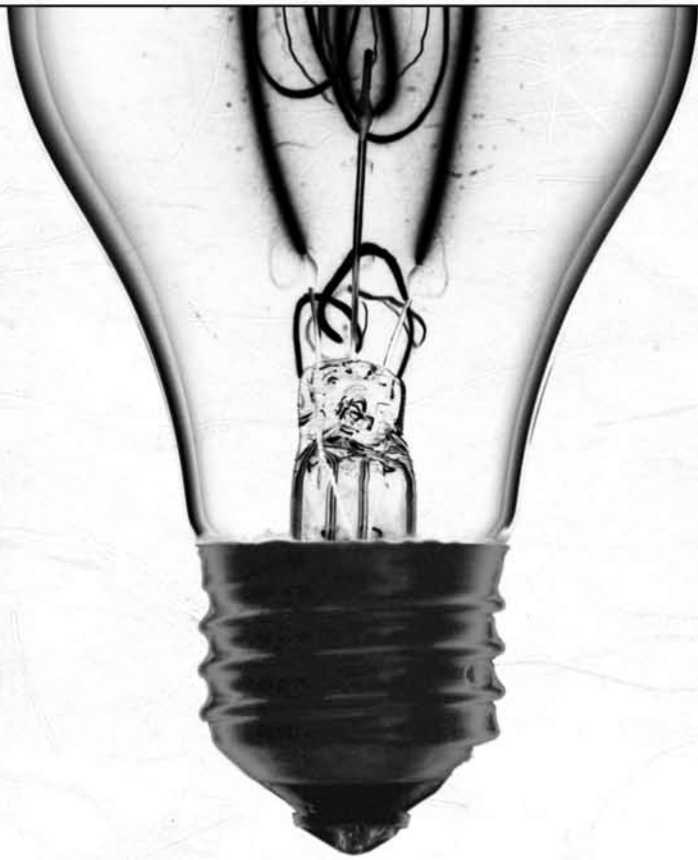
Science as Inquiry in the Secondary Setting

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,
Maine Mathematics and Science Alliance

Preface

S*cience 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

What Is Inquiry? A Framework for Thinking About Authentic Scientific Practice in the Classroom

I

Mark Windschitl, University of Washington

The idea of inquiry can be perplexing to many of us in science education. The National Science Education Standards (NRC 1996, p. 31) proclaim that inquiry is "at the heart of science and science learning" and represents "the central strategy for teaching science." Yet, if you were to visit a number of typical classrooms where students were purportedly engaged in inquiry, you would likely have great difficulty figuring out what the various activities had in common.

In one high school for example, a group of 10th-grade biology students might be trying to determine the source of pollution in a local stream and how they could clean it up. Just down the hall, a group of 12th graders in a physics class might be conducting student-designed investigations on the thermal insulating properties of manufactured materials. Across the street at the junior high school, 8th-grade Earth science students might be following a highly structured protocol to find the densities of mineral samples, while the 7th graders next door might be writing a research paper on how climate change influenced the extinction of the woolly mammoth.

Teachers in each of these classrooms would likely refer to their instruction as inquiry based, and each of these scenarios could indeed be broadly described as "working out answers to questions or problems." But these examples are not simply variations on a theme—the intellectual work required of students and the learning outcomes in each of these cases are fundamentally different.

In this chapter, a framework is suggested for organizing teacher thinking about inquiry and prioritizing the wide assortment of activities teachers typically use to familiarize their students with the processes of science. This framework articulates three families of school science activity. One family represents the core knowledge-building practices of science. A second represents activities that support the core practices in various ways. And a third family of activities—common practices that need to be reconsidered—actually distracts students from meaningful learning.

Family 1: The Core Knowledge-Building Activities of Science

Scientists engage in a wide range of activities. They watch other members of their profession perform demonstrations of new equipment and techniques, they build laboratory skills over time (e.g., safety practices, using equipment, learning specific procedures), they replicate other scientists' experiments, they invent new technologies, they conduct thought experiments, they conduct library research, and they use knowledge to solve practical problems. All of these activities are valuable for school science learning as well, but there are particular practices that are integral to the core work of science—this core being organized around the development of defensible explanations of the way the natural world works (see, e.g., Giere 1991; Longino 1990). Roughly speaking, these explanations come from the process of developing models and hypotheses and then testing them against evidence derived from observation and experiment.

