BACKGROUND INFORMATION—THE NATURE OF SCIENCE

"The whole of science is nothing more than a refinement of everyday thinking."

—Albert Einstein, 1936 in Physics and Reality

OVERVIEW

What is science? Unfortunately, most people think of science as a collection of facts, a body of knowledge. This is, however, only the "end" product of science, it is the knowledge that the *process* of science has acquired. Furthermore, ***non-scientists often perceive science to be a collection of immutable, unchanging facts***. The passive mass media (television programs, advertisements, and movies) tend to reinforce this perception, promoting science illiteracy. When a new study reports that scientists have "changed their minds," have overturned a previously held fact or idea, people tend to distrust science. Ironically, these types of events are actually the real advances in our understanding. They illustrate the true nature of science (as tentative and self-correcting), as well as the real power of science as a way of knowing.

GOALS AND ASSUMPTIONS OF SCIENCE

So, what is science? Let us start by asking, what are the goals of science? ***Science, at its most basic level, is a search for explanations about the natural world***. The goal of science is to find the best possible natural explanations for natural occurrences. Scientists seek to understand why the natural world is the way that it is, as well as how the natural world works. In order to do this, they use **methodological naturalism**[1]. Methodological naturalism is a philosophical rule used by scientists. This rule states that scientists must look for a naturalistic cause (and only

[1] Methodological naturalism is very different from the philosophical viewpoint, called metaphysical or ontological or philosophical naturalism, adherents of which believe that nature is all that there is (i.e. supernatural agents, such as God, do not exist). Science does not assume philosophical naturalism, only methodological naturalism.

a naturalistic cause) for a natural phenomenon. In other words, scientists cannot invoke supernatural explanations[2]. This method of science assumes:

1) *The natural world has an order to it*—nature follows the same general rules throughout the universe
2) N*atural phenomena have natural explanations*
3) *Humans can uncover these explanations*, using critical and objective thinking, as well as careful investigation

Why do scientists use this methodology? Because it works! It has proven to be a reliable method of uncovering explanations for natural phenomena.

THE NATURE OF SCIENCE

Science is a self-correcting process that produces reliable, objective public knowledge*.* Scientists are not super-human. The ideal of the objective unbiased scientist uncovering the "truth" is a myth. Everybody has different experiences, values and biases, and scientists are no exception. Why then should we accept what scientists have to say? The reason is that even though individual scientists are not perfectly objective and they do make mistakes, other scientists will eventually uncover those mistakes. Any result of importance will almost immediately be re-tested by other scientists. Eventually, any mistake or error produced by individual subjectivity will be found and overturned. ***Consensus is the basis for scientific knowledge****.* Scientific knowledge is not based on one person's "say-so;" it is based on the collective consensus of many scientists working on the same problem. This is the power of science as a way of producing reliable, objective public knowledge.

This is also why ***all claims in science are viewed as tentative***. There is no such thing as proof in science. Unfortunately, advertisers commonly promote this misconception by erroneously claiming that "science has proven" their product to be better than others, or to be able to cure whatever ails you. The reality is that every claim a scientist makes is tentative; it may eventually be overturned by new evidence in the future. Of course, there are varying degrees of tentative, depending on how well supported by evidence the claim is.

[2] An example of a supernatural explanation for a natural phenomenon is the long-defunct idea that evil spirits cause diseases; the scientific theory is the germ theory of disease—microorganisms (bacteria, viruses, etc.) cause diseases.

A scientific fact is a well-confirmed observation. It is a claim for which there is so much evidence that it is unlikely to be overturned. In practice, facts are claims that are no longer actively tested; they are taken as given. But the fact is, facts are not immutable. Scientists must remain open to the possibility that established facts may turn out to not be true. For example, it was once a fact that humans had 48 chromosomes. The available evidence at the time supported this fact. Now, it is a fact that humans have 46 chromosomes. New evidence (made possible by new technology, etc.) overturned the earlier fact, and replaced it with a newer (but still tentative) fact.

Similarly, hypotheses are also tentative. ***A scientific hypothesis is a possible explanation for an observed phenomenon***. Hypotheses are tested and re-tested with new observations and experiments. They are consequently rejected, supported and/or modified. *Hypotheses are never proven.* On the contrary, scientific knowledge advances by the systematic rejection of available hypotheses. Basically, the hypothesis left standing "wins." But, since it is always possible that the true explanation may not have been included in the list of available hypotheses that were tested, even a well supported, non-rejected hypothesis is still only tentative—accepted as the best explanation that we currently have, given the current state and limits of our knowledge.

