Using the History of Biology, Chemistry, Geology, and Physics to illustrate general aspects of Nature of Science

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Abstract

The Nature of Science (NOS), a description of how science works, is considered as an important element in the school science curriculum but one that is rarely included in instruction. We present a method whereby nine general NOS aspects can each be illustrated with examples from the history of biology, chemistry, geology, and physics. The entire set of examples, linked to the general NOS aspects, provides an immediate instructional resource that teachers can use to teach science content and NOS.

Keywords

Nature of science, history of science, science teaching

Résumé

La nature de la science (NOS), une description de la façon dont fonctionne la science, est considérée comme un élément important dans le plan d'études des sciences de l'école, mais qui est rarement inclus dans l'instruction. Nous présentons une *méthode par laquelle neuf aspects NOS générales peuvent chacun être illustrés par des exemples tirés de l'histoire de la biologie, la chimie, la géologie et la physique. L'ensemble des exemples, liés aux aspects NOS générales, constitue une ressource pédagogique immédiate que les enseignants peuvent utiliser pour enseigner le contenu scientifique et la NOS.*

Mots-Clés

Nature de la science, histoire de la science, enseignement scientifique

INTRODUCTION

During the past century, scholars and teachers alike have come to new understandings about how people learn, what rationales and goals support the teaching of science, which proposed definitions of science literacy make the most sense, what role inquiry offers in support of science teaching, where science fits within STEM (science, technology, engineering, and mathematics) education, and, of course, what the content of the science curriculum should be for various grade levels.

One constant during this time has been an increasing understanding of, and advocacy for, the inclusion of Nature of Science (NOS)[1] in school science. Starting more than 50 years ago with a trickle of interest and scholarship, the field has matured to the extent that virtually all would argue for a role of NOS across the science curriculum, from the elementary level to courses designed to educate future scientists.

Finding a single definition of NOS that all science educators can embrace would be difficult, but the majority would agree that NOS is the area of study in which students learn how science functions, how knowledge is generated and tested, and how scientists do what they do. McComas, Clough and Almazroa (1998, p. 4) suggested that:

> The nature of science is a fertile hybrid arena which blends aspects of various social studies of science including the history, sociology, and philosophy of science combined with research from the cognitive sciences such as psychology into a rich description of what science is, how it works, how scientists operate as a social group and how society

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[1] The name and content of this domain have been debated for decades. Some have suggested that we call it Nature of Science Studies, History and Philosophy of Science, Ideas-about-Science, Nature of Sciences, Nature of Scientific Knowledge, Views on the Nature of Science, and other such appellations. Of course, the specific name chosen conveys a certain orientation, ranging from the purely philosophical to the historical. However, given the long use of the NOS label to represent a range of meanings targeting student understanding of how science works, we will continue that tradition throughout this article.

> itself both directs and reacts to scientific endeavors. The intersection of the various social studies of science is where the richest view of science is revealed for those who have but a single opportunity [as is the case in school settings] to take in the scenery.

Five decades of research findings are also provided to show what students and teachers typically know about NOS and how NOS might best be integrated into science instruction. References are vast on both of these topics, and research studies have continued to reinforce the central findings. The conclusions are clear, as summarized by Lederman (2007):

- K–12 teachers do not typically possess "adequate" conceptions of NOS;
- Conceptions of NOS are best learned through explicit, reflective instruction rather than implicitly through experiences with simply "doing" science;
- Teachers' conceptions of NOS are not automatically and necessarily translated into classroom practice; and
- Teachers do not regard NOS as an instructional outcome of equal status with that of "traditional" subject-matter outcomes.

Teachers must also develop an understanding of NOS that is linked to methods for incorporating it into instruction. Abd-El-Khalick and Lederman (2000a) called this "NOS Pedagogical Content Knowledge." Like other forms of Pedagogical Content Knowledge (PCK), NOS-PCK implies that in order for teachers to be able to effectively integrate NOS into their classrooms, they need to possess not only the appropriate knowledge of NOS, but also the pedagogical tools related to specific science content. It is therefore necessary to understand how, and how deeply, we might engage learners at all levels with instruction in this important domain (see also Abd-El-Khalick, 2013).

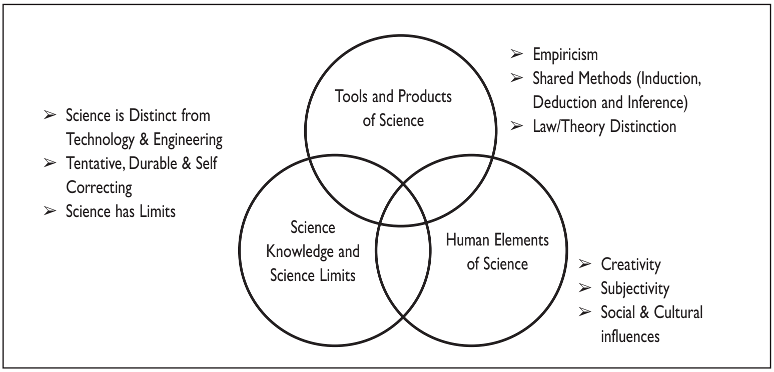
NOS AND SCIENCE INSTRUCTION

There may be little dissent about *whether* to help students gain an understanding of the scientific enterprise from the perspective of *what we know* and *how we know it,* but a firm and shared notion of what this means has been somewhat elusive. We are sure that teachers must understand this domain as well as they understand any other science content, but it would be both impractical and unnecessary to insist that K–12 science learners understand science in the way that historians and philosophers of science do.

The task of identifying exactly which general aspects of NOS to focus on has been difficult. Thinking pragmatically, it becomes clear that in all areas of science, we must agree on what to teach; otherwise, every science classroom would be nothing more than the idiosyncratic expression of what the teacher wants to teach. Fortunately, through the work of science educators such as Abd-El-Khalick (2012, 2013), Lederman (1999, 2007), McComas (1998a, 2004, 2008a), and Osborne et al. (2003), we now have a robust set of sub-elements (sometimes called "Key NOS Aspects") that might form the core of NOS instruction.

After considering various proposals for NOS content, McComas (2008a, 2008b) has developed a list of major NOS aspects (Table I) and a related conceptualization of the ways in which the various sub-elements of nature of science might fit together to guide NOS instruction in science classes. Figure I illustrates how the "big" NOS domain can be characterized as the "Tools and Products of Science," the "Human Elements of Science," and "Science Knowledge and Science Limits." In turn, each of these contains three related but separate sub-domains.

Figure 1



Some general aspects of NOS appropriate for inclusion in science instruction, arranged in three clusters, each with three related sub-domains

It is vital that readers do not leap to the false assumption that Table I contains a list of statements to be memorized by students. As with all things worth knowing, students must internalize, experience, understand, and ultimately apply NOS knowledge. In fact, our recommendation is that teachers keep these NOS elements in mind while they teach traditional science content rather than sharing these NOS aspects all at once. This notion is the basis for the historical strategy we will discuss below. It is also important to note that the above list of general NOS aspects is neither fixed nor exhaustive. Several more NOS aspects could be added, depending on the teaching goals and the educational level of students. Yet, these general aspects of NOS are important

TABLE 1

A proposed list of core NOS ideas appropriate to inform K–12 science curriculum development, instruction, and teacher education

The Tools and Products of Science

1) Science produces, demands, and relies on empirical evidence.

2) Knowledge production in science shares many common factors and shared habits of mind, norms, logical thinking, and methods such as careful observation, careful data recording, and truthfullness in reporting. The shared aspects of scientific methodology include the following:
- Experiments are not the only route to knowledge.
- Science uses both inductive reasoning and hypothetico-deductive testing.
- Scientists make observations and produce inferences.
- There is no single, stepwise scientific method by which all science is done.

3) Laws and theories are related but distinct kinds of scientific knowledge.

Science as a Human Activity

4) Science has a creative component.

5) Observations, ideas, and conclusions in science are not entirely objective. This subjective (sometimes called "theory-laden") aspect of science plays both positive and negative roles in scientific investigation.

6) Historical, cultural, and social influences impact the practice and direction of science.

Scientific Knowledge and Its Limitations

7) Science and technology influence each other, but they are not the same.

8) Scientific knowledge is tentative, durable, and self-correcting. (This means that science cannot prove anything, but scientific conclusions are valuable and long lasting because of the way in which they are developed; mistakes will be discovered and corrected as part of the process.)

9) Science and its methods cannot answer all questions. In other words, there are limits to the kinds of questions that can and should be asked within a scientific framework.

and are directly related to alternative conceptions that students hold about NOS (McComas, 1998b; Lederman, 2007). These features make them particularly appropriate for NOS instruction.

