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SI: NATURE OF STEM

S + T + M = E as a Convergent Model for the Nature of STEM

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Abstract

The paper provides a theoretical synthesis that addresses the multiple calls to consider the existence of an integrated nature of STEM (science, technology, engineering, and mathematics). The nature of STEM (NOSTEM) has been advocated for as a way to promote effective STEM instruction in K-16 education and has been challenged as being non-existent. We propose a theoretical conceptualization of the NOSTEM through a convergent model that integrates the shared characteristics of the nature of knowledge and nature of inquiry practices of each of the four STEM disciplines. We propose this model in light of the siloed individual disciplines by considering the dimensions of each and whether they are pure or applied or attend to questions and issues surrounding the physical and non-physical world(s). Using this synthesis and model, we argue that the NOSTEM is congruent with the nature of engineering (NOE). This finding has multiple implications for all stakeholders (i.e., teachers, researchers, policy makers) in STEM education. First, we caution stakeholders from using this model to create or change educational policies or standards but rather work to validate, extend, and challenge the model in light of STEM education reform. Second, with the congruency between our model of NOSTEM and NOE, we charge scholars to work to illuminate the critical aspects of the nature of engineering *knowledge*. Third, if the model withstands the scrutiny of STEM scholars (i.e., researchers and teachers), it has the potential to inform teaching and learning in STEM education.

Keywords Integrated STEM · Nature of STEM · STEM education · Engineering

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1 Introduction

Increasingly, education reform initiatives within the USA call for curriculum transformations that promote the integration of science, technology, engineering, and mathematics (STEM) (i.e., NGSS Lead States 2013). For example, two primary goals drive the current US science education policy: producing a STEM literate society and increasing the number of college students majoring in STEM (AAAS 2017; Bressoud 2015; Curtis 2014; Hossain and Robinson 2012; U.S. Department of the Interior STEM Education and Employment Pathways 2013). To achieve these goals related to STEM education, stakeholders obviously need to have a common language for articulating coherent priorities, defining learning objectives, and building learning progressions. Despite this, the literature demonstrates that the term STEM has been used inconsistently with referents to multiple meanings or no definitions articulated at all (Breiner et al. 2012; Honey et al. 2014). It is not that one definition needs to be agreed upon, but that clarity and consistency in the definition are required for it to be useful to stakeholders in promoting STEM learning goals.

Collectively, science, technology, engineering, and mathematics can be considered integrated in that they are domains that provide epistemological groundings for individuals to develop skills needed for problem-solving, critical thinking, reasoning with evidence, and understanding how to interpret data (Tanenbaum 2016). However, it is difficult to envision how these play out as curricular goals. Honey et al. (2014) described a framework for understanding and evaluating integrated STEM curricula and research related to these initiatives. The authors noted that by examining the goals, outcomes, nature, and/or implementation of STEM initiatives one could evaluate where integrated STEM is occurring. The overarching goals of this framework focused on understanding where and how STEM literacy was being addressed in the curricula. STEM literacy would necessarily include understanding the nature of science, nature of technology, nature of engineering, and the nature of mathematics as critical learning goals (AAAS 2017; Chamberlin 2013; Goldman 2004; Honey et al. 2014; Koen 2009; Lederman and Lederman 2014). Additionally, for STEM students to be proficient in each of the associated areas, they must enhance their ability to adapt knowledge of a singular domain between and among all of the STEM domains (Yakman, 2008), no easy task.

Although the integration of the domains is discussed as a goal of STEM education, research literature presents these epistemologies as distinct and not as an integrated unit, even within the integrated curricula (i.e., the nature of STEM). We define epistemology as a "theory of knowledge" that often manifests itself as the study of the nature of knowledge within a particular discipline. When we refer to the "nature" of particular STEM disciplines, we are making reference how the sources and scopes of knowledge are conceptualized within the discipline and what standards of justification for knowledge are established through disciplinary norms. In other words, this lack of congruency calls for discussions and reflection among all STEM education stakeholders as to what epistemological integration might look like. To promote these fruitful discussions among stakeholders in STEM, we propose a convergence theoretical model for the nature of STEM. In this theoretical piece, we ask the broad question, "What is STEM?" We propose that by examining the nature of the individual domains perhaps, we can have a better understanding of the labyrinth that is the nature of *Science, Technology, Engineering, and Mathematics* (NOSTEM).

In this manuscript, we first further justify the need for a common definition of STEM and examine the literature that has attempted to achieve this goal. We then provide some background on what is known about the epistemologies of each of the individual disciplines.

We label the epistemological nature of these disciplines as follows: nature of science (NOS), the nature of technology (NOT), the nature of engineering (NOE), and the nature of mathematics (NOM). These labels are consistent with the extant literature. Finally, we propose a convergent theoretical model for the NOSTEM and discuss the implications that the model may have for research and practice in integrated STEM education. We understand that our alignment of NOSTEM with the NOE may be controversial to some. We reiterate that our framework is a suggested start to a broader community discussion to establish consistent rhetorical themes, and we welcome challenges if it brings clarity to the NOSTEM.