Four Conversations That Make Up the Core Knowledge-Building Activities

When we think of doing science, we usually envision a laboratory or field activity—for example, people working with materials, collecting data, graphing results—but these activities are only part of the story. Scientists are ultimately engaged in developing persuasive arguments around competing explanations for natural occurrences. Everything else that comes before (the questioning, the hypothesizing, the measuring, the analyzing) merely sets the groundwork for the culminating argument. So, although the investigative *activity* provides the critical context for learning, the *science-specific forms of talk* move scientists' (or students') thinking forward.

Think of this talk as a set of four interrelated conversations that support students' understanding of the intellectual and material work of science.

1. Organizing what we know and what we'd like to know.

2. Generating a model.

3. Seeking evidence.

4. Constructing an argument.

As students are invited to participate in these conversations, they come to understand that "science talk" is a system of rhetoric with certain conventions about the topics of conversation (what happens in the natural world), forms of knowledge used (theories, models, laws, facts), rules for argument (e.g., explanations must be coherent, plausible, and consistent with evidence), and goals (producing explanatory accounts for natural phenomena).

Before these four conversations begin, the teacher must set the stage by considering some puzzling or otherwise motivating problem with which students can engage. Not all interesting ideas are equally important; those that can be used to explain other phenomena in the world are more central to science than are ideas that are interesting but do not increase our understanding of the world.

Studying widely applicable ideas like wave motion, inheritance, or chemical equilibrium, for example, provides students with powerful conceptual tools for understanding much of what they see around them. By comparison, if your students are interested in the relative absorbency of different brands of paper towels or finding which glue has the strongest adhesive properties, the knowledge they gain will not likely be useful in other circumstances. The point here is that inquiry experiences should foster a deep and well-integrated understanding of important content, as well as the reasoning skills and practices of science—the separation of "learning content" and "doing inquiry" is entirely unnecessary. Once interest is established in a motivating and conceptually important topic, the first of the four conversations can begin.

Conversation 1: Organizing What We Know and What We'd Like to Know. In school science, students often begin investigations with surprisingly sparse and disorganized background knowledge, which leads to superficial inquiries that add only trivial descriptive notes to what they know and fails to explore underlying causes for phenomena. Students must first gather background information on the inquiry topic (e.g., from hands-on activities, texts, guest speakers, the media, or the internet or by making systematic observations of the phenomena in question). They should then organize and "externalize" their thinking on paper in the form of scientific models.

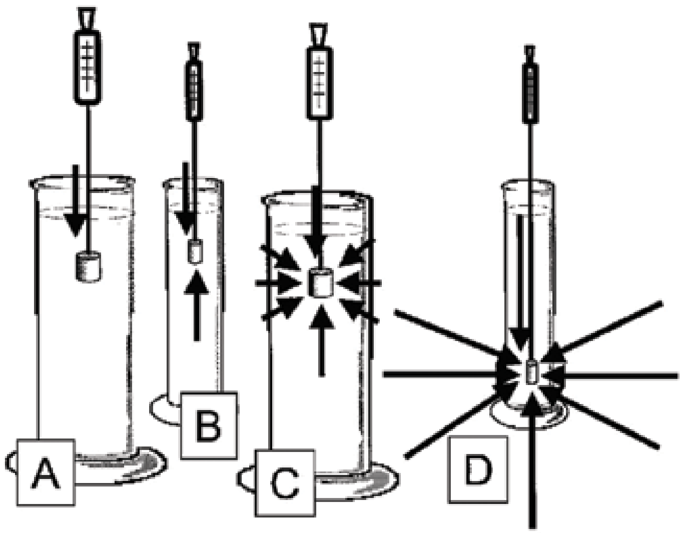
Scientific models represent ideas—ideas of how the natural world is structured or how it operates. Models can take many forms in science (e.g., written explanations, concept maps, graphs, diagrams, equations, physical representations). Regardless of the forms they take, models are anchored in phenomena and represent interrelationships among entities, properties, events, and processes. Some models are subsets of larger systems of explanation referred to as "theory" (e.g., theories of evolution, plate tectonics, molecular motion), and others represent everyday events such as the feeding habits of fish in an aquarium or the means by which a bike helmet protects a cyclist's head in an accident.

As an example, a group of 9th graders were curious about why objects feel as if they weigh less under water. Their teacher wanted to see which conceptual frameworks the students used to think about this problem and asked them to draw a diagram of how they thought forces acted on a submerged mass. The students' initial model, however, failed to suggest why the mass weighed less after it was submerged (A in Figure 1.1). B in Figure 1.1 is a more accurate version that was developed after some instruction, and C and D in Figure 1.1 are even more developed models that could be used to explain a variety of phenomena, including why submarines risk having their hulls crushed at great depths. Developing such representations is important to the learning process because

- they can be shared with others and critiqued;
- they can help learners see connections between ideas in ways that other representations (such as oral explanations) will not allow;
- they can be changed as the class (or individual) learns more; and
- the production of models helps teachers recognize gaps in students' thinking that must be addressed before the inquiry can move forward.

