Chapter 3
Principal Elements of Nature of Science: Informing Science Teaching while Dispelling the Myths

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3.1 Introduction

Although the science education community is united in support for the inclusion of aspects of nature of science (NOS) in the science curriculum, some do not embrace the recommendations offered by proponents of the consensus approach. As discussed in Chap. 2, we feel that these objections may be reasonably addressed. Furthermore, in science and in science education – particularly on matters of curriculum design – consensus is the way to make decisions. We have reached consensus about the traditional science content that is the instructional focus in biology, chemistry, physics, and every other introductory school subject, and there is no reason why shared thinking would fail us now in defining what topics from the history and philosophy of science should be woven into the science curriculum. Consensus building regarding the importance of some NOS elements started years ago with suggestions offered by many of the pioneers in this field. To be sure, some of those early suggestions, such as teaching about the scientific method, have caused problems by misrepresenting the process of science. However, both science and science education are self-correcting enterprises, so the more recent suggestions for NOS content more accurately reflect how science functions, what its philosophical presuppositions are, and even the limits under which science operates.

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3.2 Suppositions and Assertions About NOS Framing This Chapter

Before discussing this set of NOS ideas in detail, it is important to be clear about several issues and misconceptions encountered when encountering any proposals for such content.

3.2.1 NOS Content Described as a Set of Learning Goals Is Offered to Drive Instruction, Not a List to Be Memorized

The NOS recommendations discussed in this chapter are offered as a set of learning objectives but are not a list to be memorized any more than one would want students simply to memorize the names of the parts of the cell without understanding the location, context, and purpose of those parts along with an appreciation of how knowledge of cell parts might be applied to biology knowledge generally. The goal of this book is to advance the conversation of how NOS should be taught and features the views of a variety of scholars offering a variety of approaches to support this goal.

3.2.2 Science Educators Are Not Philosophers of Science

While there are a few science educators who hold degrees in or related to the history and philosophy of science (HPS), most if not all science education experts, with interests in the HPS/NOS area, are not actively contributing to knowledge in the content of these areas. This admission is not a problem or even unusual. As we will see next, educators with expertise in science learning are often called upon to translate content into curricular recommendations.

3.2.3 Science Educators Must Work with Appropriate Experts to Define NOS Learning Goals

The recommendations found throughout this book and particularly those in this chapter are included with reference to what Chevallard (1989) calls "epistemological vigilance" and "didactical transposition." What this means is that those in science education with expertise in the domain of NOS have studied the history and philosophy of science, and other related areas have now accurately – or vigilantly in his words – interpreted and summarized findings from professionals in these fields. In turn, we have made recommendations for the HPS content that is most appropriate in school science settings. Next, this NOS-related content must be transposed (i.e., transformed) into learning objectives and curriculum models and recommended as teacher content knowledge and assessment goals. Since the advent of science as a school subject at all levels, educators have been engaged in this two-part task.

However, it makes no more sense for historians and philosophers of science to be the sole arbiters of what from their content domain enters the science curriculum as it does for a Nobel Prize-winning physicist to develop a middle-school physical science curriculum only with her colleagues. Expertise is shared by those who create and define knowledge and those who make recommendations about what and how to teach it. With NOS and with all science content, we offer recommendations with vigilance and then propose effective and engaging modes of transmission or transposition. Thus, NOS is a pedagogical construct designed to inform the introductory science curriculum at all levels. Therefore, when making decisions about what to include in school science, it is vital to consider a multitude of issues, including the readiness of students to learn at a given age, how packed the curriculum is with other content, how particular NOS content might be supported by packaging it with other topics, and so on. This does not mean that any conclusions about NOS should be declared final and off limits, but a constant churning is not productive in moving toward NOS inclusion as a curriculum goal.

3.2.4 There Is No One Right Way to Teach About NOS

It seems unnecessary to make this claim, but with the specter of list memorization as constant criticism, it is wise to make this a presupposition in this chapter. There are scores of chapters in this book each of which takes a different position about NOS instruction and that is as it should be. Teachers are the ones best poised to translate the NOS destination into an enjoyable voyage for students. If we consider the views of just two contributors to this book, we note that Clough (in 2007 and in Chap. 15) recommends teaching the NOS elements as questions and Allchin (2011) advocates engaging students in case studies (Allchin et al. 2014) featuring problem-solving opportunities showing science in holistic fashion he calls "knowledge of whole science."

3.2.5 We Expect the Focus of Instruction Is on Teaching About NOS

There can be no reasonable expectation that NOS learners in introductory school science experiences are going to become philosophers of science any more than we would expect all science learners to become scientists, and this expectation logically would impact the goals of NOS instruction. We do not want to "dumb down" or mispresent issues of NOS. But, when Kötter and Hammann (2017) remind us "there is a consensus in philosophy education that it is essential to teach knowledge about different positions and aspects – rather than a specific view…" (p. 461), this is a prime example of unshared expectations and a potential source of conflict.

School science is not a philosophy class; rather the goal is to teach students about the findings from the history, sociology, and philosophy of science. This is just as true for aspects of NOS as it is for aspects of chemistry. Learners are engaged in learning about chemistry; they are not chemists and do not learn all the content of chemistry by active inquiry as chemists do. This is true with philosophy too. When students major in the philosophy of science at the university level, they are engaged in *doing* philosophy of science and ultimately contributing to it. This is not be taken as any objection to having students think philosophically, but the goal of NOS in school is for learners to come to understand what we already know about how science works. If some want to teach this in a conflict-driven discovery fashion, that is fine but is not particularly efficient given the time available, the capabilities of students, and the overall goals of NOS instruction.

3.2.6 Science Education Is Self-Correcting

If some important aspects of NOS are missing from any proposed set of pedagogical recommendations, we can reopen the conversation about the inclusion of any omissions. If we make recommendations that advocate for factually inaccurate content, NOS included, we look forward to collaboration with content experts to assist in correcting such errors.

3.3 The Development of a Consensus View of NOS for School Purposes: An Introduction

We know that NOS is complex and not a single entity and contains some relatively complex sub-elements. It is very likely that someone could have robust understanding of some of the sub-elements of NOS (called here key NOS aspects) and struggle with others. It has been useful for decades to use the "nature of science" as a quick reference, but there are a very large number of elements that comprise a full understanding of NOS, and some choices must be made with respect to which of those elements ought to be part of the school science curriculum.

Since the advent of advocacy for the inclusion of NOS in the science curriculum, many proposals have been offered for what elements of NOS we should teach. Reviewing all suggestions would both be beyond the scope of this chapter and could confuse the issue since our view of the nature of science has changed through time and older views may no longer be valid. However, if we restrict this review to the "modern" period, we would revisit the pioneering works of Michael Martin (1972) and James Robinson (1968, 1969). We might even deconstruct many of the earlier NOS assessment tools and work backward to gain perspectives regarding what those at the time believed that students should know about NOS issues.

Perhaps one of the most useful and complete sets of NOS recommendations appeared as part of *Project 2061* (AAAS 1989) later codified in the remarkable two-volume set of *Atlases of Science Literacy* (AAAS 2001, 2007). These atlases provide very useful "road maps" of when and where elements of recommended science content, including NOS, should be taught in grade K-12 settings based on research of misconceptions and learner readiness. Detailed presentations on evidence and reasoning, avoiding bias, the nature of the scientific community, and relationship of science and society are among the topics addressed. The issue of NOS learner readiness and learning progressions is discussed in more detail in Chap. 4 of this book.

