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Toward a Productive Definition of Technology in Science and STEM Education

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The lack of a definition of the T in STEM (science, technology, engineering, and mathematics) acronym is pervasive, and it is often the teachers of STEM disciplines who inherit the task of defining the role of technology within their K-12 classrooms. These definitions often vary significantly, and they have profound implications for curricular and instructional goals within science and STEM classrooms. This theoretical paper summarizes of technology initiatives across science and STEM education from the past 30 years to present perspectives on the role of technology in science-focused STEM education. The most prominent perspectives describe technology as the following: (a) vocational education, industrial arts, or the product of engineering, (b) educational or instructional technology, (c) computing or computational thinking, and (d) the tools and practices used by practitioners of science, mathematics, and engineering. We have identified the fourth perspective as the most salient with respect to K-12 science and STEM education. This particular perspective is in many ways compatible with the other three perspectives, but this depends heavily on the beliefs, prior experiences, and instructional goals of teachers who use technology in their science or STEM classroom.

Discussing K-12 education without the acronym STEM (science, technology, engineering, and mathematics) playing a role has become increasingly challenging. STEM education emerged in the 1990s as a label for policies, programs, and practices that involve one or more of the STEM disciplines (Bybee, 2010). Unfortunately for those who are looking to understand exactly what STEM education is and how to teach or "do" STEM, STEM education has many definitions and forms of enactment (e.g., Breiner et al., 2012; Constantine et al., 2017; Martín-Páez et al., 2019; Ring-Whalen et al., 2018).

The variety of perspectives and definitions of STEM education has led to much confusion and discussion; however, consensus can be found around the following: integrated STEM instruction (a) uses real-world contexts to engage students in authentic and meaningful learning (Bryan et al., 2015; Burrows et al., 2017; Kelley & Knowles, 2016; Sanders, 2009), (b) employs student-centered pedagogies, including inquiry-based learning and design thinking (Bryan et al., 2015; Kelley & Knowles, 2016), (c) supports the development of 21st-century competencies such as creativity, collaboration, communication, and critical thinking (Bryan et al., 2015; Honey et al., 2014), and (d) makes connections between STEM disciplines explicit to students (Bryan et al., 2015; Burrows et al., 2017; English, 2016; Herschbach, 2011; Honey et al., 2014; Kelley & Knowles, 2016). Despite these areas of consensus, one issue remains constant: The education community is sorely lacking a clear idea of the role that technology plays within STEM education initiatives.

The lack of a definition of the T in STEM education is so pervasive that some researchers have taken to ignoring the problem (Herschbach, 2011). While technology in the broad field of education is not a new phenomenon, research and thinking about educational technology has fallen victim to conceptual dilution, leading to the misapplication and trivialization of many concepts related to technology in the classroom (Bull et al., 2019).

The rise of STEM education presents an opportunity for the education community to better define the role of technology within the framework of STEM education, but this goal has not yet been fully realized. As a result of the ambiguous nature of technology in STEM education, teachers of STEM disciplines often inherit the task of defining the role of technology within their K-12 classrooms, and these definitions often vary significantly. This article seeks to address possible roles of technology within STEM education, leveraging historical uses of technology and examining key perspectives used today.

Not a New Challenge

While technology has been used for educational purposes throughout human history, this theoretical article will focus on initiatives that have taken place in the United States during the past 30 years. In a report from the Project 2061 Phase I Technology Panel, the American Association for the Advancement of Science (AAAS) presented not only a definition of technology, but also an approach to technology education that leverages multiple K-12 subjects, including science and mathematics (Johnson, 1989). The report defined technology as both a social and a technical process that involves “the application of knowledge, tools, and skills to solve practical problems and extend human abilities” (p. 1).

Educators have a responsibility to “provide opportunities [for students] to experience technology as well as learn about it in the abstract” (Johnson, 1989, p. 2). The panel observed, however, that “technology, unlike science and mathematics, currently has little or no place in elementary or secondary school programs” (p. 3). The solution the panel proposed was to create integrated technology programs that span the industrial arts, vocational education, the sciences, and even the humanities:

> ...a sound base in mathematics and the biological, physical, and social sciences is vital to an understanding of modern technology. They should be a part of technology education curricula, just as technology should serve to bring additional meaning to the curricula of the sciences (pp. 6-7).

The *Benchmarks for Science Literacy* (American Association for the Advancement of Science [AAAS], 1993) and the *National Science Education Standards* (*NSES*; National Research Council [NRC], 1996), were the first to give technology an explicit role in K-12 science education. For example, the *NSES* included science and technology standards for all K-12 grade levels. The *NSES* advanced the view that the “abilities of technological design” complement the abilities and understandings of scientific inquiry.

Perhaps the most visible voice in technology education today is the International Society for Technology in Education (ISTE), an organization of educators “who believe in the power of technology to transform teaching and learning, accelerate innovation and solve tough problems in education” (ISTE, 2020, para 1). The *ISTE Standards* (ISTE, 2000) directly address the role of technology in education and have been adopted by all 50 states for the purposes of program evaluation or accreditation; however, they are not explicitly addressed in science standards that directly guide classroom instruction. The *ISTE Standards* provide multiple ways in which students and teachers are expected to engage with technology, including as a tool for knowledge construction, engaging students in the design process, as a tool to enhance learning, and as a tool to support computational thinking.

