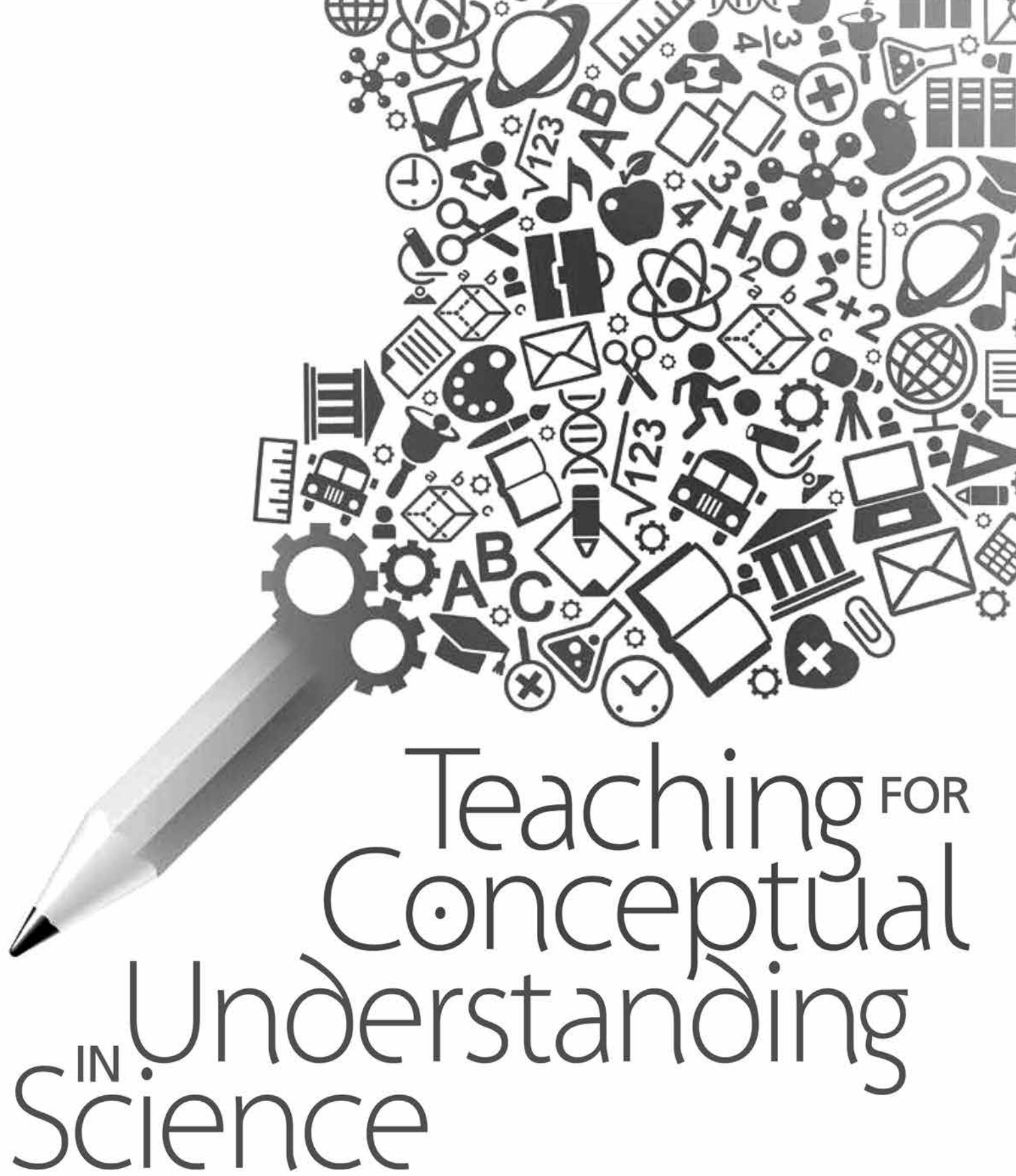


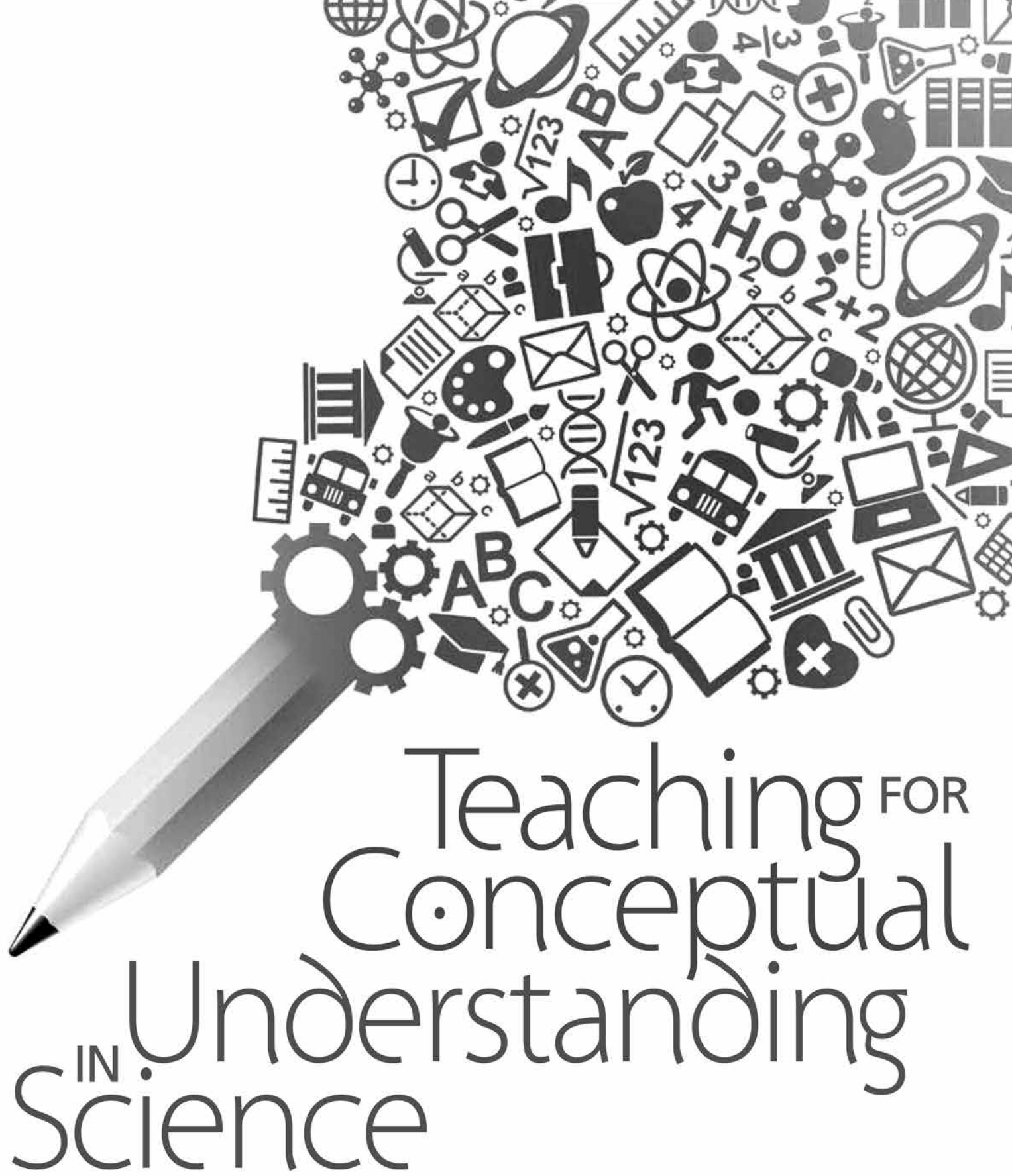
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# Teaching<sup>FOR</sup> Conceptual Understanding <sup>IN</sup> Science





# Teaching<sup>FOR</sup> Conceptual Understanding<sup>IN</sup> Science

by RICHARD KONICEK-MORAN  
and PAGE KEELEY

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National Science Teachers Association  
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# Contents

Preface.....	vii
About the Authors.....	ix
Introduction.....	xiii
Chapter 1 .....	1
Teaching Science for Conceptual Understanding: An Overview	
Chapter 2 .....	25
What Can We Learn About Conceptual Understanding by Examining the History of Science?	
Chapter 3 .....	39
What Is the Nature of Science, and What Does It Mean for Conceptual Understanding?	
Chapter 4 .....	55
How Does the Nature of Children's Thinking Relate to Teaching for Conceptual Understanding?	
Chapter 5 .....	79
What Can We Learn About Teaching for Conceptual Understanding by Examining the History of Science Education?	
Chapter 6 .....	93
How Is Conceptual Understanding Developed Through the Three Dimensions and Learning Strands?	
Chapter 7 .....	139
How Does the Use of Instructional Models Support Teaching for Conceptual Understanding?	
Chapter 8 .....	155
What Are Some Instructional Strategies That Support Conceptual Understanding?	

Chapter 9 .....	191
How Does Linking Assessment, Instruction, and Learning Support Conceptual Understanding?	
Chapter 10 .....	213
What Role Does Informal Education Have in Developing Conceptual Understanding?	
Appendix .....	221
Putting It All Together: “Balancing” Case Study	
References.....	227
Index.....	237



# Preface

## How Did This Book Come to Be?

We have pondered over the topics covered in this book for years, presented workshops together, and talked for hours about how conceptual understanding can be achieved. Page had already acquired her passion for improving conceptual understanding using formative assessment tools. She has written many books as part of the *Uncovering Student Ideas in Science* series (Keeley, 2005–2013) and *Science Formative Assessment* (Keeley 2008, 2014). While at the University of Massachusetts in Amherst, Dick spent years studying and researching children’s alternative conceptions in science, spending months working with Rosalind Driver, John Leach, Phil Scott, and other researchers at Leeds University in Great Britain, and then published his *Everyday Science Mysteries* series that contained, among other things, his collected thoughts about teaching for inquiry and conceptual understanding.

## Our Approach to This Book

Since we realized that our work had so much in common, we decided to try to put our thoughts and ideas gleaned from these experiences, research findings, and practices, into a book that would focus on this important topic. This book is a compilation of combined research findings, practices, and our personal experiences. It is woven into a conversational form of research notes, anecdotes, and vignettes showing how the principles of science might lead to better understandings. Although we have connected our writing to *A Framework for K–12 Science Education* (NRC 2012) and the *Next Generation Science Standards* (NGSS; NGSS Lead States 2013), this book is **not** meant to be a how-to manual for implementing the NGSS or other programs. There are and will continue to be ample numbers of publications written with those goals in mind. This book is, rather, a compendium, focusing on the major goal of science education for the 21st century and beyond—teaching for conceptual understanding. It is designed to be used with any set of national, state, or local science standards.

## Overview of the Book

There are 10 chapters in this book plus an appendix. In Chapter 1 we will address conceptual understanding: what it is and why it is important for teachers. Chapters 2



# Preface

and 3 will focus on the history and nature of science and their importance to anyone teaching for conceptual understanding. Chapter 4 will present the current view of the nature of children's thinking, and Chapter 5 will look back at our attempts at making science teaching more meaningful through the use of the research findings available. Chapter 6 will examine *A Framework for K–12 Science Education's* learning practices of science and engineering (although our focus is primarily science) and their role in teaching science through the learning strands, while Chapter 7 is devoted to describing instructional models. Chapter 8 asks the question, what are some instructional strategies that support conceptual understanding? Chapter 9 will focus on connecting instruction, assessment, and learning. And finally, Chapter 10 will address learning in informal environments. In the Appendix is a case study of a lesson on balancing using the principles and ideas espoused in this book and in *A Framework for K–12 Science Education*. We include reflection questions at the end of each chapter for those readers who would like to extend their reading or thinking through book studies, professional learning groups, or science education courses as well as suggestions for resources available through NSTA that can be used to extend your learning.

## Audience and Uses for the Book

This book is written for practicing teachers, administrators, professional developers, and instructors of teachers, and future teachers themselves. This may seem like an all-inclusive broad audience, and that is intentional. Different parts of this book will appeal to different audiences. While you may read the book cover to cover, you may also choose to focus on specific chapters that best fit your purpose for using this book.

## Acknowledgments

We wish to thank the reviewers of our manuscript draft for their helpful suggestions and the staff of NSTA Press for their assistance and confidence in our ability to generate a book of this nature. To say that we are grateful to the teachers at all levels and the students of all ages who provided input is a gross understatement. This book is possible because of the extraordinary teachers and students we have had the privilege to work with. Of course, we acknowledge the patience and help of our spouses without whom we could not have produced this opus.

# About the Authors

**Dr. Richard (Dick) Konicek-Moran** is a professor emeritus from the University of Massachusetts in Amherst, a former middle school science teacher, and K–12 science district curriculum coordinator, involved in science education for the last 60 years. He is the author of the *Everyday Science Mysteries* series published by NSTA Press, and has been a life member of NSTA since 1968. Dick and his wife Kathleen, an internationally known botanical illustrator, have been volunteers with the Everglades National Park for the past 15 years and more recently for the Fairchild Tropical Botanical Garden in Coral Gables, Florida.

While studying to receive his doctorate at Teachers College, Columbia University in 1967, he authored or coauthored 25 textbooks in elementary and middle school science for the American Book Company. Since that time he has published dozens of articles in journals such as *The Kappan*, *Science and Children*, and others and given talks about his research at meetings of the American Educational Research Association (AERA). Many people have cited Dick's article "Teaching for Conceptual Change: Confronting Children's Experience," cowritten with Bruce Watson and published in the *Phi Delta Kappan* (1990), as seminal to the research and thinking of the movement to teach for conceptual understanding.

At the University of Massachusetts, Dick spent years researching the area of conceptual change while working with local and international school systems to foster improvements in science teaching. He spent just shy of a year in Dar Es Salaam in East Africa consulting with the Ministry of Education of Tanzania to improve science teaching at the college, elementary, and secondary levels. He also has led workshops in Quito, Ecuador, and in Dar Es Salaam, Tanzania, for teachers in the international schools. His invitation to visit the Peoples Republic of China in 1980 was one of the first educational visits to that country following the Cultural Revolution; he traveled, visited schools, and lectured at colleges in China. His time spent as a visiting research fellow at Leeds University in the UK with Rosalind Driver and the researchers at the Children's Learning In Science Group in 1990–1991 was arguably the most growth-inspiring time of his long career.

In 1978, he received the University Distinguished Teaching Award and the Distinguished Teaching Award from the Mortar Board Honors Society and in 2008 received the Presidential Citation from the National Science Teachers Association.

## About the Authors

Dick enjoys music, playing jazz on keyboard, singing, and woodworking. He also enjoys nature and has volunteered at both Fairchild Garden (2 years) and the Everglades National Park (15 years). He is a full-time resident of Bradenton, Florida, in Manatee County.