THE NATURE OF SCIENCE AND THE NEXT GENERATION SCIENCE STANDARDS

We recognize that some of our readers are not from the United States. Nonetheless, many experts worldwide follow educational developments in the United States, if only to compare them with local considerations. With this in mind, it is vital to understand that each U.S. state governs education within its borders. Recently, the states have come together to explore shared issues of governance, policy, assessment, and standards. The most current example of this shared approach to education is the *Next Generation Science Standards* (NGSS Lead States, 2013), released in 2013 and based on an earlier *Framework* (National Research Council, 2012). Individual states are now determining whether and how to adopt the NGSS, with an expectation that the majority of states will indeed accept the NGSS in some fashion. Readers may be interested to know that the NGSS contain recommendations for science content (Core Ideas), including a variety of Cross-cutting Themes (ideas such as patterns, stability, and change) that link all of the sciences as well as science and engineering practices (such as evaluating and communicating). Although the framework on which the NGSS are based failed to explicitly define NOS, the final version of the NGSS attempted to atone for this omission by including such recommendations in an appendix (see Table 2) and by scattering NOS aspects inexpertly throughout the document.

It is clear that the authors of the NGSS, late in their development, came to recognize the lack of NOS content. Rather than really consider the range of recommendations offered by science education scholars and rewrite the standards as they should have, they simply added NOS content in a somewhat lackluster fashion. There are no clear guidelines for how to include NOS in instruction, nor is there a complete set of recommendations for where all of the recommended NOS aspects should be included across the grade levels. Sadly, it seems that NOS has been included in the NGSS basically as an afterthought in a series of footnotes.

Table 2

A list of NOS aspects recommended in Appendix H of the Next Generation Science Standards

- Scientific Investigations Use a Variety of Methods
- Scientific Knowledge Is Based on Empirical Evidence
- Scientific Knowledge Is Open to Revision in Light of New Evidence
- Scientific Models, Laws, Mechanisms, and Theories Explain Natural Phenomena
- Science Is a Way of Knowing
- Scientific Knowledge Assumes an Order and Consistency in Natural Systems
- Science Is a Human Endeavor
- Science Addresses Questions about the Natural and Material World

A comparison of the NGSS with the recommendations illustrated in Table 1 shows many similarities because the authors of the NGSS clearly referred to these earlier studies. At least one of the NGSS recommendations, "Science Is a Way of Knowing" is not really an NOS goal but is, rather, an overarching statement about science itself. Likewise, stating that "Science Is a Human Endeavor" tells us very little about what this actually means. Nevertheless, for the optimistic, it is the first time that we have seen significant and specific NOS content recommendations in an important science education document.

USING HISTORY OF SCIENCE TO TEACH ABOUT NATURE OF SCIENCE

Even with a list of key NOS aspects, the challenge for teachers and curriculum designers is how to communicate them in an engaging fashion to students. Needless to say, there is no single way to teach this important content, but there are some things we do know. First, it is unlikely that teachers would be able to devote considerable time to the consideration of NOS aspects beyond the typical cursory introduction found in the initial chapters of many science textbooks. Second, many of the NOS aspects are complex enough that they are not all appropriate at every grade level. Finally, NOS is best communicated in context so that students can learn about NOS while exploring traditional science content. The remainder of this paper is predicated on the idea that if teachers had knowledge of the major NOS aspects and knowledge of the history of science, it would be possible to use what might be called an "NOS-Historical" approach and weave NOS lessons into lessons featuring traditional science content (for a similar approach for post-secondary introductory astronomy, biology, chemistry, geology, and physics courses see Clough 2011).

This approach is not new, but it is rarely used in secondary schools. For instance, in the past half-century, some attempts have been made to introduce NOS through curriculum projects such as the History of Science Case Studies, engaging students by having them read the original reports of scientific discovery and even reenact classic experiments in the history of science. Unfortunately, most of these innovations were not widely used, and if current science textbooks contain NOS at all, they do so in a cursory fashion, while generally missing the NOS lessons that could be communicated through the history of science (see e.g. Campanile, Lederman & Kampourakis, 2015). Decades ago, science educator Joseph Schwab (1962) observed that science is taught as an "unmitigated rhetoric of conclusions in which the current and temporal constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths" (p. 24) without ever showing students where the knowledge came from and who contributed to it.

The history of science as it appears in most science books—if it appears at all—is represented by little more than a brief biography or the birth and death dates of the scientists in question. Such treatment is a lost opportunity for students to learn something about NOS through examination of the relevant historical events or by exploring something of the personal history of scientists and their discoveries. Here, we present a rich set of such historical illustrations from each of the major science disciplines, which teachers might incorporate into classroom discussions. To achieve the goal of producing a "ready to use" guide to teach about some general NOS aspects, we have reviewed some accessible books written by professional historians of science (Bowler & Morus, 2005; Dear, 2006; Fara, 2009) to find examples for each NOS aspect from biology, chemistry, geology, and physics. These examples are intended to serve as an introduction to NOS, and could be taught alongside science content. If there is time, more detailed and extended use of scholarship from history of science is possible (e.g. Kampourakis & McComas, 2010; Kampourakis, 2013).

NOS research on science instruction has shown that an explicit approach is the most effective way to communicate the relatively sophisticated content in NOS. Explicitly and repeatedly mentioning NOS is more likely to have an impact on students' understanding than the subtle inclusion of NOS found in most textbooks (Bell, Lederman & Abd-El-Khalick, 1998; Khishfe & Abd-El-Khalick, 2002). Teachers are encouraged to review the illustrations provided for their science discipline and share these examples with students throughout the year. If teachers from various science disciplines were to use the NOS illustrations pertaining to their science with the same group of students, it is very likely that students' NOS understanding could be greatly enhanced. Although teaching HOS to students and pre-service teachers is not a sufficient condition for enhancing their NOS views, it seems that explicitly addressing specific NOS aspects during of HOS courses might enhance the effectiveness (Abd-El-Khalick & Lederman, 2000b).

The illustrations presented in the present article could be incorporated into classrooms in a variety of ways. Teachers could simply share them with students when they are relevant to an aspect of instruction; there is no particular order to these key NOS aspects. The stories could be used in a group focusing on the overall nature of science. Alternatively, they could be framed as the foundation of an assignment, in which students work in small groups to expand these stories by exploring their full context and the personalities involved. Students could then present their findings to the class and show how the nature of science is illustrated. In fact, many of these stories can be used to illustrate more than the single NOS aspect to which each one of them is linked here. These stories and the respective NOS aspects are presented in Table 3.

USING HISTORY TO SHOW THAT SCIENCE RELIES ON EMPIRICAL EVIDENCE

Science requires that researchers provide data that justify all conclusions or form the basis for explanations. Data become evidence that supports or does not support some hypothesis or theory when it is seen in their light. In addition to experiments, equally important are observations, model construction, and mathematical analyses. In some cases scientists may use a combination of methods, but in all cases they look for empirical evidence to support a theory or to develop an explanation. The examples that follow show how empirical evidence was crucial in providing support for scientific theories or even for opening new fields of scientific endeavor.

Biology: Experimental evidence was important for the emergence of classical

TABLE 3

An overview of the historical examples presented here and their relation to general NOS aspects

General NOS Aspect	Biology	Chemistry	Geology	Physics
1. Science relies on empirical evidence.	The experimental evidence produced by Morgan and his group on the mechanisms of heredity and mutations	Boyle's experiments on the nature and constitution of the air to find evidence for the existence of atoms	Hooke finding evidence to show that fossils originated from organisms that lived in the past and that extinction was possible	Eddington testing and finding evidence in support of Einstein's general relativity theory
2. There is no single scientific method.	Watson and Crick's double-helix model for the structure of DNA, which relied on data accumulated by others	Rutherford and Bohr suggesting the atom model, with the latter building on the work of the former	Wegener's theory of continental drift that was plausible but required evidence in order for it to be accepted	Hubble and the separate-galaxies theory, based on calculations of the distances of particular stars
3. Laws and theories are distinct kinds of scientific knowledge.	Mendel's laws and the missing theory of heredity at the time	Mendeleev's idea of the periodic table of elements and the atomic theory that later explained it	Hess, the theory of plate tectonics, and the laws of physics	Newton's laws of motion and gravity, and the explanation for why the respective phenomena occurred in the way they did
4. Science is a creative process.	Darwin, natural selection, and the analogy from artificial selection	Lavoisier and his novel chemical nomenclature	Wegener's theory of continental drift and the torn-paper analogy	Carnot's analogy between water mill and caloric
5. Science has a subjective component.	Pasteur, a devout Catholic, conducting experiments to show that spontaneous generation is impossible	Van Helmont's experiment to prove that water was the only element	Hutton's and Lyell's deism as a motivation for uniformitarianism	Kepler initially believing that the heavens must be governed by geometry
6. There are historical, cultural, political, and social influences on science.	Darwin not publishing after the reaction to the Vestiges, then proceeding to publication in order not to lose priority to Wallace	Lavoisier and the experiments that led to the abandonment of the phlogiston theory while at the Paris Arsenal	Wegener, a geophysicist, rejected as an outsider by the community of professional geologists	Galileo's, Brahe's, and Kepler's astronomical works being sustained by royal or aristocratic patronage
7. Science and technology influence each other.	The development of the cell theory by Schleiden and Schwann following the improvement of microscopes	Becher's investigations on the origin of minerals, carried out in order to improve mining technology	Blackett's magnetometer for mines used to measure magnetism in rocks, providing evidence for the theory of continental drift	Scientists working in close cooperation with engineers during the Manhattan Project
8. Scientific knowledge is tentative.	Cuvier's conclusions that questioned Lamarck's evolutionary ideas eventually came to support evolution	Stahl's phlogiston theory, Priestley's dephlogisticated air, and Lavoisier's oxygen	Humboldt rejecting Neptunism and explaining geological changes based on earth movements	Thomson showing that Hertz's conclusions were wrong and discovering the electron
9. Science cannot answer all questions.	Owen suggesting the existence of a divine plan in nature	Priestley, aerial economy, and social order	Buckland's seeking evidence for Noah's flood	Joule's experiments as providing evidence of the way God had organized creation

