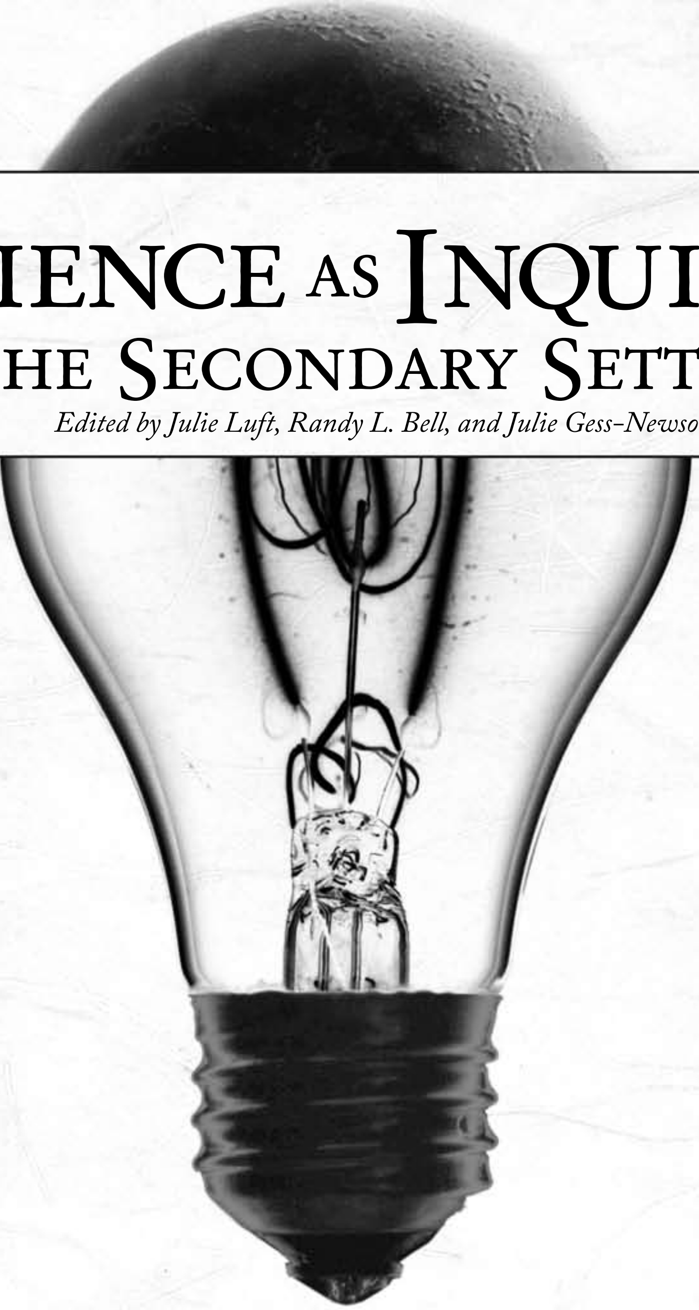

SCIENCE AS INQUIRY IN THE SECONDARY SETTING

Edited by Julie Luft, Randy L. Bell, and Julie Gess-Newsome

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Foreword

Science as inquiry has been at the forefront of science education reform since the mid-1990s. Curricular standards, instructional materials, and authentic assessments, coupled with the National Science Teachers Association's continuous support for inquiry-based science, have significantly raised the profile of science-as-inquiry in secondary school classrooms.

Even today, however, the phrase *science as inquiry* continues to conjure up multiple meanings and images of practice. Although the science education community recognizes inquiry as a centerpiece of science teaching and learning, many teachers are still striving to build a shared understanding of what science as inquiry means, and at the more practical level, what it looks like in the classroom.

In the NSF Foundations series monograph (2000), *Inquiry: Thoughts, Views, and Strategies for the K–5 Classroom,* experts in the field of elementary inquiry science shared their insights and experiences about inquiry-based science in the early, formative years. This monograph became a widely used resource to help elementary science educators introduce, implement, and sustain inquiry content and practices in their K–5 schools, classrooms, and preservice programs.