Likewise, theories also are tentative. However, theories are so very well confirmed and supported by many different types of evidence that they are very, very low on the tentative scale, and are unlikely to be overturned. ***A scientific theory is a conceptual framework that explains a variety of phenomena***. Like a hypothesis, a theory is an explanation. Unlike a hypothesis, theories are exceedingly well supported by innumerable observations from a breadth of fields of study. Theories explain facts. They explain a <u>lot</u> of facts. In science, a theory is as big as you get! *Developing explanatory theories is a goal of science.*

This is in stark contrast to the colloquial use of the word theory (and fact). In general usage, a "theory" is no better than a guess or a hunch; it is not even a respectable hypothesis. Likewise, a "fact" is TRUE and is much bigger than a theory. Not so in science. In science, facts are merely observations (well confirmed though they may be). Theories, however, have the true powers of explanation and prediction.

What then, is a scientific "law?" *A **law** is a general (or universal) statement describing an occurrence or a pattern that does not vary*. It is also tentative (but highly probable). For example, in chemistry, the law of conservation of energy has been changed to the law of conservation of matter/energy. It is important to note that the general misconception is that there is a progression from hypothesis ✍ theory ✍ law. This is not the case. *Laws, like facts, require explanations, while hypotheses and theories are explanations*. A law can be discovered and described without an adequate explanation.

THE LIMITS OF SCIENCE

> *"For the scientific method can teach us nothing else beyond how facts are related to, and conditioned by, each other… Knowledge of what is does not open the door directly to what should be."*
>
> —Albert Einstein, 1939 in Science and Religion

As Einstein well understood, *science has limits.* For example, some "facts" are not susceptible to scientific investigation. Private knowledge—emotions, motives and beliefs—cannot be scientifically tested. I know that I love my child, and that I did not choose the graduate school I attended based on their basketball team. But someone else cannot know this about me, unless I tell that person. Even so, try as I might, I still cannot convince some people that I did not go to the grad school I chose because of their basketball prowess. These are completely personal facts, and an objective observer is unable to independently observe them directly. ***Science is limited to investigation of public knowledge***—things that anybody can observe. This is why, for example, individual revelations[3] are not subject to scientific investigation—they are private matters that are not directly observable by an objective viewer.

Science is also limited to the study of the natural, physical world. It is limited to natural explanations of the natural world. Supernatural explanations are off limits and out of the realm of science. The reason for this is, simply, methodology. Supernatural explanations are not testable. A spirit or deity, by its very definition, cannot be held constant, or controlled, in an experimental design. Therefore, an explanation involving a supernatural being is not testable, not falsifiable, and is not scientific. This does not mean that it is wrong; only that it is not scientific. Science is not anti-religious by its nature; in fact, it has nothing whatsoever to say

[3] An important example of this is the Bible. Much of the Bible consists of written accounts of personal revelations. As such it does not constitute scientific evidence, because it was not gathered scientifically. This does not imply that what is in the Bible is necessarily untrue. Just that it is not scientific. You can choose to believe or not to believe that the personal revelations in the Bible came directly from God, and are therefore true. That is a matter of faith, not science.

about the existence or non-existence of God or other spiritual beings. These are questions that science simply cannot address.

Science is limited to understanding the way the world is. Science is a powerful method for understanding the way the world is. However, it tells us absolutely nothing about the way the world ought to be or the way we want it to be. Science cannot tell us what our goals or purposes in life should be. Science cannot bring meaning to our lives. People must turn to other ways of knowing, such as religion, meditation, philosophy, morality, and ethics to understand those kinds of issues. Science is a way of knowing and understanding our physical world, and it can certainly inform our decisions. But, what we do with that information is up to us, as individuals and as a society, to decide. We must also use other ways of knowing to help us make those decisions.

TEACHING ABOUT THE NATURE OF SCIENCE

It has been noted in the literature that one of the values of teaching evolution is that it provides an opportunity to address the pervasive misconceptions about science in general, and to teach about the true nature of science. There are many ways to approach this.

