Chapter 1

Take Us Out, Mr. Data

What's the most important thing to know about scientific knowledge?

In this section, you will come to see how

- scientific knowledge is based on empirical evidence, and
- science is limited to answering questions about the natural and material world.

You will be able to

- help your students perform scientific investigations via operational questions, and
- discuss similarities between student investigation activities and scientists' activities.

Here's a riddle: What do love, wind, luxury, and science all have in common? They are all easy to recognize, but hard to define, especially in ways everyone would agree upon. In the case of science, we often define the term with vague phrases, saying "science is a way of knowing" or talking about science as "a process." Sometimes my students speak even more broadly, writing that "science is everywhere" or "everything is science." Not very useful.

The demarcation problem is the philosophical issue of determining what is and is not science.

But defining science more specifically is hard. In 1997, Brian Alters published an article providing evidence that even people who study the nature of science disagreed about what it was they were studying. My colleagues quickly responded (Clough, 2007; Smith et al., 1997), accenting the disagreements as minor points. Despite widespread agreement on most points, philosophers of science nevertheless discuss the issue so much they have a special phrase to describe it: ***the demarcation problem***. How do we demarcate, or distinguish, what is science from what is not?

This is a book for teachers, so let's start addressing the question via a classroom activity, a fun one I'll call Milk Fireworks. You may also recognize it by another name like "Cat's Meow," or "Breaking the Tension" (Bergman & Olson, 2011).

ACTIVITY 1

Milk Fireworks

Overview: Students perform an investigation activity with familiar everyday materials that introduces the kinds of questions scientists ask, and the practices they use when trying to figure out answers.

Grades: This investigation activity is definitely appropriate for all grade levels. Older students, however, may be more successful than younger ones at coming up with their own questions and procedures to investigate.

Time needed: Part I takes less than 10 minutes, once materials are assembled. Time for the rest of the investigation activity varies, depending on teacher and student interest.

MATERIALS

Part I

- Petri dishes or similar shallow dishes
- Whole milk
- Food coloring (at least two colors)
- Toothpicks
- Liquid dish soap

Part II

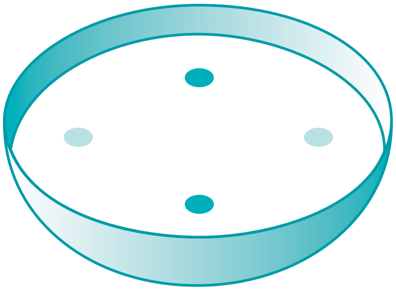
- Optional additional materials: different kinds of milk (whole milk, 2% fat milk, skim milk, cream, nondairy milks), different sized and shaped containers, other liquids (e.g., water, vegetable oil, or corn syrup), other liquid detergents or dish soaps, various colors of food coloring, milk at different temperatures, and various other materials based on student and teacher interest

TEACHER INSTRUCTIONS

Part I

1. Have students take a Petri plate or other shallow dish and put a little whole milk into the dish, enough to cover the surface of the plate.
2. Have students place two drops of food coloring at the 12 o’clock and 6 o’clock positions of the dish.
3. Then have students place two drops of a different color food coloring at the 3 and 9 o’clock positions.

FIGURE 1.1 Milk Fireworks



Milk Fireworks initial setup

4. Students should dip a toothpick into the milk in the center of the dish and quickly pull it out of the milk, then record their observations.
5. Now, they repeat the toothpick procedure, but first dip the end of the toothpick into dish soap.

Part II

6. Have a whole-class discussion asking students to brainstorm a list of questions they have about what's going on, recording the list of questions for everyone to see.
7. Take the list of questions students brainstormed and divide them into questions that can and cannot be answered directly by doing investigations. Accent how science is about asking and trying to answer the latter category, questions that are testable.
8. With your guidance, students can select one or more testable questions, figure out procedures to address the question, and go on to do the investigations. You'll probably want students to write the question(s) they are testing, what they did to try answering the question, and what they found. You can do this with a worksheet students fill out, journal, interactive notebook, or any other method you like.
9. After completing their investigations, students share what they found, stressing the evidence supporting their ideas (i.e., what they observed during their investigations). The sharing can be individually (through writing), via pairs or small-group discussions, via a whole-group discussion, or again, any other method you like.

What's Happening? Water tends to stick to itself, a phenomena scientists call surface tension. They believe detergents disrupt surface tension, ultimately pulling the water's surface in various directions.