**Page Keeley** recently “retired” from the Maine Mathematics and Science Alliance (MMSA), where she had been the Senior Science Program Director since 1996. Today she works as an independent consultant, speaker, and author, providing professional development to school districts and organizations in the areas of science, mathematics, STEM diagnostic and formative assessment, and conceptual change instruction. She has been the principal investigator and project director on three major National Science Foundation-funded projects, including the *Northern New England Co-mentoring Network*, *PRISMS: Phenomena and Representations for Instruction of Science in Middle School*, and *Curriculum Topic Study: A Systematic Approach to Utilizing National Standards and Cognitive Research*. In addition, she has designed and directed state Math and Science Partnership (MSP) projects including *Science Content, Conceptual Change, and Collaboration (SC4)* and *TIES K–12: Teachers Integrating Engineering Into Science K–12*, and two National Semi-Conductor Foundation grants, *Linking Science, Inquiry, and Language Literacy (L-SILL)* and *Linking Science, Engineering, and Language Literacy (L-SELL)*. She developed and directed the Maine Governor’s Academy for Science and Mathematics Education Leadership, which completed its fourth cohort group of Maine teacher STEM leaders, and is a replication of the National Academy for Science and Mathematics Education Leadership, of which she is a fellow.

Page is a prolific author of journal articles, book chapters, and 17 national best-selling books, including 10 books in the *Uncovering Student Ideas in Science* series, four books in the *Curriculum Topic Study* series, and three books in the *Science and Mathematics Formative Assessment: 75 Practical Strategies for Linking Assessment, Instruction, and Learning* series. She is a frequent invited speaker at regional and national conferences on the topic of formative assessment in science and teaching for conceptual change.

Prior to joining the Maine Mathematics and Science Alliance in 1996, Page taught middle and high school science for 15 years. She received the Presidential Award for Excellence in Secondary Science Teaching in 1992, the Milken National Distinguished Educator Award in 1993, and the AT&T Maine Governor’s Fellow in 1994. Since leaving the classroom in 1996, her work in leadership and professional development has been nationally recognized. In 2008 she was elected the 63rd President of the National Science Teachers Association (NSTA). In 2009 she received the National Staff Development Council’s (now Learning Forward) Susan Loucks-Horsley Award for Leadership in Science and Mathematics Professional Development. In 2013 she

## About the Authors

received the Outstanding Leadership in Science Education award from the National Science Education Leadership Association (NSELA). Page has led the People to People Citizen Ambassador Program's Science Education Delegations to South Africa (2009), China (2010), India (2012), and Cuba (2014).

Prior to teaching, Page was the research assistant for immunogeneticist Dr. Leonard Shultz at The Jackson Laboratory of Mammalian Genetics in Bar Harbor, Maine. She received her BS in life sciences from the University of New Hampshire and her master's in science education from the University of Maine.



You may note that in various places throughout the book, we will include some personal vignettes from our professional and personal lives that have relevance to the chapter. These will appear in a shaded box. We hope you find these anecdotes enjoyable and informative.

Thanks for coming along on this journey with us.

—Dick and Page



# Introduction

It has been more than four decades since David Ausubel made his famous and oft-quoted statement that the most important single factor in learning is *what the student knows*. He suggested that we find this out and teach the student *accordingly* (Ausubel 1963). And so, we have been trying for over four decades to find out what “accordingly” means. We have certainly made great progress in finding out what students bring to the classroom. Some will agree that it was the film *A Private Universe* (Schneps and Sadler 1987) that began the ACM (Alternative Concept Movement) of the 1980s and 1990s, resulting in a deluge of research about student alternative conceptions in science and mathematics. It also resulted in such books as the *Uncovering Student Ideas in Science* series and other attempts at familiarizing teachers with diagnostic and formative assessment, which helps us to focus on the ideas students bring to our classrooms and make informed instructional decisions. So we are now fairly competent in having the tools for finding out what our students know, but educators have found many different ways to bring about what has been commonly called “conceptual change.”

This is what this book is about. How do we move our students from their present, limited knowledge of certain scientific concepts toward an understanding closer to what scientists now believe and that local, state, and national standards expect? Secondly, what does current research tell us about moving students toward deeper understanding of both science as a process and a set of practices and science as a knowledge base?

As Jean Piaget said in *Genetic Epistemology*, “Knowledge ... is a system of transformations that become progressively adequate” (1968). By this we believe that he meant that knowledge in the broadest social community as well as in the personal realm is built over time and is subject to change until it becomes “adequate,” at least for the time being. We have to realize that new theories are constantly being developed that help us interpret new data that is being collected every moment.

Philosophers have argued about knowledge for centuries and, as philosophers are wont to do, continue to argue about this concept *ad infinitum*. After all, that’s their job. That’s what philosophers do. Epistemology (a form of philosophy) asks three basic questions:

- What is knowledge?
- How do we come to know?
- How do we know what we know?

# Introduction

Sound familiar? We teachers ask these and other questions of our students and ourselves day in and day out. What are we teaching? Are the standards the last word in scientific knowledge? Where did the core ideas in the standards come from? How do we know what our students and we really know? Does it matter to us, as teachers, what students think? Where does the “knowledge” that they bring to our classrooms come from? Are their beliefs useful to us in our attempts to bring them closer to that which science deems the best explanations at this time? Do these ideas have value for future learning? Is it our role to try to change their ideas to match those of the standards to which students and teachers are held accountable? Is it really possible to try to switch their ideas for new ideas?

But we are getting ahead of ourselves. These questions dominate science education today, and we want to discuss them with you and acquaint you with some ideas that might help us to answer them.

Many philosophers and educators believe that we actively develop our own ways of trying to understand the universe in which we live. In other words, humans throughout history and well into the future, develop strategies to interpret the world so that it makes sense. We do not *discover* “truths” about our world; we develop explanations, test them for their ability to help us predict the behavior of the universe, and change them according to their ability to serve us. These ideas change over time, and each time they change, we come closer and closer to ideas that are more “adequate” than the last ones. Scientists in every field of endeavor are in a process of evolving ideas so they become more and more powerful in helping us to understand how our world works. We do this individually and socially. We do it as educators. We do it in science. We do it in economics. We do this in all of the major areas of thought and study. We put new theories out for public scrutiny and ask the societies of scientists, economists, historians, and others to evaluate them and see if they are acceptable and better in explaining our world than the older theories. Over time, if the new theories prove more powerful and useful, they replace the old ideas and thus, the disciplines evolve and knowledge grows.

Do we ever find “truth”? Perhaps the best answer is “yes and no.” At this time, the ideas of an Earth that is a globe has been verified by modern technology that has given us a view from space that prior scientists who believed this were not privileged to have. However, we know that even though humans have walked upon the Moon, the data gathered there are still under scrutiny, and theories about the Moon, its origin, and its relation to the Earth are still being debated among societies of scientists called astronomers and geologists.

We posit that the same process goes on in life and in particular in schools, where children come to us with their own conceptions about what makes the world work. They do not appear before us with blank minds but with minds full of ideas that



they have developed over their growing years that help them to understand, in their own way, what makes the world tick. Up to that point, their ideas were sufficient and allowed them to function, but then in school they are introduced to ideas that may be different from those they held before.

And thus, the problem is generated. These prior concepts are usually sound enough for the children to be comfortable with them; but we know that broader ideas—often those that seem, to the ordinary person, to fly in the face of all they know (what science educators call *counterintuitive*)—are more useful and powerful. Students' ideas are also thoroughly ingrained and persistent. How in children, just as in society in general, do these ideas change and become more useful? Let's look at the research, the history of science, the thinking, and the dreams that are leading us toward a better way to help children learn science and be active participants in science along with us who teach it.



# Chapter 1

## Teaching Science for Conceptual Understanding: An Overview

### What Do We Mean by Teaching for Conceptual Understanding?

A primary goal of science education is teaching for conceptual understanding. But what does this mean in an environment where scores on standardized tests are equated with student achievement in learning science? Do passing scores on standardized tests indicate students deeply understand science? Does filling students' heads with "mile-wide, inch-deep" information so they will be prepared for testing support conceptual understanding? Even when not faced with the pressures of testing, do our instructional routines get in the way of teaching for conceptual understanding? We argue that teaching for conceptual understanding can and should exist alongside the pressures of testing, "covering the curriculum," and instructional routines, if we change our beliefs about teaching and learning. But first we need to examine what conceptual understanding means.

Conceptual understanding is very much like making a cake from scratch without a recipe versus making a cake from a packaged mix. With the packaged mix, one does not have to think about the types and combination of ingredients or the steps involved. You make and bake the cake by following the directions on the box without really understanding what goes into making a cake. However, in making the cake from scratch, one must understand the types of ingredients that go into a cake and cause-and-effect relationships among them. For example, someone who understands baking knows that baking soda and baking powder are essential ingredients, understands the effect each has on the cake, how much to add of each, and when and how they should be added to the mixture in order to ensure batter uniformity. In other words, making the cake from scratch involves conceptual understanding rather than simply following a recipe.

Let's begin with the term *understanding*. One of the impediments to teaching for understanding lies in the way science instruction is sometimes delivered through direct instruction involving the passing on of information from the teacher to the student through techniques such as lecture, which involve little or no student interaction with the content. There is the story of the teacher who, upon seeing that most of the students had failed a test given at the end of a unit, responded, "I taught it, they just didn't learn it." The difference

# Chapter 1

here, of course, is in the distinction between teaching and learning. Teaching does not automatically produce understanding. An important aspect of teaching is communication, yet “teaching as telling,” even when combined with diagrams, computer simulations, and demonstrations, ignores how the student is making sense of the information if instruction is primarily focused on presenting information. A teacher can utter words and sentences, write symbols and equations on the board, use PowerPoint slides, and perform virtual or live demonstrations without effectively communicating ideas or concepts. In 1968, Robert Mager wrote, “If telling were teaching, we’d all be so smart we could hardly stand it” (p. 7).

Reading science textbooks, defining vocabulary, filling out worksheets, and answering low-level questions at the end of the chapter are also forms of passive instruction. These activities often involve pulling information from text with minimal intellectual engagement. The student may be able to reproduce the words or symbols she receives without understanding the meaning behind them or the power of using them to argue or predict and delve deeper into the ideas involved. People who are very good at memorizing facts and definitions often engage in what may be called *literal understanding*. Do you recall students who did well in school because they had eidetic or photographic memories? They could tell you what was on any page in the textbook or reproduce any graph or picture at a moment’s notice exactly as it appeared in the book. Usually, because of the nature of testing, they scored very well. Yet, these students might not have been able to understand basic concepts that provide explanatory evidence for ideas about phenomena.

**Figure 1.1. “Wet Jeans” Probe**

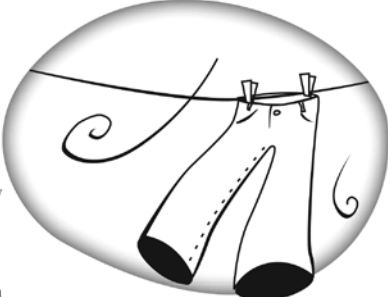
## Wet Jeans

Sam washed his favorite pair of jeans. He hung the wet jeans on a clothesline outside. An hour later the jeans were dry.

Circle the answer that best describes what happened to the water that was in the wet jeans *an hour later*.

- A** It soaked into the ground.
- B** It disappeared and no longer exists.
- C** It is in the air in an invisible form.
- D** It moved up to the clouds.
- E** It chemically changed into a new substance.
- F** It went up to the Sun.
- G** It broke down into atoms of hydrogen and oxygen.

Describe your thinking. Provide an explanation for your answer.



Source: Keeley, Eberle, and Farrin 2005.

Take the concept of *evaporation* as an example. A student who is taught the water cycle may be able to recite word for word the definitions of *evaporation*, *condensation*, and *precipitation*. Furthermore, the student may be able to reproduce in detail a drawing of the water cycle, including a long arrow that points from a body of water to a cloud, labeled *evaporation*. On a standardized test, the student can answer a multiple-choice item correctly by matching the water cycle processes with the correct arrow on a diagram. All of this knowledge retrieved from memory may pass for understanding. However, when presented with an everyday phenomenon, such as the one in Figure 1.1, many students do not understand conceptually that when water evaporates, it goes into

the air around us in a form we cannot see called water vapor (Keeley, Eberle, and Farrin 2005). They rely on their memorization of the term *evaporation* and the details of a water cycle diagram showing long arrows labeled *evaporation* to select distracter D: “It moved up to the clouds.” The student lacks the conceptual understanding of what happens after water evaporates. This student may also have difficulty explaining why there is dew on the grass in the morning or why water forms on the outside of a cold drink on a hot summer day. The student may use the words *evaporation* and *condensation*, yet not understand where the water went or where it came from to explain a familiar phenomenon.

A typical routine in science classrooms is to assign a reading from a textbook or other source and have students answer a set of questions based on the reading. The text becomes the “deliverer” of information. Take for example, the passage, The Chemovation of Marfolamine in Figure 1.2.

Now answer the following questions based on the passage:

1. What is marfolamine?
2. Where was marfolamine discovered?
3. How is marfolamine chemovated?
4. Why is marfolamine important to us?

### Figure 1.2. The Chemovation of Marfolamine


Marfolamine is a gadabolic cupertance essential for our jamination. Marfolamine was discovered in a zackadago. It was chemovated from the zackadago by ligitizing the pogites and then bollyswagging it. Marfolamine will eventually micronate our gladiwonos so that we can homitote our tonsipows more demicly.

Were you able to answer all four of the questions correctly, including the essential question in #4? Then you must know a lot about marfolamine! But do you understand anything about marfolamine? No, all you did was look for word clues in the text and parrot back the information. You did not need to intellectually interact with any of the concepts or ideas in the text. You did not share any of your own thinking about marfolamine. Probably you didn’t need to think at all! While this is an exaggeration of a familiar instructional scenario, it is also typical of what some students do when asked to answer questions based on reading science text, especially text that is heavily laden with scientific terminology.

Lectures and recalling information from text are not the only instructional routines that fail to develop conceptual understanding. Picture the teacher who does a demonstration to show how the Moon’s orbit around the Earth is synchronous with its rotation. The teacher provides the information about the Moon’s orbit and rotation and then demonstrates it in front of the class using a lamp to represent the Sun, a tennis ball to represent Earth, and a Ping-Pong ball to represent the Moon. The students watch as the teacher demonstrates and explains the motion. But what if, instead, the teacher starts by asking students an

**Figure 1.3. “How Long Is a Day on the Moon?” Probe**

## How Long Is a Day on the Moon?



Four students were designing a Moon base for a science project. Planning the Moon base was easy. But deciding what a day-night cycle on the Moon base would be like was hard! All four students had different ideas. Here is what they said:

**Hannah:** “I think the length of the day-night cycle on the Moon is 24 hours.”

**Sachet:** “It depends where the Moon base is. If it is on the dark side of the Moon, there will never be daytime.”

**Ravi:** “I think there would be about two weeks of sunlight and two weeks of darkness.”

**Manuel:** “It depends on the Moon phase. In a crescent Moon, daylight would be much shorter. When there’s a full Moon, daylight would be much longer.”