First, ***know your students***. What are their perceptions about science? This can most easily be done with a survey. If you know your students and their conceptions, then you can address these explicitly. See "Surveys on the Nature of Science and Evolution." [[Link to Surveys file]]

Next, ***explicitly address the perceived conflict between science and religion***. Help them to bridge the false dichotomy that is so pervasive: "if you believe in God, you can't accept evolution." One way to do this is to make students aware of the range of philosophical beliefs about evolution and religion. See Eugenie Scott's Creation/Evolution Continuum. [[www.ncseweb.org/resources/articles/1593_the_creationevolution_continu_12_7_2000.asp]] Scott has also suggested several constructivist exercises, such as brainstorming what they think is meant by the terms: "evolution" and "creation;" give them a quiz with quotes about evolution and religion from various religious leaders, and see if they can figure out who said what. You could even have them go out and interview their own local religious leaders. Just being aware of the diversity of opinions can be helpful in breaking down this false dichotomy of evolution vs. God.

A note of caution: in public schools it is unlawful to promote a specific religion. Use these methods with great care and sensitivity. The most important thing is to **treat your students' views with respect**, and make sure students treat each other with respect as well. Students can feel a very real conflict, which they must resolve or learn to manage on their own terms, you cannot do it for them.

It is also important to ***distinguish between science and non-science***. You can talk about *how terms are used differently in science and outside of science* (theory, fact, belief, etc.). For example, what does it mean when a scientist says he *believes* that bird feathers evolved for thermoregulation and not flight? Contrast this with what a Christian means when he says he *believes* Jesus is the Son of God. The scientist *believes* or *accepts* that bird feathers evolved first for thermoregulation based on the evidence for this hypothesis (comparative studies of a large number of birds; reptiles and fossils suggest that the feathered ancestors of birds could not fly—thus feathers probably initially served another purpose; thermoregulation is a plausible alternative explanation for the first function of feathers, based on other types of evidence). The Christian *believes* or has *faith* that Jesus is the Son of God because of his personal experiences (maybe this is what his/her parents taught him to believe; maybe he/she had a personal revelation; maybe it just makes sense to him/her, based on personal experiences). In the first case, belief was based on objective public evidence. In latter case, the belief is based on interpretations of personal experiences. In the future, publicly obtained evidence could refute the scientific belief. It is not likely, however, to publicly obtain evidence that would refute the religious belief, since it is based on personal, private knowledge.

Discuss what types of questions are appropriate for science, and what kinds of questions are appropriate for other types of disciplines/ways of knowing. Is there a God? How should I choose a spouse? What determines the order of the colors of a rainbow? What is the meaning of life? Is there a meaning of life? Why do the leaves of maple trees change color in the fall? Ask a variety of questions like these, and help the students decide if they are appropriate for a scientific investigation or not.

Help students ***understand the true nature of science***. Give students a feel for the process of science, not just the end products of science. Talk about the *tentative and self-correcting* *process of science*. Instead of just presenting the most widely accepted current scientific view of some topic, give an historical perspective of the scientific ideas that came before it, and why they were rejected in favor of the currently accepted idea. For example, give an historical perspective of the search for the genetic code. How do we know that "DNA holds the genetic code?" Why do we no longer think that the genetic code is found in proteins (a once viable hypothesis)?

Use a *crime scene investigation as an analogy* to investigation in the historical sciences. How can a police detective "know" what happened at a crime scene if he/she was not there to witness the crime? The answer is that events that took place in the past leave clues that we can use in the present to piece together what happened.

Emphasize the *variability in the strength of support* that different ideas have. Craig Nelson's article: Effective strategies for teaching evolution and other controversial topics in The Creation Controversy and the Science Classroom, NSTA [[php.indiana.edu/~nelson1/NSTA2.html]] has a "Big Mac" metaphor, with the "meatier" topics being the ones that are well confirmed (e.g. shared ancestry), with the "bun" topics being those we do not know as much about (e.g. origin of life).

RESOURCE LIST

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LESSONS AND RESOURCES ON THE NATURE OF SCIENCE

Resources on the Nature of Science

The website of the Evolution and the Nature of Science Institutes (ENSI) has many lessons on the nature of science, in three separate categories: realms and limits, basic processes, and the social context of science. [[www.indiana.edu/~ensiweb/natsci.f.html]] They also have a suggested lesson plan for a unit on the nature of science. [[www.indiana.edu/~ensiweb/lessons/unt.n.s.html]] Another website to check out would be Access Excellence's page: Activities Exchange Mystery Spot [[www.accessexcellence.org/AE/mspot/]] This site has online mysteries for students to solve.