genetics during 1910–1915, through the research by Thomas Hunt Morgan and his group, who linked "Mendel's laws" to chromosomes. Morgan's group conducted experiments with *Drosophila* (fruit fly) and showed that genes could be envisioned as sections of chromosomes that were related to characters in the organism. A careful breeding program and statistical analyses of the experimental results showed that changes in particular genes could account for changes in particular phenotypes in *Drosophila.* The Morgan team's further research established that each chromosome carried a collection of genes. They also studied the production of new genetic characters by mutations and showed that these could be caused by external factors such as radiation. More importantly, they showed that not all mutations were harmful and that they could be a source of new variation, which is necessary for the evolution of a population by natural selection (Bowler & Morus, 2005, p. 203; Fara, 2009, p. 341–343). In this case, experimental evidence was crucial for the emergence of a whole new research field.

Chemistry: Robert Boyle was greatly influenced by Francis Bacon and his view that investigations should begin by collecting as much empirical data as possible and then trying to explain the observations, and not by first having an idea and then looking for evidence to support it. Boyle believed that everything was made up of matter in motion, and he used air-pump experiments to establish a number of claims about the constitution and nature of the air. Boyle, and his assistant, Robert Hooke, built the first working air pump in the late 1650s. Although there were several technical problems and although Boyle knew that it was not self-evident that the way the air behaved inside the pump accurately reflected its natural behavior, he produced detailed reports of his observations during the experiments. He also carried out his experiments in public so that people could witness the results. On the basis of these experiments, Boyle argued that the air was made up of spring-like particles and that it was because of their properties that the air could resist any force exerted on it and later expand when the force was removed. Again, experimental evidence was important for advancing a new field, though even Boyle himself was skeptical about what might be inferred from his experiments (Bowler & Morus, 2005, p. 37, 44–45, 60; Fara, 2009, p. 161).

Geology: Experiments are not the only way to obtain empirical evidence. In the 1660s, Robert Hooke (and anatomist Nicholas Steno) correctly identified fossils as the remains of organisms. At that time, it was thought that fossils were just stones that had somehow come to look like organisms. Hooke successfully showed that fossil wood was similar to its modern equivalent under the microscope. He also noted the appearance of fossils within layers of rock that seemed to have been deposited under water, although they were actually exposed on dry land. One possible explanation for such observations had been that all the sedimentary rocks were laid down from sediment created during Noah's flood. However, Hooke had noticed that a whole sequence of events seemed to had taken place and formed the structure of the Earth's surface. The characteristics of the strata gave the impression that they had been extensively transformed after being laid down. Hooke even postulated earthquakes that had raised new areas of land from the bottom of the oceans to the surface. The observation that fossils seemed to represent organisms that were no longer alive raised the possibility that species might have become extinct in the course of time (Bowler & Morus, 2005, p. 106–108). In this case, careful and detailed observation provided new insights crucial for understanding the history of life.

Physics: Albert Einstein suggested in 1907 that his theory of relativity might be expanded into a theory of gravitation. This theory and its implications were fully worked out in 1915. Einstein noted that his theory was open to empirical confirmation, having already demonstrated that it could be used to account for anomalies in the orbit of Mercury, which could not be explained by the Newtonian gravitational theory. Arthur Eddington attempted to test this theory and, in particular, Einstein's prediction of light bending in a gravitational field. He aimed to use the 1919 solar eclipse in order to photograph the positions of stars around the Sun's corona that would normally be blocked by its light. By comparing these positions to those the stars appeared to occupy when the Sun was not in their part of the sky, he expected to determine whether the Sun's gravitational field caused light to bend. The results supported the general relativity theory, although not immediately and not as conclusively as Eddington had suggested (Bowler & Morus, 2005, p. 263–264; Fara, 2009, p. 298–299). No matter how well Einstein's theory was established in theoretical terms, it could become widely accepted only after empirical evidence would have been obtained through observation.

The common, underlying idea in these historical examples is that empirical evidence is crucial in order to support, and later establish, theoretical claims. No matter how logical or sophisticated one's claims are, they can be widely accepted only insofar as adequate evidence is found that supports them. This, of course, is not a linear or straightforward process, and contradictory evidence may always be found. Yet only empirical evidence, ideally stemming from independent sources, can suffice to establish theoretical claims in science.

HISTORICAL EXAMPLES DEMONSTRATING THAT THERE ARE SHARED METHODS BUT NO STEP-BY-STEP METHOD USED BY ALL SCIENTISTS

Although there certainly are some common features in the practice of science, there is no universal, step-by-step scientific method. Of course, at some point in any investigation, scientists will "define the problem," "form a hypothesis," "test the hypothesis," "make conclusions," and "report results." The examples that follow show that doing science is a mixture of performing standard processes, such as doing experiments, interpreting the experiments of others, and making careful observations. However, quite often, scientists come to conclusions in highly personal ways.

Biology: In 1953, James Watson and Francis Crick proposed the double-helical model of DNA, without doing a single experiment themselves. Instead they interpreted, appropriately, the experimental evidence accumulated by other researchers. Erwin Chargaff had earlier shown that any DNA molecule contained equal proportions of adenine and thymine, as well as of guanine and cytosine. John Griffith had pointed out that adenine and thymine, as well as guanine and cytosine, could fit together, linking up through hydrogen bonds. Maurice Wilkins and Rosalind Franklin had performed X-ray diffraction studies of DNA, suggesting a spiral arrangement of the molecule. In many ways, the photographs taken by Franklin were the key piece of evidence that Watson and Crick combined with the earlier findings to come up with the model of the double-helix structure of DNA. They built actual models of the molecule, having been inspired by Linus Pauling's model-building of molecules. They were lucky and insightful, and eventually they came up with an appropriate model, although it took several years and many other scientists to work out all the details (Bowler & Morus, 2005, p. 206–297; Fara, 2009, p. 375–381). Overall, Watson and Crick proposed the model of the double helix for the structure of DNA by relying on evidence accumulated by other researchers.

Chemistry: In 1911, Ernest Rutherford announced his model of the atom, based on his experiments on radioactivity. He had been investigating how alpha particles were scattered when passed through thin metal foil. In the course of the experiments, it seemed that some of these particles bounced back off the metal foil. Rutherford believed that this was the result of the encounter between the alpha particles and a large, concentrated positive charge. Hence, he suggested that the atoms were made up of a relatively large, positively charged core, the nucleus, surrounded by a number of relatively small orbiting electrons. However, in this model the electrons should be radiating energy and losing momentum, and so atoms should not exist for very long. This problem was solved by Niels Bohr, who based his work directly on Rutherford's model. During 1913, Bohr suggested a model of atomic structure similar to Rutherford's, which he combined with Max Planck's concept of the quantum. According to Planck, changes in energy were not gradual but occurred in discrete packets, or quanta. According to Bohr's model, the electrons could occupy only particular levels of orbital energy. Thus, electrons were not radiating continuously but released their energy in distinct packets of energy with particular frequencies (Bowler & Morus, 2005, p. 258–259; Dear, 2006, p. 142–147). In this case, Bohr advanced the work done by Rutherford by working further on it, both theoretically and experimentally.