Students should learn to talk about the framework of their existing knowledge *as* a model—recognizing that models are not "copies of reality," that a model is tentative and can contain unseen entities or processes (such as forces and buoyancy in Figure 1.1), that there can be multiple forms of models for the same phenomenon, and that models help generate ideas.

FIGURE 1.1. PROGRESSIVE MODELS OF FORCE ON A SUBMERGED OBJECT



Based on the idea that "organizing what we know and what we'd like to know" is a critical first step in authentic inquiry, certain kinds of student conversations are necessary to make this a meaningful process within the larger context of the investigation. The following are a number of key questions that engage students in such conversations (not all can be explored, of course, in any one inquiry).

- What do we already know about this situation, process, or event?
- Could there be more than one way to represent this situation, event, or process?

- Is our model purely descriptive of the situation, process, or event, or does it have parts that try to explain what is happening?
- What questions does this model help us ask?
- What additional information do we need in order to improve the initial model before asking our final inquiry questions?
- How can our questions be framed so that they can be answered by collecting and analyzing data?

Conversation 2: Generating a Model. Models created by students represent their best current understanding of how some aspect of the world works. Students' inquiry questions should relate to some puzzling "piece" of this model. The model not only helps prompt more informed questions, it becomes the logical basis of the hypothesis. A hypothesis is a prediction for the kind of results one would expect from data collection if the initial model were accurate or complete. For example, students might use the model in C in Figure 1.1 to predict that a mass weighs less when immersed just below the surface, and this weight does not change significantly when it is submerged at greater depths.

As mentioned earlier, students may be so unfamiliar with a phenomenon that they will need to do some hands-on activity and make initial observations before they are able to develop any sort of model. Questions that can prompt students to explore a model include the following:

- Do we need to do some initial exploration and data collection before we can begin to develop a tentative model?
- What aspect of the model do we want to test?
- When we look at our tentative model and consider the question we want to ask, what would our model predict?
- How can we test the model in a way that generates better descriptions of how this phenomenon happens?
- Can we test the model in a way that helps us understand some process that is not directly observable?

These questions are often addressed in conjunction with the third set of conversations—referred to as seeking evidence.

Conversation 3: Seeking Evidence. At this point, students have proposed a model and are considering what the model might predict about real-world outcomes. These outcomes are the products of systematic data collection. Data can be generated from controlled experiments, but data can also come from observations in which students do not actively manipulate variables (astronomers, for example, make carefully timed observations of new stars, and field biologists record the advance of invasive species in selected environments). Conversations about generating data should include the method students will use to analyze that data and represent it. Here are some questions that students need to discuss in order to grasp the meaning of "generating evidence" and be able to design their own studies eventually:

- How can we define our variables in ways that will allow us to record consistent and accurate measurements?
- How does the data we want to collect help us test our hypothesis?
- What will it mean to collect data "systematically"?
- To test our hypothesis, should we observe the world as it is or actively manipulate some variables while controlling others?
- When we analyze our data, will we compare groups? look for correlations between variables? seek other kinds of patterns?
- What forms of representation (e.g., tables, graphs, charts, diagrams) are most appropriate for the type of data we will collect?

Conversation 4: Constructing an Argument. In science, arguments are about whether hypotheses, based on a model, "fit the world"—that is, are the data consistent with what the model predicted? Data become evidence when they are used to support an argument. The most famous investigations in science history had to be put forward to the science community as evidence-based arguments (the Sun-centered universe by Copernicus and Galileo, plate tectonics by Wegner, relativity by Einstein, natural selection by Darwin). Argument is not the same as stating a conclusion. Too often, students end their investigations by declaring that they found an unexpected trend, a difference between an experimental and control group, or some other pattern. They further claim that their data collection strategy was appropriate, that they were careful and accurate in collecting the data, and that they analyzed the data properly. Although these are important pieces of an argument, this way of ending an investigation neglects key elements of the persuasive core of science.

