Teaching Science to Child

USING CULTURE AS A STARTING POINT

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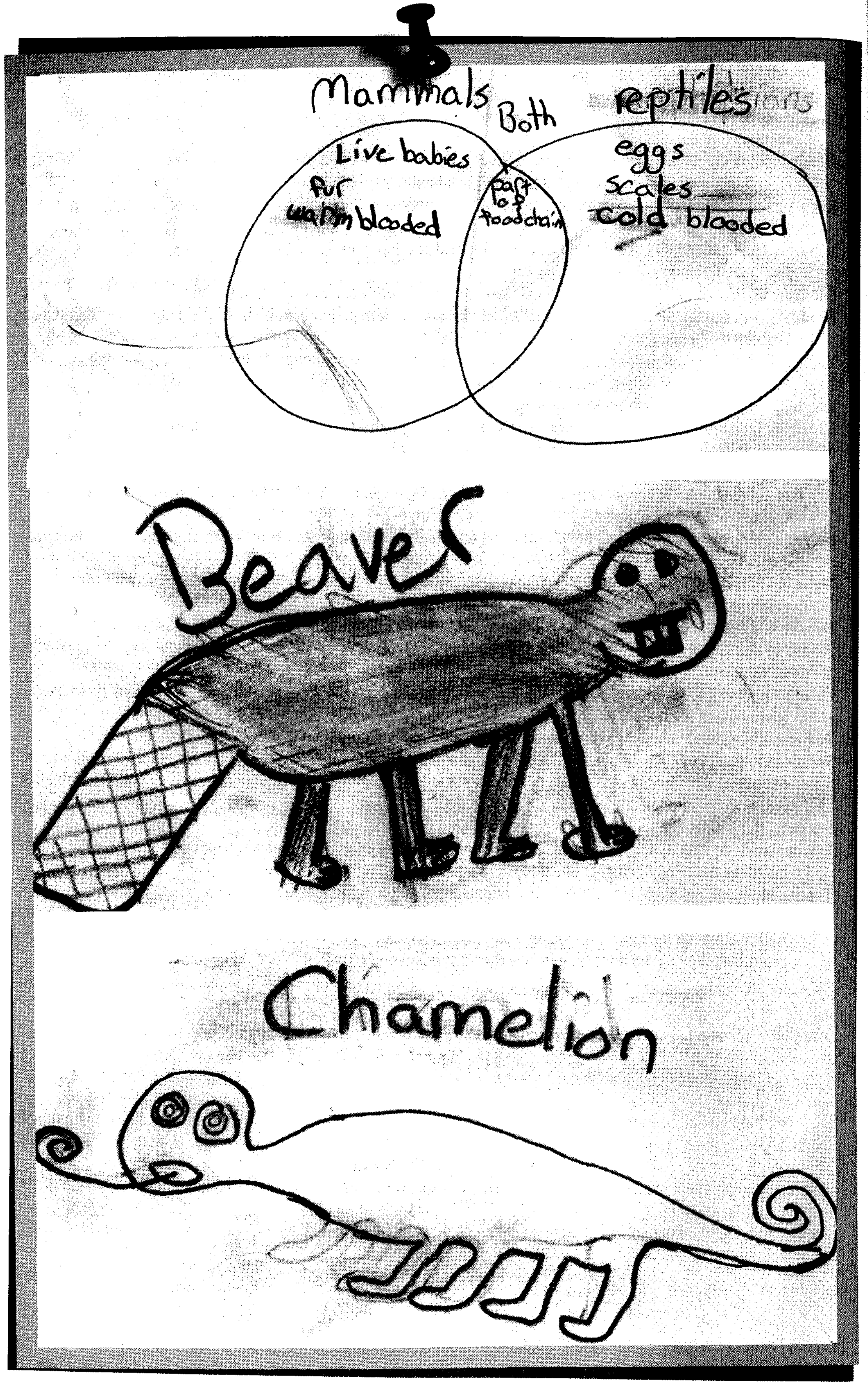

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The Nature of Science

Chapter Highlights

- The nature of science is central to the culture of science which makes it necessary to allow students to recognize the value and power of the knowledge it produces.
- Science is a distinctive way of knowing that demands the availability of evidence to support knowledge claims. Other worldviews may not require such an emphasis on empiricism and recognizing this is a valuable realization.
- Creativity is just as essential to science as within other ways of knowing. Students can be creative in science as they develop multiple ways to observe and measure, when they propose inferences and suggest predictions, and when they stretch to develop more than one explanation for data.
- Scientists make the effort to identify the opinions and biases they have that might influence their observations and explanations. Prior knowledge can help us make sense of what is taking place, but it also places constraints on our thought processes.
- Even though it is a prevalent idea in textbooks and classrooms, there is not a singular scientific method. Although certain actions are characteristics of people doing science, it is improper to believe that science proceeds by a fixed sequence of steps that culminates with scientific truth.
- Collaboration by students in their science learning echoes the social nature of science for practicing scientists. Just as professional scientists do, students should present their work and ideas to others as part of the science community.
- Scientific explanations are tentative and open to revision if sufficient evidence or arguments can be provided. Scientific knowledge advances as old ideas are replaced by better explanations. In a similar way, student ideas can be replaced with more scientifically acceptable explanations.

Too often, science is viewed as a fixed body of somewhat obscure knowledge. For example, many of us have seen the Periodic Table but the usefulness may not be apparent for anyone outside of science classrooms and laboratories. What insiders to the culture of science know is that the Periodic Table is not only a clever way of organizing all the elements but it also reflects centuries of debate. In addition, the Periodic Table continues to undergo change. A new element was named in February 2010 and all Periodic Tables since then have been updated to include copernicium (its symbol is Cn) as the 112th element known to humankind. Admittedly, this information may not be a topic of conversation over lunch with your peers and is probably not relevant to the students at your field placement site. But what this little example alerts us to is the ever-changing aspect of science. Like all other cultures, science is defined by its objects and actions. In addition, few cultures are fixed and unchanging. Instead, a culture can shift over the years in response to adjustments in attitudes as old members move along and new members come in to the group. This is all to say that to appreciate that science is a culture requires recognizing that science, despite its distinctive features, is gradually changing. Another way to describe the science culture is to explore the "nature of science" since it gives a sense for the cultural norms. Understanding the nature of science represents a way of becoming a competent and confident participant in the science culture.

Explanation of the Nature of Science

We often find ourselves facing a flurry of seemingly contradictory scientific information. For example, here are actual scientific statements related to nutrition: "A low-carbohydrate diet helps you lose weight and control cholesterol levels"; "A low-carbohydrate diet is unsafe because it is often high in fat and places too much stress on the kidneys"; "Eat high amounts of grains and fruits and a minimum of meats and dairy for a well-balanced diet"; and "Eat a limited amount of grains and a high amount of meats and other protein for a well-balanced diet." How can scientists produce these contradictory messages? Isn't there some mechanism for resolving these contradictions? Shouldn't scientists all say the same things? The goal of this chapter is to examine how scientific knowledge is produced. While that will not resolve the contradictions listed above, it will allow us to illustrate why this apparent sloppiness and confusion is evidence of scientific knowledge being developed. A deeper understanding of the nature of science by a teacher will shape how science is taught in the classroom. This in turn will benefit the understandings of the students.

In the midst of doing their work, scientists may not attend to the grander ideas of their profession—but then neither do most professionals. Scientists have to worry about if their equipment is in working condition, if their schedule allows them to gather the data they need, and if the data they are collecting will help them to solve the questions they are investigating. Because they are so involved, scientists may not often sit back to think about how their research connects to the bigger picture. Consider the work of other professionals such as a nurse, police officer, or cook. Each profession has its own global concerns (health, justice, and nutrition) and those have the power to subtly shape what the individuals do as they go about their work. But as a nurse gives a patient a shot, as a police officer interviews a witness, and as a cook goes about measuring and sifting flour, they probably aren't focused on the big picture. But if you asked, they probably can explain how they see their tasks connecting to something bigger and more important than just these mundane activities. So it is with the professional scientist.

The phrase the **nature of science** describes the underlying tendencies and unspoken assumptions that guide the actions of scientists, as individuals and as part of a larger cultural group, in shaping the knowledge science produces. As a result of these traditions, the knowledge that is created retains these embedded characteristics. The phrase "scientific inquiry" refers to actions involved in scientists' pursuit of knowledge: that is, the manner in which they seek explanations of natural phenomena. It is difficult to clearly distinguish concepts related to the nature of science and scientific inquiry because the two interact and shape one another. We will discuss both in tandem to provide a coherent portrait of the culture of science.