PBS' "Evolution" series has a couple of useful resources. Check out the last episode of the series, "**What About God?**" but not necessarily for use in the classroom. Also check out the video "**Learning and Teaching Evolution**," [[www.pbs.org/wgbh/evolution/educators/teachstuds/svideos.html]] which is a companion to the series. This video has four case studies on different aspects of teaching evolution and the nature of science, as well as seven short segments from the series that can be used with your students. Segment one ("**Isn't Evolution Just a Theory?**") is particularly useful for introducing the nature of science and evolution. Segment seven ("**Why is Evolution Controversial Anyway?**") explores different viewpoints of the perceived conflict between religion and science.

Distinguishing between science and non-science

ENSI has a lesson, "**Of Sunsets, Souls, and Senses**" [[www.indiana.edu/~ensiweb/lessons/sunsets.html]] that explores the limits of science, and what kinds of topics are appropriate for scientific investigation. They also have a lesson, "**CONPTT: Science vs Non-Science**" [[www.indiana.edu/~ensiweb/lessons/conptt.html]] that explores the six criteria of science, to help identify the differences between science and "emerging science," "non-science," and "pseudoscience."

Another idea is to put together a list of questions and have the students decide whether the questions are appropriate for a scientific investigation. Example questions:

What is a sunset?
What chemicals make up the sun?
Is there a God?
Is there such a thing as ghosts?
What makes an object fall to the earth?
Should I get married?
For what purpose am I here?
How can we best treat cancer?
Why do flowers smell good?

Understanding the true nature of science

ENSI has several lessons on what they call the "social context" of science. "**Crime Scene**" [[www.indiana.edu/~ensiweb/lessons/crime.html]] and the highly recommended "**Checks Lab**" [[www.indiana.edu/~ensiweb/lessons/chec.lab.html]] both explore the tentative nature of hypotheses.

PBS' Teacher's Guide [[www.pbs.org/wgbh/evolution/educators/teachstuds/tguide.html]] also has several lessons on the nature of science. Go to the online Teacher's Guide, click on "download PDF" under Unit 1: What is the Nature of Science? "**Observe This**" and "**Different Points of View**" are about making observations and developing hypotheses to explain their observations; "**Solving the Puzzle**" is similar to ENSI's "Checks Lab."

Another lesson is to choose a current scientific discovery from the newspaper. Then find a magazine article on the same discovery, and the original scientific paper. Every week, the two biggest general science journals, Science and Nature, as well as other journals give press releases of "hot" discoveries. Newspapers pick these up pretty quickly, and then you can find articles in popular periodicals within a month or so. It is a very interesting lesson to compare science, as written by scientists in science journals, with the same science written by journalists for the public (both general and interest-specific). Often, the social or societal implications of the science are speculated upon by the journalists, but not by the scientists themselves. This would be a good opportunity to discuss the *limits of science* to describing the way things are; you need to go outside of science to figure out what to do with this information. This would especially work well if you have a unit or emphasis on scientific writing.

Another good idea about learning about the nature of science is presented by Cunningham and Helms (1998; JRST 35: 483-499): *learn about the process of science by actually doing it!* They discuss a teacher who has her students conduct experiments with Fast Plants (*Brassica rapa*). Bean seeds also work well. Working in groups, students brainstorm questions they might ask (based on their observations, etc.), and then with your guidance, develop hypotheses, figure out how to test those hypotheses (what treatments to use, including controls), and then conduct their experiments, collect data, analyze their data, and make conclusions. Groups of students may come up with their own questions, or the whole class may be presented with a single question (with which each group figures out on their own how to address it). The question could be as simple as: how does fertilizer affect plant growth and development? Or, how does amount of water available to a plant affect its growth?

This type of lesson will take a month or two to complete, but it is nice in that students will become aware of what it really is to do science, with all of the messiness, successes, failures, and decision-making involved. This is much preferable to an exercise in which they follow a cookbook formula experiment where there is a "right" answer. It will also help them to become more aware of how we know something in science. Instead of just taking for granted that water or nutrients (for example) are important for plant growth, they will actually discover this on their own, and in the process, find out how we "know" something in science.