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Valarie L. Akerson
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# Critical Questions in STEM Education

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# Foreword to *Critical Questions in STEM Education*

For those working in STEM education as teachers, principals, teacher educators, and researchers, a central concern in recent years is developing a consensus on what STEM education can and should be, in terms of curricular content, pedagogy, and application to real-world problems. Perhaps heightening a sense of urgency regarding this task is STEM's near-juggernaut quality as an educational movement internationally. Meanwhile, a rush by various discipline advocates to claim curricular "terrain" in K-12 STEM has led to calls for STEAM (adding art), STREAM (reading), CSTEM (coding or computer science), and so on, which complicates development of a clear understanding of what STEM education should include. STEM as "ambiguous slogan" (Bybee 2013) nonetheless has rapidly diffused across many mass education systems, proving to be an effective tool to advocate for resources (Shaughnessy 2012). The contributions in this volume offer several cornerstones, comprising the parts of the book, from which to examine questions about the contours of STEM in a thoughtful and research-informed manner. The point of departure here is a working definition of STEM that includes a renewed focus on the variation across individual disciplines as well as the meaningful interdependence that connects disciplines constituting STEM.

Since the early days of STEM being promoted as a kind of curricular package, a frequent element of the sloganeering blithely portrayed STEM education as "integrated" and "interdisciplinary," even as curriculum scholars have emphasized the tremendous difficulty for interdisciplinary knowledge to secure a place in the school curriculum. STEM education scholars could benefit from prior work on the challenges of developing and implementing interdisciplinary curricula, however appealing their ring, such as in social studies and "humanities" (Ravitch 2003; Wineburg & Grossman 2000). In this volume, we find a serious attempt to conceptualize the limits of the interdisciplinarity of STEM, starting in the first part with a series of chapters articulating the "nature of" each of the four areas (extending Lederman's groundbreaking work on the nature of science) and their varied epistemological and ontological underpinnings. In an overview of this first part, Akerson and colleagues boldly suggest that given the substantial differences in the core natures of the disciplines (and even within each area), there can be no analogous and fully coherent "nature of STEM." If these scholars are right, the implicit question emerges regarding how truly integrated and interdisciplinary STEM can be.

This tension is illustrated in Part 2, which views STEM education from the ground up, considering approaches to teaching STEM, both at the level of the classroom and the school, but also the challenges in preparing teachers to support integrated STEM learning. The self-study by Yin (Chap. 7) is particularly illustrative on this point, as even a seasoned science teacher educator struggled to balance and integrate all four major fields in a STEM education course for pre-service teachers. University Technical Colleges in England (Dobrin, Chap. 8) offer an organizational form that affords opportunities and time to both integrate and apply STEM knowledge, but even there, students are encouraged to choose areas of particular interest to focus on during group projects (e.g., "Do the part you are interested in"), effectively de-integrating the STEM work to some extent.

The final part raises broader questions about perceptions of STEM by various stakeholders. Perhaps, in a sense, school-based STEM is what school STEM does. Newman and colleagues (Chap. 10) consider how schools certified as "STEM schools" by the state of Indiana portray STEM, while Sgro, Bobowski, and Oliveira (Chap. 11) systematically consider visions of STEM proffered by practitioner journals, demonstrating the difficulty of meaningfully integrating across all four areas. In both chapters, STEM integration is threatened by the dominance of one or more of the component disciplines. Sgro and his co-authors resolve this by taking the position that STEM cannot be a discipline in its own right, but rather should be seen as a "meta-discipline." When considering experiences and the STEM identity of college students majoring in and in some cases switching out of STEM, Song, et al. (Chap. 13) ground coding decisions about what is and what isn't a "STEM major" based on whether the major was located in the institution's College of Natural Sciences and Mathematics, which raises questions of how new or rapidly changing fields (like psychology) are classified with respect to the STEM umbrella. In the end, there are numerous echoes of the doubts raised in Part 1 about whether there can be a coherent "nature of STEM."

Rather than hunting down a perfectly balanced and interdisciplinary "quark" (Renyi, 2000) called STEM, the brightest potential for STEM education may lie in its core focus on engaging with complex, "ill-formed" problems, as highlighted in many of the contributions here. Comprising a vigorous pedagogical culture (Weld, 2017), rather than a strictly delineated and official school subject, the varied tools of STEM could be used as a springboard into learning to analyze Shakespeare, predict profits, develop video games, and address and communicate about environmental problems or model voter turnout. It all potentially demands quite rigorous STEM thinking, obviating the need for demarcating "proper" applications of STEM in schools. The contributions in this volume point in this direction, implicitly answering Zollman's (2012) call for "STEM literacy for learning," serving as a helpful resource for leaders in STEM education at all levels.

