Session 1: The Nature and Practices of Science

Contents

Overview

In this session, we address "what is science," and "how does science work?" Participants gain insight into the nature and practices of science in the best way possible—by ***doing*** and ***reflecting*** on science.

— After an introductory brainstorm about "What is science?" participants investigate a strange substance called "Oobleck," and then, using the evidence they've gathered, make generalizations about the substance, and derive "Laws of Oobleck." This turns out to be much more complex than they may have imagined!

— The experience provides a sense of the actual practices involved in doing science and helps communicate the nature of science as an evidence-driven human endeavor to investigate, find out about, understand, and make generalizations about the natural world.

— Participants also take a critical look at what is and is not an accurate view of science. These misinterpretations, conscious and unconscious, are widespread, and examining them can help hone our own understanding of what science is and is not. Through attempting to define science, participants can gain a deeper understanding of its strengths and limitations.

— Tinker and Thornton describe science: " …not as a noun...but as a process, a set of activities, a way of proceeding and thinking." (Tinker, R. F. & Thornton, R. K. (1992). Constructing student knowledge in science. In E. Scanlon & T. O'Shea (Eds.), *New directions in educational technology* (pp. 153–170). Berlin: Springer-Verlag.)

Not all of us learned science in this way; some of us needed to wait until graduate school to become authentically engaged with doing science. And yet, as is illustrated through the Oobleck experience in this session, science *can* be introduced to the youngest of students in ways that engage them in the firsthand collection and evaluation of evidence.

Background Information for the Presenter

Note: The science background information included here is for the presenter, and is not meant to be read aloud to participants. The background information is designed to help presenters respond to participants' questions, and be aware of inaccurate ideas that research indicates students may bring to the classroom.

About the Nature and Practices of Science

Why Reflecting on the Nature and Practices of Science Is Important. In the modern world, we are constantly presented with scientific and non-scientific information. As citizens, we vote on many issues that are informed by scientific studies. To understand the meaning and value of scientific information in these situations, it's important to understand how the scientific field gathers information, and how it comes up with explanations. (The *National Science Education Standards*, National Research Council, 1996)

The *National Science Education Standards* call on science educators to move beyond having students just *learn about* science, and be guided to *inquire about* the natural world, using the inquiry methods that scientists themselves use. Being able to critically inquire about the world will prepare students not only for future science studies, but also for life itself, as they increase their ability to make informed decisions based on evidence and to acquire new knowledge. Teaching students about the nature of science has also been shown to increase student interest in science (Lederman, 1999; Meyling, 1997; Tobias, 1990)

Understanding the nature of science is important for citizens and students, and particularly for anyone who teaches science. Science teachers who do not have a background in the nature of science tend to primarily teach vocabulary and facts, while neglecting more important aspects of science, such as how scientific knowledge is generated, and how knowledge claims are cautiously evaluated

The better understanding teachers have of the nature and practices of science, the better they can make this explicit for students. The fact is that many children and adults, including science teachers, hold a combination of accurate and inaccurate ideas about what science is. And many science teachers have not had the valuable opportunity of reflecting on the nature of science. (Gess-Newsome & Lederman, *Examining Pedagogical Content Knowledge*.)

What is Science? Science is an extremely valuable way of knowing. The scientific enterprise is a union of science, mathematics, and technology, as well as logic and imagination. Science assumes that the world around us is understandable, and that the basic rules that exist in one part of the Universe can be applied to others. Like many other systems of thought, science is a quest for truth, yet one of its greatest strengths is that it recognizes that it can never completely arrive at the truth. Nothing is ever completely proven in science. Science is not only open to new evidence and ideas, but actively seeks them out. Science helps us understand the world around us, and in a practical sense, it has great predictive value. Some people think science is infallible. Others see it as a static accumulation of information. Others see it as arrogant, biased, or heartless. In actuality, it is none of these things.

Note: See the handouts, Science is… and Science is not… for more information on "what is science?" (pages 52 and 53)

Science, Evidence, and Explanations. At its core, science is about ***evidence*.** In an attempt to understand some aspect of the natural world (as opposed to supernatural), observations are made and data collected in as objective a manner as possible. Scientific explanations are based on *all* the available evidence. Explanations that are based on selective evidence, and which ignore or exclude evidence that doesn't support the explanation, are considered to be pseudoscience.

Science is Self-correcting and Durable. In science, evidence, investigations, and explanations are discussed and reviewed by peers. Investigations are repeated, and if the results are not comparable, the results are questioned. More evidence is always sought and welcomed, and if an accepted explanation doesn't match new evidence, it is revised or replaced. Scientists also seek ways of testing explanations, and if tests show an explanation to be false, then it is revised or replaced. In this sense, science is self-correcting. Scientific knowledge and explanations are accepted within the scientific community based on consistency and strength of argument. Scientific knowledge evolves over time as the community of scientists inquires in different and deeper ways to uncover new evidence that changes and/or refines the accepted understanding of the natural world. Despite this embrace of change, and acknowledgment that science cannot attain "absolute truths," most scientific knowledge is durable. New evidence sometimes leads to refinement of current ideas, rather than complete rejection.

The Myth of the Scientific Method. A common misconception about science is that there is a single scientific method—a rigid series of sequential steps scientists follow to arrive at a conclusion. This myth has been spread widely by science educators, but is a source of frustration for scientists who are aware of its limitations in describing what they do. The source of the myth is described in the following quote:

> "In the 1940s a man named 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 then turned into a questionnaire and given to many professional scientists for their response. Keeslar took the questionnaires as they were returned to him and put the items receiving the highest rankings into an order that seemed "logical" and published these findings in an education journal (McComas, 2000). Even though he was reporting on scientists' uses of different thinking strategies without trying to describe a nice neat sequence, that's unfortunately how his work has been used. 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 most scientists (which makes us wonder what teachers are trying to portray by drilling students on the scientific method)." [From Settlage, J. and Southerland, S.A. (2007). *Teaching Science to Every Child: Using Culture as a Starting Point*. New York, Routledge.]

In actuality, there are many different paths scientists follow to answer questions. The methods used by an astronomer studying a distant star are quite different from those used by a biologist studying an insect. The scientific enterprise also involves human imagination and creativity.

> "What appears to [the working scientist] as the essence of the situation is that he is not consciously following any prescribed course of action, but feels complete freedom to utilize any method or device whatever which in the particular situation before him seems likely to yield the correct answer…In short, science is what scientists do, and there are as many scientific methods as there are individual scientists." (Percy W. Bridgman —"On Scientific Method")

Scientific investigations are also peer-reviewed, reflecting the fact that the real "scientific method" is bigger than the work of an individual scientist or even the combined work of a particular group of scientists. Scientific discourse and communication are also instrumental. Scientific papers are published in journals to be reviewed by other scientists. Shared critique and discussion of methods and ideas are ongoing within the scientific community.

Science and Human Nature. Although a goal in science is to be objective, in reality, evidence is collected, interpreted, and influenced by current scientific perspectives and understandings and by the society, culture, and even the scientists' sometimes-unavoidable personal subjectivity. There are patterns and habits of human thinking that present challenges in scientific endeavors, but the methods of science have been designed and re-designed to account for these.

Scientific Facts, Laws, and Theories. These three terms describe important aspects of the nature of science, but are often misunderstood. Each has a meaning in common usage that is different from its meaning in the scientific community, and this can cause confusion. These are the definitions as written by the National Academy of Sciences.

Fact: In science, an observation that has been repeatedly confirmed and for all practical purposes is accepted as "true." Truth in science, however, is never final, and what is accepted as a fact today may be modified or even discarded tomorrow.

Law: A descriptive generalization about how some aspect of the natural world behaves under stated circumstances.

Theory: In science, a well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses.

The contention that evolution should be taught as a "theory, not as a fact" confuses the common use of these words with the scientific use. In science, theories do not turn into facts through the accumulation of evidence. Rather, theories are the end points of science. They are understandings that develop from extensive observation, experimentation, and creative reflection. They incorporate a large body of scientific facts, laws, tested hypotheses, and logical inferences. In this sense, evolution is one of the strongest and most useful scientific theories we have. [Adapted from *Teaching About Evolution and the Nature of Science (1998).* National Academy of Sciences, Washington, D.C.: National Academy Press.]

Science and Language. Although "scientific proof" is a an expression that's often used by the general public, use of the words, "prove" or "proof" in science is generally inappropriate, because they imply that scientific ideas can be absolute truths. There are also many other words used in science that also are used in everyday language. Misunderstandings often arise when these words have very specific meanings in science, but more vague or sometimes quite different meanings in everyday language. For example, the word "theory" in common language is often used to describe an idea that is a guess or an explanation that has not been well tested. In science, however, as noted above, it is actually used to describe big ideas that are supported by a large body of scientific facts, laws, tested hypotheses, and logical inferences. See *Vocabulary Mix-ups*, in the *Misconceptions About Science section* of University of California Museum of Paleontology (UCMP) *Understanding Science* website: http://undsci.berkeley.edu/teaching/misconceptions.php

Note: Before presenting this session, even if the instructor is an experienced science teacher and/or scientist, it is strongly recommended that the instructor thoughtfully read the handouts and teaching notes on *Science Is…* and *Science is not…* (pages 46–47). It's also recommended to spend some time exploring the UCMP Understanding Science website: **http://undsci.berkeley.edu/**

Acknowledgments and References

We would especially like to thank Dr. Kevin Padian, of the University of California, Berkeley, Professor, Department of Integrative Biology and Curator of Paleontology at the UC Museum of Paleontology. We interviewed Dr. Padian at length and he made important contributions to this session, particularly the "Science Is" handout and related discussion.

Thanks as well to Ellen Granger, Professor in the Department of Biological Science, Florida State University, and Todd Bevis, also at Florida State, both also from the Great Explorations in Math and Science (GEMS) Center there, for conversations on the nature of science and the "Communicating Science" course.

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About Oobleck

What Kind of Mixture Is Oobleck? Oobleck is a suspension of cornstarch in water. A suspension is a type of mixture, as are solutions, colloids, and precipitates. In a mixture, two or more substances are combined. In a solution, a solid dissolves into a liquid. The atoms, molecules or ions become evenly dispersed in the liquid. In a suspension the ingredients keep their own properties and usually can be separated fairly easily. Colloids and suspensions are both types of mixtures in which a solid is mixed into a liquid without dissolving. What distinguishes the two is that the particles in a colloid are smaller than those in a suspension. In a colloid the particles also tend to remain suspended (like milk), whereas those in a suspension tend to settle out. When Oobleck is kept moist and allowed to sit for a long time, the cornstarch will begin to separate from the water on its own. In a precipitate a solid forms in a solution due to a chemical reaction. This solid does not dissolve in the particular liquid.

