack science knowledge and confidence in their ability to teach science.

Not much research has been done on the benefits of using subject matter specialists, and the results of these studies are mixed. Evidence suggests that teacher leaders can have an important influence on their peers' practice, although such arrangements tend to be more common in schools that are acting on a number of fronts simultaneously. Schools with teacher leaders in science also tend to have students who do better in science, at least when such science specialists are embedded within broader reform efforts.

As research has made clear, teachers have not had access to the kinds of professional learning opportunities necessary for effective science teaching. Much remains to be learned about the connection between what teachers know and how their knowledge affects student learning. Future research will need to focus on a range of topics, from the effectiveness of professional learning support groups to the value of analyzing student work. In the meantime, educators and administrators will need to implement good reflective practice until research provides a more definitive direction.

## Next Steps

Many schools and school systems are not currently poised to plan and enact a whole-scale systemic shift to support K-8 science in all of the ways described in this book. But this should not deter progress. Individuals and groups can take steps forward on specific aspects of this agenda. We describe some of the specific ways individuals can make incremental changes to build a system that supports K-8 science education locally.

### *Educational Administrators*

Administrators play a critical role in supporting high-quality science education. This book describes some of the features of good science instruction that administrators can encourage teachers to initiate and that they themselves can look for in classrooms. Administrators can play an important role in encouraging everyone—teachers, students, curriculum and assessment professionals, and teacher educators—to revisit basic assumptions about science and how students learn it. Curriculum and assessment developers and professional development staff, for example, will need to learn about the four strands of proficiency and consider how the instructional system supports them, how students progress across the strands, and what kinds of teacher learning opportunities they should provide for science teachers. Administrators play a critical role in creating the space, time, and incentives for these actors to engage with the ideas in this book and critically examine their current practice.

School-level administrators can help create a school community that actively supports science learning. What this means will vary from school to school. For example, in schools in which science instruction is weak, administrators can share this book with teachers and ask them to think about what small steps they can take to improve science teaching (see below for specific ideas). In a school with a few teachers who are "early adopters" of the ideas in this book, administrators can play a critical support role. They can help educate other teachers, students, and parents about the changes that they observe in these teachers' classrooms. Classrooms may be a bit noisy at times. The student work that hangs on classroom walls—student-generated graphs and diagrams, lists of working hypotheses, histories of the group's thinking—may seem strange. Administrators can help build understanding of what early adopters are doing and encourage others to join and support them.

### Professional Development Staff

Professional development is needed to help teachers understand science, how children think about and learn science, and how to teach it. If teachers are to create rich and productive science learning experiences for students, they themselves must have experiences working with the four strands of proficiency over time and in ways that relate directly to their own classroom practice. Teachers must be supported to become learners and investigators—of the science they teach, of their students' thinking, and of the best ways to orchestrate their students' learning of complex concepts, tools, and practices.

Professional development staff will need to study this book and other current literature on science learning to develop sustained, science-specific professional development. To create and support professional development that is rooted in science and student learning, they should interact with teachers, school administrators, and science curriculum specialists. They may need to lobby their colleagues and supervisors for support and for increased access to teachers. They can premise their arguments for support on the evidence outlined in this book and the study from which it is derived, *Taking Science to School.*

Tools and resources are necessary to sustain teacher learning. District- and school-level professional development staff can play an important role in identifying and sharing resources with teachers. In particular, educators will need access to instances of excellent science teaching that they can study in real time, in texts like this one, or through video and interactive technologies. Professional development staff may need to scour local resources and consult professional networks to find materials that exemplify excellent practice in science teaching.

### *Curriculum Developers*

The curriculum is a critical tool for improving science education. It articulates goals for science education and characterizes the experiences students should have to advance toward those goals. Yet curricula often fail to identify and support the range of practices that underlie effective science learning.

While some curriculum specialists will be part of a system that is ready to tackle a systemic revision of its K-8 science curriculum and to build it in ways resonant with core concepts, learning progressions, and science as practice, others may need to find smaller ways to improve their curricula. They can begin to discern the ways in which their curricula map onto the goals outlined in this volume and identify how to make revisions. They can begin to ask themselves: Does our curriculum present science as a process of building theories and models using evidence, checking them for internal consistency and coherence, and testing them empirically? Are discussions of scientific methodology introduced in the context of pursuing specific questions and issues rather than as templates or invariant recipes? Does discussion of scientific method include a focus beyond experiments and incorporate examples from disciplines of science that employ observational and historical methods? Posing these questions will help curriculum professionals identify shortcomings in their local curriculum on which they can focus their energies.

### *Teachers*

Teachers may want to know what they can do immediately to improve science teaching, as they go into the classroom tomorrow and plan units of study for the coming weeks and months. Although some of the changes described in this book will benefit from (or require) major changes in the education system, individual teachers can begin immediately to practice aspects of the science teaching described here.

Organizing a science curriculum around core concepts that are revisited in increasingly complex ways over months and years is a central theme in this book. Even without control over the K-8 curriculum, teachers can work with existing curriculum materials and embrace the principles of learning progressions and core ideas. A teacher may choose to begin with a familiar science unit to clarify the central scientific ideas it frames. Teachers will need to use their judgment and available resources to determine what level of understanding is appropriate to target at a given grade. With central ideas and goals in hand, teachers can use textbooks and other support materials to build investigations over several weeks and to identify how the strands of proficiency can be harnessed and particular skills taught within that unit. Again, there are examples of how effective science teachers have done this in this volume, and we hope that teachers will find ways to build on these examples.