Geology: Alfred Wegener was the first to develop a theory to explain the apparent fit between the coastlines of Africa and South America. For Wegener, the older contraction mechanism of mountain building through cooling was insufficient. In addition, it had been found that continents were not made by the same material as the ocean floors. Therefore, another mechanism should have been at work. Wegener thought that horizontal movements of the continents could provide an alternative explanation. In 1915, he proposed his theory of continental drift, in which he suggested that there once had been a single supercontinent, Pangaea, which very gradually drifted apart into recognizable continents. The evidence he used to support this theory was the significant similarities between the fossil records and geological formations on either side of an ocean, such as between the strata of Africa and Brazil. He also pointed out that his theory could explain the historical patterns of glaciation far away from the poles (Bowler & Morus, 2005, p. 238–242; Fara, 2009, p. 385–389). In this case, evidence was crucial in proposing a new explanation for particular observations. Although the apparent fit between the two continents made this explanation very plausible, additional evidence was required in order for it to become accepted.

Physics: At the beginning of the 1920s, it was widely accepted that the universe was dominated by the Milky Way Galaxy. Despite evidence to the contrary, Edwin Hubble managed to show that nebulae like the Andromeda Nebula (or Andromeda Galaxy) could not be part of the Milky Way Galaxy. Previous studies had identified a constant relationship between the period (the time between instances of highest luminosity) of a Cepheid variable (a particular class of star) and its luminosity. Hence, measurements of this period could be used to calculate its absolute luminosity, which—when compared with its apparent luminosity (how bright it appeared in the night sky)—could eventually be used to approximate its distance. This was possible because, when comparing different objects with the same absolute level of brightness, the less bright the object appears, the farther away it is. Hubble identified a Cepheid variable in the Andromeda Nebula and calculated its approximate distance, using the calculations of Henrietta Leavitt (almost a million light years; we now know that it is even farther away). The results suggested that it was too distant to be part of the Milky Way Galaxy. This gave rise to the "island universe" model (Bowler & Morus, 2005, p. 283–284; Fara, 2009, p. 390–391).

Watson and Crick obtained no evidence by themselves but based their conclusions exclusively on work done by others. The work of Bohr was not only based on, but also advanced in many ways the work of Rutherford. Wegener advanced an idea that seemed obvious but worked for years in order to obtain supportive evidence, whereas Hubble advanced an idea that seemed contrary to the available evidence and soon managed to show that he was right. These examples demonstrate that there is no single, step-by-step method for doing science and that science is done in a unique and personal way.

HISTORICAL ILLUSTRATIONS TO SHOW THAT LAWS AND THEORIES ARE DISTINCT AND NOT HIERARCHICALLY RELATED KINDS OF SCIENTIFIC KNOWLEDGE

One common misconception about science is that theories gradually mature until they become laws, which suggests that laws are superior to the theories that preceded them. Laws and theories are related, but they are distinct kinds of scientific knowledge. Laws are generalizations or patterns in nature, whereas theories are explanations for why such laws operate in the way they do (McComas, 2004). It is a common misconception that, with time and evidence, theories become laws. As a note of caution, the label given to an idea, whether "law" or "theory," is not always indicative of its true nature.

Biology: Gregor Mendel is widely known for setting the foundations of genetics. Following the results of many breeding experiments, Mendel was ready by 1865 to present his conclusions, which we now know as "Mendel's laws." Almost every biology textbook presents the "law of segregation" and the "law of independent assortment" as examples of the conclusions that Mendel reached, although we now know that there are numerous exceptions. However, within limits, these laws permit accurate predictions. The distinction between laws and theories is particularly clear in this case, as Mendel was not able to provide a theory that would explain his observations and why his laws held. He talked about characters running through generations, but he had no idea of the gene as the explanation for his observations in inheritance. An interesting possibility is that Mendel was not actually trying to develop a theory of heredity. Rather, he focused on the study of hybridization in plants (Bowler & Morus, 2005, p. 196–198; Fara, 2009, p. 340–341). It should be noted that several theories of heredity were proposed during Mendel's life, all of which were developed in an evolutionary perspective, contrary to what Mendel was doing (Kampourakis, 2013).

Chemistry: Dimitri Mendeleev is famous for coming up with the idea of the periodic law (although he was not the only one to do so), which led to the invention of the periodic table. Initially, he thought of arranging the elements, such as copper, silver, and gold, according to their chemical properties. Then he thought that it would also make sense to arrange the elements in the order of their atomic weights (which were possible to measure although the structure of atoms was unknown at the time). However, this way of arranging elements did not work well. Instead of changing his hypothesis, Mendeleev "changed" the data. He suggested that some atomic weights had been measured wrongly. He therefore slightly rearranged the order of the elements to make them fit in the pattern that he had conceived, so that elements with similar properties would lie underneath one another in the columns of the table. This left gaps in the table for other elements that were not yet discovered at that time, the properties of which were possible to predict. Such elements were discovered later on and confirmed Mendeleev's predictions. Mendeleev's idea was entirely confirmed in the 20th century when the atomic theory was developed and it was shown that the properties of an element depended on its atomic number (the number of protons in its nucleus), whereas its atomic weight depended on the total number of protons and neutrons in its nucleus. The modern version of the periodic table ranks the elements in order of increasing atomic number, all elements in the same column having the same number of free electrons (Fara, 2009, p. 330–332). Mendeleev described a law that he could not explain in detail and which was later explained by the atomic theory.

Geology: Harry Hess proposed that ocean ridges were areas where molten rock welled up from the interior of the Earth. According to this "seafloor spreading" model, the hot mantle material spreads out, with the youngest rocks becoming solidified next to the ridges and the oldest rocks, laid down millions of years earlier, found farther away from the ridges. This model of seafloor spreading was strengthened by the observation of patterns of magnetism that had been revealed on the seabed, particularly through the existence of parallel stripes of normal and reversed magnetism alongside the mid-ocean ridges. As new rock welled up, it was imprinted by the current direction of the magnetic field of the Earth. When this field reversed, a new strip of reverse-magnetized rock would begin to form that would push the initial strip away from the ridge. This evidence, coupled with a comparison of fossils in West Africa and eastern South America, gave rise to the unifying explanation for all of these phenomena—the theory of plate tectonics—proposed by Fred Vine and Drummond Matthews (Bowler & Morus, 2005, p. 247–249; Fara, 2009, p. 388). In this case, the laws of physics formed the basis for supporting the theory of plate tectonics.

Physics: In 1687, Isaac Newton's work commonly known as the *Principia* was published, in which he proposed and established the inverse square law of gravity and the three laws of motion. He also established that the same kind of force was responsible both for maintaining the Moon in its orbit and for causing the acceleration of falling bodies at the surface of the Earth. However, although Newton had established the existence of these laws, he had no theory to explain why phenomena were taking place in the way described by them. For example, Christian Huygens accepted the existence of the inverse square law of gravity, but he thought that it was the task of natural philosophy to also explain it in mechanical terms. Newton knew that he was unable to do this and defended his work by saying that the demonstration of the existence of universal gravity to a near mathematical certainty was enough. For him, natural philosophy was a matter of establishing knowledge of natural effects, not necessarily of specifying the causes. Eventually, the fact that no one could properly understand Newton's gravitational forces was not an obstacle to their acceptance because they proved useful (Bowler & Morus, 2005, p. 46–48; Dear, 2006, p. 36–37). In this case, laws were established and were accepted although there was no theory available to explain them.

USING THE HISTORY OF SCIENCE TO SHOW THE CREATIVE ASPECT OF SCIENCE

Scientific knowledge may often be presented as a set of facts and conclusions, but it involves a dynamic and exciting process that leads to such knowledge. Scientists apply creativity through their questions, methods for investigation, and inspirations that lead from evidence to conclusions. This is illustrated in the cases in which scientists were inspired by simple analogies to provide novel explanations for particular questions.

Biology: In 1859, after considering a vast body of evidence for many years, Charles Darwin published his theory of evolution by natural selection. One crucial argument in support of natural selection came from an analogy between "natural" and "artificial" selection. The production of artificial varieties (such as fancy colors in pigeons) by breeders was a case in which major characteristics in animals were observed to change selectively from one generation to another. The study of animal breeding helped Darwin realize that the individual variation existing in animal populations could be used as raw material by breeders, who created new varieties using artificial selection. They selected individuals that happened to possess the traits of interest, allowing only those to breed while rejecting the others. Darwin thought that something similar might take place in nature. Through a process similar to artificial selection, natural selection, individuals that were better adapted might survive in a given environment, whereas individuals that were not well adapted might be eliminated (Bowler & Morus, 2005, p. 146–147; Dear, 2006, p. 97). As is obvious in this case, analogical thinking is a highly creative act. Animal breeding, both as a hobby and for economic purposes, was a popular endeavor in Britain at that time. Many people were involved in it, but only Darwin perceived the analogy between artificial selection and natural selection.