What Are Non-Newtonian Fluids? One of the most fascinating things about Oobleck is precisely the ambiguity that students explore when they consider whether Oobleck is a liquid or a solid. Substances that flow, such as liquids and gases, are called fluids. Oobleck is a fluid, but a fluid of an uncommon sort. Its unusual nature relates to its viscosity and how its viscosity changes. Viscosity is a measure of how strongly layers of fluid resist flowing past each other when under stress, or shear forces. Words such as "thickness" or "gooiness" are often synonyms for viscosity.

Newtonian fluids, such as water, gasoline, and mineral oil, are those whose viscosity does not change as a result of a shear force exerted upon it. When you agitate a liquid by hitting it or moving your fingers through it, you are applying a shear force. Isaac Newton observed that for many fluids the flow increases in a regular way when the shear forces increase, indicating that the viscosity is a constant even when shear forces or fluid velocities change. In other words, no matter how hard you hit water or how quickly you move your fingers through it, it will have the same viscosity. Fluids that behave this way are called Newtonian fluids, and they include all gases and many liquids. Fluids that don't behave this way are called non-Newtonian fluids.

There are some non-Newtonian fluids that actually become *less* viscous when subject to shear forces. If you hit a deep pool of one of these fluids or quickly move your fingers through it, it will become less viscous. Although these are more unusual than Newtonian fluids, there are some common examples, such as blood, shampoo, fruit juice concentrates, mayonnaise, gelatin, liquid cement, paint, and ketchup. Common practical experience with this is when people shake a container to get one of these non-Newtonian fluids to flow more easily.

Even rarer are another type of non-Newtonian fluids, like Oobleck, that become *more* viscous when subject to shear forces. Your students discovered this as they noticed more resistance when they increased the shear force by hitting it hard or moving their fingers through it quickly. These fluids make transitions from liquid to a solid-like state that defy expectations of how a substance ought to behave. Quicksand also becomes more viscous with agitation, which is why trying to move quickly if stuck in quicksand would make it more difficult to move. To confuse matters more, most of these fluids will also become *less* viscous if only a low shear rate is applied

There are also non-Newtonian fluids known as *plastic* fluids. These won't flow until a certain shear stress is applied. Some examples are toothpaste, hand cream, grease, and some ketchups. Toothpaste will not flow without pressure, but once the right amount of pressure is applied, it flows easily. *Time-dependent* non-Newtonian fluids either become less viscous with time (like yogurt or paint in a sealed container), or more viscous with time (like gypsum paste).

What Makes Oobleck Behave As It Does? Why Oobleck has such properties remains somewhat of a mystery. Some scientists have approached this question on a particle level and some at a molecular level. Here are three of their explanations:

1. Sand in Water Model. In this model, the starch particles in Oobleck are compared to sand and water in a plastic squeeze bottle. The grains of sand are packed closely together, with a little water in between. The surface tension of the water does not allow all of the spaces between the grains to be filled. Squeezing the bottle gently forces the grains of sand to slide against each other, increasing the spacing between some of the grains, and allowing more water to fill the spaces. The more gently you squeeze, the more time there is for the water to fill the spaces between the grains and provide lubrication so they will slide against each other, and flow. But when the bottle is squeezed quickly, there is not enough water between the spaces to start with, and friction between the grains of sand resists the flow. Although the grains of starch in Oobleck are much smaller than grains of sand, starch molecules are relatively large, as molecules go. Therefore, a mixture of water and cornstarch may act very much like a mixture of sand and water. This is one explanation for why Oobleck flows like a fluid, yet when suddenly compressed offers the resistance we associate with a solid.

2. Long Chains Model. This model bases Oobleck's behavior on chemical structure. Cornstarch is made of long chains called polymers. This model speculates that when a mixture of cornstarch and water is compressed, the chains are stretched in a direction at right angles to the direction of compression. The molecules become "tangled," can't slide easily against each other, and offer the resistance we associate with a solid.

3. Electrical Charge Model. This model suggests that the particles in Oobleck acquire an electrical charge as they rub together. The faster they're rubbed, the more electrical attraction is created between the particles, causing an increase in the mixture's viscosity.

These are among the ways scientists have attempted to explain the unusual properties of Oobleck and similar substances. An excellent discussion is provided by Jearl Walker in two articles in "The Amateur Scientist" section of *Scientific American* and there is quite a bit of scientific literature on related subjects, including an article by Albert Einstein. If you're interested in reading more, below are some references and additional notes.

Billmeyer, Fred W. *Textbook of Polymer Science,* 3rd edition, John Wiley and Sons, New York, 1984.

Einstein, A. (1905) "On the Motion of Small Particles Suspended in Liquids at Rest Required by the Molecular-Kinetic Theory of Heat." *Annalen der Physik* ***17,*** 549–560. Einstein, A. (1905) "A New Determination of Molecular Dimensions." *Annalen der Physik* ***17,*** 549–560. Einstein sought to explain Brownian motion, the zigzag motion of microscopic particles in suspension, as in a colloid. He suggested the cause as the random motion of molecules of the suspension medium as they bounced against the suspended particles. Using a statistical method, he could estimate the number and size of molecules in a cubic centimeter of liquid. This made an important contribution to proving that molecules *actually do exist,* not generally accepted at the time.

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Moring, Gary F. *The Complete Idiot's Guide to Understanding Einstein,* Indianapolis, Alpha Books, Macmillan USA, 2000, pages 140–161.)

Walker, Jearl. The Amateur Scientist, *Scientific American,* volume 239, number 5, pages 186–198, November, 1978, and volume 246, number 1, pages 174–180, January 1982.

Some Additional Information on non-Newtonian Fluids. From http://www.ccmr.cornell.edu/education/ask/index.html?quid=14: The molecules that make up cornstarch are very different from the small water molecules. They consist of long chains of repeating units called sugars. Sucrose or table sugar has two such repeating units per molecule, whereas starch has many, many, more. In pure cornstarch, the sugar chains stick strongly and cannot move past one another, thus starch is a solid. However, if we add water to starch, the water gets between the starch chains, separates them and allows the chains to slide past one another; the mixture behaves as a liquid. If we apply pressure to the starch mixture, the water is squeezed out from between the chains and they are able to grab one another. Sliding is prevented and the material behaves as a solid. If we release the pressure, the water can enter between the chains to allow sliding once more. This behavior is not limited to the molecular scale. A similar phenomenon occurs when you run on wet sand at the beach. If you run fast and generate pressure quickly the sand feels hard as water is squeezed out and the sand particles cling to each other. If you step slowly to apply the pressure gradually, the sand particles have time to move past one another—your foot sinks! The sand-and-water process described here is directly comparable to the liquefaction of sediment that can take place during earthquakes. See: www.tulane.edu/~sanelson/images/liquefaction.gif

For a discussion of different kinds of non-Newtonian fluids, with viscosity graphs, and more on this general scientific topic of flow in matter, or rheology, see: http://www.sju.edu/~phabdas/physics/rheo.html

Two articles in *The Physics Teacher* report some interesting findings about how a bowl of dried beans can act as a liquid and related issues. See "On the Difference Between Fluids and Dried Beans" by Rolf Winter (February 1990) and "Liquid beans" by Robert Prigo (volume 26, 1988). There is considerable scientific literature and fascinating findings on sand (see for example, a New York Times article of September 7, 1996—"From Grains of Sand: A World of Order").

Materials and Preparation

Materials Needed for the Session
For the whole group (if using overhead transparencies instead of PowerPoint slides):

- ❑ overheads of *Science Scenarios*
- ❑ overheads of *A Few Perspectives on Science*
- ❑ overhead *Science Is…*
- ❑ overhead *Science is not…*
- ❑ overhead *Inquiry and the National Science Education Standards*
- ❑ overhead *NSES Recommendation*
- ❑ overhead *Session Summary*
- ❑ overhead *Reflection is a powerful learning tool*
- ❑ overhead *Quick Write prompt*

Materials Needed for the Categorizing Statements Activity

For each group of 4–6 participants:

- ❑ 1 set of *"Scientific Statements"* (master on page 45)
- ❑ 1 copy of *"Misinterpretations of the Scientific Process"* (masters on pages 46–51)

Materials Needed for the Oobleck Lab Investigation

For each group of 4–6 participants:

- ❑ 1 bowl (to contain about 1.5 cups of Oobleck)
- ❑ 1 work station covered with old newspapers
- ❑ 1 large sheet of paper (a piece of flip-chart paper works well)
- ❑ 1 felt-tipped marker or crayon
- ❑ Assortment of Oobleck exploration/test items: cork, plastic spoons, metal washers, Styrofoam, film canisters, wooden craftsticks, etc. *(A quantity of these can be placed in one location in the room for teams to pick up as they investigate.)*

For the entire group:

- ❑ cornstarch (4–5 boxes is enough for 6 groups of 4–6 participants each)
- ❑ water
- ❑ green food coloring
- ❑ measuring cup
- ❑ paper towels

Materials Needed for the Oobleck Scientific Convention

For each team of 4–6 participants:

- ❑ 1 bowl of Oobleck (from the Lab Investigation)

For the entire group:

- ❑ water
- ❑ paper towels
- ❑ lists of properties (from the Lab Investigation)
- ❑ chalkboard
- ❑ 1 felt-tipped marker or crayon
- ❑ 1 roll of masking tape

Materials Needed for the Session Summary

For each participant:

- ❑ handout *Science Is…*
- ❑ handout *Inquiry and the National Science Education Standards*
- ❑ handout from *Why People Believe Weird Things*

Preparing for the Session

For the Categorizing Statements Activity

1. Duplicate *Science Statements*. Use the master found on page 45 to duplicate enough sets of statements so each group of six will have a copy (e.g., if you have 36 participants, then make six copies of the entire page of statements). Cut each page into individual statements and put them into an envelope, or paperclip them together, for each group.

2. **Duplicate *Misinterpretations of the Scientific Process*.** Use the masters found on pages 46–51 to duplicate enough sets of statements so each group of six will have a copy.

For the Oobleck Lab Investigation

1. Preparation and Mixing. If possible, start mixing the Oobleck about two hours before class. It's possible to mix the Oobleck shortly before class, but you can make any necessary adjustments more easily if you allow yourself more time. In any case, allow at least 45 minutes to prepare the Oobleck, and to set up the work stations and the equipment station for the lab investigation.

2. Prepare the Oobleck. The proportions used here—4 boxes cornstarch, 6 3/4 cups (1600 ml) water, and about 15 drops of food coloring—will make enough for six teams of students to have about 1 1/2 cups of Oobleck each. Keep an additional box of cornstarch on the side to thicken the mixture in case it becomes too soupy.

PLEASE NOTE: Different brands of cornstarch may require slightly different amounts of water, so you should always test the Oobleck as follows: the Oobleck should flow when you tip the bowl, but feel like a solid when you hit it or rub your finger across the surface. If it is too thick to flow, add a little water. If it is too soupy, add a little more cornstarch.

a. To prepare the Oobleck, add 15 drops of green food coloring to 6 3/4 cups (1 liter or 600 ml) of water in a dishtub or large mixing bowl. Slowly sprinkle in the contents of four boxes of cornstarch. Swirl and tip the bowl to level the contents.