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# Preface

This edited book resulted from our efforts to develop an understanding of the nature of STEM knowledge for our doctoral students and ourselves. It began as a graduate seminar in science education where we explored the natures of the individual STEM disciplines (science, technology, engineering, and mathematics) and research in STEM education alongside our students. The intention was to find overlaps among the characteristics of science, technology, engineering, and mathematics knowledge and develop an idea about the nature of STEM from those overlapping ideas. Over the course of the semester, however, we came to question if there could be a separate nature of STEM knowledge if it is a combination of existing knowledge bases. Further complicating the academic journey was the fact that most STEM research focus on one of the disciplines that comprises STEM itself. We subsequently explored what would STEM teacher education research look like if all the disciplines were truly intertwined and how does this image compare to educators and educational researchers' existing perceptions of STEM. Our journey grew to include teacher educators from different disciplines in higher education institutions across the country. That academic journey was so powerful that we sought to expand the discussion throughout our educational community with this edited book.

This book explores critical questions in STEM education. The questions were prompted by a desire to respond to the educational demands that twenty-first century teachers, and subsequently teacher educators, have had placed on them. When previously they have been teachers of individual disciplines, such as science, math, or technology (and occasionally engineering), they are now often considered STEM teachers. The purpose of the book is to provide a practical resource for teacher educators who seek to prepare teachers to address STEM in a meaningful and interdisciplinary manner. It is not a thorough ontological or epistemological treatment of STEM, although such considerations certainly provide the framework for the writings.

There are three parts within the book, all of which adhere to the definition of STEM as a meaningful interdependence among all disciplines that comprise STEM. In other words, all individual disciplines of STEM are included in ways that are meaningful and showcase the interdependence of the fields. The first part, Nature of the STEM Disciplines, provides the foundation for the discussion of meaningful interdependence by establishing the natures of the component disciplines of STEM (science, technology, engineering, and mathematics). This part does not include epistemological or ontological treatments of the disciplines but rather practical discussion for teaching and research. Concluding this part, the editors explore whether there is a separate STEM discipline with its own nature as well as the challenges and benefits of presuming a nature of STEM. The second part, Critical Questions in Teaching STEM, features applied research on critical questions teacher educators are actively exploring. Chapters in this part showcase their action research, case studies, self-studies, and other classroom-based research connected to learning to effectively prepare classroom teachers to teach STEM in meaningful and interdisciplinary ways. The third part, Critical Questions in STEM, includes chapters that systematically explore and discuss the overall applied constructs of STEM education. These chapters explore such ideas as public perceptions of STEM education, phenomenological case studies on STEM experiences, and content analyses of STEM education documents and texts.

The book you hold is the result of very real and interesting discussions among scholars of teacher education. It includes scholars from all four STEM education disciplines and applied research across these disciplines. Working on this volume has been a very interesting process, and we hope this contribution will be helpful to the fields that comprise STEM and stimulate conversations across the fields.

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# About the Editors

**Valarie L. Akerson** is a Professor of Science Education at Indiana University and a former elementary teacher. Her research focuses on preservice and inservice elementary teachers' ideas about Nature of Science as well as their teaching practices. She is a Past President of the Association for Science Teacher Education and a Past President for NARST: a worldwide organization for improving science teaching and learning through research.

**Gayle Buck** is an Associate Dean for Research, Development and Innovation as well as a Professor of Science Education. Previously a middle-level science teacher in both urban and rural schools, Professor Buck now teaches courses in science, STEM education, and teacher education. Her research explores (1) student populations traditionally underserved in science education, (2) neglected epistemological assumptions in teaching and learning, and (3) pragmatic and participatory approaches to educational research.