2 A Brief History of Defining STEM

2.1 Why Do we Need a Common Definition of STEM?

National attention has been given to the importance of producing STEM graduates to help combat a projected workforce deficit (President's Council of Advisors on Science and Technology 2012). A metaphor for how this deficit manifests itself is as a "leaky pipeline" with many students often having an initial and perhaps inherent interest to engage in STEM fields but subsequently and progressively "leaking" out due to various perceptions, motivations, structural pressures, and identity struggles (e.g., Alper and Gibbons 1993; Cannady et al. 2014; Ellis et al. 2016). The problem with the STEM pipeline metaphor is that without knowing what STEM is beyond a rhetorical device, we do not know what the "end of the pipe" looks like. In addition, understanding how to "patch holes" in the pipeline (prevent student attrition) or provide "in-flows" of students into the pipeline (provide opportunities for all students to productively re-enter STEM fields) is also a challenge without knowing what is "STEM."

Due to this well-established deficit, educational researchers have focused on enhancing STEM education by studying best practices that engage and maintain students' interest in the associated domains (Bressoud 2015; Carver et al. 2017; Czerniak and Johnson 2014; Hossain and Robinson 2012; Schuchardt and Schunn 2016; U.S. Department of the Interior STEM Education and Employment Pathways 2013). This includes policies that recommend teachers, specifically science teachers in K-12 settings, to effectively teach integrated STEM (NGSS Lead States 2013). However, as Honey et al. (2014) note, without a clear definition of STEM, innumerable challenges arise for defining STEM learning objectives and goals, developing STEM curricula, proving professional development for STEM teachers, and studying the impacts of STEM initiatives on critical outcomes.

Despite the overwhelming attention to STEM as a rhetorical device in policy matters, the term is still only loosely defined (NSB 2015). Defining STEM requires reflection upon whether the domains have truly integrated epistemological characteristics or whether they are combined in less integrated ways (i.e., transdisciplinary, multidisciplinary, siloed; Czerniak and Johnson 2014; Lederman and Niess 1998; Yakman 2008). In the following section, we provide a brief overview of some previous attempts at defining STEM and justify our stance on a focus of the epistemology of the disciplines as both a critical and challenging arena for defining STEM.

2.2 Recent Attempts at Defining STEM

Recently STEM education scholars have called for renewed investment in defining exactly what the term STEM means to support curricular and policy initiatives, including asking if there *is* a nature of integrated STEM (Peters-Burton 2014). Currently, there seem to be three major perspectives on conceptualizations of the nature of STEM: (1) there is not a nature of STEM; (2) there is not a nature of STEM, but there is a nature of STEAM, a consideration of the creativity of arts and language; or (3) uncertainty in that more research is needed to determine the interdisciplinary nature of STEM.

Bybee (2013) suggested that the term STEM is a politically driven buzzword and nothing more than rhetoric. Akerson et al. (2018) recently supported this position as well. Through an investigation of the siloed nature of the STEM disciplines, the authors concluded that "STEM is not a discipline in and of itself and therefore has no nature - there is no nature of STEM, but there are natures of the individual disciplines that compose STEM" (Akerson et al. 2018, p. 6). What this stance ignores is, whether or not a true nature of STEM exists, teachers are still being pressured to teach integrated STEM without having an idea of how the disciplines compare, contrast, or complement each other (Honey et al. 2014; Peters-Burton 2014). Therefore, we believe it is important to consider how STEM *could* be integrated from a curricular perspective, taught, and learned by comparing the similarities of the nature of the individual disciplines. Instead of promoting a deficit model, we ask, if there is a nature of STEM, how might it be theorized?

In the second perspective, scholars suggest that STEM disciplines are hierarchical and are held together with creativity and richness of the liberal arts disciplines (Yakman 2008). For example, Yakman (2008) noted that the arts, and engineering, can provide context to situate science and technology driven by mathematics. However, this model does not acknowledge the creativity and historical richness of the individual siloed disciplines (i.e., scientists and mathematicians are creative and socioculturally embedded outside of art as well). Therefore, the integration of arts may not be needed when investigating what the nature of STEM could be. Additionally, this model does not account for the integration of the nature of knowledge and inquiry (i.e., NOSK, NOMI), two fundamental aspects of developing a STEM literate society (Lederman and Lederman 2014).

In the final perspective, some scholars have noted that a discussion of the nature of STEM is premature and that only time and further research will provide a conclusion (Honey et al. 2014; Peters-Burton 2014). In an editorial piece, Peters-Burton (2014) charged the field with the need for understanding and determining the existence of the nature of STEM by looking beyond the discipline-specific ideas and acknowledging how each discipline shares cycles of inquiry. Similarly, Honey et al. (2014) suggested that the nature and scope of the integration of STEM could be found by examining the STEM disciplines and their connections to one another.

3 The Nature of S+T+E+M

In this section, we provide a brief overview of each epistemological stance for the individual disciplines (i.e., NOS, NOT, NOE, NOM), as these individual epistemologies provide a foundation for deciphering the nature of the integration. Specifically, we discuss the characteristics of each discipline with multiple views, if present, from the perspective of the nature of the knowledge produced and nature of the practices professionals engage in to create the knowledge (e.g., Lederman 2006; Pair 2017; Pleasants et al. 2018). We choose to represent a referent to knowledge production in a discipline with a "K" and inquiry practices that the field engages with using an "I." Thus, the nature of technology knowledge is represented as

"NOTK," and the nature of engineering inquiry practices is represented as "NOEI" for example. This is aligned with previous notations in the literature such as the nature of scientific inquiry being abbreviated as NOSI. We conclude each section with a brief discussion of the importance of the nature of each discipline in and for education.

