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Bridging STEM With Mathematical Practices

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ABSTRACT

Science, technology, engineering, and mathematics (STEM) is often defined as a meta-discipline wherein content from all fields is integrated. However, many teachers are not content experts within each of these disciplines and bridging these individual fields can be a challenge. Yet, content integration need not be the only means by which STEM integration occurs; common practices that focus on thinking and reasoning can and should also exist within classrooms. Even though each STEM field has their own distinct ways of thinking, there are common practices that can link learning to increase students' readiness for the 21st century. This paper highlights how the *Common Core State Standards for Mathematics*' Standards for Mathematical Practice can serve as a common framework around which educators across grade levels can integrate STEM thinking into their own classrooms.

Keywords: Integration; Mathematics; Mathematical Practices

Much attention has been placed on developing student interest and competencies in science, technology, engineering, and mathematics (STEM), and rightfully so. The demand for STEM professionals in the United States outpaces supply and proficiency in mathematics and science is declining (Jobs for the Future, 2007; National Assessment of Educational Progress, 2007). The need to increase and develop K–12 students' mathematical and scientific literacies in STEM education is ever growing and urgent. In the United States alone it is projected that eight million jobs in science, technology, engineering, and mathematics related fields will be needed in the next ten years (United States Department of Commerce, 2011). Furthermore, literacy in STEM has several benefits including the ability to understand and participate in societal and economic matters relevant to an individual's environment, situation, and context (Zollman, 2012) and students who excel in STEM content areas often have several attributes that are valued in higher education and the workforce (Teaching Institute for Excellence in STEM [TIES], 2006). The National Research Council (National Research Council [NRC], 2011) states that even students who do not pursue careers in STEM related fields will need and benefit from being appropriately literate in science and mathematics. Therefore, excellence in STEM education is relevant and necessary to all students.

Traditionally, secondary schools operate within a departmentalized framework that often inhibits the integration of content areas, emphasizing knowledge in silos; this approach may be easiest, but does not meet the needs of students. Teachers with specific content expertise also often struggle in making the connection between disciplines, especially when involving mathematics (Russo, Hecht, Burghardt, Hacker, & Saxman, 2011). The same dilemma exists within many preservice teacher development programs. Preservice teachers complete specific content and methods courses but rarely learn how to blend or infuse content. While elementary schools offer ideal learning situations with flexible periods of time for integrated learning, many elementary teachers lack the content knowledge to effectively create such situations in STEM (Russo et al., 2011).

Furthermore, mathematics has been, and will continue to be, one of the main content areas at the forefront of standardized testing. Historically, testing of this nature has focused on procedural content knowledge and does little to help students learn mathematical problem solving or reasoning. Nor does this discrete measure of isolated facts help students learn to reason across STEM disciplines or other related 21st-century skills. In order to address the STEM career and college readiness needs, greater attention needs to be on developing STEM thinkers and problem solvers who can effectively communicate and collaborate with others. In essence, educators need to find ways to bridge STEM disciplines by supporting student thinking and reasoning regardless of the STEM content.

One of the more recent initiatives for improving student performance in mathematics came from the development and implementation of the *Common Core State Standards for Mathematics* (National Governors Association Center for Best Practices [NGA Center] & Council of Chief State School Officers [CCSSO], 2010). These standards seek to increase students' mathematical performance and understanding through the development of conceptual and relational understanding; the knowing of what to do, how to do it, and why particular mathematical methods are appropriate and effective for problem solving. For quite some time now there has been substantial attention on high-stakes testing to raise test scores and measure student learning (Popham, 2008). In doing so, an over-emphasis is placed on developing students' computational skills and not on reasoning and thinking skills; skills applicable beyond just mathematics. Part of the *Common Core State Standards for Mathematics* includes the Standards for Mathematical Practice (SMP), the behaviors and habits of mind used by proficient and creative mathematical thinkers. While other content areas, both within and beyond STEM disciplines, might have practices that support and develop the necessary behaviors within their discipline, mathematics is the cornerstone for all STEM disciplines. It is the language by which the sciences, technology, and engineering verify, validate, or construct their work and understandings. The focus of this paper is on using the mathematical practices to bridge STEM-related practices; practices that have their roots in a shared structure, mathematics. In doing so, K–16 educators will have a common framework from which to support relevant and contextually-based and integrated student learning experiences across STEM disciplines.