It is difficult to list the components of the nature of science just as it is challenging to summarize the parts of any culture. If you've wondered about how to effectively teach science to a particular category of students (e.g., girls, children with hearing disabilities, students who are not fluent with the English language), then you can appreciate why it's hard to quickly and accurately define the nature of science. Just as it is impossible and perhaps unwise to reduce any of these groups of students to a list of specific characteristics (e.g., girls like to work in groups, children with disabilities don't like to be singled out, English language learners will need particular help in the sciences)—as there is so much variability and complexity within these groups—it is very difficult to reduce the knowledge about science to a specific list of characteristics. So why should we try? Think about it this way: if you were trying to explain your cultural traditions to an outsider, you would need to help them recognize some major themes of your culture. Knowing the timing of special events, knowing the kinds of food that are eaten, and knowing the special phrases that are used are only surface features. A genuine cultural tradition consists of much more than its rituals.

Traditions have their bases in underlying beliefs and norms. When outsiders focus on just the surface feature of a culture's tradition, they fail to recognize the significance of those traditions to the members of the culture. To study science without an understanding of the nature of science is to become familiar with the surface features of that culture but to never fully understand, be comfortable with, or be able to work within the culture of science. What we will try to accomplish in this chapter is to provide a sense of what is included within the nature of science as an important step toward understanding what is meant by the culture of science. The short-term goal is strengthening your understandings of the nature of science. The long-term goal is to ensure that your teaching about science is consistent with the nature of science.

Unpacking Students' Ideas about the Nature of Science

When we ask students "What is science?" we often receive the same sorts of responses whether they are elementary school, middle school, high school, or college students. Students point to a biology book and say, "That is science." Or they may give a list courses, such as geology, physics, biology, and chemistry. With additional probing, they'll cite the scientific method as an explanation of how science is done. As we spend even more time discussing these matters, students (again from across the age and grade spectrums) explain that science is a large body of very sure facts, facts that are "discovered" by objective scientists as they study all aspects of the world,

For Reflection and Discussion

If you were asked to draw or describe a scientist without thinking about it too deeply, what characteristics would you include? If elementary or middle school students held the same views of scientists, how might that influence their desire to become participants in that culture?

a study that is sometimes described as "prying open" the natural world as if the answers are hidden inside like a prize. These scientists are often viewed as "lone rangers" who work in isolation and surprise the world with their discoveries after long hours of diligent work.

How do we develop our ideas about science and scientists? It is notable that students' responses are very similar across ages. This suggests that these ideas are first learned early in life and little occurs to reduce these perceptions. Elementary schooling might contribute to this situation. Unfortunately not many students actually study science during their elementary careers. So where do these ideas come from? It seems that much of what students "know" about the culture of science comes from the media—the news, movies, cartoons, and so on. Think about the scientists you've seen on television and in movies, fictional stories, and educational programs. What do many of these scientists have in common? They are usually seen as White men with wild hair who are just a bit different from all the others around them. Even programs supported by the National Science Foundation for educational purposes, such as *Bill Nye the Science Guy,* can reinforce such stereotypes.

Few accurate portrayals of science, as performed by actual scientists, are available to most of us. The stereotypical versions of science, although comical, send a clear message to students that only certain people can become scientists. These misperceptions of science may actually cause students to believe that science is not something they can do or would want to do. Our working hypothesis is that if students' mythical notions are unpacked, if we can help teachers and students to understand the actual nature of science and scientific inquiry and who does it, then more students will understand that they can be capable science learners.

Students will enter their formal studies of science class holding many perceptions about the nature of science. In the following section, we will describe the most relevant aspects of the nature of scientific inquiry for elementary and middle school students. As we examine the nature of science concepts, we point out the common myths held by students (and far too many people from the general public). Next we address those concepts that are potentially the most pertinent for effectively teaching science in a diverse setting. Finally we will provide suggestions about infusing the nature of science throughout science instruction.

The Empirical Aspect of Scientific Knowledge

The actions of science include the scientific tasks of collecting information (data or evidence) about that world, and the objects of science are the constructed explanations. One defining feature of the actions of science is that they center on a process of inquiring into the physical world. That is, at some level the actions of science can never stray too far away from the world surrounding us. Thus given that a central goal of science is to develop useful understandings of the physical world, its methods are inherently **empirical**. This term describes knowledge that is grounded in observations and experimentation not in opinions, sentiments, or sensations. If a biologist wishes to empirically understand the behavior of snails along a coastline, at some point she will need to collect data about these behaviors (e.g., where they are during different times of the day, what they eat, how quickly they move) and data about a variety of other environmental factors (such as salinity, water temperature, ambient temperature, presence of edible plants, and potential predators). All these data may allow the biologist to construct an explanation that allows her to accurately describe and predict snail behavior. If the explanation she constructs is helpful to her and to other scientists in predicting accurately the behavior of the snails, then this explanation is regarded as a useful piece of scientific knowledge.

The work of scientists is powered by the desire to understand the physical world. Its actions center on collecting data about the natural world, so it is empirical. However, the empirical aspect is only part of the science culture. There are other very dynamic aspects of doing science. Science is empirical, first and foremost. But it is also many other things.

The Creativity of Science and Scientific Knowledge

Where do the scientific explanations about the world come from? In part they begin as careful observations of nature. You should recognize that the making of explanations entails creativity on the part of scientists. In contrast to the well-recognized empirical character of science are three of the creative aspects of the nature of science. These aspects are as follows: (a) explanations are generated from evidence, (b) personal bias influences the creative process, and (c) science benefits from creativity. In the following sections, we will illustrate some of the creative aspects of the culture of science.

Explanations are Generated from Evidence

Doing science is much more creative (and interesting) than simply stringing together pieces of data to create an explanation about what has been studied. For example a scientist may watch the steam rise from a boiling pot of water and explain that the heat from the stove was transferred to the water, causing the water molecules to speed their motion, take up more space and thus become less dense than the surrounding air, and then rise. The evidence is the water vapor rising from the pot on the stove. The explanation involves the relationship between heat, molecular movement, and density. Andy Anderson of Michigan State University suggests that the core of scientific inquiry is the cycle between evidence and explanations (Anderson, 2006). By this he means that the opportunity for creative thinking within science is embedded within making the leap between what has been empirically described (the evidence) and a reasonable description about how things are as we have found them (the explanations).

Another example comes from the biological world. Imagine a potted plant that is wilting. After giving it a generous watering, you are impatient to see if it recovers. However, the plant doesn't seem to perk up very much. You touch the surface of the soil to reassure yourself that it is damp. You provide the plant with fertilizer and even several hours later the plant fails to be as healthy as you expect. You peer into the dish under the pot to see if there is any water there, and you are startled to see roots poking out of the pot's bottom. When you lift the plant out of its pot, you discover that there are so many roots that they have grown into the exact shape of the interior of the pot. This evidence of tangled roots leads you to the understanding (and explanation) that the wilting is because the roots are too tightly packed and that you need to put the plant and a liberal supply of soil into a larger pot. Once the plant returns to its vigorous and non-wilting condition, you become convinced by your explanation that the wilting of the leaves had something to do with the roots' inability to take up water. The evidence was your observations that the leaves were wilting, the roots were filling the pot, and that the behavior of the plant changed once the plant was placed into a larger container. The explanation has to do with the movement of water through the vascular system of the plant.

Anderson's claim that inquiry involves the cycling between evidence and explanations (see Figure 2.1) can be challenging to understand. This might be because many of us believe that the work of scientists involves uncovering nature—taking the lid off the natural world to see what's happening inside. Many people see the actions of science as simply a set of procedures that must be followed. Within this incorrect interpretation, generating science explanations is the process of detailed description, as though the physical world is waiting to tell the scientists how things work. Those holding this view regard the evidence as synonymous with the explanation. To such people, Anderson's suggestion that creativity is essential to science may

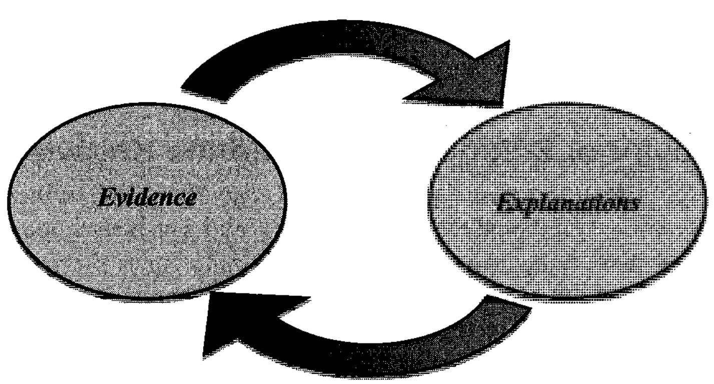


FIGURE 2.1. Evidence and explanation influence each other.

seem odd. But the reality is that scientists must draw upon creativity to be productive with their work.