Understanding what science, technology, engineering, and mathematics are requires one to understand what knowledge is and how it is justified in a field (i.e., epistemology) and how that knowledge is generated (i.e., processes and practices). Although both the knowledge and processes are important to the larger understanding of the field, research has noted that conflating these two constructs is not beneficial to teaching them. For example, Lederman and Lederman (2014) discussed how understanding scientific processes (NOSI) does not promote understanding of NOSK. Similarly, Pair (2017) argued that mathematical knowledge (NOMK) is distinct from how it is discovered or generated (NOMI) especially in classroom contexts.

3.1 The Nature of Science (NOS)

The goal of producing scientifically literate students has remained and, in fact, flourished given K-16 science educational reform (AAAS 2011; NGSS Lead States 2013). Although the conceptualization of scientific literacy is not agreed upon, science education experts agree that it should include an understanding of the NOS (Lederman and Lederman 2014; Lederman et al. 2013). The NOS is heavily informed by the philosophy of science and is often represented in science curricula as a list of aspects in science education curricula (e.g., Lederman 2007; McComas et al. 1998). However, there are multiple conceptualizations of NOS other than the "list view" including the Family Resemblance Approach (FRA) (Dagher and Erduran 2016; Irzik and Nola 2010; Kaya and Erduran 2016), the features of science approach (Matthews 2015), and that found in the NGSS Appendix H, just to name a few of the most prevalent discussed in the literature. We have combined our discussion of all of these conceptualizations of NOS and organized them into two categories: the nature of knowledge within the discipline (NOSK) and the processes or practices used to generate the knowledge (NOSI).

We understand that this decision to collapse NOSK and NOSI into a single discussion may be contentious due to the academic debates that currently exist in the literature. However, our intent is not to take a stand on a single definition of the nature of science or its inquiry nor is it to extensively review the literature and highlight the critiques we see as relevant on both sides. Our goal is to provide a utilitarian definition of the NOS below to be used in production of our integrated framework. The two most relevant to this discussion are the "list view" and the Family Resemblance Approach, briefly discussed below.

Both the consensus list view and the NGSS conceptualize science as a way of understanding the natural world by explaining the phenomena that occur in the physical and natural world (McComas et al. 1998; NGSS Lead States 2013). These views emphasize a list of aspects for NOS: (1) scientific knowledge is tentative; (2) science is subjective and objective; (3) scientists use creativity in their work; (4) scientific knowledge is socioculturally embedded; (5) scientific knowledge is organized using theories, laws, and models; (6) observations and inferences are used to generate scientific knowledge; and (7) there are multiple scientific methods. The first five of the list presented above represent characteristics of scientific knowledge, and the last two represent inquiry practices used to generate this knowledge.

The Family Resemblance Approach to the NOS arose out of critiques to the consensus list as being too narrow to encapsulate the breadth of science disciplines, practices, and characteristics (Dagher and Erduran 2016; Erduran and Dagher 2014). While this acknowledges the "aspects" of the consensus list, it extends it by positing that science methods differ based along disciplinary lines. Allchin (2011) argued for the inclusion that other broader aspects are required for a full understanding of the NOS. This includes funding sources and roles, peer review, and methodological validation of scientific methods. Given the theoretical and empirical support for these different conceptions of the NOS, we synthesize them into a brief overview of how we define NOSK and NOSI for this paper.

NOSK Science is a way of knowing (i.e., generation of knowledge about and explanations for the natural world; McComas et al. 1998; NGSS Lead States 2013). These explanations come in the form of theories and models. This results in the generation of new knowledge about how the world works and provides scientists with hypotheses to test related to these theories and models. This knowledge is tentative; however, it is durable and changing it requires a substantial amount of empirical evidence. Furthermore, scientific knowledge is socioculturally embedded. Our cultural backgrounds influence our science, and this means that science is inherently subjective and open to peer review (Dagher and Erduran 2016; Kampourakis 2016; Lederman and Lederman 2014; McComas et al. 1998). For instance, science is influenced by sociocultural aspects such as power structures, religious perspectives of scientists, and politics (Lederman et al. 2013). Finally, there are disciplinary differences in how the sciences collectively approach the search for truth, but these can be subsumed under a larger generalizable understanding of science as a collective.

NOSI While there is no one scientific method, scientific knowledge is generated through a *combination* of observations, experimental evidence, and argumentation (Abd-El-Khalick 2012; Dagher and Erduran 2016; Lederman and Lederman 2014; Lederman et al. 2013; McComas et al. 1998). According to the FRA, what counts for evidence in one scientific discipline may not be equivalent to evidence in another scientific discipline (Dagher and Erduran 2016). For example, astronomers rely upon observational evidence, while chemists often rely upon experimental evidence. Scientists are also creative and skeptical when it comes to generating new knowledge. This ties back into the social NOS and the peer review process for critiquing claims and scientific works (Dagher and Erduran 2016).