Which student do you think has the best idea? \_\_\_\_\_ Explain why you agree.

Source: Keeley and Sneider 2012.

interesting question such as the one in Figure 1.3, listens carefully to their ideas, and then plans instruction that involves the students creating and using a model to figure out the best answer to the question? Clearly this example, which gives students an opportunity to think through different ideas and interact with a model used to explain the phenomenon, is more likely to result in conceptual understanding.

Teaching for conceptual understanding is a complex endeavor that science teachers have strived for throughout their careers. David Perkins, a well-known cognitive scientist at Harvard University, has been examining teaching for understanding for decades. He says that while teaching for understanding is not terribly hard, it is not terribly easy, either. He describes teaching for understanding as an intricate classroom choreography that involves six priorities for teachers who wish to teach for conceptual understanding (Perkins 1993):

1. Make learning a long-term, thinking-centered process.
2. Provide for rich, ongoing assessment.
3. Support learning with powerful representations.
4. Pay heed to developmental factors.
5. Induct students into the discipline.
6. Teach for transfer.

These teaching priorities identified two decades ago apply to current science teaching. In addition, recent research on learning in science is helping us understand even more what it means to teach for conceptual understanding in science. We will dive into past and present research and efforts to support teaching for conceptual understanding in science

throughout this book, but first we need to define what we mean by a concept and explore factors that affect how we teach and learn science concepts.

## What Do We Mean by Concept?

The word *concept* has as many different meanings to science educators as the word *inquiry*. In this book, we equate it with a general idea that has been accepted by a given community. A. L. Pines defines a concept as “packages of meaning [that] capture regularities [similarities and differences], patterns or relationships among objects [and] events” (1985, p. 108). Joseph Novak, known for his research on concept mapping, similarly defines a concept as a perceived regularity in events or objects, or records of events or objects, designated by a label. The label for most concepts is a word, but it could be a symbol, such as % (Novak and Cañas 2006).

To give an example, *table* is a concept. Once a person has the concept of *table*, any object that fits a general description or has common attributes can be called a table. It may have three legs, be round or square or rectangular, or sit on the floor as in a Japanese restaurant. It may be made of many substances. But if we have internalized the concept of *table*, we know one when we see it. The same would be true of the concept *dog*. Whether it is a St. Bernard or a Chihuahua, we know a dog when we see one. Before a child is familiar with the superordinate concept of *dog*, she may call any furry four-legged animal a dog. But once she has internalized the characteristics of “doggyness” she recognizes one, regardless of breed.

A concept is an abstraction. Tables did not come into this world labeled as such. In fact, depending on where you live in this world, a table is called by many names, depending on which language you use. However, whatever the language, whatever the name, the concept of *table* remains the same in all cultures. The concepts of table or dog are *constructions* of the human mind. A concept is basically a tool constructed for the purpose of organizing observations and used for the prediction of actions and classification.

In science, we use fundamental building blocks of thought that have depth and call them *concepts*. Words, such as *energy*, *force*, *evaporation*, *respiration*, *heat*, *erosion*, and *acceleration*, are labels for concepts. They are abstractions developed in the minds of people who tried to understand what was happening in their world. Concepts may also consist of more than one word or a short phrase such as *conservation of energy*, *balanced and unbalanced forces*, *food chain*, or *closed system*. Concepts imply meaning behind natural phenomena such as phases of the Moon, transfer of energy, condensation, or cell division. When we use a concept, there is usually some understanding of what is associated with it. For example, *condensation* is the concept. It conjures up an image of water drops formed on an object. The concept becomes an idea when we try to explain or define it. For example, the concept of *condensation* becomes an idea when we associate water vapor in the air reappearing as a



## Chapter 1

liquid when it comes in contact with a cool object. It becomes a definition when we define condensation as the conversion of water in its gaseous form to a liquid. Concepts are the building blocks of ideas and definitions. Another way to distinguish concepts from other ways to express one's thinking is to imagine that a teacher asks a student what is in her backpack. The student replies, "my school books, some supplies, and snacks." These are concepts that imply meaning of the kinds of things the student has in her backpack rather than saying, "my biology textbook, my social studies book, my math book, two notebooks, pencils, pens, assignment pad, a granola bar, a bag of chips, and an apple." Behind all concepts in science are data, a history of observation and testing, and a general agreement of scientists within any given domain.

When students have an *understanding* of a concept, they can (a) think with it, (b) use it in areas other than that in which they learned it, (c) state it in their own words, (d) find a metaphor or an analogy for it, or (e) build a mental or physical model of it. In other words, the students have made the concept their own. This is what we call *conceptual understanding*.

### Learning to Speak and Understand a New Language

Words and symbols are important. Language is the way of communicating science concepts, but the language of science is not always the language of everyday life. Language can affect how we think about concepts in science. Often, a word or symbol has a special meaning to a scientist, different from the way a nonscientist may use the word. A scientist knows what is meant when someone says, "Close the door—you're letting the cold in," even though she or he understands that in thermodynamics, that there is no such thing as "cold" and that heat always moves from warmer to colder areas. The scientist has conceptual understanding that overrides the incorrect terminology. The same is true of "sunrise" or "sunset" which is really the *illusion* of the apparent motion of the Sun in the sky. Someone with a conceptual understanding of the phenomena understands that it is the Earth's rotation that is responsible for this visual effect. Some concepts used in the science classroom are counterintuitive to students' ideas. For example, the definition in physics of *acceleration* can mean slowing down as well as speeding up (or changing direction). This does not make sense to students based on their everyday encounters with the word *acceleration*, which to them means going faster. After all, don't you make the car go faster by pushing down on the "accelerator"?

Many of us live or work in areas with increasingly diverse populations. For example, the authors of this book both live in Florida for part of the year. This often means that people who speak a language different from our first preference surround us. If the trend continues, a majority of the residents that make up our neighborhoods may speak Spanish. To communicate effectively, we may need to learn Spanish and to become bilingual. It takes perseverance and a desire to think in a new language, rather than merely translate word for word. Instead we must learn dialog, cadence, colloquialisms, a new vocabulary,

and most importantly, culture. Phrases cannot be taken literally when translated from one language to another. For example, someone might say “So long” meaning “goodbye,” which makes no sense, if you think about it literally. Speaking science is very much the same but can pose even more problems.

Speaking science has an added difficulty for students. One problem is that in colloquial language a scientific word may have a different meaning altogether, which affects our understanding of the concept underlying the word. For example, you might hear someone say, “Oh, that’s just a theory,” meaning that it is just a guess or unproven idea, when in science *theory* means a well-supported explanation of phenomena, widely accepted by the scientific community. People who recognize both the scientific concept of a theory and the way the word is used in our everyday language can accommodate the two meanings, but this is not the case with students new to the language of science. As science teachers, we need to be aware of the differences in meanings between our students’ daily use of certain words and the scientific meaning of these same words. Another problem is that the language of science is tied directly into the practices and rules of science and therefore is tied to experience within the discipline. Students need to experience the practices of science in order to understand conceptually the language that is used.

Many teachers use the technique of “word walls.” This technique is often used in classrooms with English as a Second Language (ESL) students, but it is an effective way to introduce vocabulary in context to all students—and if arranged in an interactive way, it is also a way to organize concepts into instructional plans so science is not treated as vocabulary but rather vocabulary is introduced for the purpose of communicating scientific ideas.

Traditional word walls have objects or pictures of objects and their names posted on the wall to help students become familiar with new words that represent a concept. The interactive word wall is an organic, growing wall that is planned by the teacher but developed with the help of the students. The class adds ideas and objects to the wall with the help of the teacher, and as the unit grows toward completion, the wall grows to include the newest concepts and the objects and ideas that go with it. The word wall is used to develop understanding, as students organize words for deeper conceptual meaning. Conceptual teaching strategies such as word walls will be explored further in Chapter 8.

Although vocabulary is important for science learners, we must remember that words are not science. Zoologists do not study words but use words to communicate their study of animals with others who share the same vocabulary. Vocabulary needs to be introduced to students in the midst of their engagement with objects. Since we advocate hands-on, minds-on science activities, the time to introduce vocabulary is either during the activity or during the discussion afterward. For example, when learning about the motion of pendulums, the word *amplitude* would be introduced while the students are investigating

# Chapter 1

whether the pendulum's motion is changed when the pendulum is allowed to travel through a smaller or larger arc.

Science as a discipline has words and symbols that have specific meanings. Think of scientific fields that deal with symbolic structures like genome sequencing. Math, too, uses symbols to express ideas and concepts. Understanding the nature of science presents challenges in the way we use language and symbols. Let's take a look at some of the most important words and phrases that often have a popular *double entendre* when used to describe the nature of science. Please note that the descriptions provided below are a simplified view of the nature of science. Philosophers and linguists might argue about each of these points, but for the purpose of helping you, the teacher, understand the language of the nature of science in the context of K–12 education, we hope these points and descriptions will suffice.

## Theory

As we mentioned above, in everyday speak, this word may mean a hunch, an opinion, or a guess. In science, it means an idea that has been tested over time, found to be consistent with data, and is an exemplar of stability and usefulness in making predictions. A theory explains why phenomena happen. You may hear people say, "I have a theory that the Chicago Cubs will win the World Series next year." This is usually based on a belief system grounded in a preference steeped in loyalty (and sometimes fruitless hope). Unfortunately for Cubs fans, there are few data that will support this "theory." You may also hear someone dismiss the theory of biological evolution as "just a theory." You can be assured that this person has a lack of conceptual understanding about how a theory in science is tested, rooted in evidence, and thus held in the utmost respect by the scientific community as being accurate and useful. We see evidence of biological evolution happening every day. Bacteria evolve into drug-resistant strains and animals and plants adapt to changing environmental conditions over time. The theory of natural selection attempts to explain how this happens, and it does this quite successfully. Figure 1.4 is an example of a formative assessment probe used to elicit students' (and teachers') conceptual understanding of a scientific theory. The best answers are *A*, *D*, *G*, and *I*. The distracters (incorrect answer choices) reveal common misunderstandings people have about the word *theory* as it applies to science.

## Hypothesis

A hypothesis in science is often an "if ... then" statement in response to a scientific question that provides a tentative explanation that leads an investigation and can be used to provide more information to either strengthen a theory or develop a new one. A hypothesis is a strongly developed prediction, based on prior observation or scientific knowledge that if something is done, an expected result will occur. It is constructed with a great deal of planning and a reliance on past evidence. Some educators use the term *educated guess* to describe

a hypothesis. This is another example of the misuse of language. There is no guesswork involved in developing hypotheses and using language in that way incorrectly portrays the concept of a hypothesis.

In science, a hypothesis is never a “sure thing” and scientists do not “prove” hypotheses. Students who complete an investigation and claim that their results prove their hypothesis should be encouraged to say their results support their hypothesis. Scientists learn from hypotheses that are shown to be wrong as well as those that provide expected results. Science teachers are often guilty of asking children to hypothesize something that cannot be more than just a wild guess or unsubstantiated prediction. Students should learn that a hypothesis should be acceptable only if there is preliminary evidence through prior observation or background knowledge to back up the hypothesis.

**Figure 1.4. “Is It a Theory?” Probe**

## Is It a Theory?

Put an X next to the statements you think best apply to scientific theories.

☐ **A** Theories include observations.

☐ **B** Theories are “hunches” scientists have.

☐ **C** Theories can include personal beliefs or opinions.

☐ **D** Theories have been tested many times.

☐ **E** Theories are incomplete, temporary ideas.

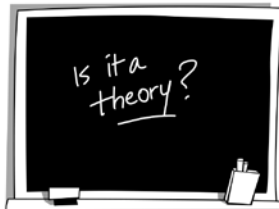
☐ **F** A theory never changes.

☐ **G** Theories are inferred explanations, strongly supported by evidence.

☐ **H** A scientific law has been proven and a theory has not.

☐ **I** Theories are used to make predictions.

☐ **J** Laws are more important to science than theories.



Examine the statements you checked off. Describe what a theory in science means to you.

Source: Keeley, Eberle, and Dorsey 2008.

## Author Vignette

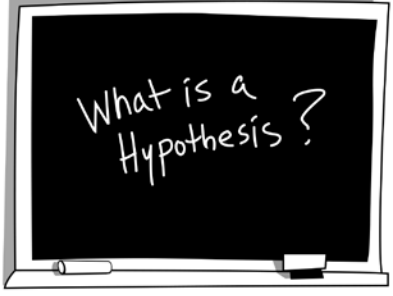
I recently worked with a group of middle school teachers, using the formative assessment probe “What Is a Hypothesis?” to uncover their ideas about the word *hypothesis* (Keeley, Eberle, and Dorsey 2008). Using the card sort technique, the answer choices were printed on a set of cards and teachers sorted them into statements that describe a scientific hypothesis and statements that do not describe a scientific hypothesis.

**What Is a Hypothesis?**

Hypotheses are used widely in science. Put an X next to the statements that describe a hypothesis.

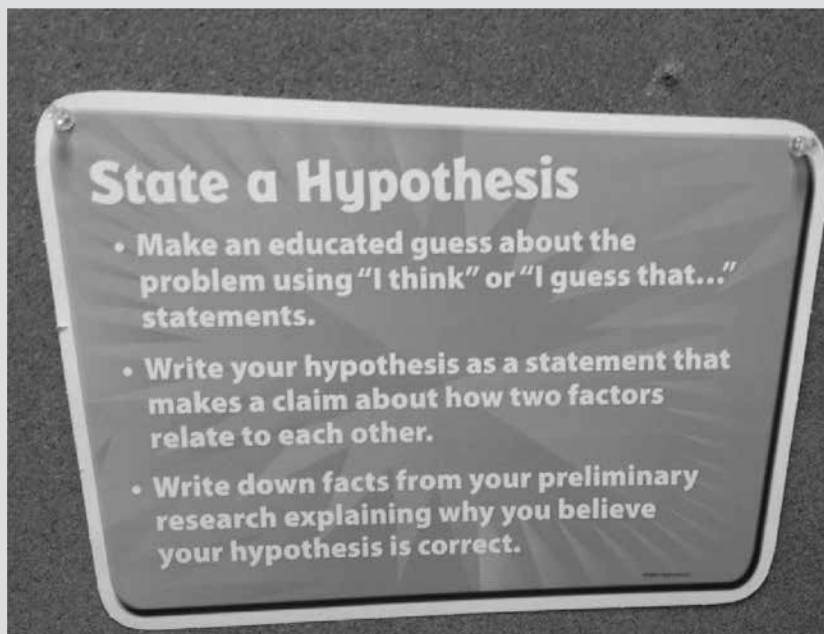
- ☐ **A** A tentative explanation
- ☐ **B** A statement that can be tested
- ☐ **C** An educated guess
- ☐ **D** An investigative question
- ☐ **E** A prediction about the outcome of an investigation
- ☐ **F** A question asked at the beginning of an investigation
- ☐ **G** A statement that may lead to a prediction
- ☐ **H** Included as a part of all scientific investigations
- ☐ **I** Used to prove whether something is true
- ☐ **J** Eventually becomes a theory, then a law
- ☐ **K** May guide an investigation
- ☐ **L** Used to decide what data to pay attention to and seek
- ☐ **M** Developed from imagination and creativity
- ☐ **N** Must be in the form of “if...then...”

