

A Practical Approach to Teaching the Nature of Science

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The scientific enterprise is organized around several tenets which comprise what is called “the nature of science” (NOS). These tenets serve to standardize and guide scientific inquiry around the globe. Understanding the nature of science helps to promote scientific literacy. A scientifically literate person has the knowledge and habits of mind needed to make informed personal decisions and contribute to society. If we are to produce scientifically literate citizens who are fully able to “take part in our country's political discourse” (Hazen & Trefil, 1991, p. xi) and compete in a competitive global economy we must explicitly teach the nature of science.

The recent changes in the Virginia Science Standards of Learning provide an opportunity for science educators to thoughtfully incorporate a discussion of the nature of science into the work they currently do with their students. In this way students will come to understand that that nature of science is much more than mere “experimental design” as has often been presented in the past.

The purpose of this article is to (1) elucidate the seven key concepts related to the nature of science and (2) to provide a model that teacher can use to help students “make connections between the components of the nature of science and their investigations and the greater body of scientific knowledge and research” (VA SOL Curriculum Framework, Physical Science, p. 4).

Seven Key Concepts of the Nature of Science

1. The Natural World is Understandable

Perhaps the most foundational component of the nature of science is the universal belief that the natural world is understandable through the careful collection and critical analysis of empirical evidence (American Association for the Advancement of Science, 1993). Every discipline in modern science has derived its principles and paradigms through this process. Knowing that scientific conclusions are formed in this manner, allows the public “to react thoughtfully to scientific claims and [makes them] less likely to reject them out of hand or accept them uncritically” (AAAS, 1993). Most importantly, this way of thinking precludes the actions of supernatural beings as causative agents of natural phenomena and helps to focus research on testable questions.

Truth filters. Each year billions of dollars are spent by business, political, and other interests to find out what people believe to be true about a given topic. Rather than asking what people believe to be true, it might be more informative to ask *how* they arrived at this decision and *what* criteria were involved.

An understanding of the different criteria people use as to “truth filters” (Toffler, 2006, p. 123) is critical to understanding the nature of science. As it turns out, people use a variety of methods to guide them in determining truth and making decisions in their personal and professional lives. For example, when deciding which movie to see or book to purchase, a person might use a “consensus” filter. “Authority” is another often used “truth filter” and relates to the importance bestowed upon the opinions and beliefs of influential people. Whether earned or not - we tend to place more weight on the viewpoints of people and institutions which represent authority. National newscasters, successful entrepreneurs, political leaders, respected print and news media, and movie stars are just a few of the authorities people currently look to for truth. Truth can also be inherited. If a fact, story, or opinion has been around for a long time then it is more likely to be believed because it has withstood the rigors of time. Toffler (2006) states that, “for most of us today it is hard to appreciate just how important inherited truth was before the Enlightenment and the industrial revolution” (p. 126).

This brings us to science as a “truth filter. “Of all these various criteria for determining truth, science is probably the one we rely on least in our daily lives yet none in recent centuries has had a greater impact on wealth” (Toffler, 2006, p. 126). Scientific thinking has proven to be a powerful engine for technological and economic growth (Toffler, 2007). The major difference between science and other “truth filters” is that rather than relying on external sources for information and validation such as group consensus, authority, or durability over time, science demands clear and unbiased collection, analysis and reporting of empirical data.

2. Science Demands Evidence

Scientists use data to make inferences and formulate explanations about phenomena. Scientists use the data they collect to make inferences and formulate mental constructs around which disciplines are organized. These data can be obtained through observation or experimentation. Both types of data are equally useful and valuable in the scientific endeavor. For example, data about the efficacy of a new cancer treatment drug would require a formal experiment protocol using a control and levels of the independent variable, but a modern astronomer would use observations collected from space telescopes to look for patterns from which to formulate inferences and conclusions.

Unfortunately, there is a mistaken belief that all scientific knowledge has been experimentally derived (Chen, 2006). It is, therefore, important to point out that constructs such as biological classification, plate tectonics, or the current model of the atom were not experimentally derived. These represent “theoretical rather than experimentally derived constructs” (Chen, 2006). One can assume that students hold similar misconceptions that must be addressed if they are to accurately understand the nature of science. Thus, it's important to call to students' attention the fact that the data they collect through observation or experimentation are equally useful in helping them formulate scientific conclusions.