3.2 The Nature of Technology (NOT)

Scholars have warned against conflating technology with science or engineering (i.e., Pacey 1983; Skolimowski 1966). While there are similar and shared characteristics between science, engineering, and technology, as well as with scientific knowledge and technological knowledge, there are differences that allow technology to stand alone as a discipline. One conceptualization of technology is "a human-constructed means to achieve a particular end" (Dosi and Grazzi 2010, p. 173). Skolimowski (1966) in his discussion of technology as a *cognitive process* stated, "technology is a form of human knowledge" (p. 372) and "[technology] provides the means…for producing 'better' knowledge" (p. 375). In other words, technology can be defined as a tool or a way to reach a goal. In this sense, technology could be a physical artifact (i.e., a computer), a non-physical artifact (i.e., a recipe or research method), or a process (i.e., design) (Skolimowski 1966). This design process is a characteristic shared with engineering; however, the physical and non-physical artifact conceptions of technology separate it from engineering and other epistemologies. Regardless of which of these views technology is conceptualized as, three characteristics are shared among them: technology is dynamic and tentative (similar to scientific and mathematical knowledge), technology is socioculturally embedded (similar to scientific and mathematical knowledge), and technology is value-laden (in contrast to science being theory-laden). Because we are examining the epistemologies and practices of each of the STEM disciplines, we will only focus on technology as a knowledge base and technology as a process.

NOTK Technology as a knowledge is defined by its practical value. It is both an understanding of how technologies work and the knowledge used to construct a solution to a problem (Skolimowski 1966). However, technological knowledge and advancement can be constrained by funding, scientific knowledge development, and physical resources. Technological knowledge is a means to reach a goal (Dosi and Grazzi 2010); therefore, there is a purpose to create an artifact or devise a plan to construct something. Skolimowski (1966) described this as the thinking required by engineers to build buildings and other structures such as bridges (i.e., engineering). There is a purpose to building the bridge as well as a purpose in the design of the bridge. Although this example parallels the engineering design process (discussed in Section 3.4), there is an important distinction between technological and engineering knowledge.

Technological knowledge is socially and culturally embedded. DiGironimo (2011) discussed how the ages of people influence their conceptions of technology. Children from two different cultures would not only have differing views of technology, but their views could also differ from others in the same culture but of a different age. For example, a 5-year-old girl may consider the role of technology as a form of play, whereas an adult may consider technology as a form of communication (DiGironimo 2011). This is similarly aligned with how scientific knowledge is socioculturally embedded. Furthermore, knowledge of technologies and their societal impacts represent a foundational aspect of NOTK (Pleasants et al. 2019). Therefore, technological knowledge (NOTK) is value-laden as the consequences of technology use and creation can have significant impacts on people and societies (Pacey 1983). That is, the role of technologies in our daily lives has impacted the way we live and society in general. However, this is not to say that the *purpose* of new technologies was intended to change society overall. Technologies can change the physical nature of the world, where engineering has a direct and explicit impact on society and all people within that society. Consequently, this demonstrates the direct link between technology and engineering. Where engineering requires technological advances, but technology is not necessarily driven by the same needs as engineering design (i.e., societal need).

NOTI Technology is dynamic and always changing. Arthur (2009) discussed how technologies follow a combinatorial evolutionary pathway to develop. This development or technological progress (Arthur 2009; Pleasants et al. 2019; Skolimowski 1966; Waight and Abd-El-Khalick 2012) refers to the creation of "better" objects (defined as more reliable, effective, faster, etc.). Oftentimes this progresses the design and development of innovations through modeling for solving problems (Waight and Abd-El-Khalick 2012). The term modeling in this case means to create a representation of a phenomenon or object and apply it to a natural context (Roth 2001). In other words, science explains the natural world through manipulatives, models, and theories whereas technology applies theories, models, and manipulatives to change the natural world (Roth 2001). In this sense, technology is the process of creating reality from ideas to tangible aspects of the world (Arthur 2009). However, this is not to indicate that technology is only applied science but that the two are intricately interwoven (Arthur 2009; Roth 2001; Skolimowski 1966).

While we do not explicitly address technology as an artifact above, it is important to note that this is a critical aspect that separates technology from science and engineering.

3.3 The Nature of Mathematics (NOM)

The problem with mathematics in the integrated STEM phenomenon is that it is often equated to simple data analysis or creation of graphs (Coad 2016). However, NOM is vast and has many different views. Therefore, we attend to each of them in our discussion of the NOMK and NOMI. The views of NOM differ in terms of the NOMK (i.e., instrumentalist, Platonist, and fallibilist) and the NOMI (i.e., absolutist, formalist, and conception) in more ways than any other STEM domain. For the purposes of our STEM model, we consider each view of NOMK and NOMI to gain an overall understanding of how mathematics can be viewed. We do this because even practicing mathematicians can fall between two differing views of NOMK and NOMI (Hersh 1997; Pair 2017; Watson 2019). For example, Hersh (1997) proposed that many mathematicians at times may fall between two different views: Platonist and fallibilist. However, there are more than just these two views, and the term NOM itself can take on different meanings which can be held by mathematics learners, teachers, and mathematicians (Kean 2012; Pair 2017).

Another important reason to acknowledge all views of NOM is due to the observation of how the view one holds of the NOMK can largely influence how they believe mathematics is learned (Jankvist 2015; Watson 2019). We provide a description of the three prominent views for NOMK and NOMI and their relations to each other, as well as a proposed unified view of NOM from Watson (2019) that is grounded in the mathematical standards documents *Principles and Standards for School Mathematics* (National Council of Teachers of Mathematics (NCTM) 2000 and *Adding it Up* (National Research Council (NRC) 2001).