Describe what a hypothesis is in science. Include your own definition of the word *hypothesis* and explain how you learned what it is.



The best answer choices are *A*, *B*, *G*, *K*, *L*, and *M*. Almost all of the teachers selected *C* and *I* as statements that describe a scientific hypothesis. As we debriefed and discussed, the teachers were adamant that *C* and *I* accurately described a scientific hypothesis. One teacher even took the group over to her classroom to point out *The Scientific Method*

bulletin board she had in her classroom made up of purchased placards that depicted stages of the scientific method, including the one shown below that implies a hypothesis is an educated guess:



Furthermore, I noticed another placard titled, "Analyze/Make a Conclusion," in which the last bulleted suggestion was, "If the results prove your hypothesis to be correct, perform the experiment again to see if you get the same results." No wonder some teachers hold these misunderstandings! We discussed the need to be aware of these misrepresentations of the nature of science when purchasing and displaying materials such as these that further perpetuate students' misuse of words such as *prove* (a better choice is *support*) or *educated guess* when referring to hypotheses.

—Page Keeley

# Chapter 1

## **Data**

*Data* is the plural form of *datum*. Data are a collection of observations or measurements taken from the natural world by means of experiments or the observation of information that shows a consistent pattern. One of the most consistent errors (even in the public media) is to fail to differentiate between the singular and the plural forms of this word. Data *are* and a datum *is*. Data do not come with an inherent structure. According to *Ready, Set, SCIENCE!* structure must be imposed on data. By this the authors mean that data can be processed in many ways but they must be organized and reorganized to answer questions. Using data correctly is one of the most important lessons students can learn in science (NRC 2007).

## **Evidence**

This term is used to describe a body of data or a base that shows consistent correlations or patterns that become the basis for a *scientific claim*. Observations and experience lead to claims. A *claim* in our everyday language can be an opinion or belief. *Scientific claims* are always based on scientific evidence and educators should make this clear to students who are making claims. In other words, a reasonable response to a child who makes a claim would be, “What is the scientific evidence that supports your claim?”

For example, I notice in the morning that my car is covered in water droplets. I could make a claim that it has rained, but it really is not a scientific claim until I have searched for other evidence. Has anyone watered the area with a hose overnight? Has relative humidity had anything to do with the water droplets? Is there water on anything else but the car? Could the water come from dew? I must take into consideration many more factors before I can make a scientific claim. Whenever a student makes a claim in a classroom, the teacher must ask for evidence supporting it. After time, claims made will become more carefully considered, and claims backed by scientific evidence will become common practice.

## **Experiment**

There is a tendency for people to refer to any activity involving science that occurs in a classroom as an experiment. This is an overgeneralization. All experiments are investigations, but not all investigations are experiments. Experimentation is a process in which variables are identified and conditions are carefully controlled in order to test hypotheses. Think of all of the things that must be done before an experiment can be designed and carried out: Students first develop a true hypothesis that is based on sufficient evidence and claims. The experimental hypothesis will most likely have an “if ... then” statement and will be set up with all available variables controlled so that the data collected can lead to a definitive answer. For example: “If I change the length of the pendulum *then* the period of the pendulum will change.” To test this idea, one must keep the mass and shape of the bob the same, and use the same angle of release. The only thing changed is the length of the string.



Featured one morning on the Weather Channel was a physical model made at the Massachusetts Institute of Technology (MIT) that showed how the air currents of different temperatures were affected by the rotation of the Earth. Unfortunately, in their exuberance about how the model explained what they were showing on their maps, the hosts of the show called the demonstration an *experiment*. Here we are again being treated to the kind of everyday—but for our purposes—sloppy language usage that permeates our society and helps to confuse the meaning of science concepts. One of our prime targets in correcting the language of science should probably be the national media.

## Learning the Language of Science Education

Even the terminology we use as science educators to describe conceptual understanding may be unfamiliar language to some teachers. The following are a few of the important words used to describe conceptual teaching and learning that we will use throughout this book:

### **Alternative Conceptions**

Basically, *alternative conceptions* are mental models conceived by individuals to try to explain natural phenomena: “The Moon phases are caused by shadows.” “Density is caused by how tightly packed the molecules in matter are.” “When water appears on the outside of a glass in warm, humid weather, the glass is leaking.” “Cold creeps into a house if there are leaks in the structure.” “Metal objects are always cooler than wooden objects, even when they are in the same room for a long time.” These are all examples of alternative conceptions or, as some would call them, *misconceptions*. They are incomplete theories that people have developed to try to understand their world. By “incomplete,” we mean that they are not fully thought out and have limited use. Misstating the number of chromosomes in the human cell (which happened in textbooks in the 1950s) is not an alternative conception; it is merely misinformation. For a statement to be an alternative conception, it must be a theory that is used to explain a phenomenon, and is usually self-discovered by a person trying to explain that phenomenon.

Example: A person who has heard the term *population density* will probably first apply the idea of tightly packed individuals to scientific ideas of density. If she does not realize that atoms have different masses and that packing does not cause the difference in mass in objects of the same size, she will have a completely erroneous conception of molecular mass and density. Holding on to this alternative conception will make it very difficult to think of *density* in the accepted scientific paradigm. Children (and adults) are perfectly capable of holding on to several theories at the same time without seeing them as contradictory. As science teachers, we have an obligation to try to see the world through a child’s eyes, to listen to their conceptions and use them to introduce the child to other ways of viewing the world.

## **Conceptual Change**

Throughout history, ideas have been debated, and every so often old ideas are either put aside or modified in order to match current observations, data, or the need to explain phenomena in a more useful and simpler way. As we will discover in Chapter 2, sometimes change has happened smoothly and other times, a revolution in thinking has occurred (Kuhn 1996). In many cases, the older ideas do not “go quietly into this good night” (apologies to poet Dylan Thomas!). Those of us who have used a theory or concept with success are loathe to giving it up to a new idea unless we are convinced that the newer idea is better in every way and explains phenomena more cogently. Einstein’s theories of special and general relativity took years to be a dominant paradigm in physics.

In order to participate in conceptual change, we must be convinced that another explanation that uses the concept is more useful. The same is true of children who enter our classrooms with concepts they have used, possibly for years, with great success. Why would they want to change them unless they were seen to be no longer useful? Children’s naive conceptions are built individually but are strongly affected by social and cultural conditions. They are not fully developed, but they work for the children and form a coherent framework for explaining the world.

For example, imagine a middle school child observing the Moon’s phases changing each night. She cannot ignore the phenomenon, and therefore forms her own theory to explain it. The child has had previous experiences interacting with objects through play and other activities where she observes when an object blocks light from the Sun, a dark shadow is cast on the ground by the object. Part of the area around the object is in light, part is in shadow. The child uses this experience to develop a personal theory for the phases of the Moon by explaining that the Earth blocks part of the sunlight shining on the Moon and casts a shadow on that part of it.

Shapiro says it best in her book *What Children Bring to Light*. “When we teach science, we are asking learners to accept something more than scientifically verified ideas. We are asking them to accept initiation into a particular way of seeing and explaining the world and to step around their own meanings and personal understandings of phenomena into a world of publicly accepted ideas” (1994, xiii).

This is not always easy, as we know from experience. We will discuss this aspect of teaching further in subsequent chapters.

## **Paradigm**

In Thomas Kuhn’s landmark book, *The Structure of Scientific Revolutions*, he says “[Paradigms are] examples of actual scientific practice—examples of which include law, theory, application and instrumentation together—provide models from which spring particular coherent traditions of scientific research” (1996, p. 10). Some examples of

paradigms in science are: Ptolemaic astronomy, Copernican astronomy, and Newtonian corpuscular optics.

If you are a scientist, your research is influenced by and committed to a particular paradigm, and you follow certain rules and practices in your research dictated by that paradigm. For example, a dominant paradigm of Western science in the middle ages was that Earth was the center of the universe and that celestial bodies such as the Sun moved around the Earth. Can you imagine being a disciple of the new Copernican paradigm in, say, the 1540s that stated that the *Sun*, not the Earth, was the center of the universe, and deciding to do research in this “heretical” idea? Its influence would have probably made you work in secret for fear that the Roman Catholic Church of that time would excommunicate you or worse. Today, Copernicus’s heliocentric theory is regarded by the Roman Catholic Church and scholars as one of the great revolutions in science.

Kuhn goes on to theorize that the history of science is rife with what he termed “paradigm shifts,” during which time new paradigms influenced groups of converts and changed the whole nature of scientific thought (1996). In the same way, it may take a “revolution” in thinking to shift the paradigm that forms the basis for a person’s alternative conception. (Carey 2009). We’ll examine paradigms in depth in Chapter 2.

### Author Vignette

I remember when I was in graduate school, one of the required readings in our seminar class was Kuhn’s *The Structure of Scientific Revolutions*. I initially found it to be rather wordy and challenging. I had to read a chapter several times, through sheer drudgery, in order to understand it. My first reaction was negative—why read such a dense, philosophical book if not to help me fall asleep with ease? Why can’t we read something more modern and applicable to science teaching? How is this going to help me be a better science educator? After a couple chapters—and the first discussion we had in class, artfully facilitated by our professor—I became enthralled and enamored by this book. The term *paradigm*, which I had encountered in the popular lexicon, had new meaning for me, as did *revolution* and the term *normal science*. I was particularly interested in how Kuhn described the process of how one paradigm can replace another. Through our seminar discussions, my view

of the nature of science was reshaped—I experienced my own paradigm shift as my assumptions about the scientific enterprise and words I used to describe it were challenged! Three years ago, I had to smile when my son gave me a copy of the book at Christmas. He had read it in one of his graduate courses and thought I would enjoy it (little did he know that I had to read it in one of my courses decades before). Today, this book sits on my shelf as one of the most important contributions to understanding the history and nature of science. As a science educator, I frequently see Kuhn’s landmark book cited in the education literature on the nature of science. Perhaps it is one of the best and most authentic descriptions (albeit wordy and dense) of the nature of science that every science educator should read.

—Page Keeley

## ***Crosscutting Concepts***

One of the major concerns in learning any subject is that of organizing our thinking around major topics for easier retrieval and transfer of learning to the many related areas of a domain of knowledge. One of the secrets to internalizing knowledge is seeing its relationship to a larger, more encompassing set of ideas. Relationships among ideas give them credibility and help us all to group big ideas into larger, more comprehensive groups. If we can see that periodic motion can be used with the pattern of the planets and moons in our solar system and the motion of a pendulum or a reproductive cycle, we can see how they fit together. After all, science is all about finding patterns and using those patterns to explain the behavior of our natural world. *A Framework for Science Education* (NRC 2012) and the *Next Generation Science Standards* (NGSS Lead States 2013) identify the *crosscutting concepts* all students should master by the time they finish grade 12:

- Patterns
- Cause and effect: Mechanism and explanation
- Scale, proportion, and quantity
- Systems and system models
- Energy and matter: Flows, cycles, and conservation
- Structure and function
- Stability and change

If our students were to be familiar with these crosscutting concepts and be able to organize their learning in these groupings, transfer of knowledge and retrieval of information would become much more efficient.

### **Models**

The authors of *Ready, Set, SCIENCE!* define *models* as things that make our thinking visible (Michaels, Shouse, and Schweingruber 2008). When some people hear the word *model*, they think of a physical representation that is built to look like the real thing. But models are more than just physical replicas. For example, mental models are those we hold in our minds to try to explain the phenomena we see daily. They are personal models. For example, some young students have a mental model of the Earth, which allows them to understand why they seem to be on level ground although they may believe that the Earth is a sphere. Their model either has them in the center of the globe on a flat surface or standing on a flat part of the Earth within the round Earth. Early scientists like Ptolemy had a mental model that eventually became a conceptual model for his peers that specified Earth was the center of the planetary system. This conceptual model remained for many years because it corresponded to their observations that the Sun appeared to move across the sky and was consistent with the views of the Roman Catholic Church at that time. It took centuries before scientists such as Copernicus and Galileo had the courage to oppose the dominant model of that time and create their own mental models that showed that the Sun was the center of the planetary system.

Models can be mathematical, physical, conceptual, or computer generated. Models are often developed to try to approximate the real thing in a form that can be manipulated and studied in cases when a real situation cannot. Models also help students clarify and explain their ideas. The common classroom activity that involves building a replica of a cell out of food items or representing parts of an atom using cereal contributes to students' understanding of models as replicas made out of "stuff." While these may be representations that are not much different from 2-dimensional drawings, students seldom use them to explain their ideas or manipulate them to make predictions. In essence, they often fall more in the realm of arts-and-crafts projects than scientific models. Having a conceptual understanding of what a model is and is not is just as important as developing and using models in science.

We hope that looking at these examples of words we use to describe science and the understanding of science will be helpful to you as you think about designing instruction for conceptual understanding. We must realize that we are asking students to "step around" their own mental models and accept those ideas that are now considered the publicly accepted ideas (Shapiro 1994). They must also be aware that there may be "revolutions" in thinking and that paradigm shifts may occur in science during their lifetimes. This does not make science look weak, but helps us to see that scientific knowledge evolves. It is the nature of the discipline and its strongest attribute. Scientific knowledge is not dogma but a continuously changing set of ideas that are undergoing never-ending scrutiny by the

# Chapter 1

members of the society we call scientists. We will explore this in more depth when we look at the nature of science in Chapter 3.

## From Words to Listening for Conceptual Understanding

One of the most important watchwords for teaching for conceptual understanding will be *listening*. A student's alternative conceptions are very important, and teachers need to be able to understand what the student is thinking. Alternative conceptions, no matter how naive or seemingly incorrect, are the foundations for building new and more complete conceptions. They provide us with a place to start teaching and with the information necessary to plan next steps.