Note: *Food coloring should not be added after the cornstarch, because at that stage it is difficult to mix evenly. Also, adding more than the recommended amount of food coloring may cause Oobleck to temporarily stain hands.*

b. Mix the Oobleck with your hands (not a spoon) to ensure an even consistency. Do not try to push through the Oobleck mixture as if mixing batter, as that will prove very difficult. Instead, keep "lifting" the Oobleck from the bottom of the bowl to the top by slipping your fingers under it, until an even consistency is reached.

c. A few minutes before you plan to start the activity, mix one more time if water has separated.

d. Pour about 1 1/2 cups (350 ml) of Oobleck into each team's bowl. Then put the bowls aside until after you introduce the activity.

For the Session

Duplicate handouts. Make copies of the take-away handouts:
Science Is… Is Not… (pages 52 and 53)
Inquiry and the National Science Education Standards (pages 54–55)
Why People Believe Weird Things (pages 56–57)

Instructor's Guide

Session Objectives

In this session, participants deepen their understanding of the nature and practices of science through an appreciation of the following points:

- Science strives to find the best explanations for phenomena in the natural world, based on all the available evidence.
- Scientists use a wide range of inquiry methods as they inquire about the natural world.
- Science is a socially embedded, collaborative enterprise
- Scientific "truth" evolves over time as the community of scientists inquire in different and deeper ways to uncover new evidence that changes and/or refines the accepted understanding of the natural world.

Time Frame

Total Workshop: 2 hours
Thought Swap and Categorizing Statements
Concept Invention: *What is Science?*
Exemplar: Oobleck Lab Investigation (25 minutes)
Scientific Convention (20 minutes)
How We Acted Like Scientists (10 minutes)
Application to *What is Science?* (10 minutes)
Summary (5 minutes)

Session Activities at a Glance

Thought Swap: What is Science? (10 minutes)

This session begins with a "Thought Swap," in which participants share their ideas in rotating pairs and discuss the questions:

- **What is science?**
- **How does science work?**
- **When is something not science, but appears scientific?**
- **Why is learning about how science works important for students?**
- **Why is learning about how science works important for teachers?**
- **What is the value (or usefulness) of a scientific approach to understanding the natural world?**
- **How is a scientific view distinct from other ways of knowing?**

Partners are then encouraged to share interesting statements to begin to gain a preliminary understanding that science is based on testable evidence.

Categorizing Statements (30 minutes)
The participants are seated in groups of ~ 4 and presented with statements about science that they are challenged to categorize as accurate or inaccurate.

For each statement, participants discuss the criteria they used to classify them. Participants' exact choices of which statement belongs in which group are not as important as the discussion. (Controversy, after all, is also the stuff of science.) Then in the large group, each small group shares a statement they thought was inaccurate, and why. Then they share one statement they thought was accurate. Afterward, the instructor shows the UCMP Understanding Science website the statements came from, and reveals that *all* the statements are actually considered misconceptions.

What is Science? (10 minutes)
The instructor now introduces (via overhead transparencies or PowerPoint slides) *"A Few Perspectives on Science"* as well as a generally accepted definition of science titled *"Science is based on..."* These criteria are used to evaluate some of the statements they previously sorted.

Classroom Exemplar (55 minutes)
For each Communicating Science session there is a portion of the class where we model lessons from actual classroom science activities. Depending on your audience, you may select particular activities that relate to a particular subject area that you may find more appropriate for your situation.

The activities and potential audiences are listed here:

Oobleck (included in this write-up): topic is properties of matter, primarily for physical science students or faculty, as well as preservice and inservice teachers.

Ice Cubes Activity (included in optional activities): The topic is Ocean Science (specifically density), primarily for ocean science students or faculty

Oobleck: Laboratory Investigation and Scientific Convention
Participants then take part in the GEMS unit entitled, *Oobleck: What Do Scientists Do?* In these activities, participants first investigate the properties of a substance called Oobleck, said to come from a newly discovered moon in our Solar System. Then, as a community of scientists, they conduct a scientific convention at which they attempt to write their own scientific statements about Oobleck. The activities they experience demonstrate the meticulous nature of scientific exploration and debate, the challenge of making a scientific generalization that all can agree upon, and the joy of inquiry!

The exemplar portion concludes with participants reflecting on how they acted like scientists during the Oobleck activities. The presenter introduces the terms for inquiry skills and abilities used with students and relates them to the original list they brainstormed for "What is Science?"

Session Summary (5 minutes)
Participants examine some of the pitfalls and stumbling blocks of science, as they read a handout from *Why People Believe Weird Things*. This handout also addresses problems in "pseudoscientific " thinking and how some of our natural human tendencies may get in the way of thinking scientifically.

Introduce Session

1. Introduce common conceptions about scientists. Ask participants what immediately comes to mind when they think of a scientist. Take a few responses from the group.

2. Connect to ideas people have about science. Tell participants that the image of a scientist (whether positive or negative) has a certain mystique and aura, some of which may be fantasy, and some of which is accurate. Young students often enjoy wearing the trappings of science, such as goggles and lab coats and doing activities that make them feel "scientific." Similarly, non-scientists sometimes dress up their ideas in the trappings of science to tap into its mystique. This may create misconceptions about what science is and what it is not. These inaccurate ideas may survive, in part, because the general public has not been engaged in discussion about the nature of science.

3. Explain rationale for session. Tell them that, since they will be teaching about science, it's extremely worthwhile to spend some time thinking about the nature of science and how this can be communicated to others.

4. Display three scenarios. Revealing one at a time, introduce the three situations listed below. Ask them to think about whether each scenario could be characterized as science.

- A traditional healer uses information passed down from generations to administer herbs for healing purposes.
- A scientist argues that the complexity of current life forms could not have taken place without the involvement of a creator.
- A committee of scientists decides that Pluto should be classified as a dwarf planet rather than as a planet.

Thought Swap: What is Science?

1. Introduce Thought Swap. Tell participants they will be discussing a series of questions in order to share some of their ideas about the session's topic—the Nature and Practices of Science.

2. Line up participants and establish partners. Have participants stand shoulder to shoulder to form two parallel lines, so each person is facing a partner. Participants standing side by side should be at least six inches apart. Tell them to look across at the other line and figure out who their partner is. Tell anyone without a partner to raise their hand, and make adjustments as necessary. If you have an odd number of students, you may choose to partner with a student, or have a group of three.

3. Explain procedure for discussing questions. You will be raising a question for them to talk about with their partner facing them. They will have about a minute to talk. You will signal them to be quiet to prepare for the next question or statement by gently tapping on the shoulder of the first two participants at the end of the lines (the "tap of silence"). These two will then pass the tap on down the line, till the entire group is quiet.

4. Begin the Thought Swap. Pose the first question for participants to discuss:
What is science?

5. Share responses with group. After about a minute, tap the first two participants at the ends of the lines and wait for the entire group to become silent. Repeat the question, "What is science?" and ask a few participants to share with the large group what their partner told them.

6. Change partners for discussion. Tell participants which one of the lines will shift with each question, while the other remains in place. Tell the person at one end of the line that will shift to walk down and rejoin the line at the opposite end. Have this line now shift one position to the left so everyone is facing a new person. Everyone now should have a new partner.

7. Discuss the next four questions. Pose the questions listed below, shifting partners in the same way after each one. Pause to briefly discuss each question with the whole group.

- **How does science work?**
- **Why is learning about how science works important for students and teachers?**
- **How is a scientific view distinct from other ways of knowing and what is the value of a scientific approach to understanding the natural world?**
- **When is something not science, but appears scientific?**

8. Seat participants in small groups. Ask participants to return to their seats with a group of ~ 4 people, formed from those standing next to them in the Thought Swap lines.

9. Record large group brainstorm of "What is Science." Write "What is Science?" on a piece of chart paper and ask the whole group to brainstorm some statements for you to record. Don't correct any of the statements, but encourage students to respectfully discuss, disagree, and propose changes to statements given by others.

Categorizing Science Statements

1. Introduce sorting of science statements. Tell participants each small group will receive a set of statements about science. Each strip of paper has a different statement about science on it. Their challenge is to discuss each statement with their group, then categorize it as to whether they think it is accurate or inaccurate.

2. Explain purpose of sorting activity. Let them know that reaching "right" answers is not the point of the activity, the purpose is to create an opportunity to discuss and think about what science is and what it is not. They should discuss each statement thoroughly before placing it in a category.

3. Emphasize thinking about criteria for sorting. Let participants know that some statements will be fairly easy to categorize, but others will be challenging. Tell them that even with the relatively easy ones, they should discuss why they think they should be sorted that way.

4. Distribute statements to categorize. Give a set of statement strips to each small group ~ 4 participants, and have them begin.

5. Begin class discussion by sharing statements they classified as inaccurate. After most groups have completed the sorting task, regain the attention of the whole group. Ask groups to share a statement they sorted into the "Inaccurate" category. Ask them to explain why they decided it was inaccurate. Do this for a several statements.

6. Groups share statements they thought were accurate. Ask groups to share one statement they sorted as accurate. **This time do not ask them to explain why they sorted them as accurate.**

Note: In a moment, the groups will learn that ***all*** *the statements are inaccurate. To avoid embarrassment, it's enough that they simply share the statements they thought were accurate, without investing time into explaining why they thought they were accurate.*

7. Use the UCMP Understanding Science website to reveal that all the statements were inaccurate. Tell the group all the statements they just sorted came from a web page produced by the University of California Museum of Paleontology (UCMP). Use the projector to display the website home page titled *Understanding Science*:

http://undsci.berkeley.edu/

Select the "Resource Library" tab at the top of the page, and click on the "Misconceptions" link. This takes you to the main "Misconceptions About Science" page where you can scroll down the list of misconceptions to access more detailed information about each. Share with the group that all the statements they sorted came from this list, and therefore are considered inaccurate.

8. Groups read about misconceptions from UCMP website sheet. Click on one of the misconceptions, and show the paragraph explaining why it is an inaccurate description of science. Distribute to each group a copy of the *Misinterpretations of the Scientific Process* handout, and tell them it contains explanations for each of the misconceptions about science. Ask them to have one member of their group read aloud what the website has to say about each of the statements they classified as accurate. Encourage groups to discuss these statements once again, incorporating the additional information.

> ***Note:*** *You might want to share with the group that the intention behind the sorting activity was not to trick them into thinking some of the statements were true. The purpose was to challenge them to think deeply about their own beliefs and ideas about the nature of science and scientific approaches, and to become aware of possible misconceptions on the topic. The sorting activity also provides an incentive for participants to explore the Understanding Science website.*

9. Show the "How Science Works" page. Also found on the "Resource Library" page of the *Understanding Science* website is a link to "How Science Works—the flow chart." Show how each of the circles on the flow chart leads to more pages addressing what scientists really do, as opposed to the commonly taught steps of the "scientific method." Encourage them to explore the website later and tell them that part of their homework will be to examine the *Understanding Science* website.