TRY IT!

Unless you're teaching students about surface tension, properties of water, or colloids (see the *What's Going On in the Science* section, below), it may be difficult to connect this investigation activity with a larger 5E or learning-cycle model based science unit. However, students find the activity highly *engaging*, and it works well as an *exploration*. When you add in the fact its materials are familiar and readily available, Milk Fireworks works well early in the school year or as a 1-day standalone activity. It's easy, cool, and accents how science is about asking and answering questions.

TEACHING TIPS

Steps 1–4: Even though I don't want to spoil the spirit of inquiry, I am going to give it away: After completing the first four steps in the investigation, that is, when students dip a toothpick into the center of the milk-filled dish, they will observe nothing. Nothing much happens. But . . .

Step 5: When students then dip a toothpick with detergent on the end into the dish, something cool happens. The milk and food coloring will appear to move, with the colors swirling.

If you've never done this activity before, you should give it a try first on your own. Notice what happens, imagine how your students will react, and think through how you'll manage the activity. As you are an experienced teacher, I don't feel it's my place to tell you how to manage the more general aspects of investigation activities. But, I do offer suggestions from some of your colleagues in Appendix B.

Steps 6–8: At this stage of the activity, as you facilitate a classroom discussion about your students' observations and questions, here are three things to keep in mind.

First, I recommend you simply accept what students say, neither praising nor rejecting—by saying things like "OK," "got it," repeating what the student says, or saying "thank you"—write their questions someplace for everyone to see, and encourage continued question generation. Students will start generating questions like

- "Why did the milk swirl?"
- "Will it still swirl with skim milk instead of whole milk?"
- "Will we be able to see the milk swirling without any food coloring?"
- "What will happen if we put the soap on the food coloring?"
- "Will it work with other soaps?"
- "What if we use warm milk?"

Key Takeaway

Accepting student responses, and waiting several seconds after a student has responded, encourages other students to respond.

Operational questions are those that can be investigated and directly answered with evidence from investigations.

Second, once your students have generated some questions, divide them into two categories: those that can and those that cannot be answered directly via an investigation. All the questions I just listed except the first one are ***operational questions***, meaning they can be investigated and answered pretty directly with evidence from investigations. To find out if the milk swirls any differently with skim and whole milk, for example, you would perform the procedure with whole milk, then perform it again keeping everything the same other than substituting in skim milk, and observe what happens. You might do it again or make sure others get the same results when they perform the same procedure, just to be sure, and you'll have an answer.

"Why did the milk swirl?" is different. It cannot be answered as directly as the others via an investigation. It's not an operational question.

If you can envision, almost immediately, how to figure out an answer to a question a student generated in Step 6, you'll know it's an operational question. "Will we be able to see the milk swirling without any food coloring?" Repeat the procedure as before, but don't use any food coloring this time. "What will happen if we put soap directly on the food coloring?" Repeat the procedure as before, but put the soap directly on the food coloring this time.

Key Takeaway

The more tangible and observable an idea, the more students will understand it; this is especially true for younger students.

Operational questions like these, sometimes also called *investigable questions*, have special significance for elementary and middle school teachers. The more directly investigable a question, the closer the idea being investigated comes to being tangible and directly observable. And the more tangible an idea, the more likely students are to understand it. Generally speaking, elementary and middle school students are more likely to understand concrete, tangible, observable ideas than more abstract ones. Tangible concepts are more likely to be near students' experiences than abstract concepts. Directly investigable questions and problems don't just make for good science, as I explain below, they also make for good learning.

Third, even after limiting the list to operational questions, some questions may not reasonably be addressed in the classroom setting. They may be too complex, take too much time, or use materials you don't have. You may need to help students eliminate questions they cannot reasonably complete in Step 8, even if the questions are investigable. Still, it's good to have a variety of materials available for the investigations students might carry out. I listed several above.

WHAT'S GOING ON IN THE SCIENCE?

The scientifically accepted explanation for the swirling milk behavior seen in Milk Fireworks is surprisingly complex. That's why I didn't link it to a specific *Next Generation Science Standards* (NGSS) disciplinary core idea (and associated performance expectation). It's often explained in terms of surface tension. Scientists would say water molecules stick to themselves (one part of the molecule has a slight positive charge, another part a slight negative charge, and the oppositely charged sides of adjacent molecules are attracted). This stickiness explains why light bugs can walk on the surface of water, and you can slightly overfill a glass without spilling. Soaps and detergents chemically break surface tension. When the surface tension is broken, water molecules start moving around, and we see the food coloring being carried along with the moving water.