An authentic argument has four features:

1. It describes a potential explanation for the phenomenon of interest.

2. It uses the data collected as evidence to support this explanation.

3. It acknowledges any other possible explanations that would fit the data.

4. It describes if and how the initial model of the phenomenon should change in light of the evidence.

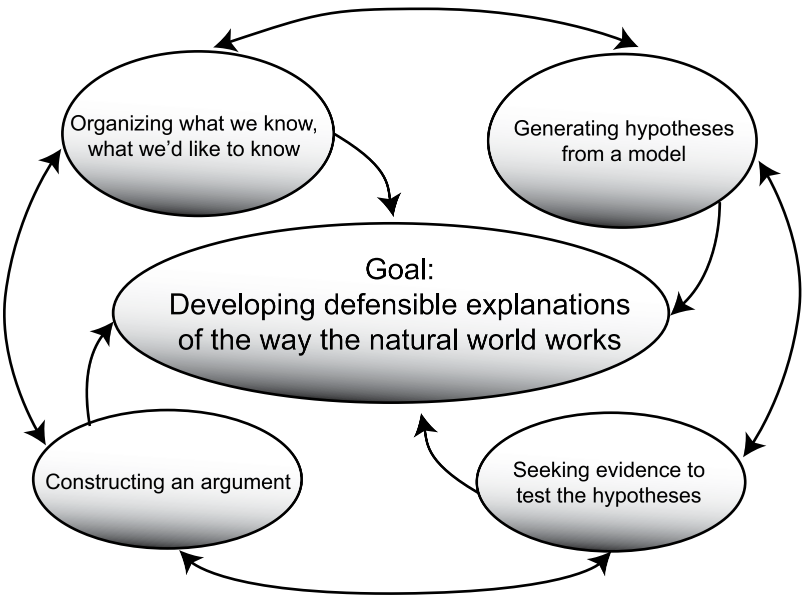
The following are questions students should explore as part of these conversations:

- Was the prediction of our original model consistent with the data we collected?
- Are we using our data to argue for a simple cause-and-effect relationship between variables, or are these variables only correlated (without causing one another)?
- Do the data provide support for theoretical (unobservable) processes in our model?
- How consistent and coherent is our final explanation for the phenomenon of interest?
- Do other possible explanations for the data exist, and if so, how strong is the evidence for these alternatives?
- Should our model change in light of the evidence?

Summary of the Four Conversations

At first glance, it appears that these four sets of conversations should take place in the sequence described here, but they rarely do (see Figure 1.2). As with authentic inquiry conducted by scientists, student investigations are organic, recursive processes requiring students to revisit previous conversations constantly when new information emerges. For example, in the midst of data collection, even before it is analyzed, scientists often learn things that put them back into conversations about the models they had developed earlier. Revisiting previous conversations like this is the rule rather than the exception. Of course, no teacher can ask all of these questions during the course of any one inquiry, but every inquiry should include some parts of these four conversations. As students gain experience with guided forms of investigation, they become more competent inquirers by "internalizing" these conversations—eventually asking themselves these questions without prompting from the teacher. In this way they come to understand the meaning and interconnectedness of these scientific activities.

Figure 1.2. The Four Conversations Supporting the Core Knowledge-Building Activities of Science



A number of research reports provide evidence that this teaching approach is effective for learning both content and scientific reasoning. See, for example, research on high school students studying genetics (Cartier 2000) and physics topics (Wells, Hestenes, and Swackhamer 1995), middle school students inquiring about force and motion (Schwarz and White 2005), and 4th graders exploring how light interacts with materials (Magnussen and Palincsar 2005).

Two vignettes are included in this chapter that illustrate how teachers can infuse these critical conversations into an inquiry. The first is of an 8th-grade Earth science teacher using a guided investigation to help his students understand the relative motions of the Earth, Moon, and Sun. This example illustrates a number of opportunities for student talk and also demonstrates that inquiry can be used to deepen students' understanding of important concepts in science. This vignette is paraphrased from *Inquiry and the National Science Education Standards* (NRC 2000). The second vignette is based on the experiences of a 10th-grade biology teacher who had her students investigate the local causes of asthma in young people. It represents inquiry that emerges from student interest and is complex in that it has no single right answer.

Vignette 1. Phases of the Moon[1]

Mr. Gilbert, a middle school teacher, knows that most of his students have difficulty constructing an explanation for the Moon's phases that is consistent with their everyday observations. He also knows that a grasp of this phenomenon is important because it demonstrates that objects in the solar system have predictable motion and that these motions explain other occurrences, such as eclipses, the year, and the day/night cycle.

Mr. Gilbert begins by asking his students what they think they know about the Moon and listing these ideas on the board (starting the "Organizing What We Know" conversation). The students call out that "the Moon changes shape," "the Moon is smaller than the Earth," and "people have walked on the Moon." Next Mr. Gilbert asks about questions they have and writes these out as well: "Should we try to land on the Moon again?" "Why don't eclipses happen more often?" "How wide across is the Moon?" and "How often do we get a full Moon?"