What is Science?

1. Introduce contrasting perspectives on science. Explain that well-known scientists and educators have also pondered the question of "What is Science?" Display the overhead transparency or PowerPoint slides titled *"A Few Perspectives on Science,"* and briefly introduce each in the following order:

> **"Science is a limitless voyage of joyous exploration"**
> **Walt Whitman**
>
> **"Science is a set of methods designed to describe and interpret observed or inferred phenomena, past or present, and aimed at building a testable body of knowledge open to rejection or confirmation."**
> **Michael Shermer**
> **Director of Skeptics Society**
>
> **"Science is a limited way of knowing, looking at just the natural world and natural causes. There are a lot of ways human beings understand the universe—through literature, theology, aesthetics, art or music."**
> **Dr. Eugenie Scott**
> **Executive Director National Center for Science Education**
>
> **"We should talk about science not as a noun…but as a process, a set of activities, a way of proceeding and thinking…"**
> **Tinker and Thornton, 1992, *Constructing Student Knowledge in Science*, p. 155**

2. Introduce a definition of science. Display the slide *"Science is …"* Tell participants that they will receive a copy of this as a handout. Emphasize that the following list came from various sources including an extensive literature search and conversations with scientists and educators. Explain that this summary is intended to represent the generally accepted elements of science:

Evidence-based: In science there are accepted methodologies, standards of evidence, and logical ways of answering questions, all of which are based on using observations, tests, and other types of data to provide evidence. The acceptance or rejection of a scientific idea depends upon the quality of relevant evidence—not upon dogma, popular opinion, or tradition.

Making Explanations: Scientific explanations must show an explicit cause and effect relationship based on observable evidence. They involve looking for patterns and correlations. Explanations deal specifically with explaining the natural world and are not focused on supernatural questions.

Testable: If an explanation offers no way to be tested, or does not have the potential to be shown to be false by evidence, it is not scientific. Repeatability of tests is often a goal in experimental types of science, but much of science does not solve problems through experimentation, relying on inferences from patterns and observations that are not necessarily repeatable.

Consistent: A scientific explanation needs to do more than provide a plausible account; it must fit all the observable facts better than alternative explanations do. It must be consistent with *all* available evidence, not just selected evidence.

Scientific Community: The scientific community is the people and organizations that generate scientific ideas, test those ideas, publish scientific journals, organize conferences, train scientists, distribute research funds, etc. The scientific community provides the cumulative knowledge base that allows science to build on itself. It is also responsible for the further testing and scrutiny of ideas and for performing checks and balances on the work of community members. Individual scientists may have lots of different agendas and can put forth a variety of opinions—these don't necessarily represent scientific knowledge. Scientific experts in one field may not know about other fields of science. This is why we look to communities of experts to help ratify explanations and judge the evidence for scientific arguments.

Ongoing and Self-correcting: Answering one question inspires deeper and more detailed questions for further research–the more we know, the more we know what we don't yet know. Scientists are very careful about what they say they know and how they know it. Science is open-minded, not empty-headed. Scientists are tentative about their findings and focus on whether evidence supports or doesn't support their idea. This is a strength, not a weakness, because scientific ideas are revised and improved on an ongoing basis.

Scientific ways of thinking, doing and communicating: Science involves using multiple scientific methods, involving many different steps and procedures. The processes of science are well defined, but are used in flexible and practical ways.

Creative: Creativity is involved in all aspects of science whether it is developing new questions, techniques, explanations, or hypotheses. Anyone can have an idea in science, it is non-discriminating and it is not sentimental.

3. Introduce what is *not* science. Display the next slide and explain the following points:

> **Science is not…**
>
> **The absolute truth**: Scientific knowledge is only our current best approximation based on all available evidence. In science, no explanations are considered "proven." All explanations are open to replacement or refinement, if warranted by new evidence. Yet most scientific knowledge is durable, and has withstood the test of time and critique.
>
> **Democratic:** Science is not based on how many people vote for an idea, it's based on the evidence. It doesn't matter how many scientists there are with a particular opinion—the evidence is what counts. It's also not the authority of the scientist that matters, but the quality of the evidence that provides the strength of the argument.
>
> **The "Scientific Method":** There is no one method for doing science. Science involves many different steps and procedures, depending on the field of science and the question being investigated.

***Note:** As the handout on "What science is not…" pointed out, science is not "democratic" in the sense that "the most votes" or a "majority" determine what is accurate or which concept is correct. They do not. Scientific accuracy and conceptual correctness must be based on repeatable evidence. In another sense, however, science is democratic—it doesn't matter who you are, your race or culture, your economic status, or what country you come from—your scientific findings are (or should be) weighted equally with anyone else's, so long as they are evidence-based and the procedures are scientifically valid.*

4. Explain that science is only one way of knowing. Ask participants to briefly think about other systems of looking at the world. [art, history, philosophy] Emphasize that science is one of many systems for understanding the world around us, but not necessarily a superior system. Point out that science has great predictive value because it is a way of looking at the world with logic and evidence that helps us plan for future events. Many other disciplines also employ logic, and many also employ evidence. When science is described as studying and explaining the natural world, many people interpret this as the study of nature. However, in this context, "natural world" refers to everything in the Universe that doesn't fall into the category of supernatural.

5. Introduce an activity used to teach about the nature of science. Tell participants that in the next activity, they will be attempting to write their own scientific statements. They will get an opportunity to *do* science, both to help them refine their own understanding, and to experience a classroom exemplar designed to teach children about the nature and practices of science.

Oobleck Laboratory Investigations

1. Set stage for Oobleck explorations. Tell participants to imagine they are on a space ship far out in space and have sent a space probe down to a recently discovered moon within our Solar System. The moon is covered with what appear to be large green oceans, and three probes have been sent down. Contact with the first probe was lost, and what happened to it is unknown. The second probe is stuck on the surface, but the third probe managed to return with a sample of the ocean material.

2. Participants as scientists. Ask the participants to imagine they are a group of scientists in a laboratory on board a spaceship orbiting the newly discovered moon. It is their task to investigate the properties of the sample and collect evidence about the substance.

3. Explain Oobleck is safe to handle. Show participants the bowls of Oobleck, but don't distribute them yet. Mention that preliminary studies have shown that Oobleck is safe to handle. Add that a team of chemists is trying to find out its exact composition, and their results will be revealed when their research is completed.

4. Introduce materials and begin investigations. Explain that their job is to investigate the properties of Oobleck. Hold up a pencil (or another convenient observable object) and ask them, "What is a property of this pencil?" As they offer examples, make sure they understand that a property is anything you can observe directly about an object. Point out where they can collect the assorted test items, and the newspapers for covering their tables. Distribute a bowl of Oobleck to each table group and have them begin investigating.

5. Distribute paper for recording properties. After participants have investigated Oobleck for a few minutes and discovered some of its unexpected properties, give each group a large sheet of paper and a felt-tipped marker to start recording the properties. (If needed, help participants by circulating and asking questions such as, "How does Oobleck behave when you press on it?" "When does Oobleck behave like a solid?" "When does Oobleck behave like a liquid?")

6. Suggest participants test their ideas. Encourage them to resolve disagreements by performing experiments or discussing ways to describe a property so everyone on the team agrees.

7. Indicate properties related to solid or liquid characteristics. Ask each lab group to put a star on their list next to the property of Oobleck they think is most important in explaining under what circumstances Oobleck acts as a solid or as a liquid.

Oobleck: Scientific Convention

1. Introduce context for scientific conventions. Remind participants that professional scientists in most fields and disciplines travel all over the world to attend meetings called *scientific conventions.* The topics might be "Heart Disease," or "The Planet Mars" or "Earthquake Prediction."

2. Explain purpose of convention. Point out that during a convention, scientists listen to each other's experimental results and research findings and critically discuss them. The goal of the convention is *not* to prove each other right or wrong, but to ***arrive at the most accurate scientific understanding and to state it as clearly and completely as possible.***

3. Present discussion guidelines. Tell participants they're about to hold a scientific convention on Oobleck. The starred properties listed on the board from their lab work are the scientific results they will discuss, according to the following guidelines:

a. Only one property of Oobleck will be discussed at a time. The instructor will select a statement to begin. The lab teams will then explain or demonstrate the observations and/or experiments that led to the property that is being discussed. This is how they will present the **evidence** for their statement of the property.

b. Participants who wish to agree or disagree with the property being discussed are asked to raise hands to **explain why**. They can refer to their own experience for evidence to support their position. In doing so, they are *making explanations based on evidence*—an essential science inquiry ability.

c. Encourage participants to find ways to change the wording of a property so everyone can agree on it.

d. After fully discussing a property, vote on whether or not it is really a property of Oobleck. If three-quarters of the group votes for a property, it will be called a "Law of Oobleck." To illustrate what is meant in this case by a "law," say that most scientists would agree that "water turns from liquid to solid below 32 degrees Fahrenheit," so it could be called a "law" of water. (Note: To be completely accurate, water turns from a liquid to a solid at 32 degrees Fahrenheit—*at 1 atmosphere of pressure*.) (Also see the "Note" on the use of the word "Law" in science.)

It could be pointed out here, or a participant may do so, that the "voting" in this case is a convenient way to get a quick sense of group thinking in a class or workshop, but it is NOT a model of what science is or how science advances

NOTE: Participants may be familiar with the quite elevated use of the word "Law" in science, as in the Laws of Motion, or the 2nd Law of Thermodynamics. These are very general statements about physical forces and processes. Technically speaking a "law" in science has been defined as ***a descriptive generalization about how some aspect of the natural world behaves under stated circumstances.*** *Taking Oobleck as an "aspect of the natural world" participants are indeed trying to come up with "descriptive generalizations" about one or more of its properties/behaviors "under stated circumstances." However, scientists themselves differ on definitions. For many, the freezing point of water would not usually be considered a "law," but a property that has been demonstrated by considerable evidence. Although the refined statements participants come up with may or may not be "laws," the use of the term adds status and motivation to their quest for scientific accuracy. There are some teachers who prefer to use terms such as " scientific fact" or "accurate statement" or "hypothesis" or "class property." The use of the term "fact" can be problematic because in everyday language it implies unchanging "truth."* ***Scientific fact*** *should be defined as in a National Academy of Sciences publication, with our emphasis on the last sentence: "If something has been observed many times by many different scientists, and no evidence has ever been found that it is not true, then it is considered to be a scientific fact.* ***A scientific fact is always open to being changed or eliminated if new evidence shows it to be inaccurate****."*

Facilitating the Discussion

1. Suggestions for leading the discussion. The scientific convention is one of the most exciting parts of the Oobleck experience because participants *are* like scientists when they debate their views and refine their statements of properties in order to seek the most accurate scientific statement. Your role as facilitator of the discussion is critical to its success. Following are some suggestions for moderating a successful discussion:

• The process used to arrive at a "Law of Oobleck" can take some time. Some groups start squirming in their seats after 20 minutes. Other groups are still going strong after 45 minutes. If participants are deeply involved in the discussion, you may want to continue the discussion the following day so they can further refine their communication skills. Above all, be aware of the interest level of the group, and end the discussion when you think it is appropriate.