This explanation is fairly satisfying and, as such, can be used to tie the investigation activity in with content about the structure and properties of matter (which is disciplinary core idea PS1-A, encompassed in NGSS performance expectations like 5-PS1-1, "Develop a model to describe that matter is made of particles too small to be seen.").

However, the explanation falls short a little. You can demonstrate this empirically by repeating the procedure, but substituting water for milk. If food coloring moves (only) because water's surface tension is broken, you'd predict similar observations with water as for milk. I'll let you test for yourself to see what happens. That's the kind of person I am.

A better explanation is beyond the scope of this book. However, milk is a special type of solution (a colloid). Fats and other substances are suspended in water. Ultimately, the soap probably not only breaks the surface tension, but also literally connects the water and fats in the milk in ways that disrupt their previous connection. Part of the movement, we observe comes from the effects of this change, too.

PRACTICES IN PRACTICE

As I mentioned in the preface, in Appendix F NGSS's authors describe the activity of science in terms of eight overarching science and engineering practices (SEPs). One or more of these practices are part of *every* NGSS performance expectation, and they represent what scientists do when creating new knowledge. (Performance expectations are NGSS's equivalent of standards. Readers can find a brief introduction to NGSS in Appendix A.)

Just about any time students complete investigations as open ended as the ones in this activity, they will be using multiple practices. That's how it should be. If you select an investigation activity to teach your class, see if

Key Takeaway

Students make use of multiple science and engineering practices during good investigation activities.

you can identify more than one SEP students use during the activity. It should be possible to do this with classroom activities in which students are learning science by doing science. In fact, I'd suggest being careful before selecting any classroom activity where students are only using a single SEP; strive for activities where students use multiple SEPs. NGSS's authors stress this point on p. 3 of Appendix F with boldface type: "The eight practices are not separate; they intentionally overlap and interconnect." Let's examine some of the ways this plays out in this investigation activity:

NGSS Connection:
SEP1 Asking questions or defining problems

- Students are clearly *asking questions or defining problems (SEP1)* in Milk Fireworks. After all, the activity's main goal is helping students recognize investigable questions. As an elementary or middle school teacher, you might not be teaching students about phrases like "empirical evidence," but students can still understand that scientists ask and answer questions answerable with observations and data. To be most effective, the teacher should be explicit in making sure students recognize and learn the activity's purpose.

NGSS Connection:
SEP3 Planning and carrying out investigations

- Students are *planning and carrying out investigations (SEP3)* in Step 8 of Part II above. After choosing an operational question to investigate, students go on to complete the investigation. As teacher, you can increase the likelihood students learn about how science works by telling them scientists answer questions by planning and carrying out investigations. You can also encourage students to write a description of what they plan to do, an important part of planning and carrying out investigations (so that scientists can later compare their procedures and results, especially if others thought they were answering the same question but obtained different results; comparing procedures it usually turns out they actually performed slightly different procedures that can account for the different results).

NGSS Connection:
SEP4 Analyzing and interpreting data

- Once students finish their investigations, they will immediately, almost instinctively, *analyze and interpret data (SEP4)* when deciding on answers to their questions. As a teacher, you can explicitly point out that they are interpreting what they observed to come up with their conclusions (perhaps by simply teaching students and then using the phrase "interpreting data" whenever appropriate), adding that scientists do the same thing—they always base their thoughts on data.

CONNECTING TO THE NATURE OF SCIENCE

Our natural human tendency when we observe something interesting or unexpected is to immediately ask, "Why?" We want to explain our observations. We witness ***phenomena*** and try to make sense of what we have observed. My colleague Jill Grace defines phenomena as things in the natural world that can be observed and wondered about. Given this definition, empirical data would be firsthand observations about phenomena.

Phenomena are things in the natural world that can we can observe and wonder about.