The Importance of Technology in Science and STEM Education

Minimizing or overlooking the importance of technology in K-12 science and STEM education comes at a cost. The National Assessment of Educational Progress (NAEP) Technology and Engineering Literacy (TEL) Assessment was designed to measure the degree to which students can apply technology and engineering skills to real-life situations (NAEP, 2018). The TEL assessment is organized into three content areas: Technology and Society, Design and Systems, and Information and Communication Technology.

The TEL assessment was first administered in 2014 and revealed that eighth-grade students who performed higher on the assessment were more likely to engage in technology activities both in and out of school compared to their lower-performing peers (NAEP, 2018). These in-school technology activities most often occurred in a science classroom, with 66% of students reporting that they studied technology and engineering topics in science class.

Fifty-five percent of Black female students and 61% of Hispanic female students reported never taking an engineering or technology course, compared to only 41% of their White male peers (Change the Equation, 2016). In other words, the majority of students who are most underrepresented in the STEM workforce as adults (i.e., women of color) learn about engineering and technology in the context of a science classroom and not in stand-alone industrial arts, engineering, or computer science courses, underscoring the importance of science teachers engaging their students in STEM activities with strong technology integration.

With little guidance on how to integrate STEM, in general (and, in particular, technology), science teachers struggle to incorporate rich STEM lessons in their classrooms to provide students access to strong technology experiences, which affects those underrepresented in STEM. For example, Wang et al. (2011) investigated teachers' perceptions and practices of technology in the context of STEM integrated learning and discovered that teachers struggle most with understanding the role of technology and how to integrate it.

In analyzing integrated STEM curriculum units, Ring-Whalen et al. (2018) found that science teachers primarily used technology (along with mathematics) as a tool or a way to support science and engineering activities in their classrooms. Often, this technology appeared in the form of pedagogical choices (such as using a Smartboard for instruction or videos to enhance students' understanding of science content). Occasionally, technology was leveraged in the form of software to assist students with graphing data collected in a science investigation. Ring-Whalen et al. and Dare et al. (2019) also identified that teachers struggle to describe verbally what technology means within the context of STEM education, occasionally referring to technology as the "mystery piece."

Toward a Productive Definition of Technology in Science and STEM Education

The lack of agreement among teachers concerning the T in STEM is not surprising. This article reports a review of the most common perspectives on technology in the context of science and STEM education and evaluate which perspective may be the most productive for science and STEM educators. Our efforts were grounded in two manuscripts that identified broad categories for varying perspectives on the role of technology in STEM education.

The first, authored by Honey et al. (2014), identified three such perspectives.

1. Technology in STEM education can be viewed as *the product of engineering* given its historical connection to vocational education.
2. Technology in STEM education can be defined as *educational or instructional technology* that is used to enhance teaching and learning.
3. Technology in STEM education may be defined as *the tools used by practitioners of science, mathematics, and engineering*.

The second manuscript (Sivaraj et al., 2019), also identified three perspectives on the role of technology in STEM education, with two of the three perspectives overlapping with the product of engineering and educational or instructional technology from Honey et al. (2014). However, Sivaraj et al. also identified the role of technology in STEM education as *coding or computational thinking*, which can complement mathematical and engineering thinking in a variety of contexts (Wing, 2006).

In this manuscript, we drew on the four unique perspectives identified by Honey et al. (2014) and Sivaraj et al. (2019) for the purpose of analyzing the potential impact of these interpretations on K-12 teacher education, particularly with respect to curricular and instructional goals within science and STEM classrooms.

Perspective 1: Technology as Vocational Education, Industrial Arts, or the Product of Engineering

In the early 1990s, technology education emerged from the industrial arts and vocational education; in turn, engineering education emerged as a central component of technology education through the development of national programs such as Project Lead the Way (Williams et al., 2016). The history of the development of STEM through engineering education, with its strong historical connections to technology and vocational education, has led to the common merging of engineering and technology as synonymous concepts. Similarly, the history of vocational education as a trade or job skills program is echoed in the STEM workforce rhetoric of STEM and engineering education.

Many definitions of technology demonstrate this entanglement of engineering and technology and explain the tendency for the T in STEM to become technology as the product of engineering. For example, the International Technology Education Association (ITEA, 2000) defined technology as the "innovation, change, or modification of the natural environment in order to satisfy perceived human wants and needs" (p. 242). Similarly, AAAS (1993) stated, "In the broadest sense, technology extends our abilities to change the world: to cut, shape, or put together materials; to move things from one place to another; to reach farther with our hands, voices and senses" (p. 41). This definition extends into documents that guide the implementation of STEM in K-12 classrooms.