# Part I
# Nature of the STEM Disciplines

# Chapter 1
# Nature of Scientific Knowledge and Scientific Inquiry

**Norman G. Lederman and Judith Lederman**

## 1.1 Introduction

Before carefully considering how nature of scientific knowledge (NOSK) and scientific inquiry (SI) relate to science, technology, engineering, and mathematics (STEM), it is critical to "define" or explain what is meant by "science." There are many conceptualizations of science. The rotunda in the National Academy of Science contains the following inscription: "To science, pilot of industry, conqueror of disease, multiplier of the harvest, explorer of the universe, revealer of nature's laws, eternal guide to truth. "The quote is not attributed to any individual and the building was built in 1936. It is not clear if the quote is older than 1936. Nobel Prize winning physicist Richard Feynman defined science in the 1970s as "the belief in the ignorance of experts (Feynman & Cashman, 2013). Most recently, Arthur Boucot (famous paleobiologist) in a personal conversation characterized science as "an internally consistent set of lies designed to explain away the universe." These statements are quite varied and as provocative as Boucot's and Feynman's definitions may be they are closer to how science is characterized in recent reform documents, such as the *Next Generation Science Standards* (NGSS Lead States, 2013) and the *National Science Education Standards* (National Research Council, 1996). The question still remains, "what is science?" What conceptualization would be most appropriate for K-12 learners? Commonly, the answer to this question has three parts. First, science is a body of knowledge. This refers to the traditional subjects or body of concepts, laws, and theories. For instance, biology, chemistry, physics etc. The second part refers to how the knowledge is developed. That is scientific inquiry. Inquiry will be discussed in more detail later, but as a student outcome it usually includes the doing of inquiry (e.g., asking questions, developing a design,

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collecting and analyzing data, and drawing conclusions). Additionally, inquiry as a student outcome also includes knowledge about inquiry (e.g., knowing that all investigations begin with a question, there is no single scientific method, research questions guide the procedures, etc.).

Finally, because of the way the knowledge is developed, scientific knowledge has certain characteristics. These characteristics of scientific knowledge are often referred to as nature of scientific knowledge (Lederman, Lederman, & Antink, 2013). Again, these characteristics will be discussed in more detail later, but they usually include, but are not limited to the idea that science is empirically based, involves human creativity, is unavoidably subjective, and is subject to change (Lederman, Wade, & Bell, 1998). Often individuals conflate nature of scientific knowledge (NOSK) with scientific inquiry. Lederman (2007) also notes that the conflation of NOSK and scientific inquiry has plagued research on NOSK from the beginning and, perhaps, could have been avoided by using the phrase "nature of scientific knowledge" as opposed to the more commonly used nature of science (NOS). In this chapter, we will use the term "nature of scientific knowledge" instead of "nature of science" as it more accurately represents its intended meaning (Lederman & Lederman, 2004). Now the critical point is what is the appropriate balance among the three components of science in the science curriculum and science instruction? Current reforms have appropriately recognized that the amount of emphasis has traditionally emphasized the body of knowledge to the detriment of any emphasis on inquiry or nature of scientific knowledge.

Current visions of science education are returning to the perennial goal of scientifically literacy. Again, the roots of scientific literacy and its justification will be discussed in more detail later. But, in general, the goal is to help students use their scientific knowledge to make informed decisions about scientifically based global, societal, or personal decisions. The literate individual can not make such decisions based on scientific knowledge alone. They must also understand the source of the knowledge (i.e., scientific inquiry or the more current term science practices) and the ontological characteristics of the knowledge (i.e., NOSK).

The focus of this chapter is to elaborate on how the interplay among scientific inquiry, NOSK, and STEM may, or may not, contribute to the achievement of scientific literacy. Thus this begs the question of "What is STEM?" For sure STEM has been discussed in each of the chapters in this book. For the sake of brevity, a brief conceptualization follows. STEM has become one of the newest slogans in education, and some critics have noted its ubiquitous and ambiguous use (Bybee, 2013) throughout policy and science education literature. Bybee (2013) coined the phrase "STEM literacy" to make the goal of STEM education more explicit. A STEM approach to science instruction and curriculum incorporates real life problematic situations that require knowledge of nature of scientific knowledge and scientific inquiry, in part, which leads toward the end goal of scientific literacy. Therefore, it could be argued that scientific literacy is the ultimate goal of the integrated STEM approach. It is important to note, here, that contrary to prevalent misconceptions, STEM goes well beyond just placing more emphasis on each of the STEM disciplines. The integration of the STEM disciplines is the intent of the STEM movement. Again, this chapter will focus on whether the interplay of scientific inquiry, nature of scientific knowledge, and STEM can facilitate the development of scientific literacy.