Mr. Gilbert realizes at this point that his students need more information before they can develop even a beginning model of the behavior of the Moon. Using homemade sextants constructed of protractors, straws, and string, he asks students to collect data about the position of the Moon in the sky and the Moon's shape. He then initiates a conversation around how to be systematic about collecting and recording this data (a part of the "Seeking Evidence" conversation). Some of his students comment that the Moon should be viewed at the same time every day. Others add that everyone should follow the same directions for using the sextants (see Sidebar 1).

A few weeks later, when students have made their observations, Mr. Gilbert returns to the Moon unit and asks students to display their observation charts on the wall of the classroom. Students talk about the patterns they see in the changing shape of the Moon and offer explanations that might account for their data. Prompted by these descriptive models, some students want to know what causes the patterns they have just witnessed. Mr. Gilbert presses everyone to suggest an explanatory account of the observed phenomenon (see Sidebar 2).

Some students immediately propose that the Earth's shadow covers different amounts of the Moon's surface at various times of the month. Others contend that as the Moon moves through its orbit we see different sides of the Moon illuminated by the Sun. Mr. Gilbert then asks students to divide into small groups and make a labeled drawing that supports each group's explanation for the Moon's changing shape (getting further into the "Organizing What We Know" conversation). He asks students to talk with one another about how they might use the models to test the two different explanations (starting the "Generating a Model" conversation).

The next day, students design an investigation using globes for the Earth, tennis balls for the Moon, and an overhead projector for the Sun (they participate in the second round of the "Seeking Evidence" conversation). Mr. Gilbert circulates among the groups, probing their understandings and focusing their thinking on the relationship between evidence and explanation: "Where would the Moon have to be in your model to result in a Quarter Moon?" "Show me where the Earth's shadow would be." "What evidence do you have that supports your conclusions or causes you to change your mind?" (See Sidebar 3.)

When needed, he asks students to refer back to their chart of the Moon's phases and reminds them, "A good model will explain that data" (all questions and prompts here are part of the "Constructing an Argument" conversation).

Mr. Gilbert begins the next class by asking each group to post its model drawings and invites the rest of the class to examine

Sidebar 1

Here Mr. Gilbert has accomplished several things. First, the activity has generated interest and focused students on the phases of the Moon. Second, he has asked students to talk about what they currently understand about the Moon. This gives him a picture of what additional kinds of activity will be necessary for them to ask more meaningful questions. Third, the Moon-charting activity has allowed students to talk about being systematic in collecting data. The chart serves as a kind of initial model from which hypotheses can be generated.

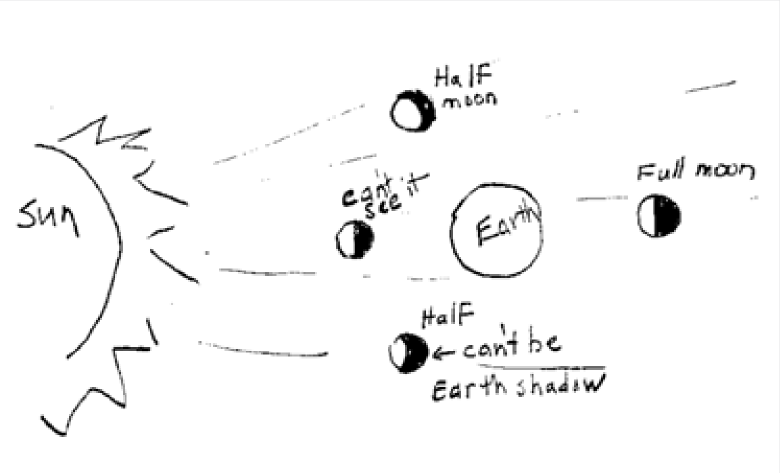
Sidebar 2

Mr. Gilbert now helps his students explore the difference between description and explanation. The students begin to offer hypotheses about what causes the Moon's phases, but Mr. Gilbert wants them to create explicit representations of how they think this phenomenon happens, prompting them to develop both a causal model and a hypothesis that can be logically derived from it.

the results. Most observations seem to support the explanation that as the Moon moves in orbit around the Earth the amount of the lighted side that can be seen from the Earth changes. The students agree that comparing the order of the phases in their model to the order of Moon phases shown on a calendar helps them assess the apparent relationship between the Earth, Sun, and Moon.

One team points out that during the first quarter phase of the Moon the Earth's shadow would have to turn at a right angle in order to fall on the Moon, and they note that light and shadows do not work that way (Figure 1.3).