For example, in the *Framework for K-12 Science Education* (NRC, 2012) and *Next Generation Science Standards* (NGSS Lead States, 2013), technology was explicitly defined as the product of engineering. Within the

NGSS, "the term 'engineering design' has replaced the older term 'technological design,' consistent with the definition of engineering as a systematic practice for solving problems, and technology as the result of that practice" (p. 103). This use of terminology reflects the understanding that "technologies result when engineers apply their understanding of the natural world and of human behavior to design ways to satisfy human needs and wants" (NRC, 2012, p. 12).

The drive to incorporate engineering in K-12 classrooms came with the arrival of K-12 engineering standards, which appear as part of the *NGSS* (NGSS Lead States, 2013), as well as other state science standards that included engineering (Moore et al., 2013). The NRC (2009) reported on the status of K-12 engineering and proposed three mechanisms to advance K-12 engineering: ad hoc infusion, stand-alone courses, and interconnected STEM education.

While the *Framework* subsequently promoted the integration of engineering into science classes (NRC, 2012), stand-alone engineering and STEM courses continue to exist in K-12 schools. Initially, high-quality STEM curricula and professional development opportunities were rare. As science teachers lacked the knowledge of engineering and skills to integrate engineering into their curriculum, technology teachers were often called upon to infuse engineering concepts into K-12 education (Sanders, 2009). In a review of K-12 engineering curricula, technology was unsurprisingly noted as having primarily "been used to illustrate the products of engineering and to provide a context for thinking about engineering design" (NRC, 2009, p. 9).

This stance toward technology within STEM persists; for example, Massachusetts, an early adopter of K-12 engineering standards, currently utilizes the Massachusetts Science and Technology/Engineering Curriculum Framework to guide K-12 STEM instruction (Massachusetts Department of Education, 2016). Throughout this document (including the title), technology and engineering are intertwined, making them nearly synonymous with one another.

While acknowledging that science and technology are linked, the authors of the *NSES* also recognized key distinctions between the two:

> The central distinguishing characteristic between science and technology is a difference in goal: The goal of science is to understand the natural world, and the goal of technology is to make modifications in the world to meet human needs…Technology and science are closely related. A single problem often has both scientific and technological aspects. The need to answer questions in the natural world drives the development of technological products; moreover, technological needs can drive scientific research. And technological products, from pencils to computers, provide tools that promote the understanding of natural phenomena. (NRC, 1996, p. 24)

This statement is an example of a perspective on technology as the product of engineering, where technological tools are designed to meet specific needs and are used to support investigations. Using this definition, the

NSES defined science and technology standards that "establish connections between the natural and designed worlds and provide students with opportunities to develop decision-making abilities" (NRC, 1996, p. 106). The authors of the *NSES* made it clear that these standards were not intended to support anything other than student learning about engineering design:

> They are not standards for technology education; rather, these standards emphasize abilities associated with the process of design and fundamental understandings about the enterprise of science and its various linkages with technology.... Science as inquiry is parallel to technology as design. Both standards emphasize student development of abilities and understanding. (p. 106).

Further, the authors of the *NSES* explicitly avoided any consideration of technological tools designed to support learning: "The use of 'technology' in the Standards is not to be confused with 'instructional technology,' which provides students and teachers with exciting tools – such as computers – to conduct inquiry and to understand science" (NRC, 1996, p. 24).

For example, in many ways, makerspaces and digital fabrication labs are the modern instantiations of vocational education or shop class. Makerspaces are "physical spaces that have been designed or set aside to support the maker in the creation, design, and building of new projects and technologies" (Blackley et al., 2017, p. 23). Makerspaces can be found in spaces such as libraries, museums, and schools, and they often resemble studio arts learning environments, where participants work with materials to design and make (Halverson & Sheridan, 2014).

The range of products produced by makers is vast and includes crafts, drawings, paintings, electronics, and computer code (Sheffield et al., 2017). Makers are expected to engage in an iterative design process to create these products (Rodriguez, Harron, & DeGraff, 2018), which makes this use of technology a prime example of technology as the product of engineering.

The emergence of making and makerspaces in schools is a growing trend (Adam et al., 2016). The turn of the century saw dramatic decreases in the costs of equipment such as laser cutters and 3D printers, making them more accessible to K-12 schools. The Massachusetts Institute of Technology was the first to develop such equipment in a standardized, low-cost lab (called the FabLab), which can be used in K-12 schools, community spaces, and universities (Gershenfeld, 2008; Mikhak et al., 2002).

The focus of makerspaces and FabLabs is on the individual or collaborative development of an artifact or product, often through "tinkering with materials with an endpoint in mind" (Sheffield et al., 2017, p.149). Similarly, Halverson and Sheridan (2014) pointed out that the focus in design for learning within makerspaces is on the process and the product.

Researchers describe the process within makerspaces and FabLabs as a creative and iterative process using the concepts of tinkering and engineering design to describe the work engaged in by makers. This description reflects alignment and compatibility between actions performed with makerspaces and the science and engineering practices of *NGSS* (Martin, 2015; Quinn & Bell, 2013; Rodriguez et al., 2018;). Science and engineering practices are used by makers when they formulate questions, design models, make measurements, iteratively test their products, and communicate information. Further, STEM-focused makerspaces can address the core ideas and disciplinary practices of STEM fields (Bevan, 2017).