In a study comparing various suggestions made in the past few decades to describe elements of NOS that should be included in school science, Al-Shamrani (2008) found much overlap. Through the contributions of AAAS (1989, 2001, 2007), Lederman (1992, 1998), Lederman and Lederman (2004), McComas (1998, 2004, 2008), Osborne et al. (2003), and many others, there has emerged a robust set of elements, with some variation. The *Next Generation Science Standards* (Achieve 2013) – the major science standards document in the USA – has incorporated many of the shared notions that define NOS for instructional purposes. Therefore, it would be comforting to think that, at some level, we have decided on the focus within NOS that is best suited to guide classroom science instruction and related science teacher preparation. What has resulted from this work may be called the "key NOS aspects," "general NOS aspects," or a "NOS consensus view." Frankly, I would accept even the label "a pragmatic consensus views of NOS for science teaching and learning" to avoid any misrepresentation of the purpose of these recommendations. This certainly will not catch on because it results in an unwieldy acronym.

With both NOS and traditional science content domains, decisions must be made about what aspects to include and at what level or depth and complexity. As mentioned, there are many overlapping proposals for what elements of NOS should inform the science curriculum, but how could there be a method that would guarantee that this content is properly represented beyond the consensus that seems to have been achieved? We will continue to grapple with this reality and argue for inclusion and exclusion based on our knowledge of the potential NOS elements, our professional experiences with learners (i.e., what might they find interesting, what can they understand at particular age levels), the goals we hold for science instruction, an appreciation for teachers' abilities, the time constrains inherent in school, and some judgments regarding the utility of NOS knowledge in society. Even as the quest to produce shared recommendations for NOS in school science continues, it seems reasonable to conclude that students must have the opportunity to understand how knowledge is generated in the discipline called science. It is nature of science that can provide such an opportunity for understanding.

3.4 A Proposal for Key Aspects of NOS Recommended for Inclusion in the Science Curriculum

The set of recommendations for NOS content included in Fig. 3.1 reflects many of the recommendations widely offered but is unique in that related NOS elements are clustered into three bigger domains labeled the *tools and products of science*, *the human elements of science*, and *science knowledge and its limits*. This proposal had its roots in the suggestions offered by others and original research that involved a review of a variety of recent books written for the general public by professionals in the HPS community (McComas 2008). There was a surprising degree of agreement on what the most important aspects of the philosophy of science should be at an introductory level. The veracity of this summary could be checked every few decades as I did recently by examining a new book by philosopher of science Steven French (2016) with content that neatly parallels the recommendations for NOS content featured here.

The section that follows features a detailed discussion of all nine of the key NOS aspects along with mention of various misconceptions linked to each. Before proceeding, it will be useful to talk briefly about why this set of NOS elements is reasonable.

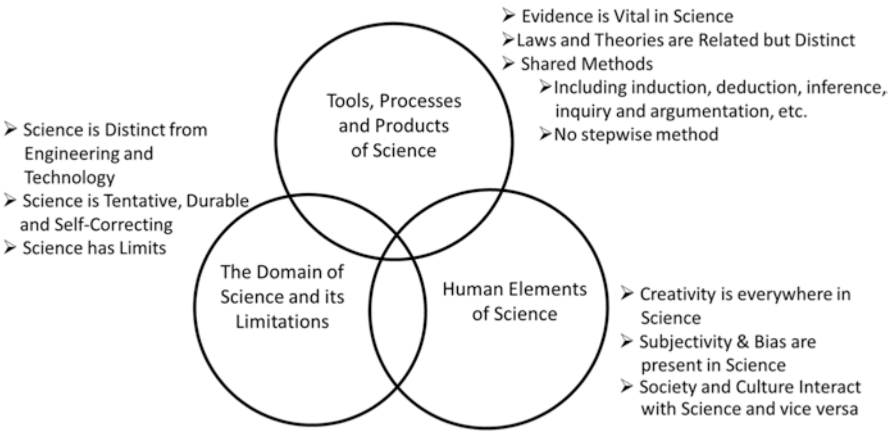

Fig. 3.1 The nine major sub-elements or key NOS aspects often recommended for inclusion in science instruction, arranged in three related clusters. (Modified from McComas (2008) and reflected in the US *Next Generation Science Standards* Achieve (2013)) A complete view of NOS lies at the intersection of these three domains and is achieved when learners have robust understanding of all nine elements

3.4.1 Why Recommend These Elements of NOS for Science Instruction?

Of course, the major reason why these elements are recommended as the foundation for NOS teaching and learning is that they are the ones most frequently mentioned by science educators. Furthermore, these elements function across the science disciplines even if there are some interesting differences as discussed in the case of laws (or "invariant generalizations" for those who reject referring to certain biological generalizations as laws) and theories in biology. Also, this list is short enough that it is not a burden on the science curriculum. In fact, one of the best ways to teach about nature of science is to weave it in to the traditional science content using that content to exemplify the aspects of NOS. Finally, these aspects are understandable to teachers and students at various levels. It is vital to remember that any recommendation for NOS content in the science curriculum represents an introduction to how science functions rather than a graduate-level treatment for the education of future philosophers of science.

3.5 Discussion and Description of Recommended Key NOS Aspects

As pointed out in the previous chapter, we must stop arguing about what might be a perfect list of NOS elements for school purposes and cease the unproductive conversation that there are not common elements linking the sciences. This chapter takes the position that we do possess strong rationales for the consensus view and embraces the recommendation attributed to both Voltaire and Confucius that we *not allow the perfect be the enemy of the good*. Therefore, it is better that science learners have some familiarity with important aspects of NOS than to have ill-informed or missing knowledge as is often the typical situation. No matter if NOS learning objectives are stated in lists, objectives, or questions, these are sophisticated ideas none of which should be satisfactorily communicated to students in some list of definitions to be memorized.

However, it is true that because of the complex and contextualized nature of these NOS elements we must attend to Matthew's (2014, p. 394) concern "that at critical points, there is ambiguity that mitigates the usefulness of items on the [consensus] list as curriculum objectives, assessment criteria and goals of science teacher education courses." This real concern can only be overcome with precise descriptions, focused education opportunities for science instructors, and clearly written NOS standards. Just as Matthews offered in his recent book, this chapter provides succinct descriptions of each of the key NOS ideas in Fig. 3.1 to remove as much potential ambiguity as possible.

Readers must realize that there are substantial "size" differences among these nine key NOS aspects. Some key NOS aspects, such as the role of evidence in science, are relatively discrete and easy to describe, but others, such as the discussion of scientific methods, are much more involved. This difference in the complexity demanded by a discussion of the key NOS aspects proposed here has resulted in a lengthy treatment of some and not of others. Teachers will rightly assume that sharing some of these key aspects will be easier and require less time than doing so with others. Finally, in this section, there will be discussion of each of the key aspects and a discussion of misconceptions regarding each NOS aspect. This chapter adopts and expands on the "myth" approach used in previous publications (McComas 1996, 1998, 2004, 2015, 2017).

3.6 The Tools and Products of Science

The key elements of NOS in this cluster are related because they are required of science (evidence and specific shared techniques) or are produced (laws and theories) using scientific methodology. The necessary role of evidence in science is clear even to young learners, while the lack of a stepwise method and the distinction between laws and theories is a source of confusion to many that results in a variety of misconceptions.

3.6.1 Evidence in the Practice of Science

A fundamental requirement of science is that evidence must exist both to inspire scientific investigation initially and to support scientific conclusions. This interplay between evidence, investigation, and conclusion is dynamic. One way that science works is when evidence in the form of data, facts, inferences (discussed in a later section), and even anomalies present themselves in ways that provoke curiosity causing scientists to look more deeply into phenomenon. As scientists engage in deeper investigations, more evidence is generated through experiments and observations which coalesces into conclusions regarding that phenomenon.