The myth of the scientific method. It often comes as a surprise to science teachers (and others) when they learn that, contrary to what is presented in most science textbooks, there is no universally accepted scientific method agreed upon by the scientific community. In reality, scientists apply various methods in doing research (Chen, 2006; Hanuscin et al., 2006) and no clear and consistent definition concerning what constitutes a scientific investigation exists. Although no set "scientific method" exists, science does demand that evidence (observational or experimental) be empirically collected and analyzed (National Science Teachers Association, 2000). While controlled experiments can offer compelling evidence to support a hypothesis or theory, it is a myth to believe that the most credible scientific theories are supported by controlled experiments (Chiapetta & Koballa, 2004).

Example: spontaneous generation. We may laugh at the notion now but, before microscopes were invented people generally believed that life sprang from inanimate matter - that life could spontaneously be generated from inanimate matter. This view had first been introduced by Aristotle who said that some animals could grow spontaneously and that such animals need not come from others of their own kind. Earlier philosophers believed that the earliest men must have sprung up, fully formed, from the soil in adult form because they never could have survived otherwise. Before we laugh too hard at these ideas we should note that many scientists – even up to the 1800's – held these same views. In fact, recipe books for making animals were written and one such recipe for making a scorpion called for basil to be layered between two bricks and then placed in the sunlight. Real science, however, relies on empirical evidence and replicable results. Thankfully, the myth of spontaneous generation was finally put to rest in 1859 by Louis Pasteur.

3. Science is a Blend of Logic and Imagination

Albert Einstein once said “logic will get you from A to B. Imagination will take you everywhere.” Scientific knowledge involves human imagination, creativity, and inference (Sterling, Greene, & Lewis, 2002). Scientists and children alike use science process skills to gather data about

the natural world. Whereas children use their five senses, scientists use more sophisticated instruments (Llewellyn, 2002). To determine which data constitutes evidence, and what that evidence means, are not entirely based upon logic, however.

Much of the scientific enterprise is governed by the ability and creativity of scientists to visualize different situations and predict outcomes. Einstein's "thought experiments" about Special Relativity and Schrodinger's "cat" are two examples of how visualization and creativity can be used to help in formulating and conveying science concepts.

Example: the structure of benzene. Since its discovery in 1825, the molecule benzene was known to contain carbon atoms and hydrogen atoms. However, their exact arrangement was a mystery for decades and eluded the scrutiny of many scientists. About 40 years after its discovery, a young chemist by the name of August Kekule devised the hexagonal structure of the now familiar molecule. According to Kekule, the idea came to him in a dream during an afternoon nap. In his dream, the atoms were moving about in front of him in "long rows, sometimes more closely fitted together, all twining and twisting in snake-like motion." He was amazed to see that "one of the snakes had seized hold of its own tail, and the form whirled mockingly before my eyes." Thus the ring-like structure of benzene was discovered during a chemist's afternoon nap.

4. Scientific Knowledge is Durable

Those scientific ideas and explanations that are able to withstand the scrutiny of the scientific community form the backbone of our current understandings of the natural world and how it functions (Kuhn, 1996). For example, our understanding of planetary motion is derived from the work of Ptolemy, Copernicus, Galileo, and Newton - each contributing a bit of information to the planetary puzzle. Sharing scientific ideas and explanations is a critical component of the scientific enterprise. This practice not only disseminates new information, it also ensures that explanations will be exposed to the scrutiny of others. Continually tested in this way, scientific ideas are revised when new, compelling data become available (AAAS, 1993; Sterling, Greene, & Lewis, 2002).

Theories and laws. A major misconception exists with respect to scientific theories and laws. Theories and laws are two different types of knowledge used by scientists to describe natural phenomena and, within the scientific community, slight distinction is made between the two. Both theories and laws have substantial supporting evidence and it is false to believe that "hypotheses become theories and theories become laws" (Colburn, 2008). Theories combine many facts, concepts, and laws to form scientific understandings around which disciplines are organized.

A good example of this is atomic theory which includes the law of conservation of mass, Avogadro's Law, Boyle's Law, Periodic Law, etc." (Chen, 2006; Chiapetta & Koballa, 2004, Hanuscin et al., 2006). From this example it is clear that the theory provides the framework for more detailed explanations of phenomena which are represented by laws. Therefore, "we should not think of scientific theories as ideas built on shaky facts and flimsy evidence because many of the major theories of science have held up to considerable scrutiny and have shown to be durable" over time (Chiapetta & Koballa, 2004).