NOMK There are essentially three main differing views of NOM regarding the nature of and the creation of mathematical knowledge. First, the instrumentalist view sees mathematics as a set of isolated rules used to solve problems (Chamberlin 2013). Within this view, the role of proof is to create absolute mathematical truths (Ernest 1991). The second view, Platonist, sees mathematics as a set of connected body of discovered knowledge (Hersh 1997). Within this view, mathematics is still a static body of discovered truths, and although proof, logic, and reasoning are important to discover mathematics, once a truth is obtained, it cannot be changed (Ernest 1991). Platonist places more value on understanding the structure of mathematics than instrumentalist and therefore do not see mathematics as simply a set of rules to follow but instead as a connected body of mathematics in which value is placed on understanding (Watson 2019). The last view, fallibilist, sees mathematics as a created body of knowledge that is dynamic, discoverable through exploration and problem-solving, and subject to validation and revision (Ernest 1991; Hersh 1997; Lakatos 1976; Pair 2017; Watson 2019). Ultimately, the NOMK can be viewed as a static and unconnected body of knowledge, a static-unified discovered body of knowledge that consists of absolute truths or a dynamic body of knowledge open to revision (Ernest 1991; Hersh 1997; Lakatos 1976; Pair 2017; Watson 2019).

NOMI In 1990, Lerman described different views of the NOMI as two opposing poles. The first is the absolutist view of mathematics, in which mathematics is certain, independent of human knowledge (Chamberlin 2013). This view often relates to a teaching style that focuses on procedures one needs to perform which were developed by past mathematicians (Chamberlin 2013) and highlights the facts, rules, and procedures of mathematics without a focus on understanding. Mathematics teachers who hold this view of NOMI generally teach using a traditional lecture style (Lerman 1990) and envision mathematics as a bag of tools (Watson 2019). On the opposite end of this continuum, Chamberlin (2013) described the conception view of mathematics. This view emphasizes mathematics as created through problem-solving, established through social validation (i.e., argumentation and validation of proof), and is always open to revision (Thompson 1992). Between the two ends of the continuum, Chamberlin (2013) described this middle as the perception view (!i.e., where Platonist and formalist fall on the continuum). This view still sees mathematics as independent of human knowledge (i.e., discovered and absolute) but focuses on the logic and understanding of the procedures and connections within mathematics unlike the absolutist view (Chamberlin 2013).

NOM Continuum When it comes to understanding mathematical knowledge and understanding the NOMI, we can align these six main views on a continuum as shown in Fig. 1 (J. Pair, personal communication, October 24, 2019; L. Watson, personal communication, October 24, 2019). Note the intentional misalignment of the continuum; this is to indicate that a person can hold a view of NOMK such as fallibilist and view of NOMI such as formalist (J. Pair, personal communication, October 24, 2019). Additionally, the purposeful placement of Platonist (i.e., slightly to the right) and formalist (i.e., slightly to the left) is to indicate these two are not equivalent views of the nature knowledge and inquiry. That is, the formalist view of mathematical inquiry would still correspond to a more traditional teaching style and would place more emphasis on structure than perhaps a mathematician who creates mathematics with a Platonist view of NOMK.

Proposed Unified View of NOM In her dissertation work, Watson (2019) attempted to identify characteristics for a unified view of NOM. However, she did not distinguish between the nature of knowledge and inquiry but instead refers to the discipline of mathematics (i.e., answer the question "what *is* mathematics"). Specifically, this view "includes characteristics that are applicable to mathematics regardless of the context of mathematics. That is, regardless of one's potential use of mathematics, the characteristics in the Proposed Unified View do not change" (Watson 2019, p. 59). The following are the characteristics of this possible unified view:

1. Mathematics involves exploration.
2. Mathematics involves multiple strategies.
3. Mathematical ideas are communicated and verified through proof/justification.
4. Mathematics requires justification of ideas to others.
5. Critique of mathematical ideas leads to refinement.
6. Structure and patterns are inherent in mathematics.
7. Mathematics uses multiple representations.
8. Mathematics is useful and worthwhile.

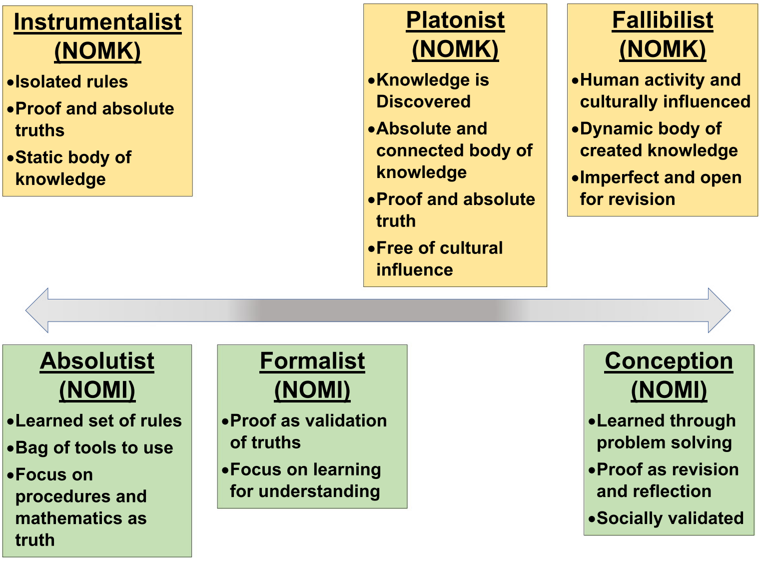

Fig. 1 The NOMK+NOMI continuum

9. Anyone can be a learner of mathematics.
   (Watson 2019, p. 59)

We present this view along with all of the historical views of mathematics in an attempt to better understand the NOM in STEM. The proposed unified view is included to illuminate two other characteristics of NOM (i.e., mathematics as useful and worthwhile and that anyone can be a learner of mathematics) that may not be explicit in the six views outlined in this section. Additionally, this view (the proposed unified view) has structural similarities to constructs in science such as the NOS and features of science (see Section 3.1).