Another way that evidence plays a role in science is when ideas are proposed (usually themselves based on other lines of evidentiary support) by theoreticians which then encourage other scientists to validate those proposed ideas. When Einstein offered his view from thought experiments that light passing near a massive object, such as a star, would bend slightly, the scientific community rose to the challenge during the 1919 eclipse and demonstrated the predicted effect with evidence.

As with many NOS notions, the role of evidence in science is not quite as simple as it seems. As students make the transition from an absolutist view of the nature of evidence that they encounter in their personal lives (evidence that they can "see and hold"), they might enjoy learning about interesting nuanced positions. Consider the example of the evidence for quarks. There are six subatomic entities called quarks, each with a fractional charge. Assemblages of these quarks, in turn, comprise larger particles called hadrons (protons and neutrons are kinds of hadrons). Physicists are almost universally "sure" that quarks exist, but these can never be observed directly because of the issue of "color confinement." Quarks are thought to have a property called color which acts like a charge whose attractive force binds them together. For this reason, one never sees an individual quark. Therefore, strong support for the reality of quarks of different "colors" comes from indirect or perhaps inferential evidence provided by predictions based on the examination of hadrons (Han 1999). The evidence here, which is well accepted by the scientific community, is decidedly less concrete and direct that many would typically envision, but it is evidence nonetheless.

Young children quickly recognize that direct evidence (date or facts) is required to support personal conclusions, while older children accept that inferential evidence too is also quite valuable and valid. Therefore, this key NOS element may be among the easiest to teach, but it is vital to do so. It is regrettable that many adults currently seem not to be able to distinguish between credible and fanciful truth claims perhaps because of what should could as evidence.

Targeted Misconception Scientific evidence is not a "matter of opinion" such that even widely accepted facts can be ignored just as one might discount a personal view with which an individual disagrees.

3.6.2 Laws and Theories Are Equally Important but Distinct Kinds of Knowledge

There is a general belief that with increased evidence, there is a developmental sequence through which scientific ideas pass on their way to final acceptance (Fig. 3.2) as mature laws. The implication is that hypotheses and theories are less secure and therefore less credible than laws. As an example, this confusion is revealed whenever someone says that evolution is "just a theory."

Entire books have been written about the distinction and relationship between theories and laws, so anything said here may be dismissed as incomplete. However, we trust readers will forgive this since the discussion here is intended as an introduction. With that said, theories and laws are very different kinds of knowledge. Laws are generalizations, principles, or patterns in nature, and theories are the explanations of those generalizations with some appending the notion that laws are discovered while theories are invented (Rhodes and Schaible 1989; Horner and Rubba 1979; Campbell 1953; McComas 2003). Of course, there is a relationship between laws and theories, but it is not the case that one simply becomes the other – no matter how much empirical evidence is amassed.

Dunbar (1995) addresses the distinction by referring to laws as "cookbook science" and the explanations as "theoretical science." He cites multiple examples of the kind of science practiced by traditional peoples as "cookbook" because members

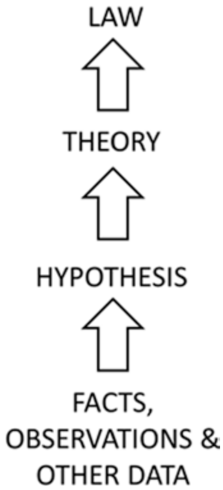

Fig. 3.2 Illustration of the false hierarchical relationship between facts, hypotheses, theories, and laws. Note: Please do not show this to students or you may inadvertently promote this myth to students

of those societies can apply the rules after recognizing patterns in nature, even if they do not understand why nature operates in the way that it does. In many cases, it is enough that the rules work. It has been said that an indigenous group might be negatively impacted if moved even a few hundred kilometers because the "rules" of nature (i.e., when to plant and harvest) may not function as they were known to do previously. Certainly, humans are adaptable and can reason and may quickly learn the "rules" of their new location or even adjust to changes in their current setting. However, the basic idea is valid that there is a distinction between a trial and error adjustment to changed circumstances and an alteration in practices based on a more scientific understanding of the world.

Even in highly sophisticated settings, "cookbook science" may be practiced because it can be quite useful. For example, Newton described the relationship of mass and distance to gravitational attraction between objects with such precision that we can use the law of gravity to plan space flights. During the Apollo 8 mission, astronaut Bill Anders responded to the question of who was flying the spacecraft by saying, "I think Isaac Newton is doing most of the driving right now" (Chaikin 1994, p. 127). To those with knowledge of the history of science, his response was understood to mean that the capsule was simply following the basic laws of physics described by Isaac Newton centuries earlier.

The more interesting issue with respect to gravity is the explanation for why the law operates as it does. Even now, there is no single well-accepted theory of gravity. Some physicists suggest that gravity waves are the correct explanation, while others talk about a kind of gravity particle, but with clear confirmation and consensus lacking, most feel that the theory of gravity still eludes science. Interestingly, Newton addressed the distinction between law and theory with respect to gravity. Although he discovered the law of gravity, he refrained from speculating about its cause. In *Principia*, Newton states "…I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypothesis…" "…it is enough that gravity does really exist, and act according to the laws which we have explained…" (Newton 1720/1946, p. 547).

It is true that laws and theories operate somewhat differently in the different sciences – particularly biology – but it should be clear that some things are pattern-like and some offer explanations, and that is the difference between law and theory. For instance, Darwin proposed the mechanism for evolution (i.e., the theory of evolution by natural selection), but he did not discover the idea that populations of organisms change through time. That is evolution itself and has lawlike character even if the predictions with such a law will be less secure than those to be made by the application of Boyle's law in the physical sciences.

Related Misconception There is a widespread belief that theories are a sort of guess, and with time and evidence, they mature into laws. This is untrue. Theories and laws are important and related kinds of knowledge, but one does not become the other.

Having mentioned the faulty lineage from theory to law, we should spend a moment talking about the term hypothesis. This word has taken on an almost mantra-like life of its own in science class with most students labeling it an "educated guess." If a hypothesis is always an educated guess as students typically assert, the question remains, "an educated guess about what?" The best answer for this question must be that, without a clear view of the context in which the term is used, it is impossible to tell; there are at least three distinct definitions. For that reason, the term "hypothesis" probably should be abandoned and replaced or at least used with caution. For instance, when Newton said that he framed no hypothesis as to the cause of gravity, he was saying that he had no speculation about an explanation of why the law of gravity operates as it does. In this case, Newton used the term hypothesis to represent an immature theory.

Sonleitner (1989) suggested a solution to the hypothesis problem by simply making things clearer. He proposes that we label tentative or trial laws as *generalizing hypotheses* with provisional theories referred to as *explanatory hypotheses*. What this means is that, with evidence, generalizing hypotheses may become laws and speculative theories might become theories; however, under no circumstances do theories become laws. Finally, when students are asked to propose a hypothesis during a laboratory experience, the term now means a prediction. As for those hypotheses that are really forecasts, perhaps they should simply be called what they are, predictions. I cannot predict if this new nomenclature will replace the potentially confounding term now used, but doing so would increase the level of precision used in science class and avoid much confusion. Even a term like "hypothesis" demands a degree of sophistication that only deep knowledge of NOS possessed by teachers and students can resolve. See Fig. 3.3 for a summary of this situation.

Targeted Misconception The term "hypothesis" means an educated guess, but this is not true. In practice, hypothesis could be a predication, a tentative law, or a tentative theory. With that many potential definitions, perhaps we could do without it altogether.