Rethinking Integration

Integrated content represents an ideal situation for learning; content is often inherently linked in practical or real-world situations and thus it should be linked in learning experiences, too. However, content integration need not be the only means by which STEM reasoning can be promoted and developed. In fact, content integration need not even be the first means by which STEM reasoning is developed.

Since reasoning skills are at the root of all STEM disciplines (TIES, 2006), a logical first step would be to focus on common habits of mind that link scientific and mathematical practices, engineering design processes, and technology foundations. The CCSS SMP (NGA Center &

CCSSO, 2010) provide an ideal framework by which educators in all core STEM disciplines can infuse essential practices that promote reasoning, communication, problem solving, and using appropriate tools to support and justify thinking. Specifically, the eight SMP are:

1. Make sense of problems and persevere in solving them.
2. Reason abstractly and quantitatively.
3. Construct viable arguments and critique the reasoning of others.
4. Model with mathematics.
5. Use appropriate tools strategically.
6. Attend to precision.
7. Look for and make use of structure.
8. Look for and express regularity in repeated reasoning. (NGA Center & CCSSO, 2010, p. 10)

While originally framed around the Process Standards from the National Council of Teachers of Mathematics' *Principles and Standards for School Mathematics* (2000) and the National Research Council's (2001) report, *Adding It Up*, the SMP fundamentally extends beyond mathematics and bridge the STEM disciplines. When learning science and engineering, students engage in practices that parallel the thinking practices of scientists and engineers; they learn to understand how science is done. As in mathematics, "doing science" or "doing engineering" is not an algorithmic procedure, sometimes not even experimental, but a reasoning process that is open to exploration and discovery.

In the science classroom, students are encouraged to plan and carry out investigations and use skills necessary as they "make sense of problems and persevere in solving them" (NGA Center & CCSSO, 2010, p. 10). Engineering investigations, in particular, are designed to solve problems given constraints. *A Framework for K–12 Science Education* (NRC, 2012) defines engineering "in a very broad sense to mean any engagement in a systematic practice of design to achieve solutions to particular human problems" (p. 3), problem solving aspects also found within the SMP and scientific design.

In using the SMP as a guiding framework around which teachers can support STEM thinking skills, the need to have extensive content knowledge in numerous and specific STEM areas is diminished; helping students learn to think is what matters (Roberts & Billings, 2009). Each SMP begins with the language "mathematically proficient students" (NGA Center & CCSSO, 2010, p. 6–8), but by replacing the word *mathematically* with the word *STEM*, a different picture and conceptual framework for infusing STEM skills begins to take shape. It is through this STEM focused SMP lens that the integration of STEM thinking in the classroom can be promoted and developed.

Infusing the Standards for Mathematical Practice

This section highlights the cross-cutting capabilities of each of the SMP. Language from the CCSS SMP is provided as a reference, although some of the specific wording dealing with mathematical tasks or examples has been removed to provide a more STEM-focused context.

Student-centered learning experiences are presented with discussions on how teachers from various STEM disciplines might infuse each SMP to promote a cohesive approach to developing STEM reasoning. It should be noted that while the SMPs are listed separately, they are often interrelated and can support each other. This means that while they are presented as separate components, they can and should be integrated themselves.

SMP 1: Make Sense of Problems and Persevere in Solving Them

> *[STEM] proficient students start by explaining to themselves the meaning of a problem and looking for entry points to its solution. They analyze givens, constraints, relationships, and goals. They make conjectures about the form and meaning of the solution and plan a solution pathway rather than simply jumping into a solution attempt. They consider analogous problems, and try special cases and simpler forms of the original problem in order to gain insight into its solution. They monitor and evaluate their progress and change course if necessary. (NGA Center & CCSSO, 2010, p. 6)*

This SMP focuses on students understanding problems so that they know how to begin to develop a solution strategy to solve the problem. This requires that they analyze information provided within the problem and make a logical plan based on previous experiences instead of just “jumping into” solving the problem. At times, this may mean that students will need to make changes to their plan and ask if their plan, along with supporting work or evidence, makes sense. Additionally, students will be able to explain all elements of their plan including any work or relationships through other representations such as graphs, pictures, or words. Finally, STEM proficient students will recognize that complex problems have multiple correct plans and will be able to identify similarities in other plans.