Chemistry: Antoine Lavoisier insisted on the importance of empirical, quantitative data for doing chemistry. He insisted that, as in physics, only experimental evidence could form a basis for the claims of chemists. Central in this new approach to chemistry was the creative development of a new chemical nomenclature in 1782, which Lavoisier and his colleagues claimed was based on direct experience and observation. According to this system, the simplest substances should be given simple names, whereas the chemical compounds should have more complex names to indicate the simpler ones from which they were formed. The main aim behind this nomenclature was to summarize the chemical experience of making or using each substance. For instance, sulfate of iron and sulfate of nickel were the compounds produced by the reaction of sulfuric acid with iron and nickel, respectively. Similarly, Lavoisier wanted to give simple names to substances that seemed to be absolutely simple. In this case, he relied on their properties and reactions. For instance, hydrogen got its name because its combustion produced water (Greek *hydor*), whereas oxygen got its name because its combustion with metals or carbon was thought to produce acids (Greek *oxy*). Lavoisier's highly creative act influenced chemistry after that time (Bowler & Morus, 2005, p. 67–71; Dear, 2006, p. 72–76).

Geology: As already mentioned, in 1915 Alfred Wegener suggested a theory of continental drift whereby continents moved away from or toward each other, giving rise to oceans or mountain ranges, respectively. To explain his model, he used an analogy with a newspaper torn into fragments. Wegener suggested that if the fragments could be reassembled so that the words on the paper could join up to make coherent sentences, it would be compelling evidence that the fit of the pieces was correct. Hence, in geological terms, if continents that were far apart seemed to fit each other when joined together—both in terms of shape and in light of other evidence (e.g., paleontological)—as, for example, Africa and South America do, it would show that these continents are fragments of a larger continent (in this case, Pangaea) that underwent a breakup sometime in the past. Unfortunately, although Wegener had produced a model that was very intuitive and simple, he offered no underlying mechanism to explain how this might work and so it was not accepted at the time (Bowler & Morus, 2005, p. 238–244; Fara, 2009, p. 385–389).

Physics: In 1824, Nicolas Sadi Carnot explained what happened in a steam engine as the result of the transfer of caloric (a fluid with which heat was associated) from one part of the engine to the other. In particular, Carnot suggested that what was important was the movement of caloric from a hot to a cold body, not its consumption as had previously been thought. The caloric that was developed in the furnace incorporated itself with the steam and was carried in the condenser that was above. There, the caloric was transferred from the steam to the cold water, which was thus heated. Hence, throughout the process, the steam was only a means of transporting the caloric. This idea was based on an analogy of the water movement in the water mills that Carnot's engineer father had studied. In a water-powered mill, water did work by falling from one level to a lower one. Hence, water was conserved while producing work. Carnot, in a creative leap, thought that in a similar manner caloric (which was then considered a fluid) did work in a heat engine by falling from one temperature to a lower one (Bowler & Morus, 2005, p. 82–83).

USING THE HISTORY OF SCIENCE TO DEMONSTRATE THE SUBJECTIVE COMPONENT OF SCIENCE

Science, like all human activities, has a subjective component. Two scientists looking at the same data may interpret it differently because of their prior experiences and expectations. This does not make science less rigorous or useful, because the results must be discussed, debated, and confirmed within the wider scientific community in order to gain acceptance. However, quite often scientists are subjective in their decisions as they reach conclusions to confirm preconceived ideas.

Biology: Spontaneous generation, the idea that life could emerge from inanimate matter, was widely accepted in the 18th century. Georges-Louis Leclerc, Comte de Buffon, one of the most influential naturalists of his period, accepted spontaneous generation. In 1778, in his *Epochs of Nature,* he suggested two particular episodes of spontaneous generation in the course of the Earth's history, one to produce the creatures living in the early, hot conditions of the Earth and the other to produce the ancestors of the modern forms. The issue of spontaneous generation was resolved less than a century later by Louis Pasteur, through a series of debates with the materialist physician Felix Pouchet. In a series of experiments, Pasteur showed that in all circumstances when the experimental apparatus was properly sterilized and contamination from the environment was prevented, no organisms appeared. What was initially seen as spontaneous generation was in fact the result of the contamination of the experimental apparatus by microorganisms coming from outside. However, Pasteur's motivations were not solely scientific. He was a conservative Catholic who aimed to counter the arguments of the radical materialist Pouchet. In a sense, Pasteur did not aim to discover what was going on but, rather, to confirm a conclusion he had already arrived at subjectively and for nonscientific reasons. Ironically, it was eventually concluded that both were right, given that boiling kills most microorganisms but also that some can nevertheless survive by forming spores (Bowler & Morus, 2005, p. 135–136, 447–448; Fara, 2009, p. 305–306).

Chemistry: Joan Baptista van Helmont thought that water was the only element in nature, contrary to the prevailing view that everything was composed of one or more of four elements (air, earth, fire, water). Van Helmont is famous for an experiment that nowadays would be considered as providing evidence for photosynthesis. In 1649, he planted a willow tree in 200 pounds of dried soil and regularly nourished it with distilled rainwater. In the course of five years, the tree grew in weight from 5 to 169 pounds, while the weight of the soil remained the same. However, from this experiment, van Helmont concluded that the increase in size and weight of the tree had been exclusively due to the water added. Van Helmont performed this experiment to support his claim that water was the only element in nature and did not consider any other explanation for what he observed (Bowler & Morus, 2005, p. 59).

Geology: James Hutton and Charles Lyell are considered the founders of uniformitarianism, the view that considered the Earth's history as a cycle of slow, gradual changes and that ruled out any appeal to unknown causes. Hutton had been the first to insist, in 1795, that the processes responsible for forming the rocks had all occurred at the same rate as could be observed in his day. According to him, there was a perfect cycle at work in which the elevation of new land exactly balanced the destruction of the old land by erosion. However, Hutton's theory did not attract much attention. The uniformitarian model was revived in 1830–1833 by Lyell, who provided evidence of just how much change was actually occurring through the action of volcanoes, earthquakes, and erosion. He eventually rejected catastrophism as an explanation for the changes that the Earth had undergone and suggested that a long sequence of ordinary changes could have produced the observed effects, given enough time. It is interesting that both Hutton's and Lyell's motivation for setting up such a theory was their own religious beliefs. Both were deists who believed that a benevolent and wise God had designed a machine that could work forever without His involvement (Bowler & Morus, 2005, p. 120–122; Fara, 2009, p. 268–271).

Physics: Like most of his 17th-century contemporaries, Johannes Kepler was a Platonist and thought that the universe operated according to harmonic principles. Although he accepted Copernicus's idea that there were six planets including Earth, he was puzzled over why this *had* to be the case. To answer this question, Kepler thought that the number of planets might be related to the number of solid figures that could be constructed using Euclidean geometry (octahedron, icosahedron, dodecahedron, tetrahedron, and cube). He thought that if he nested these figures one inside the other—so that, in each case, the corners of the inner figure just touched the surface of the sphere surrounding the solid, and this sphere, in turn, just touched the inner sides of the surface of the next solid—he could define six spheres, one for the orbit of each planet. In this model, there was a magnetic soul—the Sun—that attracted and repelled the planets in order to control their paths. This idea was based on a mystical belief that the heavens must be governed by geometry. However, he later rejected this idea as he came to realize that the shape of the orbits of the planets was actually elliptical. Kepler thought that an imaginary line, joining the Sun to a planet moving in orbit around it, swept out equal areas at equal times. After this discovery and after trying several possibilities, he realized that each planet moved in its own elliptic orbit, rather than conforming to a specific geometric expectation (Bowler & Morus, 2005, p. 32–33; Fara, 2009, p. 135–137). Kepler had a Platonic view of the universe and was convinced that it should be true. Yet, he later rejected this subjective view in the light of empirical data.

USING THE HISTORY OF SCIENCE TO ILLUSTRATE THE HISTORICAL, CULTURAL, POLITICAL, AND SOCIAL INFLUENCES ON SCIENCE

Science is an enterprise that lies within society and, as such, both reacts to and is somewhat governed by societal norms and needs. The kind of research performed is best understood by considering factors such as history, religion, culture, and social priorities. The expense usually associated with scientific research, as well as the impact that its conclusions may have on society, make science a process that cannot be properly understood outside its context. Doing science not only involves having novel ideas or clever insights, but also depends on factors that have to do with the personality of the scientist and the societal context in which the work is done.