Because of this, one of the most important best practices that has come to the forefront is *diagnostic and formative assessment* for the purpose of understanding student thinking and making decisions based on where students are conceptually in their understanding. One of the authors of this book (Page Keeley) specializes in science diagnostic and formative assessment. As a nation, we have been so extremely invested in summative testing since the advent of No Child Left Behind (NCLB) that some educators have often referred to it as No Child Left Untested. We agree that it is necessary and important to test for achievement and accountability, but it is evident that unless teachers know where their children are in their current conceptual development, they cannot plan for helping their students make changes in thinking as they design and facilitate instruction. This requires listening and responding to children when they think out loud. In order for us to hear them out loud, we have to give them a chance to tell us about their thinking and explain their ideas. We will address the topic of diagnostic and formative assessment and "science talk" in more detail when we get to Chapters 8 and 9 in this book.

One important researcher who addresses the issue of listening to children is Bonnie Shapiro from the University of Calgary. In her book *What Children Bring to Light*, she examines a fifth-grade classroom and the real responses of children to a vigorously taught series of lessons about how we see. In her research, she found that in her sample of six children, all but one did not believe what the teacher said, even though they successfully passed the unit by filling out their worksheets and completing their tests. The teacher never knew it because he didn't listen or probe the children's thinking. We'll examine Shapiro's research more fully in Chapter 4.

Often, when children and adults talk to each other, there is a problem of *incommensurability*. This term means, simply, that two people in a conversation are not speaking the same "language." Thomas Kuhn referred to this problem when he described a similar problem in the history of science (1996). Not only are teacher and student using different language, but also they are operating in different paradigms or rules about how the world

is seen and studied. The students notice different things and focus on different questions than do adults. The teacher must be the one to try to overcome this incommensurability.

Two philosophers, Paul Thagard and Jing Zhu (2003), point out that there can be different emotional valences (i.e., weights or connotations) to incommensurability in conceptual understanding. They state that the concepts *baby* and *ice cream* have positive valences for most people, while the concepts *death* and *disease* have negative valences. People in the media, who are adept at “spin”—using language that makes their clients appear as positive as possible—have long been aware of this. Thagard and Zhu note that in order for conceptual change to occur, especially in emotionally charged areas of thought, each of the communicants would have to change their valence on the issues from negative to positive. They give as an example a Darwinian evolutionist and a creationist trying to reach a common ground. In order for each to achieve commensurability, each would have to change their emotional valence, and this may be very difficult, even impossible (look at our own ideologically charged political system). But it is important for teachers to be sensitive to the emotional impacts that the curriculum might be presenting to the children and be aware of the language they can use to change emotionally-based concepts to more evidence-based concepts.

Teachers often feel committed to changing a “wrong” idea as quickly as possible by whatever means they have at their disposal. Instead, since you are cast in the role of teacher-researchers we suggest that this is the time to listen as carefully as possible and to question the student(s) to find out as much as possible about where the ideas originated and how deeply the student(s) are committed to the idea to explain certain phenomena. Make them see how interested you are in how they think, and you will encourage them to consider their own thinking, and engage in what is known as *metacognition* (thinking about their thinking). The conversation does not have to be one-on-one. Instead, we suggest that students talk to each other and the teacher out loud, bringing students’ thoughts to the front so all students can hear. Teachers have found that when they concentrate on the conceptual history of the group, the groups itself remains interested, even when the conversations may involve only a few members.

### Intentional Conceptual Change and a Community of Learners

This leads us to consider the recent pedagogical theory on *intentional conceptual change*. If we believe that both scientists and science learners gain knowledge in a community and that that knowledge is defined as a community consensus, it leads toward a belief that the teacher and the students are most effective when there is an intent to learn or change on the part of the learner and the community of students are goal-oriented toward understanding a new idea. When there is peer support and encouragement for learning, there is an atmosphere more conducive to conceptual change and understanding (Sinatra and Pintrich 2003). This may certainly lead us to building a community of learners as recommended by Bransford, Brown, and Cocking (2000). Hennessey suggests that metacognition (thinking



# Chapter 1

about one's own thinking) is a primary ingredient in the working of a community of learners, stating that students have to be aware of how they came to their own knowledge claims before they can discuss them with others (2003). These knowledge claims raise the question of how to create the community of learners (including the teacher as learner) and conduct a class where the community is motivated toward solving a common question or problem. However, as Vasniadou points out, making an assumption that students will intentionally create strategies for developing intentional learning might be rather optimistic (2003).

We all know students can develop strategies for completing simple school-type tasks. It takes more effort to create the kind of atmosphere and curriculum that “grabs” the students and entices them into wanting to develop an inclusive community, intent on solving a common problem. One of the authors of this book (Dick Konicek-Moran) has published a series through NSTA Press called *Everyday Science Mysteries*. These mystery stories describe a common problem that can be used to motivate and capture the interest of all students in the class. The series provides open-ended stories that require metacognition and inquiry to find the best solution to the problem.

The following personal author vignette describes how a community of learners helped each other solve a common problem:

## Author Vignette

I once worked in a fifth-grade classroom in New England where the students had shown a great deal of interest in the apparent daily motion of the Sun. This came about through the reading of the story, “Where are the Acorns?” This story is about a squirrel that buries acorns using the Sun's effect on tree shadows during the Fall to predict where the acorns will be during the winter season (Konicek-Moran 2008).

Since the shadows change in the story, the students organized their own curriculum to find out as much as they could about the apparent movement of the Sun on a daily basis as well as seasonally. They predicted that the Sun would cast no shadow at midday (a common naive conception). They had already decided, through experimentation and discussion that midday was not necessarily noon but could be defined as a point halfway between sunrise and sunset. The children needed to find

the midday point for a given day. They chose to use the tables in *The Old Farmer's Almanac*. Mathematically, this is not as easy a task as it might appear. We found that there were at least five different methods invented by the class of 30 students.

The students shared their methods with each other and found that they had all come to the same answer, although their methods were very different. Some students spent a great deal of time and many calculations while others took very little time. Those who found their answer very quickly typically used a 24-hour clock method while the others struggled with trying to work with a 12-hour clock. A very thoughtful discussion arose, as each student tried to defend his or her method to the others. Some had never thought of time in a 24-hour paradigm before and resisted the acceptance of the 24-hour model. The argument and discourse went on for some time, but finally the class came to a consensus about a method that was the most expedient and efficient. The beauty of the experience to the teacher and me was how the students' interest reached a level of discussion that left us almost completely out of the picture. They were thinking about each other's ideas and their own and comparing the efficacy of the methods used. In other words they were thinking about their thinking, comparing, making decisions, and deepening their understanding of the concept of *time* as it related to a problem they wanted to solve. I hasten to say that it works with adults too.

—Dick Konicek-Moran

# Chapter 1

As we all know, the ways in which schools sometimes operate make the time-consuming option described in the vignette above difficult to implement. Lisa Schneier sums the problem up succinctly in the following quotation:

*The fact remains that schools are structured to bring students to fixed points of knowledge in a certain length of time. Teachers and students are accountable to elaborate structures of assessments that are wielding more and more power. These assessments carry with them assumptions about learning and knowledge that exert a constant narrowing force on the work of schools. Often the decision as it confronts teachers is whether to short-circuit substantive work that is happening in their classrooms in order to prepare students for these tests. How to balance these forces against the deeper knowledge that we want for students is a continuing question for me. (quoted in Duckworth 2001, p. 194)*

We have faith that since we are now poised on the cusp of a new era in teaching for conceptual understanding with the release and implementation of the *Next Generation Science Standards*, teachers can focus on fewer topics each year and teach for deeper understanding. With different means to assess student learning and the application of that learning, including continuous formative assessment, we can build a bridge from learner's initial theories about the way the natural world works and how science is practiced to where they need to be to understand scientific concepts and practices.

And now, in Chapter 2, we move to the history of science, to see how we may learn from the past so we can move forward in the present to prepare our students for a future that depends on a conceptual understanding of science and scientific practices.

## Questions for Personal Reflection or Group Discussion

1. Examine your own teaching practice. What percentage of an entire school year do you think you actually teach for conceptual understanding in science versus "covering the curriculum?" What initial change(s) could you make to shift that percentage more toward conceptual understanding?
2. The term *habits of practice* describes teaching practices that have become so routine that we don't bother to question them. Can you think of a habit of practice that interferes with teaching for conceptual understanding? What can you or others do to change that habit of practice?
3. Dick Konicek-Moran's NSTA Press series *Everyday Science Mysteries* and Page Keeley's *Uncovering Student Ideas* series are popular resources for uncovering what students (and teachers) really think related to scientific concepts. Think of a story or probe you may have used from one of their books that uncovered a lack of conceptual understanding. What surprised you about your students' (or

teachers') ideas? How did this chapter help you better understand why some students or teachers harbor ideas that are not consistent with scientific knowledge or ways of thinking?

4. Keep track of everyday or "sloppy use" of science terms for a designated time period as you find them in the media, in conversations with others, or even in your curriculum. Make a list and consider what could be done to change the way these terms are used in the public and school vernacular.
5. List some examples of concepts that you once may have thought you understood but later found you lacked clarity and depth of understanding.
6. Look at the list of crosscutting concepts on page 16. Review these concepts by reading pages 83–101 in *A Framework for K–12 Science Education* (NRC 2012) or online at [www.nap.edu/openbook.php?record\\_id=13165&page=83](http://www.nap.edu/openbook.php?record_id=13165&page=83). Identify examples of ways these concepts can be included in the curricular units you teach.
7. Change is more effective when learners experience it together, whether it is students learning a concept or teachers learning about teaching. How would you go about setting up a climate for intentional conceptual change within a community of learners at your school or organization?
8. React to Lisa Schneier's comments on page 22 regarding balancing time against deeper knowledge. How do you think the *Next Generation Science Standards* or your own set of state standards will fare against this issue of time for teaching versus depth of understanding?
9. Choose one "golden line" from this chapter (a sentence that really speaks to or resonates with you). Write this on a sentence strip and share it with others. Describe why you chose it.
10. What was the biggest "takeaway" from this chapter for you? What will you do or think about differently as a result?

### Extending Your Learning With NSTA Resources

1. Read and discuss this article, which shows how elementary children connect newly learned material to their existing knowledge: Kang, N., and C. Howren. 2004. Teaching for conceptual understanding. *Science and Children* 41 (9): 29–32.
2. Read and discuss this article, which explains how to create and use an interactive word wall: Jackson, J., and P. Narvaez. 2013. Interactive word walls. *Science and Children* 51 (1): 42–49.
3. Read and discuss this article, which describes how thought and language are intricately related: Varelas, M., C. Pappas, A. Barry, and A. O'Neill. 2001. Examining

## Chapter 1

language to capture scientific understandings: The case of the water cycle. *Science and Children* 38 (7): 26–29.

4. Read and discuss this article, which describes the crosscutting concepts: Duschl, R. 2012. The second dimension: Crosscutting concepts. *Science and Children* 49 (6): 10–14.
5. Read and discuss this article about use of the words *theory* and *hypothesis*: McLaughlin, J. 2006. A gentle reminder that a hypothesis is never proven correct, nor is a theory ever proven true. *Journal of College Science Teaching* 36 (1): 60–62.
6. Read and discuss this article about how word choice affects students' understanding of the nature of science: Schwartz, R. 2007. What's in a word? How word choice can develop (mis)conceptions about the nature of science. *Science Scope* 31 (2): 42–47.
7. Read and discuss this NSTA Press book about building data literacy: Bowen, M., and A. Bartley. 2013. *The basics of data literacy: Helping your students (and you!) make sense of data*. Arlington, VA: NSTA Press.
8. Read and discuss Chapter 3 “Foundational Knowledge and Conceptual Change” in Michaels, S., A. Shouse, and H. Schweingruber. 2008. *Ready, set, SCIENCE!* Washington, DC: National Academies Press.
9. The authors' NSTA Press series *Everyday Science Mysteries* (Konicek-Moran) and *Uncovering Student Ideas in Science* (Keeley) contain a wealth of information on children's alternative conceptions and strategies for eliciting children's ideas. Read and discuss sections from these books. You can learn more about these books and download sample chapters at the NSTA Science Store: [www.nsta.org/store](http://www.nsta.org/store)
10. Watch the NSTA archived NGSS webinar on developing and using models: [http://learningcenter.nsta.org/products/symposia\\_seminars/NGSS/webseminar6.aspx](http://learningcenter.nsta.org/products/symposia_seminars/NGSS/webseminar6.aspx)
11. View videos of authors Dick Konicek-Moran and Page Keeley discussing the importance of understanding children's ideas: [www.nsta.org/publications/press/interviews.aspx](http://www.nsta.org/publications/press/interviews.aspx)

# Index

Page numbers printed in **boldface** type refer to figures or tables.