In the *Next Generation Science Standards* (Achieve, 2012), students will be expected to learn about the three phases of problem solving: “defining and delimiting an engineering problem,” “developing possible solutions,” and “optimizing the design solution” (NRC, 2012, p. 203) These three phases can each be connected back to the CCSS SMPs. For example, students should be “defining and delimiting” engineering problems which follow a similar process within the CCSS SMP, designing plans to generate a solution to engineering-based problems. Students will need to generate a number of possible solutions, evaluate potential solutions to see which ones best meet the criteria and constraints of the problem, and then test and revise their designs. Lastly, students need to “optimize” their design plan, which involves a process of tradeoffs; the final design is improved by trading less important features for those that are more important. This process may require a number of iterations before arriving at the best possible design.

For example, an activity that teaches engineering design and problem solving, as well as forces, motion, and buoyancy, challenges students to design a system wherein helium balloons float at a specified altitude (National Aeronautics and Space Administration, 2012). To be successful, students must use criteria and constraints, along with understanding some of the relationships and goals. In essence, proficient students develop a plan, based on current understandings and past experiences, before leaping into a solution. Specifically, they must analyze the problem (helium balloons typically will float to the ceiling), identify criteria and constraints, develop several possible plans, select a design, build a model or prototype, test their plans, and refine the design; all of which require perseverance.

SMP 2: Reason Abstractly and Quantitatively

> *[STEM] proficient students make sense of quantities and their relationships in problem situations. They bring two complementary abilities to bear on problems involving quantitative relationships: the ability to decontextualize—to abstract a given situation and represent it symbolically and manipulate the representing symbols as if they have a life of their own, without necessarily attending to their referents—and the ability to contextualize, to pause as needed during the manipulation process in order to probe into the referents for the symbols involved. (NGA Center & CCSSO, 2010, p. 6)*

This SMP deals with reasoning skills. Specifically, the need for students to view problem solving in two ways: within the context and removed from the context. In doing so, students can break down a problem into separate, and possibly abstract, parts; investigate these parts; and reason how they relate to each other. All the while, students must still be able to reflect on their reasoning as it relates to the whole problem. In essence, proficient students examine details and yet keep the original context in mind, questioning their findings along the way. Both methods involve creating meaningful representations of information and understanding the *how* and *why* involved in the solution path.

Scientists and engineers also develop explanations and solutions and need to view problems from a decontextualized and contextualized framework. They draw from theories and models and propose extensions to theory or create new models. For instance, a concept in multiple grade levels that students have many misconceptions about is the properties of matter. Students in upper grade levels learn to represent matter symbolically (e.g., CHO_2) and manipulate those symbols to balance equations and make predictions based on the structure of the chemical composition. In such situations, students must decompose a problem into parts, investigate these parts, and reason about how they relate to each other. Yet, they still must be able to reflect on their reasoning as it relates to the whole problem. Students must consider the details of manipulating the chemical symbols while keeping the original context in mind (e.g., the properties of the matter they are working with) in order to draw conclusions and make predictions about the effect of combining or manipulating the matter as it relates to the original problem.

SMP 3: Construct Viable Arguments and Critique the Reasoning of Others

> *[STEM] proficient students understand and use stated assumptions, definitions, and previously established results in constructing arguments. They make conjectures and build a logical progression of statements to explore the truth of their conjectures. They are able to analyze situations by breaking them into cases, and can recognize and use counterexamples. They justify their conclusions, communicate them to others, and respond to the arguments of others. They reason inductively about data, making plausible arguments that take into account the context from which the data arose…[STEM] proficient students are also able to compare the effectiveness of two plausible arguments, distinguish correct logic or reasoning from that which is flawed, and—if there is a flaw in an argument—explain what it is. (NGA Center & CCSSO, 2010, p. 6–7)*

At its heart, this SMP focuses on engaging in meaningful discourse. When students engage in discourse they need to use learned definitions, assumptions, and results when they defend or justify their ideas and conclusions to others. They also need to use these skills when critiquing the arguments of others. In order to effectively engage in this level of discourse students will need to listen to or read their peer's arguments, determine if it makes logical sense, compare arguments for effectiveness, and identify flaws in reasoning as necessary. Furthermore, students will need to ask questions of each other in order to improve arguments, be it their own or their classmates.