While the ideal is for each group to present their starred property to the class, discussing and voting to come up with one or two "laws" may be sufficient to highlight the importance of communication and debate in science.

• One way to maintain interest in the discussion is to break to allow one group to test a particular property of Oobleck using the bowl you saved for this purpose, demonstrating for the class, then sharing the results in a class discussion.

If you are in the unusual situation where all groups could have quick access to Oobleck, and it would not be too disruptive, then all groups could test the disputed property.

• Disagreements are starting points for fruitful discussions. After the first group has read their starred property and explained their choice, ask if anyone disagrees with that property or any part of it. If no one challenges it, ask if anyone can think of a case where that property would **not** be true.

• Once you've provoked disagreement, challenge participants to find ways of *changing the wording* so everyone can agree on a statement of the property and/or pursue one or more of the options suggested below.

2. Resolving issues with statements. Following are some common ways of resolving problems you might suggest to help participants refine their findings.

a. **Add a phrase.** For example, in one class one team listed this property: "Oobleck dries out when left on paper." A student objected, saying that this is not true when Oobleck is put on paper for just a few seconds. The teacher asked how to resolve the disagreement. The students added the phrase, "for more than ten minutes." Adding such qualifiers is the essence of good scientific reporting.

b. **Define terms.** One team listed the property: "Oobleck is sticky." When challenged to define *sticky,* the students realized there are several different kinds of "stickiness." After a brief debate, they changed the property to read: "Your finger will get stuck if you try to pull it out fast." A discussion like this highlights the importance of using precise terms that are agreed on by every scientist who works in a given field.

c. Do Another Test. In some cases, further testing can best resolve disagreements. By keeping bowls of Oobleck on hand during the convention, you can have two or three students do the test. For example, one team proposed that contact with air made Oobleck "liquidy." Another student suggested putting Oobleck into a plastic bag where it could not touch the air. It turned out to be just as "liquidy" in the bag as it was in the bowl. After this test, the students voted not to make that particular property a "Law of Oobleck." Similarly, professional scientists sometimes report initial findings that later experiments show to be erroneous.

3. Modeling scientific discourse. Throughout the scientific convention, ask questions and probe for reasoning. It's of tremendous importance that the presenter/teacher model respect and acceptance of all ideas while facilitating the discussion. One of the most important components of science learning is the chance to discuss and reflect upon an experiment or experience, both individually and as a group. This is a chance for you and your participants/students to engage in scientific "discourse," to encounter different ideas, confront them, consider evidence, and, when possible, arrive at a new level of understanding that encompasses observations and findings more accurately.

Introduce Spacecraft Design Activity

1. Discuss the importance of applying findings. Mention to participants that in the *Oobleck: What Do Scientists Do?* GEMS unit, there are two other activities. One of these is another very important part of what scientists (and engineers) do, and that is to *apply their findings*. In a similar way, in education one key criteria for evaluating or assessing student learning is whether or not students can apply what they've learned in a different context.

2. Describe spacecraft design assignment. In the *Oobleck* unit, students are asked to design a spacecraft that would be able to land on the ocean of Oobleck, explore the whole moon, and take off again, with all passengers aboard.

3. Explain how some students have used what they've learned about Oobleck. Tell participants that some elementary school students have come up with very creative ideas, such as flying machines with thousands of little feet that continuously press on the Oobleck so it stays solid. Others have suggested a hovercraft concept, a craft with Oobleck dryers, or a landing platform with a detachable return shuttle.

Explaining about the Substance of Oobleck

1. Reveal composition of Oobleck. Announce that the team of chemists mentioned earlier has reported its findings on the exact composition of Oobleck. The scientists have revealed that Oobleck is made up of cornstarch, water, and green food coloring.

2. Briefly discuss explanations for Oobleck's behavior. Explain that no one really knows exactly why Oobleck behaves both like a solid and a liquid, though there are many explanations. You may want to indicate that materials like Oobleck are known as non-Newtonian fluids. Wet sand is another example of a non-Newtonian fluid— which behaves as a solid when compressed, yet flows when released.

Reflecting on Participants Behaving as Scientists

1. Review Oobleck activities: laboratory, scientific convention and spacecraft design. Ask participants to think back over the session, from their first discussions about the scientific statements, through their experiences with and reflections on Oobleck's properties. Remind them that there were three parts to the Oobleck activity: a laboratory session, the scientific convention, which they took part in, and a spacecraft design session they were told about. All of these activities involve doing many things that scientists do.

2. List how they behaved as scientists during the three activities. At the top of the whiteboard (or a piece of chart paper) write four headings: Science Statements Discussion, Oobleck Lab Investigations, Scientific Convention, and Spacecraft Design. Ask: **Throughout class today, in what ways were you acting as scientists?**

Possible responses related to each part of the session are listed below.

Science statements: *collaborated, discussed, explained, debated, applied knowledge, reflected.*
Laboratory investigations: *looked, touched, smelled, recorded observations, experimented, tested ideas, talked, used instruments (plastic spoons, etc.), compared Oobleck to other known substances.*
Scientific convention: *talked, disagreed, argued, explained our experiments, changed words, defined words, criticized, did more experiments, voted, decided if we thought something was accurate.*
Spacecraft Design: *drew pictures, thought about laws of Oobleck, invented machines, imagined walking on Oobleck, changed ideas.*

3. Connect responses back to the list of "What is Science?" As appropriate, connect the scientific behaviors they suggest to the first chart they generated about the characteristics of science. Explain that this is how these activities can be used to teach about the nature and practices of science with children.

4. Importance of student opportunities to struggle with ideas—including inaccurate ideas. Point out that the Oobleck activities are focused on processes of science, which are absolutely essential to understanding the nature and practices of science. In many classrooms, these processes can be neglected in favor of teaching specific and accurate science content. Scientists come up with and try out lots of ideas, including inaccurate ones, to arrive at understandings. They discuss them, and compare them with available evidence. The more chances students have to do this themselves, the more scientific their thinking can become.

Inquiry Abilities and Understandings

1. Introduce inquiry as defined by NSES. Display the slide "*Inquiry and the National Science Standards*." Explain that these are the descriptions they will find most often listed in education standards for what students should know and be able to do in science, related to science process skills and inquiry practices. Display the slide "*NSES recommendation…*" and tell them the recommendation here is that students learn about science by engaging in the practices of inquiry.

2. Explain that students must also reflect on how science knowledge is generally developed. Tell them the *National Science Education Standards* go a step further by recommending that students should also generalize about how science applies these skills to finding out more about the natural world–referred to as "Understanding About Inquiry." Emphasize that participants should become familiar with these descriptions of inquiry practices and how inquiry is used by scientists, so that they can identify and discuss scientific behaviors and the nature of science with students.

Session Summary

1. Emphasize importance of teaching about the nature of science. Tell participants that the reason this session is devoted to this topic is because it is arguably the most important—yet historically neglected—aspect of science that can be taught in a science classroom.

— We are surrounded by scientific and non-scientific information in the world.

— Increasingly, citizens must vote on issues involving science.

— Teachers often don't understand the nature of science, and therefore tend to teach science as vocabulary and facts or as a rigid "scientific method."

For students to gain understanding of science, every science lesson should ideally highlight some of the aspects of the nature of science.

2. Discuss some of the drawbacks and limitations encountered in science. Mention that, unfortunately, the scientific enterprise sometimes goes astray or "misses the mark." Ask your students to briefly consider some possible pitfalls and stumbling blocks of science and discuss this with the people at their table. Ask if they have heard about any controversial events in the scientific community, or other occasions when science might "miss the mark." Ask if they can think of situations where attempts at science become unscientific because they do *no*t meet all of the main points on the slide. After a few minutes have a few groups quickly share a situation that they discussed.

3. Overview of Shermer handout. Distribute copies of the handout modified from the book *"Why People Believe Weird Things,"* by Michael Shermer. Tell them that this is a summary of some of the possible reasons for the mishaps that occur around science, as described in the book.

> ***Note**: You may want to mention here that the book* Why People Believe Weird Things *by Michael Shermer is very interesting reading about science and pseudoscience. It also provides useful information about becoming an advocate for scientific thinking.*

4. Distribute handouts. At this time you can give participants the copies of the *Science is…* and *Inquiry and the National Science Standards* handouts. Ask if there are any questions about the session or the handouts.

5. Display summary slide. Display the summary slide and emphasize these main points:

- **science is based on observations and hypotheses within a testable framework of ideas**
- **scientific results must be able to be tested in order to be valid**
- **science is a collaborative enterprise and a product of the scientific community**
- **scientific knowledge evolves over time**
- **scientists use a wide range of inquiry methods**
- **students should learn science through scientific inquiry**

6. Explain importance of reflection. Display the slide titled *Reflection is a powerful learning tool*. Have participants read the text and explain that you will introduce a reflection prompt for a Quick Write at the end of every session.

7. Introduce Quick Write prompt. Display prompt. Give participants a few minutes to think and write about the session, using the following prompt:

Reflect on how your ideas about the nature of science may have changed during this session…and if so, what do you think made your ideas shift? How might you apply ideas from this session to your science teaching?

Presentation Slides

Slides 1–3: Science Scenarios

Slides 4–7: A Few Perspectives on Science

Slides 8–9: Science is … Science is Not…

Slide 10: Inquiry and the National Science Education Standards

Slide 11: *NSES* Recommendation

Slide 12: Session Summary

Slide 13: Reflection is a powerful learning tool

Slide 14: Quick Write prompt

A traditional healer uses information passed down from generations to administer herbs for healing purposes.

A scientist argues that the complexity of current life forms could not have taken place without the involvement of a creator.

A committee of scientists decides that Pluto should be classified as a dwarf planet rather than as a planet.

“Science is a set of methods designed to describe and interpret observed or inferred phenomena, past or present, and aimed at building a testable body of knowledge open to rejection or confirmation.”

Michael Shermer
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"Science is a limitless voyage of joyous exploration"

— Walt Whitman

"Science is a limited way of knowing, looking at just the natural world and natural causes. There are a lot of ways human beings understand the universe—through literature, theology, aesthetics, art or music."

Dr. Eugenie Scott
Executive Director
National Center for Science Education

"We should talk about science not as a noun…but as a process, a set of activities, a way of proceeding and thinking…"

Tinker and Thornton, 1992, *Constructing Student Knowledge in Science,* page 155

Science is …

- Evidence-based
- Making Explanations
- Testable
- Consistent
- Scientific Community
- Ongoing & Self-correcting
- Scientific ways of thinking, doing, and communicating
- Creative

Science is not…

- The absolute truth
- Democratic
- The “Scientific Method”

Inquiry and the National Science Education Standards

- Learners are engaged by scientifically-oriented questions.
- Learners give priority to evidence, which allows them to develop and evaluate explanations.
- Learners formulate explanations from evidence to address scientifically-oriented questions.
- Learners connect their explanations to scientific knowledge.
- Learners communicate and justify their proposed explanations.

