

STEM WAYS OF THINKING

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We explore the epistemological issues that arise when considering STEM as a curricular and instructional construct. Our approach is somewhat unique in that we are not focused on the curricular or instructional boundaries of STEM education, but consider the nature of the cognitive activity at play during STEM-focused activity, with an emphasis on mathematical thinking. We focus specifically on the epistemological underpinnings of mathematics and other STEM disciplines, and the possibility of an epistemology of STEM as a curricular construct. The implications on students' STEM ways of thinking (SWoT) are discussed in detail from a theoretical and empirical lens. Future research directions are identified.

Keywords: Advanced mathematical thinking; Learning theories; Reasoning and proof

Objectives

This paper explores various theoretical perspectives on what we are terming *STEM ways of thinking* (SWoT). We provide an extensive review of the literature on the perspectives taken on this topic, followed by a discussion of our own empirical work in this area. We are not focused on the nature of STEM itself, but on the ways in which students think about STEM in interdisciplinary curricular contexts. We focus specifically on SWoT as **argumentation in STEM contexts (argumentation)** and **thinking about STEM interdisciplinary concepts (explanation)**. The roles of epistemology, content, schooling, and cognition are considered.

Theoretical Perspectives

Teachers' facilitation of classroom conversations that both model and provide opportunities for students to use reasoning and conceptual understanding is an ambitious practice receiving significant attention in teacher education (Ball, Sleep, Boerst, & Bass, 2009; Lampert & Graziani, 2009; Franke, Borko, & Whitcomb, 2008) as well as within STEM education policy and standards (CCSSI, 2010; NRC, 2001; NGSS, 2013). Argumentation or explanation, as well as other valued mathematical practices such as perseverance, modeling, and attending to precision (CCSSI 2010), can develop from conceptually-based conversations embedded in problem-solving contexts. In mathematics, problem-solving processes utilize representations (e.g., numbers, polygons, graphs) in support of arguments and explanations, but different representations and processes are often foregrounded in other STEM areas. For example, in science, student arguments usually derive from experimental evidence linked to scientific principles. In engineering, they usually derive from the testing, data analysis, and redesign efforts central to design-based project activities. The claims, evidence, reasoning (CER) framework is a widely-used perspective on scientific thinking related to argumentation (McNeill & Krajcik, 2012) that can be generalized to both mathematics and engineering (Figure 1).

In addition to differences in representations, processes, and expectations for the certainty of evidentiary claims, each STEM discipline also has its own theoretical frameworks for discussing content-specific ways of thinking in relation to the development of conceptual understanding (Wasserman & Rossi, 2015). For example, there are specific ways that children think about

fractions, including as part-whole relations, ratios, and numbers (Lamon, 2012). Middle and high school students often initially conceive of functions as an output-producing action before developing a more object-oriented understanding grounded in domain-range correspondences and the properties possessed by function classes, such as lines and parabolas (Sfard, 1991; Slavit, 1997). There are numerous other frameworks in mathematics, science, and engineering that help describe students' ways of thinking about disciplinary concepts.

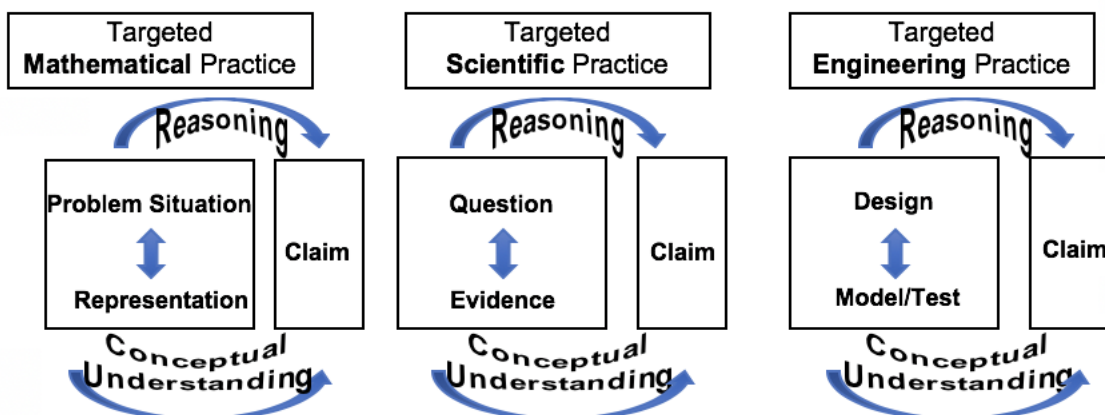


Figure 1: Disciplinary Ways of Thinking; Using Reasoning to Make Claims in Mathematics, Science, and Engineering