Now, with *Science as Inquiry in the Secondary Setting*, we have a full picture of K–12 inquiry. *Science as Inquiry in the Secondary Setting* moves beyond "inquiry science rhetoric" and connects school science to authentic characteristics of the scientific community. Addressing the critical importance of a high-quality secondary science education, this book brings inquiry-based teaching and learning together in a conceptually and strategically powerful way. The authors are not just armchair theorists. Their work and research are grounded in teachers' classrooms, and the rich vignettes and examples they include help the reader make connections between the information presented and what it looks like in practice.

Whether you have already begun your journey into teaching science through inquiry or are just starting, you will find this book to be a welcome catalyst for your professional growth. Although individuals can gain considerable new knowledge by reading this book on their own, powerful new learning will result when the book's chapters are shared through discussion with fellow science educators at all levels, including preservice teachers, inservice teachers, and those who educate teachers of science. Professional learning communities will find this book to be an excellent resource to provoke thinking and stimulate conversation in collaborative settings. Reading chapters at regular intervals and coming together as a learning community to discuss implications for improved teaching and learning can stretch teachers in thinking beyond their current practice, stimulate growth and renewal, and help jump-start future and new teachers in the early stages of their careers.

By moving away from the isolation of individual classrooms toward supporting science classrooms in which all students in a middle or high school are actively engaged in authentic science learning, teachers will see measurable scores of skills and knowledge increase. Just as important, they will see their students' deeper engagement with, interest in, and appreciation of science grow and flourish.

Get ready for an intellectually inspiring and challenging experience as your journey into inquiry either begins or continues with this book. Whatever your level of teaching experience and wherever you or your professional learning community chooses to start in this book, each chapter will challenge you to think about your own beliefs about learning, teaching practice, and students in new ways—ways that will ultimately help all students to succeed in school and in life.

—Page Keeley
NSTA President-Elect 2007–08
Science Program Director,
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Preface

Science as Inquiry in the Secondary Setting and its companion volumes, *Technology in the Secondary Science Classroom* (now available from the National Science Teachers Association [NSTA]) and *Science Education Reform in the Secondary Setting* (in development at NSTA), have a long and interesting history. The ideas for these books emerged from our work with secondary science teachers, supportive program officers at the National Science Foundation, and the science education community, which is always seeking a connection of theory and practice. In order to ensure that these books were connected to each of these stakeholders, we adopted a writing plan that involved representatives from all three groups. We considered novel approaches to identify and support science teachers and science educators to participate in the project, and we sought guidance from program officers about the format and dissemination of the final product.

To begin with, we identified three topics of interest to both science teachers and science educators—science as inquiry, educational technology, and science education reform. We wanted the community of science educators to help define the content of each book, so we solicited chapter proposals from science teachers and science educators. The response was impressive, with over 50 chapter proposals submitted for the three books. Our selection of the chapters was based on the clarity of the topic, the type of idea presented, and the importance of the topic to science teachers.

Chapter authors were then asked to generate a first draft. These chapters were shared among the authors of their respective books for review. We met as a group at the annual meeting of the Association of Science Teacher Educators, in Portland, Oregon, to discuss and provide feedback to one another on our chapters. This session was extremely useful, and several of the authors returned to their chapters, ready for another revision.

Once the second revision was complete, we wanted to draw on the expertise of science teachers, whom we felt should ground this work. We contacted NSTA and placed a “call for reviewers” in their weekly electronic newsletter. Over 200 teachers offered to review our chapters. Reviews were shared with the chapter authors.

The second revision was also shared among the authors within each book. Each author now had external reviews from teachers, as well as reviews from other authors. To discuss these reviews and the final revision of the chapters, we met one more time at the annual meeting of the National Association for Research in Science Teaching, in San Francisco, California. At the conclusion of this meeting, chapter authors were ready to write their final versions.