Scientists and engineers often engage in an iterative process or evaluation wherein they develop and refine ideas. Argumentation and critique are central activities in this process; they "attempt to establish or prove a conclusion on the basis of reasons" (Norris, Philips, & Osborne, 2007, p. 90). Activities that teach argumentation and reasoning in science encourage students to evaluate alternative perspectives and the acceptability, relevance, and sufficiency of the reasons used to support different perspectives (Osborne, Erduran, & Simon, 2004). For example, students can be asked to develop a tentative explanation or claim for a natural phenomenon such as the phases of the moon. Students then extend their explanation and reasons into a succinct argument using evidence, such as a lunar calendar or direct observations, and models, such as globes and foam shapes, then present their justifications to their peers who can then ask questions, refute statements, or otherwise engage in a discursive interaction based on the original argument. From this discourse and sharing of ideas, students can determine which models offer the best representation or solution path based on logic and evidence just as they do in mathematics.

SMP 4: Model with Mathematics

> *[STEM] proficient students can apply the mathematics they know to solve problems arising in everyday life, society, and the workplace…. They are able to identify important quantities in a practical situation and map their relationships using such tools as diagrams, two-way tables, graphs, flowcharts and formulas. They can analyze those relationships mathematically to draw conclusions. They routinely interpret their mathematical results in the context of the situation and reflect on whether the results make sense, possibly improving the model if it has not served its purpose. (NGA Center & CCSSO, 2010, p. 7)*

This SMP is rather direct. Students will need to use their knowledge of mathematics to solve real problems without previously having encountered a specific problem or scenario. During this process, students may use a variety of representations to show the relationship between the elements of the problem, as this will help them generate conclusions on the relationships. Students will also be able to interpret, reflect upon, simplify, and make assumptions based on their mathematical knowledge to help them solve real-world problems.

Students might use this SMP when exploring and investigating the water quality of a stream or river. Several variables must be considered when examining the health of a water system, many of which must be modeled mathematically in order to see patterns or draw conclusions, including, but not limited to, the levels of dissolved oxygen, nitrogen, pH, chlorine, and sediments. Measuring dissolved oxygen, for example, requires students to measure the amount of molecular oxygen (O_2) not associated with H_2O in water, the oxygen available for animals that live in water to breath. It is one of many measures of the health of an ecosystem, as dissolved oxygen changes based on temperature, atmospheric pressure, salinity, and the absence or presence of plants or animals that live in the water. Dissolved oxygen is typically measured with an electronic probe, and students often begin to understand the relationships between dissolved oxygen and temperature, pressure, and salinity as they represent their data mathematically using graphs, tables, and formulas. Modeling with mathematics allows students to identify and analyze relationships between variables in the context of water quality and infer conclusions about the health of the system.

SMP 5: Use Appropriate Tools Strategically

> *[STEM] proficient students consider the available tools when solving a…problem…. Proficient students are sufficiently familiar with tools appropriate for their grade or course to make sound decisions about when each of these tools might be helpful, recognizing both the insight to be gained and their limitations. (NGA Center & CCSSO, 2010, p. 7)*

A diverse toolkit is essential in the sciences. Students need to know how and why specific tools are necessary in solving a problem as well as the constraints of those tools. This SMP states that students need to know when and how to use available tools to solve problems, be it with paper and pencil, calculators, computers, or other data collection tools. Regardless of students' grade level or the course, they should have sufficient knowledge to determine when and which tools will be of benefit to their needs; this also includes knowing when certain tools may not be useful.

Scientists use a variety of tools to obtain information, reveal patterns, and determine relationships about objects that are too large or too small using only human senses. As part of planning and carrying out any investigation, scientists need to utilize appropriate tools (e.g., rulers, beakers, graduated cylinders, telescopes, and microscopes) for evidence collection to substantiate claims. For example, when learning to understand weather phenomena, students utilize thermometers to measure temperature, barometers to measure air pressure, anemometers to measure wind speed, and hygrometers to measure the amount of moisture in the air. However, as stated in the SMP, it is useful to not only know the information that can be gained from a specific tool (e.g., that a barometer is a tool to measure atmospheric pressure) but to know and recognize the limitations of a given tool (e.g., often barometers have elevation limitations) and take that into account when using the data from a tool to justify claims.