In its simplest sense, this is the essence of how science works—observe phenomena you find interesting, for whatever reasons; notice patterns, trends, regularities; try to explain or make sense of what you've observed. In the Milk Fireworks investigation activity, the swirling milk is unexpected and therefore interesting. Students are naturally curious about what's going on (so are adults!), and further experiments help them understand and make sense. **In the Milk Fireworks investigation activity, students are *doing* science.** They are asking scientific questions and carrying out investigations. Their findings are scientific knowledge. I grant that "My food coloring swirls better with whole milk than skim milk" may not win the Nobel Prize but it *is* scientific knowledge!

Key Takeaway

Science is a way of making sense of our observations as we witness particular phenomena

NGSS discusses eight major themes related to the nature of science that should be part of schooling at all levels, K–12. I listed them in the preface and Appendix A of this book. They are discussed more fully in the NGSS Appendix H (NGSS Lead States, 2013b).

I believe the best place to start examining these themes is recognizing that scientific knowledge must ultimately be based on evidence from observations. There has to be some sort of physical evidence supporting an idea if it counts as science. One of the NGSS Appendix H themes is "scientific knowledge is based on empirical evidence," and another is "science is limited to answering questions about the natural and material world" (NGSS Lead States, 2013b). I've mentioned empirical evidence a few times already. ***Empirical evidence*** is the kind of evidence that comes from the senses, the observations we make by seeing, smelling, listening, etc. If phenomena are things in the natural world that can we can observe and wonder about, empirical data are firsthand observations about phenomena.

Empirical evidence is the kind of evidence that comes from the senses—seeing, smelling, listening, etc.; often referred to as synonymous with data.

How do these themes relate to Milk Fireworks? When students doing Part II of the investigation come up with answers to their operational questions, the knowledge they create is based on empirical evidence—what they observe

Key Takeaway

Scientific knowledge is based on empirical evidence—NGSS Appendix H

while doing their investigations. They are demonstrating one of the key tenets about the nature of scientific knowledge: Answers to science questions are based on empirical evidence.

The other theme, "science is limited to answering questions about the natural and material world," relates to Milk Fireworks in that operational questions, by definition, will be questions about the natural and material world (note that the opposite of natural is supernatural; it's not "artificial"). If student questions include examples like "Why do we have to do this?", "Does this count for a grade?", or "Do you like teaching science?" then they would *not* be scientific questions. They are not about the observable world, and they cannot be answered with evidence from observations. Many valuable and important questions are nevertheless not scientific questions.

To help you think about what your students might be able to understand about these themes, NGSS Appendix H differentiates expectations or standards for Grade 3–5 and 6–8 students.

- **In the 3–5 Classroom:** NGSS Appendix H notes learning outcomes and expectations students in these grade levels should ultimately understand include
    - science findings are limited to what can be answered with empirical evidence;
    - science findings are based on recognizing patterns; and
    - scientists use tools and technologies to make accurate measurements and observations.
- **In the 6–8 Classroom:** On the other hand, the appendix notes learning outcomes and expectations students in these grade levels should ultimately understand include
    - scientific knowledge is constrained by human capacity, technology, and materials;
    - science limits its explanations to systems that lend themselves to observation and empirical evidence;
    - science knowledge can describe consequences of actions, but is not responsible for society's decisions;
    - science knowledge is based upon logical and conceptual connections between evidence and explanations; and
    - science disciplines share common rules of obtaining and evaluating empirical evidence.

Beside their use as guideposts for what your students might or might not be able to understand, these expectations can also provide middle school teachers with a teaching progression. If you are a middle school teacher, look first to Grade 3–5 expectations and decide whether you believe your students understand them. If not, start there. Worry about Grade 6–8 expectations only after you believe most students understand Grade 3–5 expectations.

Case in Point

The Story of Barbara McClintock

Nobel Prize–winning scientist Barbara McClintock

To end the Chapter, I present the story of Barbara McClintock's work. Perhaps you can use it to illustrate for your students some aspects of what science is and how it works. Or perhaps you'll just use it yourself toward that goal. At the end of the story, I'll discuss some ways her story is similar to your students making food coloring swirl!

Barbara McClintock and modern genetics were born together, around the turn of the 20th century. Geneticists in the 1920s were trying to link how things looked (or behaved) with parts of their chromosomes. McClintock became fascinated by corn whose kernels had yellow and purple spots (kernels are usually either all yellow or all purple).

Just as students see food coloring swirling in a dish and wonder what's going on, McClintock saw funny looking corn and wondered what was going on. Recognizing a pattern, like the occasional presence of spotted corn kernels, however, is different than an explanation or model that helps us understand and predict the corn's behavior.