Creativity includes not only designing experiments for testing a hypothesis but also thinking about the data after they have been gathered. Being able to interpret the data to develop a reasonable explanation demands creative thinking, and the intellectual leap into the unknown will only benefit by an infusion of creative thinking about the possibilities. Yes, a scientist's role is to describe nature, but from those descriptions and those observations, they need to generate inferences to develop ideas based on those descriptions. The objects of science are the explanations based on the evidence scientists collect. As such, evidence and explanations are closely related and interdependent.

> But the process of reaching the absent from the present is peculiarly exposed to error. . . . The exercise of thought is, in the literal sense of that word, inference; by it one thing carries us over to the idea of, and belief in, another thing. It involves a jump, a leap, a going beyond what is surely known to something else. . . . The very inevitableness of the jump, the leap, to something unknown, only emphasizes the necessity of attention to the conditions under which it occurs so that the danger of a false step may be lessened and the probability of a right landing increased. (Dewey, 1910/1991, p. 26)

By now we hope you are beginning to appreciate the role of creativity in the doing of science. Far from being a mindless and mechanical gathering of evidence, the work of science benefits from personal creativity and the ability to shift from data to explanations. In the process of generating explanations, a scientist's prior thinking may come into play. Because scientists must interpret evidence, their biases and background knowledge become important.

The Subjective Nature of Science

Scientists can become impassioned about their work and genuinely excited about creating explanations of the world. It is reasonable to imagine that their eagerness might cause them to view scientific evidence through hopeful, biased, and thus subjective eyes. **Subjectivity** refers to the role that a person's individual perspective plays in shaping what the person perceives. Because scientists are human, we accept that their preconceived ideas will influence what they notice. Perhaps a key difference between the culture of science and other fields is the desire and effort to remain as objective as possible and to limit the impact of a scientist's bias in the meaning he or she makes. To amplify the impact of the empirical world on the sense science makes of it, scientists make the effort to reduce the influence of bias within their work so they can better "see" what is there.

We acknowledge that bias shapes the construction of scientific knowledge. What a scientist already knows influences what he or she finds out during an investigation. Background knowledge affects what sorts of questions are posed, the kinds of data collected, and, as we saw in the preceding section, the interpretation of those data. Scientific knowledge progresses because of an endless supply of explanations. Scientists rely on previously constructed explanations as they examine the evidence they collect, making the actions and objects of science slowly build on themselves. Without background knowledge or knowledge of previous explanations—some sort of "theoretical bias"—scientists couldn't begin to understand the meaning of the data they collect, and they would not be particularly effective in collecting such data. In short, the reliance on preceding work influences scientists' subsequent efforts.

One example of the impact of bias on scientific explanations can be found in the stars, through the work of two astronomers, Tycho Brahe and Johannes Kepler. Brahe was a well-established astronomer in the 1500s, and the tools he employed allowed him to make the most detailed observations of planetary motions possible at that time. Using his scientific instruments, Brahe collected incredibly detailed data about planetary motion that he used to construct an explanation of the solar system; his explanation placed the earth at the center. Brahe's model was similar to models of the universe commonly accepted at the time, and he used his data to support the geocentric world.

Kepler, using the same data, proposed an alternative explanation for planetary motion, one based on a model that positioned the sun in the center with the planets orbiting around it. The knowledge that shaped Kepler's views was different from that held by Brahe, and Kepler was willing to consider the possibility that the shape of orbits could be an ellipse—unlike Brahe, who strictly adhered to the idea of circular orbits. Brahe and Kepler used the same set of data describing planetary motion, yet these two scientists constructed different explanations from these data. This example illustrates the role of bias in the actions and objects of science. Brahe's biases (i.e., his background knowledge and beliefs) prevented him from seeing the potential of a sun-centered universe. Looking back, it seems reasonable for Brahe to have organized the universe with the earth at the center. After all, that was the conventional wisdom—although his resulting model for predicting planetary motion was exceedingly complicated.

Because of the subjective nature of science and the role of bias in shaping the efforts of scientists, the varied background experiences of scientists benefit discovery. One example of how the knowledge produced through science is different when new scientists with fresh perspectives begin to participate can be found in biology's explanation of the process of fertilization. For years it was understood that the sperm cells were active participants in fertilization whereas the egg was relatively passive. The standard scientific explanation was that a sperm cell had to swim vast distances (relative to the size of a cell), compete with other sperm, locate an egg cell, and penetrate the egg by releasing enzymes that digested the covering of the egg. In this characterization, the sperm is seen as the active participant. In other words, the explanation was that the sperm did all the work while the egg simply waited to be fertilized.

As more women scientists began studying the process of fertilization, a very different portrait of this event was produced. It was recognized that the egg actually "grabbed" the sperm, in effect pulling it in. It was also shown that the enzymes released by the sperm were not active until they interacted with another secretion from the female. Thus the updated and generally accepted explanation is that the sperm and the egg are both active agents in fertilization. Although some evidence leading to this new explanation for fertilization was made possible by the development of new instrumentation (the electron microscope), other bits of evidence have been around since 1919; the relatively male-dominated science field was not yet ready to recognize them.

There is an unavoidably subjective nature to the construction of scientific knowledge, as science is a creative human activity. Because of the role of bias in creating explanations, scientific explanations benefit through the participation of scientists with varied backgrounds.

Creativity in the Methods of Science

Like the creativity used to construct explanations based on evidence, creativity is an essential aspect of the scientific inquiry process. It is sad that there is a long-standing myth in science that appears in far too many science textbooks and that makes it seem that creativity is unimportant within the doing of science. What we need to do is recognize that creativity is essential to doing science despite this fictional icon: the myth of the Scientific Method.

In the 1940s a man by the name of Keeslar wished to describe the different elements of scientists' work. He began by generating a list of all the things he imagined scientists did: carefully making measurements, maintaining detailed written records, defining a research problem. This list was used as the basis of a questionnaire that he sent to professional scientists. They were asked to indicate which of the activities were part of their scientific work. This list was then turned into a questionnaire and distributed among many professional scientists. Keeslar took the returned questionnaires and tallied the items according to how often scientists selected the different activity descriptions. He organized the items receiving the highest rankings into a sequence that seemed logical and published these findings in an education journal (McComas, 2000).

Keeslar was simply reporting on scientists' uses of different thinking strategies, but his report was interpreted as describing a nice neat sequence of how science is performed. A science textbook writer saw Keeslar's list and turned it into the Scientific Method—touting it as *the* way science proceeds. Indeed there is really no such thing as a singular **scientific method**, and this list doesn't accurately portray the work of scientists. Because this list of the steps of the scientific method is based upon an inappropriate interpretation of Keeslar's study, there is very little that is factual about it. One could reasonably wonder what teachers are trying to portray by drilling students on the scientific method.

The Scientific Method Myth*

1. Define the problem
2. Gather information
3. Form a hypothesis
4. Make relevant observations
5. Test the hypothesis
6. Form conclusions
7. Report results.

**Note.* This *really* is a myth!

Indeed in checking with scientists, we discover that the Scientific Method is a gross oversimplification of the process of scientific inquiry. Keeslar never intended for his work to be used in this manner. A problem with the Scientific Method Myth is the implication that there are particular steps that must be followed in science and that scientists progress through the steps in this specific order. Maybe it's more comfortable to imagine that scientists are such logical individuals. But the life of a professional scientist is not quite so neat and orderly, and much more creative. Turning the work of scientists into a strict sequence is as full of problems as trying to reduce other complex activities to a to-do list. Try to imagine putting your family's preparations for a celebratory meal into a neat little sequence.

1. Construct a list of materials you will need for the meal, and purchase them from the local grocery.
2. Twenty-four hours in advance, thaw out the avian protein, and cook the vegetables for inclusion in later casseroles.
3. Early in the morning of the event, the avian protein is placed in a covered pan and placed in the oven for a time to be determined by its weight.