However, "without deliberate professional learning and planning, the glamor of new tech tools can overshadow the importance of pedagogy within makerspaces" (Peterson & Scharber, 2019, p. 43). Professional development efforts for K-12 teachers focus both on learning about the making philosophy, familiarity with available tools, and pedagogies designed to promote tinkering, "fiddling" and the development of 21st-century skills (Peterson & Scharber, 2018; Rodriguez et al., 2018).

Oliver (2016) stated that teachers should first become familiar with common makerspace tools by diving into "making to understand how different activities are structured and what can be learned from them" (p. 162). Other researchers have agreed that experiences with making are critical for teachers, but they argue that teachers also need opportunities to debrief and reflect on the pedagogies used within these maker experiences (Peterson & Scharber, 2018; Rodriguez et al., 2018).

Much of the scholarship on professional learning for teachers related to makerspaces has not been subject specific; however, some researchers specifically argue the need to explicitly articulate the practices of engineering, and applications of science and mathematics for students in makerspaces (Bevan, 2017). An effective makerspace approach to integrated STEM education requires "strong and explicit connections to the curricula of mathematics and science" (Sheffield et al., 2015, p. 151).

Perspective 2: Technology as Educational or Instructional Technology

The 2000s featured an explosion of technological development, primarily with respect to internet-capable devices and the proliferation of online resources, media, and communication tools. These advances resulted in greater consideration of not only the technologies themselves, but also the role that these technologies could play in supporting educational objectives. Mishra and Koehler (2006) are among early researchers positing a conceptual framework that explicitly relates technology, pedagogy, and content. Building off of the conceptualization of pedagogical content knowledge (PCK; Shulman, 1986), Mishra and Koehler extended the PCK model to include a third domain: technology. They describe the intersection of these three domains as technological pedagogical content knowledge, or TPCK (later styled technology, pedagogy and content knowledge or TPACK; see Koehler et al., 2013). Mishra and Koehler (2006) advance the TPCK framework as a conceptual model with theoretical, pedagogical, and methodological implications for educators who sought to use technological tools as educational or instructional technology.

One area that has received a great deal of attention in both research and practice is the area that would be defined by Mishra and Koehler (2006) as technological pedagogical knowledge, or TPK. This domain features approaches to technology integration that would be accessible to practitioners in K-12, higher education, and other contexts regardless of the content being taught.

Hughes (2005) claimed that teachers must develop a technology-supported pedagogy and skills base in order to be effective in integrating technology into their instruction. Such pedagogies and skills have been articulated in the *ISTE Standards for Educators*, which "define the digital age skills and pedagogical insights educators need to teach, work and learn" (ISTE, 2000). As these standards are focused on TPK, they are content- and grade-level agnostic.

The absence of a content focus is an important characteristic of this approach, and it is distinct from approaches that Mishra and Koehler (2006) might classify as relating to content (i.e., TCK or TPCK). This is not necessarily a critique; in fact, it can be viewed as a benefit, as these tools can be applied in a variety of content areas and educational settings.

For example, Habowski and Mouza (2014) described a technology integration course in a secondary science education program that was effective in modeling the use of presentation technologies and online resources in a science classroom. This use is consistent with recommendations from Windschitl (2009) regarding the need for science teachers to provide technology to students that will allow them to gather information more effectively and resources germane to the topic being investigated.

Similarly, McCrory (2008) noted that science teachers often use "technology unrelated to science that can be used in the service of science (e.g., word processors, spreadsheets, graphic software)" (p. 197). While this approach may seem more science-like, it is still an example of pedagogy-oriented technology use (i.e., TPK) that does not directly promote content learning.

An increasingly common example of educational/instructional technology in the K-12 science classroom can be found in one-to-one initiatives. These kinds of initiatives are defined by "access to personal portable technologies in a wireless environment" where "students can learn at their own pace, ability levels, and take advantage of the worldwide experiences and resources available online" (One-to-One Institute, 2020, para. 2).

Examples of personal portable technologies include laptops, tablets, and smartphones. A number of school districts in the United States have initiated one-to-one programs; for example, in 2016, approximately 55% of schools in the state of Minnesota had a one-to-one program (Minnesota Department of Education, 2016), and that number was expected to grow.

The primary function of one-to-one initiatives is to provide teachers and students with the technological devices that facilitate teaching and learning. As such, these devices are not content-specific, but they are often configured and equipped for educational purposes. For example, Constantine and Jung (2019) explored an elementary classroom where fifth-grade students used district-provided iPads as digital notebooks during science lessons as a replacement for traditional science notebooks. The iPads featured apps that allowed students to take notes using a variety of media that included handwriting, typing, photos (which could be captured by the iPad camera), audio, and figures. Students could then submit these notes at the end of the unit as a class assignment. Additionally, the instructor created assignment templates that were shared with the students as digital notebook pages.