5. *Scientific Ideas are Subject to Change*

Normal science is predicated upon a system of collectively held beliefs (called paradigms) about the natural world and how it works. The drive to examine and explain the finer points of a paradigm is what drives "normal science" (Kuhn, 1996). To this end, new instruments are developed for the purpose of collecting extremely precise measurements in order to "match fact with theory" (Kuhn, 1996) related to a paradigm. In this way, science strives to continually test and refine our understanding of the natural world. Paradoxically, the sensitive instruments developed to explain these finer points contribute to uncovering ambiguities in the expected data. Only by having an idea of what to expect are scientists able to recognize when it does not occur. New paradigms often arise from researchers who are able to view discrepant data with fresh eyes. Although subject to gradual refinement "the main body of scientific knowledge is very stable and grows by gradually being corrected" (AAAS, 1993) over time.

Example: the theory of plate tectonics. In 1912 Alfred Wegener noticed that the world's continents seemed to fit together like a giant jigsaw puzzle and proposed that the continents were once compressed into a single continent which he called Pangaea. According to Wegener, the continents had drifted apart over time into their current locations. Although Wegener's theory was able to provide support that the continents were once connected and had subsequently moved, it failed to present a plausible mechanism to explain the continents' movement. As a result, Wegener's ideas fell out of favor with the scientific community.

In 1929, Arthur Holmes helped to renew interest in Wegener's theory by proposing that continental drift was caused by thermal convection currents in the Earth's mantle. He proposed that these convection currents acted as a giant conveyor belt moving continents from one place on the Earth to another. Holmes' idea was later supported by the discovery of deep sea trenches and mid-ocean ridges in the 1960's and the existence of convection currents within the mantle which caused sea floor spreading.

Today, the theory of plate tectonics is derived from Wegener's theory of "continental drift" and is universally accepted to explain the motion of the Earth's crust. Thus, the example provided by the work of Alfred Wegener and others demonstrates that scientific knowledge is durable yet subject to refinement as new instrumentation and data become available.

6. Scientists Try to Identify and Avoid Bias

Within the scientific community there are ethical practices, such as the accurate and truthful reporting of data and peer and public review, which guarantee that scientific endeavors are carried out under universally accepted standards around the world (National Research Council, 1996). The world's public trusts and believes in the results of scientific research only because of the professional rigor imposed by the community in an effort to identify and avoid personal bias (Balzer, personal communication, October 2010).

Because scientists within the same field tend to share common methodologies and views (Kuhn, 1996) their objectivity must continually be challenged to ensure validity of results (AAAS, 1993). Although scientists strive for objectivity in their data analysis they nonetheless rely on a healthy skepticism within the scientific community to replicate and verify their results. The scientific community self-regulates and will not tolerate those who falsify or misrepresent their data. In addition to ensuring professional credibility, such scrutiny helps to protect the public from the impact of poor science. Perhaps the details of cases of scientific misconduct are less important than the swift and sure condemnation and ostracism of the perpetrator(s) by the scientific community.

Example: cases of scientific fraud. Scientists in the mid-1800s hypothesized that air pollution was to blame for the decline in the percentage of light-colored varieties in the peppered moth population. To test this hypothesis, Bernard Kettlewell conducted a study which indicated that birds preferred the lighter-colored moths to the darker-colored variety. A major flaw in his study, however, is that he created an artificial situation by nailing dead moths to the tree trunks. Live moths rarely landed on the trunks during the day and, therefore, birds rarely looked for prey in that location until it was made readily available to them through the kindness of the researcher. For many years the "peppered moth" case was held up as the canonical example of natural selection in action but has since fallen out of favor with scientists and teachers alike.

A more recent case of scientific fraud is alleged to have been perpetrated by Dr. Andrew Wakefield. His study linking the measles, mumps, and rubella (MMR) vaccine with autism was found to be based on falsified data. It is reported that Dr. Wakefield falsified data in all twelve case histories in his study. So serious are the allegations that he has been stripped of his medical license and the

journal issued a retraction of the study which was originally reported in the international medical journal, *The Lancet*.

7. Science is a Complex Social Activity

Scientific research can take place in a laboratory or out in the “real” world in deep sea submersibles, space shuttles, field observation posts, etc. The one critical linking factor is that the gathered data will ultimately be shared with others for their review and critique. Scientific research is dependent upon financial support and this can sometimes make it difficult for scientists to carry out the research that most interests them (AAAS, 1993) because funding can be influenced by religious, commercial, or political agendas. There are also numerous examples where scientific research was scorned by the community at the time, only to be validated at a later date. Trying to convince a skeptical audience that your observations have led to new discoveries is often a difficult and complex social activity in and of itself. For this reason it is important to recognize that scientific knowledge is tied to social and cultural factors (Sterling, Greene, & Lewis, 2002).