Examining and listening closely to students' ideas are crucial components to science teaching. Even novice teachers can begin immediately to find ways to elicit student thinking and connect it with the science curriculum. Throughout this book there are examples of the types of problems and prompts that expert teachers use to get students to express their thinking in writing and diagrams or through spoken language. Teachers may begin to make progress on this by reviewing those examples, creating analogous questions and prompts for the topics they are teaching, and trying these with their students.

In classrooms in which students practice science, teachers and students strive to have ideas flow freely, support students' "first draft thinking," and encourage critical analysis of their classmates' ideas. As this book has indicated, creating such classrooms takes tremendous effort and requires that students and teachers alike build and agree to norms for participation. The examples of Ms. Carter and Ms. Wright in Chapter 5 may be particularly illustrative as they depict how teachers can encourage and monitor productive and safe exchange among students.

For some teachers, the prospect of students critiquing one another's ideas may be daunting, and they may wish to start out by creating small periods of time for these discussions. Alternatively, teachers may wish to hold off on extensive spoken exchanges among students until they understand how to establish and monitor norms for participation. They may ask students to write down their thinking about a topic and list students' ideas in a public space for them to consider. This will allow students to see the diversity of ideas they have about scientific concepts and may form the basis for asking clarifying questions and generating explanations that capture a broad range of observations. Short of helping students generate competing explanations, teachers may select texts that characterize historical developments in science and that depict disagreements and how those are handled in science. These initial efforts will not necessarily help students learn how to operate in a scientific community, but they will help them see that argumentation and competing ideas are essential to science.

In addition to school system educators, many groups influence science education in the United States. Parents, scientific societies, museums and science centers, universities, publishers, and community organizations can all play an important role in supporting science learning. Each of these groups can work individually and together to advance science education, and we urge them to think about their work in terms of the research basis for science learning.

The science teaching and learning taking place in American classrooms today could and should do much more. Students should be able to build on the knowledge they bring to the classroom, pose good questions, find ways to explore those questions, investigate and evaluate alternative models, and argue their points of view.

With an increasingly diverse student population and persistent gaps in science achievement, the goal of scientific proficiency for all students may seem difficult to achieve. It is important to remember that young children come to school with a strong foundation of basic reasoning skills, knowledge of the natural world, and innate curiosity. In order to tap into these skills, teachers need to be sensitive to their students' shared strengths as well as the ways in which each student is different. Teachers need to be willing and able to acquire or deepen their science content knowledge, and they need to be supported to take calculated risks in embracing instructional approaches that have been shown to benefit all students. This is possible when teachers act on the premise that, regardless of previous experience, existing knowledge, and cultural and linguistic differences, each and every one of their students is capable of learning science.

Much work still needs to be done to identify the best ways to bring about the kind of science instruction we describe in this book. But enough is known now to begin to move forward in the right direction. Research has shown us how much students can achieve in effective science learning environments. It has shown us what science education can and should be and where it needs to go. So let's get going! Ready, set, science!

# Notes

## Chapter 1

[1] This case is based on work with teachers involved in the Accountable Talk in Math and Science Project, funded by the Davis Foundation and the Springfield, Massachusetts Public Schools, directed by Susan Catron, Sarah Michaels, and Richard Sohmer. For more information, visit http://www.investigatorsclub.com.

[2] National Research Council. (1999). *How people learn: Brain, mind, experience, and school.* Committee on Developments in the Science of Learning. J.D. Bransford, A.L. Brown, and R.R. Cocking (Eds.). Washington, DC: National Academy Press.

[3] This case derives from the Accountable Talk in Math and Science Project, funded by the Davis Foundation and the Springfield, Massachusetts Public Schools, directed by Susan Catron, Sarah Michaels, and Richard Sohmer.

## Chapter 2

[1] The image of a length of rope representing interwoven strands is borrowed from a previous National Research Council volume on teaching and learning mathematics: National Research Council. (2001). *Adding it up: Helping children learn mathematics.* Mathematics Learning Study Committee. J. Kilpatrick, J. Swafford, and B. Findell (Eds.). Washington, DC: National Academy Press.

[2] National Research Council. (1996). *National science education standards.* National Committee on Science Education Standards and Assessment. Washington, DC: National Academy Press.

[3] This case is based on the work of teachers and researchers involved with the Modeling Nature Project, directed by Rich Lehrer and Leona Schauble at Vanderbilt University, as well as the work of botanist and teacher educator Glenn Adelson at Wellesley College.

## Chapter 3

[1] The term "theories" in this sense refers to the conceptual structure of children's ideas. Children's theories (or naïve theories) are like scientific theories in that they reflect interrelated and, to varying degrees, coherent accounts of the natural world. However, they are not explicit, accurate, or complete scientific accounts of phenomena.