And so on. As official and logical as these steps seem, the reality is much less tidy and allows for much greater individuality. To turn the preparation of a meal into such a sequence is inaccurate and misleading; it also shields us from appreciating the creativity involved in the process and the significance of the final product. The same criticism applies to using the Scientific Method as to using this recipe to prepare a great meal. Creativity is not simply allowable within doing science, but is necessary.

For Reflection and Discussion

Think about the implications for outsiders if some human activity that is very creative was reduced to a checklist. Examples include painting, dancing, singing, and so on. If any of these pursuits were presented to students as steps they would have to follow, how interested do you think they would be about participating? How might the perceived lack of creativity in science serve as a barrier to students becoming interested in doing science?

Just as each of us has slightly different or very different actions in the process of participating in a cultural event, scientists have slightly different or very different actions in the process of participating in the culture of science. A biologist discussed previously goes about her work much differently than the astronomers (Brahe, Kepler) of yesteryear or even the astronomers of today. There isn't a single scientific method that encapsulates the work of scientists even within a single discipline (physiology, evolutionary biology, ecology) much less between disciplines (biology, chemistry, physics, geology). Even within biology, some professionals focus on describing body structures (anatomists) or behaviors of a species (ethologists). In these cases, close descriptions are required. Other biologists may focus their work on systems that have already been closely described, and their work often focuses on explaining how things work, such as the physiologist who performs experiments on organisms to investigate the biochemistry of muscular movement. Each of these endeavors represents science, but each employs very different approaches to scientific inquiry.

Imagine for a moment that you are required to do a science fair project as part of your science teaching methods course. Your instructor is open to letting you study anything of interest to you as long as you employ the Scientific Method. Look at the steps presented earlier and think about how you might proceed. According to the guidelines you are supposed to start at item 1, then move to item 2, and so on. Feeling frustrated, overwhelmed, or irritated? So would we. The reality is that you might well start at item 4, then go to item 2, then go back to item 4, and eventually get around to item 1. And guess what: that's what scientists do. The Scientific Method is not the golden staircase to scientific enlightenment. It's just one way of many, many pathways describing how scientists can go about their work. Just as scientists must be creative in posing explanations to account for the evidence they collect, they must use creativity to develop ways to gather evidence.

Within this discussion about the nature of science, we are emphasizing the creativity possible within doing science. We want to dispose of the Scientific Method because it is inaccurate and it perpetuates an anti-creative view of doing science. If we throw the myth of the Scientific Method how do we replace it? What is a science teacher to do? Perhaps a way to begin thinking about the scientific method is as one method of scientific inquiry and as just one pathway an individual can take in solving a problem. Once students have experienced such a method and become comfortable with the actions of science, then other questions can be pursued, with a classroom conversation establishing the logical sequence of actions and comparing those steps with those originally introduced. The point here is to emphasize to students that this list is one way of pursuing a question but certainly not the only one.

Science as a Social Enterprise

Given that so much of science involves making that creative leap from evidence to explanation, as well as creating appropriate ways to collect evidence, a significant part of the actions of science is convincing others in your field of the value of your ideas and methods. The exchange of ideas among scientists is included within the actions of science. As a direct reflection of this, the journal *Science* often has an average of more than four authors per research article. That means these individuals worked together in writing the report, in gathering data in the lab or field, and in formulating the research design in the initial discussions. Although the mass media often depicts science as a solo endeavor, in reality working in isolation is not an accurate or honest portrayal of the actions of science.

The entire process of sharing and debating scientific ideas and methods—core actions in the culture of science—must occur within a social setting. Conferences are held so scientists can share their ideas with other scientists who, in turn, question if those ideas make sense in terms of the data. One of the most valuable ways scientists check for the influence of bias on interpretations of data includes having numerous scientists conduct and analyze the same experiment or having different groups of scientists with different theoretical biases study the same problem. In part science needs to be social to ensure that scientists are making the best explanations of the physical world, and this is done through the comparison and debate about findings. Before a scientific article is published in a journal, it must be reviewed and critiqued by knowledgeable colleagues who determine if the work attains the standards of that scientific community. Even without face-to-face conversations, the ways in which scientific knowledge is generated, evaluated, and distributed is necessarily situated within a social sphere.

A common caricature of a scientist is someone working in almost complete isolation. The cartoonish view of a scientist is a person who is painfully awkward in social settings—suggesting that scientists are awkward because they are rarely around other people. With this common stereotype is it any wonder that many students fail to see any appeal in the prospects of becoming scientists? We need teachers to assist us with debunking the myths of the lone scientist and the Scientific Method if students are to develop robust understandings about how science is done. They need to see that science is a social enterprise and understand the role debate, discussion, and other forms of communication play in scientific culture. By emphasizing the social aspect of the doing of science, teachers can better emphasize the community aspect of the learning of science. Just as is true for scientific inquiry, important aspects of the learning of science come from talking, debating, and writing about the sense students are constructing in the classroom. Just as these activities are important in doing science, they are important in learning science.

The Tentative Nature of Scientific Knowledge

To this point we have portrayed science as a process of creating explanations from evidence gathered in the physical world. In addition we have illustrated how science is a creative process influenced by the backgrounds and biases of scientists. Third we have described an image of science as a social activity for debating the validity of the evidence and the explanations constructed based on that evidence. Because the production of scientific explanations involves many creative processes, it should not be surprising to recognize that scientific knowledge can change. Students and adults often think that once science produces knowledge and once a scientist offers an explanation of some aspect of the physical world (like our snail-studying biologist mentioned at the outset of this chapter or Brahe's description of an earth-centered solar system) and this explanation is accepted by the entire scientific community, that knowledge will never be modified. Using this line of thought, science textbooks can be expected to grow only larger as knowledge is added. If scientific knowledge does not change, one would never expect science books to be revised or rewritten. However, the explanations scientists create about the physical world are always open to revision, and scientists recognize this as part of the culture.

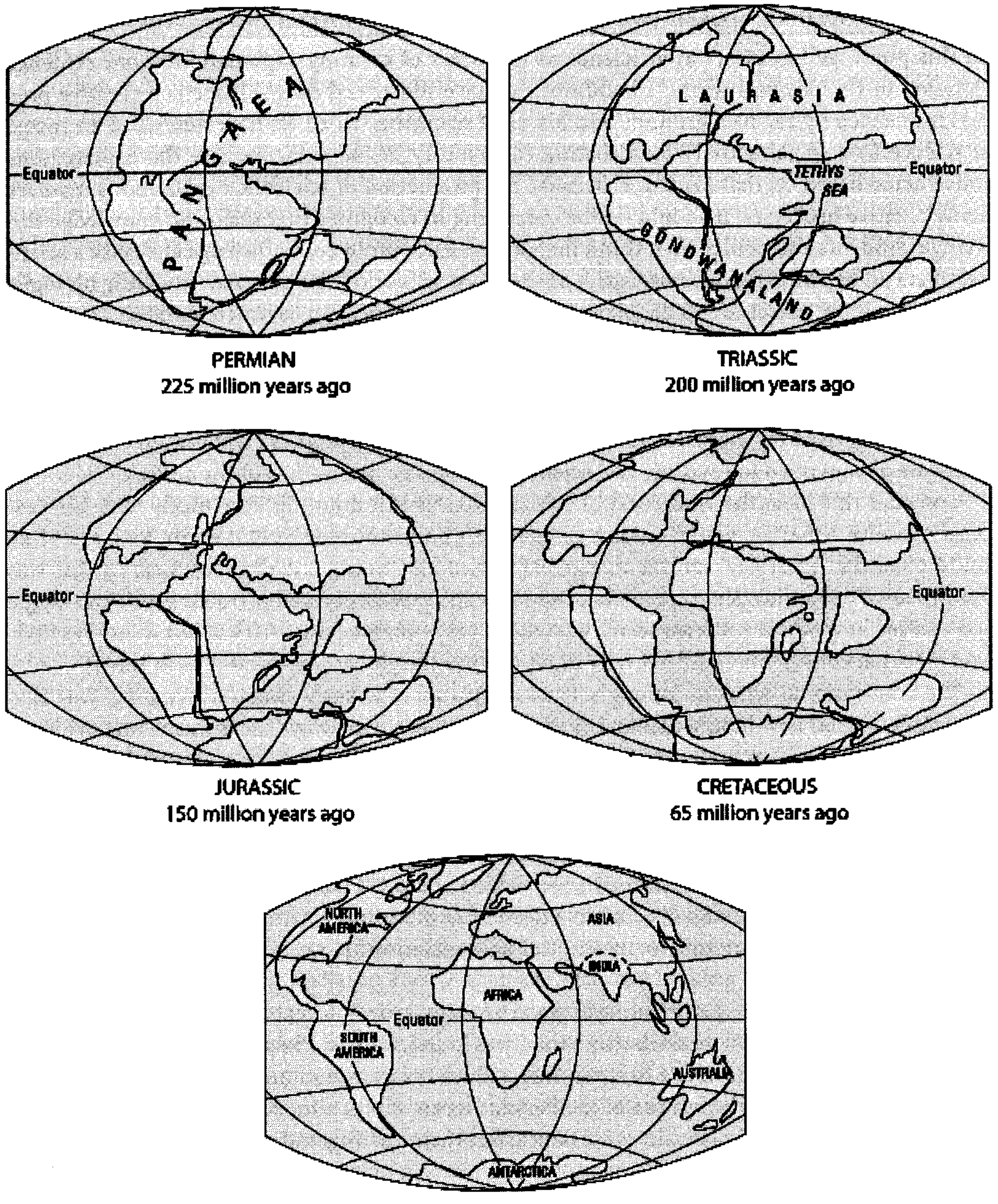
Consider this idea: the west coast of Africa looks as if it might fit very nicely with the east coast of South America. Figure 2.2 is a geographer's effort to show what it might look like if we could push the American continents against Africa and Europe. A drawing such as this was published in 1858, but geographers had noticed this possibility before 1600. From this angle you can see how South America seems to snuggle very nicely against Africa. But there was little evidence that continents could actually move around the globe: what would push them?