From *Inquiry and the National Science Education Standards*, Chapter 2, pages 24–27.

National Science Education Standards recommendation for how to teach science…

Students, at all grade levels and in every domain of science, should have the opportunity to use scientific inquiry and develop the ability to think and act in ways associated with inquiry, including asking questions, planning and conducting investigations, using appropriate tools and techniques to gather data, thinking critically and logically about relationships between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments.

From *Inquiry and the National Science Education Standards,* page 105

Session Summary

- science is based on observations and hypotheses within a testable framework of ideas
- scientific results must be able to be tested in order to be valid
- science is a collaborative enterprise and a product of the scientific community
- scientific knowledge evolves over time
- scientists use a wide range of inquiry methods
- students should learn science through scientific inquiry

Reflection is a powerful learning tool:

“When students summarize or paraphrase, they are doing the work of moving surface learning deeper into the schema by making the connections that constitute meaning.”

— From K. Patricia Cross (1999) *Learning is About Making Connections: The Cross Papers #3*, Laguna Hills, CA, League for Innovation in the Community College and Princeton, NJ, Educational Testing Service.

Quick Write Prompt:

Reflect on how your ideas about the nature of science may have changed during this session…and if so, what do you think made your ideas shift?

How might you apply ideas from this session to your science teaching?

Handouts

1. Science Statements (used in class only)

2. Misinterpretations of the Scientific Process (used in class only)

3. Science is … Science is Not…(2 pages)

4. Inquiry and the National Science Education Standards (2 pages)

5. Why People Believe Weird Things (2 pages)

Scientific Statements *(for the Categorizing Statements activity)*

Science is a collection of facts.

Science is complete.

There is a single Scientific Method that all scientists follow.

The process of science is purely analytic and does not involve creativity.

When scientists analyze a problem, they must use either inductive or deductive reasoning.

Experiments are a necessary part of the scientific process. Without an experiment, a study is not rigorous or scientific.

"Hard" sciences are more rigorous and scientific than "soft" sciences.

Scientific ideas are absolute and unchanging.

Because scientific ideas are tentative and subject to change, they can't be trusted.

Scientists' observations directly tell them how things work (i.e., knowledge is "read off" nature, not built).

Science proves ideas.

Science can only disprove ideas.

If evidence supports a hypothesis, it is upgraded to a theory. If the theory then garners even more support, it may be upgraded to a law.

Scientific ideas are judged democratically based on popularity.

The job of a scientist is to find support for his or her hypotheses.

Scientists are judged on the basis of how many correct hypotheses they propose (i.e., good scientists are the ones who are "right" most often).

Investigations that don't reach a firm conclusion are useless and unpublishable.

Scientists are completely objective in their evaluation of scientific ideas and evidence.

Science is pure. Scientists work without considering the applications of their ideas.

Handout #2: From UCMP Understanding Science Website: http://undsci.berkeley.edu/teaching/misconceptions.php#b1

Misinterpretations of the scientific process

- **Science is a collection of facts.** Because science classes sometimes revolve around dense textbooks, it's easy to think that's all there is to science: facts in a textbook. But that's only part of the picture. Science *is* a body of knowledge that one can learn about in textbooks, but it is also a process. Science is an exciting and dynamic process for discovering how the world works and building that knowledge into powerful and coherent frameworks. To learn more about the process of science, visit our section on How science works.
- **Science is complete.** Since much of what is taught in introductory science courses is knowledge that was constructed in the 19th and 20th centuries, it's easy to think that science is finished—that we've already discovered most of what there is to know about the natural world. This is far from accurate. Science is an ongoing process, and there is much more yet to learn about the world. In fact, in science, making a key discovery often leads to many new questions ripe for investigation. Furthermore, scientists are constantly elaborating, refining, and revising established scientific ideas based on new evidence and perspectives.
- **There is a single Scientific Method that all scientists follow.** "The Scientific Method" is often taught in science courses as a simple way to understand the basics of scientific testing. In fact, the Scientific Method represents how scientists usually write up the results of their studies (and how a few investigations are actually done), but it is a grossly oversimplified representation of how scientists generally build knowledge. The process of science is exciting, complex, and unpredictable. It involves many different people, engaged in many different activities, in many different orders.
- **The process of science is purely analytic and does not involve creativity.** Perhaps because the Scientific Method presents a linear and rigid representation of the process of science, many people think that doing science involves closely following a series of steps, with no room for creativity and inspiration. In fact, many scientists recognize that creative thinking is one of the most important skills they have—whether that creativity is used to come up with an alternative hypothesis, to devise a new way of testing an idea, or to look at old data in a new light. Creativity is critical to science!
- **When scientists analyze a problem, they must use either inductive or deductive reasoning.** Scientists use all sorts of different reasoning modes at different times—and sometimes at the same time—when analyzing a problem. They also use their creativity to come up with new ideas, explanations, and tests. This isn't an either/or choice between induction and deduction. Scientific analysis often involves jumping back and forth among different modes of reasoning and creative brainstorming! What's important about scientific reasoning is not what all the different modes of reasoning are called, but the fact that the process relies on careful, logical consideration of how evidence supports or does not support an idea, of how different scientific ideas are related to one another, and of what sorts of things we can expect to observe if a particular idea is true.
- **Experiments are a necessary part of the scientific process. Without an experiment, a study is not rigorous or scientific.** Perhaps because the Scientific Method and popular portrayals of science emphasize experiments, many people think that science can't be done *without* an experiment. In fact, there are *many* ways to test almost any scientific idea; experimentation is only one approach. Some ideas are best tested by setting up a controlled experiment in a lab, some by making detailed observations of the natural world, and some with a combination of strategies.
- **"Hard" sciences are more rigorous and scientific than "soft" sciences.** Some scientists and philosophers have tried to draw a line between "hard" sciences (e.g., chemistry and physics) and "soft" ones (e.g., psychology and sociology). The thinking was that hard science used more rigorous, quantitative methods than soft science did, and such methods were more trustworthy. In fact, the rigor of a scientific study has much more to do with the investigator's approach than with the discipline. Many psychology studies, for example, are carefully controlled, rely on large sample sizes, and are highly quantitative.

- **Scientific ideas are absolute and unchanging.** Because science textbooks change very little from year to year, it's easy to imagine that scientific ideas don't change at all. It's true that some scientific ideas are so well established and supported by so many lines of evidence, they are unlikely to be completely overturned. However, even these established ideas are subject to modification based on new evidence and perspectives. Furthermore, at the cutting edge of scientific research—areas of knowledge that are difficult to represent in introductory textbooks—scientific ideas may change rapidly as scientists test out many different possible explanations trying to figure out which are the most accurate.
- **Because scientific ideas are tentative and subject to change, they can't be trusted.** Especially when it comes to scientific findings about health and medicine, it can sometimes seem as though scientists are always changing their minds. One month the newspaper warns you away from chocolate's saturated fat and sugar; the next month, chocolate companies are bragging about chocolate's antioxidants and lack of trans-fats. There are several reasons for such apparent reversals. First, press coverage tends to draw particular attention to disagreements or ideas that conflict with past views. Second, ideas at the cutting edge of research (e.g., regarding new medical studies) may change rapidly as scientists test out many different possible explanations trying to figure out which are the most accurate. This is a normal and healthy part of the process of science. While it's true that all scientific ideas are subject to change if warranted by the evidence, many scientific ideas (e.g., evolutionary theory, foundational ideas in chemistry) are supported by many lines of evidence, are extremely reliable, and are unlikely to change.
- **Scientists' observations directly tell them how things work (i.e., knowledge is "read off" nature, not built).** Because science relies on observation and because the process of science is unfamiliar to many, it may seem as though scientists build knowledge directly through observation. Observation *is* critical in science, but scientists often make inferences about what those observations mean. Observations are part of a complex process that involves coming up with ideas about how the natural world works and seeing if observations back those explanations up. Learning about the inner workings of the natural world is less like reading a book and more like writing a non-fiction book—trying out different ideas, rephrasing, running drafts by other people, and modifying text in order to present the clearest and most accurate explanations for what we observe in the natural world.
- **Science proves ideas.** Journalists often write about "scientific proof" and some scientists talk about it, but in fact, the concept of proof—real, absolute proof—is not particularly scientific. Science is based on the principle that *any* idea, no matter how widely accepted today, could be overturned tomorrow if the evidence warranted it. Science accepts or rejects ideas based on the evidence; it does not prove or disprove them.
- **Science can only disprove ideas.** This misconception is based on the idea of falsification, philosopher Karl Popper's influential account of scientific justification, which suggests that all science can do is reject, or falsify, hypotheses—that science cannot find evidence that *supports* one idea over others. Falsification was a popular philosophical doctrine—especially with scientists—but it was soon recognized that falsification wasn't a very complete or accurate picture of how scientific knowledge is built. In science, ideas can never be completely proved or completely disproved. Instead, science accepts or rejects ideas based on supporting and refuting evidence, and may revise those conclusions if warranted by new evidence or perspectives.
- **If evidence supports a hypothesis, it is upgraded to a theory. If the theory then garners even more support, it may be upgraded to a law.** This misconception may be reinforced by introductory science courses that treat hypotheses as "things we're not sure about yet" and that only explore established and accepted theories. In fact, hypotheses, theories, and laws are rather like apples, oranges, and kumquats: one cannot grow into another, no matter how much fertilizer and water are offered. Hypotheses, theories, and laws are all scientific explanations that differ in breadth—not in level of support. Hypotheses are explanations that are limited in scope, applying to fairly narrow range of phenomena. The term *law* is sometimes used to refer to an idea about how observable phenomena are related—but the term is also used in other ways within science. Theories are deep explanations that apply to a broad range of phenomena and that may integrate many hypotheses and laws.

