TEACHING ABOUT SCIENTIFIC INQUIRY AND THE NATURE OF SCIENCE: TOWARD A MORE COMPLETE VIEW OF SCIENCE

Science education reform efforts emphasize teaching science for all Americans, and identify scientific literacy as a principal goal of science education [1, 2]. Scientific literacy has been defined in many ways, but generally refers to the ability to read and understand media accounts of science and scientific issues [3]. Additionally, scientific literacy involves the ability to make informed decisions on socio-scientific issues. Ultimately, scientific literacy addresses the need for citizens to actively participate in a technologically advanced democracy [4].

Achieving scientific literacy requires more than teaching and learning science as a body of knowledge. Rather, developing scientific literacy requires a broader view of science that includes three principal components: the knowledge of science, the methods of science, and the nature of science (see Figure 1). **Scientific knowledge**, the most familiar component of scientific literacy, includes all of the scientific facts, definitions, laws, theories, and concepts we commonly associate with science instruction. The **methods of science** refer to the varied procedures that scientists use to generate scientific knowledge. While these methods can be very complex, K-12 science instruction typically focuses on the more basic inquiry skills, including observing, inferring, predicting, measuring, and experimenting. Additionally, scientific inquiry refers to a specific instructional approach in which students answer research questions through data analysis. The **nature of science** is the most abstract and least familiar of the three components of scientific literacy. The nature of science addresses the characteristics of scientific knowledge itself and is perhaps easier described than defined. It depicts science as an important way to understand and explain what we experience in the natural world, and acknowledges the values and beliefs inherent to the development of scientific knowledge [5]. These three essential components of scientific literacy are highly interrelated and K-12 science instruction should reflect the synergy that exists among scientific knowledge, methods of science, and the nature of science. Finally, a basic understanding of mathematics and the nature of mathematics is one additional, necessary component to develop scientific literacy among students [6].

The Virginia *Science Standards of Learning* address each of the three principal components of scientific literacy [7]. The majority of standards in each content area focus on scientific knowledge. Science methods and process skills are primarily addressed in *SOL* X.1 of each content area or grade level. These methods and process skills in combination with scientific knowledge are used to perform scientific inquiry, where students investigate aspects of the world around them and use their observations to construct reasonable explanations. *Standards of Learning* X.1 also briefly refers to the nature of science. However, to understand more specifically what should be taught about the nature of science, one must refer to the *Curriculum Framework for the Virginia Standards of Learning* [8].

The purpose of this Task Force Report is to provide working definitions for both scientific inquiry and the nature of science, describe the rationale for teaching about these important aspects of science, and outline how scientific inquiry and the nature of science may be effectively addressed in K-12 classrooms.