Biology: Charles Darwin had been considering the possibility of evolutionary change as early as 1839, but he hesitated to publish his ideas because he wanted to accumulate as much evidence as possible in support of them and because he was also concerned about the reaction of people with strong religious views (his own wife included), as they might consider his theory an insult to the established beliefs of the time. In 1844, a book titled *Vestiges of the Natural History of Creation,* anonymously published by Robert Chambers, caused an enormous public reaction, being the first book to instigate a widespread discussion of evolutionary issues. This reaction made Darwin concerned, and he realized that if he published his work, it would be compared to the (largely speculative) theory presented in the *Vestiges.* Therefore, it was crucial for Darwin to establish his theory on solid grounds, and also to let the instability subside. So, in 1844, Darwin wrote a sketch of his theory and also shared his views with Joseph Dalton Hooker in a letter that he wrote in the same year. Darwin later changed his mind and gradually started working on a big treatise that he intended to call *Natural Selection.* However, a letter of June 1858 from Alfred Russel Wallace, who discussed the mechanism of evolution in ways that looked similar to Darwin's, forced Darwin's decision to publish his views. He immediately started writing an extended version (what he called an "abstract") of his theory that was published in November of 1859 as the *Origin of Species* (Bowler & Morus, 2005, p. 147–149; Fara, 2009, p. 277–280). It should be noted that Darwin's theory was not complete before 1857, and there were several differences between the version in the *Origin* and earlier conceptualizations. Darwin was diligently accumulating evidence in support of his theory for years, but social factors played a crucial role both in his hesitance to publish his ideas and, finally, in encouraging him to proceed to publication.

Chemistry: The importance of social status in the pursuit of science is illustrated by the case of Antoine Lavoisier. The independently wealthy Lavoisier had established a reputation as a chemist by performing a series of experiments on the nature of the air. In 1775, he was appointed as commissioner to run the gunpowder industry, and he set up his laboratory in the Paris Arsenal. On the basis of his work there, he established the superiority of the model of combustion to the phlogiston theory and gave oxygen its name. It was also there that he carried out experiments on respiration, in collaboration with Pierre Laplace, and concluded that animals maintained their body temperature by the conversion of oxygen into "fixed air" (an old name for carbon dioxide), in the same way that charcoal gave off heat when it burned. In parallel with all this activity, Lavoisier was a tax collector and lawyer. Because of his financial dealings, after the

French Revolution he was considered a wealthy landowner who exploited the poor, and so he was executed in the guillotine. Thus, the career and the life of an influential chemist was terminated for political reasons (Bowler & Morus, 2005, p. 67–71; Fara, 2009, p. 209–213).

Geology: Although Alfred Wegener, as we already described, suggested the theory of continental drift as early as 1915, it was not given much attention until the early 1960s. His critics rejected Wegener's theory because it had implications that contradicted much of the available evidence, which in turn seemed to support other types of explanations. However, this was not the only reason for the criticisms. They also arose from the fact that Wegener was an outsider to the community of professional geologists and was considered not to have paid his debts in the field. Wegener was a geophysicist and meteorologist, and he was likely seen as trying to enter a territory claimed by others. His proposal was widely rejected and, in some cases, even ridiculed; he was depicted as an uncritical enthusiast who had surveyed the literature to find support for his claims and ignored several arguments to the contrary (Bowler & Morus, 2005, p. 244).

Physics: The importance of social factors, especially of patronage, to the practice of science is clearly seen in the case of Galileo, Brahe, and Kepler. By 1609, Galileo Galilei had discovered four new planets through his newly improved telescope. He named the planets *Medicean Stars* and dedicated his book to the Grand Duke Cosimo de Medici of Tuscany in an attempt to attract his patronage. Galileo's reward was a major change in status: he was made professor of philosophy at the University of Pisa and was appointed court philosopher and mathematician to Cosimo. Tycho Brahe was the son of an influential member of the Danish court. Hence, he was not only in the position to finance his career in astronomy but also received support from the Danish crown. Moreover, Brahe worked for Emperor Rudolph starting in 1599. Following his death in 1601, Johannes Kepler succeeded Brahe as Rudolph's mathematician and inherited his astronomical instruments and the even more precious observational records. Kepler named his set of planetary calculations the *Rudolphine Tables* in order to honor his patron (Bowler & Morus, 2005, p. 29–32; Fara, 2009, p. 132–138). These examples highlight the importance of aristocratic and royal patronage for sustaining astronomical work.

SCIENCE, ENGINEERING, AND TECHNOLOGY INFLUENCE EACH OTHER BUT ARE NOT THE SAME

The questions investigated by science are either related to particular practical needs or aim at a fundamental understanding of nature. We now usually distinguish between science, engineering, and technology and describe the ways in which they affect each other. There are cases in which scientific advancements improved technology, but what is even more interesting is how technological advancements supported the advancement of science. The key issue of concern is that students see both the relationship and the distinctions between technology, engineering, and science and recognize the discrete roles played by each. It would be unfortunate, for instance, if students were to confuse as too similar the basic knowledge-seeking rationale of science with the application and problem-solving rationales that guide engineering and technology. The goals and rationales of science are simply not the same as those for engineering and technology.

Biology: Robert Hooke was one of the early microscopists, and the one who coined the term "cell." In 1665, he published *Micrographia,* the first substantial book on microscopy that brought the small-scale world into attention. However, the nature and function of cells remained a mystery until the 19th century, when improved microscopes allowed a more fine-grained analysis of the structure of tissues. This led to the cell theory, that tissues were made up by cells, proposed by Matthias Jakob Schleiden in 1838 for plants and extended a year later by Theodor Schwann to animals. In his *Microscopical Researches,* published in 1847, Schwann provided microscopic studies of cells and their nuclei and showed that every tissue, animal, and plant was composed of cells. From these observations, he argued that the cell was the basic unit of life. In 1855, Robert Remak showed that cells were formed by a process of division initiated in the nucleus. In 1858, Rudolph Virchow provided the final element to the cell theory: that the cell is the basic unit of life, and that each new cell is formed only by the division of preexisting cells (Bowler & Morus, 2005, p. 172–173; Fara, 2009, p. 160–161). The detailed study of cells was therefore highly dependent on the technological advancement of microscopes.

Chemistry: Johann Becher performed chemical investigations into the origins of minerals with the hope of finding new ways of exploiting relevant resources for economic gain. In his *Physica Subterranea* (1667), he suggested that minerals were made up of three types of earth: mercurous earth, fatty earth, and vitreous earth. When a substance was burned, he supposed that the fatty earth was liberated, a conception that formed the basis of Stahl's phlogiston theory. Becher's ideas and experiments on the nature of minerals and other substances were also published in his *Physica Subterranea.* His research into the theory of mineral production was an effort to improve mining technology for the benefit of the state. Through his attempt to improve a specific technology and to better understand the origins of minerals, a better understanding of the natural world also emerged (Bowler & Morus, 2005, p. 60–61).

Geology: During World War II, Patrick Blackett helped produce an extremely sensitive magnetometer for the detection of magnetic mines. He later used this device to trace minute magnetic fields locked into the rocks of the crust of the Earth. It was assumed that these fields had been imprinted onto the rocks when they were formed, and so by measuring them one could produce a record of the Earth's magnetic field through geological time. As soon as details of the remnant magnetism (paleomagnetism) from rocks in different areas were compared, it was made clear that they were not aligned with the current state of the Earth's field or with each other. This meant either that the rocks had moved since their formation or that the magnetic poles of the Earth had shifted. The most likely explanation was that the continents had moved from the position they had occupied in earlier geological periods, given that the remnant magnetic fields were different in rocks coming from different parts of the world (Bowler & Morus, 2005, p. 246–247). In this case, a technology developed for war purposes eventually provided evidence for one of the most important developments in modern geology.

Physics: Fearing that the Nazis were working on an atomic bomb, the British made the first moves toward its design. By 1939, it had become clear that the only way to derive significant amounts of energy from the breakup (fission) of radioactive atoms was by starting a chain reaction. Some radioactive elements, such as uranium-235 and the artificial element plutonium, liberated neutrons that, in a quantity that exceeded a critical mass, could produce a chain reaction. If this were done without control, a vast amount of energy would be liberated in the form of an explosion. The central problem was what that critical mass should be. In 1940, two German scientists, Otto Frisch and Rudolf Peierls, who had been working in England, calculated that the critical mass should be about 5 kg. However, there was, as yet, no way of extracting this amount of fissionable material from natural sources. Hence, a way of extracting uranium-235 in quantity was required. However, it was suggested that given the threat of German invasion in England, the actual production should be done in the United States. The US administration's key scientific advisers, Vannevar Bush and James B. Conant, were convinced that the program was likely to be successful, so President Roosevelt approved funds for research. In 1942, Enrico Fermi, who during World War II escaped from Italy to work in the United States, soon built a reactor and initiated a controlled chain reaction. One function of the reactor was to convert uranium-238 into plutonium, another potential fissionable material for a bomb. Research went ahead with the aim of making bombs with both uranium-235 and plutonium, at the start of what became known as the Manhattan Project. Meanwhile, Robert Oppenheimer began the design of the bomb. As technical problems emerged, a closer cooperation between the theoretical physicists and the engineers was required. Hence, in a sense, the Manhattan Project was changing the way in which science was done, requiring scientists to engage in close cooperation with military and industrial engineers (Bowler & Morus, 2005, p. 471–479; Fara, 2009, p. 370–374) in work that was complementary but not the same, either in practice or in underlying philosophy. It is important that students understand this distinction.