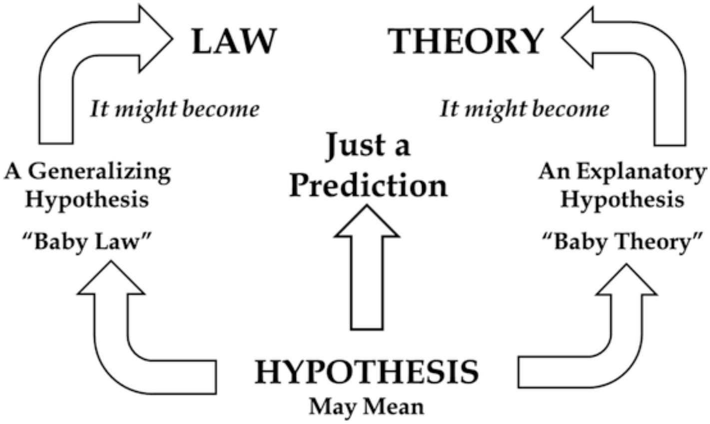

Fig. 3.3 "Family tree" of the term hypotheses, illustrating its multiple definitions and related sources of confusions

3.6.3 There Are Many Shared Methods in Science but No Single Stepwise "Scientific" Method

Discussion of this NOS aspect begins with an apparent contradiction. While there are many shared methods in science, there is no single scientific method. What this means is that there are most certainly generalized techniques that all scientists share that students themselves should practice. However, there is no single step-by-step method (i.e., the so-called scientific method that many science learners are taught that scientists use in all cases).

In this section, we will discuss both issues, shared practices and the lack of a commonly applied and standardized method with some number of fixed steps, and this reality may be confusing if one moves too quickly. Since there are methods, but there is no method, it may be best to discuss the methods that scientists do share before tackling the issue of what they do not.

3.6.3.1 Shared Methods of Science

Of course, there are methods that virtually all scientists would recognize as legitimate scientific practices. Here, we are not talking about procedures and techniques found within a given discipline like titration in chemistry, gene amplification in biology, and the like. No, there are a wide number of activities that scientists universally would find both acceptable and even required including careful record keeping; high ethical standards; the use of logical tools such as deduction, induction, and inference; proposing models; the use of deduction and other considerations like the norms of publishing; the process of grant funding to support research; and other sociocultural aspects of science discussed elsewhere in this chapter. Sober (2015) nicely summarizes this issue as he agrees that there is no single method, but there are most certainly shared methods of reasoning and collective values.

In fact, there have been several curriculum projects which shared the goal of teaching students about the work of scientists by engaging them in the use of scientific methods. One such project from the heyday of US science curriculum development was Science – A Process Approach (S-APA) (AAAS 1967). The authors of S-APA observed and interviewed scientists to define a suite of skills (usually known as "science process skills") that might describe the range of their shared work. These process skills became the focus of instruction. Although the project was somewhat naive in its pedagogical focus, generations of science teachers have come to know at least some of these skills (observation, measuring, defining operationally, etc.) proposed by the project along with other shared processes such as modeling. An initiative in the UK, the *Warwick Process Science Project* (Screen 1986), had similar aims.

A more recent analysis (Peters-Burton and Baynard 2013) found that scientists agree that they share as many as 27 characteristics, a list that is more robust and philosophically grounded but not antithetical to those proposed by S-APA. These characteristics include the use of multiple data sources, making testable assertions, maintaining healthy skepticism, building on past reliable information, the value of reproducing results, looking for counterarguments, changing conclusions with the advent of more information, engaging in multiple experiments, and the importance of peer review, among others. We should also add that argumentation (structured debate) and inquiry (or enquiry as it is called in much of the non-US-English-speaking world) are also tools or "methods" of science. It is with some trepidation that I even mention inquiry because this has been the topic of much debate in science education; is it or is it not part of NOS? There are arguments to be made on both sides. Inquiry is a complex set of actions and philosophical presuppositions that is certainly part of science. Like the other methods of science, it is not exclusive to science but would be recognized as something that scientists do and many other nonscience fact-finding and problem-solving endeavors. For this reason, it is appropriate to see inquiry in the same light as the other tools of science, but I am not prepared to give it the same status as the other NOS recommendations offered here.

So, even as we explore any list of shared methods used by scientists we must remind ourselves that all such methods are used in other professions and in daily life. Even if these methods are not exclusive to science, they are useful in helping to define scientists' practices. It would be foolish to attempt to list all practices *not* used by scientists generally, but "reading" the entrails of a freshly killed chicken to gain insights about the future, using a Ouija board to gain insights about the world, and making judgments based on the position of the stars at the time of one's birth would be on the short list. With no further digression, let us move on to discuss three major shared scientific methods, induction, deduction, and inference, that students should have an opportunity to explore.

Induction, Deduction, and Inference as Shared Methods of Science

One particularly important shared method is represented by the widespread use of the twin logical tools of induction and deduction (Fig. 3.4). All of us, including scientists, collect and interpret empirical evidence through these processes. Induction, for instance, is a technique by which individual pieces of evidence are collected and examined until a law is discovered or a theory is invented. Frances Bacon (1620/1952) first formalized induction as a method in the seventeenth century. In his 1620 book, *Novum Organum*, Bacon advised that facts should be assimilated without bias to reach a conclusion. The method of induction he suggested is in part the principal way by which humans traditionally have produced generalizations that allow predictions. Baconian induction and the related process of deduction (or hypothetico-deductivism) are illustrated in Fig. 3.4. There is something missing in this discussion of induction that will be discussed later, so for now, the process of Baconian induction is most accurately characterized as naive induction. Lawson (2000, p. 482) essentially called such thinking *the* method of science. He states "biology as well as other sciences, is largely hypothetico-deductive in nature…and not at all new to science…."

The proposal of a new generalization (i.e., law) begins through induction as facts are heaped upon other relevant facts. Deduction is useful in checking the validity of a law. For example, if we postulate that all swans are white, we can evaluate that assertion law by predicting that the next swan found will also be white. If it is, the law is supported (but not proved as we will discuss later). Locating even a single actual black swan will seriously damage the credibility of the proposed law.

We conclude this section with a brief discussion of inference, a commonly used method in science and everyday experience. A composition definition shows inference to be a conclusion based on facts, evidence, and data already known to extrapolate to a conclusion (or other data) not seen directly. A favorite example is that of the

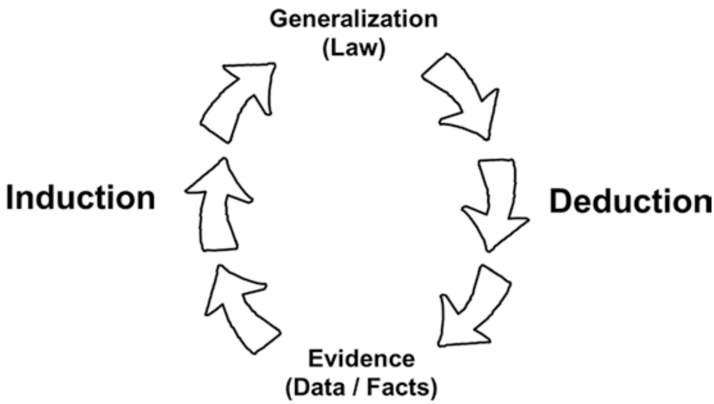

Fig. 3.4 A typical view of Baconian knowledge production. Bacon's view (induction on the left) related to the production of new generalizations and deduction or hypothetico-deductivism (on the right) for the testing of such generalizations. The diagram does not imply that the laws produce new facts but rather that a valid law would permit the accurate prediction of facts not yet known

late-night swimmer. Suppose you have a pool and hear splashing in the middle of the night, but when you investigate, you find nothing in the pool but with wet tracks from some four-footed creature leading away. What might you infer? Logically, you would conclude that some animal was in the pool. You might even measure and photograph the footprints, look in a nature guide, and add to your inference that the animal was a bear. So, with great confidence and perhaps even some enthusiasm, you announce that there was a bear in your pool. Yet you did not see the bear. However, as you recite the evidence, most would agree that your conclusion is reasonable and even likely. This is how inference works. Sure, perhaps someone faked the evidence in the middle of the night for some unknown reason, but such a conclusion seems so unlikely that such a suggestion would be prime fodder for conspiracy mavens.