McClintock *really* wanted to understand what was going on. She moved next to her corn field and worked for years, by herself, experimenting, collecting, and analyzing data.

To explain her observations, she came to suspect something was breaking in a particular chromosome. She reasoned if the area (or gene) on the chromosome she studied was working properly, the resulting corn kernel would look purple. And if it was not working properly, the kernel would look yellow or white. She came to the creative conclusion that something in the middle of the area (or gene) was appearing and disappearing, turning it off and on.

Scientists at the time had a model of a chromosome as being like a string. A gene was a piece of the string. Every chromosome, they believed, consisted of many genes arranged in a sequence, one after another like pearls on a necklace. No one thought about chromosomes or genes changing the way McClintock did. She thought very differently than others about the chromosome model.

Year after year, McClintock amassed overwhelming data supporting her idea. But nothing is considered "true" in science unless it has been accepted by peers. And so, 6 years after beginning the work, she felt ready to stand before her colleagues and tell them about her work.

At a 1951 symposium before a group of leading scientists, she laid out evidence supporting her model. And then she waited to see how her colleagues would react. The work would mean little unless she convinced other scientists of its merit.

And she did not get it.

She went on to publish the work in a long paper. And almost no one read the article.

How would you react if you spent 6 years working on something, and no one paid attention? If your peers didn't seem to care? I'd be mortified, crushed.

"I was startled when I found they didn't understand it, didn't take it seriously," McClintock said,

> but it didn't bother me. I just knew I was right. People get the idea that your ego gets in the way a lot of time—ego in the sense of wanting returns. But you don't care about those returns. You have the enormous pleasure of working on it. The returns are not what you're after. (McGrayne, 1993, p. 168)

Wow. That is one dedicated scientist!

Although she had no idea it would happen, the rest of the scientific world finally started catching up to McClintock when the same thing was observed in things other than corn. The scientific understanding of genes, like all scientific knowledge, started to change as evidence continued rolling in supporting McClintock's ideas. Honors started rolling in and, in 1983—32 years after her initial presentation—Barbara McClintock was awarded the Nobel Prize.

Remarkably, she seemed to harbor no bitterness in the time it took for the rest of the scientific community to come to accept her work. Thirty-two years is a long time, but she was emphatic about the point. "It's such a pleasure to carry out an experiment when you think of something—carry it out and watch it go—it's a great, great pleasure," she said.

> It couldn't be nicer. . . . I just have been so interested in what I was doing, and it's been such a pleasure, such a deep pleasure, that I never thought of stopping. . . . I've had such a good time, I can't imagine having a better one. . . . I've had a very, very satisfying and interesting life. (McGrayne, 1993, p. 173)

CONCLUSION

This chapter and much of this book is about you and ultimately your students understanding what's unique about science as a way of knowing. (I didn't mention it previously, but the idea *science is a way of knowing*—which implies there are other ways of knowing—is one of NGSS's nature of science themes.) This chapter is also about two other themes—that *science addresses questions about the observable world*, using *knowledge based on empirical evidence*. Barbara McClintock was studying questions about the observable world, creating answers matching the available empirical evidence, and so are your students when investigating swirling milk.

The McClintock story illustrates how models and explanations are different from the observations themselves. I did not emphasize the point discussing the Milk Fireworks activity investigation—it's for you, understanding the ideas at a deeper level than your students—but your students' investigations in the activity help them understand what's happening with the phenomena *without necessarily developing scientific models explaining why the swirling occurred*. But that does *not* mean the investigation isn't appropriate for young children.

Finally, McClintock's work demonstrates the human side of science. Science is a social activity, requiring scientists convince each other their ideas work. Children engaged in Milk Fireworks will exhibit their own human tendencies and, undoubtedly, will also try convincing each other their ideas work. Sometimes we forget the human side of science. An accurate representation of science should always include our human-ness. The next chapter builds on this one, as we discuss important knowledge and questions that are *not* scientific.

Additional Resources

To learn more about Milk Fireworks, see Bergman, D. J., & Olson, J. (2011). Got inquiry? *Science and Children, 48*(7), 44–48. You can also see the basic procedure illustrated on Steve Spangler's science website at www.stevespanglerscience.com/lab/experiments/milk-color-explosion/. His version differs from mine only in where food coloring is initially placed. Try both versions; see which one you like better!