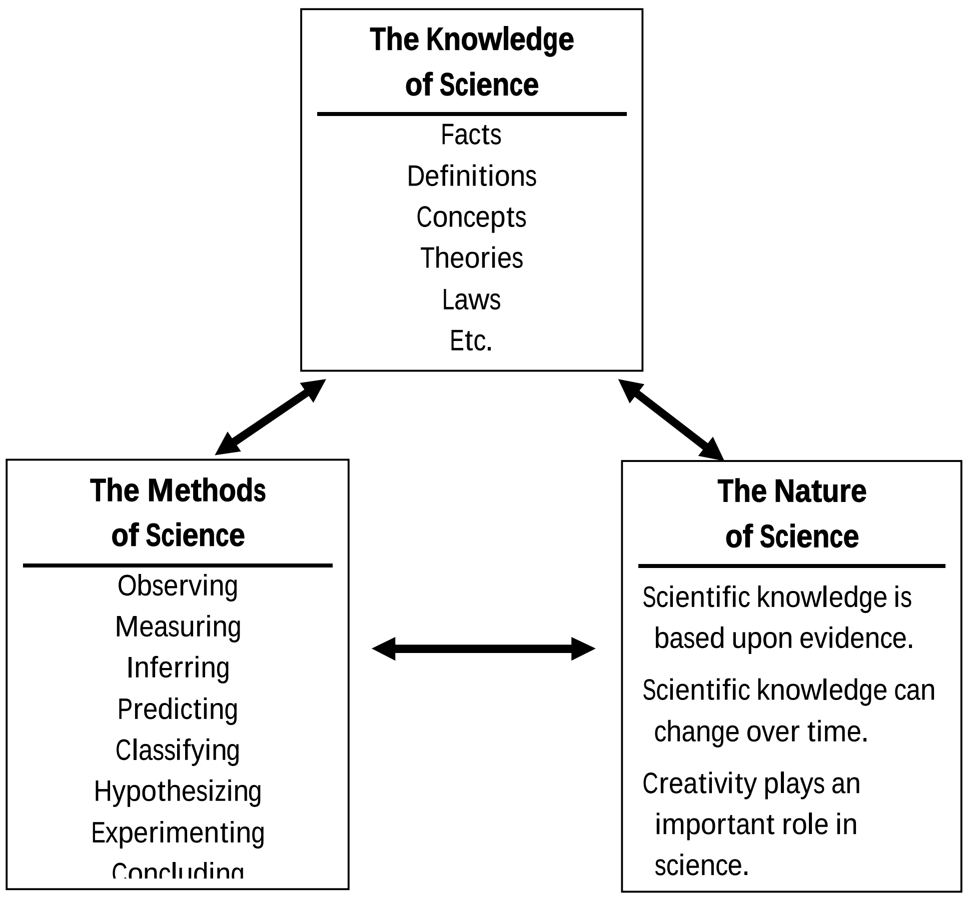

Figure 1. Three components of scientific literacy.

What Is Scientific Inquiry and Why Teach It?

Inquiry is at the heart of the scientific enterprise and, as such, demands a prominent position in science teaching and learning. The *National Science Education Standards (NSES)* refer to two important aspects of inquiry that are important to science instruction:

> Scientific inquiry refers to the ways in which scientists study the natural world and propose explanations based on evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world [2].

Engaging students in scientific inquiry is an important component of science instruction that helps students develop scientific literacy and provides them with the opportunity to practice important science process skills in addition to critical thinking and problem solving skills. Furthermore, research suggests that engaging students in scientific inquiry can lead to achievement gains in science content understanding, and critical thinking and problem solving skills [9].

The *NSES* describe both the essential understandings students should have about inquiry and the essential abilities necessary for students to do scientific inquiry [2]. According to the *NSES,* students should understand the following:

- scientists use many methods to conduct a wide variety of investigations;
- scientists rely on technology and mathematics; and,
- scientific explanations must be logically consistent, abide by rules of evidence, be open to questions and modification, and be consistent with current scientific knowledge [2].

In order to engage in scientific inquiry, the *NSES* propose that students should do the following:

- design and conduct scientific investigations;
- use technology and mathematics;
- formulate and offer explanations using logic and evidence; and,
- communicate and defend a scientific argument [2].

One way to think about inquiry is of a coin with two distinct sides. On one side is the content that students need to learn, including what students should be able to understand about the nature of scientific inquiry, as well as the attitudes and abilities they should develop by actively engaging in inquiry. Standard X.1 of the Virginia *Science Standards of Learning* focuses on this aspect of inquiry [7]. On the other side of the coin are the teaching approaches and learning strategies that enable teachers to teach science concepts through inquiry. While it is very important for teachers to be familiar with and incorporate Standard 1 in their instruction, they also need practical strategies for evaluating curriculum materials that are inquiry oriented and strategies for revising those that are not. Therefore, at its core, inquiry instruction can be defined simply as "an active learning process in which students answer a research question through data analysis" [10].