The use of the iPads afforded students opportunities to share their knowledge in ways that would not be possible using paper notebooks or worksheets. Examples included capturing a photo, annotating that photo, and submitting it online.

The utility of educational technology (such as mobile devices) is ultimately defined by the way in which the teacher uses the technology. In many cases, advanced digital technologies serve to replace more traditional means of learning, as in the example from Constantine and Jung (2019) regarding digital science notebooks versus traditional (i.e., paper) science notebooks. These technologies also hold the potential to significantly amplify current instructional methods and potentially transform learning in new and innovative ways. Hughes et al. (2006) described these uses via the Replacement, Amplification, and Transformation (RAT) framework.

For example, Constantine and Jung (2019) noted that the use of the iPads to capture, annotate, and submit photos of an in-class activity was an example of technology amplifying instruction. Although many secondary science teacher education programs include courses and experiences designed to support preservice science teachers in using technologies applicably in their future classrooms (e.g., Flick & Bell, 2000), not all science/STEM teachers are adequately prepared to use technology in innovative or transformative ways.

Constantine et al. (2017) found that elementary teachers who codesigned and implemented a STEM curriculum unit featuring one-to-one tablets used them in ways that varied widely from teacher to teacher. These uses, which ranged from no use at all to use that was closely aligned with content learning, were found to be the product of personal beliefs that developed in the absence of formal opportunities to learn about technology integration, such as preservice programs or in-service professional development.

Perspective 3: Technology as Coding or Computational Thinking

In a review of the state of computing, Grover and Pea (2013) described how computing in K-12 education has evolved to focus on the secondary level, with multiple National Science Foundation (NSF) initiatives primarily catering to the development of computing competencies in grades 9-12. In 2012, the Expanding Computing Education Pathways (ECEP) alliance was formed. Diverse programs formed collaborations to address critical challenges related to the incorporation of computing and computational skills, which include various STEM contexts (e.g., CSforALL, SciGirls Code, and Code.org). This type of initiative, in conjunction with increased national funding for computer science and STEM-related opportunities in K-12 education (e.g., NSF STEM+C grants), have brought the perspective of technology as coding or computational thinking to the forefront, offering another perspective of how technology is incorporated in K-12 science and STEM education.

Wing (2006) used the term "computational thinking" to refer to designing systems, solving problems, and understanding human behavior. Wing noted that computational thinking does not necessarily require the use of computers, but instead focuses on the skills required to address various computational issues. Barr and Stephenson (2011) presented computational thinking as a problem-solving process, which included decomposing a problem in order to make it solvable using computational tools, analyzing and representing data systematically, utilizing algorithms, and applying a wide range of solutions.

As computers, coding, and other computational activities have become increasingly ubiquitous in educational settings, a growing number of researchers and policymakers have suggested that technology as coding or computational thinking should occupy an important role in both science and STEM education. For example, the Committee on STEM Education of the National Science and Technology Council (NSTC, 2018) report, *Charting a Course for Success: America's Strategy for STEM Education,* called for a focus on computational thinking as integral for all education in order to develop computational literacy. As such, computational thinking is "the new literacy of the 21st century" (Wing, 2010, p. 3), as computing is becoming increasingly necessary in nearly every career. The Association for Computing Machinery (ACM, 2013) predicted that in 2020, one in every two jobs in STEM will be in computing.

Both coding and computational thinking share a number of elements with STEM disciplines, including data collection, data analysis, data representation, problem decomposition, design, evaluation, and communication (Swaid, 2015). Computational thinking is thus, unsurprisingly, identified by the *NGSS* as one of the eight science and engineering practices (NGSS Lead States, 2013), further cementing the role of computational thinking in K-12 science and STEM education.

Sengupta et al. (2013) suggested that computational thinking has the potential to enrich STEM learning by enhancing student access to abstract concepts while working through systematic computational practices. In the example that follows, we further describe the potential of coding and computational thinking in science and STEM learning contexts.

One common approach that incorporates computational thinking through design within K-12 science and engineering instruction includes LEGO® Robotics and LEGO® MINDSTORMS® (Brophy et al., 2008). LEGO Robotics activities allow students to work with a set of LEGO materials while solving a task or challenge. Students can engage in basic programming using the Evolution 3 (EV3) programming environment to direct their mobile creations to complete specific tasks.

Examples of such tasks include basic motion (i.e., forward, reverse, and turning), line and object detection, and even autonomous parking. These tasks require students to apply systematic problem-solving skills and develop algorithms in the form of codes and loops needed to carry out a command or series of commands. Gura (2012) noted that LEGO Robotics creates opportunities for experiential learning in STEM contexts and describes how LEGO Robotics is incorporated in a middle school science classroom, where "students solve problems that involve designing, building, programming, and operating robots to move from location to location and to carry and deposit objects" (p. 14). Through the use of block coding as an introduction to programming, the series of tasks can be viewed as a starting point for students as they develop skills needed to pursue formal computer science or programming opportunities related to STEM and other fields.