When the chapters were completed and the books were in a publishable format, we approached NSTA about publishing them both in print and online, so that they would reach as many teachers as possible. NSTA has historically offered one chapter of a book for free, but the opportunity to break new ground by offering each chapter of this book free online would be new publishing territory. Of course, paper copies of each book are available for purchase, for those who prefer print versions. We also asked, and NSTA agreed, that any royalties from the books would go to NSTA’s teacher scholarship fund to enable teachers to attend NSTA conferences.

This process has indeed been interesting, and we would like to formally thank the people who have been helpful in the development and dissemination of these books. We thank Carole Stearns for believing in this project; Mike Haney for his ongoing support; Patricia Morrell for helping to arrange meeting rooms for our chapter reviews; the 100+ teachers who wrote reviews on the chapters; Claire Reinburg, Judy Cusick, and Andrew Cocke of NSTA for their work on these books; Lynn Bell for her technical edits of all three books; and the staff at NSTA for agreeing to pilot this book in a downloadable format so it is free to any science teacher.

—Julie Luft, Randy L. Bell, and Julie Gess-Newsome

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Scientific Inquiry: The Place of Interpretation and Argumentation

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Secondary school students typically believe that scientific inquiry begins with a direct observation of the natural world and that scientific laws and theories become apparent from these observations. Many students even believe that scientific evidence is conclusive *only* if it is directly observable. We know, however, that scientific observation is an interpretation of nature rather than a direct reading and that the movement from observation to laws and theories involves enormous mental and physical effort and resources. Students come by their overly simple view of science from a variety of sources, including science trade books (Ford 2006) and their textbooks.

This chapter suggests how secondary school science education can offer a more accurate picture by emphasizing the role of interpretation and argumentation in scientific inquiry. Interpretation is concerned with questions of meaning and explanation. Argumentation is concerned with justifications of what to conclude and what to do. We provide an extended example demonstrating strategies for making interpretation and argumentation more central to science instruction. We begin, however, with a shorter example to illustrate how the simple view of science is connected to a general misconstrued understanding of learning *as itself simple*—as a process of locating information and memorizing facts. Learning, in this view, is like a conduit, carrying information unobstructed from one person to another. On the contrary, however, all communication is fraught with complexities of comprehension and understanding (see Reddy 1979).

The Simple View of Learning

Certain common testing practices illustrate well the simple view of learning. Try the following example that mimics standard tests of reading comprehension. Read the passage and answer the multiple-choice questions that follow.

Quantum Damping

> *We assumed that the atomic energy levels were infinitely sharp whereas we know from experiment that the observed emission and absorption lines have a finite width. There are many interactions which may broaden an atomic line, but the most fundamental one is the reaction of the radiation field on the atom. That is, when an atom decays spontaneously from an excited state radiatively, it emits a quantum of energy into the radiation field. This radiation may be reabsorbed by the atom. The reaction of the field on the atom gives the atom a linewidth and causes the original level to be shifted. This is the source of the natural linewidth and the Lamb shift.* (Louisell 1973, p. 285)

1. The underlined word decays means: A. splits apart, B. grows smaller, C. gives off energy, D. disappears.

2. According to the passage, observed emission lines are: A. infinitely sharp, B. of different widths, C. of finite width, D. the same width as absorption lines.

3. According to the passage, the most fundamental interaction that may broaden an atomic line is: A. the Lamb shift, B. the action of the atom on the radiation field, C. the emission of a quantum of energy, D. the reaction of the radiation field on the atom.

4. It can be inferred that when an atom decays it may: A. return only to a state more excited than the original one, B. not return to its

original excited state, C. return to its original excited state, D. return to a state less excited than the original one.

5. It can be concluded from the information in this passage that the assumption that atomic energy levels are infinitely sharp is: A. probably false, B. false, C. true, D. still under question.