We are interested in the theoretical notion of SWoT and its particular relationship to mathematical ways of thinking. This theoretical endeavor has three immediate challenges. First, there are virtually no current frameworks on which to draw. Second, there are differences in the epistemologies of each individual STEM discipline, making the construction of an epistemology of STEM difficult to conceive. Herschbach (2011), one of the few scholars who have addressed this issue, states the following:

The four STEM fields, in sum, have epistemological characteristics that differ markedly. These characteristics must be fully recognized and accommodated in programming in order to preserve the intellectual integrity of each field. Otherwise a very limited understanding results that undervalues specific intellectual contributions or ignores the collective value of each. (p. 110)

Third, STEM is not a well-defined term, making the construction of a theory related to SWoT problematic. For example, Holmlund, Lesseig, and Slavit (2018) illustrated the variety of perceptions of STEM education held by content teachers, administrators, and policy makers. However, we hypothesize that STEM-focused instruction could support the development of cognitive processes consistent with our view of SWoT, delineated further in this paper. This hypothesis includes the development of the discipline-focused ways of thinking discussed above, including mathematical thinking. However, it might also include a way of thinking specific to STEM when manifested in interdisciplinary contexts.

Our theoretical approach to SWoT consists of two related but different cognitive processes: **argumentation in STEM contexts**, and **thinking about STEM interdisciplinary concepts**. These types of thinking are not independent, but not necessarily interdependent.

Because science, mathematics, and engineering are grounded in their own epistemologies, ontologies, and practices, it is an open question as to whether such cross-disciplinary SWoT can actually exist. Can STEM be a discipline in and of itself with its own ways of thinking? If so, what are the ways of thinking that define it? This paper will explore the theoretical issues related to the above questions. We begin with a discussion of five distinct ways of considering SWoT found in the current literature. These include relationships between SWoT and 1) learning theory, 2) 21st-century skills, 3) disciplinary lenses, 4) curricular foci, and 5) epistemology.

Learning Theories Related to SWoT

Some researchers have explored the notion of SWoT by relating it to specific theories of learning. Asunda (2014) presented a conceptual framework for attaining STEM integration based on principles of pragmatism that drew from four different theoretical underpinnings: systems thinking, situated learning theory, constructivism, and goal orientation theory. Denick and colleagues (2013) emphasized social learning theory and discourse, as SWoT and integrated thinking require understanding concepts from multiple perspectives. Kelley and Knowles (2016) presented a conceptual framework grounded in situated cognition that foregrounded SWoT in the context of engineering design. They suggest that both students and practitioners engage in communities of practice to integrate and develop interdisciplinary thinking, including engagement with mathematicians and other STEM experts. Because of the common use of interdisciplinary, real-world projects in STEM education, it seems natural that the theories of learning most commonly related to SWoT involve discourse and draw from a situated or community of practice perspective.

SWoT as 21st-century Skills Applied in Real-world Contexts

From this perspective, SWoT is more than thinking across the four disciplines of STEM. Instead, primary importance is given to the presence of 21st-century skills, such as inquiry processes, problem-solving, critical thinking, creativity, and innovation (English, 2016). While content-based thinking and knowledge are important, these are secondary in focus to the above-mentioned process skills. Hence, SWoT can bridge disciplinary thinking by deemphasizing content-isolating topics, and emphasizing more general thinking processes. Chalmers et al. (2017) suggest that STEM-encompassing endeavors (or “grand challenges”) promote the exploration and transfer of “big ideas” across disciplines, using these broader ways of thinking. The encompassing big ideas are important problems that can invoke a particular SWoT, which students need to solve these problems. From this perspective, STEM is more than the sum of its parts and fostering 21st-century skills is fundamental.

While also emphasizing the influence of curriculum on SWoT, Chalmers et al. (2017) proposed that students need to be inducted into STEM “habits of mind” that will promote application of STEM ideas. They presented three types of “big ideas” that can facilitate in-depth STEM learning: within-discipline ideas, cross-discipline ideas, and encompassing big ideas. Within-discipline ideas are those primarily found in one STEM discipline that have application in another (e.g., scale, ratio, proportion, energy). Cross-discipline ideas are represented by content or processes found in two or more STEM disciplines (e.g., variables, patterns, models, computational thinking, reasoning and argument, etc.). The final type, encompassing big ideas, can also be manifested by either concepts or content. Chalmers et al. claim that conceptual encompassing big ideas (e.g. representations, conservation, systems, coding, change) create interdisciplinary lenses across the STEM disciplines to be utilized on important, thematically-based problems that relate to global challenges.