The conventional wisdom among scientists up until the early twentieth century was that volcanoes created new mountains and that erosion wore them away. There wasn't any evidence the continents might actually move, and the apparent matching of the continent's edges was regarded as a coincidence. Indeed in 1915 Alfred Wegener, a geologist, suggested that the earth's continents were once connected, and as a result his colleagues in the scientific community ridiculed him (Smith & Southard, 2001). Over the years more evidence has accumulated. As new instrumentation was invented, scientists were able to map the floor of the ocean. They expected it would be fairly smooth and covered in a deep layer of sediment. After all, the erosion of millions of years should amount to substantial accumulation. However, their predictions were not correct.

First, the depth of the sediment layer wasn't nearly as deep as expected. There should have been much more sediment on the bottom than was found. Second, the floor wasn't smooth at all: running along the middle of the Atlantic Ocean floor is a giant mountain range, and a massive trench was found along the bottom of the Pacific Ocean. It was almost as if new rock was being added to the continental plates in the Atlantic but then melting and submerging into a trench along the floor of the Pacific.

Other bits of evidence emerged. Volcanoes and earthquakes seemed to exist in only certain regions. The idea was that different continental plates rubbed against each other as they moved. The volcanic and earthquake events took place where these seams occurred. It was suggested that the events occurred as seams of the continental plates rubbed against each other. Furthermore, there were fossils that were found only in places that were separated by large distances. It is interesting that the fossils' locations matched the places where the Africa and South America puzzle pieces touched, as shown in Figure 2.3.

It wasn't until the 1960s that science textbooks finally began to describe "plate tectonics" as a legitimate scientific theory, finally vindicating the ideas Wegener had ventured decades earlier. Geologists have identified thirty plates that make up the solid crust and documented the melted mantle just below that crust. As this liquid mantle flows, it pushes the massive plates (both



PERMIAN
225 million years ago

TRIASSIC
200 million years ago

JURASSIC
150 million years ago

CRETACEOUS
65 million years ago

PRESENT DAY

FIGURE 2.2. This illustration shows how the continents fit together like pieces of a puzzle. Source: U.S Geological Survey (http://pubs.usgs.gov/gip/dynamic/graphics/Fig2-5globes.gif).

continents and ocean floors are part of these plates) and they move about, at a maximum speed of two inches per year. At times these plates collide with one another. The Himalayan Mountains are an example of plate collisions. Although moving very slowly, the India plate is "slamming" into the Eurasian plate creating the tallest mountains on earth—at least among those mountains that aren't underwater.

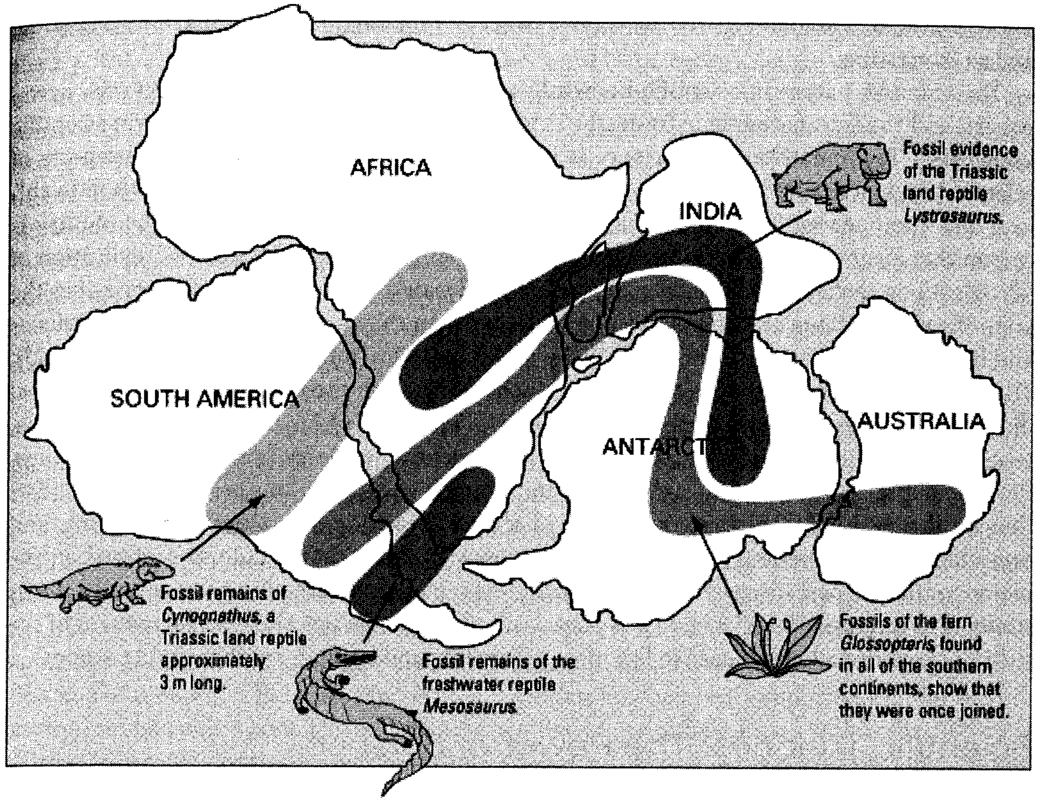


FIGURE 2.3. This map shows how fossil evidence supports the explanation of plate tectonics. Source: U.S Geological Survey (http://pubs.usgs.gov/gip/dynamic/graphics/Fig4.gif).

Although Wegener's ideas help us make sense of a great many physical features of the earth (mountains, basins, patterns of volcanic activity), this doesn't mean that the story is completely solved. Indeed according to the United States Geological Survey, there are still some unresolved questions in terms of the earth's physical features. The following paragraph reinforces the dynamic and changeable aspect of science:

> Plate tectonics has proven to be as important to the earth sciences as the discovery of the structure of the atom was to physics and chemistry and the theory of evolution was to the life sciences. Even though the theory of plate tectonics is now widely accepted by the scientific community, aspects of the theory are still being debated today. What is the nature of the forces propelling the plates? Scientists also debate how plate tectonics may have operated (if at all) earlier in the Earth's history and whether similar processes operate, or have ever operated, on other planets in our solar system. (United States Geologic Survey, 1999)

It is important to note that when we say that scientific knowledge is **tentative**, we do not mean that the current scientific theories are especially flimsy or undependable—far from it. Indeed the currently accepted scientific explanations are based on a great deal of experimental and observational evidence. But the actions of science are structured so that if another idea comes along that is better at explaining all the available data, then that new idea could replace the current ideas that scientists rely on. This portrait of a robust, useful but tentative scientific knowledge allows students to see the actions of science for what they are: dynamic, changing, and so interesting.