Teaching Scientific Inquiry

Far too often, teachers equate inquiry instruction with hands-on activities. While inquiry instruction is student-centered in that students are actively engaged, not all hands-on activities promote inquiry. Conversely, not all inquiry activities must be hands-on. It is possible for students to engage in inquiry through analyzing existing data, without the need for hands-on data collection. Many teachers believe that, in order for students to engage in inquiry-oriented activities, they must design investigations and carry them out on their own. This perception is too narrow. Students cannot be expected to design and carry out valid investigations without substantial support and instruction. Therefore, teachers should scaffold inquiry instruction to enable students to develop their inquiry abilities and understandings to the point where they can confidently design and conduct their own investigations from start to finish [11]. Further, instructional objectives should play a significant role in the design of an inquiry-based activity for a particular lesson. Luft, Bell, and Gess-Newsome provide content-specific examples of inquiry lessons that provide varied levels of support by teachers and are appropriately aligned with instructional objectives [12]. In some lessons, it might be best for students to learn a science concept inductively through inquiry-based experiences. For other lessons, the focus may be on developing specific inquiry skills, such as measuring and using lab equipment to collect data.

<u>Is It Inquiry?</u> **—** The primary question to consider when determining whether an activity is inquiry-based is: Are students answering a scientific question through data analysis? Many worthwhile hands-on activities traditionally performed in science classrooms do not involve students in these essential components of inquiry. For example, constructing a model of the atom, organizing a leaf collection, or building a soda-bottle water rocket can all be excellent instructional activities. However, unless these activities involve research questions and the opportunity to analyze data, they do not qualify as inquiry activities.

Thus, when evaluating whether an activity involves students in scientific inquiry, the first question for teachers to ask is: Does the activity include a research question? Specifically, does the activity include a research question that can be answered through a scientific investigation? Appropriate research questions include the following examples:

- Does the moon rise and set at the same time every night?
- How does concentration influence the rate of a particular reaction?
- What effect does the intensity of light have on plant growth?

Each of these questions can be answered through analysis of observational or experimental data. Note that scientific questions may be posed by the teacher or students, depending on the specific goals of the lesson and abilities of the students.

The second critical question in evaluating whether an activity supports inquiry is: Do students engage in data analysis to answer the research question? Activities in which students are simply gathering information from secondary sources via the Internet or library research are not inquiry activities. Students must analyze data themselves. Note, however, that students do not necessarily need to collect their own data in order to satisfy this condition. Data can be presented by the teacher to students for analysis or obtained from other sources, such as the Internet or a simulation. At the heart of this question is "Are students doing their *own* data analysis to draw conclusions and answer the research question?" It is essential to note that activities engaging students in pure observation may be inquiry-based if they meet the above criteria. It is not necessary for students to design and carry out *experiments* in order to do inquiry.

<u>Scaffolding Inquiry Activities</u> — When considering activities that fit the two conditions for inquiry, it is important to realize that not all inquiry activities are equivalent. Herron identified four levels of openness for inquiry in science activities [13]. Based partly on Herron's work, Rezba, Auldridge, and Rhea developed a four-level model of inquiry instruction, which was subsequently modified by Bell, Smetana, and Binns [10, 14]. This model of inquiry instruction illustrates how inquiry-based activities can range from highly teacher-directed to highly student-directed, based on the amount of information provided to the student (see Figure 2).

		How much information is given to the student?		
	Level of Inquiry	Question?	Methods?	Solution?
Teacher-Directed	1- Confirmation	✓	✓	✓
↕	2- Structured	✓	✓	
	3- Guided	✓		
Student-Directed	4- Open			

Figure 2. Four-level model of inquiry [10].

Level 1 and Level 2 activities are characterized as “low level” inquiry activities. They are often referred to as “cookbook labs,” in that the procedure is typically laid out for students in a step-by-step sequence. Level 1 inquiry activities provide students with the research question and the method through which the research question can be answered. Additionally, the expected answer to the research question is known in advance. In these activities, students are confirming what is already known. Level 2 inquiry activities, referred to as structured inquiry, are those in which students are given a research question and the prescribed procedure, but the answer to the research question is not known in advance. Note that a Level 1 activity can easily be changed to a Level 2 activity by changing when students do the activity with respect to instruction. For example, if students are taught a concept that provides them with the expected results of an inquiry activity before they perform it, the activity would be considered a Level 1. However, if the inquiry activity is completed prior to learning the concept such that students do not know the expected outcome, it would be considered a Level 2 activity.