The decision for noncomputer-science teachers to incorporate technology *as coding or computational thinking* in STEM classrooms presents both opportunities and challenges for STEM education. The potential of integrating computational thinking in STEM learning contexts is largely driven by available resources, but it is also constrained by the mindset and skill set of educators related to problem-solving and programming (Brophy et al., 2008).

Angeli and Jaipal-Jamani (2018) observed preservice teachers with no prior experience in computational thinking interact with LEGO WeDo products, building and programming robots in the context of a science lesson focused on gears. The authors noted that at the end of the 6-hour module, the preservice teachers "developed some aspects of computational thinking, but they also further improved their conceptual understanding about gears" (p. 139), which consequently led to significant gains in the teachers' self-efficacy related to teaching science content utilizing robotics.

Sengupta et al. (2018) underscored the need for a shift away from a technocentric focus, taking into consideration teachers' experience with STEM content and computational tools, to sustain computational thinking in K-12 STEM classrooms. However, preparing teachers to incorporate computational thinking across K-12 remains a critical challenge (Angeli & Jaipal-Jamani, 2018; Grover & Pea, 2013).

Perspective 4: Technology as Tools and Practices Used by Science, Mathematics, and Engineering Practitioners

A great variety can be found among conceptions and definitions of STEM education, yet agreement exists surrounding several features of integrated STEM instruction. Among these central features is the importance of a real-world context to engage students in meaningful, student-centered learning that allows students to learn through hands-on, inquiry-based activities (e.g., Breiner et al., 2012; Bryan et al., 2015; Brown et al., 2011;

Kelley & Knowles, 2016; Kennedy & Odell, 2014; Labov et al., 2010; Moore et al., 2014; Rinke et al., 2016; Sanders, 2009).

Together, these components allow students to engage in authentic STEM learning tasks that reflect the work of STEM professionals, highlighting the importance of authenticity within STEM education. The focus of the *NGSS* on science and engineering practices (NRC, 2012) highlights this authenticity by emphasizing that students should be doingscience and engineering rather than simply memorizing a body of facts.

Promoting authentic STEM engagement among students is imperative not only in preparing students for future STEM careers, but also in arming students with 21st-century competencies in general (Honey et al., 2014). To support student engagement in the authentic practices of STEM professionals, learning tasks should include the use of STEM-specific tools or technologies (e.g., Bell & Bull, 2008; Guzey & Roehrig, 2009; McCrory, 2008; Niess, 2005, Novak & Krajick, 2004).

Novak and Krajick (2004) explained, “Utilizing learning technologies in an inquiry-based classroom closely emulates how scientists work in the real world. Students can collect and analyze real-time data much like scientists do” (p. 76). Similarly, Bell and Bull (2008) suggested that technology should be used in a science classroom “to facilitate data collection and analysis, to enhance scientific understandings through imagery and visualization, and to extend inquiry through communication and collaboration” (p. 92). Since technology is central to the authentic work of STEM professionals (Niess, 2005), including everything from scales to supercomputers (Honey et al., 2014), technology can also be viewed as the tools and practices used by science, mathematics, and engineering practitioners.

McCrory (2008, p. 197) defined three categories of technology use that science educators can leverage when supporting science content learning in their classrooms: (a) technology that is not related to science but can facilitate science learning (e.g., word processing and digital spreadsheets), (b) technology created expressly for teaching science (e.g., animations and simulations), and (c) technology that is authentic to the work that scientists do (e.g., probes and microscopes). While the first two categories are most aligned with the perspective of technology as educational and instructional technology, the third category is certainly aligned with the perspective of technology as the tools and practices used by science, mathematics, and engineering practitioners. The following section desvribes two examples of technology use from this third category.

Perspective 4 Example: Data Collection and Analysis With Probes

Probes are a form of technology common to science classrooms. One popular system is the Vernier LabQuest® system, which includes over 80 sensors and coordinating data collection and analysis software that can be used for a wide range of purposes. For example, temperature probes can be used to collect continuous data to compare the rate of heat transfer through different materials, including conductors and insulators. The software can display an instantaneous temperature and also generate a real-time graph that illustrates changes in temperature over time. The latter option allows students to see the graph develop as the experiment is underway, affording them an opportunity that would not have been possible without this specific piece of technology.

This authentic example illustrates technology used by STEM professionals to collect and represent data, as professionals would use similar tools and technologies to collect reliable temperature data in comparable experiments. Nondigital tools, like analog glass thermometers and hand-drawn graphs, could be used to reach the same learning goals in this investigation; however, in this case, the authentic use of STEM technologies increases the efficiency and accuracy of the data collection and analysis. Bell and Bull (2008) summarized this approach:

> Essentially, technology use in the science classroom is most effective when it encourages deeper student engagement with science content, when it is used to support rather than replace what we know about effective science instruction, and especially when it stretches the boundaries of what is possible in the science classroom. (p. 93)

As time constraints are often a common concern for science teachers implementing hands-on activities, teachers may be tempted to use digital technologies for data collection whenever they are available. Temperature probes and analysis software would certainly decrease the amount of time that students would spend creating a graph by hand. However, it is important to consider the purpose of the activity and whether students have the foundational knowledge to understand the processes underlying the technologies.