The tentative nature of scientific knowledge is readily apparent as news programs, newspapers, and the Internet provide fresh stories about scientific debates and changes in scientific knowledge. The tentativeness of science is in large part connected to the creative aspects of science. In science there is always another question to ask, another piece of information to collect, and another way to interpret the evidence. But the social nature of scientific inquiry is responsible for the mechanisms responsible for changes (the scientific actions of replication of investigations, review by colleagues, and scientific debate). If students are not aware that the scientific explanations are supposed to be tentative, then they may misinterpret these debates and become dismissive of science (i.e., "Why do I have to learn this if it is going to change?"). The alternative is that if they see science as unchanging, with the exception of the occasional discovery, science can seem boring, as if all of the real discoveries have already been made. Instead by helping students see examples of how scientific explanations can and do change, they can appreciate the debates, arguments, and changes in explanations produced by scientists that are the defining features of the actions of science. Learning the culture of a dynamic and ever-changing enterprise is more appealing to many students than a culture centered on the memorization of past discoveries. Emphasizing the tentative nature of science not only allows students to interpret the science as it is played out in the media but also this component of the culture of science allows science to feel more interesting and engaging within the classroom.

Scientific Theories: The Power of Science

Sometimes you may hear the phrase "it's only a theory." People tend to use this phrase when dismissing an idea or when suggesting that an explanation is weak. Indeed that science can and does change seems to support this notion of scientific theories as flimsy guesses. Yes, science is tentative and scientific explanations do change. Paradoxically, because of this tentative nature and explanations are tested and revised, the actions of science produce durable and dependable explanations. The tentative nature of science contributes to its durability and utility. So where do scientific theories fall into this?

In our everyday lives we have often said things such as "I have a theory about . . ." or "The reason the washing machine broke is . . ." (or why the cat is losing weight or why the car makes a bizarre noise). By theory we mean we have a good guess about some phenomenon (the washing machine, the cat, or the car). This is very, very different from the way scientists use the term *theory.* Scientists tend to reserve the term **theory** for their best, most powerful, and most supported and accepted explanation for natural phenomena. In science, explanations achieve the status of theory only after many scientists have investigated them and found the ideas able to explain a wide range of evidence. In science to say "it is only a theory" is nonsensical. It is akin to saying "it's only a million dollars" or "it's only the best explanation anyone, anywhere has ever generated to explain this situation." A scientific theory is our best attempt to explain how something happens, based on empirical evidence, logical explanation, and much debate. Keep in mind that the goal of science is a set of explanations about the physical world, and these explanations are articulated as theories.

This understanding of theory becomes important in the event that someone wants to dismiss controversial scientific ideas by saying "that's only a theory." When that happens, we need to remind him or her that theories are the best, most powerful objects that science can produce. One of the fascinating aspects of the biological world is the immense variety in the types of objects that are considered living. To explain the cause for biological diversity, we can rely on the process of natural selection. Too often this explanation is attacked because evolution is a theory. The criticism of evolution often focuses on the theoretical nature of evolution, without understanding (or perhaps deliberately ignoring) the intended meaning of *theory.* There are other scientific theories, including the theories of photosynthesis, atomic structure, inheritance, and plate tectonics. Like evolution, these explanations are tentative; by definition, all scientific theories are explanations open to debate and possible modification. But also like evolution, these explanations are widely accepted in the scientific community and represent the best, most useful explanations scientists have been able to construct. Theories are not simple guesses or flimsy conjectures. Even though theories are viewed as open to change and tentative, they provide the very foundation for science. Even though scientific explanations may change, theories are not likely to change until there is considerable contrary evidence.

How do theories as specific products of science compare to other well-known products such as laws and hypotheses? A common myth regarding the nature of science is that theories, once proved, will turn into laws. In this myth, laws are regarded as unchanging, indisputable, and the most important piece of scientific knowledge. In reality scientists think of laws as specific, straightforward, and simple descriptions of patterns in nature, such as the law of universal gravitation. The role of laws is to describe common patterns in the physical world; they don't explain those patterns. For example the law of universal gravitation doesn't explain gravitation, it just describes the effects of gravitation between two objects. Although laws are durable and they enjoy a great deal of empirical support, their role is not explanation: laws are descriptive. Using this line of thought, it becomes obvious that theories, however well supported, cannot be promoted into becoming laws. Instead, theories and laws have different uses within the culture of science, one explanatory and one descriptive. In contrast, hypotheses are very tentative, exploratory ideas scientists develop to focus and structure their inquiries. Hypotheses will be refined as scientists test them against data that support or refute them. Hypotheses are initial attempts to explain, but they are trial explanations whose fates are determined by the tests of more data.

Point–Counterpoint

The nature of science appears to be a valuable component of science education. Yet there is some uncertainty about whether nature of science ideas can and should be fully revealed to students. For example the tentativeness of scientific knowledge can be held as a way to push open the door to science to a wider variety of students. However, others wonder whether emphasizing the tentativeness may serve to confuse students and distract them from comprehending the widely accepted scientific theories. So in response to the question "How should the nature of science be taught in schools?" we are treated to two diverse stances.

Emphasizing the Tentative Nature of Science in the Classroom

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I'm continually asking myself what it is that we really want our students to understand about science in the long run. Do I want them to know something about forces and motion? Something about how research is done? Maybe we should all find application of science in our everyday lives? Yes. All of these are valid, but none of them are sufficient. What we really need is to give children—our future citizens, voters, decision makers, and so on—a grander view of what science is and how it works, a sense of ownership in the scientific process, and, perhaps more than anything, a sense of wonder for the natural world.

Science is a way of knowing that is both powerful and limited, and I want my students to deeply understand how this is and what it means. I want students to see what science can and cannot do for them. Too often, the "answers" of science are overstated, and similarly too often the "answers" of science are dismissed out of hand. If our students are to understand anything about science and the knowledge that it produces, they need to understand the tentative nature of the knowledge it produces.

The fact that the knowledge of science is tentative is foundational to what science is. Science will never end, for there will always be another question to ask, another rock to turn, another explanation to propose. Because all of science's knowledge must be testable, it must always be tentative. Even the most known piece of science knowledge—for example, the explanation that all stuff is constructed from atoms—is continually open for further investigation. If it weren't for this philosophy and attitude, science would stop. If we stopped asking questions and testing what we know, our knowledge would become dry, tasteless, and stale. But with an ongoing quest for explanation, we have a science that is always fresh, even if the universe stays the same.

At the same time, this ongoing quest and testing of our understandings makes science durable. For me, this is an exciting irony. The philosophy that our knowledge is always subject to testing and change allows us to feel that it really has been legitimately probed, and if we are wrong about something, we're eventually going to find a way to make corrections. We rely on Newton's laws not because they are in a textbook but because they have been put through the ringer. We are always using these ideas, seeing how they apply, and searching out their limitations. This makes science something that we can lean on to give us useful, reliable information.

Tentativeness also points to the different levels of scientific knowledge. We collect data, and certainly there is always more data to collect, but if this were all that science was about we wouldn't think any more of science than we would of stamp collecting. Even more interesting and useful than our data is our set of creative explanations. To make science mean anything, we have to try to create an understanding for ourselves that we can communicate to others. These creations of explanation are always based on the data, but they are creations nonetheless. Clearly, we should always ask ourselves if we have these explanations right, and continually test them against our data. For students to see this interaction between the facts of the natural world and the explanations of these facts is invaluable, for it shows exactly how creative an endeavor the scientific process is.

I want students to embrace this creative science, because, besides representing science for what it truly is, the creative science is an open invitation to all students. One of my biggest frustrations with science education is that students come to view science as being unapproachable. If we let entities such as science books present science, it is a bunch of static facts and equations that simply sit there, waiting for the user to turn to page 735 to look up the atomic mass of nitrogen. However, if science is not so much a book of facts but a pursuit of new, dynamic explanation, then suddenly the entire landscape is changed. Only when students view science's knowledge as being tentative can they see that there is room for a new question, a new investigation, and a new answer. This is the science that I want my children to have in their classroom, and it is the science that I want citizens to embrace. If they see science as static, then they will misinterpret facts as dogma. If they miss the point that science is always being tested, then they can take any scientific claim and consider it ludicrous.

Finally, I like science for many reasons, but most of all because it makes me say things such as "ooh" and "wow." The tentative nature of science is something that fits hand in hand with the ideals of inquiry, trying out new experiments, asking new questions, and looking at things in new ways. This is exactly what I want my classroom to look like. If science is not tentative, then there really isn't anything to do. If my students come to class with the hopes that I will give them the next correct answer from out of the back of the solutions manual, then they aren't getting what science is really all about. I want my students to come to class every day with the possibility that they're going to ask the next question that needs to be asked. Emphasizing the tentative nature of science emphasizes this openness to the inquiry process and the learning goals that I envision for my students.