SWoT Through a Disciplinary Lens

Some researchers argue a specific content area should be the framework for analyzing STEM thinking. Bennett and Ruchti (2014) suggested using the Standards for Mathematical Practices (SMPs) from the CCSSM to provide links across the four disciplines of STEM. This approach could serve two purposes; the SMPs would make the mathematical connections across STEM contexts clear and more accessible, and it would also help emphasize the role of practices in the development of content knowledge. Bennett and Ruchti mention that other standards (e.g., the NGSS Science and Engineering Practices) could also serve this role, but the mathematical connections would not be as clear and connected in such an approach. While English (2016) highlighted the need for a more balanced integration of STEM subjects, she suggested mathematics should be foregrounded to more explicitly emphasize this discipline.

A focus on other STEM disciplines is also present in the literature. Asunda (2014) suggested that the *Standards for Technological Literacy* provide an approach to integrate STEM, and that Career and Technical Education (CTE) be the platform for STEM integration. Sengupta, Dickes, and Farris (2018) argued that computational thinking serves as a disciplinary entrée into STEM due to its uncertain and complex nature. Many researchers, either implicitly or explicitly, assign engineering as the framework for SWoT, with mathematics and science as supporting roles (English & King, 2015). Denick et al. (2013) suggested that engineering design through model-eliciting activities supports an “integrated thinking” in STEM, specifically in informal environments. Kelley and Knowles’ (2016) conceptual framework, grounded in situated cognition, suggests that engineering is the context in which all four STEM disciplines can exist on an equal platform, and thus where STEM thinking best takes place. While focused on “learning by design,” Purzer et al. (2015) considered SWoT as “making knowledge-based decisions” using a combination of scientific inquiry and engineering design. They highlighted the similarities between engineering design and scientific inquiry that support this framework, including an emphasis on reasoning and the role of uncertainty as a starting point for SWoT.

SWoT as a Product of a Curricular Focus

Some researchers claim that interdisciplinary student thinking in STEM is dependent on how the teacher frames the STEM task, and the type of integration emphasized by the curriculum. There are several examples of this in the literature. In an engineering design context, English and King (2015) found that students were able to identify mathematics and science concepts, particularly in the latter stages of the design process (including redesign), but only 1/3 of the students did so, and after the teacher intervened and explicitly highlighted this content. Kelley and Knowles (2016) argued that students might not naturally know how to integrate content and thinking across disciplines. Like English and King, this suggests that SWoT are not natural cognitive processes for students, or perhaps the complexities of SWoT do not lend themselves to easy development. Mathematics can be more difficult to integrate than other STEM disciplines, as there is evidence that effect sizes of STEM integration on student achievement are lower when M is integrated than other integrated curricular models (e.g., S-T and E-S-T) (Becker and Park, 2011). Kelley and Knowles claim that students have difficulty knowing which ideas are relevant across disciplines when engaged in interdisciplinary content. For example, students need support to elicit relevant science and mathematics ideas in an engineering design task and to reorganize their thinking to be interdisciplinary, rather than a composite of different kinds of content-based thinking. However, current instructional norms do not always lend themselves to this way of thinking. Chalmers et al. (2017) applied their disciplinary framework, discussed above, to discuss how to introduce topics and develop contexts for SWoT. They suggest a sequence that

begins with a *worthwhile task*, then an exploration of *big ideas*, followed by a *synthesizing activity* to provide closure and attempt to make the big ideas explicit knowledge objects of thought through reflection on and refinement of the students' understandings and SWoT.

Purzer et. al (2015) found that while engaging in design work, the focus of two students' thinking was primarily on engineering processes. However, near the end of the project, when the students were asked to examine the different affordances and constraints of their designs, the students began to engage in scientific inquiry, particularly when working within the explicit constraints of the problem. This suggests that the intentional introduction of specific constraints in an engineering design task could elicit more integration of science content knowledge and inquiry, which aligns with the claim of English and King (2015) that interdisciplinary thinking tends to take place in the latter stages of engineering design. The lack of presence of mathematical thinking is notable, and English (2016) called for more research on whether sequenced and structured mathematics instruction hinders in-depth STEM learning. It seems that mathematics is not normally perceived as the central content focus of STEM, and that mathematical thinking can be difficult to include in SWoT or need explicit scaffolding. This somewhat nebulous role of mathematics in the above findings surfaces several questions about the role of mathematics in SWoT. For example, what are the implications of Bennett and Ruchti's (2014) recommendations to make mathematics the overarching framework of STEM? Does the above evidence support the need to foreground mathematics when designing curriculum, or does it discourage educators from including mathematics in integration?