A few years ago, we in the USA were presented with a televised debate between a supporter of evolution and a creationist. As is often the case with these affairs, there was no winner and there really could not be. The evolution supporter shared vast amount of evidence, much of it in the form of the "hard facts" we often expect of science along with a fair amount of logical inference. Throughout the conversation, the creationist continually said, "but were you there, did you see it?" Any observer should quickly realize that this was not a debate because the two experts did not agree in advance on what should be accepted *as* evidence. If we disallow inferential thinking, many well-established scientific conclusions would cease to exist. The creationist continually stated his belief and acceptance of what was written in the religious literature even though he was not there to see it, but that issue seemed to cause him no problem. Either out of respect or recognizing the mismatch of world views, the creationist was never reminded of this clear logical fallacy. Teaching students about inference as evidence and a shaded method of science is vital. Much conclusion-making in our daily lives is inferential, so even if students forget that they explored this issue in science class, they will long remember the importance of this tool.

3.6.3.2 The Issue and Challenge of the Scientific Method

The notion that a common series of steps is followed by all research scientists must be among the most pervasive myths of science given the appearance of such a list in the introductory chapters of many precollege science texts. The steps listed for the scientific method vary somewhat from text to text but usually include (a) defining the problem, (b) gathering background information, (c) forming a hypothesis, (d) making observations, (e) testing the hypothesis, and (f) drawing conclusions. Some texts also include "communicating results" as the final stage (Fig. 3.5).

The multistep method started innocently enough when Keeslar (1945a, b) prepared a list of the characteristics associated with scientific research. This list included establishing controls, keeping accurate records, and making careful observations and measurements. This is not unlike the process engaged in by the developers of SAPA. This list was refined into a questionnaire and submitted to research scientists for validation. Items that were highly ranked were then put in a logical order and made part of the final list of elements associated with the investigation of

Fig. 3.5 The typical steps associated with the so-called scientific method. The existence of a linear and universal scientific method is one of the most pervasive myths of science in science instruction. As with Fig 3.2 you should not share this diagram with students

scientific problems. In time, the list was reduced from what was an original set of ten to the steps shown in the figure. In the hands of generations of textbook writers, a simple list of characteristics associated with scientific research became a description of how all scientists work. The list is particularly beguiling to teachers because it seems right, is easily taught, looks good on classroom posters, and quickly became the focus of assessment.

Another reason for the widespread belief in a general scientific method may be the way in which results are presented for publication in research journals. The standardized style makes it appear that scientists follow a standard research plan. Medawar (1991) reacted to the common style exhibited by research papers by calling the scientific paper a fraud since the final journal report rarely outlines the actual way in which the problem was investigated. The report is simply a highly stylized but ultimately artificial account of the actual work accomplished. Gone are the days when a scientist could begin a paper by stating as in this fanciful example, "it was a glorious and sunny day when I perchance encountered a highly unusual flower that attracted my eye…" as was often the way Victorian naturalists began a report of discovery.

Those who have studied scientists at work have shown that no stepwise research method is applied universally (Carey 1994; Gibbs and Lawson 1992; Chalmers 1990 and Gjertsen 1989). The notion of a single scientific method is so pervasive that many students must be disappointed if they have an opportunity to discover that scientists do not have a framed copy of the steps of the scientific method posted above each laboratory workbench.

One reaction seen among science teachers when talking about the lack of a stepwise method is legitimate argument that the canonical method shown in Fig. 3.5 seems to be useful in approaching problems. This is an excellent point and one that should be briefly discussed. As a problem-solving tool, the canonical or so-called scientific method can be quite useful and, in that regard, should even be recommended. There are shared methods by which knowledge is gained in science, and these methods can and should be used by all problem-solvers. Science is no different from other human endeavors when puzzles are investigated. Fortunately, this is one myth that may eventually be displaced since many newer texts are abandoning or augmenting the list in favor of discussions of *methods* of science. For a more accurate diagram of the process of scientific investigation, readers are encouraged to consult Reiff-Cox in Chap. 6, who discusses her work on the inquiry wheel.

Targeted Misconception Many believe that there is a general stepwise scientific method that all scientists use, but this is not the case. Although there are many shared methods in science (such as induction, deduction and inference), there is no standard step-by-step method that all scientists use to explore nature.

3.7 There Are Human Elements in Science

The issues found in this cluster of NOS elements are related because they all pertain to the reality that humans do science. That may seem like a self-evident notion, but because humans engage in science, we must be concerned with human strengths, frailties, and associations. We will begin by discussing the vital role played by creativity in science, move on to the issue of subjectivity, and conclude with sociocultural links between scientists and between science and the rest of the world.

Please note that some unpacking is necessary when considering how the label "human elements" is applied. NOS recommendations here may relate most strongly to the work of individuals (a psychological frame), while others are more applicable to scientists interacting in groups and/or with society at large (a sociological perspective). The notions of creativity and subjectivity, discussed in this section, might logically be more psychological, while the sociocultural elements of science likely operate more sociologically. However, having said this, a case could be made that both psychological and sociological impacts function in all three sub-elements of this domain, the human elements of science.

3.7.1 Creativity Plays a Significant Role in Science

We accept that no single guaranteed method of science can account for the outstanding success of science. We do realize that induction, the collection, and interpretation of evidence (usually in the form of relevant facts) providing the raw materials for laws and theories, is at the foundation of most scientific endeavors. However, this suggests a paradox. If induction itself is not a guaranteed method for arriving at conclusions, how do scientists develop useful laws and theories?

Induction makes use of evidence that is collected, analyzed, and examined. Some observers may perceive a pattern in these data and propose a generalization in response, but there is no logical or procedural method by which the pattern is suggested. With a theory, the issue is much the same. Only the creativity of the individual scientist and/or team permits the discovery of laws and the invention of theories. If there truly was a single scientific method, two individuals with the same expertise could review the same facts and likely reach identical conclusions. There is no guarantee of this because the range, nature, and application of creativity is personal, based on prior experiences, and situated with what Kuhn called the paradigm or prevailing framework of science. It is possible to enhance creative thinking, and perhaps that should be an element of the school curriculum, but some folks are simply more creative than others. Figure 3.6 is very similar to the previous illustration of induction and deduction but now includes the somewhat intangible but necessary creative and human spark in the knowledge generation process. It is very likely that two individuals with access to the same facts might reach quite different decisions about what those facts mean based on the prior knowledge and creativity of one.

Creativity and imagination are found throughout science as can be illustrated by countless examples from the history of science (Porterfield 1941). Everything from the identification of a problem worth considering, the specific methods by which that problem may be addressed and, of course, the interpretation of results, has a creative component. Accounts of science are replete too with example of the language of creative such as calling ideas beautiful, economical, imaginative, or even elegant (Glynn 2010). Unfortunately, many common science teaching orientations and methods serve to work against the creative element in science.