Possibilities of Degrees of Tentativeness of Science in the Classroom

Scott Sowell
Middle School Science Teacher

As has been mentioned, an extremely important part of a sophisticated nature of science (NOS) understanding is recognizing that scientific knowledge is tentative. Indeed, we know that successful participation in science requires addressing the common misconception that science is about discovering or unearthing a preexisting set of certain and absolute truths. Learning science is much more than the rote memorization of vocabulary terms in the textbook chapters. However, for those of us teaching science in K-12 classrooms, there may be practical reasons to not emphasize that all scientific knowledge is equally tentative in all circumstances.

Elby and Hammer (2001) questioned the either/or way we think about students' tentative views about the nature of science: either naive or sophisticated (e.g., either students correctly describe scientific knowledge as created or tentative or they incorrectly describe it as discovered or fixed). Rather than relying on generalities about what students do or do not know, Elby and Hammer made an eloquent argument for paying attention to the contexts and nuances of both practicing scientists' and nonscientists' NOS understandings. In particular they make the distinction between the correctness and productivity of a NOS understanding. Although believing that science is about discovering objective truths may be incorrect (in terms of the science education community's best understandings about NOS), it may be productive for a student to work to understand a scientific explanation through a classroom activity. The "correct" beliefs about science expressed by practicing scientists and other academics may be different from the "productive" beliefs that assist in students' learning.

It is important to recognize that not all knowledge is equally tentative, and it is not productive for practicing scientists (or even students) to even think so. For example Elby and Hammer mentioned how the degree of tentativeness varies when considering two different scientific explanations: the round shape of the earth versus the theories of dinosaur extinction. Or consider how the degree of tentativeness differs between the knowledge presented in an introductory biology textbook and the knowledge being generated by biologists working in a tropical rain forest. When we consider that the work done at the leading edges of science is more tentative than many of the basic theories and principles that underlie such work, it becomes more sophisticated to attend to context and nuance, and this sophistication makes us consider degrees of tentativeness. For example, when working with students on an understanding of how today's genetic research explores human biology, there may be a need for students to grasp that, although not written in stone, our models about the double-helix structure of DNA are less tentative than our explanations concerning the links between genes and certain disorders. Therefore rather than being limited to either/or ways of talking about students' NOS understandings (sophisticated = tentative and evolving versus naive = fixed and absolute), we might want to consider the value in using Elby and Hammer's terminology of sophisticated tentativeness versus naive tentativeness.

Although I want my students to have a strong appreciation about the tentative nature of science, I would be wary of instances in which individuals might hide within extreme relativity and view science as simply a set of continually evolving stories or creations. This may be especially true when considering more controversial theories in science, such as evolution, that may tempt some students to engage in discrediting the findings of science on the grounds of its tentativeness. Therefore discussions about tentativeness need to be couched within conversations about how the culture of science creates durability as its findings, explanations, and theories are strengthened through peer review and professional debate.

This conversation forces us to ask if there are instances in which younger students, or students in introductory science courses, benefit from viewing the science they encounter as fixed truths rather than as evolving human constructions. Does this perspective assist them in situating the science content within their own lived experiences rather than simply viewing it as a constantly recreated invention? Should we be asking our students to think about the degrees of scientific tentativeness rather than merely having them reject science as a set of discovered truths? Although these questions have yet to be resolved, the work of researchers such as Elby and Hammer push us to think beyond our current understandings of tentativeness in the science classroom. We need theoretical arguments such as this to recognize the possible limitations of our current practices and to search for better ways to teach science. In other words, it helps us to see our own teaching practices as tentative and evolving.

Science as a Way of Knowing

Science can be useful for understanding the physical world by virtue of the way scientific inquiry shapes the knowledge it produces. In an attempt to best encapsulate this conversation, we find it useful to use Moore's (1999) description of **science as a way of knowing**. By this he meant that scientific knowledge and scientific inquiry have particular characteristics that set them apart from other ways of knowing the world. Characteristics of science as a way of knowing include the empirical, creative, social, and tentative dimensions. The notion of science as a way of knowing acknowledges that the actions of science are based on a particular set of assumptions. Assumptions of the culture of science include that the best explanations are logical and straightforward and do not employ supernatural forces or agents. This brief description acknowledges that science is simply one way of knowing and distinguishes science from other ways of knowing the world, ways such as the arts (whose standards do not require logic, evidence, or reason) or traditional belief systems that have assumptions in direct conflict with those of science (such as the religious belief in supernatural agents). We wish to be quick to indicate that there is no implied hierarchy to these "ways of knowing." Rather, each of us relies upon a range of strategies for understanding our world. We live in complex worlds, and although science can help us think through some things, there are other circumstances where science is of little use. We must rely upon other ways of knowing that allow us to consider the interpersonal and the internal, the just and fair, the patriotic and the rebellious.

Although the characteristics of scientific inquiry and the assumptions underlying those inquiries make science a powerful way of knowing the world, these assumptions of the action of science also limit what can be understood scientifically. As pointed out by Poole (1996), there are occasions when a scientific account may provide an inadequate, even inappropriate, approach to a topic:

> The scientific study of a work of art, say a picture, may give an exhaustive account of the chemical constitution of the pigments, the wavelengths of the light they reflect, their reflection factors, masses and physical distributions. But such a scientific account has hardly begun to say much of interest to the viewer or to the artist. Aesthetic considerations, issues of meaning and matters of purpose are of far greater importance. A sociological study of the influences on artists' work will have similar limitations. It is not that pictures cannot be described in terms of chemicals, or mental activities in terms of brain functions—they can. What is wrong to assert (for it cannot be demonstrated) is that these scientific accounts are the only valid ones there are. (Poole, 1996, p. 165)

Given that scientists begin their work by making various assumptions, the teacher's role is to help students become aware of these assumptions to help in determining what kinds of questions can be pursued scientifically and what kinds of questions cannot be reasonably investigated using this way of knowing.

It is important to understand that science as a way of knowing is very helpful in explaining some aspects of our daily lives but is nearly useless for understanding others. Although it may seem that science contradicts or refutes other ways of knowing, this idea is based on the narrow view that science claims to be the only way of knowing the world. One feature of doing science is that one may not invoke supernatural or metaphysical explanations in constructing a scientific explanation. Scientific explanations must instead rely on logic, observable evidence, and testing. That is not the same as saying that unobservable, nonphysical forces do not exist but that in doing science we cannot resort to the power of nonempirical agents. If the metaphysical or supernatural must be used to construct an explanation, then that explanation violates the assumptions of science and so is considered nonscientific. This is a crucial distinction. The fact that an explanation is not scientific does not make it a weak or flawed explanation—it is simply a nonscientific explanation. That same explanation may be useful for a great number of people in understanding their lives, but that explanation is simply not consistent with science as a way of knowing.

One strategy to assist students is by presenting a number of questions that they are to place along a continuum between more and less scientific. This list can include the following prompts: Is it wrong to keep porpoises in captivity? How was the earth made? Do ghosts haunt old houses at night? Am I in love? Is there a god? Through discussing these and other questions, students may begin to recognize what science is particularly good at helping to answer. It can also show what is clearly outside of the scope of scientific investigation. Once we begin this conversation in the classroom, we begin to understand that there are important aspects of our lives that are out of the boundaries of scientific investigation (religious beliefs, interpersonal relationships, morality, and so on), because they rely on the supernatural or metaphysical or because they are not empirical. But just because these things are out of the bounds of science does not prevent them from playing a huge part in our lives.

Why is this discussion of science as a way of knowing so important to have in a classroom? In the past century, American culture has become so enamored with the products of science (antibiotics, jet engines, computers) that it seems that our society has treated science as the best way of knowing. Because science and the technological by-products have proved so amazingly powerful in almost every aspect of our daily lives, the American culture has begun to view science as perhaps the only legitimate way of knowing. Many scientists and science teachers have become dismissive of ideas generated outside the culture of science. It is unfortunate that as they dismiss nonscientific ways of knowing, they also dismiss students who hold alternative perspectives. Within the classrooms of the past century, it was common for science to be presented as the only real way of understanding the world. Along the way far too many students may have felt as if they had to reject science because it was so contradictory to their family traditions or cultural beliefs. When science is presented in this uncompromising way, it seems reasonable to expect that students from non-Western families or students with strong religious or spiritual convictions will be intimidated, discouraged, or disenfranchised. The consequence may well be that the students in diverse classrooms come to view science as a powerful and alienating way of knowing the world.