[2] This case is based on work with teachers at a middle school in Worcester, Massachusetts. It highlights the curriculum developed by Richard Sohmer for the Investigators Club, funded by the Spencer Foundation (for more information, visit http://www.investigatorsclub.com), and

draws on the teaching and writing of high school physics teacher and science educator Jim Minstrell (for more information, visit http://www.facetinnovations.com).

## Chapter 4

[1] National Research Council. (1996). *National science education standards.* National Committee on Science Education Standards and Assessment. Washington, DC: National Academy Press.

[2] American Association for the Advancement of Science. (1993). *Benchmarks for science literacy.* New York: Oxford University Press.

[3] Schmidt, W., Wang, H., and McKnight, C. (2005). Curriculum coherence: An examination of U.S. mathematics and science content standards from an international perspective. *Journal of Curriculum Studies, 37*, 525-559.

[4] Much more on this learning progression can be found in Smith, C., Wiser, M., Anderson, C.A., and Krajick, J. (2006). Implications of research on children's learning for standards and assessments: A proposed learning progression for matter and atomic molecular theory. *Measurement: Interdisciplinary Research and Perspectives, 4.*

[5] This and the following two cases are based on an actual program, the Investigators Club, developed and researched with funding from the Spencer Foundation.

[6] This case is based on Sohmer, R., and Michaels, S. (2007). The Investigators Club: An alternative to textbook science. In *Voices in Urban Education, 14*(winter). Providence, RI: Annenberg Institute for School Reform. For more information and downloadable videos of the Air Puppies, visit http://www.investigatorsclub.com.

[7] Given the age and experience of his students, Mr. Figueroa made a pedagogical decision to avoid distinguishing "weight" from "mass." He recognizes that mass is the correct scientific term to refer to the amount of matter something contains and that weight is the measurement of the pull of gravity on an object. Mass is a universal measurement, whereas weight changes with location. His children will learn these distinctions in subsequent years of instruction. However, because his children used the term weight and his goal was to help them understand that weight (or mass) can be measured in more precise ways than sense of feel, he chose to use weight.

[8] For some teachers, two volleyballs and a bicycle pump will not be so easy to come by. The activity can be done with balloons as well. In this case, the teacher places two uninflated balloons on a pan balance and adjusts the scale so that they balance. With balloons, the demonstration is a bit more complex because the size of the balloon with air expands so dramatically and creates additional issues relating to air resistance. The inflated balloon will (as the children will likely point out) fall more slowly than the uninflated balloon, even though it is indeed heavier.

[9] Smith, C., Maclin, D., Grosslight, L., and David, H. (1997). Teaching for understanding comparison of two approaches to teaching students about matter and density. *Cognition and Instruction, 15*(3), 317-393.

## Chapter 5

[1] This chapter draws on work by Cathy O'Connor and Sarah Michaels in "Accountable Talk: Classroom Conversation That Works" (3 CD-ROM set), Institute for Learning, University of Pittsburgh. (For more information, visit http://www.instituteforlearning.org.)

[2] Chapin, S., O'Connor, C., and Anderson, N. (2003). *Classroom discussions: Using math talk to help students learn: Grades 1-6*. Sausalito, CA: Math Solutions.

[3] This case is based on the work of teacher Gina Lally, in collaboration with researchers Suzanne Chapin and Cathy O'Connor. For more detail on establishing norms for productive class discussions, see Chapin, S., O'Connor, C., and Anderson, N. (2003). *Classroom discussions: Using math talk to help students learn. Grades 1-6.* Sausalito, CA: Math Solutions.

[4] This section draws heavily on text from the "Accountable Talk: Classroom Conservation That Works," e-book chapter "Equity and Access," by Cathy O'Connor, Sarah Michaels, and Lauren Resnick. For more information, visit http://www.instituteforlearning.org.

[5] Lipka, J. (1998). Expanding curricular and pedagogical possibilities: Yup'ik-based mathematics, science, and literacy. In J. Lipka with G.V. Mohatt and the Ciulistet Group (Eds.), *Transforming the culture of schools: Yup'ik Eskimo examples.* Mahwah, NJ: Lawrence Erlbaum Associates.

[6] Au, K.H. (1980). Participation structures in a reading lesson with Hawaiian children: Analysis of a culturally appropriate instructional event. *Anthropology and Education Quarterly, 11*(2), 91-115. See also: Tharp, R., and Gallimore, R. (1989). *Rousing minds to life: Teaching, learning, and schooling social context.* Cambridge, MA: Cambridge University Press.

[7] Lee, C.D. (2001). Is October Brown Chinese? A cultural modeling activity system for underachieving students. *American Educational Research Journal, 38*(1), 97-141.

[8] Lee, O. (2002). Science inquiry for elementary students from diverse backgrounds. In W. Secada (Ed.), *Review of research in education* (pp. 23-69). Washington, DC: American Educational Research Association.

[9] Warren, B., Ballenger, C., Ogonowski, M., Rosebery, A.S., and Hudicourt-Barnes, J. (2001). Rethinking diversity in learning science: The logic of everyday sense-making. *Journal of Research in Science Teaching, 38*(5), 529-552.

[10] Hudicourt-Barnes, J. (2003). The use of argumentation in Haitian Creole science classrooms. *Harvard Educational Review, 73*(1), 73-93.