Many laboratory exercises in school science are little more than verification activities. The teacher discusses what is going to happen in the laboratory, the manual provides step-by-step directions, and the student is expected to arrive at an expected answer. Not only is this approach the antithesis of the way in which science operates, but such a portrayal must seem dry, clinical, and uninteresting to many students. In her book, *They're Not Dumb, They're Different*, Tobias (1990) argues that many capable and clever students reject science as a career because they

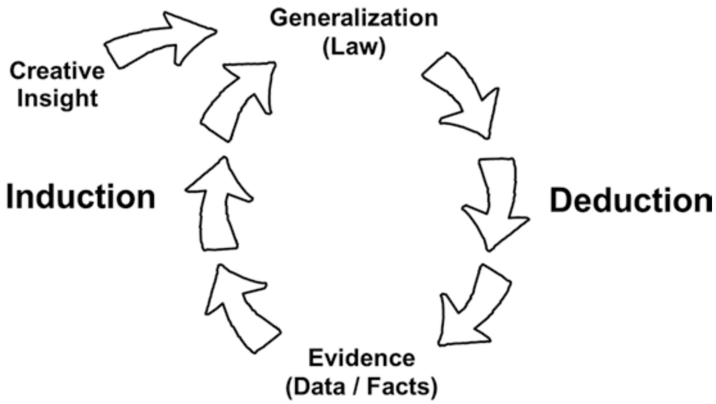

Fig. 3.6 A more accurate illustration of knowledge generation in science. Here, the creative spark or creative leap is included as a necessary element facilitating the move from evidence to generalization

are not given opportunities in school science to see science itself as an exciting and creative pursuit. The moral is that science may be impoverished when students who feel a need for a creative outlet eliminate it as a potential career because of the way it is taught.

Targeted Misconception The myth of the stepwise scientific method has led many to believe that science must be a kind of linear, rote, formulaic pursuit that is nothing like the making of art, for instance. This is not true. There are creative elements all through science including the role of imagination in seeing problems, recognizing patterns, and intuiting solutions.

3.7.2 Science Involves Some Subjectivity

Much of the process of scientific investigation is conducted out of sight, and only the most surprising or potentially useful conclusions are even released to the public. Perhaps for this reason, scientists are likely seen as highly intelligent, savant-like individuals who operate at some superhuman level. The portrayal of scientists on film – particularly from the 1950s – does little to dispel this view. What is much closer to the truth is that scientists are certainly more knowledgeable about what they study than are the rest of us but are human just the same.

What this means is that scientists have the same level of subjectivity (i.e., a lack of total objectivity) as do the rest of us. We all view the world through the lens of our prior experiences in ways that may lead to certain expectations called "theory-laden" observation (Hodson 1986). Scientists, like all observers, hold myriad preconceptions and biases about the way the world operates. These notions, held in the subconscious, affect the ability of everyone to make observations. It is impossible to collect and interpret facts without any bias. Often bias is seen as negative, but that is not necessarily the case. Bias can cause you to miss something because of prior expectations but may just as likely allow the visualization of something that others might miss because the observer is prepared to see it.

There have been countless cases in the history of science in which scientists have failed to include certain results in their final reports. This occurs not because of fraud or deceit but because of the prior knowledge possessed by the individual. Certain facts either were not seen at all or were deemed unimportant due to these prior expectations. This notion, part of the "human dimension of science," discussed in detail in Chap. 6, is not widely understood nor it is widely discussed in science class. Therefore, the challenge of subjectivity becomes a worthy key NOS element.

There is one aspect of subjectivity that relates more closely to scientist than to the observer and that is the relationship of theory-based observations to the paradigm. Thomas Kuhn (1970), in his groundbreaking analysis of science through the lens of its history, suggests that scientists work within a research tradition called a paradigm. This research tradition, shared by those working within a given discipline, provides clues to the questions worth investigating, dictates what evidence is admissible, and prescribes the tests and techniques that are reasonable. Although the paradigm provides direction to the research, it may also stifle or limit investigation. Anything that confines the research endeavor necessarily limits objectivity.

While there is no conscious desire on the part of scientists to limit discussion, it is likely that some innovative ideas in science are rejected because of the paradigm issue. When research reports are submitted for publication, other members of the discipline review them. Ideas from outside the paradigm are liable to be eliminated from consideration as crackpot or poor science and thus will not appear in print. It would be misleading to conclude even this brief discussion of scientific paradigms in a negative fashion. Although the examples provided do show the contrary aspects associated with paradigm fixity, Kuhn would argue that the blinders created by allegiance to the paradigm help keep scientists on track. Kuhn's review of the history of science demonstrates that paradigms are responsible for far more successes in science than delays.

Examples of scientific ideas that were originally rejected and hence delayed in the widespread acceptance of the scientific community because they fell outside the accepted paradigm include the sun-centered solar system, warm-bloodedness in dinosaurs, the germ theory of disease, the asteroid explanation of the demise of the dinosaurs, and RNA as a carrier of genetic information. These ideas now held as valid scientific conclusions were not universally and quickly embraced by many scientists.

For instance, when the idea of moving continents was first proposed early in this century by Alfred Wegener, it was vigorously rejected. Scientists were simply not ready to embrace a notion so contrary to the traditional teachings of their discipline. Continental drift was finally accepted in the 1960s with the proposal of a mechanism or theory to explain how continental plates move (Hallam 1975 and Menard 1986). This fundamental change in the earth sciences, called a revolution by Kuhn, might have occurred decades earlier had it not been for the strength of the prevailing paradigm.

Ideas that help to fill in the gaps that come from the perspective of the existing research framework typically find their way into print realatively easily. However, if the idea is a significant departure from orthodoxy, is counterintuitive, or comes from someone outside the discipline, its acceptance is by no means quick and easy. As we will see later, science is a self-correcting enterprise so even when innovative ideas are held down by senior members of the scientific community, they will eventually rise. On the other hand, this reluctance among scientist immediately to change established norms is probably a good thing in general at least until the major arguments have been resolved.

This issue of subjectivity has clear implications for science teaching. We do not typically discuss the issue of subjectivity, and to make matters worse, teachers often provide learning experiences without considering students' prior knowledge. In the laboratory, for instance, students are asked to perform activities, make observations, and then form conclusions. There is an expectation that the conclusions formed will be both self-evident and uniform. In other words, teachers anticipate that the data will lead all pupils to the same conclusion. This could only happen if each student had the same prior conceptions and made and evaluated observations using identical schemes. This does not happen in general in science, nor does it occur in the science classroom.

It would be premature to end this section leaving readers with the idea that science is nothing more than a subjective morass. It is reasonable to mention the subjective factor resident within scientists and perhaps even within research teams, but science is a community affair. So, the biases – both pro and con – held by some are not held by others engaged in the same work. Therefore, we should talk about science as an intersubjective enterprise, a very useful concept initially proposed by Logino (1990). Some have co-opted this notion for postmodernist purposes, but that challenge aside, it is a useful way of explaining how the strengths and weaknesses, differential biases, and varying experiences of scientists come together in the final marketplace of ideas to move the work of science toward the most reasonable conclusions. This myth targets individuals and small working groups of scientists; thus, the final form of any scientific idea as embraced by the scientific community is essentially free of bias and subjectivity.

Targeted Misconception There is a dominant misconception that scientists are more objective than the rest of us. Scientists know more than others about whatever they are about to explore, but the issues of prior knowledge and theory-based observation and the notion of the paradigm operate against complete objectivity. However, science as an enterprise makes use of intersubjectivity that tends of cancel out any biases held by individual scientists or research teams, thus minimizing negative impacts of theory-based observation.

3.7.3 There Are Sociocultural Impacts on Science and Vice Versa

This NOS aspect found within the domain of "human elements of science" reminds us that because humans do scientific work and engage with each other in a variety of ways, all scientific work will be impacted by these human interactions.