## A

- A Framework for K–12 Science Education*, 16–17, 23, 44, 57, 63, 71, 76, 82  
 description of cause and effect in, 179  
 development of, 90, 93  
 instructional models and, 143, 147  
 purposes of, 93  
 three dimensions of  
   crosscutting concepts, 16–17, 23, 24, 39, 50, 89–90, 94, 96  
   disciplinary core ideas, 50, 82, 89–90, 93–95, 117, 136, 161, 192, 200, 211  
   integration in case study on balance, 221–225  
   scientific and engineering practices, 44, 50, 52, 89–90, 94, 97–138 (*See also* Scientific and engineering practices)
- A New System of Chemical Philosophy*, 31
- A Private Universe*, xiii, 64, 86–87, 91, 218
- ABC-CBV (activity before concept, concept before vocabulary) strategy, 157–159
- ABC (activity before concept) teaching, 157
- Abell, Sandra, 212
- Achieve, Inc., 90
- Active Chemistry*, 157
- Active Physics*, 85, 123, 144, 157
- Alexander, Robin, 70
- “Alphabet soup” programs, 80–83, 91
- Alternative conceptions, xiii, 13, 15, 18, 24, 63, 145, 194.  
*See also* Misconceptions/preconceptions  
   in *A Private Universe*, xiii, 64, 86–87, 91, 218  
   research on, 62
- Amburgy, Leonard, 116
- American Association for the Advancement of Science (AAAS), 25, 37–38, 40, 88, 96, 79, 81  
 Project 2061, 86, 90, 91
- American Educational Research Association (AERA), 56
- American Institute of Biological Sciences, 83
- Analogical reasoning, 160
- Analogies, 6, 102–103, 105, 146, 153, 159–161  
 bridging, 160
- Analyzing and interpreting data, 112–117, **118**. *See also* Data
- Andre, T., 106
- “Apple in the dark” probe, 209, **209**
- Argument-Driven Inquiry in Biology: Lab Investigations for Grades 9–12*, 71, 153
- Argument-Driven Inquiry in Chemistry: Lab Investigations for Grades 9–12*, 71, 153
- Argument-Driven Inquiry (ADI) model, 147–149, **148**, 152, 153  
 teacher behaviors during, 148–149, **149–151**
- Argumentation, 40, 52, 71–73, 77, 161–168, 180  
 attempting consensus and civility, 72–73  
 benefits of, 161  
 in classroom, 71–72, 76, 161–162  
 definition of, 71, 130  
 engaging in argument from evidence, 128–132, **133**  
 facilitation of, 162  
 goal of, 130, 161  
 instructional models for, 130  
 as instructional strategy, 161–168, 188  
 questions for, 162  
 relationship between conceptual understanding and, 161  
 teaching norms and conventions for, 130–131, 188  
 VDR (vote-discuss-revote) strategy for, 162–166  
 written arguments, 166–168
- Aristotle, 26, 31, 34, 38
- Asking questions and defining problems, 98–99, **100**.  
*See also* Questions
- Assessment, 4  
 formative, xiii, 18, 66, 191–212 (*See also* Formative assessment; Probes)  
 high-stakes testing, 210  
 standardized tests, 1, 2

- summative, 18, 66, 88, 195, 198, 209
  - teaching to the test, 91
  - Trends in International Math and Science Study (TIMSS) test, 88
- Atkin, J. Myron, 140
- Atlas of Science Literacy*, 25, 54, 86
- Ausubel, David, 170
- Averaging, 119
- B**
  - Bacon, Francis, 41
  - "Balancing" case study, **221**, 221–225
  - The Basics of Data Literacy: Helping Your Students (and You!) Make Sense of Data*, 117
  - Beck, T., 98–99
  - Benchmarks for Science Literacy*, 25, 32, 37–38, 40, 86, 88, 93, 96
  - Big ideas in science, 16, 96. *See also* Crosscutting concepts
  - Biological Sciences Curriculum Study (BSCS), 83–84, 143
    - 5E Instructional Model, **143**, 143–144, 152, 153
    - formative assessment in, 144, 145, 196–198
    - modifications of, **144**, 144–145, 152
  - Black, Joseph, 29
  - Blickenstaff, Jacob, 216
  - Bowen, M., 176, 189
  - Brahe, Tycho, 26, 119
  - Bransford, J. D., 19, 143–144
  - Brilliant Blunders*, 35–36
  - Brooks, Michael, 47
  - Brown, A. L., 20, 143–144
  - Bubbles, **194**, 194–195
  - Buttemer, Helen, 110
  - Bybee, Rodger, 89, 92, 139, 143, 152
- C**
  - "Can it reflect light?" probe, 205–206, **206**
  - Card sort technique, 10, 192, 193, 206, 207, 208
  - Careers in science, 89, 132
  - Carey, Susan, 28, 29, 32, 34, 41, 59, 68
  - Causal cognition, 179
  - Causal Patterns in Density*, 180
  - Causal Patterns in Science Project, 180
  - Causal relationships, 61, 179–180
  - Chemical reactions, 31, 34–35, 75
  - Chen, Zhe, 40
  - Children and Nature Network, 217
  - Children's Learning in Science (CLIS) project, 62, 102
  - Children's thinking, 55–77
    - current models of cognitive development and
      - conceptual change, 59–61
      - causal models, 61
      - conceptual ecology, 61
    - conceptual "facets," 60
    - phenomenological primitives, 60
    - theory-theory model, 59
  - how education research is done, 55–56
  - how to effect conceptual change, 62–64
  - keeping long-term perspective of learning, 74–75
  - models of conceptual development, 57–59
    - constructivism, 58–59
    - Piaget, 57–58
  - NSTA resources on, 76–77
  - questions for reflection or discussion on, 75–76
  - relationship to talking and language, 69–73
    - argumentation, 71
    - attempting consensus and civility, 72–73
    - classroom argumentation, 71–72, 76
    - dialogic teaching, 70–71
  - sorting through conceptual change models, 62
    - alternative conception research, 62
  - techniques for teaching for conceptual change, 65–69
    - asking questions, 66–69
    - listening and probing, 65–66, 76
  - understanding the "pain" of changing ideas, 73–74
  - what children are capable of learning in science, 56–57, 76
- Christensen, Bonnie, 25
- Chromosome number, 13, 29
- Circuits, 140
- Claim-support-question (CSQ) strategy, 168–169
- Claims, Evidence, and Reasoning (C-E-R) Framework, 125–126, 128–129
- Claims, scientific, 12, 20, 27, 72, 88, 103–105, 116–117
  - argumentation for validation or refutation of, 130–132
  - evidence-based, 12
  - test of replication of, 27
- Clement, John, 62, 102, 172, 160
- CmapTools software, 170
- Cocking, R. R., 20, 143–144
- Cognitive development. *See* Children's thinking
- Cognitive research, 88–89
- Cold fusion claim, 27
- College Board Standards for College Success in Science*, 93
- Common Core State Standards in English Language Arts*, 72
- Common themes of science, 96. *See also* Crosscutting concepts
- Communication
  - engaging in argument from evidence, 71–73, 128–132, **133** (*See also* Argumentation)
  - importance of questions, 47–48, 66–69
  - language of science, 6–19
  - listening to children, 18–19, 65–66, 76, 160, 203
  - obtaining, evaluating, and communicating information, 132–135, **136**



- problem of incommensurability, 18–19, 28, 29, 37, 41, 66, 67, 68
  - science talk, 18, 48, 70, 88, 161, 181–182, 183, 192, 199
  - talk moves, 180–183
  - talking and language, 69–73
    - argumentation, 71
    - attempting consensus and civility, 72–73
    - classroom argumentation, 71–72, 76
    - dialogic teaching, 70–71
    - for formative assessment, 203
  - triad nature in classrooms, 72
  - Community of learners, 19–22, 23, 139
  - Computational thinking, 117–124, **124**. *See also* Mathematics
  - Computer technology, 2, 17, 101, 108, 119, 142. *See also* Technology
  - Concept(s)
    - alternative (*See* Alternative conceptions; Misconceptions/preconceptions)
    - analogies and metaphors for, 6, 102–103, 105, 146, 153, 155, 159–161
    - counterintuitive, xv, 6, 46, 160
    - crosscutting, 16–17, 23, 24, 39, 50, 89–90, 94, 96
    - definition of, 5–6
    - labels for, 5
    - operational definitions of, 172–173
    - in science, 5–6
  - Concept mapping, 5, **169**, 169–170, **171**
  - Conceptual change, xiii, 14
    - commensurability in, 28
    - vs. conceptual exchange, 63–64, 76
    - current models of cognitive development and, 59–61
      - causal models, 61
      - conceptual ecology, 61
      - conceptual “facets,” 60
      - phenomenological primitives, 60
      - theory-theory model, 59
    - emotional valence and, 19
    - factors associated with, 62
    - history of science and, 27–30
      - Black’s conceptual revolution in heat, 28–29
      - science textbooks and current science, 29–30
    - how to bring about, 62–64
    - inquiry for, 50–52, 203
    - intentional, 19–20, 23, 63, 146
    - keeping long-term perspective of learning, 74–75
    - nature of science teaching and, 50
    - sorting through models of, 62
      - alternative conception research, 62
    - understanding the “pain” of changing ideas, 73–74
  - Conceptual Change Model (CCM), 145–147, 152, 153
    - formative assessment in, 146, 196–197
    - revisions of, 146
  - Conceptual ecology, 61, 76
  - Conceptual exchange, 63–64, 76
  - Conceptual “facets,” 60
  - Conceptual models, 17, 52, 102, 106, 146, 160, 172, 185, 208. *See also* Analogies; Metaphors
  - Conceptual Physics*, 123
  - Conceptual understanding, xiii–xv. *See also* Teaching for conceptual understanding
    - definition of, 1, 6
    - formative assessment strategies to support, 198–202, 209–210
    - incommensurability in, 18–19, 28, 29, 37, 41, 66, 67, 68
    - language for, 6–9
    - listening for, 18–19, 65–66
    - vs. literal understanding, 2
    - vs. memorization, 2, 3, 31, 95, 106, 119
    - relationship between argumentation and, 161
    - role of informal education in development of, 213–219
  - Condensation, **2**, 2–3, 5–6, 156
  - Constructing explanations and designing solutions, 124–128, **129**
    - Claims, Evidence, and Reasoning (C-E-R) Framework, 125–126
    - engineering design, 126–128
    - Invention Convention, 127
  - Constructing Physics Understanding* (CPU), 142
  - Constructivism, 58–60, 77, 87, 88, 106, 145, 176
  - Continental drift theory, 73
  - Copernicus, 15, 17, 26, 38
  - Cosmos*, 36
  - Creating the prepared mind, 45–46
  - Creative Model Construction in Scientists and Students: The Role of Imagery, Analogy and Mental Simulation*, 160
  - Critical experiences, 65
  - Crosscutting concepts, 16–17, 23, 24, 39, 50, 89–90, 94, 96
  - Curie, Marie, 27
- ## D
- Dalton, John, 31, 37
  - Darwin, Charles, 27, 35–36, 37, 45
  - Data, 12
    - analysis and interpretation of, 112–117, **118**
    - collection and organization of, 110, 112, 114
      - in Argument-Driven Inquiry model, **148**, **149**
    - extrapolation or prediction from, 114–115
    - graphing of, 115
    - inferential evidence and inferential distance, 116–117
    - statistical thinking about, 119–121
    - validity of data sources and, 116
  - Descartes, Rene, 26, 41
  - Demonstrations, 2, 3, 13, 33–34, 81, 146, 160, 177, 185
  - Density, 13, 187, 119, 180, 187



Developing and using models, 100–108, **109**. *See also* Models in science  
 Dewey, John, 58, 79–80, 91  
 Dialogic teaching, 70–71  
 Disciplinary core ideas, 50, 82, 89–90, 93–95, 117, 136, 161, 192, 200, 211  
 Discrepant events, 72, 146  
 Discrepant questioning, 155, 172  
 DiSessa, Andrea, 60  
 “Does the example provide evidence?” probe, 162–163  
 “Doing science” probe, **42**, 43, 53  
 Drawings, 2, 17, 101, 108, 135, 172, 198, 208–209  
 Driver, Rosalind, 62, 68  
 Duckworth, Eleanor, 65, 66, 68, 75, 114, 189  
 Duran, Emilio, 144

## E

“Earth or Moon shadow?” probe, **193**, 193–194  
 Earth Science Curriculum Project (ESCP), 84  
 Education research, 55–56  
 Einstein, Albert, 14, 30, 38, 41, 86  
*Einstellung*, 37  
 Eisenkraft, Arthur, 85, 123, 144, 152, 157, 189  
 Electric charge, 162–166  
 Elementary Science Study (ESS) program, 82, 110  
 Elicitation of student ideas, 64, 94. *See also* Formative assessment; Probes  
   concept mapping for, 170, **171**  
   in *Constructing Physics Understanding* model, 142  
   in 5E Instructional Model, **143**, 144, 196  
   formative assessment for, 198, 199, 203, 205, **205**, 206  
   technology and, 204–205  
   in Group Interactive Frayer Model, 172–173  
   KWL strategy for, 175  
   in predict-observe-explain sequences, 177  
   to promote metacognition, 185  
   in 7E Instructional Model, 144, 152  
 Elicitation of teachers’ ideas, 43  
 Engaging in argument from evidence, 128–132, **133**. *See also* Argumentation  
   Claims, Evidence, and Reasoning (C-E-R)  
     Framework, 128–129  
     Initiate, Respond, Evaluate method, 129–130  
 Engineering design, 126–128. *See also* Scientific and engineering practices  
 English language learners, 7  
 Epistemology, xiii–xiv, 40, 57, 106, 135  
 Evaporation, **2**, 2–3, 169  
 Everett, J., 160  
 Everglades National Park, 216, 217  
*Everyday Earth and Space Science Mysteries*, 193  
*Everyday Life Science Mysteries*, 193  
*Everyday Science Mysteries* series, 20, 22, 33, 38, 66, 72, 99, 109, 123, 126, 158, 162, 176, 20, 22, 33, 38,

66, 72, 99, 109, 123, 126, 158, 162, 176, 193, 196, 199, 206, 210, 211  
 Evidence, 12  
   arguments based on, 161–168  
   Claims, Evidence, and Reasoning (C-E-R)  
     Framework, 125–126, 128–129  
   dialogue about, 73  
   “does the example provide evidence?” probe, 162–163  
   evaluating strength of, 116–117  
   inferential, 116–117  
*Exemplary Science in Informal Education Settings*, 219  
 Experimentation, 12–13  
 Explanations, construction of, 124–128, **129**  
 Exploring Physics, 85  
 Extrapolation from data, 114–115

## F

Falk, J., 219  
 “Falling through the Earth?” probe, 186, **186**  
 Feedback, providing to students, 130  
   in Claims, Evidence, and Reasoning Framework, 126  
   dialogic teaching for, 70  
   formative assessment for, 197, 198, 199, 208–209, 210  
 Fermi, Enrico, 45  
 Finklestein, Nancy, 64  
 Firestein, Stuart, 45  
 5E Instructional Model, **143**, 143–144, 152, 153  
   formative assessment in, 144, 145, 196–198  
   modifications of, **144**, 144–145, 152  
 Fleming, Alexander, 45–46  
 Floating and sinking, 172–173  
 “Food for corn” probe, 184  
 Forbus, K., 160  
 Formative assessment, xiii, 18, 66, 191–212. *See also* *Everyday Science Mysteries* series; Probes; *Uncovering Student Ideas in Science* series  
   benefits of, 198–199  
   big idea of, 198  
   in Conceptual Change Model, 146, 196–197  
   definition of, 195  
   to encourage reflection, 204  
   in 5E Instructional Model, 144, 145, 196–198  
   grading and, 204  
   linking with instruction and learning, 22, 191–212  
   NSTA resources about, 199, 211–212  
   purpose of, 195–196, 202–203, 210  
   questions for reflection or discussion on, 210–211  
   research support for, 195  
   sample lesson framework for use of, **205**, 205–210  
   strategies that support conceptual understanding, 198–202  
   suggestions for use of, 202–204

in talk format, 203  
 technology and, 204–205  
 Formative assessment classroom techniques (FACTs),  
 199–200, 202, 205, 206, 209, 211  
 Frayer, Dorothy, 172  
 Frayer Model, 172–174  
 Freyberg, P., 196  
 “Friendly talk” probe, 184  
 Full Option Science System (FOSS), 85

## G

Gagne, Robert, 81  
 Galileo, 17, 25, 26, 34, 41, 118–119, 185  
 Gallas, Karen, 48, 98, 99, 131  
 Galton, Francis, 35  
 Gentner, D., 160  
 Gertzog, W. A., 145–146  
 Glass, H. Bently, 83  
 Go-cart test run graph, 121, **121**  
 Goldberg, Fred, 142  
 Golden age of science education, 80  
 Goodall, Jane, 46–47, 53  
 Gordon, William, 159  
 Grahame, Kenneth, 82  
 Graphs, 115, 119  
   go-cart test run, 121, **121**  
   histogram of peas in pea pod, 122, **122**  
   time-distance, **119**  
   understanding, 121–122  
 Gravity, 36, 82, 102, 118, 160, 168, 186  
 Grobman, Arnold, 83  
 Grotzer, Tina, 61, 180  
 Group Interactive Frayer Model, 172–175, **175**  
 Grouping students, 203–204