For example, the skill of reading an analog thermometer may be important for students to develop. Alternatively, if students are learning how to create graphs to represent their data, utilizing software that automatically generates a graph may result in a missed learning opportunity. Therefore, teachers must be intentional in selecting when and how to use technologies, even those that are authentic to STEM professionals, to ensure that learning objectives related to both science content and science practices are met.

Perspective 4 Example: Modeling With CAD Software

Another example of technology that "stretches the boundaries of what is possible in the science classroom" (Bell & Bull, 2008, p. 93) can be found in computer-aided design (CAD) software and 3D printing technologies, which are becoming increasingly accessible to schools with respect to cost and ease of use. Custom software interfaces and editable templates provide feasible entry points to 3D design even for elementary students (Wieselmann et al., 2019) and, when used as a tool for modeling and prototyping, these technologies are authentic to STEM professionals. For example, Wieselmann et al. described how students can design and 3D print rocket fin prototypes to test in a model rocket launch. With fin designs of varying shape and size, students can investigate how the independent variables of fin size and shape relate to the stability and distance of the rocket's flight. The results from their prototype testing can be used to refine their designs, which is representative of how professional engineers use rapid prototypes.

The mere use of CAD software or 3D printers may not inherently be an authentic use of STEM technologies, however. For example, providing students with premade CAD files for toys or trinkets and allowing them to 3D print the parts is not authentic to how professional engineers use 3D printing in their work. While this type of experience could be valuable to instill in students a sense of excitement about 3D design and printing that is later built upon in more authentic ways, it is not considered an authentic use of STEM technologies in itself. Teachers must carefully consider whether CAD software and 3D printers are being used for modeling or developing and printing testable prototypes, which is how STEM professionals use these technologies.

Synthesis and Discussion

After reviewing the four perspectives and their associated examples of classroom enactment, we have identified Perspective 4 as the most productive with respect to K-12 science and STEM education curricular and instructional goals. While each of the four perspectives has the potential to promote and advance science and STEM content learning and instructional goals, this relationship is most explicit in Perspective 4, making it a particularly useful definition of technology for science and STEM educators. The sections that follow include detailed comparisons of Perspective 4 to each of the other perspectives and a fuller articulation of the advantages and disadvantages of each perspective for science and STEM educators.

Perspectives 1 and 4: What Are We Making?

Perspective 1 (technology as vocational education, industrial arts, or the product of engineering) provides an accurate representation of the connection between engineering and technology: Engineers do indeed design and develop technologies in the form of a new product or process. However, reducing technology to the output of engineering is limiting for teacher educators working toward improving science teachers' understanding and implementation of STEM content. Perspective 1 provides a vague definition of the T in STEM; in this perspective, STEM has been reduced to SEM or S(T/E)M, in which technology and engineering are interchangeable and not distinct from one another. Unfortunately, implementations of this perspective focus almost exclusively on engineering, which is unsurprising given the historical connections to vocational education.

When considering K-12 initiatives such as makerspaces or FabLabs, the focus is on using the iterative design process to produce a product (i.e., the technology). While students engage in some of the *NGSS* science and engineering practices within a maker environment, the activities are often best described as tinkering. Engineers draw on their knowledge of science and mathematics to develop solutions to a problem; they do not simply tinker.

A makerspace approach to integrated STEM education can be an authentic and robust pedagogical practice only if there are “strong and explicit connections to the curricula of mathematics and science” (Sheffield et al., 2015, p. 151). With these explicit connections present, engineering in maker contexts would allow students to engage in the *NGSS* science and engineering practices and apply content knowledge to authentic problems. In other words, to promote an effective approach for STEM instruction, it is necessary to focus on how these tools and practices are used by STEM professionals, as articulated by Perspective 4.

For Perspective 1 to be a more meaningful enactment of the T in STEM, teacher educators must provide professional preparation for the implementation of STEM-rich making; otherwise, students will be “deeply engaged in the realm of investigation, without shifting to scientific practices of sense-making and critique” (Bevan, 2017, p. 97). Both preservice and in-service teachers must be made aware of this distinction, as Perspective 1 is pervasive in schools and curricula that teachers are likely to encounter, such as *Engineering Is Elementary*. All teachers need to learn about the limitations of this approach and develop a full understanding of the varying perspectives of the T in STEM.

Perspectives 2 and 4: The Relationship Between Technology and Content

When comparing Perspective 2 (technology as educational or instructional technology) and Perspective 4 (technology as the tools and practices used by science, mathematics, and engineering practitioners), the most obvious difference is the role of content in determining best practices for technology use. The TPCK model (Mishra & Koehler, 2006) certainly notes the importance of content when integrating technology, but many K-12 technology initiatives today are intended to support multiple content disciplines and, therefore, focus on general pedagogical supports over content-specific applications.

