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 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).

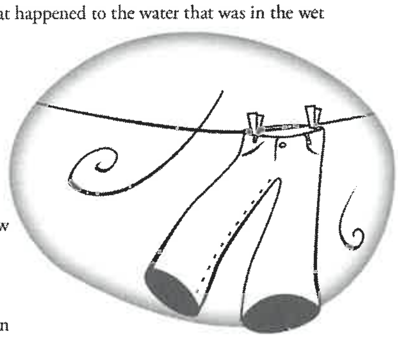
Reading science textbooks, defining vocabulary, filling out worksheets, and answering low-level questions at the end of the chapter are also forms of passive instruction. These activities often involve pulling information from text with minimal intellectual engagement. The student may be able to reproduce 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:

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 bollyswaggering it. Marfolamine will eventually micronate our gladivones so that we can homitote our tonsipows more demicly.

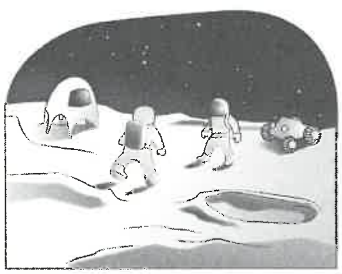
1. What is marfolamine?
2. Where was marfolamine discovered?
3. How is marfolamine chemovated?
4. Why is marfolamine important to us?

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 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 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

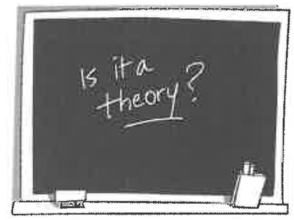
A hypothesis in science is often an "if … then" statement in response to a scientific question that provides a tentative explanation that leads an investigation and can be used to provide more information to either strengthen a theory or develop a new one. A hypothesis is a strongly developed prediction, 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.

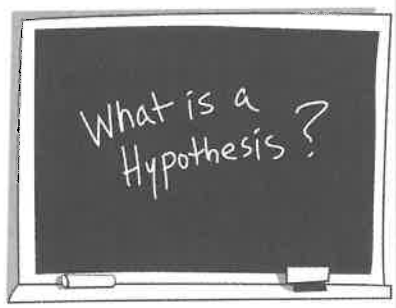
Source: Keeley, Eberle, and Dorsey 2008.

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?

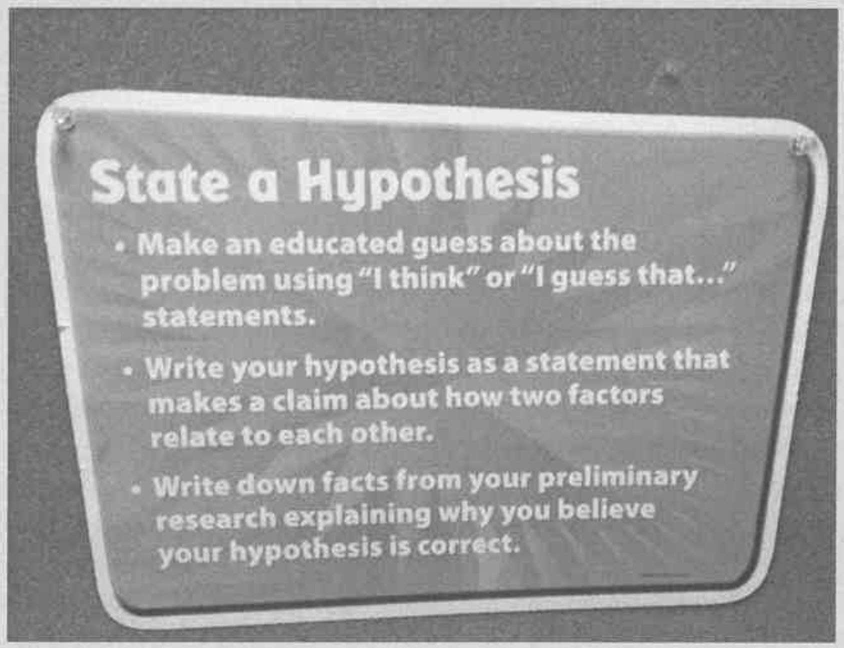
Hypotheses are used widely in science. Put an X next to the statements that describe a hypothesis.



_____ **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

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 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). Hennesey suggests that metacognition (thinking 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

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*. 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

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*
10. Watch the NSTA archived *NGSS* webinar on developing and using models: *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*