## H

Habits of practice, 22  
 Hakim, Joy, 38  
 Hand, Brian, 134  
 Hands-on, minds-on learning, 7, 82, 94, 108, 129  
 Hands-on activities, 7, 50, 51, 52, 81, 82, 97, 108, 187,  
 200, 201  
 Harvard Project Physics, 84  
 Harvard Smithsonian Center for Astrophysics, 64, 86, 94  
 Harvey, William, 159  
 Hattie, John, 195  
 Hawkins, David, 82, 118  
 Haysom, J., 176, 189  
 Heat and temperature, 6, 28–29, 32–35, 38, 158, 201–  
 202  
 Hein, George, 66  
 Hennessey, M., 20  
 Hewett, Paul, 123  
 Hewson, P., 63, 145–146, 147

History of science, 15, 18, 22, 25–38, 45, 224  
 Aristotle, 26  
 case study on examination of heat in the classroom,  
 32–35  
 conceptual change and, 27–30  
   Black’s conceptual revolution in heat, 28–29  
   science textbooks and current science, 29–30  
 correlations between historic and classroom  
   persistence of theories, 35–36  
 modern science, 27  
 NSTA resources on, 37–38  
 paradigms and revolutions in science, 14–16, 30–31  
 questions for reflection or discussion on, 36–37  
 religion and science, 15, 17, 26–27, 159  
 similarity of science classrooms to historic  
   communities, 32  
 History of science education, 79–92, 139  
   analysis of early programs, 85  
   Dewey, 79–80  
   early standards of development and cognitive  
   research, 88–89  
   *A Framework for K–12 Science Education* and  
   NGSS, 89–91  
   golden age of science education, 80  
   NSTA resources on, 92  
   other influential reform movements and projects, 86  
   *A Private Universe* and alternative conceptions,  
   86–88  
   programs for elementary schools: “alphabet soup”  
   programs, 80–83, 91  
   programs for secondary schools, 83–85  
   questions for reflection or discussion on, 91  
 Holden, Gerald, 84–85  
 “How far did it go?” probe, 123, **123**  
 “How long is a day on the Moon?” probe, **4**  
*How People Learn*, 88, 143–144  
 Hume, David, 97  
 Hurd, Paul DeHart, 81  
 Hypothesis, scientific, 8–11  
   “what is a hypothesis?” probe, 10, 53

## I

“Ice water” probe, 157, **157**  
 Ideal gas laws, 161  
*Ignorance: How It Drives Science*, 45  
 Incommensurability, 18–19, 28, 29, 37, 41, 66, 67, 68  
 Inferences, 116  
 Inferential evidence and inferential distance, 116–117  
 Informal science education, 213–219  
   curricula for, 217–218  
   misconceptions resulting from, 218  
   museums, 214–215, 218  
   NSTA resources on, 216, 219  
   questions for reflection or discussion on, 218  
   state and national parks, 127, 216–217

strands of, 213  
 technology sources for, 216, 218

Inhelder, Barbell, 40

Initiate, Respond, Evaluate (IRE) method, 129–130, 181

*Inquiry: The Key to Exemplary Science*, 153

Inquiry-based education, 5, 20, 39–40  
 for conceptual change, 50–52, 203  
 emphasis in *National Science Education Standards*, 88  
 formative assessment and, 201  
 scientific and engineering practices and, 97

Inquiry boards, 110

The Inquiry Project/Talk Science, 71, 131, 183, 188

Insights program, 85

Instructional models, 139–153, 155  
 adult-led, 139  
 Argument-Driven Inquiry model, 147–149, **148–151**, 152, 153  
 child-led, 139  
 community of learners, 19–22, 23, 139  
 Conceptual Change Model, 145–147, 152, 153  
   formative assessment in, 146, 196–197  
   revisions of, 146  
 definition of, 139  
 5E Instructional Model, **143**, 143–144, 152, 153  
   formative assessment in, 144, 145, 196–198  
   modifications of, **144**, 144–145, 152  
 vs. instructional strategies and curriculum, 139  
 Learning Cycle Model, 81, 82, 139–142, **140**, **141**, 152  
 NSTA resources on, 152–153  
 questions for reflection or discussion on, 151–152  
 7E Instructional Model, **144**, 144–145

*Instructional Science*, 146

Instructional strategies, 155–190  
 ABC-CBV (activity before concept, concept before vocabulary), 157–159  
 analogies and metaphors, 6, 102–103, 105, 146, 153, 155, 159–161  
 argumentation, 161–168, 188  
 claim-support-question (CSQ), 168–169  
 concept mapping, **169**, 169–170, **171**  
 discrepant questions used with a visual model, 172  
 Group Interactive Frayer Model, 172–175, **175**  
 vs. instructional models, 139  
 KWL, 175–176  
 list of, 155–156  
 NSTA resources on, 189–190  
 Our Best Thinking Until Now, 176  
 personal selection of, 187–188  
 predict-observe-explain sequences (POE), 176–178, **178**  
 questions for reflection or discussion on, 188–189  
 RECAST activities, 179–180  
 role-playing, 179  
 talk moves, 180–183

thinking about thinking: metacognition, 183–185  
 thought experiments, 185–187

Intentional conceptual change, 19–20, 23, 63, 146

Invention Convention, 127

Investigating the Earth, 84

Investigations, planning and carrying out, 108–112, **113**

“Is it a model?” probe, 107, **107**

“Is it a rock? (version 2)” probe, 174, **174**

“Is it a solid?” probe, 103–105

“Is it a theory?” probe, 8, **9**, 53

“Is it matter?” probe, 191, **191**

“Is the Earth really round?” probe, 166, **167**

## J

*Journal of College Science Teaching*, 24

*Journal of Learning Sciences*, 60

*Journal of Research in Science Teaching*, 56, 83

*Journal of Teacher Education*, 56

Junior Ranger Program, 216

## K

Karplus, Robert, 81, 140, 141

Keeley, Page, 18, 22, 24, 66, 90  
*Science Formative Assessment*, 199, 211  
*Uncovering Student Ideas in Science* series, xiii, 22, 24, 33, 53, 66, 72, 99, 109, 162, 184, 196, 199, 201, 202, 204, 206, 210, 211  
 vignettes by, 10–11, 15–16, 43–44, 51–52, 59, 87, 90–91, 103–105, 115, 120–121, 142, 156, 162–166, 184–185, 187, 201–202, 217  
*What Are They Thinking?*, 53, 103, 189, 211

Kelly, George, 58

Kepler, Johannes, 26, 45, 119

Klahr, David, 40

KLEW model, 175–176

Kolb, David, 58

Konicek-Moran, Richard, 20, 22, 24, 66, 68, 202, 214, 216, 217, 218  
*Everyday Science Mysteries* series, 20, 22, 33, 38, 66, 72, 99, 109, 123, 126, 158, 162, 176, 193, 196, 206, 210, 211  
 vignettes by, 20–21, 31, 47–49, 51, 64, 67–69, 72, 74, 75, 83–84, 94, 101, 110–111, 114, 116, 122, 127–128, 131, 173, 214–215

Kuhn, Deanna, 40

Kuhn, Thomas, 14, 15–16, 18, 28, 30, 32, 41

Kukele, Friedrich, 52

KWL model, 175, 189

## L

Laboratory experiences, 55, 108, 155, 189  
 Argument-Driven Inquiry and, 147–149

*The Lagoon: How Aristotle Invented Science*, 26

- Language of science, 6–18, 40  
   activity before concept, concept before vocabulary strategy, 155, 157–159  
   data, 12  
   evidence, 12  
   experiment, 12–13  
   hypothesis, 8–11  
   learning of, 13–18  
     alternative conceptions, 13  
     conceptual change, 14  
     crosscutting concepts, 16–17  
     models, 17–18  
     paradigm, 14–16  
   science talk, 18, 48, 70, 88, 161, 181–182, 183, 192, 199  
   “sloppy” use of terms, 13, 23  
   talk moves, 180–183  
   theory, 7, 8, **9**
- Last Child in the Woods: Saving Our Children From Nature-Deficit Disorder*, 217
- Leach, John, 68, 83
- Learning Cycle Model, 81, 82, 139–142, **140**, **141**, 152
- Learning goals  
   for laboratory experiences, 147  
   lesson-specific, 207, 209  
   performance expectations and, 89, 205, 207  
   in science education standards, 32, 39, 88, 89, 93, 96  
   as target of formative assessment, 196, 200, 205, 207
- Learning partners, 203–204
- Learning progressions, 89
- Learning Science and the Science of Learning*, 89
- Learning Science in Informal Environments*, 213
- Learning strands, viii, 136–137, 138, 213, 221, 225
- Learning Style Inventory*, 58
- Lecturing, 1, 3, 50, 51, 83, 132, **150**
- Leishman, E., 98–99
- Leroi, Armand Marie, 26
- Life cycles, 179
- Light reflection, 205–210  
   “apple in the dark” probe, 209, **209**  
   “can it reflect light?” probe, 205–216, **206**
- Listening to students, 18–19, 65–66, 76, 160, 203
- Livio, Mario, 35–36
- Logical reasoning, 40, 41
- Looking at Learning*, 64
- Looking at Learning Again*, 64
- Louv, Richard, 217
- M**
- Mager, Robert, 2
- Magnetic force, 168–169, **178**
- Mathematics, 117–124, **124**  
   statistical thinking, 119–120  
   understanding concepts first, 123, **123**  
   understanding visual representations of numbers, 121–122
- Matter, **191**, 191–192
- McClintock, Barbara, 27
- McDermott, Michael, 134
- Meaningful learning vs. rote learning, 170
- Measurement, 123
- Memorization, 2, 3, 31, 95, 106, 119
- Mendel, Gregor, 35, 37
- Metacognition, 19, 20, 73, 97, 101, 135, 147, 156, 183–185, 195, 198, 199, 200
- Metaphors, 6, 61, 102, 155, 159–160
- Metz, Kathleen, 57
- Michaels, S., 77, 138, 181
- Mile wide and inch deep (“M&M”) curriculum, 1, 89, 95
- Miller, Robert, 204–205
- Minds of Our Own*, 63, 91, 140
- Minstrell, Jim, 60, 62, 94
- Misconceptions/preconceptions, 13, 44, 51, 53, 54, 60, 76, 87, 170. *See also* Alternative conceptions  
   about causality, 179, 180  
   challenging of, 155, 156  
   children’s building on, 80  
   in Conceptual Change Model, 145, 146  
   conceptual ecology of, 61  
   about condensation, 156  
   about density, 13, 187  
   in 5E Instructional Model, **143**  
   about heat, 201  
   informal science resources and, 218  
   in learning cycle model, 141  
   listening and probing for uncovering of, 65–66, 146, 199, 203, **205**, 205–207 (*See also* Formative assessment; Probes)  
   about models, 107  
   about Moon phases, 14, 193  
   patterns of, 62  
   about pendulums, 109  
   phenomenological primitives and, 61  
   recognition and evaluation of, 72, 87–88, 99  
   refutational text on, 106–107  
   student self-evaluation of, 97  
   theory-theory model of, 59
- “Mixing water” probe, 33, **33**, 38, 120
- Models in science, 17–18  
   analogy and, 102–103, 105  
   creating and changing, 101–106  
   developing and using, 100–108, **109**  
   epistemology and, 106  
   interest in topic and, 106  
   “Is it a model?” probe, 107, **107**  
   refutational text and, 106–107  
   understanding concept of, **107**, 107–108
- Montessori, Maria, 58
- Moon, xiv, 13, 14, 107, 132  
   “Earth or Moon shadow?” probe, **193**, 193–194

"how long is a day on the Moon?" probe, 3–4, **4**  
 Morrison, Philip, 82  
 Motivation of students, 20, 55, 108–109, 146, 176, 188, 196, 213, 215  
 MTV (make your thinking visible) technique, 184  
 Museums, 214–215, 218

## N

National Association for Research in Science Teaching (NARST), 56  
 National Defense Educational Act (NDEA), 80, 81  
 National Park System's Environmental Education section, 127  
 National Research Council (NRC), 88, 89, 90, 93, 95, 213  
*National Science Education Standards* (NSES), 88, 93, 95, 96  
 National Science Foundation (NSF)  
   Instructional Materials Development Program, 85  
   projects funded by, 80, 81, 82, 83, 84, 85, 142, 180  
 National Science Teachers Association (NSTA)  
   NSTA Learning Center, 92, 152, 153, 190, 212  
   position statements of  
     on importance of informal science, 219  
     on nature of science, 39  
   resources of  
     on classroom argumentation, 71–72  
     on development of conceptual understanding through three dimensions and learning strands, 137  
     on formative assessment, 199, 211–212  
     on history of science, 37–38  
     on history of science education, 91  
     of informal education, 216, 219  
     on instructional strategies, 189–190  
     on nature of children's thinking, 76–77  
     on nature of science, 53–54  
     on *NGSS*, 89, 92, 138  
     Outstanding Science Trade Books for Grades K–12, 25, 37  
     on teaching for conceptual understanding, 23–24  
     on use of instructional models, 152–153  
   role in development of *NGSS*, 90–91  
   Science Anchors project, 90  
   Science Matters website, 219  
*Nature*, 216  
 Nature-deficit disorder, 217  
 Nature of science, 15–16, 18, 24, 27, 30, 36, 39–54, 97, **150**  
   attributes of, 40  
   connections in *NGSS*, 39, 53  
   creating the prepared mind, 45–46  
   driven by "ignorance," 45  
   importance to science educators, 39  
   inclusion in *NGSS*, 39

language and social constructs of, 46–49  
 language of, 8–13  
 misrepresentations of, 11  
 models of, 40–41  
   logic and reasoning, 40  
   participation in science societies, 41  
   theory change, 41  
 NSTA position statement on, 39  
 NSTA resources on, 53–54  
 questions for reflection or discussion on, 53  
 science teaching and, 50–52  
 substituting science practices for the scientific method, 41–44  
 "Needs of seeds" probe, **192**, 192–193, 210  
 Newton, Isaac, 27, 30, 31, 36, 38, 41, 45, 119  
*Next Generation Science Standards* (*NGSS*), 16, 22, 23, 25, 32, 50, 57, 76, 80, 85, 89–91  
 Appendix F matrix in  
   analyzing and interpreting data, 117, **118**  
   asking questions and defining problems, 99, **100**  
   constructing explanations and designing solutions, 128, **129**  
   developing and using models, 108, **109**  
   engaging in argument from evidence, 132, **133**  
   obtaining, evaluating, and communicating information, 135, **136**  
   planning and carrying out investigations, 112, **113**  
   using mathematics and computational thinking, 124, **124**  
 challenges in transition to, 91  
 development of, 90–91  
 instructional models and, 143, 147  
 nature of science connections in, 39, 53  
 performance expectations in, 89, 205, 207  
 role of argumentation in, 71  
 scientific and engineering practices in, 44, 50, 52, 63, 44, 50, 52, 89–90, 94, 97–138 (*See also* Scientific and engineering practices)  
 use by Environmental Education section of National Park System, 127  
 No Child Left Behind (NCLB) legislation, 18  
 Normal science, 15, 30, 31  
 Nova, 57, 216  
 Novak, Joseph, 5, 169  
 Novick, N., 146  
 NSTA Learning Center, 92, 152, 153, 190, 212  
*NSTA Reports*, 216  
 NSTA Toshiba Exploravision competition, 127  
 Nussbaum, J., 146