Level 3 and Level 4 inquiry activities are characterized as “high level” inquiry activities, as they require significant cognitive demand on the part of the student. In Level 3 inquiry activities, students are presented with a teacher-posed research question, but students devise their own methods and solutions to answer the question. In this “guided inquiry,” students practice research design. A Level 1 or Level 2 inquiry activity can be transformed into a Level 3 activity by having students develop their own, teacher-approved method to answer the research question.

Level 4 inquiry activities are those in which students are responsible for choosing the research question, designing their own procedure for answering the question, and developing their own solutions to the research question. Only after students have completed activities at the first three levels are they prepared to tackle the open inquiry of Level 4.

By varying the amount of information provided to students, teachers can scaffold inquiry activities for their students over the course of the academic year. Teachers can model the process of scientific inquiry for students by beginning the year with Level 1 and Level 2 activities, eventually introducing Level 3 activities and Level 4 activities. By gradually transferring the amount of ownership and responsibility of inquiry activities to students, teachers can reduce the support provided to students during inquiry instruction to the point where students are ready to successfully design and conduct their own scientific investigations [10]. Appendix A provides a list of resources for inquiry activities, including examples of inquiry activities at each of these levels.

What Is the Nature of Science?

Understanding and actively engaging in scientific inquiry is only part of the picture when it comes to developing scientific literacy. Equally important is an understanding of the nature of science, or "science as a way of knowing." The nature of science has been defined in a variety of ways, and these definitions are hotly debated among philosophers and sociologists of science [15]. Some science educators have defined the nature of science as "the values and assumptions inherent to the development of scientific knowledge" [16]. One assumption central to the scientific enterprise is that the universe is knowable. Many of the assumptions and values related to the scientific endeavor are too abstract and esoteric to be meaningful to K-12 students [17]. Therefore, the major science education organizations have delineated the nature of science concepts that should be addressed in K-12 classrooms [1, 2, 18]. These documents paint a consistent picture of the nature of science that is most appropriate for developing scientific literacy among students, and there is little debate over these key components of the nature of science appropriate for K-12 instruction [19, 20]. The following is a brief description of seven key characteristics of the nature of science.

1) **Scientific knowledge is empirically based—**"Empirical" refers to knowledge claims based upon observations of the natural world. While some scientific ideas are theoretical and are derived from logic and reasoning, all scientific ideas must

ultimately conform to observational or experimental data. Empirical evidence, in the form of quantitative and qualitative data, forms the foundation for scientific knowledge.

2) **Scientific knowledge is both reliable and tentative—**Scientific knowledge should not be viewed as absolute, but tentative and revisionary. For example, many scientific ideas have remained largely unchanged over long periods of time; however, scientific knowledge can change in light of new evidence and new ways of thinking. New scientific ideas are subject to skepticism, especially if they challenge well-established scientific ideas. Once generally accepted by the scientific community, scientific knowledge is durable. Therefore, it is reasonable to have confidence in scientific knowledge while still recognizing that new evidence may result in changes in the future. Related to the tentative nature of science is the idea that regardless of the amount of empirical evidence supporting a scientific idea (even a law), it is impossible to prove that the idea holds for every instance and under every condition. Einstein's modifications to the well-established Newtonian Laws are a classic case in point. Thus, "Truth" in the absolute sense lies outside the scope of science [21]. Scientific laws do not provide absolutely true generalizations; rather, they hold under very specific conditions [22, 23]. Scientific laws are our best attempts to describe patterns and principles observed in the natural world. As human constructs, these laws should not be viewed as infallible. Rather, they provide useful generalizations for describing and predicting behavior under specific circumstances.

3) **Scientific knowledge is the product of observation and inference—**Scientific knowledge is developed from a combination of both observations and inferences. Observations are made from information gathered with the five senses, often augmented with technology. Inferences are logical interpretations derived from a combination of observation and prior knowledge. Together, they form the basis of all scientific ideas. An example of the interplay of observation and inference is the manner in which we determine the distances to stars. Stars are so far away that only a relatively small fraction of star distances can be measured through direct observation and the application of geometry. For the rest of the stars and other distant celestial objects, a complex combination of observations and

inferences must be employed (see Murphy and Bell, 2005 for a more complete description of how astronomers determine distances to stars) [24].