## 1.2 Scientific Literacy as the Primary Goal of Science Education

Why should our students learn science and to what extent? Are we teaching our students to make them scientists? What happens to those students who do not continue studying science? Don't they need to learn a minimum amount of science? These questions are critical to portray the goal of science education. Science educators believe that the goal of science education is to develop scientific literacy. Since the first use of 'scientific literacy' in the late 1950s, science educators and policy makers have gradually reconceptualized the term to such an extent that one author remarked relatively recently that "scientific literacy is an ill-defined and diffuse concept" (Laugksch, 2000, p. 71). Policy makers and educators often get confused between "science literacy" and "scientific literacy." Often they are considered synonymous, although the two have very different meanings. Science literacy focuses on how much science you know. It is not about applying knowledge and making decisions. "Science literacy" is mostly associated with AAAS Project 2061 (American Association for the Advancement of Science, 1993). In 1985 AAAS, the Carnegie Corporation of New York and the Andrew W. Mellon Foundation launched a project that promised to be radical, ambitious, comprehensive and long-term, in other words, risky and expensive (American Association for the Advancement of Science, 1994). With that philosophy, the program was aptly named "Project 2061." In view of the numerous local, state, and national obstacles and turf infringements, many wondered whether it would take that long to achieve the goals of the program. *Benchmarks for Science Literacy* is the Project 2061 statement of what all students should know and be able to do in science, mathematics, and technology by the end of grades 2, 5, 8, and 12. The recommendations at each grade level suggested reasonable progress toward the adult science literacy goals laid out in the project's 1989 report *Science for All Americans AAAS, 1989). Benchmarks* helped educators decide what to include in (or exclude from) a core curriculum, when to teach it, and why.

On the other hand, "scientific literacy" deals with the aim of helping people use scientific knowledge to make informed decisions. This is a goal that science educators have been striving to achieve, but unfortunately many of us have not truly realized the importance of scientific literacy or might have misrepresented the goal in various platforms. DeBoer (2000) states that the term "scientific literacy" since it was introduced in the late 1950s has defied precise definition. Although it is widely claimed to be a desired outcome of science education, not everyone agrees with what it means.

The goal of science education became formalized at different times in history. After the 1960s the science education community became concerned about the role of science in society, especially given the launching of Sputnik by the Soviet Union in 1957. This event led to a significant increase in funding for science education in an attempt to increase the science pipeline. The primary driving forces were concerns for national security and economic health. In the immediate post-war years, it was proposed that science educators should work to produce citizens who understood science and were sympathetic to the work of scientists (DeBoer, 2000). The U.S. was lacking in producing a workforce who could live and work in such a rapidly changing world. The goals of science teaching, for general education purposes, within this new environment came to be called scientific literacy. According to the Rockefeller Brothers Fund (1958) report, "among the tasks that have increased most frighteningly in complexity is the task of the ordinary citizen who wishes to discharge his civic responsibilities intelligently" (p. 351). The answer was scientific literacy. The Board said:

> Just as we must insist that every scientist be broadly educated, so we must see to it that every educated person be literate in science]…. We cannot afford to have our most highly educated people living in intellectual isolation from one another, without even an elementary understanding of each other's intellectual concern. (p. 369)

The national review of Australian science teaching and learning (Goodrum, Rennie, & Hackling, 2001) defined the attributes of a scientifically literate person. In particular, it stated that a scientifically literate person is (1) interested in and understands the world about him, (2) can identify and investigate questions and draw evidence-based conclusions, (3) is able to engage in discussions of and about science matters, (4) is skeptical and questioning of claims made by others, and (5) can make informed decisions about the environment and their own health and wellbeing.

The current NGSS stresses science practices, but there is very little emphasis on understanding the practices or scientific inquiry and NOSK. Later in this chapter the critical role of scientific inquiry and NOSK for the achievement of scientific literacy will be elaborated in detail. Doing science is necessary as a means, but it should not be the end goal. The end goal should be scientific literacy, which unfortunately is not explicitly mentioned in the standards.

## 1.3 STEM as a Mechanism to Achieve Scientific Literacy

STEM education must have an educative purpose which goes beyond the slogan "to meet 21st century skills." In the 1990s, the National Science Foundation (NSF) introduced the STEM acronym as an instructional and curricular approach that stresses the integration of science, technology, engineering, and mathematics. But, its ubiquitous and ambiguous use in the education community has created much confusion (Angier, 2010). One of the possible reasons could be the lack of consensus on the meaning of STEM. However, even without a common understanding of

STEM, the development and implementation our STEM curriculum over the years has not been deterred. Bybee (2013) addressed four components of STEM literacy. STEM literacy refers to an individual's

- knowledge, attitudes, and skills to identify questions and problems in life situations, explain the natural and designed world, and draw evidence-based conclusions about STEM related-issues
- understanding of the characteristic features of STEM disciplines as forms of human knowledge, inquiry, and design;
- awareness of how STEM disciplines shape our material, intellectual, and cultural environments; and
- willingness to engage in STEM-related issues and with the ideas of science, technology, engineering, and mathematics as a constructive, concerned, and reflective citizen.