[11] This case highlights the work of teacher researcher Judith Richard and is based on videotapes and verbatim transcripts from her class. The names of the teacher and students are pseudonyms. For more information, see Michaels, S., O'Connor, M.C., and Richards, J. (1994). Literacy as reasoning within multiple discourses: Implications for policy and educational reform. In *Proceedings of the Council of Chief State School Officers 1990 Summer Institute on Restructuring Learning* (pp. 107-121). Washington, DC: Chief State School Officers.

## Chapter 6

[1] Lehrer, R., and Schauble, L. (2006). Scientific thinking and science literacy. In W. Damon, R. Lerner, K.A. Renninger, and I.E. Sigel (Eds.), *Handbook of child psychology, 6th edition* (vol. 4). Hoboken, NJ: Wiley.

[2] Wisconsin Fast Plants is a popular curriculum tool that uses a small, hardy, fast-growing plant species bred by Paul Williams of the University of Wisconsin–Madison for use in educational settings.

[3] Lehrer, R., and Schauble, L. (2004). Modeling natural variation through distribution. *American Education Research Journal, 41*(3), 635-679. Reproduced with permission from the publisher.

## Chapter 7

[1] Reiser, B.J., Tabak, I., Sandoval, W.A., Smith, B.K., Steinmuller, F., and Leone, A.J. (2001). BGuILE: Strategic and conceptual scaffolds for scientific inquiry in biology classrooms. In S.M.

Carver and D. Klahr (Eds.), *Cognition and instruction: Twenty-five years of progress* (pp. 263-305). Mahwah, NJ: Lawrence Erlbaum Associates.

[2] Krajcik, J., and Reiser, B.J. (2004). *IQWST: Investigating and questioning our world through science and technology.* Evanston, IL: Northwestern University.

[3] Palincsar, A.S., and Brown, A.L. (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. *Cognition and Instruction, 1,* 117-175.

[4] This case is based on a composite of classroom examples adapted from the research of Carol Smith and colleagues and Leslie Rupert Herrenkhol and colleagues. For more details, see: Smith, C., Snir, J., and Grosslight, L. (1992). Using conceptual models to facilitate conceptual change: The case of weight-density differentiation. *Cognition and Instruction, 9,* 221-283; Herrenkhol, L.R., Palincsar, A.S., DeWater, L.S., and Kawaki, K. (1999). Developing scientific communities in classrooms: A sociocognitive approach. *Journal of the Learning Science, 8*(3,4), 451-493; Herrenkhol, L.R., and Guerra, M.R. (1998). Participants, structures, scientific discourse, and student engagement in fourth grade. *Cognition and Instruction, 16,* 433-475.

[5] This vignette is taken from Hennessey, M.G., and Beeth, M.E. (1993). *Students' reflective thoughts about science content: A relationship to conceptual change learning*. Paper presented at the Symposium on Metacognition and Conceptual Change at the annual meeting of the American Educational Research Association (Atlanta, April 1993). Available from the Education Resources Information Center (ED407271).

[6] Smith, C.L., Maclin, D., Houghton, C., and Hennessey, M.G. (2000). Sixth-grade students' epistemologies of science: The impact of school science experiences on epistemological development. *Cognition and Instruction, 18,* 349-422.

## Chapter 8

[1] Newmann, F.M., Smith, B., Allensworth, E., and Bryk, A. (2001). Instructional program coherence: What it is and why it should guide school improvement policy. *Education Evaluation and Policy Analysis, 23*(4), 297-321.

[2] Banilower, E.R., Boyd, S.E., Pasley, J.D., and Weiss, I.R. (2006). *The LSC capstone report: Lessons from a decade of mathematics and science reform.* Chapel Hill, NC: Horizon Research.

[3] Windshitl, M. (2004). Folk theories of "inquiry": How preservice teachers reproduce the discourse and practices of the scientific method. *Journal of Research in Science Teaching, 41,* 481-512.

[4] Stoddart, T., Pinal, A., Latzke, M., and Canaday, D. (2002). Integrating inquiry science and language development for English language learners. *Journal of Research in Science Teaching, 39*(8), 664-687.

[5] Hart, J.E., and Lee, O. (2003). Teacher professional development to improve the science and literacy achievement of English language learners. *Bilingual Research Journal, 27*(3), 357-383.

[6] Amaral, O., Garrison, L., and Klentschy, M. (2002). Helping English learners increase achievement through inquiry-based science instruction. *Bilingual Research Journal, 26*(2), 213-239.

[7] Kahle, J., Meece, J., and Scantlebury, K. (2000). Urban African-American middle school science students: Does standards-based teaching make a difference? *Journal of Research in Science Teaching, 37*(9), 1019-1041.

# Appendix A Questions for Practitioners

## Chapter 1

**1.** Does the story about Ms. Fredericks at the beginning of this chapter seem familiar to you? In what ways are Ms. Fredericks's experiences as a teacher similar to your own or to those of teachers in your school or district? In what ways are they different?

**2.** What did Ms. Martinez and Mr. Dolens do, specifically, to help their students build on the knowledge, interest, and experience they brought with them to school, while extending their understanding of scientific tools and practices?