4) **Scientific knowledge is the product of creative thinking**—Scientists do not rely solely on logic and rationality. In fact, creativity is a major source of inspiration and innovation in science. Scientists often use creative methods and procedures throughout investigations, bound only by the limitation that they must be able to justify their approaches to the satisfaction of their peers. Within the limits of peer review, creativity permeates the ways scientists design their investigations, how they choose appropriate tools and models to gather data, and how they analyze and interpret their results. Creativity is clearly evident in Darwin's synthesis of the theory of natural selection from a wide variety of data and ideas, including observations from his voyage on the *H.M.S. Beagle*, his understanding of the geologic principles of Lyell, and even Malthus' theory of populations. Although known as a careful and methodical observer, Darwin’s recognized genius stems from his creative work of synthesizing a powerful scientific explanation from a variety of sources and clues.

5) **Scientific laws and theories are different kinds of scientific knowledge—**A scientific law is a description of a generalized relationship or pattern, based on many observations. Scientific laws describe *what* happens in the natural world and are often (but not always) expressed in mathematical terms. Scientific laws are simply descriptive—they provide no explanation for why a phenomenon occurs. For example, under relatively normal conditions, close to room temperature and pressure, Boyle’s law describes the relationship between the pressure and volume of a gas. Boyle’s law states that at constant temperature, the pressure of a gas is inversely proportional to its volume. The law expresses a relationship that describes *what* happens under specific conditions, but offers no explanation for *why* it happens. Explanations for why this relationship exists require theory. Scientific theories are well-supported explanations for scientific phenomena. Theories offer explanations for *why* a phenomenon occurs. For example, the kinetic molecular theory explains the relationship expressed by Boyle’s law in terms of the inherent motion of the molecular particles that make up gases. Scientific theories and laws are similar in that both require substantial evidence before they are generally accepted by scientists. Additionally, either

can change with new evidence. However, since theories and laws constitute two different types of scientific knowledge, one cannot change into the other.

6) **Scientists use many methods to develop scientific knowledge—**There exists no single "scientific method" used by all scientists. Rather, scientists use a variety of approaches to develop and test ideas, and to answer research questions. These include descriptive studies, experimentation, correlation, epidemiological studies, and serendipitous discovery. What many refer to as the "the scientific method" (testing a hypothesis through controlling and manipulating variables) is really a basic description of how *experiments* are done. As such, it should be seen as an important way, but not the only way, that scientists conduct investigations, as scientists can make meaning of the natural world using a variety of methodologies.

7) **Science is a social activity that possesses inherent subjectivity—**Science is a human endeavor and, as such, it is open to subjectivity. For example, the scientific questions considered worth pursuing, the observations that count as data, and even the conclusions drawn by scientists are influenced to some extent by subjective factors. Such factors as the existing scientific knowledge, social and cultural contexts, external funding sources, and the researchers' experiences and expectations can influence how they collect and analyze data, and how they draw conclusions from these data. While subjectivity cannot be totally removed from scientific endeavors, scientists strive to increase objectivity through peer review and other self-checking mechanisms.

These seven tenets of the nature of science present a more appropriate view of scientific knowledge and address the major misconceptions about science documented by science educators [19, 25]. Taken as a whole, they serve as reminders that a principal strength of scientific knowledge is that it can change as needed and is required to better fit existing data. However, it is important to realize that change in science is not arbitrary. Scientific knowledge changes only as a result of further inquiry, debate, collaboration, and evidence. Thus, changes in science move our understandings toward important "truths" about the natural world. Although these truths should not be viewed as absolute or final, they are among the most reliable that we have at any given point in time. No other means of inquiry has proven more successful or trustworthy. One need only consider the advances in science-related fields, such as medicine, agriculture, and engineering, for verification that science works.

Why Teach the Nature of Science?