It can be a struggle for students to concentrate in a classroom in which a large part of their lives doesn't belong or is devalued. Who among us would want to participate in a culture that is dismissive of much of who we are? Helping students to recognize science as one way of knowing the world becomes necessary when teaching science in diverse classrooms. Allowing students to understand the power, as well as the limitations, of science fosters powerful classroom conversations. By treating science as another culture, teachers and their students are more likely to recognize other important, but nonscientific, aspects of students' lives.

For Reflection and Discussion

Gather the following materials: several ceramic mugs, a metal spoon, sources of hot and cold water, and an almost endless supply of powdered hot chocolate mix. When making a mug of hot chocolate, we can observe an interesting and not-easily-explained phenomenon. After stirring the hot chocolate mix into the water, tap on the bottom of the cup and you will notice that the tone produced is a relatively low pitch, but gradually the tone rises in pitch as you keep tapping. Stirring the hot chocolate again will restore the lower tone, but as you continue to tap with the spoon, the tone will again rise. As you continue to mess about with these materials, consider these questions: are you doing science and, if so, what is there about your efforts that can be considered scientific?

Nature of Science and Diverse Classrooms

Our portrayal of science is as follows. It is a way of knowing the world. It is tentative. It is limited in its scope and use. It is increasingly performed by a variety of people. It is situated in a community populated by individuals with varied backgrounds and biases. It is accomplished through the use of a range of methods. It is the consequence of individuals working together to create theories that explain evidence collected from the physical world. We argue that working from and toward a portrayal of the culture of science is necessary when teaching science in diverse settings. Why? This portrayal is dynamic and intriguing, emphasizing a culture based upon recognizing the need for change and placing a premium on scientists with diverse knowledge and backgrounds. Science becomes more inviting than our traditional characterization of science as a solo activity in which ideas are gathered and recorded and for which the bulk of the real creative work and important discoveries have already been accomplished.

The central idea to the nature of science is that science is a way of knowing, a way that differs from others, a way that is powerful, but also a way that is limited in the kind of knowledge it produces because of the nature of inquiry it employs. By emphasizing science as a way of knowing, students can begin to understand that just because another way of knowing is nonscientific does not mean it is flawed but simply that line of thought differs from science. Such realizations permit students to understand that schools, schooling, and schoolteachers do value things other than science and so value a large portion of these students' lives. Such knowledge is essential for demystifying the culture of science, making it far less threatening and far more inviting for students.

Who Does Science? Who Can Do Science?

When students are asked to draw pictures of scientists, they often portray scientists as men in white lab coats working in a chemistry laboratory. If students see science as an activity in which only White men participate, many will direct their energy elsewhere. Thus, both science (which could benefit from the contributions of scientists with varied backgrounds and biases) and the learners (who will need scientific knowledge to negotiate their lives) lose out. Over the years, this stereotype seems less evident in children's drawings, indicating that this notion about science is gradually fading away. Even in television and movies, scientists are becoming a bit more diverse. We see more women and people of color in the roles of scientists—a change we applaud and hope intensifies. Teachers can support this change by pointing out the limitations in the portrayal of scientists in popular culture (teaching their students to ask questions such as "Why is the lead scientist always a White man?") and bringing in many alternatives for students by emphasizing the contributions of non-Westerners, people of color, and women to the scientific enterprise.

But beyond the more obvious barriers that we can observe on television are the more subtle but persuasive barriers to students' access to science that may be created or supported by parents and teachers. Parents often may dismiss their child's efforts in science, saying, "I was never good at it, so I can't expect her to be," or "She'll probably never really need this stuff." Women teachers might shy away from teaching science or show uneasiness or squeamishness through playful squeals or yelps when the more "icky" aspects of the natural world (i.e., worms, snakes, mold) come up as they so often do when students engage in science. These seemingly harmless comments and comical gestures are soaked up and internalized by children, just as they mimic behavior of characters in their favorite films. Subconsciously some students begin to think that they cannot do and cannot learn science.

If you want to help students become comfortable working with the culture of science, a common component of your classroom culture must be to have high expectations of the science learning of all students regardless of gender, ability, or background, and these expectations and your reasons behind them must be conveyed constantly to the children and to their parents. And remember that as their teacher, you have become one of their role models. For them to become comfortable working in the culture of science, you must show that you are comfortable in the culture of science.

There is a wealth of research on the teaching and learning of the nature of science that demonstrates that the more traditional approaches to teaching about the culture of science—having students read about it, having students do science—are insufficient if we desire for students to grasp the nature of science (Abd-El-Khalick, Bell, & Lederman, 1998). The educational research has revealed that instruction that explicitly addresses nature of science concepts and encourages learners to be aware of their nature of science ideas and reflect on their ideas and how they change is essential for students to learn about the nature of science (Akerson, Abd-El-Khalick, & Lederman, 2000). For students to come to understand the culture of science, they not only have to be actively involved in it but also need to explicitly think and talk about the nature of science and focus on how their own ideas about the nature of science have changed during instruction. Crafting such an explicit, reflective, activity-based approach to the nature of science is a difficult thing for teachers, but it is essential if students are to become familiar and comfortable operating in and understanding science.

Chapter Summary

- To increase the likelihood that all students will engage in the culture of science, they and their teachers must have a better appreciation of the nature of science. The stereotypes of scientists are more than inaccuracies and may actually discourage students from wanting to be successful in science.
- Because of its demand for evidence to support any and all knowledge claims, the culture of science is distinct from many other worldviews. Unless ideas are supported by data, they are unlikely to be given any consideration within the scientific culture.
- Using creativity is acceptable and desirable within the culture of science. Suggesting explanations based on the available data is necessary for scientific knowledge to advance. The valuing of creativity is a feature the culture of science shares with many cultures.
- Objectivity is a goal of science, even though it is generally understood that biases and preconceived ideas can influence what scientists perceive and propose. Reducing the influence of bias is something scientists strive to achieve within their work.
- A common myth is that scientists follow particular steps toward a scientific discovery. The reality is that science is not nearly as linear and sequential as the scientific method suggests.
- The work of individual scientists must ultimately be presented to a larger scientific community for evaluation and possible acceptance. The social feature of the culture of science is often in contrast to the stereotype of scientists working in isolation.
- The tentativeness of scientific explanations accepts the possibility of theories and laws being modified as new data are gathered and different interpretations of the evidence are proposed. Despite the tentativeness, scientific theories are based on reliable data and are very useful within the work of science.
- In making "science for all" a reality within diverse classrooms, teachers should educate students about the nature of science so they can recognize how to function within the culture of science and realize they can be successful within this culture.

Key Terms

Empirical: information based on data and evidence not on opinions or beliefs.
Nature of science: specific characteristics of the knowledge produced through science, characteristics that are influenced by the practices and beliefs specific to the culture of science.
Science as a way of knowing: perspective about the world that relies on empiricism and, though distinct from other worldviews, should not be regarded as superior to other ways of knowing or as providing the sole pathway to the truth.

Scientific method: although often presented as a fixed sequence of steps followed by scientists, it is a myth that is based on an incorrect interpretation of the nature of science. When "the scientific method" or "methods of science" are viewed as a combination of thought processes that do not necessarily occur in certain sequence, we have a more accurate representation of the ways science proceeds.
Subjectivity: interpreting the world through the filters of one's own perspectives.
Tentative: an idea or explanation that is considered accurate for right now, but has the potential for being modified as more information becomes available.
Theory: an explanation that is based on well-documented evidence and is accepted by the scientific community as the most scientific way to make sense of a phenomenon. A theory is not merely a guess but the best-substantiated explanation agreed on by a group of scientists.

Suggested Readings

Smith, M. J., & Southard, J. B. (2001). Exploring the evolution of plate tectonics. *Science Scope, 25*(1), 46–49.

In this article the authors summarize in very clear ways the changing explanations about the movement of continents. The article also is a nice illustration of the historical shifts in scientific explanations. In addition this article is an example of the "science content" articles sometimes appearing in National Science Teachers Association publications.

Reeves, C., & Chessin, D. (2003). Did you really prove it? *Science Scope, 27*(1), 23–26.

The authors situate the challenges of teaching students about nature of science within the context of student science fair projects and lab activity reports. Within the article they describe characteristics of the nature of science in a clear, straightforward fashion.

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