- **Scientific ideas are judged democratically based on popularity.** When newspapers make statements like, "most scientists agree that human activity is the culprit behind global warming," it's easy to imagine that scientists hold an annual caucus and vote for their favorite hypotheses. But of course, that's not quite how it works. Scientific ideas are judged not by their popularity, but on the basis of the evidence supporting or contradicting them. A hypothesis or theory comes to be accepted by many scientists (usually over the course of several years—or decades!) once it has garnered many lines of supporting evidence and has stood up to the scrutiny of the scientific community. A hypothesis accepted by "most scientists," may not be "liked" or have positive repercussions, but it is one that science has judged likely to be accurate based on the evidence. To learn more about how science judges ideas, visit our series of pages on the topic in our section on how science works.
- **The job of a scientist is to find support for his or her hypotheses.** This misconception likely stems from introductory science labs, with their emphasis on getting the "right" answer and with congratulations handed out for having the "correct" hypothesis all along. In fact, science gains as much from figuring out which hypotheses are likely to be wrong as it does from figuring out which are supported by the evidence. Scientists may have personal favorite hypotheses, but they strive to consider multiple hypotheses and be unbiased when evaluating them against the evidence. A scientist who finds evidence contradicting a favorite hypothesis may be surprised and probably disappointed, but can rest easy knowing that he or she has made a valuable contribution to science.
- **Scientists are judged on the basis of how many correct hypotheses they propose (i.e., good scientists are the ones who are "right" most often).** The scientific community *does* value individuals who have good intuition and think up creative explanations that turn out to be correct—but it *also* values scientists who are able to think up creative ways to test a new idea (even if the test ends up contradicting the idea) and who spot the fatal flaw in a particular argument or test. In science, gathering evidence to determine the accuracy of an explanation is just as important as coming up with the explanation that winds up being supported by the evidence.
- **Investigations that don't reach a firm conclusion are useless and unpublishable.** Perhaps because the last step of the Scientific Method is usually "draw a conclusion," it's easy to imagine that studies that don't reach a clear conclusion must not be scientific or important. In fact, *most* scientific studies don't reach "firm" conclusions. Scientific articles usually end with a discussion of the limitations of the tests performed and the alternative hypotheses that might account for the phenomenon. That's the nature of scientific knowledge—it's inherently tentative and could be overturned if new evidence, new interpretations, or a better explanation come along. In science, studies that carefully analyze the strengths and weaknesses of the test performed and of the different alternative explanations are particularly valuable since they encourage others to more thoroughly scrutinize the ideas and evidence and to develop new ways to test the ideas.
- **Scientists are completely objective in their evaluation of scientific ideas and evidence.** Scientists do strive to be unbiased as they consider different scientific ideas, but scientists are people too. They have different personal beliefs and goals—and may favor different hypotheses for different reasons. Individual scientists may not be completely objective, but science can overcome this hurdle through the action of the scientific community, which scrutinizes scientific work and helps balance biases.
- **Science is pure. Scientists work without considering the applications of their ideas.** It's true that some scientific research is performed without any attention to its applications, but this is certainly not true of all science. Many scientists choose specific areas of research (e.g., malaria genetics) because of the practical ramifications new knowledge in these areas might have. And often, basic research that is performed without any aim toward potential applications later winds up being extremely useful.

Misunderstandings of the limits of science

- **Science contradicts the existence of God.** Because of some vocal individuals (both inside and outside of science) stridently declaring their beliefs, it's easy to get the impression that science and religion are at war. In fact, people of many different faiths and levels of scientific expertise see no contradiction at all between science and religion. Because science deals only with natural phenomena and explanations, it cannot support or contradict the existence of supernatural entities—like God.
- **Science and technology can solve all our problems.** The feats accomplished through the application of scientific knowledge are truly astounding. Science has helped us eradicate deadly diseases, communicate with people all over the world, and build technologies that make our lives easier everyday. But for all scientific innovations, the costs must be carefully weighed against the benefits. And, of course, there's no guarantee that solutions for some problems (e.g., finding an HIV vaccine) exist—though science is likely to help us discover them if they do exist. Furthermore, some important human concerns (e.g. some spiritual and aesthetic questions) cannot be addressed by science at all. Science is a marvelous tool for helping us understand the natural world, but it is not a cure-all for whatever problems we encounter.

Misleading stereotypes of scientists

- **Science is a solitary pursuit.** When scientists are portrayed in movies and television shows, they are often ensconced in silent laboratories, alone with their bubbling test-tubes. This can make science seem isolating. In fact, many scientists work in busy labs or field stations, surrounded by other scientists and students. Scientists often collaborate on studies with one another, mentor less experienced scientists, and just chat about their work over coffee. Even the rare scientist who works entirely alone depends on interactions with the rest of the scientific community to scrutinize his or her work and get ideas for new studies. Science is a social endeavor.
- **Science is done by "old, white men."** While it is true that Western science used to be the domain of white males, this is no longer the case. The diversity of the scientific community is expanding rapidly. Science is open to anyone who is curious about the natural world and who wants to take a scientific approach to his or her investigations.
- **Scientists are atheists.** This is far from true. A 2005 survey of scientists at top research universities found that more than 48% had a religious affiliation and that more than 75% believed that religions convey important truths.[1] Some scientists are not religious, but many others subscribe to a specific faith and/or believe in higher powers. Science itself is a secular pursuit, but welcomes participants from all religious faiths.

Vocabulary mix-ups

Some misconceptions occur simply because scientific language and everyday language use some of the same words differently.

- **Fact**: Facts are statements that we know to be true through direct observation. In everyday usage, facts are a highly valued form of knowledge because we can be so confident in them. Scientific thinking, however, recognizes that, though facts are important, we can only be completely confident about relatively simple statements. For example, it may be a fact that there are three trees in your backyard. However, our knowledge of how all trees are related to one another is not a fact; it is a complex body of knowledge based on many different lines of evidence and reasoning that may change as new evidence is discovered and as old evidence is interpreted in new ways. Though our knowledge of tree relationships is not a fact, it is broadly applicable, useful in many situations, and synthesizes many individual facts into a broader framework. Science values facts but recognizes that many forms of knowledge are more powerful than simple facts.

- **Law**: In everyday language, a law is a rule that must be abided or something that can be relied upon to occur in a particular situation. Scientific laws, on the other hand, are less rigid. They may have exceptions, and, like other scientific knowledge, may be modified or rejected based on new evidence and perspectives. In science, the term *law* usually refers to a generalization about data and is a compact way of describing what we'd expect to happen in a particular situation. Some laws are non-mechanistic statements about the relationship among observable phenomena. For example, the ideal gas law describes how the pressure, volume, and temperature of a particular amount of gas are related to one another. It does not describe how gases *must* behave; we know that gases do not precisely conform to the ideal gas law. Other laws deal with phenomena that are not directly observable. For example, the second law of thermodynamics deals with entropy, which is not directly observable in the same way that volume and pressure are. Still other laws offer more mechanistic explanations of phenomena. For example, Mendel's first law offers a model of how genes are distributed to gametes and offspring that helps us make predictions about the outcomes of genetic crosses. The term *law* may be used to describe many different forms of scientific knowledge, and whether or not a particular idea is called a law has much to do with its discipline and the time period in which it was first developed.
- **Observation**: In everyday language, the word *observation* generally means something that we've seen with our own eyes. In science, the term is used more broadly. Scientific observations can be made directly with our own senses or may be made indirectly through the use of tools like thermometers, pH test kits, Geiger counters, etc. We can't actually *see* beta particles, but we can observe them using a Geiger counter.
- **Hypothesis**: In everyday language, the word *hypothesis* usually refers to an educated guess—or an idea that we are quite uncertain about. Scientific hypotheses, however, are much more informed than any guess and are usually based on prior experience, scientific background knowledge, preliminary observations, and logic. In addition, hypotheses are often supported by many different lines of evidence—in which case, scientists are more confident in them than they would be in any mere "guess." To further complicate matters, science textbooks frequently misuse the term in a slightly different way. They may ask students to make a *hypothesis* about the outcome of an experiment (e.g., table salt will dissolve in water more quickly than rock salt will). This is simply a prediction or a guess (even if a well-informed one) about the outcome of an experiment. Scientific hypotheses, on the other hand, have explanatory power—they are explanations for phenomena. The idea that table salt dissolves faster than rock salt is not very hypothesis-like because it is not very explanatory. A more scientific (i.e., more explanatory) hypothesis might be "The amount of surface area a substance has affects how quickly it can dissolve. More surface area means a faster rate of dissolution." This hypothesis has some explanatory power—it gives us an idea of *why* a particular phenomenon occurs—and it is testable because it generates expectations about what we should observe in different situations. If the hypothesis is accurate, then we'd expect that, for example, sugar processed to a powder should dissolve more quickly than granular sugar. Students could examine rates of dissolution of many different substances in powdered, granular, and pellet form to further test the idea. The statement "Table salt will dissolve in water more quickly than rock salt" is not a hypothesis, but an expectation generated by a hypothesis. Textbooks and science labs can lead to confusions about the difference between a hypothesis and an expectation regarding the outcome of a scientific test.
- **Theory**: In everyday language, the word *theory* is often used to mean a hunch with little evidential support. Scientific theories, on the other hand, are broad explanations for a wide range of phenomena. They are concise (i.e., generally don't have a long list of exceptions and special rules), coherent, systematic, and can be used to make predictions about many different sorts of situations. A theory is most acceptable to the scientific community when it is strongly supported by many different lines of evidence— but even theories may be modified or overturned if warranted by new evidence and perspectives.

- **Falsifiable**: The word *falsifiable* isn't used much in everyday language, but when it is, it is often applied to ideas that have been shown to be untrue. When that's the case—when an idea has been shown to be false—a scientist would say that it has been falsified. A falsifi*able* idea, on the other hand, is one for which there is a conceivable test that might produce evidence proving the idea false. Scientists and others influenced by the ideas of the philosopher Karl Popper sometimes assert that only falsifiable ideas are scientific. However, we now recognize that science cannot once-and-for-all prove any idea to be false (or true for that matter). Furthermore, it's clear that evidence can play a role in supporting particular ideas over others—not just in ruling some ideas out, as implied by the falsifiability criterion. When a scientist says *falsifiable*, he or she probably actually means something like *testable*, the term we use in this website to avoid confusion. A testable idea is one about which we could gather evidence to help determine whether or not the idea is accurate.
- **Uncertainty**: In everyday language, uncertainty suggests the state of being unsure of something. Scientists, however, usually use the word when referring to measurements. The uncertainty of a measurement (not to be confused with the inherent provisionality of all scientific ideas!) is the range of values within which the true value is likely to fall. In science, uncertainty is not a bad thing; it's simply a fact of life. Every measurement has some uncertainty. If you measure the length of a pen with a standard ruler, you won't be able to tell whether its length is 5.880 inches, 5.875 inches, or 5.870 inches. A ruler with more precision will help narrow that range, but cannot eliminate uncertainty entirely. For more on a related idea, see our discussion of *error* below.
- **Error**: In everyday language, an error is simply a mistake, but in science, error has a precise statistical meaning. An error is the difference between a measurement and the true value, often resulting from taking a sample. For example, imagine that you want to know if corn plants produce more massive ears when grown with a new fertilizer, and so you weigh ears of corn from those plants. You take the mass of your sample of 50 ears of corn and calculate an average. That average is a good estimate of what you are really interested in: the average mass of *all* ears of corn that could be grown with this fertilizer. Your estimate is not a mistake—but it does have an error (in the statistical sense of the word) since your estimate is not the true value. Sampling error of the sort described above is inherent whenever a smaller sample is taken to represent a larger entity. Another sort of error results from systematic biases in measurement (e.g., if your scale were calibrated improperly, all of your measurements would be off). Systematic error biases measurements in a particular direction and can be more difficult to quantify than sampling error.
- **Prediction**: In everyday language, *prediction* generally refers to something that a fortune teller makes about the future. In science, the term *prediction* generally means "what we would expect to happen or what we would expect to observe if this idea were accurate." Sometimes, these scientific predictions have nothing at all to do with the future. For example, scientists have hypothesized that a huge asteroid struck the Earth 4.5 billion years ago, flinging off debris that formed the moon. If this idea were true, we would *predict* that the moon today would have a similar composition to that of the Earth's crust 4.5 billion years ago—a prediction which does seem to be accurate. This hypothesis deals with the deep history of our solar system and yet it involves predictions—in the scientific sense of the word. Ironically, scientific predictions often have to do with past events. In this website, we've tried to reduce confusion by using the words *expect* and *expectation* instead of *predict* and *prediction*.
- **Belief/believe**: When we, in everyday language, say that we believe in something, we may mean many things—that we support a cause, that we have faith in an idea, or that we think something is accurate. The word *belief* is often associated with ideas about which we have strong convictions, regardless of the evidence for or against them. This can generate confusion when a scientist claims to "believe in" a scientific hypothesis or theory. In fact, the scientist probably means that he or she "accepts" the idea—in other words, that he or she thinks the scientific idea is the most accurate available based on a critical evaluation of the evidence. Scientific ideas should always be accepted or rejected based on the evidence for or against them—not based on faith, dogma, or personal conviction.