Science educators and researchers have presented a variety of rationales for teaching about the nature of science. Perhaps the most straightforward justification is that an accurate understanding of the nature of science helps students identify the strengths and limitations of scientific knowledge, develop accurate views of how science differs from other ways of knowing, and helps students delineate the types of questions science can and cannot answer [26]. Additionally, research suggests that teaching students the nature of science can enhance their content knowledge and increase student achievement [27-29]. Furthermore, an appropriate understanding of the nature of science is essential to understanding the relationship between science and religion, the controversy over "creation science" and "intelligent design," and the essential differences between scientific and non-scientific disciplines [30]. Additionally, teaching the nature of science helps increase awareness of the influence of scientific knowledge on society [31-33]. Research also indicates that teaching the nature of science may increase student interest in science by making instruction more engaging and meaningful [32, 33]. Most importantly, developing appropriate conceptions of the nature of science is cited as a critical aspect of scientific literacy and, as such, is central to national standards documents and the *SOL* [1, 2]. Examples of the *SOL* that address each of the seven aspects of the nature of science presented in the previous section are included in see Appendix B.

Effective Nature of Science Instruction

Science instruction should help students develop meaningful understandings about the foundational and somewhat abstract concepts that constitute the nature of science. Research indicates that explicitly teaching students the nature of science, allowing students to experience the nature of science in a meaningful context, and linking the nature of science to process skills instruction are three specific ways educators can make instruction about the nature of science effective and engaging for students.

A large body of research indicates that the most effective way to teach nature of science concepts is through explicit instruction [15, 34, 35]. Explicit refers to making the nature of science a specific goal of instruction, with lesson objectives, activities, and assessments all including specific aspects of the nature of science when it is appropriate to do so. While nature of science instruction should be explicit, this does not mean that it must be didactic. Students are not likely to glean a meaningful understanding of the nature of science merely from having someone tell them that science is empirically based or that theories cannot become laws. Rather, particular aspects of the nature of science should be illustrated to students within the context of inquiry activities, exploration of socio-scientific issues, and discussions of key episodes in science history. Learning in a meaningful context can help students assimilate the abstract elements of the nature of science more deeply than memorizing a list of the key concepts.

Engaging students in hands-on science activities alone will not likely lead them to appropriate understandings of the nature of science and the scientific enterprise [34]. Rather, students must engage in purposive discussion and reflection about the nature of science in order to learn about the nature of science:

> Learning about the nature of science requires explicit discussion and reflection on the characteristics of scientific knowledge and the scientific enterprise—activities students are not apt to engage in on their own, even when conducting experiments. Students need someone to guide them through the process of learning *about* science as they *do* science [26].

Thus, effective nature of science instruction requires students both to engage in science and to reflect on what they learned about the scientific enterprise. To this end, linking nature of science concepts to process skills instruction has been shown to be effective [36]. In this approach, students learn about the nature of science and the scientific enterprise as they develop the skills necessary to do science. The teacher explicitly links nature of science concepts to activity-based lessons incorporating science process skills, such as observing, inferring, predicting, measuring, and classifying. Bell provides dozens of activities that utilize this process skills-based approach to nature of science instruction [26]. Additional resources for teaching the nature of science are provided in Appendix A.

Research has demonstrated that effective nature of science instruction does not come naturally for most teachers. Some confuse teaching the nature of science with inquiry and process skills [17]. Others do not consider the nature of science to be a necessary component of the science curriculum [37, 38]. Still others may possess the same misconceptions about science as their students [15]. Including the nature of science in the Virginia *Science Standards of Learning* is an important first step toward legitimizing nature of science instruction and delineating what teachers should teach [7]. However, knowing what to teach and actually teaching it are not the same. Implementing nature of science instruction requires specific professional development that includes instruction on what the nature of science is and how to teach it, as well as support for teachers as they begin to integrate the nature of science into their own instruction [37, 39, 40].