While these approaches are valuable and have the potential to support teachers’ abilities to replace, amplify, and even transform their instruction (Hughes et al., 2006), the absence of content-driven technology practices poses a unique problem for science and STEM educators. Flick and Bell (2000) noted that many preservice science teachers participate in a generic educational technology course in their program that introduces them to a variety of technological tools and practices that they must then apply to their science classroom. Instead, technology should be introduced in the context of science and STEM teaching as a means to the end of supporting meaningful science learning. This approach is more closely aligned with Perspective 4, where science teacher educators consider the tools and technologies that are not only representative of the work of scientists and other STEM professionals, but directly support understanding of the science content.

A number of barriers to moving from Perspective 2 to 4 can be identified. Graham et al. (2009) noted that both elementary and secondary science teachers are more comfortable using technologies designed for teaching science over technologies designed for doing science. This finding could be the result of a number of possible factors, including limited science content knowledge among participating teachers, limited availability of scientific equipment in the classrooms, and teacher preference to leave technologies in the hands of the instructor, not the students. While access to applicable technologies is indeed a first-order barrier (Ertmer, 1999), Hechter et al. (2012) noted that teachers

> with the knowledge, skills, abilities, dispositions, creativity, and desire to integrate technology into classroom teaching and learning encounter barriers … employ their innovative and critical problem-solving abilities to structure lessons with technological variety using what is at hand, and what can be obtained or accessed. (p. 138)

Researchers have contended that teacher beliefs about technology use, not access to technologies, is one of the largest determining factor of technology use in classrooms (e.g., Constantine & Jung, 2019; Ertmer, 2005; Hechter et al., 2012). Teachers will only begin to adopt and use technology that is authentic to the work of scientists though awareness of and exposure to such uses.

Perspectives 3 and 4: Computational Thinking in STEM Contexts

In today's increasingly digital world, computational thinking is evolving as an interdisciplinary toolkit, and the integration of technology as coding or computational thinking within a STEM learning context can be a purposeful application of this toolkit. When computational thinking is viewed as a practice that both STEM professionals and students can use, programming skills are utilized and developed as a by-product, not as the primary objective. In other words, computational tools in a STEM context create authentic opportunities to engage with real world problems, and coding is one such tool that can allow students to investigate and design meaningful solutions in this digital age.

What differentiates Perspective 3 (technology as coding or computational thinking) from Perspective 4 (technology as the tools and practices used by science, mathematics, and engineering practitioners) is primarily the context. Technology as coding or computational thinking is an expansive view, with no consensus regarding a definitive way in which computational thinking is understood (Weintrop et al., 2016). Perspective 3, therefore, includes computational thinking in STEM learning contexts, but does not rule out the incorporation of computational tools and thinking in other contexts (such as collaborative problem-solving in a social studies context) or without any context at all (such as focusing solely on learning a new programming language).

For example, LEGO® Robotics activities without a STEM context can involve computational thinking but may not result in creating connections with real-world problems and solutions. However, when students utilize materials like LEGO Robotics sensors and build robots to respond to the readings on the sensors (e.g., Gura, 2012), computational tools can contribute directly to meaningful STEM learning because computational thinking is integrated as technology within a STEM learning context. Students can learn STEM content while also building programming, critical thinking, and problem-solving capabilities using computational tools.

Sengupta et al. (2018) suggested that computational thinking should be implemented in STEM classrooms through experiential rather than technocentric approaches. Teacher education must emphasize experiential approaches so that the incorporation of computational thinking in STEM learning contexts deepens the learning of STEM content using computational tools. This approach creates what Weintrop et al. (2016) described as a reciprocal relationship, where teachers use "computation to enrich mathematics and science learning and [use] mathematics and science contexts to enrich computational learning" (pp. 128-129). Such an approach could be aligned with both Perspective 3 and Perspective 4, where computational thinking is integrally connected to an authentic STEM learning context and computational tools create opportunities to deepen the STEM learning experience.

Conclusions and Implications

After reviewing these four perspectives on the role of technology in science and STEM education, the perspective with the greatest potential for positively impacting science and STEM learning is Perspective 4, where students learn using technologies that are analogous to the tools and techniques that practitioners of science, engineering, and mathematics use in the field. By using authentic STEM tools and techniques, students can learn both the content and the practices of science, engineering, and mathematics. Although the other three perspectives can be meaningfully incorporated in a science or STEM classroom, Perspective 4 is in many ways compatible with these perspectives.

With the wide range of technologies available to science and STEM teachers, it is important to empower teachers to be critical consumers of technology. Classroom technologies should be carefully selected based upon their alignment to the desired learning outcomes, and rather than focusing on which technologies to select, teachers should instead focus on how they are being used. Even technologies that are widely accepted as central to STEM fields (such as 3D printers) can be used in inauthentic ways. Technology for the use of technology's sake often does not lead to student conceptual learning.

In conclusion, the perspectives advanced in this article are by no means the only perspectives that researchers, educators, and practitioners should adopt. While Perspective 4 holds the greatest potential for positively impacting science and STEM teaching and learning, we do not discount the value of activities that include the technological products of engineering, learning technologies that are designed to support students in any discipline, or engaging students in coding or computational thinking. The need is critical to share all four perspectives with in-service teachers through professional development and with preservice teachers through courses that promote content-specific technology uses.

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