**3.** The case studies describing Ms. Martinez's and Mr. Dolens's classes suggest that, in science, it is more important for children have a solid theory of measure, one that crosses several kinds of qualities and units, than to simply know how to measure things. What's the difference between this and teaching children how to measure? Where do you see evidence in these case studies of the teachers helping their students develop an understanding of the *principles* of measurement?

**4.** If you were either Ms. Martinez or Mr. Dolens, how might you bring parents into the exploration of measurement, so that they understood what you are doing in the classroom and extended their children's learning at home?

**5.** For principals: How could you facilitate a discussion with teachers, community leaders, or parents using either this chapter or the case studies in this chapter as a starting point?

## Chapter 2

**1.** Where do you see evidence of the four strands of scientific learning in Mr. Walker's and Ms. Rivera's investigation of biodiversity in their schoolyard? Which elements of their investigation could be implemented in your own classroom, school, or district?

**2.** If you were to implement a similar investigation in your classroom or school, how would you begin? What kind of support would you need? What resources would you use?

**3.** For principals and science specialists: How would you support teachers to carry out an extended project like the biodiversity project? How would you adapt the project to fit your particular geographical location, as well as your particular district and school?

**4.** What does "science as practice" mean to you?

## Chapter 3

**1.** How can educators harness young children's shared base of understanding and skill to help them learn science?

**2.** How can children's misconceptions about science act as stepping-stones to greater scientific understanding? How does this differ from past thinking about children's misconceptions?

**3.** Imagine you were going to do the same demonstration with the aquarium and the empty glass that Ms. Faulkner's class did. Assume that before the demonstration, students came up with the following four predictions:

1. The glass will be filled with water and the paper will get wet.
2. A lot of water will go in the glass but the paper will not get wet.
3. A little water will go in the glass but the paper will not get wet.
4. No water will go in the glass and the paper will not get wet.

Which prediction would you use to begin a discussion? Why? What would you do if no one came up with Prediction 3 or 4?

**4.** Did you think that Ms. Faulkner's unit on air pressure was successful? Why or why not? In what ways could it be improved? To the extent that it was successful, what were the most critical factors in its success?

**5.** For parents: If your child were a student of Ms. Faulkner, what would you want to know about the air pressure investigation? How would you want to be kept informed about your child's participation and learning? What questions or concerns would you have?

## Chapter 4

**1.** How does the idea of building on core concepts over longer periods of time differ from the science practice you currently use in your classroom or school? What do you see as the benefits and challenges to teaching this way?

**2.** In the Mystery Box case study, what are some of the ways that Ms. Winter helped prepare her students for science learning in later grades?

**3.** As a teacher, what ideas would you have for adapting a single science unit to fulfill both short-term and long-term goals in a learning progression?

**4.** What common threads do you see across the three case studies described in this chapter?

## Chapter 5

**1.** Tape record a science lesson and listen for the nature and quality of talk that occurs. Is there evidence of an I-R-E recitation pattern? What is the balance of talk between teacher and students? Do some students talk more than others? Is there evidence of talk moves described in this chapter? How is student reasoning made public and visible?

**2.** What are the unique features of position-driven discussion? How does this differ from typical forms of classroom discussion? What are the benefits of position-driven discussion for science learning?

**3.** What are some of the ways that you make your students' ideas public in your classroom or school?

**4.** Why is it so important to distinguish between scientific argumentation and everyday argumentation? What do you think the main differences are between the two?

**5.** What methods does Ms. Carter use to encourage talk and argument and support scientific thinking? How does she include all of her students in the conversation? Are her methods successful?

## Chapter 6

**1.** Choose two units of study in a specific grade level in your school. Examine the teacher materials and student texts for evidence that modeling and representation are taught. Are children asked to develop models and representations (conceptual, mathematical, graphical, etc.) of scientific phenomena? What questions are children trying to answer in developing models? Are they given extensive, repeated opportunities to scrutinize, critique, and improve on their own models and representations of scientific phenomena? What could you do to improve instruction in modeling and representation?

**2.** For principals and professional development staff: prearrange with teachers to visit every classroom in your school during a science lesson. Observe the lessons for evidence of the metacognitive roles of both students and teachers, as set forth in the table of Sr. Gertrude Hennessey's findings. How does what you observe in the practices of teachers and students across the grades in your school compare with Sr. Hennessey's findings? Encourage faculty to examine their own classrooms and compare notes with colleagues across the grades in your school.

## Chapter 7

**1.** Choose an exemplary unit in your school or district K-8 science curriculum. Are children asked to work on scientific problems over time? Do problems satisfy the dual definition of "meaningful" in this chapter? If so, how? If not, what can be done to improve the problems and students' ability to see them as meaningful?

**2.** For teachers, science specialists, or principals: observe students engaged in scientific discussion or explanations. Do you see evidence of the claim-evidence-reasoning framework described in this chapter? How might current practice be adapted to make better use of this framework?

**3.** How does scripting student roles help support more equitable participation in the classroom? What are some of the other methods described in this book that help support equitable participation?

## Chapter 8

**1.** Whose responsibility is it to make sure that the teachers have a good science curriculum? Whose responsibility is it to make sure that the teachers have time built into their days to participate in study groups or professional development opportunities? What specific roles should teachers, principals, professional development staff, and assessment professionals play in creating and refining science curriculum?