Conclusion

Science is more than a body of knowledge and a way of developing and validating that knowledge. Science is a social activity that reflects human values, including curiosity, creativity, integrity, and skepticism. Developing scientific literacy requires meaningful, engaging instruction that integrates the knowledge of science, the methods of science, and the nature of science. Scientific inquiry as both content and as a process for learning provides opportunities for students to develop inquiry skills, use critical thinking, and deepen their understanding of science content. Furthermore, research strongly supports our experience that students enjoy the challenges of scientific inquiry when given appropriate support, and that they are enthusiastic participants in learning about the nature of science and how we know what we know. Teaching the nature of science and inquiry encourages students to develop scientific habits of mind that will enable them to be effective decision makers beyond the classroom.

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Appendix A
Teaching Resources for Inquiry and Nature of Science
Resources for Teaching Inquiry

Books:

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Appendix B
Nature of Science in the *Virginia Standards of Learning* Curriculum Framework

NOS Tenet	*SOL/Curriculum Framework* Examples
Scientific knowledge is empirically based.	K.1 Observation is an important way to learn about the world. Through observation one can learn to compare, contrast, and note similarities and differences. 4.1 Accurate observations and evidence are necessary to draw realistic and plausible conclusions. BIO.1 The analysis of evidence and data is essential in order to make sense of the content of science.
Scientific knowledge is tentative.	PS.1 The analysis of data from a systematic investigation may provide the researcher with a basis to reach a reasonable conclusion. Conclusions should not go beyond the evidence that supports them. Additional scientific research may yield new information that affects previous conclusions. BIO.2 The scientific establishment sometimes rejects new ideas, and new discoveries often spring from unexpected findings. CH.1 Constant reevaluation in the light of new data is essential to keeping scientific knowledge current. In this fashion, all forms of scientific knowledge remain flexible and may be revised as new data and new ways of looking at existing data become available.
Scientific knowledge is the product of observation and inference.	4.1 An *inference* is a conclusion based on evidence about events that have already occurred. Accurate observations and evidence are necessary to draw realistic and plausible conclusions. 4.1 To communicate an observation accurately, one must provide a clear description of exactly what is observed and nothing more. Those conducting investigations need to understand the difference between *what is seen* and what inferences, conclusions, or interpretations can be drawn from the observation.

	5.1 Scientific conclusions are based both on verifiable observations (science is empirical) and on inferences.
Scientific knowledge is the product of creative thinking.	PS.1 Scientists rely on creativity and imagination during all stages of their investigations. PH.3 Science is a human endeavor relying on human qualities, such as reasoning, insight, energy, skill, and creativity as well as intellectual honesty, tolerance of ambiguity, skepticism, and openness to new ideas.
Scientific laws and theories are different kinds of scientific knowledge.	ES.1 *Scientific laws* are generalizations of observational data that describe patterns and relationships. Laws may change as new data become available. ES.1 *Scientific theories* are systematic sets of concepts that offer explanations for observed patterns in nature. Theories provide frameworks for relating data and guiding future research. Theories may change as new data become available.
Scientists use many methods to develop scientific knowledge.	LS.1 Investigations can be classified as *observational* (descriptive), *studies* (intended to generate hypotheses), or *experimental studies* (intended to test hypotheses). LS.1 Experimental studies sometimes follow a sequence of steps known as the Scientific Method: stating the problem, forming a hypothesis, testing the hypothesis, recording and analyzing data, stating a conclusion. However, there is no single scientific method. Science requires different abilities and procedures depending on such factors as the field of study and type of investigation. PS.1 Different kinds of problems and questions require differing approaches and research. Scientific methodology almost always begins with a question, is based on observation and evidence, and requires logic and reasoning. Not all systematic investigations are experimental.
Scientific knowledge is subjective and culturally influenced.	PS.1 Investigation not only involves the careful application of systematic (scientific) methodology, but also includes the review and analysis of prior research related to the topic. Numerous sources of information are available from print and electronic sources, and the researcher needs to judge the authority and credibility of the sources. BIO.1 It is typical for scientists to disagree with one another about the interpretation of evidence or a theory being considered. This is partly a

	result of the unique background (social, educational, etc.) that individual scientists bring to their research. Because of this inherent subjectivity, scientific inquiry involves evaluating the results and conclusions proposed by other scientists.