First, much of science relies on external funding and that funding, in turn, is controlled by governments and private foundations that have their own agendas. One might criticize a government that steps up funding due to a national demand such as war and not be as critical when this funding is increased to fight an insect infestation. However, in both cases, there is a problem to be solved, and basic knowledge will be generated in the process as specific problems are addressed. Very few scientists are free to investigate whatever they find interesting unless such tasks are incredibly inexpensive; almost all rely on external funding. For good or bad, that funding is mediated by some public interest typically reflected in the priorities of those providing the money. One only had to look at the past several federal administrations in the USA to recognize that public interests change at least as perceived by those in power. Much more could be said about this, but for an example, consider that one recent administration in the USA wanted to halt stem cell research and the next one found such research worthy of support. As I write this, the current US administration is skeptical and even derisive of the conclusion that the global climate is warming. Previous leaders reached the opposite conclusion and developed policies to slow global warming based on the same data and scientific conclusions now held as unreliable.

Bell (2004) provides several useful historical examples of the interplay between science and society. He said that cultural influences have:

> the potential to impact what research is done, how scientific findings are reported and received, and even the conclusions of scientific investigations. One need only consider such well-known episodes as the Catholic Church's suppression of Galileo's discovery that the moons of Jupiter revolve around the planet or Darwin‘s 17-year long delay in publishing his theory of natural selection to illustrate the major impact that society can have on science. (p. 436)

There is a second sociological element to science found within science itself; the enterprise of science is basically a community affair. Knowledge generation and validation is run through a people-centered process. When a scientist has a new idea, she first introduces it at a professional meeting, takes note of any criticism and suggestions for improvement, and ultimately submits the work for publication. Other scientists read and comment on the findings and evidence and collectively decides if the article is worthy of publication. This process ideally improves the quality of the scientific work but also acts as a gatekeeper blocking some ideas, and the scientists who contribute them, while accepting others. Students must gain knowledge of the human aspects of science, both in the way that teachers talk about doing science and in the learning experiences they are provided in science classes.

Targeted Misconception Some may believe that scientists generally are permitted to work on problems of interest and, although they do follow their interests and expertise, there are two basic limits on the scientific enterprise. First, scientists need funding; with it, they might work on projects that they were not as personally invested in but for which money is available. At the same time, lack of funding generally blocks work that scientists would like to do personally. Second, even the conclusions offered by scientists must be validated (i.e., endorsed) by others if they are to become part of the shared knowledge base of science.

3.8 The Focus of Science and Its Limitations

This final cluster of NOS elements contains three key aspects that relate to the boundaries of science with implications for its limits. Here, I offer the somewhat controversial position that because of the rules of science (one being the focus on the natural world), there are limits on what science can know, although of the "rules" is that scientific conclusions are ultimately tentative (subject to change) but still long-lasting. The cluster of NOS notions ends with the idea that science is something quite special that is related to other disciplines (i.e., the science vs. engineering/

technology distinction), but science is unique historically and philosophically, and students will be best served if they learn of the distinct nature of science.

3.8.1 Science Is Limited in Its Ability to Answer All Questions

As with others of these NOS aspects, this one is not easily summarized. There would seem to be at least two reasons why we can suggest that there are limits on what science can know. Here, I am not saying that there are things that science does not yet know but that science can never know. The first is the notion that science can provide proof in the classic sense of a definitive answer for all time, and the second relates to areas of inquiry where the methods of science simply do not function.

A common view of science is that, when we know something resulting from the processes of scientific investigation, the idea has been *proved*. However, we must recognize the "problem of induction" whereby it is both impossible to make all observations pertaining to a given situation and illogical to secure all relevant facts for all time, past, present, and future. On a personal level, this problem is of little consequence, but in science, the problem can be significant. Scientists formulate laws and theories that are supposed to hold true in all places and for all time, but the problem of induction makes such a guarantee impossible (Horner and Rubba 1978; Lopushinsky 1993).

Consider the example of the white swans discussed earlier. One could search the world and see only white swans and arrive at the reasonable generalization that "all swans are white." However, the discovery of one black swan has the potential to overturn, or at least result in modifications of, this proposed law of nature. Finding yet another white swan does not prove anything; its discovery simply provides some comfort that the original idea has merit. This is the major issue within science. We can definitively assert that something is not true (i.e., find a black swan). We can never know that we have seen every swan that ever lived and know that they are all white, and thus "prove" the white swan rule. What science does is to investigate a problem to such a degree that finding any contrary evidence is unlikely and therefore decide the case is closed. So, this is a legitimate limit on the ability of science to answer all questions. We will return to this issue when discussing the next key NOS aspect.

The second example of the limits of science is more controversial because it is based on the proposition that there are some areas that simply cannot be explored with the methods of science. Here, we enter the distinction between science, a realm that demands evidence, and religion, a domain of faith where understanding operates without the necessity of evidence. There are also areas arguably beyond the tools of science related to ethical decision-making and even aesthetics. Indeed, entire books have been written exploring what science can legitimately investigate with some proponents of science such as Richard Dawkins who see no limits to the grasp of science. The thoughts offered here can only be an introduction.

It might seem odd to ask the question "why did religion develop?" in the context of suggestions for what students should learn about how science functions, but the two are tied together. Both religion and science are tools that humans have developed to gain answers about the world. We like to think of ourselves as more "advanced" than our forebears, and some – again Dawkins – think that we should have dispensed with religion by now. However, if we consider even the biggest of religious questions such as the nature of a God, science tells us very little. It is useful to engage in a thought experiment and ask what evidence we might collect that God exists and what evidence might we find to demonstrate that God does not.

Suppose one holds a deistic view of God, the notion that there is a supreme being who does not interact with humanity. With such a deity, prayer could have no effect. In such a case, it would be hard to imagine any evidence for or against such a deistic God that could be provided by science. Despite this challenge, some have looked to science to provide evidence nonetheless. Some suggest that the anthropic principle (Barrow and Tipler 1986) provides such evidence. This notion puts forward the premise that there are so many things about the Earth (i.e., oxygen level, distance from the sun, etc.) that it had to be created for humans, and our existence could not possibly be an accident of evolution. Still, given the problem of induction, can science really use even this argument to prove the existence of a metaphysical entity such as God?

There exist a range of other interesting questions well beyond the reality of God it seems that science can make no definitive claim to have resolved. Even when we consider all that science has taught us about fetal development, science cannot tell us whether abortion is ethical or not. Art galleries are filled with a range of genres, individual examples that attract legions of visitors, but can science tell us whether a Vermeer paining is better than a De Kooning? Such puzzles abound, and science can play some role in evaluating them, but it seems clear that science cannot definitively answer all questions. It is reasonable to address this notion with students. Doing so not only shows science in its proper light as one way of understanding the world but also embraces students' individual experiences and keeps them in the conversation about the role of science rather than encouraging them to question the utility of science as many seem inclined to do in recent times. Thoughtful theologians, ethicists, and scientists have carved out their spheres of influence and expertise and have coexisted with little acrimony. Those who fail to understand the distinction between science and other ways of knowing will continue to confuse the rules, roles, and limitations of these important world views. Asking an interesting question of the wrong experts will result in misunderstanding and increase the potential of wholesale rejection of an entire area of expertise. Finally, we might argue that by discussing the limits of science, teachers help to avoid inadvertently encouraging a scientistic worldview in students. Scientism, of course, is the position that science can answer all the questions of humankind and that we need no other explantory or investigative tools.

Targeted Misconception Some believe that science offers absolute proof and can potentially address all questions, but both views are incorrect. Simply put, there are limits on the range of scientific methods.

3.8.2 Scientific Knowledge Is Tentative and Self-Correcting but Ultimately Durable

The methods of science have been shown to provide humankind's best way to probing the natural world and developing understanding that stands the test of time. In this sense, the facts and conclusions offered by science are valid. However, new tools, techniques, and interpretations may cause us to change our initial views. Science is constantly undergoing fine-tuning with the occasional radical changes that Kuhn (1970) called "revolutions." We have shifted from an Earth-centered to a sun-centered system, from protein as the most likely molecule to code genetic information to DNA, from a stable Earth to continental drift, and countless other such examples.