**2.** What are some immediate steps you can take to improve science teaching in your district, school, or classroom? What can you do individually? Who can you partner with to work more broadly?

**3.** In what ways are assessment, curriculum, instructional practices, and opportunities for teacher learning aligned in your school or district? What shortcomings do you observe in this respect? What are the hurdles to improving alignment?

**4.** What are the challenges and possibilities in your school or district for supporting teachers' ongoing learning with colleagues, focusing on the science content they are expected to teach?

# Appendix B Assessment Items Based on a Learning Progression for Atomic-Molecular Theory

## Grades K-2

**A.** Give students a set of objects that differ in various ways that have been explored in the classroom, such as by type of material, type of object, color, size, and so on. Ask the students to sort the objects into different categories by type of material, type of object, or other characteristics. In each case, students should explain the basis for their groupings. This task calls for students to form exhaustive classifications based on the distinguishing characteristics of objects. Students who do not understand classifications will fail to systematically pick out all the items of a given type.

**B.** Representing data about the properties of objects in a data table.

***Paper and pencil item:*** Show the child a picture of a set of objects (labeled A, B, C, etc.) that differ in color (red, blue), shape (cube, sphere), and size (large, small). Ask the child to make a table that describes each object with respect to the properties of color, shape, and size. As an alternative to asking the child to make a table, a more open-ended task would be to ask the child to design a way of showing all the important things we could tell people about each of these objects. In this case, the task lets the child struggle with ways of designing a communicative representation. This variation will no doubt produce a wide variety of solutions, which can be compared and interpreted by other students who did not make them.

***Performance item:*** Give students a set of shapes (geometric solids) that differ in color, shape, and size (large, medium, small). Ask them to make a table that describes each object definitively with respect to the properties of color, shape, and size (provide a photograph of the setup). These attribute shapes can also be used in the Mystery Box activity, getting students to ask questions to identify which object (by color, shape, and size) is inside the box.

***Performance item:*** Give students a set of objects that vary along a given dimension (length, area, weight, or volume). Ask them to measure the dimension in question and make a data table that shows the values of each of the objects for that dimension.

***Interpretation:*** These items call for students to construct simple but organized tables to represent their data in clear ways. An important aspect of their performance would be their ability to describe each object accurately and completely according to all the properties or dimensions in question and to have separate columns (or rows) for each property or dimension.

## Grades 3-5

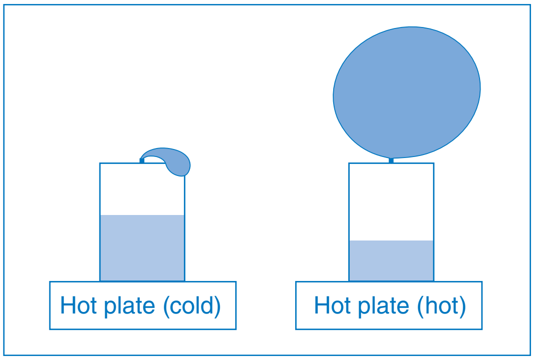
***Paper and pencil item:*** Here are two empty balloons in balance. (Show picture or drawing of two uninflated balloons in balance, each hanging from the end of a rod that is suspended with a string tied to its midpoint.) Which of the following pictures shows what will happen when one balloon is filled with air? How do you know?

- **A.** Picture shows the uninflated and inflated balloons are both still in balance.
- **B.** Picture shows the inflated balloon is heavier (tips down).
- **C.** Picture shows the inflated balloon is lighter (tips up).
- **D.** There is no way to predict from the information given.

***Interpretation:*** This item assesses whether students realize that air has weight and hence that adding air will make the balloon heavier and the rod tip down. If students understand this, they should select B and explain that air has weight, so it should make the rod go down. Common alternative ideas are that air is weightless (adding air will not change how things balance) or that air has negative weight (things rise when air is in them, so the side of the rod with the balloon will go up). Other items could be created, asking about the weight of a ball (or tire) as air is added or removed.

## Grades 6-8

***Paper and pencil item:*** A container with a little hole at the top is placed over a hot plate. There is water in the container. A deflated balloon is attached to the hole. The hot plate is turned on. The water starts boiling and the balloon inflates (see picture):




**1.** What is the balloon filled with?

- **A.** Air
- **B.** Oxygen and hydrogen gas
- **C.** Air and water vapor
- **D.** Heat

**2.** Consider the combined mass (amount of stuff) of the container, water, and balloon (deflated or inflated) and what the balloon contains. When the water boils:

- **A.** Mass (amount of stuff) stays the same because_______________________
- **B.** Mass (amount of stuff) decreases because__________________________
- **C.** Mass (amount of stuff) increases because___________________________
- **D.** There is no way to predict.

***Interpretation:*** These questions test whether students believe that what escapes from the boiling water is material, whether they apply conservation of mass to this situation, and what they think escapes from the water. The proportion of students who believe that what escapes from boiling water is still water increases through middle school. Some students believe that what escapes from the boiling water is air, or they might say that the water breaks down into oxygen and hydrogen (evincing a confusion between chemical and physical transformations). Students may correctly apply conservation of mass and predict that when the liquid water changes state, there is no change in mass. Alternatively, they may believe that the mass of the gas will be less than the mass of liquid because gases are thought to be light or weightless.