Figure 1.3. Student's Model of the Cause of Moon Phases



Based on such evidence, even the students who proposed the "Earth's shadow" model decide to reject it. Mr. Gilbert adds a provocative question: "Some of your models predict that an eclipse would happen every month, but we know that doesn't happen. (See Sidebar 4.) How would we have to change your models so that doesn't happen?" He later asks, "Which features of your models work well? Which don't?" (All these questions are part of the "Constructing an Argument" conversation.) The students respond that their models still do not do a good job of explaining the height of the Moon above the

Sidebar 3

Here Mr. Gilbert repeatedly encourages students to talk about the relationship between their models, their hypotheses, and the evidence they are collecting.

Sidebar 4

In the final days of class, students are asked to share their models and reflect on and talk about how logical their model-based explanations are ("light cannot turn at right angles"), how predictive their models are, which features of their models work well and which don't, and how they might revise their models based on evidence and more library research.

Earth's horizon each day, but they do show how the phases of the Moon occur. He asks them to do more reading in the library to help them make their models even more consistent with how the Moon behaves (returning to the "Organizing What We Know" conversation).

As a final assessment, Mr. Gilbert asks students to look at the activities the class had completed and record in a summary table all the evidence that supports or refutes the class model of the phases of the Moon. While his students complete this task outside of class, Mr. Gilbert uses the final two days of the unit to explore with his students the classic debates about the Earth-centered versus Sun-centered models of the solar system and the evidence that Copernicus and Galileo used to support their explanatory model (an extension of the "Constructing an Argument" conversation into historical episodes).

[1]This vignette is paraphrased from National Research Council (NRC). 2000. *Inquiry and the national science education standards: A guide for teaching and learning*. Washington, DC: National Academy Press.

Vignette 2. Studying Asthma in Young People

Ms. Thompson teaches 10th-grade biology in an urban high school. Her students come from working class families, and most of them have at least one family member or friend with some sort of respiratory illness. In planning a unit on the human body, Ms. Thompson thought she could "hook" students on studying asthma to better understand the influences of the environment on the body.

Ms. Thompson opened the unit by showing her students newspaper articles of how the rate of local children hospitalized with asthma had risen by more than 25% over the past 10 years. Students immediately began to ask questions: "Is asthma genetic?" "Is asthma triggered by outdoor pollution or indoor conditions?" "Can we do something about the rates of asthma in our neighborhoods?"

The students' first task was to sketch out on poster board different sources of pollution that students believed could trigger asthma attacks (beginning the "Organizing What We Know" conversation). When they had completed their drawings, Ms. Thompson noticed that they were aware of many sources of pollution, but that these were all outdoor examples—most students included pictures of industrial sources and their own school buses.

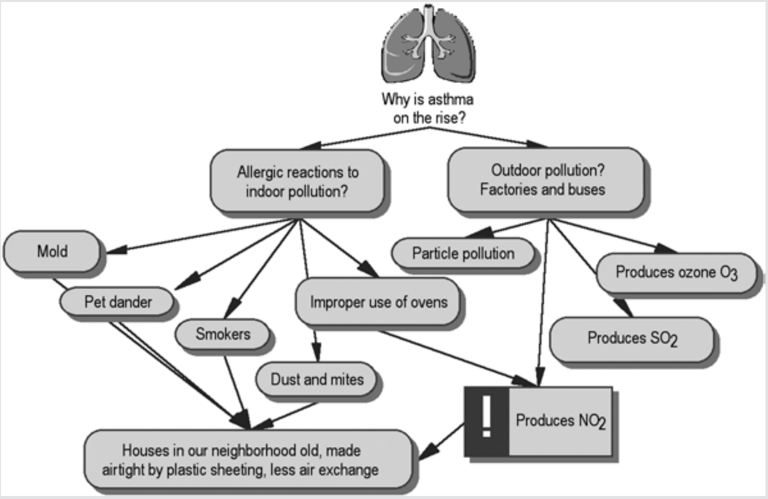
The next day Ms. Thompson distributed public service announcements from the Centers for Disease Control and Prevention that outlined common triggers for asthma attacks, including some indoor sources (dust, mold, cold air). These information sources included details about how studies on asthma were conducted (e.g., the sample populations, types of data collected, methods of analysis). Ms. Thompson then asked students to form small groups to specialize in one of these triggers and to find evidence-based information that could be presented to the class. Students were asked not only to share information, but to describe the strength of the evidence for the claims in the studies they cited. This prompted a discussion about what is meant by "convincing evidence" (the "Constructing an Argument" conversation using existing data; see Sidebar 5).