SWoT Through an Epistemological Lens

There are very few treatments of STEM in the context of its underlying epistemology that exist in the current literature base. Sengupta et al. (2018) argue that an "epistemology of computational thinking" can foreground the uncertainty and complexity that should exist in STEM classrooms. Their discussion of epistemology highlights the role of abstraction and representation in thinking, as well as the contexts that ground this thinking in use. They suggest that computational thinking can bring in other disciplinary ways of thinking and highlight modeling as a key potential tool for integration. Herschbach (2011) developed an "organization of knowledge" framework to argue for the incompatibility of epistemologies across the STEM content areas, and the resulting challenge this yields for STEM education. Treating STEM as a curricular concept best represented through activities, he distinguishes formal and applied knowledge, constructs he claims are inherent in STEM, to further argue for the difficulty in a coherent STEM epistemology.

Limitations of the Current Literature

While useful in a variety of theoretical and practical ways, the above theoretical perspectives and empirical findings have collective limitations. Perhaps most notably, not much research exists on STEM ways of thinking, with only a few researchers broaching the role of epistemology. Variations in defining STEM education can also create differences in STEM education models, and subsequent differences in conceptualizations of SWoT. This can lead to a variety of methodological issues related to how SWoT might be measured, and a lack of consistency across studies. The many different models for how STEM content should be integrated, or which content should be foregrounded, makes analyses of SWoT not applicable to all STEM scenarios. Current methods also have limitations; for example, English and King (2015) used annotations in students' notebooks and verbal explanations in their empirical analysis, but these might not accurately represent the students' actual SWoT. The existing

research also tends to report small samples and effects (e.g., English and King, 2015; Becker and Park, 2011), and more research is needed on students from diverse groups (Purzer et al., 2015).

Many of the existing empirical studies target the effectiveness of STEM in increasing student learning outcomes, but do not address student thinking. Becker and Park (2011), in a meta-analysis of 28 studies that related the impact of STEM education on student achievement, found no study that explicitly highlighted student thinking. English (2016) has argued the need to better highlight connections among STEM disciplines, and make them more transparent to both teachers and students. Finally, we note that our literature search did not reveal interdisciplinary ways of thinking as a model of SWoT, with perhaps the best approximation found in the set of studies related to SWoT as 21st-century skills in interdisciplinary contexts. Thus, we see a distinct theoretical need for such a perspective.

Modes of Inquiry

Our basic research question is: What SWoT are evident in student activity and discourse during classroom activities involving STEM content and practices, and what role does mathematical thinking play in these cognitive processes? Our analysis is exploratory and qualitative in nature. Our primary data source is 69 videotaped segments of second grade (24), middle (35), and high school (10) classrooms during interdisciplinary, project-based instruction. The videos ranged from a few minutes to over one hour, with the majority lasting approximately 15 minutes. Our sampling was opportunistic, as we leveraged our relationships with local schools and teachers doing project-based instruction. Most episodes were of design-based engineering activity and included examples of interdisciplinary thinking grounded in argumentation. Our observations targeted the nature of the SWoT enacted by students during student-student interactions, although instructional segments and whole-group discussion were also included in the longer videotaped segments.

Two researchers (the first two authors) individually coded all videotaped segments, and met regularly to discuss coding decisions and results. Due to the exploratory nature of the analysis, open coding (Merriam & Grenier, 2019) was used. Three levels of analysis were progressively initiated, with codes based partly on the five ways of describing SWoT discussed above. First, we conducted a “meta” analysis to identify and describe the target content and the nature of collaboration that was occurring amongst the students. For example, a video segment might be coded as a design-based project that highlighted mathematical functions, with brief lecture followed by student group investigation. Codes related to the nature of the SWoT were then added, which were later refined through the use of analytic memos to include specific attention to the epistemological stances taken by the students, particularly when using reasoning to make claims (see Figure 1). Finally, codes related to interdisciplinary thinking were constructed to more fully articulate the SWoT being observed. For example, students who used geometric ideas and explanations to make a claim about the design of a lunchbox, and perhaps how this might help keep items inside cool, were noted as interdisciplinary across S-E-M. Students who modeled a buoyancy situation with a quadratic function to find its maximum were noted as superficially interdisciplinary, with an emphasis on mathematical skills.