The correct answers are found at the bottom of this page.

How did you do? Almost everyone who has taken this little test has performed well.

So what is the point? If we constrain learning to the simple view, we must conclude that everyone who performed well on the test learned from reading the passage. They were able to locate information in the text, isolate facts, and answer various inferential questions. Yet, there is a problem with this conclusion. Except for a few, including perhaps some of you, most people who have taken this test do not have the faintest idea what the Quantum Damping passage means.

Performing well on such items—which mimic many items that students face in school—does not imply understanding or learning, because all they test is word recognition and information location. Teaching according to the simple view of learning gives credit for performance that does not require the deep understanding that educators wish students to achieve in science education. As a consequence, students receive an inflated assessment of their ability in science, learn to believe that science does not have to make sense, and acquire a simple view of science.

The purpose of this chapter is to show how student understanding of science concepts can be enhanced through concerted attention to interpretation and argumentation, which are at the core of scientific inquiry.

Interpretation and Argumentation

Interpretation and argumentation are complementary aspects of scientific inquiry. We are each required to engage in interpretation whenever we wish to go beyond the plain and obvious meaning of something. Interpretation requires judgment and is one of the defining features of inquiry.

Interpretation is *iterative*. It proceeds through a number of stages, each aimed at greater refinement:

1-C; 2-C; 3-D; 4-C; 5-B

- Lack of understanding is recognized.
- Alternative interpretations are created.
- Available evidence is used and new evidence is sought as necessary.
- Judgment is suspended until sufficient evidence is available for choosing among the alternatives.
- Interpretations are judged and, when necessary, modified or discarded.
- Alternative interpretations are proposed, sending the process back to the beginning.

Interpretation is also *interactive*. It involves a back-and-forth movement between evidence, the interpreter's background knowledge, existing interpretations, and emerging interpretations. Progress is made by actively imagining new representations of the world—not as it is but as it might be—and then negotiating what is imagined against the evidence and existing background knowledge.

Finally, interpretation is *principled*. The principles are used to weigh and balance conjectured interpretations against the evidence and accepted science. Striving for completeness and consistency are the two main principles. Neither principle is enough by itself, and both must be used in tandem.

Because the meaning of scientific data can never be read directly, any interpretation must be justified with an argument. In the sense we intend, argumentation is the attempt to establish or prove a conclusion on the basis of reasons. A conclusion, in this context, is not simply the end of something; rather, it is a proposition someone is trying to support. *Reasons* is the most general term for the support offered for conclusions. In science, the term *evidence* is often used, especially when the support is provided by data.

However, scientists also provide reasons for what research to pursue, for which data to collect, and for which procedures to use. Moreover, they frequently offer logical arguments for conclusions. Galileo, without appeal to evidence, argued that it is logically inconsistent to claim that heavier objects because of their natures fall at a faster rate than lighter objects. Einstein, also without appeal to evidence, argued that it is logically inconsistent to hold that all observers, regardless of their relative motion, would make the same judgments about the simultaneity of events. In these latter cases, reasons, not data, were brought to bear.

Within the framework of this chapter, an argument is not a dispute. Argumentation, like interpretation, is a defining feature of scientific inquiry (Driver, Newton, and Osborne 2000). Both can be learned with the right experience.

The Experience Needed

From time to time during their secondary school science education, students need to experience extended inquiries. The aim of these experiences is to show the difficulty and complexity of reaching scientific conclusions. The activities we contemplate emphasize a depth of understanding over a breadth of understanding. Students are asked to linger on a topic, to resist closing off investigation too quickly, and to learn to be more skeptical and less credulous. Generally, they are to attend closely to the reasoning behind scientific understandings and to the interpretation and argumentation involved in securing them.