SMP 6: Attend to Precision

> *[STEM] proficient students try to communicate precisely to others. They try to use clear definitions in discussion with others and in their own reasoning. They state the meaning of the symbols they choose, including using the equal sign consistently and appropriately. They are careful about specifying units of measure, and labeling axes to clarify the correspondence with quantities in a problem. They calculate accurately and efficiently, express numerical answers with a degree of precision appropriate for the problem context. (NGA Center & CCSSO, 2010, p. 7)*

Precision matters greatly in STEM (Achieve, 2012); without it little matters. This SMP highlights the need for students to use precision in written and oral language; models and representations, symbolic or otherwise; measurements and their units; and calculations and their referent solutions. Precision, which is the degree to which something can be replicated, has a different meaning than accuracy, which is how closely something is measured; however, both are important. Within STEM contexts, this means that the focus is on students being able to validate arguments, replicate procedures, and express findings based on logical and systematic thinking. Historically, and from a mathematical perspective, precision may have been thought of as just referring to calculations. But, the National Council of Teachers of Mathematics (2000) has long framed precision in a larger context of problem solving, reasoning, and communication; this is a trait of effective STEM professionals across disciplines. Although some teachers of mathematics may not attend to precision when dealing with some computations, such as when calculating the area of a 3 cm by 2 cm quadrilateral (writing it as 3 x 2 = 6 cm^2 instead of 3cm x 2 cm = 6 cm^2), ultimately the student's work and explanation must attend to precision. When the famed mathematician G. H. Hardy stated, "there is no permanent place in this world for ugly mathematics" (1940/2005, p. 14) he was, in a sense, referring to precision. All STEM disciplines must attend to precision, in that the practical, technical work as well as the communication of this work needs to be stated simply and efficiently.

Students should have numerous opportunities, both formally and informally, to practice attending to precision. Precision has several facets in STEM, which include but are not limited to using appropriate and accurate vocabulary, expressing ideas in written and spoken form, and conducting investigations. Similar to the use of precision in mathematics, scientists use mathematics to communicate meaning related to their observations. Meaning in science often involves measurements, but measurements have limited precision. For example, in an activity dealing with force and motion, students release a small car at the top of a ramp to determine if the height of the ramp affects the distance the car travels. One of the tasks in this activity requires students to measure elapsed time with a stopwatch from when the car is released to when the car comes to rest. Afterwards, students compare and discuss their results with the rest of the students in the class, using specific language and details from their exploration. They discover that there are differences in their elapsed time due to the limitations in precision of their tool.

SMP 7: Look for and Make Use of Structure

> *[STEM] proficient students look closely to discern a pattern or structure…. They also can step back for an overview and shift perspective. They can see complicated things … as single objects or as being composed of several objects. (NGA Center & CCSSO, 2010, p. 8)*

Students need to be able to look for patterns and structures as they work in all STEM related disciplines in order to gain deeper insight into the topic under study. This means not only being able to identify a pattern or structure but also having the ability to reflect on their investigations, evaluate the effectiveness of their work in producing the desired results, and possibly take a new approach if their efforts seem not to be working as planned. Furthermore, students who are able to look for and make use of structure can break down complex problems into either several objects or single objects. In essence, they can see the proverbial forest and the trees simultaneously, allowing them to make adjustments to their thinking or methods to more effectively arrive at a solution.

This SMP is evident in the importance of understanding systems, "groups of related parts that make a whole and carry out functions that individual parts cannot" (NRC, 2011, p.107), as a crosscutting science and engineering concept taught at different grade levels. For example, in an upper elementary study of matter and energy in ecosystems, students would construct models to explain the relationships of each of the individual parts (plants, animals, fungi) as it relates to the ecosystem as a whole. The model would describe the interactions of systems within the larger ecosystem in terms of the flow of energy and the cycling of matter. Since complicated systems are composed of multiple parts, students learn to view the whole system as single objects comprised of related subparts with a clear structure, as described in this SMP.