3.4 The Nature of Engineering (NOE)

There has been little research regarding conceptions of the NOE (Koen 2009; Pleasants and Olson 2019). With the inclusion of engineering practices in recent K-12 education standards, understanding the NOE has become increasingly important to engineering as a discipline and for recognizing the relationships between engineering and other STEM disciplines in classroom settings (Goldman 2004; Pleasants and Olson 2019). Commonly, engineering is conceptualized as a process in which engineers *design* which is the key process that distinguishes the engineering from scientific practices (Goldman 2004; Koen 2009; ABET 2001; Mills and Treagust 2003). For the purposes of our model, the process of engineering design will be referred to as the NOEI. This leaves the NOEK difficult to interpret and differentiate from other disciplinary natures; however, it is important to understand the NOEK and its relationship to other domains (i.e., NOS; Antink-Meyer and Brown 2019). Recent work by Pleasants and Olson (2019) had noted the importance of distinguishing the NOE(K) from the design process. This forms the basis for defining NOEK in this manuscript.

NOEK It is hard to describe the nature of engineering without discussing science, technology, or mathematics. The Accreditation Board for Engineering and Technology (ABET 2001) defined engineering as:

> The profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind.

What does this mean about the NOEK? Pleasants and Olson (2019) identified nine disciplinary features of engineering: (1) design in engineering; (2) specifications, constraints, and goals; (3) sources of engineering knowledge; (4) knowledge production in engineering; (5) the scope of engineering; (6) models of design processes; (7) cultural embeddedness of engineering; (8) the internal culture of engineering; and (9) engineering and science. Most of the nine features involve *design*. In fact, this word appears 147 times in the paper. Science, however, was mentioned second most (82 occurrences of "science" and 43 of "NOS") followed by 82 mentions of technology. The term mathematics was only mentioned five times within the article. This highlights the intertwined nature of engineering with the other STEM disciplines.

In an attempt to tease out the NOEK characteristics from the other STEM disciplines, we focus on three of the nine characteristics from Pleasants and Olson (2019): sources of engineering knowledge, knowledge production in engineering, and the scope of engineering. The source of engineering knowledge is more than simply applying science and understanding technologies (Pleasants and Olson 2019). For example, Secundo et al. (2015) survey of Italian and Japanese engineers identified two distinct differences of engineering knowledge as "know-what" and "know-how." Secundo et al. (2015) described procedural knowledge as the "know-how" for engineers. This knowledge is accumulated repetition and practice of skills and thus is considered part of NOEI (below). Information knowledge is considered the "know-what" (Secundo et al. 2015). Engineers need to know what variables to use and when to apply certain procedures. This is the logic component of engineering and requires understanding the relationships between interacting variables. Ultimately, engineers, through their knowledge of mathematics, science, and technology, use design principles to create new technologies for social purposes.

NOEI When considering the nature of the *practice* of engineering, there is an implicit agreement in the literature that this can be defined as design (Mills and Treagust 2003). The view of engineering as design distinguishes the practice of engineering from science (Goldman 2004; Koen 2009; Pleasants et al. 2018; Smith 1988). Engineers need to balance and combine past knowledge and create new knowledge to solve novel problems (Secundo et al. 2015). Often, engineers make conscious decisions regarding the development of a design with partial information (Goldman 2004). This process is not conducted in isolation, as engineers largely work by collaborating with other engineers and scientists (Pleasants and Olson 2019; Secundo et al. 2015). For example, an electrical engineer and mechanical engineer may need to combine their respective contextual knowledge to solve a particular task. Often one engineer may not be aware of all of the knowledge needed when developing or testing a design and must necessarily collaborate with others (Secundo et al. 2015).

The engineering design process has many parallels with scientific inquiry and mathematical problem-solving with a possible difference being their specifications, constraints, and goals

(Pleasants and Olson 2019). The design process starts with understanding the problem, brainstorming ideas, selecting an idea, planning and testing, and creating prototypes and tests and then iterative improvement (Tayal 2013). Smith (1988) described design as "an interactive decision-making process used to optimize the value of human resources" (p. 3). Smith goes on to equate design to problem-solving activities with a specific goal. Goldman (2004) stated that engineering designs are open-ended problems that evolve over time. This includes a tentative nature of the process of problem-solving and design of solutions.

4 Proposition of Convergence Model for the Nature of STEM

Now that we have provided a brief overview of science, technology, engineering, and mathematics' individual knowledge and inquiry practices, we will discuss the overlapping (i.e., similarities) between each of the disciplines (Fig. 2). This will provide the foundation for the convergence of the STEM disciplines for the *Convergent Model for the Nature of STEM* (Fig. 3). The goal of this section is to (1) show the similarities between the knowledge and inquiry practices discussed above and (2) converge them into a framework that represents the most parsimonious overlap based on whether the disciplines are pure or abstract and whether the pure representations of each discipline are focused on the natural world or beyond the natural world.