Extended inquiries can take several forms. In one sort of inquiry, students explore a scientific question starting from its inception, through the research design, data collection, and analysis, to the write-up and presentation of the results. These sorts of inquiries can be valuable, especially when the questions explored come from the students. The approach we describe differs in that it focuses on historical science and questions already settled. The inquiry relies on the teacher making salient for the students the question "How did we come to be so sure?" Students need to feel perplexed, as described in Chapter 4.

The lessons from such activities can be particularly valuable if the conclusion in question is one that students take for granted. These lessons include the following:

- Plants grow by capturing light energy and converting it to chemical energy in a process called "photosynthesis."
- Much of what is now dry land was once under the oceans.
- The heart is a pump that circulates blood throughout the body.
- Water is a compound, each molecule of which is composed of two hydrogen atoms and one oxygen atom.

For each of these conclusions, ready sources of data are available, either through students' own experience, observations, or experiments possible in the high school classroom. However, none of the conclusions is self-evident and arguments must be constructed to justify all of them.

In summary, conditions conducive to showing the place of interpretation and argumentation in scientific inquiry are found in extended activities that

- Emphasize depth over breadth.
- Promote skepticism and challenge credulity.
- Examine everyday and cherished beliefs.
- Have data readily available.
- Can use data from students' observations and experiments.

An Example of Extended Inquiry

The following is an example of such an activity that builds on the question "Why do we experience day and night on Earth?" A teacher who introduces this as a question in the secondary classroom must first convince students that the question is meant as genuine. Likely, students will produce a quick and certain response that they learned in elementary school: "Day and night are caused by the spinning Earth." You can initiate argumentation by asking something like "How do you know?" or "What makes you so certain of your knowledge?"

Students may provide responses that are legitimate appeals to authority: "My science textbook in eighth grade said so" or "Our teacher two years ago told us this was the reason." However, the point of scientific inquiry is to get students to wonder about the basis for what they know. You could keep the argument alive by asking the students why they believe the textbook or how their former teacher could know the answer, but we recommend another route.

Begin by asking students whether the answer is as self-evident as it seems. After all, during the course of a day, which appears to move—the Sun or the Earth? At this point you have a number of possible routes to follow. The class could be divided into two or more groups, each charged with mustering the most solid case they can for the conclusion. Alternatively, you could facilitate a whole-class discussion. In either arrangement, a good place to start is with *possible* answers to the question. Begin by asking students to imagine that they do not know what causes day and night—indeed that nobody knows the answer. Ask them to think what might be its cause and what evidence and reasoning they can assemble to support their answer. To do that they have to start with conjectures.

Conjectures

Conjectures are interpretations held tentatively. The mode of thinking involved in conjecturing is central to science: "*If* such-and-such were the case, *would* that explain the phenomenon?" This form of suppositional thinking is hardly ever easy. To the question of what causes night and day, secondary students should be able to imagine the two historical rivals: (1) the Earth spins, making a complete revolution each 24 hours, thus over the course of a day exposing varying parts of its surface to the Sun; and (2) the Sun orbits the Earth once per day, thus shining its light on different parts of the Earth's surface as it does so.

However, the phenomenon of day and night itself is not so cut and dried. Not all days are of equal length; in most places, days are longer in summer, shorter in winter, and in-between lengths in the fall and spring. Further complicating the phenomenon is that the longest days in the Northern Hemisphere correspond to the shortest ones in the Southern Hemisphere and vice versa.

Now the interpretive questions become:

- *If* the Earth were spinning, what would cause days of different length?
- *If* the Sun were orbiting the Earth, what would cause days of different length?
- What in each model would lead to differences between the two hemispheres?

These questions are more difficult to answer, because models that will produce the effects are not easy to imagine. It is important in this phase to help students reflect on what they are doing. They are making tentative interpretations. They are involved in creating ideas and judging whether they *could* explain the phenomenon of day and night. They are holding in abeyance a decision on the truth of those ideas while they pursue available evidence and judge its relevance.