From the above components of STEM literacy, it is evident that students need to have experiences to apply their knowledge and skills. But the debate over other aspects of STEM education has not been settled yet. For instance, is STEM a separate discipline or just an integrated curriculum approach? The idea of considering STEM as a separate discipline has been a puzzle for many science educators. STEM disciplines are all different ways of knowing and have different conventions for what constitutes data and evidence. STEM is an integrated curriculum approach, but because it deals with different ways of knowing, true integration is never achieved; just an interdisciplinary connection. Individual STEM disciplines "are based on different epistemological assumptions" and integration of the STEM subjects may detract from the integrity of any individual STEM subject (Williams, 2011, p. 30). If STEM is conceptualized as a curriculum approach, its interdisciplinary nature entails not just the acquisition and application of scientific knowledge, but also the other knowledge bases. Wang, Moore, Roehrig, and Park (2011) explained that *interdisciplinary integration* begins with a real-world problem. It incorporates cross-curricular content with critical thinking, problem-solving skills, and knowledge in order to reach a conclusion. Students engage themselves in different real-life STEM related personal and societal situations to make informed decisions. More specifically, STEM curriculum in classrooms and programs can ensure five skill sets including adaptability, complex communications, nonroutine problem solving, self-management, and systems thinking (NRC, 2008). The National Research Council (2010) elaborated on these five skills in its report, *Exploring the Intersection of Science Education and 21st-Century Skills*. Furthermore, in a second report (NRC, 2012), *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century* it was emphasized that these 21st century skills are necessary if students are to solve the personal and societal problems. This is what it means to be an informed citizen. If we put the components of scientific literacy alongside STEM in terms of science instruction, it can be argued that both focus on the context of the world we live in and the decisions we make in everyday life. Those decisions are not just based on science. Different social, political, cultural perspectives are all part of these decisions. While making those decisions, people are supposed to apply some of their other knowledge bases such as mathematical reasoning and technological and engineering processes. For example, if individuals are supposed to make any decisions about whether wind or solar energy is best for the environment and economy, it must be kept in mind that the solution is not just based on scientific knowledge, but also knowledge of other technical or engineering features that explain how these two types of energy sources actually operate. Further, mathematical knowledge is needed to be able to calculate the economic efficiency of the two sources of energy. Can we imagine any activity that requires this type of decision making as a part of the STEM curricular approach? The answer is clearly yes. Thus, it can be argued that STEM as an instructional and curricular approach is consistent with the idea of scientific literacy.

## 1.4 The Role of Scientific Inquiry in Science Education

As previously discussed, the unclear definitions and multiple uses of the phrase "scientific literacy" resulted in much confusion. However, the phrase "scientific inquiry" is guilty of the same. What it means has been elusive and it is at least one of the reasons why the *Next Generation Science Standards* (NGSS Lead States, 2013) emphasizes "science practices" as opposed to scientific inquiry. The *National Science Education Standards ([NSES]* National Research Council, 1996*)* arguably made the most concerted effort to unpack the meaning of scientific inquiry. The NSES envisioned scientific inquiry as both subject matter and pedagogy in its three part definition. However, with all the effort, confusion remained and the National Research Council had to develop an addendum of sorts, a few years later, titled *Inquiry and the National Science Education Standards* (NRC, 2000). On the one hand, scientific inquiry was conceptualized as a teaching approach. That is, the science teacher would engage students in situations (mostly open-ended) they could ask questions, collect data, and draw conclusions. In short, the purpose of the teaching approach was to enable students to learn science subject matter in a manner similar to how scientists do their work. Although closely related to science processes, scientific inquiry extends beyond the mere development of process skills such as observing, inferring, classifying, predicting, measuring, questioning, interpreting and analyzing data. Scientific inquiry includes the traditional science processes, but also refers to the combining of these processes with scientific knowledge, scientific reasoning and critical thinking to develop scientific knowledge. From the perspective of the *National Science Education Standards* (NRC, 1996), students are expected to be able to develop scientific questions and then design and conduct investigations that will yield the data necessary for arriving at answers for the stated questions.

Scientific inquiry, in short, refers to the systematic approaches used by scientists in an effort to answer their questions of interest. Pre-college students, and the general public for that matter, believe in a distorted view of scientific inquiry that has resulted from schooling, the media, and the format of most scientific reports. This distorted view is called THE SCIENTIFIC METHOD. That is, a fixed set and sequence of steps that all scientists follow when attempting to answer scientific questions. A more critical description would characterize THE METHOD as an algorithm that students are expected to memorize, recite, and follow as a recipe for success. The visions of reform, as well as any study of how science is done, are quick to indicate that there is no single fixed set or sequence of steps that all scientific investigations follow. The contemporary view of scientific inquiry advocated is that the research questions guide the approach and the approaches vary widely within and across scientific disciplines and fields (Lederman et al., 1998).