In Fig. 2, we use a triple Venn diagram to show both knowledge and inquiry practices that are unique and similar to science, technology, and mathematics. Engineering did not have any unique characteristics outside of these three disciplinary domains, and therefore, there is not an engineering circle in the diagram. This figure was created by listing the characteristics of knowledge and inquiry practices for each domain and comparing similarities. The authors use the literature (as discussed in the previous sections) to define the characteristics. These definitions were used as a codebook to compare across the domains. Similarities, and differences were discussed by the authors until a consensus had been reached.

As discussed in the previous sections, each disciplinary domain has many aspects to the nature of their knowledge and the nature of the inquiry practices associated with each. Rather than focus our attention to the uniqueness of each siloed domain, we propose examining the shared aspects between the domains. In Fig. 3, we provide a visualization of the *Convergent Model for the Nature of STEM*. This model is represented by a three-dimensional tetrahedron based on (1) the focus of each disciplinary domain on the physical/natural world or the non-physical/non-natural world, (2) the focus on whether the discipline can be in a pure or applied form, and (3) the many ways the disciplines can be integrated.

The first dimension of the *Convergent Model for the Nature of STEM* is depth. Science and technology represent ways of understanding and manipulating the natural world. This is in contrast with mathematics which can cross the boundaries to answer questions related to both the physical and non-physical world(s). For instance, technology is a way to solve problems (sometimes created by science) for producing enhanced tools and processes. However, mathematics is not limited by this and can ask questions about things such as "what does probability mean in an eleventh dimension?" Engineering is specific to addressing real-world problems (Pleasants and Olson 2019).

The second dimension (height) imposed on our model is whether each discipline can attend to pure and/or applied aspects. Science (as a pure field) can ask basic research questions such

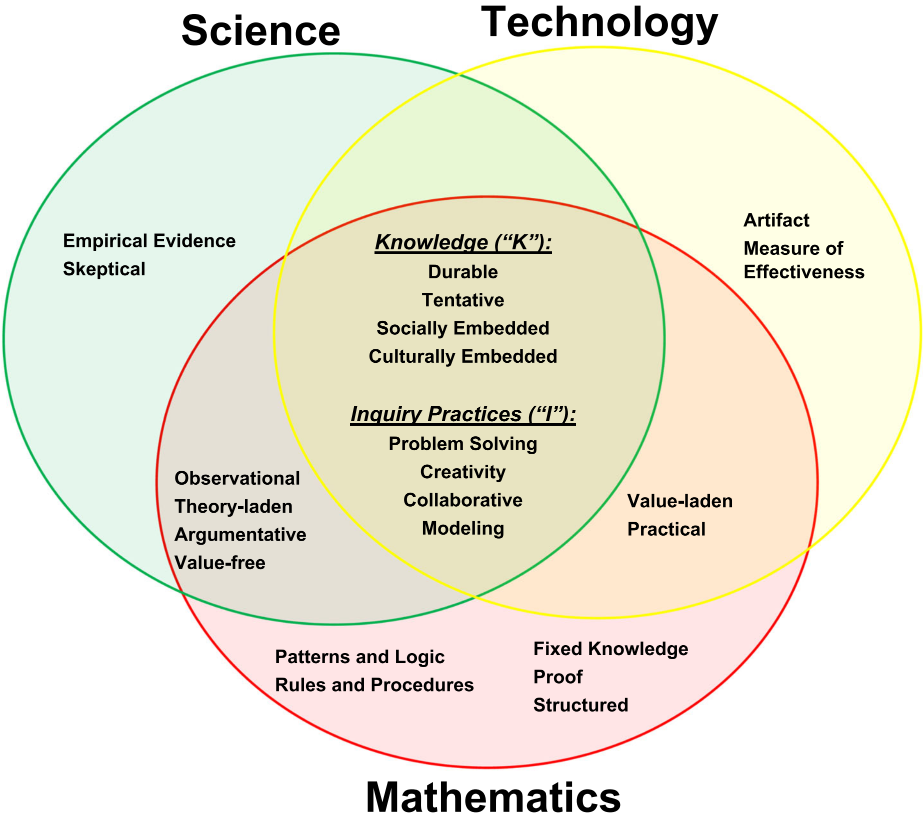

Fig. 2 Shared knowledge and inquiry practices of science, technology, and mathematics

as "how are black holes formed?" However, engineering is primarily associated with human judgments to better mankind. In Fig. 2 above, we show that science, technology, and mathematics are congruent with (1) each domain being a way of knowing; (2) knowledge is described as durable, tentative, and socioculturally embedded; and (3) involve inquiry practices that include problem-solving, are creative, and use modeling. We also found that each of these is also shared with the NOE.