Results

Although the observed content revolved mostly around engineering ideas, the instructional context shifted this focus on several occasions. For example, an exploration of water flow by a group of middle school students shifted from engineering principles to mathematical formulas

related to force when the teacher inserted this focus into the discussion. A noted shift in the epistemological stance taken by the students was revealed in this episode, and the nature of claims and reasoning shifted from conceptual-based claims on aspects of force in a boating context to procedural-based claims related to force using abstract, mathematical formulas.

Our collective observations suggest that integration in the realm of SWoT consists of shifting disciplinary practices across STEM contexts. Student thinking that explored real-world problems and drew on 21st-century skills possessed such fluidity, but when the disciplinary content and practices became more explicit (we refer to this as being “hardened”), the different tools, practices, representations, and epistemologies within the STEM disciplines provided barriers for interdisciplinary thought. When the interdisciplinary ideas that were the subject of SWoT were not hardened, the individual epistemologies mattered less.

Several student groups were seen exploring STEM content that was accessible and perceived as “fun,” with a focus on successful task accomplishment. This led to a variety of ways of thinking about the STEM activity. Other times, the presence of a specific content objective, such as solving algebraic equations, grounded thinking and limited the nature of SWoT present. For example, a group of second-grade students exhibited interdisciplinary thinking when designing a lunch container with a cold bottle attached to the top. The SWoT observed in this action had aspects of mathematics (solids and volume, area and measurement), science (heat flow, energy transfer), and engineering design. But the S, E, and M emerged very informally, and the epistemologies of each discipline were not in conflict. We assert that the notion of SWoT is highly dependent on the nature of each discipline, the nature and intent of the activity, the instructional oversight, and the (internal and external) epistemological forces that drive student thought. We hypothesize that the existence of shifting practices across the STEM disciplines allows for more fluid SWoT. It also appeared that shifting practices occurred more frequently during exploratory phases of STEM activity, and less frequently when seeking solutions, as occurred in the case above when a mathematical formula was inserted into the SWoT.

Discussion

STEM as a curricular construct is usually considered through a disciplinary lens (single or interdisciplinary), or as a forum for the application of 21st-century skills in real-world problem contexts (Holmlund et al., 2018). STEM education consistently balances student curiosity and subsequent “natural” ideas with the need to explore predetermined academic content, a situation complicated by the competing epistemologies of the STEM disciplines. From a cognitive perspective, claims and reasoning tend to drive the activity (Figure 1), but the practices and ways of thinking often shift depending on the content and nature of the activity. Mathematical problem solving might be bypassed because of the curricular or instructional focus, or because of the current epistemology at play during student exploration. Prior research, such as English and King (2015), suggests that teacher scaffolding of mathematics content through the design process can allow for a more integrated way of thinking that aims to balance the representation of all STEM subjects. Specifically, students should be given sufficient time to complete the engineering design process so that the latter stages can be highlighted. One possible implication of this work is that students do not have natural SWoT, but rather that SWoT need to be facilitated in explicit ways. We claim the place of any content-specific cognitive activity, including mathematical thinking, is ill-defined in many STEM education contexts, and needs explicit nurturing.

Our observations suggest that when content becomes hardened, epistemological stances change and interdisciplinary thought becomes more difficult. We do not claim that there is a

universal epistemology around STEM, or that the individual STEM disciplines are either universally compatible or incompatible. Our observations suggest that the nature of certain STEM activity, particularly that which does not involve hardened content and facilitates shifting practices across STEM disciplines, lends itself to more conceptual and fluid interdisciplinary thought, as epistemological barriers matter less.

This paper yields more questions than answers. When exploring STEM contexts, do students shift between disciplines, or think about them collectively? What is the implication of siloed content-based instruction, or interdisciplinary STEM instruction, on SWoT and/or mathematical thinking? What curricular and instructional adjustments might be necessary to promote SWoT or mathematical thinking in STEM contexts? Our limited observations indicate curriculum and instruction that limits the hardening of content can facilitate interdisciplinary SWoT. More research is needed to identify the nature, and even presence, of a SWoT and its relationship to mathematical thinking. Further delineation of SWoT can aid researchers' and mathematics educators' efforts to engage students in conceptually-based argumentation and explanation.

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