SMP 8: Look for and Express Regularity in Repeated Reasoning

> *[STEM] proficient students notice if calculations [or ideas] are repeated, and look both for general methods and for shortcuts…. As they work to solve a problem … [STEM] proficient students maintain oversight of the process, while attending to the details. They continually evaluate the reasonableness of their intermediate results. (NGA Center & CCSSO, 2010, p. 8)*

This SMP focuses on students being able to identify and explain processes and structures of thinking based on repeated reasoning. This means that students will examine and consider strategies from a macroscopic and microscopic perspective, keeping the overall goal in mind while paying attention to details. Students may take shortcuts during their investigations, or when solving a problem, and make logical adjustments based on their findings, continually evaluating results for accurateness and reasonableness.

Finding and analyzing regularity is also an important scientific and engineering practice. Revealing the repeated reasoning or regularity in the natural world can lead to inferences about cause and effect relationships, which can then be used to extrapolate information and make predictions. Engineers commonly analyze and diagnose design failures based on repeated regularity, thereby helping design a more effective solution. When using a systematic process for evaluating solutions under similar conditions and tests, the regularity and repeated reasoning found in these comparisons reveal the optimal solutions to a problem. For example, a common engineering activity that might be found within a secondary classroom involves comparing the power utput of different turbine blade designs. Systematically, students can investigate the effects of blade length, number of blades, pitch, shape, and materials used to explore patterns in power output and decide on the best design. Their findings then become generalizations around which shortcuts can be developed. For example, not every length of blade must be tested as regularity in the design and testing stages will dictate the optimal size for a blade. The regularity within the patterns and the repeated reasoning during the design–redesign process also become the basis for evaluating the reasonableness of results.

Conclusions

Helping students develop as proficient STEM thinkers does not have to be restricted to content integration. By infusing the Standards for Mathematical Practice from a broader STEM perspective into the curricula, students can learn to think like mathematicians, scientists, and engineers. Although the described framework represents one way in which teachers can accomplish this goal, it is by no means the only way. Under ideal circumstances, both content and practices would be integrated, though as described earlier, not all teachers possess sufficient pedagogical, content, and process knowledge to do so effectively (Russo et al., 2011). Similarly, the Scientific and Engineering Practices proposed by *A Framework for K–12 Science Education* (NRC, 2012) could be used as a means of integrating STEM, but the connection to mathematical thinking may not be as clear to mathematics teachers. Regardless, the integration of STEM is vital to meeting the goals and challenges currently facing schools in helping students become STEM literate within the 21st century (Zollman, 2012); therefore, action needs to be taken.

The implications for teaching and learning are promising if such a model were adopted and implemented in schools. Cuoco, Goldenberg, and Mark (2012) conceptualized the learning of mathematics around *mathematical habits of mind*—the methods, procedures, and process mathematicians use when problem solving—and found that curriculum became more coherent and that the methods teachers needed to use to make connections between vastly different mathematics curricula was substantially reduced. Ultimately, learning for students became more accessible and focused. Similarly, a unified vision and framework of STEM habits of mind based on the CCSS SMP holds the same promise, fewer and more coherent methods to support student learning across curricula. Adopting and implementing such a framework directly addresses the call to understand how standards for science and mathematics (Ferrini-Mundy, 1998) and technology/engineering and science (Brown, Brown, & Merrill, 2011) mutually support each other. The suggested STEM practices provide educators from across STEM disciplines the opportunity to begin or further their conversations, at the classroom level, on methods that they can use to support student learning. The suggested practices should also provide another area for research, the examination of an interim step in moving from the traditional "silo" view of STEM to the integration of STEM habits of mind, by first integrating common practices.

Although the classroom scenarios described above are but a snapshot of the potential ways in which the CCSS SMP could be integrated, it is quite reasonable for teachers outside of the traditional core of STEM classes to support the development of STEM thinking based on the SMP. Regardless, building creative and innovative thinkers that can apply content knowledge and reasoning, within and between any STEM discipline to facilitate a deeper understanding of these interconnected and mutually supportive disciplines is long overdue. It is time to bridge STEM.

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