The perception that a single scientific method exists owes much to the status of classical experimental design. Experimental designs very often conform to what is presented as THE SCIENTIFIC METHOD and the examples of scientific investigations presented in science textbooks most often are experimental in nature. The problem, of course, is not that investigations consistent with "the scientific method" do not exist. The problem is that experimental research is not representative of scientific investigations as a whole. Consequently, a very narrow and distorted view of scientific inquiry is promoted in our K-12 science curriculum.

At a general level, scientific inquiry can be seen to take several forms (i.e., descriptive, correlational, and experimental). Descriptive research is the form of research that often characterizes the beginning of a line of research. This is the type of research that derives the variables and factors important to a particular situation of interest. Whether descriptive research gives rise to correlational approaches depends upon the field and topic. For example, much of the research in anatomy and taxonomy are descriptive in nature and do not progress to experimental or correlational types of research. The purpose of research in these areas is very often simply to describe. On the other hand, there are numerous examples in the history of anatomical research that have lead to more than a description. The initial research concerning the cardiovascular system by William Harvey was descriptive in nature. However, once the anatomy of blood vessels had been described, questions arose concerning the circulation of blood through the vessels. Such questions lead to research that correlated anatomical structures with blood flow and experiments based on models of the cardiovascular system (Lederman et al., 1998).

To briefly distinguish correlational from experimental research, the former explicates relationships among variables identified in descriptive research and experimental research involves a planned intervention and manipulation of the variables studied in correlational research in an attempt to derive causal relationships. In some cases, lines of research can been seen to progress from descriptive to correlational to experimental, while in other cases (e.g., descriptive astronomy) such a progression is not necessarily possible. This is not to suggest, however, that the experimental design is more scientific than descriptive or correlational designs but instead to clarify that there is not a single method applicable to every scientific question.

Scientific inquiry has always been ambiguous in its presentation within science education reforms. In particular, inquiry is perceived in three different ways. It can be viewed as a set of skills to be learned by students and combined in the performance of a scientific investigation. It can also be viewed as a cognitive outcome that students are to achieve. In particular, the current visions of reform (e.g. NGSS Lead States, 2013; NRC, 1996) are very clear (at least in written words) in distinguishing between the performance of inquiry (i.e., what students will be able to do) and what students know about inquiry (i.e., what students should know). For example, it is one thing to have students set up a control group for an experiment, while it is another to expect students to understand the logical necessity for a control within an experimental design. Unfortunately, the subtle difference in wording noted in the reforms (i.e., "know" versus "do") is often missed by everyone except the most careful reader. The third use of "inquiry" in reform documents relates strictly to pedagogy and further muddies the water. In particular, current wisdom advocates that students learn science best through an inquiry-oriented teaching approach. It is believed that students will best learn scientific concepts by doing science (NGSS Lead States, 2013).

In this sense, "scientific inquiry" is viewed as a teaching approach used to communicate scientific knowledge to students (or allow students to construct their own knowledge) as opposed to an educational outcome that students are expected to learn about and learn how to do. Indeed, it is the pedagogical conception of inquiry that it is unwittingly communicated to most teachers by science education reform documents, with the two former conceptions lost in the shuffle. Although the processes that scientists use when doing inquiry (e.g. observing, inferring, analyzing data, etc.) are readily familiar to most, knowledge *about* inquiry, as an instructional outcome is not. This is the perspective of inquiry that distinguishes current reforms from those that have previously existed, and it is the perspective on inquiry that is not typically assessed. In summary, the knowledge *about* inquiry included in current science education reform efforts includes the following (NGSS Lead States, 2013, NRC, 1996):

- Scientific investigations all begin with a question, but do not necessarily test a hypothesis
- There is no single set and sequence of steps followed in all scientific investigations (i.e., there is no single scientific method)
- Inquiry procedures are guided by the question asked
- All scientists performing the same procedures may not get the same results
- Inquiry procedures can influence the results
- Research conclusions must be consistent with the data collected
- Scientific data are not the same as scientific evidence
- Explanations are developed from a combination of collected data and what is already known