A couple of days later, as students shared their findings, they were surprised to discover that their own neighborhoods had the highest rates of asthma in the city and that the causes of these asthma attacks were not well understood. From their background readings, the students then developed a class concept map of the triggers for asthma attacks (elaborating on the "Organizing What We Know" conversation). From this tentative model (see Figure 1.4), students noticed that one possible trigger, NO_2, was an air pollutant produced by factories, but also produced in homes when people used their ovens.

Sidebar 5

Notice here that the "Constructing an Argument" conversation does not have to take place at the end of an inquiry. The order of these conversations is contingent on student interest and opportunity.

Figure 1.4. Students' Group Model for Triggers of Asthma



Several students commented that they knew people in poor neighborhoods who heated their homes in the winter by keeping their ovens on all night. Other students proposed that exposure to cigarette smoke was the cause of the high rates of asthma. Ms. Thompson asked her students to decide what kind of data they would need to collect to test these different hypotheses (initiating the "Generating a Model" conversation).

As a class, the students decided to create an anonymous survey about conditions in homes that could lead to asthma attacks and distribute it to all 200 students in their sophomore class. Before writing questions for the surveys, Ms. Thompson asked students to imagine taking the responses and putting that data in a table. She asked, "What would this table look like?" "Are you asking yes/no questions about smokers in the house? the number of people in the house who smoke? where they smoke?" "What kind of data analysis would each of these different kinds of data allow you to make?" (pressing students on the "Seeking Evidence" conversation).

After students found and fixed flaws in their questioning strategies, the final surveys were distributed. As the surveys were returned, students interested in testing the hypothesis about smoking decided to correlate the number of cigarettes smoked in the house with the number of asthma incidents of residents in the past month. They put their findings into a scatterplot and found a modest but significant correlation. The group testing the oven hypothesis found that only five respondents had indicated their family used ovens to heat their homes, so they felt their findings were inconclusive.

Ms. Thompson then asked students to present final arguments to their peers and for everyone to play a role in critiquing the claims (includes all students in the "Constructing an Argument" conversation). When those presenting the smoking hypothesis concluded that their evidence was strong—that exposure to cigarette smoke caused asthma attacks—several students in the audience asked why they believed this was a causal relationship and not just a correlation. When Ms. Thompson asked if there were any alternative explanations for their findings, one group of students noted that in the surveys, many of those respondents who said they smoked also said that they placed plastic on their windows during the winter to keep the house warm. These students then suggested that rates of smoking also correlated with keeping homes sealed up and that lack of air circulation may be a complicating factor in deciding what actually causes asthma attacks.

For a final assessment, Ms. Thompson asked her students to write individual proposals for a follow-up investigation that would take into account findings from their current study and disentangle correlation from causation with regard to exposure to cigarette smoke and the triggering of asthma attacks.

These vignettes provide just two examples of students creating and critiquing evidence-based explanations of how the world works. If any investigation in which students have the opportunity to engage in these four conversations can be considered a core inquiry experience, then a wide variety of circumstances exist in which this experience can happen. Students, for example, might use existing databases to pose and answer questions; they could also use computer-based simulations to generate and analyze data. In other cases, teachers could set up conditions for thought experiments in which students discuss what-if scenarios. An example would be presenting a food web diagram and asking, “What if this species of plant were to die out? What would be the impact on the rest of the system?” Students could also deconstruct claims and arguments of existing scientific reports written in nontechnical terms. Finally, long-term projects can provide rich contexts for authentic inquiry. A problem like “How does run-off from agricultural land affect local aquatic ecosystems?” can be of such scope that it contains numerous opportunities for empirical investigations (e.g., determining the effects of a single chemical on one species of macro-invertebrate in a pond).

Family 2: Activities That Support the Core Work of Inquiry

In addition to the core work of inquiry previously described, many other types of classroom activities are often referred to as inquiry. These, however, may be better thought of as *supporting activities* of inquiry. Supporting activities prepare students to participate more meaningfully in the core activities of inquiry by acquainting them with necessary concepts, ideas, and skills. Here are some examples:

- Conducting background library/internet research.
- Watching teacher-led demonstrations.
- Performing lab-practicals where one identifies natural materials or features (e.g., rocks, xylem versus phloem in plant stems, different gases).
- Engaging in exercises to “make something happen” (e.g., convection currents in an aquarium, an acid-base reaction).
- Designing/building machines or other technologies.
- Learning the use of equipment or lab procedures.

These supporting activities can contribute to students’ abilities to engage in the core conversations of inquiry. Too often, however, these are treated as the inquiry itself. Students might, for example, learn to replicate the experiments of others but never design their own, or they might do library research on current scientific controversies without ever getting to argue about evidence *they* have generated in support of a hypothesis. Part of good teaching is knowing when and how the supporting activities can contribute to students’ conversations about the core knowledge-building activities of science.