Relevance

Before the investigation can go much further, the issue of what is relevant must be addressed. A lot is known, but only some of it is pertinent to the question of why there is day and night. You have considerable discretion about when to bring new facts into play. However, it is important to have a number of potentially relevant facts at hand in order to introduce them in a timely fashion as provocations and to sustain the argument. Here are some such facts as an illustration:

- The stars appear to move in a counterclockwise circular direction around Polaris as the approximate center.
- There is seasonal change in the Sun's altitude at noon and in its daily duration in the sky.
- There are monthly phases of the Moon.
- Seasonal transition times vary: spring to summer, 92 days; summer to fall, 94 days; fall to winter, 90 days; winter to spring, 89 days.

Relevance is sometimes difficult to judge, but it is a crucial judgment scientists need to make; otherwise, they will be inundated with more information than they can possibly handle. Students need to learn that judgments of relevance are part of the process of scientific inquiry, and students require practice making them.

Consider the fact that the stars appear to rotate around one fixed star, and imagine students' judging its relevance to the question. Your role is to frame the issue: "Is the fact relevant to the question of what causes night and day? If it is, why? If it is not, why not?" Students are asked not only to make a judgment, but to defend it with reasons.

The demand to provide reasons is what motivates arguments. Students may say that this fact is relevant, because if the Earth were spinning, then the stars would appear to turn. So the fact is evidence that the Earth is spinning. Your role now is to push for deeper thought: "If the Earth were spinning, wouldn't you land on a different spot when you jumped straight up? What would happen if you jumped straight up in an airplane?" The aim in asking these questions is to bring the students to understand that some evidence (where you land when you jump) is irrelevant to deciding whether the Earth is spinning, because it stands neither for nor against the conjecture.

Evidence

A point that should be made clear to students is that evidence is created through arguments such as those just considered. Evidence is not simply found. It is a fact that the stars appear to move in circular paths. For that fact to become evidence, it must be linked through an argument to an interpretation. The link is that a spinning Earth would create the appearance of stars moving in circular paths around the axis of spin.

That is, if the Earth *were* spinning that would explain the circular motions of the stars as well as the occurrence of day and night. In contrast, the link from the fact of circular star movement to the idea that the Sun orbits the Earth is less direct. An additional and separate conjecture is needed to establish that connection—something like the stars also are spinning with respect to the Earth. According to this conjecture, the motion of the stars would not be apparent, but real.

Counterevidence

The word *evidence* often is understood only in its positive connotation. Indeed, there is research undertaken by social psychologists showing that there is a confirmation bias in people's reasoning. People tend to see positive evidence but overlook negative evidence, especially when the conjecture under test is a favorite idea (Nisbett and Ross 1980). However, just as there can be evidence *for* a conjecture, there can be evidence *against* it. It is important for students to learn that the surest guard against credulity is the disposition to seek counterevidence—in short, to be skeptical.

What counterevidence could students find against the conjecture that the Earth spins? There are several challenges that can be mounted. If the Earth were spinning, then either it would spin under the air, making all clouds, birds, and other things in the sky appear to be carried the opposite way, or the air would spin, with the Earth making it difficult or impossible for birds and planes to fly against the wind created. That wind speed would be very high all the time, because at the equator the speed of rotation would have to be on the order of 1,600 kph. A spinning Earth would either burst from such motion, literally flying apart, or objects not fixed to the Earth would fly off. Furthermore, if the Earth were spinning, surely you would not land on the same spot when you jumped straight upward. But we know that we do land in the same spot. Students can create even more arguments against the conjecture of the spinning Earth.

Each of these challenges is based upon an interpretation of what would happen were the Earth spinning. Students should be encouraged to provide arguments both for and against these interpretations. That is, the interplay between interpretation and argumentation continues beyond the presentation of evidence and counterevidence, to further arguments—themselves based on evidence—that attempt to counter the counterevidence. In principle, there is no end to how long this back and forth reasoning can proceed. In practice, it ends when scientists conclude that the evidence and argument are sufficient to support one interpretation over the others. Closure, after all, is a goal of science. Scientists move to the next problem once the current one has a coherent solution with sufficient evidence for it.