## 1.5 Scientific Inquiry as a Component of Scientific Literacy and Its Relationship to STEM

Although scientific inquiry has been viewed as an important educational outcome for science students for over 100 years, it was Showalter's (1974) work that galvanized scientific inquiry, as well as NOSK, important components within the over arching framework of scientific literacy. As previously discussed, the phrase scientific literacy had been discussed by numerous authors before Showalter (Dewey, 1916; Hurd, 1958; National Education Association, 1918, 1920; National Society for the Study of Education, 1960, among others), it was his work that clearly delineated the dimensions of scientific literacy in a manner that could easily be translated into objectives for science curricula. Showalter's framework consisted of the following seven components:

- **Nature of Science** – The scientifically literate person understands the nature of scientific knowledge.
- **Concepts in Science –** The scientifically literate person accurately applies appropriate science concepts, principles, laws, and theories in interacting with his universe.
- **Processes of Science** – The scientifically literate person uses processes of science in solving problems, making decisions and furthering his own understanding of the universe.
- **Values** – The scientifically literate person interacts with the various aspects of how universe in a way that is consistent with the values that underlie science.
- **Science-Society** – The scientifically literate person understands and appreciates the joint enterprise of science and technology and the interrelationships of these with each other and with other aspects of society.
- **Interest –** The scientifically literate person has developed a richer, more satisfying, and more exciting view of the universe as a result of his science education and continues to extend this education throughout his life.
- **Skills** – The scientifically literate person has developed numerous manipulative skills associated with science and technology.

(Showalter, 1974, p. 1–6)

Science processes (now known as inquiry or practices), and NOSK) were clearly emphasized. The attributes of a scientifically literate individual were later reiterated by the National Science Teachers Association [NSTA] (1982). The NSTA dimensions of scientific literacy were a bit expanded from Showalter's and included:

- Uses science concepts, process skills, and values making responsibly everyday decisions;
- Understands how society influences science and technology as well as how science and technology influence society;
- Understands that society controls science and technology through the allocation of resources;

- Recognizes the limitations as well as the usefulness of science and technology in advancing human welfare;
- Knows the major concepts, hypotheses, and theories of science and is able to use them;
- Appreciates science and technology for the intellectual stimulus they provide;
- Understands that the generation of scientific knowledge depends on inquiry process and conceptual theories;
- Distinguishes between scientific evidence and personal opinion;
- Recognizes the origin of science and understands that scientific knowledge is tentative, and subject to change as evidence accumulates;
- Understands the application of technology and the decisions entailed in the use of technology;
- Has sufficient knowledge and experience to appreciate the worthiness of research and technological developments;
- Has a richer and more exciting view of the world as a result of science education; and
- Knows reliable sources of scientific and technological information and uses these sources in the process of decision making.

The importance of scientific inquiry, or practices as it is called in the NGSS, as a critical component of scientific literacy should be clear.

STEM, in current conceptions, is characterized as an integrated approach to curriculum that addresses the interactions of science, technology, engineering, and mathematics to solve problems in a more authentic manner than the current curriculum approach. That is, the typical science curriculum has perennially separated the various disciplines during precollege instruction, not to mention the exclusion of any formal attention to technology or engineering. Current questions about the natural world and/or societal or personal issues are more commonly not the purview of any singular discipline, but rather require the collaboration of various individuals, working in a team, with various backgrounds and expertise. This is the nature of STEM. We are not saying that STEM is a discipline with its own "nature" as in nature of science. We are merely characterizing STEM as a curriculum approach.

## 1.6 Understanding Nature of Scientific Knowledge as a Goal of Science Education and Its Relationship to Scientific Literacy

The relationship and differences between nature of scientific knowledge (NOSK) and nature of scientific inquiry (SI) is often discussed and confused within existing literature (Lederman & Lederman, 2014). NOSK, as opposed to the more popular nature of science (NOS) is used here to be more consistent with the original meaning of the construct (Lederman, 2007).

Given the manner in which scientists develop scientific knowledge (i.e., SI), the knowledge is engendered with certain characteristics. These characteristics are what typically constitute NOS (Lederman, 2007). As mentioned before there is a lack of consensus among scientists, historians of science, philosophers of science, and science educators about the particular aspects of NOSK. This lack of consensus, however, should neither be disconcerting nor surprising given the multifaceted nature and complexity of the scientific endeavor. Conceptions of NOS have changed throughout the development of science and systematic thinking about science and are reflected in the ways the scientific and science education communities have defined the phrase "nature of science" during the past 100 years (e.g., AAAS, 1990, 1993; Central Association for Science and Mathematics Teachers, 1907; Klopfer & Watson, 1957; NSTA, 1982).