Family 3: Common Practices That Need To Be Reconsidered

Many teachers already engage their students in a range of interesting activities. These practices could be considered good starting points from which to move toward more authentic forms of inquiry. Although each of the common practices described here have some shortcomings, they can be modified to become more like the core knowledge-building practices of Family 1.

First, a word about the "scientific method." Science textbooks have placed much emphasis on this formula (making observations, defining the problem, constructing hypotheses, experimenting, analyzing results, drawing conclusions), but most scientists say it is a misrepresentation of the way science really works. First, within the traditional scientific method, questions are often based on what is interesting or doable, but they are not grounded in any coherent model. As a result, school science investigations are often uninformed and without content (e.g., experiments to determine which paper towels hold the most water). Data from these experiments are then analyzed to determine only how outcomes are related to conditions (e.g., whether small crystals of sugar will dissolve faster in water than large sugar crystals), but underlying explanations (how molecular motion helps break the chemical bonds of sugar) are rarely addressed (Chinn and Malhotra 2002; Driver et al. 1996).

The second flaw is related to the first: Because the scientific method has no provisions for students to develop an initial model to inform their questions, there can be no argument at the end of the inquiry about how their evidence fits the model. The third problem with the scientific method is that it often promotes experimentation as the only method of investigating the world (where there is a comparison between a control group and a manipulated experimental group). In science fields such as geology, field biology, natural history, and astronomy, controlled experiments are all but impossible—yet scientists in these fields all use systematic collection of data and coordination of evidence to propose explanations.

A collective reliance on oversimplified formulas for inquiry learning has given rise to some classroom practices that need to be reconsidered. Here are four examples:

Investigating arbitrary questions. Science inquiry does not involve questions such as "Will my bean plants grow faster listening to rock and roll music or classical music?" A question like this, although testable, has little to do with the development of any coherent understanding of underlying causes.

Investigations outside the bounds of the natural world. School science includes the broad domains of physics, biology, Earth and space sciences, and chemistry. It does not investigate questions of human behavior, such as, "How many students prefer pizza versus tacos for lunch?" or "Does extrasensory perception really exist?" Although these can be motivational hooks for students, they are essentially inquiries without content.

Cookbook investigations. Some activities are so rigidly scripted that students do not have to employ any reasoning skills—all they have to do is follow instructions. Students can, in fact, get passing grades in these activities without having a clue about the meaning of the work they are doing. Such confirmatory exercises can have a legitimate role when students have no previous inquiry experiences at all to draw upon, but a steady diet of these will soon cause students' enthusiasm for science to wither away.

Substituting isolated process skills for complete inquiries. From the research on learning, there is little evidence that process skills (observing, classifying, measuring, predicting, hypothesizing, inferring, and so forth) learned in isolation help students understand the purpose of these skills or how they should be used in real investigations. Inquiry should instead be treated as a *coordinated set* of activities and *taught as a whole*. Inquiry should be kept complex, but the teacher should scaffold students' efforts as needed.

Conclusion

School science inquiry was presented here as a persuasive enterprise based on four interrelated conversations in which students engage. These conversations link models, hypotheses, evidence, and argument, but more to the point for students, they help answer the question, "Why are we doing this activity?" The aim of doing more authentic science in schools is not to mimic scientists, but to develop the depth of content knowledge, the habits of mind, and the critical reasoning skills that are so crucial to basic science literacy.

Framing inquiry as a set of conversations means that teachers will need to be skilled in orchestrating productive discussion in the classroom. They will have to encourage a climate for conversation, pay close attention to students' ideas, scaffold complex activities, and assess the intellectual development of students as they learn to "talk science." On a more systemic level, it will require that schools measure the rigor of a curriculum not by the sheer quantity of topics addressed but by the in-depth understanding sought through an engagement with a limited number of key ideas in science.

The ideas presented in this chapter challenge common beliefs about what passes as inquiry in science classrooms. For teachers interested in changing their practice, the most effective way to begin is to join like-minded colleagues to discuss the inquiry framework outlined here ("How does this framework differ from how we understand inquiry?"), analyze how inquiry is currently being practiced in their classrooms ("Where does our current practice fit into the 'families' of inquiry presented here?" "Are there elements of these four conversations that already take place in our curriculum?"), and then ask how they might support one another in adapting practice to include the core knowledge-building practices of science ("How could we systematically foster these kinds of conversations about questions, models, data, evidence, and argument?").

As you read the following chapters in this book, consider how the images of inquiry presented in this chapter reappear in creative and dynamic ways.

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