Coherence and Sufficient Evidence

Challenge students as follows: "Even if we accept the relevance of the counterclockwise circular motion of the stars and accept that it is evidence for the claim that the Earth spins, is it sufficient evidence? If so, why? If not, why not?" Help students see that the occurrence of day and night cannot be considered in isolation from other phenomena. If day and night are explained by a spinning Earth, we are still left to explain the seasons, the variation in the altitude of the Sun, the opposition of the seasons in the Northern and Southern Hemispheres, the motion and brightness of the planets, and the phases of the Moon. However we explain these additional phenomena, the explanations must be consistent with the idea that it is the Earth that spins, or something must be abandoned.

Students need to learn that interpretations of a single phenomenon rarely can be judged in isolation from the interpretations of other related phenomena. The accepted explanation of the Sun's changing altitude is that the Earth's axis of rotation is tilted 23.5° with respect to the plane of its orbit around the Sun. Some students might cite this explanation, but they should be challenged to show how it works. The comparative merits of a spinning and orbiting Earth on a tilted axis and an orbiting and oscillating Sun can be raised.

Conclusion

We started by identifying a simple view of science that many students hold even after years of science instruction—that the evidence for scientific beliefs must be directly observable. This misunderstanding of the nature of science is sufficiently problematic that it must be countered. Scientific ideas are imaginative and creative models of objects and processes that often are too small to be seen or too large to be comprehended in a single observation. In short, they are models that must be defended with arguments.

We have proposed a focus on the interpretation and argumentation required to come even to people's most cherished scientific beliefs. For example, nobody, even with all of our space travel, has directly observed that day and night are caused by the spinning Earth (at least nobody from this planet!).

The aim of our extended example was to illustrate how to think about our certainty regarding well-established scientific facts with the purpose of teaching important ideas about science:

- Observation provides only highly inferential access to knowledge.
- All scientific knowledge, even the seemingly simple ideas, is hard won.

Producing this knowledge requires going beyond what our senses tell us and imagining how the world might be. The example showed also that we cannot judge interpretations of one phenomenon without considering many others. Science is an interconnected web of ideas. Tweaking, adding, or removing a strand in one place has ramifications throughout the structure. The rebalancing is a difficult job requiring strategies of interpretation and argumentation:

- Conjectures must be made.
- The relevance of available facts and information must be judged.
- Evidence and counterevidence must be brought to bear upon each conjecture.
- The coherence and sufficiency of the evidence must be assessed.

A major aim of the science curriculum is for students to acquire an understanding of the scientific view of the world and to use scientific reasoning when appropriate. Ironically, this aim is undermined when students commit to memory a great deal of scientific knowledge but grasp little of the grounding for that knowledge, even of the broad shape that grounding might take. We know it is impossible for anyone to know the basis of all the knowledge upon which he or she must be prepared to act. We must accept much of what we know on the basis of credible authority and without ourselves inquiring into the evidence. Wholesale skepticism is debilitating.

Nevertheless, it is important to imbue students with a reasonable level of skepticism; otherwise, they may fall into another equally undesirable frame of mind—credulity. The science classroom is an appropriate site for learning that we can believe too easily and that what appears self-evident often is not. Ask yourself, how you would convince a serious skeptic that matter is made of atoms; that the Earth is not motionless; that nearly all the matter in a tree did not come from the ground; and more?

Science education offers an important context for the critical examination of belief—a frame of mind that is as important outside of science as it is within science. Paying close and detailed attention at least occasionally to the interpretation and argumentation that underwrite even the most taken-for-granted scientific facts is one means for promoting healthy levels of skepticism and for avoiding credulity—in short, for teaching scientific inquiry.

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