Scientific Knowledge is Tentative but Durable and Self-Correcting

The logical and careful knowledge-generation process of science is an effective way to study the natural world, and the scientific conclusions formed in this fashion are usually long-lasting and useful. One of the hallmarks of science, however, is its ability to remove incorrect ideas in favor of ones that are more accurate and, thus, even more useful.

Biology: Jean Lamarck was a French naturalist who made important contributions to invertebrate taxonomy and proposed the first theory of evolution in 1809. He believed that a process of progressive adaptive evolution was at work and that organisms were always changing into something else. Georges Cuvier ridiculed Lamarck's evolutionary theory, arguing that the structure of each species was so carefully balanced that transitional forms would not be able to survive. However, it was Cuvier's anatomical work and study of fossils that eventually provided evidence for evolution. Cuvier focused on the internal structure of organisms and showed that seemingly very different organisms shared crucial similarities. He also showed that extant organisms were similar to extinct ones found in the form of fossils, as e.g. he demonstrated that mastodons and mammoths were similar to but distinct from modern elephants. Finally, he also showed that the older a rock was, the more unfamiliar were the fossil organisms found in it. Eventually, proponents of evolution, including Charles Darwin, relied a lot on Cuvier's conclusions to support the idea that species have evolved through time (Bowler & Morus, 2005, p. 136–138; Fara, 2009, p. 275–277). The data that were initially thought to question the idea of evolution eventually came to its support.

Another wonderful example of this NOS aspect is found in the story of a misidentified fossil tooth, as told by Stephen Jay Gould (1991) and by paleontologist Donald Prothero (2007). In 1917, an odd-looking and fragmentary tooth discovered in a rich Miocene bone bed in western Nebraska was sent to Henry Fairfield Osborn at the American Museum of Natural History in New York, who somewhat quickly suggested that it might be the tooth of an anthropoid ape. This was not as bizarre an idea as one might think, given Osborn's prediction that ape-like ancestral humans might have migrated from Asia with Miocene-age animals. Despite doubts, he published the specimen as *Hesperopithecus haroldcookii* in 1922. The tabloid *Illustrated London News* picked up the story and even published a reconstruction of an ape-man who had presumably lost the tooth millions of years earlier. The story of "Nebraska Man" was born and passed quickly from science into the popular sphere. The reason that we no longer talk about Nebraska as a site of human origins is that after study of additional fossils, the tooth was soon found to be that of a peccary, a pig-like animal. Although at many levels peccary and human teeth are quite similar, a mistake is still a mistake. A paper correcting it was published by Osborn colleague William King Gregory in 1927, and the tooth was quickly forgotten by those interested in human origins. Unfortunately, creationists got involved and trumpeted the error as a major faux pas on the part of scientists, evidence—for them—that science can't be trusted and that there are no valid human fossils. Sadly and frustratingly, creationists never use this story to demonstrate that, although scientists do make mistakes, science itself will correct them. The Nebraska Ape is a wonderful story of the self-correcting nature of science and provides clear evidence that scientific ideas that survive the test of time are worth accepting.

Chemistry: Georg Stahl developed his theory of phlogiston in the early 18th century to explain why certain metallurgical processes work. According to this theory, pure metals were the result of the combination of metal ores with phlogiston during the heating process. Phlogiston was a hypothetical substance that was supposed to leave a burning object. By about 1770, Lavoisier was convinced that the air must also play a role in this reaction. In 1772, on the basis of his experiments, he suggested that heating metal in air led to the production of a calx (a combination of metal and gaseous material) and liberated phlogiston in the form of heat. On the basis of his experiments, Lavoisier hypothesized that the main process during combustion was the combination of the burning substance (e.g., metal) with aerial matter, which was why the substances increased in weight. By the same year, Carl Scheele suggested that air was a mixture of two substances, one that prevented burning and one that promoted combustion. In 1774, Joseph Priestley found that when red calx of mercury was heated, an air that seemed to contain little or no phlogiston at all was produced. This was termed "dephlogisticated air" because it contained little or no phlogiston. By 1775, Lavoisier refined Priestley's account and argued that it was dephlogisticated air (which he called "oxygen") that played the key role in combustion. In introducing oxygen, Lavoisier led to the abandonment of the phlogiston theory (Bowler & Morus, 2005, p. 63–64, 67–69; Dear, 2006, p. 77–78). The replacement of the phlogiston theory by the oxygen theory is another example of the tentative and self-correcting aspect of scientific knowledge.

Geology: During the late 18th century, Abraham Werner promoted the "Neptunist" idea that land was exposed because a vast ocean that once covered it had gradually diminished in depth. Werner assumed that as the ocean dried up, the chemicals in it were dropped out in a particular sequence and each type of rock was laid down in a particular period in Earth's history. As a result, erosion of the land surface would add a regular sequence of sedimentary rocks. Neptunism was widely accepted, and some scientists even tried to link it to Noah's flood. However, this theory was refuted by evidence that the same types of rocks could be laid down at different periods, and by the early 19th century it could no longer be sustained. Alexander von Humboldt viewed the power of volcanoes and earth movements when he studied the Andes Mountains; he and many others abandoned Neptunism and suggested that earth movements explained how the sedimentary rocks were elevated to form land (Bowler & Morus, 2005, p. 111–112).

Physics: In 1883, Heinrich Hertz performed experiments on cathode rays in order to determine whether they carry an electric charge. In one experiment, he separated cathode rays from ordinary electricity produced in a cathode tube and caused the cathode rays to enter an electrometer, but no electric charge was identified. In a second experiment, he introduced oppositely electrified plates into the tube to see whether the cathode rays were deflected electrically, but no deflection was produced. Hertz concluded that cathode rays carry no electric charge and, hence, are not composed of charged particles. A few years later, Joseph John Thomson showed that Hertz was wrong to assume that the air in the cathode tube was sufficiently evacuated to allow electrical effects to occur. Thomson concluded that the rays are indeed composed of electrically charged particles (later called "electrons"). He also experimentally measured their ratio of mass to electric charge by deflecting the cathode rays in a magnetic field and, later, in an electrostatic field. For his experiments with cathode rays, Thomson is credited with the discovery of the electron (Bowler & Morus, 2005, p. 254–257; Fara, 2009, p. 324; see also Achinstein, 2008).

SCIENCE CANNOT ANSWER ALL QUESTIONS

This is a rather difficult issue in the nature of science. This NOS idea may seem to include the questions that *science has not answered yet* (but may answer in the future), but it actually includes those that *science cannot answer* (because they fall outside its realm). There are questions that science cannot answer because no relevant evidence could be found or because the methods of science are simply not applicable. For instance, science cannot answer questions concerning the value of art (which painting is better than another?), morality (what is the correct moral choice?), or faith (which religion is the most valid?).

Biology: In 1848, Richard Owen proposed a basic pattern for all vertebrate animals, known as the *vertebrate archetype*. This was an idealized model of the simplest conceivable vertebrate, of which all real vertebrate species were adapted modifications. In this sense, primitive fish possessed the simplest modifications and humans the most. This offered a better form of the argument from design (the idea that organisms were artifacts designed by a wise and benevolent Creator), because it implied that such an underlying archetypal pattern could only have arisen in the mind of the Creator. It is interesting that Owen went so far as to define the concept of homology—the idea that the same combination of bones could be modified in different species adapted to different environments. However, despite this and the fact that he saw the successive expressions of the archetype as a progressive pattern unfolding through time, he did not consider the possibility of evolution and he insisted that each species was a distinct unit in the divine plan. It was Darwin who, drawing on a similar developmental model, elaborated his theory of branching evolution (Bowler & Morus, 2005, p. 139). Whether such a plan exists and what exactly God had in mind when he conceived it are questions that cannot be answered by science.