Science is…

• **Evidence-based**: In science there are accepted methodologies, standards of evidence, and logical ways of answering questions, all of which are based on using observations, tests and other types of data to provide evidence. The acceptance or rejection of a scientific idea depends upon the quality of relevant evidence—not upon dogma, popular opinion, or tradition.

• **Making Explanations:** Scientific explanations must show an explicit cause and effect relationship based on observable evidence. They involve looking for patterns and correlations. Explanations deal specifically with explaining the natural world and are not focused on supernatural questions.

• **Testable:** If an explanation offers no way to be tested, or does not have the potential to be shown to be false by evidence, it is not scientific. Repeatability of tests is often a goal in experimental types of science, but much of science does not solve problems through experimentation, relying on inferences from patterns and observations that are not necessarily repeatable.

• **Consistent**: A scientific explanation needs to do more than provide a plausible account; it must fit all the observable facts better than alternative explanations do. It must be consistent with *all* available evidence, not just selected evidence.

• **A Product of the Scientific Community:** The scientific community is the people and organizations that generate scientific ideas, test those ideas, publish scientific journals, organize conferences, train scientists, distribute research funds, etc. This scientific community provides the cumulative knowledge base that allows science to build upon itself. It is also responsible for the further testing and scrutiny of ideas and for performing checks and balances on the work of community members. Individual scientists may have different agendas and therefore put forth a variety of subjective opinions. Also, scientific experts in one field may not know about other fields of science. Therefore, we must look to the scientific community at large to help ratify explanations and judge the evidence for scientific arguments.

• **Ongoing and Self-correcting**: Answering one question inspires deeper and more detailed questions for further research–the more we know, the more we know what we don't yet know. Scientists are very careful about what they say they know and how they know it. Science is open-minded, not empty-headed. Scientists are tentative about their findings and focus on whether evidence supports or doesn't support their idea. This is a strength, not a weakness, because scientific ideas are revised and improved on an ongoing basis.

• **Scientific ways of thinking, doing, and communicating:** Science involves using multiple scientific methods, involving many different steps and procedures. The processes of science are well defined, but are used in flexible and practical ways.

• **Creative:** Creativity is involved in all aspects of science whether it is developing new questions, techniques, explanations or hypotheses. Anyone can have an idea in science, it is non-discriminating and it is not sentimental.

Science is not…

• **The absolute truth**: Scientific knowledge is only our current best approximation based on all available evidence. In science, no explanations are considered "proven." All explanations are open to replacement or refinement, if warranted by new evidence. Yet most scientific knowledge is durable, and has withstood the test of time and critique.

• **Democratic**: Science is not based on how many people vote for an idea, it's based on the evidence. It doesn't matter how many scientists there are with a particular opinion—the evidence is what counts. It's also not the authority of the scientist, but the quality of the evidence that provides the strength of the argument.

• **The "Scientific Method"**: There is no one method for doing science. Science involves many different steps and procedures, depending on the field of science and the question being investigated.

Inquiry and the National Science Standards

- Learners are engaged by scientifically oriented questions.
- Learners give priority to evidence, which allows them to develop and evaluate explanations.
- Learners formulate explanations from evidence to address scientifically oriented questions.
- Learners connect their explanations to scientific knowledge.
- Learners communicate and justify their proposed explanations.

(From *Inquiry and the National Science Education Standards*, Chap.2, pp. 24–27)

“Students, at all grade levels and in every domain of science, should have the opportunity to use scientific inquiry and develop the ability to think and act in ways associated with inquiry, including asking questions, planning and conducting investigations, using appropriate tools and techniques to gather data, thinking critically and logically about relationships between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments.”

(From *Inquiry and the National Science Education Standards*, p. 105)

Inquiry Abilities/Process Skills and Inquiry Understandings

Inquiry Abilities	Science Process Skills
Asking investigable questions	Questioning
Designing and conducting Investigations	Investigating Experimenting
Using appropriate tools and techniques to gather, analyze and interpret data	Using tools Organizing data Recording and interpreting results
Developing descriptions, explanations, predictions, and models using evidence	Describing Observing Explaining Predicting Hypothesizing Modeling
Recognizing and analyzing alternative explanations and predictions	Comparing Relating Analyzing Drawing conclusions
Communicating scientific arguments	Communicating Describing
Thinking critically about evidence and explanations	Inferring Synthesizing

Understandings about Inquiry:

- Scientific investigations involve asking and answering a question and comparing the answer with what scientists already know about the world.
- Scientists use different kinds of investigations depending on the questions they are trying to answer.
- Simple instruments, such as magnifiers, thermometers, and rulers, provide more information than scientists obtain using only their senses.
- Scientists develop explanations using observations (evidence) and what they already know about the world (scientific knowledge).
- Scientists make the results of their investigations public; they describe the investigations in ways that enable others to repeat the investigations.
- Scientists review and ask questions about the results of other scientists' work.

Modified and Adapted from Why People Believe Weird Things *by Michael Shermer*

Common Problems in Scientific Thinking

1. Prior Theory Influences Observations
Our perceptions of reality are influenced by the theories framing our examination of it.

2. The Observer Changes the Observed
The act of studying an event can change it.

3. Equipment Constructs Results
The equipment in an experiment often affects the results.

Common Problems in Pseudoscientific Thinking

1. Anecdotes Do Not Make a Science
Without corroborative evidence from other sources, or physical proof of some sort, 10 anecdotes are no better than one, and 100 anecdotes are no better than 10.

2. Scientific Language Does Not Make a Science
Dressing up a belief system in the trappings of science by using scientific language and jargon means nothing without evidence, experimental testing, and corroboration.

3. Bold Statements Do Not Make Claims True
Something is probably pseudoscientific if enormous claims are made for its power and veracity, but supportive evidence is as scarce as hen's teeth.

4. Heresy Does Not Equal Correctness
Just because it is controversial and new (like Galileo's ideas) doesn't mean it is true.

5. Burden of Proof
The person making the extraordinary claim has the burden of proving to the experts and to the community at large that his or her idea has more validity than the currently accepted idea.

6. Rumors Do Not Equal Reality
Rumors *may* be true, of course, but usually they are not.

7. The Unexplained Is Not Inexplicable
There are many genuine unsolved mysteries in the Universe and it is okay to say, "We do not yet know, but perhaps someday we will." The problem is that most of us find it more comforting to have certainty, even if it is premature, than to live with unsolved or unexplained mysteries.

8. Failures Are Rationalized
In science, failures are *valued* as a means of getting closer to the truth. This is not true of pseudoscience in which failures are ignored or rationalized.

9. Reasoning After The Fact
The fact that two events follow each other in sequence does not mean that they are connected causally. Being able to correlate events doesn't imply causality between them.

10. Coincidence
When a connection is made between two or more events, in a manner that seems impossible according to our intuition of the laws of probability (although we may have a poor understanding of the laws of probability), we have a tendency to think that something mysterious is at work. We also tend to forget the many incidences in which coincidences have not occurred.

11. Representativeness
Our tendency is to remember hits and ignore misses. We must try to remember the larger context in which a seemingly unusual event occurs, and we must always strive to analyze unusual events for how well they represent their particular class of phenomena.

Nature of Science Handout #5 Page 2

Problems with Illogical Thinking

1. Emotive Words and False Analogies
Emotive words are used to provoke emotion and sometimes to obscure rationality. Analogies and metaphors do not constitute proof. They are merely tools of rhetoric.
2. If You Can't Disprove It, It Must Be True
This is where someone argues that if you cannot disprove a claim it must be true. In science, acceptance should come from positive evidence in support of a claim, not lack of evidence for or against a claim.
3. Attacking the Messenger
These arguments redirect the focus from thinking about the idea to thinking about the person holding the idea.
4. Hasty Generalization
Conclusions are drawn before the facts warrant it. In science, we must carefully gather as much information as possible before announcing our conclusions.
5. Over-reliance on Authorities
While relying on expert opinion is useful for separating the wheat from the chaff, it can be a dangerous practice if used indiscriminately. It may lead to either accepting or rejecting an idea solely because it was either supported or refuted by someone we respect.
6. Either-Or
This is the tendency to dichotomize the world so that if you discredit one position, then the observer is forced to accept the other view.
7. Circular Reasoning
When the conclusion or claim is merely a restatement of one of the premises, it is based on faulty logic.
8. *Reductio ad Absurdum* and the Slippery Slope
The refutation of an argument by carrying the argument to its logical end and so reducing it to an absurd conclusion. The slippery slope fallacy involves constructing a scenario in which one thing leads ultimately to an end that is so extreme the first step should never be taken.

Problems With How People Naturally Approach New Ideas

1. Need for Critical Thinking Skills and Desire for Simplicity
Scientific and critical thinking does not come naturally. It takes training, experience, and focused effort. Most of us, most of the time, want certainty, want to control our environment, and want nice, neat, simple explanations. Now and then the solutions may be simple, but usually they are not.

2. Inherently Misleading Problem-Solving Tendencies
When solving problems we tend to:
- look for patterns and notice evidence that fits a pattern while ignoring those that do not.
- look for things that confirm what we already know and ignore things that don't.
- attribute causality to random events.

3. Ideological Immunity
In day-to-day life, as well as in science, we all resist a fundamental paradigm change. This is generally adaptive because we cannot constantly attend to re-evaluating every situation we encounter. Unfortunately, we tend to build up "immunity" against new ideas that do not corroborate our previously held viewpoint.