# **Appendix C** Academically Productive Talk

In addition to talk moves, teachers can engage students in a number of recurring talk formats, each of which has a particular norm for participation and turn-taking. Examples include partner talk, whole-group discussion, student presentations, and small-group work. A number of studies have suggested that what has been called "academically productive talk" has many benefits in the classroom. This kind of talk leads to deeper engagement in the content under discussion. It also elicits surprisingly elaborated and subject matter–specific reasoning by students who might not usually be considered able students. Some of the mechanisms presumed to account for its efficacy in supporting student learning are:

- Talk about theories, concepts, evidence, models, and procedures may cause misconceptions to surface. This may help the teacher recognize and address what students do and don't understand and may help students become aware of inconsistent or incorrect beliefs.

- Discourse formats, such as extended-group discussion, may play a part in helping students improve their ability to build scientific arguments and reason logically. When one student makes a claim, the teacher can ask for evidence to support it.

- Allowing students to talk about their thinking, theorizing, and evidence-based interpretations gives them more to observe, more to listen to, and more chances to participate in scientific thinking.

- Classroom talk may push learners beyond their incomplete, shallow, or passive knowledge by making them aware of discrepancies between their own thinking and that of others.

- The ability to communicate clearly and precisely is a hallmark of mature scientific reasoning. Classroom talk provides a context for the socialization of students into this practice.
- Classroom discussion may provide motivation by enabling students to become affiliated with their peers' claims and positions.

## For Further Reading

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Cazden, C. (2001). *Classroom discourse: The language of teaching and learning*. Portsmouth, NH: Heinemann.

Lemke, J.L. (1990). *Talking science: Language, learning, and values*. Norwood, NJ: Ablex.

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# Appendix D Biographical Sketches of Oversight Group and Coauthors

**Kevin J. Crowley** is associate professor of education and cognitive psychology at the University of Pittsburgh's Learning Research and Development Center, where he also directs the Center for Learning in Out-of-School Settings. His research interests focus on the development of children's scientific thinking in informal, formal, and everyday settings, focusing on how they develop knowledge and skill in such contexts as museums and on the Web and how to best coordinate their experiences in science. He has been a visiting fellow at the Department of Psychology and Education at Nagoya University in Japan. He has a Ph.D. in psychology from Carnegie Mellon University (1994).

**Janet English,** currently on leave from teaching, is the director of educational services for KOCE-TV, Orange County, California's Public Broadcasting Service (PBS) station. She has been teaching eighth-grade science and seventh- and eighth-grade multimedia communications at Serrano Intermediate School in Orange County's Saddleback Valley Unified School District for 13 years. She received the Presidential Awards for Excellence in Mathematics and Science Teaching in 2003. At KOCE-TV, she helped start the Schoolhouse Video Project, which broadcasts student video work on PBS. She has been a contributor to and a staff person for the *National Science Education Standards,* a consultant with the Cal Tech Precollege Science Initiative, and a committee member of the Defense Investment Initiative, which assists displaced scientists and engineers who are transitioning to teaching in inner-city schools. She was the director of the Institute for Chemical Education's physics and chemistry camps at the University of Northern Colorado, an instructor for the Apple Teacher Institute and the Apple Colleges of Education, and a teacher trainer for the California Technology Assistance Project. She is an associate member of the National Research Council's (NRC) Teacher Advisory Committee and serves as vice chair of the California Teacher Advisory Council.

**Sister Mary Gertrude Hennessey** is an elementary school administrator at Saint Ann's School in Stoughton, Wisconsin. Previously she taught science to students in grades 1 through 6. In addition to challenging existing theories of child development, Dr. Hennessey worked with the Harvard University Graduate School of Education on a study designed to test the claim that elementary school students can make significant progress in developing a sophisticated, constructivist epistemology of science, given a sustained elementary school science curriculum designed to support their thinking about epistemological issues. She has also conducted a multiyear study to describe the multifaceted nature of young students' metacognitive abilities. She is a founding member and past president of Wisconsin Elementary Science Teachers. She has collaborated with researchers from such institutions as the Smithsonian Institution's Center for Astrophysics, the University of Maryland's Physics Education Research Group, the Ohio State University, the North Central Regional Educational Laboratory, and the University of Wisconsin–Madison. She has received numerous national and state awards for excellence in science teaching. She has a Ph.D. in philosophy from the University of Wisconsin–Madison.

**Sarah Michaels** is professor of education and senior research scholar at the Jacob Hiatt Center for Urban Education at Clark University. A sociolinguist by training, she has been actively involved in teaching and research in the area of language, culture, "multiliteracies," and the discourses of math and science. She was the founding director of the Hiatt Center for Urban Education and works to bring together teacher education, educational research on classroom discourse, and district-based efforts at education reform. She is currently involved in rethinking teacher education and professional development so that it focuses central attention on rigorous, coherent, and equitable classroom discourse. Michaels is a coauthor of the CD-ROM suite of tools *Accountable Talk: Classroom Conversation That Works* (in collaboration with the Institute for Learning at the University of Pittsburgh), which is currently being used in large urban districts throughout the country. In promoting teacher research, she works to support teachers as theorizers, curriculum innovators, and education leaders who use the tools of ethnography and discourse analysis in generating new and usable knowledge for improving instruction and student learning in their own and others' classrooms. Michaels has published widely in the area of classroom discourse analysis, has received numerous awards for both teaching and scholarship, and serves on a wide range of review boards for journals, book series, and educational foundations. Prior to joining Clark in 1990, Michaels served as director of the Literacies Institute in Newton, Massachusetts, and as project director of a number of sponsored grants in language and schooling as a research associate and instructor at the Harvard Graduate School of Education. She has a B.A. from Barnard College and a Ph.D. in education (language and literacy) from the University of California, Berkeley.