Therefore, a hallmark of science is that it is subject to revision when additional information is presented and new insightes are offered and evaluated by the scientific community. Although it is highly unlikely that a scientific revolution will occur and only slightly more likely that smaller scientific conclusions might be overturned, we must recognize that science is tentative even as it is durable (i.e., long-lasting). Scientists and nonscientists alike should take comfort in the fact that science is not dogmatic about its conclusions.

However, some, who might like to discredit science, occasionally seize on the issue of tentativeness and translate that to suggest that scientific conclusions are little more than personal opinions. This is not reasonable, but we must be cautioned to talk about science as tentative but durable. Perhaps another way to say that is that scientific conclusions are long-lasting but might change when compelling new evidence and/or insights and interpretations become available. The "bigger" the scientific conclusion, the more likely it is to be valid and the less likely it will be to change even with more evidence. Climate change conclusions represent a very good example of this point. The data generated in support of the conclusion that the average temperature of the Earth is increasing are so vast and shared so widely by scientists that it would be foolish to expect that conclusion to be overturned.

We will end this section by thinking about tentativeness as part of the self-correcting aspect of science, a connection that is frequently ignored. Creationists are quick to criticize the conclusions of science when those conclusions counter their worldview. Often, they will use tentativeness in their criticism in a highly naive way by stating that science has made errors in the past and stating that what we know today could change tomorrow. Yes, both things are true, but only in an extraordinarily limited sense. Consider the situation in which several teeth found in Nebraska early in the 1900s (Gould 1991) were initially thought to come from primitive human. This view was overturned quickly when the teeth were found to be those of an extinct pig. Scientists made both the initial misidentification and the later revision, but those who want to find fault in the methods of science only discuss the error. There are no examples in the creationism literature where this issue is discussed. Science may not be perfect but is a self-correcting enterprise by design. All citizens should recognize this as one of the rules of the game of science.

Targeted Misconception Many consider the results of science to be final, but that is not true. One of the rules of the game of science is that scientific interpretations can change through the self-correcting mechanism built into science itself. The check-and-balance system of science produces useful and potentially long-lasting conclusions (i.e., scientific knowledge is durable), but such knowledge is always subject to change (i.e., scientific knowledge at some degree is always tentative).

3.8.3 Science and Engineering/Technology Are Related but Distinct

It might seem that this key NOS element is less important than the others, and this may be true in a philosophical sense. However, there is abundant evidence that many individuals have such a limited grasp of the rules of science that they see even something like a refrigerator as a scientific achievement. Certainly, there are scientific principles contained with the system that can maintain a cold environment inside a fashionable box that may now be found in almost every kitchen, but those who leveraged basic scientific ideas into a commercial device are engineers and technologists, not scientists.

So, despite the widespread misunderstanding that televisions, rockets, and computers *are* science, one of the hallmarks of science is that it is not necessarily practical, while air conditioners and iPhones certainly are. The pursuit of knowledge for the sake of knowledge alone is called pure science, while its exploitation in the production of a commercial product is applied science or technology facilitated by engineers. Even the knowledge-gaining agenda of scientists vs. the profit agenda of engineers and the companies they work for is a significant distinction that students should appreciate. Many years ago, the sociologist Everett Hughes offered an interesting, irreverent, and strangely accurate way to distinguish scientists from others who work in related fields when he noted that "Scientists, in the purest case, do not have clients. They discover, systematize, and communicate knowledge about some order of phenomena" (1971, p. 360). That is not to say that there are no limits on what scientists might do, as we will see, but does make the case that if a scientist wanted to study Bolivian butterfly migration patterns few would argue, but no engineer ever designed and built a bridge just because she wanted to.

Today, most investigators work on problems that are at least in part directed from outside their laboratories. Scientists may be directed by the funding they receive; that sociocultural aspect should be made clear to students, but ultimately, the quest is for new knowledge. Engineers blend their knowledge of science to solve a technology challenge almost always motivated by financial gain either because of a current contact (i.e., to build a bridge) or future potential (i.e., to produce a better handheld communication tool). Both are mediated by financial pursuits in ways that "pure" science often is not. Yes, science, technology, and engineering are intertwined (certainly engineers apply scientific methods and principles to determine, for instance, the strength of concrete formulations), but each has their own philosophical underpinning and role in society. It is vital that students – particularly those considering careers – recognize these important distinctions.

This would likely be enough to say on this topic, but two things recently have conspired to make this a critical issue of distinction. First, the education world has been inundated by the promise of some forms of STEM education. One version of STEM education demands that students study science, technology, engineering, and mathematics together in one project. On one hand, this holds promise if instruction remains focused on the individual elements of STEM. However, the integrated STEM (more accurately called I-STEM) model seems to be taking hold as the method by which to teach science in elementary schools, and that is a concern. Currently, students arrive in their secondary school science classes with some content knowledge but little vision about the philosophical factors that define science. In the future, we may see that students who have been in I-STEM learning settings understand less science content knowledge than is now the case and possess considerable confusion about how science functions having conflated the structure and function of science with engineering and even technology.

The STEM education movement growing worldwide is presumably a shared quest to produce more workers in the STEM areas. However, in the USA, there is another challenge regarding science and engineering with the release of the Next Generation Science Standards (NGSS) (Achieve 2013). In this document, we find the explicit recommendation that science teachers include engineering in their classes and have provided a chart indicating common "science and engineering practices." This is unfortunate because to the uninitiated, it now might seem that science and engineering are essentially the same since their practices have been melded together using similar language. The common science and engineering practices are said to be one of the three dimensions of science learning that does not even include NOS, a domain relegated to an appendix and a series of footnotes. This is a recipe for disaster with the potential for further misunderstandings about how these two disciplines function as pointed out by Antink-Meyer and Meyer (2016) in their study of teachers.

While on the topic of NGSS, it seems that there are four challenges that emerge when reviewing the engineering recommendations and their potential impact on NOS: (A) science and engineering are not the same in their methods, goals, and underlying philosophical orientation, but NGSS does not make this clear, (B) science teachers are now asked to teach engineering but have not been given more training or time to teach the extra subject, (C) most science teachers are not ready from a pedagogical content knowledge (PCK) perspective to help students understand the distinctions between the two great but separate disciplines of science and engineering, and (D) there is little evidence that students learn the underlying principles of science while engaging in the sorts of project- and problem-based learning advocated by those who support engineering and technology education as a part of science instruction. Society certainly needs both scientists and engineers, but students must recognize the essential differences including philosophies, skills, and motivations that separate these domains.

Targeted Misconception Many individuals see science and engineering as essentially two parts of the same pursuit. There is interplay between these two disciplines, but they are not synonymous. Each makes unique contributions and has distinct roles, history, goals, and an underlying philosophical foundation.

3.9 Concluding Thoughts

These nine key NOS elements are among the most commonly suggested of what might called the "consensus recommendations" for aspects of nature of science that should be included in science classes. These elements and others, as appropriate, should hold equal rank with the more traditional facts and processes that have long defined the science curriculum for decades. For those who disagree with the lists, it will be interesting to see other ways to define science learning goals. For those who disagree with NOS elements on the list, please get to work producing other useful and appropriate conceptualizations of NOS. I have learned from long experience that some will want NOS goals that are more limited, and others will find fault because the nuances inherent within each of these elements have not been explored more fully. There are book-length treatises available on almost all the NOS aspects, so it was impossible to possibly offer summaries to meet all expectations. I take responsibility for the content of this chapter, but all of us contributing to this book agree that it is time to recognize the necessity to include some aspects of NOS in the science classroom. After all, such knowledge lies at the foundation of understanding how science itself functions.

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