## O

Observations and inferences, 116  
 Obtaining, evaluating, and communicating information, 132–135, **136**. *See also* Communication

Ogle, Donna, 175  
 Ohm's Law, 103  
 Operational definitions, 172–173  
*Opportunity Equation*, 95  
*The Origin of Concepts*, 28  
 Osborne, R., 196  
 Our Best Thinking Until Now strategy, 176, 222  
 Outdoor Biological Instructional Studies (OBIS)  
   curriculum, 217–218  
 Outstanding Science Trade Books for Students K–12,  
   25, 37

## P

Pangenesis, 35, 37  
 Paradigm shifts, 15–16, 17, 37, 41, 51, 88  
 Paradigms in science, 14–15, 30–31, 37  
 Parks, state and national, 127, 216–217  
 Participation in science societies, 41  
 Pasteur, Louis, 46  
*PBS Market Report Science*, 216  
 Peck, Alesia, 111, 114  
 Pendulums, 7–8, 12, 16, 82, 97, 109, **110**, 176  
 Performance expectations, 89, 205, 207  
 Perkins, David, 4, 61  
*Personal Construct Psychology*, 58  
 Phenomenological primitives (P-prims), 60  
 Physical Science Study Committee (PSSC) Physics  
   program, 80, 83  
 Piaget, Jean, xiii, 40, 57–58, 68, 81, 140, 224  
*Picture-Perfect Science* series, 153  
 Pines, A. L., 5  
 Planning and carrying out investigations, 108–112, **113**  
 Posner, G., 62, 145–146  
 Pratt, Harold, 89  
 Precipitation, **2**, 2–3  
 Preconceptions. *See* Alternative conceptions;  
   Misconceptions/preconceptions  
*Predict, Observe, Explain: Activities Enhancing Scientific  
 Understanding*, 176  
 Predict-observe-explain (POE) sequences, 176–178,  
   **178**, 189  
 Prediction from data, 114–115  
 Prince, George, 159  
 Probability, 119  
 Probes, 65–66, 146. *See also* Formative assessment  
   “apple in the dark,” 209, **209**  
   “can it reflect light?,” 205–206, **206**  
   “does the example provide evidence?,” 162–163  
   “doing science,” **42**, 43, 53  
   “Earth or Moon shadow?,” **193**, 193–194  
   “falling through the Earth?,” 186, **186**  
   “food for corn,” 184  
   “friendly talk,” 184  
   “how far did it go?,” 123, **123**  
   “how long is a day on the Moon?,” **4**

“ice water,” 157, **157**  
 “is it a model?,” 107, **107**  
 “is it a rock? (version 2)?,” 174, **174**  
 “is it a solid?,” 103–105  
 “is it a theory?,” 8, **9**, 53  
 “is it matter?,” 191, **191**  
 “is the Earth really round?,” 166, **167**  
 “mixing water,” 33, **33**, 38, 120  
 “needs of seeds,” **192**, 192–193, 210  
 “the mitten problem,” 202  
 “the swinging pendulum,” 109, **110**  
 “wet jeans,” **2**, 2–3  
 “what bugs me?,” 127  
 “what is a hypothesis?,” 10, 53  
 “what’s in the bubbles?,” **194**, 194–195

Process skills, 81, 97, 137, **143**  
 Project 2061, 86, 90, 91  
 Project Learning Tree, 219  
 Project Physics Course, 84  
 Project Wet, 219  
 Proxy experiments, 185  
 Public Media International (PMI) radio reports, 216  
 Public understanding of science, 39–40

## Q

Quantum theory, 30  
 Questions, 47–48, 66–69  
   for argumentation, 162  
   asking questions and defining problems, 98–99, **100**  
   claim-support-question (CSQ) strategy, 168–169  
   dialogic teaching, 70  
   discrepant, 155, 172  
   for talk moves, 181–182  
 Questions for reflection or discussion  
   on formative assessment, 210–211  
   on history of science, 36–37  
   on history of science education, 91  
   on informal science education, 218  
   on instructional models, 151–152  
   on instructional strategies, 188–189  
   on nature of children’s thinking, 75–76  
   on nature of science, 53  
   on teaching for conceptual understanding, 22–23

## R

Rabi, Isadore, 47, 98  
 Ratio, 119  
*Ready, Set, SCIENCE!*, 12, 17, 24, 77, 93, 112, 138, 161,  
   180, 181  
 Reasoning  
   analogical, 160  
   asking students to applying their own to someone  
     else’s reasoning, 182  
   asking students to explicate, 182



- asking students to restate another student's reasoning, 181–182
  - Claims, Evidence, and Reasoning (C-E-R) Framework, 125–126, 128–129
  - logical, 40, 41
  - RECAST (REveal CAusal STRucture) activities, 179–180
  - Refutational text, 106–107
  - Religion and science, 15, 17, 26–27, 159
  - Renner, John, 141
  - The Review of Educational Research*, 56, 57
  - Revoicing technique, 181
  - Revolutions in science, 14–15, 17, 27, 28, 30–31, 41, 51, 52, 53
  - Rogoff, B., 139
  - Role-playing, 179
  - Roman Catholic Church, 15, 17, 26
  - Rosenwald, Julius, 215
  - Roth, Kathleen, 61
  - Rowe, Mary Budd, 70, 182–183
  - Ruffman, Ted, 40
  - Rutherford, F. James, 84–85
- S**
- Sadler, Philip, 64, 86
  - Sagan, Carl, 36
  - Samples, Bob, 159
  - Sampson, Victor, 71, 148
  - Schauble, L., 126
  - Schneider, Lisa, 22, 23
  - Schneps, Matthew, 64, 86
  - School Science Review*, 56
  - Schweingruber, H., 77, 138, 181
  - Science*, 216
  - Science: A Process Approach (SAPA), 81–82
  - Science Anchors project, 90
  - Science and Children*, 23–24, 38, 54, 76, 92, 110, 134, 137, 152, 189, 211
  - Science and Technology for Children (STC), 85
  - Science Curriculum Instructional Strategy (SCIS), 81, 140
  - Science Education*, 56
  - Science for All Americans*, 25, 37, 40, 86, 96, 108
  - Science Formative Assessment*, 199, 211
  - Science Friday*, 216
  - Science Matters website, 219
  - Science Media Group, 86, 87
  - Science notebooks, 47
  - Science Scope*, 24, 38, 54, 77, 92, 116, 134, 152, 170
  - Science societies, participation in, 41
  - Science talk, 18, 48, 70, 88, 161, 181–182, 183, 192, 199. *See also* Argumentation
  - The Science Teacher*, 38, 77, 92, 140, 152, 153, 170, 189
  - Science textbooks, 2, 3, 13, 26, 44, 31, 37
    - current science and, 29–30
    - Project 2061 analysis of, 86
  - Scientific American*, 216
  - Scientific and engineering practices, 44, 50, 52, 89–90, 94, 97–138
    - analyzing and interpreting data, 112–117, **118**
    - asking questions and defining problems, 98–99, **100**
    - case study on balancing using, 221–225
    - constructing explanations and designing solutions, 124–128, **129**
    - developing and using models, 100–108, **109**
    - engaging in argument from evidence, 128–132, **133**
    - obtaining, evaluating, and communicating information, 132–135, **136**
    - planning and carrying out investigations, 108–112, **113**
    - vs. process skills, 97
    - using mathematics and computational thinking, 117–124, **124**
  - Scientific Argumentation in Biology: 30 Classroom Activities*, 71, 130
  - Scientific literacy, 40, 132
  - Scientific method, 10–11, 26, 53, 54, 111
    - substituting science practices for, 41–44
  - Scott, Phil, 101–102
  - Seamless Assessment in Science*, 212
  - Seed germination, **192**, 192–193, 210
  - Self-regulated learners, 183
  - Serendipity, 46, 50, 52
  - 7E Instructional Model, **144**, 144–145
  - Shapiro, Bonnie, 14, 18, 65, 68, 87, 125
  - Shapiro, Irwin, 86
  - Shouse, A., 77, 138, 181
  - Shymansky, James, 83
  - Simulations, 2, 100, 117, 119, 142
  - Sinking and floating, 172–173
  - Smaller grain axioms, 60
  - Smith III, John P., 60
  - Sneider, Cary, 90
  - Social interactions, 63, 69–70, 145, 203–204
  - Social media, 50, 214
  - Sohmer, Richard, 161
  - Speaking skills, 131, 132, 134
    - dialogic teaching, 70
    - language of science, 6–8, 18, 29
    - science talk, 18, 48, 70, 88, 161, 181–182, 183, 192, 199
    - talk-facilitation strategies, 181–183
  - Sputnik, 80, 84, 85
  - Standardized tests, 1, 2
  - Standards-based science teaching, 88. *See also* *Next Generation Science Standards*
  - Statistical thinking, 119–121
  - Stepans, Joseph, 146
  - Sticky Bars technique, 43
  - Strike, K. A., 145–146
  - The Structure of Scientific Revolutions*, 14, 15–16, 30
  - Summative assessment, 18, 66, 88, 195, 198, 209

## T

*Taking Science to School*, 93, 101, 136–137  
 Talk moves, 180–183  
*Talking Their Way Into Science: Hearing Children's Questions and Theories, and Responding With Curricula*, 48, 98  
 Teaching for conceptual understanding, 1–24  
   definition of concept, 5–6  
   formative assessment and, 191–212  
   habits of practice that interfere with, 22  
   instructional models for, 139–153  
   instructional strategies for, 155–190  
   intentional conceptual change and community of learners, 19–22, 23  
   language of science, 6–18  
   listening to children, 18–19, 65–66, 76, 160, 203  
   NSTA resources for, 23–24  
   priorities for, 4  
   questions for reflection or discussion on, 22–23  
   teaching methods that are impediments to, 1–4, 22  
   techniques for, 65–69  
     asking questions, 66–69  
     listening and probing, 65–66, 76  
 Technology, 86, 88, 93, 95, 96, 112, 119, 126, 142  
   formative assessment and, 204–205  
   for informal science education, 216, 218  
*Tell Me More*, 65  
 Temperature and heat, 6, 28–29, 32–35, 38, 6, 28–29, 32–35, 38, 158, 201–202  
 TERC's The Inquiry Project/Talk Science, 71, 131, 183, 188  
 Thagard, Paul, 19  
 "The mitten problem" probe, 202  
*The Story of Science* book series, 38  
 "The swinging pendulum" probe, 109, **110**  
 Theories, scientific, 7, 8, **9**  
   alternative conceptions and, 13  
   correlations between historic and classroom persistence of, 35–36  
   "is it a theory?" probe, 8, **9**, 53  
 Theory change, 41, 53  
 Theory-theory model in cognitive development, 59  
 Thermal energy, 28–29, 32–35, 38, 158  
 Thermodynamics, 6, 29, 33, 38  
 Thier, Herbert, 81  
 Thinking about thinking. *See* Metacognition  
 Thought experiments, 185–187  
*Through the Wormhole*, 216  
 Tools for Ambitious Science Teaching website, 183  
 Toulmin, Stephen, 61  
 Transfer of energy, **157**, 157–158  
 Trends in International Math and Science Study (TIMSS) test, 88  
 Tyson, Neil deGrasse, 36

## U

*Uncovering Student Ideas in Primary Science*, 211  
*Uncovering Student Ideas in Science* series, xiii, 22, 24, 33, 53, 66, 72, 99, 109, 162, 184, 196, 199, 201, 202, 204, 206, 210, 211. *See also* Probes  
   digital videos of probes in, 204  
 Understandings of Consequence Project, 179–180  
 Using mathematics and computational thinking, 117–124, **124**  
   statistical thinking, 119–120  
   understanding concepts first, 123, **123**  
   understanding visual representations of numbers, 121–122

## V

Variables, 115, 117, 161  
   identification and control of, 12, 56, 108, 109–110, 126, 176  
*The Variation of Animals and Plants Under Domestication*, 35  
 Vasniadou, S., 20  
 Videos of formative assessment probes, 204  
 Vocabulary development, 2, 7–8, 66. *See also* Language of science  
   activity before concept, concept before vocabulary strategy, 155, 157–159  
   Frayser Model, 172  
 Volkmann, Mark, 212  
 Von Glaserfeld, Ernst, 58  
 Vote-discuss-revote (VDR) strategy, 162–166  
 Vygotsky, Lev, 69–70

## W

Wait time, 182–183  
 Water cycle, 2–3, 24, 169  
 Watson, Fletcher, 84, 85  
 Wegener, Alfred, 73  
 "Wet jeans" probe, **2**, 2–3  
*What Are They Thinking?*, 53, 103, 189, 211  
 "What bugs me?" prompt, 127  
*What Children Bring to Light*, 14, 18, 87  
 "What does it tell you and what do you want to know?" game, 116  
 "What is a hypothesis?" probe, 10, 53  
 "What's in the bag?" activity, 48–49  
 "What's in the bubbles?" probe, **194**, 194–195  
 Wheeler, Gerry, 90  
 Whitehead, Alfred North, 29  
 William, Dylan, 198  
*Wind in the Willows*, 82  
 Wiser, Marianne, 35  
 Wolfe, Sylvia, 70  
 "Word walls," 7  
 Writing activities, 44, 72, 101, 111, 125, 162, 197



# Index

in Argument-Driven Inquiry model, **150, 151**  
for communicating information, 132–135, 137  
for formative assessment, 193, 198, 203  
lab reports, 134, 135  
in predict-observe-explain sequences, 177  
written arguments, 166–168  
Wu, M., 160

## Y

Yager, R., 219  
*Yet More Everyday Science Mysteries*, 33  
*Young People's Images in Science*, 39

## Z

Zacharias, Jerrold, 83  
Zhu, Jing, 19

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