The dissemination of scientific findings is critical to the nature of science. Scientists share their findings with their peers through a wide variety of media such as print, electronic, and even video. While these communications serve to inform others’ of the work being done in a particular field, they also help to expose ideas to the scrutiny and criticism of the general science community. In this way, results are “peer reviewed” and challenged for authenticity.

Example: the history of stem cell research. The history of Stem cell research provides an example of the influence of social and political forces on scientific research. Early research in the mid-1800s focused on bone marrow transplantation but later shifted toward using undifferentiated cells to form other tissues. Federal funding for stem cell research has been punctuated by many starts and stops resulting from public debate about the ethics of certain aspects of the research. Amid growing concern that America was falling behind the rest of the world in stem cell research, California earmarked 3 billion dollars for the research in 1994. Although President Obama lifted the ban on using federal dollars to fund stem cell research in 2009, the history of stem cell research would indicate that the debate may not be over.

CONNECTING STUDENTS’ WORK TO THE NATURE OF SCIENCE

Teaching the Nature of Science

Teaching the nature of science is an important consideration if America is to produce scientifically literate citizens fully capable of making informed decisions and competing in a global economy. To build a critical understanding of the true nature of science, educators must come together

to formulate a simple and easy-to-understand definition as well as create curricular materials that lead teachers and students through an exploration of NOS components and their application to students' work.

To change the perception that the nature of science is little more than “experimental design,” it is necessary that teachers and students be presented with a clear, concise synthesis of the main components of the nature of science. Students must be given time to consider each of the seven main components of the nature of science and to then create a graphic and phrase that helps them summarize and synthesize what it means to them (see NOS Graphic). By creating these non-linguistic representations, students begin the process of internalizing what NOS means to them (see NOS Graphic Sample) and that they connect their own personal experiences to these over time. To promote a deeper understanding of the nature of science, teachers should frequently ask students to consider how the nature of science applies to their science investigations (see NOS Focus Questions). If presented with this type of questioning and discussion, students will build a more comprehensive understanding of the nature of science. The author has developed a website which contains resources to help teachers build their own background knowledge about NOS (see <http://mason.gmu.edu/~lpetersn/nos/>)

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NOS Focus Questions

Nature of Science Focus Questions

Students: To help you see connections between the work you do in science class and the Nature of Science, consider each of the following questions. Be prepared to justify your response(s).

| | |
|---------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| THE NATURAL WORLD IS UNDERSTANDABLE | <p><u>The natural world is understandable</u></p> <ul style="list-style-type: none"> ❖ How did your investigation support the idea that the natural world is understandable? |
| SCIENCE DEMANDS EVIDENCE | <p><u>Science demands evidence</u></p> <ul style="list-style-type: none"> ❖ How did you use inquiry to guide your investigation? <ul style="list-style-type: none"> • What questions or predictions guided your investigation? • Did you create and/or follow a procedure? • How did you evaluate the validity of your data? • Was your data experimental or observational? • Can you support your conclusion with evidence from your investigation? • Were alternate explanations considered? • How did you communicate your conclusion to others? • How did you connect your findings to the larger body of scientific knowledge on the topic? |
| SCIENCE IS A BLEND OF LOGIC AND IMAGINATION | <p><u>Science is a blend of logic and imagination</u></p> <ul style="list-style-type: none"> ❖ How did you use logic, imagination, visualization, and creativity in completing your investigation or formulating your conclusion? ❖ What experiences gave you ideas to help you make sense of the data? <ul style="list-style-type: none"> • Are there other ways you could explain your results? • What patterns did you observe in the data? Where else do you see similar patterns? |
| SCIENTIFIC KNOWLEDGE IS DURABLE | <p><u>Scientific ideas are durable</u></p> <ul style="list-style-type: none"> ❖ What scientific theories or laws did you use to help you formulate a logical conclusion? |
| SCIENTIFIC KNOWLEDGE IS SUBJECT TO CHANGE | <p><u>Scientific ideas are subject to change</u></p> <ul style="list-style-type: none"> ❖ How has the scientific understanding of your topic changed over time? What caused this change? ❖ How have your ideas about this topic changed as a result of this investigation? |
| SCIENCE IS A COMPLEX SOCIAL ACTIVITY | <p><u>Science is a social activity</u></p> <ul style="list-style-type: none"> ❖ How well did you work together and communicate to complete this investigation and/or verify results? ❖ How well could someone else understand your data and conclusion? |
| SCIENCE IDENTIFIES AND AVOIDS BIAS | <p><u>Science avoids bias</u></p> <ul style="list-style-type: none"> ❖ How did you maintain objectivity when collecting data and formulating your conclusion? ❖ What criteria did you use to verify the validity of your data? |