**Brian J. Reiser** is professor of learning sciences at the School of Education and Social Policy at Northwestern University. His research concerns the design and study of investigation environments and inquiry support tools for science. These projects explore the design of computer-based learning environments that scaffold investigation and scientific argumentation about biological phenomena and the design of inquiry support tools that help students organize, reflect on, and communicate about the progress of their investigations. This work is being conducted as part of the initiatives of the Center for Learning Technologies in Urban Schools, which is working to understand how to make learning technologies a pervasive part of science classrooms in urban schools. Reiser is also a member of the core faculty of the Center for Curriculum Materials in Science, a collaboration of Project 2061, Michigan State University, Northwestern University, and the University of Michigan. He serves on the editorial boards of *Interactive Learning Environments* and the *Journal of the Learning Sciences*. He was a member of the NRC's Committee on Test Design for K-12 Science Achievement. He has a Ph.D. in psychology from Yale University (1983).

**Leona Schauble** is professor of education at Vanderbilt University. Her research interests include the relations between everyday reasoning and more formal, culturally supported, and schooled forms of thinking, such as scientific and mathematical reasoning. Her research focuses on such topics as belief change in the contexts of scientific experimentation, everyday reasoning, causal inference, and the origins and development of model-based reasoning. Prior to her work at Vanderbilt, she worked at the University of Wisconsin, the Learning Research and Development Center at the University of Pittsburgh, and the Children's Television Workshop in New York. She recently served as a member of the Strategic Educational Research Partnership, an NRC-affiliated venture designed to construct a powerful knowledge base, derived from both research and practice, that will support the efforts of school people at all levels with the ultimate goal of significantly improving student learning. Schauble has a Ph.D. in developmental and educational psychology from Columbia University (1983).

**Heidi A. Schweingruber** *(Coauthor)* is a senior program officer with the NRC's Board on Science Education. She was a program officer on the NRC study that produced *America's Lab Report: Investigations in High School Science* and is currently directing a congressionally mandated review of NASA's precollege education programs. Prior to joining the NRC, she was a senior research associate at the Institute of Education Sciences in the U.S. Department of Education, where she served as program officer for the preschool curriculum evaluation program and for a grant program in mathematics education. She was also a liaison to the Department of Education's Mathematics and Science Initiative and an adviser to the Early Reading First program. Before moving into policy work, she was director of research for the Rice University School Mathematics Project, an outreach program in K-12 mathematics education, and taught in the psychology and education departments. She has a Ph.D. in psychology (developmental) and anthropology and a certificate in culture and cognition from the University of Michigan (1997).

**Andrew W. Shouse** *(Coauthor)* is a senior program officer with the NRC's Board on Science Education, where he currently directs a study of learning science in informal environments. He is an education researcher and policy analyst whose interests include teacher learning, science education in formal and informal settings, and communication of education research to policy and practice audiences. He previously served as codirector (with Heidi Schweingruber) of the study that resulted in the consensus report *Taking Science to School: Learning and Teaching Science in Grades K-8*. Prior to joining the NRC, he worked as an education research and evaluation consultant, a science center administrator, and an elementary and middle grades teacher. He has a Ph.D. in curriculum, teaching, and educational policy from Michigan State University (2005).

**Deborah Smith** is a second-grade teacher at Woodcreek Elementary Magnet School for Math, Science and Engineering in Lansing, Michigan. She was coprincipal investigator for science on the Delaware Statewide Systemic Initiative. She was also the author and, until she returned to the classroom, coprincipal investigator on a five-year National Science Foundation grant to the Lansing School District and Michigan State University for K-8 teacher retention and renewal. She facilitates two of the teacher professional learning communities for that grant. She has consulted for Project 2061, WestEd, Horizon Research, Annenberg CPB, and the Michigan Department of Education on matters of professional development, science standards, and curriculum analysis. While on the faculty at Michigan State University, her research investigated preservice teachers' science content understanding and their conceptions of the nature of scientific work and of science teaching. She has published her research in such journals as the *Journal of Research on Science Teaching*, *Teaching and Teacher Education*, and the *Journal of Science Teacher Education*. She received a Spencer Foundation postdoctoral fellowship and a Carnegie Academy for the Scholarship of Teaching and Learning fellowship. She is a member of the National Academies' Teacher Advisory Council. She has a Ph.D. in curriculum and instruction from the University of Delaware (1989).

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# Acknowledgments

*Ready, Set, Science!* is the result of a shared vision and commitment among a remarkable assemblage of talented people. Countless hours of individual and collaborative work and a strong commitment to creating a quality resource for science education practitioners moved this volume from a vision to a reality.

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Board on Science Education

# Credits

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