Chemistry: Joseph Priestley is famous for his "discovery" of dephlogisticated air (later called "oxygen" by Lavoisier) in 1774. Priestley believed that everything in nature had a role to play in order to maintain its economy. In particular, he believed that different "airs" played particular roles in the natural order. He regarded this as a proof of divine benevolence, a natural mechanism through which God kept the world in a state of equilibrium. But for a political and religious radical like him, this view of nature's economy had important political and social consequences. He thought that scientific instruments could help reveal the proper order of nature, on which the social order should then be based. But since there was something wrong with the prevailing social order, scientific instruments could also be used as political instruments to show how social injustices were at odds with nature (Bowler & Morus, 2005, p. 64). In other words, by using scientific processes, Priestley wanted to provide answers and solutions to social issues; but these fall outside the realm of the study of nature.

Geology: In 1812, Georges Cuvier published his study of fossil vertebrates, along with suggestive evidence for catastrophic earth movements and tidal waves. William Buckland, one of his followers in England, suggested that geology could provide evidence that Noah's flood had actually taken place. In 1823, he described a cave in the hills of Yorkshire that had been filled with mud, in which the bones of hyenas and their prey were buried. A universal flood was the only explanation for the fact that a cave in the hills had been filled in this way. In addition, this event seemed to have been accompanied by a climatic transformation, since no hyenas could be found in Europe. For Buckland, this was evidence of a catastrophic event that could fit in with the events described in the book of *Genesis* (Bowler & Morus, 2005, p. 116). But *Genesis* is not a scientific text; like any religious text, it may inform one's spiritual life but should not be read literally.

Physics: James Joule was interested in finding ways of quantifying the relationship between heat and work. The conclusion of his paddle-wheel experiments was that heat was literally turned into motive force in the process of producing work. For him, these experiments carried not only a scientific but also a theological message. He was convinced that his experiments were proof of the conversion of one force to another and of the conservation of force in general. In 1847, at a public lecture, he argued that conservation and conversion processes actually existed in nature. This was an explicitly theological argument, because what he actually claimed was that since God had created force and matter, neither of them could be lost or destroyed. Any apparent loss of force was simply the result of conversion of one kind of force to another, as happened in the paddle-wheel experiment with the transformation of work to heat (Bowler & Morus, 2005, p. 88–89). But although understanding whether energy is converted from one kind to another or is just lost is a scientific question, whether this reveals a divine plan is not a question that science can answer or even address.

Conclusions

NOS is a vital—some would say essential—element of science instruction. However, even with the support of documents like the NGSS in the United States and a growing understanding on the part of science teachers generally, it is difficult to couple NOS with traditional content. We have based this paper on an understanding that it is most likely that science teachers will be able to engage students in conversation about NOS only by interweaving such conversations with the standard content of the science curriculum. Therefore, we have endeavored to locate a variety of historical examples illustrating each major NOS idea for each of the major science disciplines (biology, chemistry, geology, and physics). We hope to encourage science teachers to blend the foundational knowledge provided by NOS with the expected science content and to do so explicitly and in context as recommended by decades of science education research. When teachers have a rich understanding of how the history of science can be leveraged to teach both historical and philosophical lessons, it will be possible to teach the expected science content while teaching about how science works.

Of course, the historical cases selected are not the only or the most appropriate ones to illustrate important NOS concepts. In fact, we would challenge our readers to add as many valid examples as possible from the history of science to enliven their teaching of the nature of science. But we wish to point out that because Mendel, Darwin, Newton, Joule, Lavoisier, Mendeleev, Wegener, Lyell, and many others are often mentioned in science textbooks, the rationale for discussing these key scientists should be clear (for the case of Mendel, see Campanile, Lederman & Kampourakis, 2015). Yet even their stories are rarely used explicitly to discuss NOS aspects. Our core argument is that even when drawing on only those historical figures mentioned in textbooks (see McComas, 2008a, 2008b), teachers should take the opportunity to use related stories to teach about NOS. We have provided here both a framework for the inclusion of NOS in science teaching and a collection of historical episodes that might prove useful for this purpose. Our hope is that we have encouraged science teachers to make these important connections with students and bring NOS and the history of science together in the classroom.

REFERENCES

Abd-El-Khalick, F. (2012). Examining the sources for our understandings about science: Enduring conflations and critical issues in research on Nature of Science in Science Education. *International Journal of Science Education, 34,* 353–374.

Abd-El-Khalick, F. (2013). Teaching *with* and *about* Nature of Science, and science teacher knowledge domains. *Science & Education, 22,* 2087–2107.

Abd-El-Khalick, F., & Lederman, N. (2000a). Improving science teachers' conceptions of Nature of Science: A critical review of the literature. *International Journal of Science Education, 22,* 665–701.

Abd-El-Khalick, F., & Lederman, N. G. (2000b). The influence of history of science courses on students' views of Nature of Science. *Journal of Research in Science Teaching*, *37*(10), 1057–1095.

Achinstein, P. (2008). Evidence. In S. Psillos & M. Curd (Eds.), *The Routledge Companion to Philosophy of Science* (pp. 338–348). New York, NY: Routledge.

Bell, R. L., Lederman, N. G., & Abd-El-Khalick, F. (1998). Implicit versus explicit Nature of Science instruction: An explicit response to Palmquist and Finley. *Journal of Research in Science Teaching, 35,* 1057–1061.

Bowler, P. J., & Morus, I. R. (2005). *Making Modern Science: A Historical Survey.* Chicago, IL: University of Chicago Press.

Campanile, M. F., Lederman, N. G., & Kampourakis, K. (2015). Mendelian genetics as a platform for teaching about Nature of Science and Scientific Inquiry: The value of textbooks. *Science & Education, 24,* 205–225.

Clough, M. P. (2011). The story behind the science: bringing science and scientists to life in post-secondary science education. *Science & Education*, *20*(7-8), 701-717.

Dear, P. (2006). *The Intelligibility of Nature: How Science Makes Sense of the World.* Chicago, IL: University of Chicago Press.

Fara, P. (2009). *Science: A Four Thousand Year History.* Oxford, UK: Oxford University Press.

Gould, S. J. (1991). An essay on a pig roast. In *Bully for Brontosaurus* (pp. 432–447). New York, NY: Norton.

Kampourakis, K., & McComas W. F. (2010). Charles Darwin and evolution: illustrating human aspects of science. *Science & Education*, *19*(6-8), 637-654.

Kampourakis, K. (2013). Mendel and the path to genetics: Portraying science as a social process. *Science & Education, 22,* 293–324.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of Nature of Science. *Journal of Research in Science Teaching, 39,* 551–578.

Lederman, N. G. (1999). The state of science education: Subject matter without context. *Electronic Journal of Science Education*, *3*(2). Retrieved from http://unr.edu/homepage/jcannon/ejse/ejse.html.

Lederman, N. G. (2007). Nature of Science: Past, present, and future. In S. K. Abell and N. G.

Lederman (Eds.), *Handbook of Research on Science Education* (pp. 831-880). Mahwah, NJ: Lawrence Erlbaum Associates.

McComas, W. F. (Ed.) (1998a). *The Nature of Science in Science Education: Rationales and Strategies.* Dordrecht, The Netherlands: Kluwer Academic.

McComas, W. F. (1998b). The principal elements of the nature of science: Dispelling the myths. In W. F. McComas (Ed.), *The Nature of Science in Science Education: Rationales and Strategies* (pp. 41–52). Dordrecht, The Netherlands: Kluwer Academic.

McComas, W. F. (2004). Keys to teaching the nature of science: Focusing on the nature of science in the science classroom. *The Science Teacher, 71*(9), 24–27.

McComas, W. F. (2008a). Proposals for core Nature of Science content in popular books on the history and philosophy of science: Lessons for science education. In Y. J. Lee & A. L. Tan (Eds.), *Science Education at the Nexus of Theory and Practice.* Rotterdam, The Netherlands: Sense.

McComas, W. F. (2008b). Seeking historical examples to illustrate key aspects of the nature of science. *Science & Education, 17,* 249–263.

McComas, W. F., Clough, M. P., & Almazroa, H. (1998). A review of the role and character of the nature of science in science education. In W. F. McComas (Ed.), *The Nature of Science in Science Education: Rationales and Strategies* (pp. 3–39). Dordrecht, The Netherlands: Kluwer Academic.

National Research Council (2012). *A Framework for K–12 Science Education: Practices, Cross-cutting Concepts, and Core Ideas.* Washington, DC: National Academies Press.

NGSS Lead States (2013). *Next Generation Science Standards: For States, By States*. Washington, DC: National Academies Press.

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What “ideas-about-science” should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40,* 692–720.

Prothero, D. R. (2007). *Evolution: What the Fossils Say and Why It Matters.* New York, NY: Columbia University Press.

Schwab, J. (1962). The teaching of science as enquiry. In J. Schwab & P. Brandwein (Eds.), *The Teaching of Science* (pp. 1–103). Cambridge, MA: Harvard University Press.