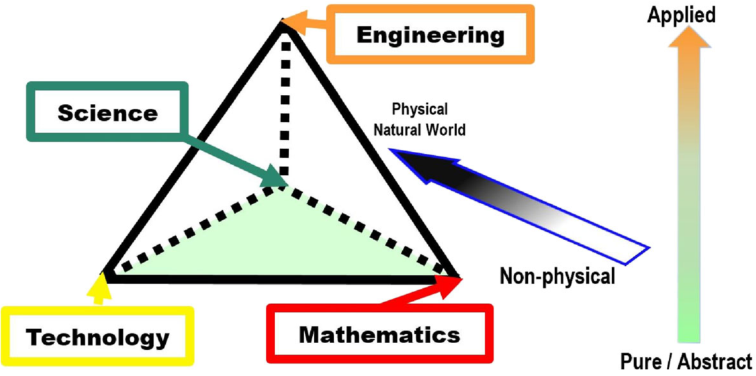

Fig. 3 The convergent model for the nature of STEM

The last dimension applied to our model is volume. In this way we argue that STEM education can move away from a single pipeline metaphor for STEM students and attend to the various ways in which science, technology, and mathematics can be integrated; therefore, producing knowledge and inquiry practices more closely aligned with engineering.

5 Discussion and Implications

Based on our work, we propose that the nature of STEM is, in fact, congruent with the NOE. That is, we can think of STEM as basically just an engineering field, and therefore, we should be measuring the understanding of and inquiry related to engineering (i.e., STEM). More research on the NOEK would help all stakeholders better understand the nature of STEM and what integration of the domains means. Mitcham (1994) stated "The engineer makes with the mind, the technician with the hands…" (p. 144). This exemplifies why understanding the NOEK is important since engineers work with their mind with the knowledge of science and mathematics. We visualize the integration *as* the NOE (Figs. 2 and 3). However, by integrating the disciplines and focusing only on the overlapping parts, we note that *pure* aspects of science, mathematics, and technology are not represented in the NOE (i.e., experimentation and proof). This means that while teachers are called to teach integrated STEM, all stakeholders must first determine the learning objectives for STEM students and re-examine the crosscutting engineering concepts in our K-12 education.

We suggest that the quote "STEM is not a discipline in and of itself and therefore has no nature - there is no nature of STEM, but there are natures of the individual disciplines that compose STEM" (Akerson et al. 2018, p. 6) does not accurately represent the nature of STEM. While we agree that STEM is not a discipline, it *can be* characterized by the NOE. Therefore, STEM education should attend to the overlapping areas of the disciplines *and* at the same time foster the development of literacy in the non-overlapping regions. This ensures that the uniqueness of each discipline is not devalued nor lost by integrating the disciplinary domains. In the convergent model for the NOSTEM, pure aspects of the disciplines (science, technology, and mathematics) are represented by the base. As one moves closer to engineering, some of these pure aspects become less explicit or less valued based on learning objectives. However, teachers can still attend to the NOS, NOT, and NOM while teaching integrated STEM. Our convergent model allows teachers, and other stakeholders in STEM education, to integrate the disciplines by attending to the learning objectives that align with the integrated nature of STEM and the nature of each discipline. For example, a STEM project along the pure/applied continuum of our model would vary with respect to the discipline focus (i.e., a pure project may not have an engineering component but focus on proof or abstraction), content focus (i.e., integrating at least two of the disciplines could be considered STEM), or learning goal. However, if all domains are integrated, then, this would correspond to the tip of the tetrahedron and be considered an engineering project. As you move down the tetrahedron, into more domain specific areas, the project may become interdisciplinary where sometimes the science, technology, or mathematics is the driving force of the project and learning goal.

Additionally, our model allows for more flexibility of the students to choose and pursue a STEM pathway breaking the STEM pipeline metaphor and instead move into a watershed STEM metaphor. In this metaphor, scholars (ourselves included) have argued that there are multiple pathways to and through STEM much like a watershed that separates water into multiple rivers, streams, lakes, etc. This opens up opportunities for students of all backgrounds to pursue STEM-related degrees through multiple avenues. Our model does this because it defines STEM as multidimensional rather than integrated (i.e., engineering can be from the integration of any two of science, technology, and mathematics). These dimensions include (1) the various disciplines of STEM, (2) the physical versus non-physical aspect, and (3) the pure/abstract versus applied nature of each discipline. These dimensions converge into a model that represents STEM as a multidimensional construct rather than a single discipline that students should be pushed toward. We are not suggesting that all STEM students are engineering students but that there are multiple pathways to STEM. We do however suggest that educators, policy makers, researchers, and others stem education stakeholders need to consider the many possibilities of STEM. We also suggest teachers who teach STEM should be prepared in a fashion that supports them to teach the overlapping epistemologies and practices of each discipline and explicitly address the interrelatedness of the disciplines.

5.1 Concluding Remarks

We invite empirical researchers to validate or disprove our model. In an attempt to test our model, we will first question engineers in multiple fields (i.e., electrical, chemical, mechanical, civil) to gain a better understanding of the nature of the knowledge they both use and create while in the field. We also caution stakeholders from using our proposed convergence model for educational policy and changes before rigorously tested and validated. One example of this would be to conduct an empirical study on whether engineers agree with the practices and knowledge aspects of the model.

Our proposed convergence model was generated through a deep study of the literature for each individual domain of science, technology, engineering, and mathematics. From this model, we propose that the nature of STEM does not exist but manifests as the NOE. Stakeholders should consider this when testing this model for its efficacy in classroom settings, and more research is needed to understand the NOE (i.e., the nature of STEM).

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Compliance with Ethical Standards

Conflicts of interest No potential conflict of interest was reported by the authors.

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