However, many of the disagreements about the definition or meaning of NOSK that continue to exist among philosophers, historians, and science educators are irrelevant to K-12 instruction. The issue of the existence of an objective reality as compared to phenomenal realities is a case in point. There is an acceptable level of generality regarding NOS that is accessible to K-12 students and relevant to their daily lives. Moreover, at this level, little disagreement exists among philosophers, historians, and science educators. Among the characteristics of the scientific enterprise corresponding to this level of generality are that scientific knowledge is tentative (subject to change), empirically-based (based on and/or derived from observations of the natural world), subjective (theory-laden), necessarily involves human inference, imagination, and creativity (involves the invention of explanations), and is socially and culturally embedded. Two additional important aspects are the distinction between observations and inferences, and the functions of, and relationships between scientific theories and laws. What follows is a brief consideration of these characteristics of science and scientific knowledge.

First, students should be aware of the crucial distinction between observation and inference. Observations are descriptive statements about natural phenomena that are "directly" accessible to the senses (or extensions of the senses) and about which several observers can reach consensus with relative ease. For example, objects released above ground level tend to fall and hit the ground. By contrast, inferences are statements about phenomena that are not "directly" accessible to the senses. For example, objects tend to fall to the ground because of "gravity." The notion of gravity is inferential in the sense that it can *only* be accessed and/or measured through its manifestations or effects. Examples of such effects include the perturbations in predicted planetary orbits due to inter-planetary "attractions," and the bending of light coming from the stars as its rays pass through the sun's "gravitational" field.

Second, closely related to the distinction between observations and inferences is the distinction between scientific laws and theories. Individuals often hold a simplistic, hierarchical view of the relationship between theories and laws whereby theories become laws depending on the availability of supporting evidence. It follows from this notion that scientific laws have a higher status than scientific theories. Both notions, however, are inappropriate because, among other things, theories and laws are different kinds of knowledge and one can not develop or be transformed into the other. Laws are *statements or descriptions of the relationships* among observable phenomena. Boyle's law, which relates the pressure of a gas to its volume at a constant temperature, is a case in point (Lederman et al., 1998).

Theories, by contrast, *are inferred explanations* for observable phenomena. The kinetic molecular theory, which explains Boyle's law, is one example. Moreover, theories are as legitimate a product of science as laws. Scientists do not usually formulate theories in the hope that one day they will acquire the status of "law." Scientific theories, in their own right, serve important roles, such as guiding investigations and generating new research problems in addition to explaining relatively huge sets of seemingly unrelated observations in more than one field of investigation. For example, the kinetic molecular theory serves to explain phenomena that relate to changes in the physical states of matter, others that relate to the rates of chemical reactions, and still other phenomena that relate to heat and its transfer, to mention just a few.

Third, even though scientific knowledge is, at least partially, based on and/or derived from observations of the natural world (i.e., empirical), it nevertheless involves human imagination and creativity. Science, contrary to common belief, is not a totally lifeless, rational, and orderly activity. Science involves the *invention* of explanations and this requires a great deal of creativity by scientists. The "leap" from atomic spectral lines to Bohr's model of the atom with its elaborate orbits and energy levels is a case in point. This aspect of science, coupled with its inferential nature, entails that scientific concepts, such as atoms, black holes, and species, are functional theoretical models rather than faithful copies of reality.

Fourth, scientific knowledge is subjective or theory-laden. Scientists' theoretical commitments, beliefs, previous knowledge, training, experiences, and expectations actually influence their work. All these background factors form a *mind-set* that *affects* the problems scientists investigate and how they conduct their investigations, what they observe (and do not observe), and how they make sense of, or interpret their observations. It is this (sometimes collective) individuality or mind-set that accounts for the role of subjectivity in the production of scientific knowledge. It is noteworthy that, contrary to common belief, science never starts with neutral observations (Chalmers, 1982). Observations (and investigations) are always motivated and guided by, and acquire meaning in reference to questions or problems. These questions or problems, in turn, are derived from within certain theoretical perspectives.

Fifth, science as a human enterprise is practiced in the context of a larger culture and its practitioners (scientists) are the product of that culture. Science, it follows, affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded. These elements include, but are not limited to, social fabric, power structures, politics, socioeconomic factors, philosophy, and religion. An example may help to illustrate how social and cultural factors impact scientific knowledge. Telling the story of the evolution of humans (*Homo sapiens*) over the course of the past seven million years is central to the biosocial sciences. Scientists have formulated several elaborate and differing story lines about this evolution.