STEM Content in Elementary School Students' Evidence-based Reasoning Discussions (Fundamental)

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Introduction and background

Science, technology, engineering, and mathematics (STEM) are currently major focuses of pre-college education in the United States. This is partially an effort to produce a greater number and variety of STEM professionals; it is thought that this effort will help the US remain competitive in a global economy [1], [2]. Regardless of career choice, STEM education has the potential to improve the STEM literacy of all students [3]. One of the current trends in STEM education is the integration of the four disciplines. A main goal of integrating STEM in pre-college classrooms is that students can make connections within and between the STEM disciplines, which has the potential to deepen their understanding of each discipline [4].

Of the STEM subjects, engineering has especially received increased attention in pre-college settings [5], [6]. This is most evident by its inclusion in science standards, including many state standards [7] and the national *Next Generation Science Standards* (NGSS) [8]. While there are several models of STEM integration [4], [9], one that is currently being explored is engineering design-based STEM integration (e.g., [10]). This model is also known as design-based learning or design-based science (e.g., [11]–[15]). In this type of STEM integration, an engineering design challenge serves as the foundation of an activity, lesson, or unit. The curriculum also includes developmentally appropriate science and mathematics content and practices; ideally, students learn this content and then apply it when solving the engineering problem. Studies with published pre-posttest results generally show positive learning gains in science content (e.g., [11], [14]) and practices (e.g., [15], [16]) as a result of implementing these types of curricula. However, studies that provide an in-depth look at students' engineering design decisions have mixed results with regards to the amount and quality of students' application of science and mathematics to the engineering challenge (e.g., [17]–[20]). Some research has shown that students have difficultly justifying their design solutions with science and/or mathematics [18], though guided reflection and evaluation about benefits and trade-offs helped them think scientifically [17]. Other research demonstrated that small groups of students were able to use science and/or mathematics frequently in their design discussions [20], though this science was not always the same science that was associated with the intended learning outcomes of the curriculum [19]. In sum, design-based STEM integration curricula have produced promising results thus far, though more research is needed.

One way to help students make connections between the STEM disciplines is the practice of *evidence-based reasoning* (EBR). We have broadly defined EBR as the practice of justifying engineering design ideas and decisions with evidence [21]. EBR emerged from the NGSS practice of *engaging in argument from evidence*; it is parallel to the science practice of *scientific argumentation* [8]. A study of engineering design-based STEM integration curricular documents found three curricular activities that had the potential to encourage students to use EBR, including defending a final design to the client at the end of the unit [22]. Through an analysis of student discussions while they generated solutions to engineering design challenges, researchers identified seven situations that prompted students to defend their design decisions: responding to adult, documenting, negotiating, correcting, validating, clarifying with team, and sharing [23].

Another study explored when in an engineering design process students used EBR [21]. While these studies have focused on when and how EBR occurred in design-based STEM integration units, there has been less focus on *what* students discuss when they use EBR. One initial exploration of student discussions demonstrated that students were able to use unit-based science and mathematics content during EBR [20]. However, there has not yet been research about whether and how all four STEM disciplines are represented in students' EBR. Thus, the purpose of this study is to do an initial exploration about the variety of STEM content that a team of students discussed when they practiced EBR. Specifically, in this project, we are interested in answering the following research question: *While generating and justifying solutions to an engineering design problem in an engineering design-based STEM integration unit, what STEM content does a team of elementary school students discuss?*

Frameworks

Conceptual framework

In this study, we used an engineering design-based STEM integration curricular unit. The design and implementation of this type of STEM integration unit was guided by the STEM integration framework [24]. The fundamental components of the STEM integration framework are standards-based science and mathematics, which are integrated through engineering design problems. These problems that are grounded in contexts that are motivating and engaging to students. Through an iterative process of design and redesign, the units facilitate learning and development of communication skills. The framework also encourages student-centered pedagogies, which includes students working in groups to create a product or process to solve the engineering design challenge. The products or processes presented as solutions to these problems are technologies, thereby incorporating the "T" in STEM. Through this definition of STEM integration, the STEM integration framework facilitates deep conceptual understanding of each STEM discipline [25].

Theoretical frameworks

The theoretical frameworks that we used to guide this study are *Toulmin's Argument Pattern* (TAP) [26] and *The Framework for Quality K-12 Engineering Education* [27]. TAP allowed us to identify instances of EBR that occurred in student discourse during the solution generation phase of an engineering design process. Those stages of a process of design that are included in solution generation are defined by *The Framework for Quality K-12 Engineering Education* [27].

TAP is a theoretical framework that posits that an argument's validity rests on a logical structure [26]. Therefore, argumentation, which is the process of reasoning systematically, requires that rational arguments reach a conclusion through logical reasoning. Toulmin explains that a rational argument has six elements (*claim, data, warrant, backing, modal qualifiers*, and *rebuttals*); these elements and their relationships are shown in Figure 1. At least some of the six elements must be present in a rational argument; however, more complex arguments require that more elements are present. TAP can be useful in arguments in STEM disciplines as well as the Liberal Arts disciplines [26]. In this study, we used TAP to identify statements that contain *claims* about designs with additional supporting information. This simplified definition, which only has two components instead of six, allowed us to explore a broader perspective of EBR in student discourse about complex engineering design problems.

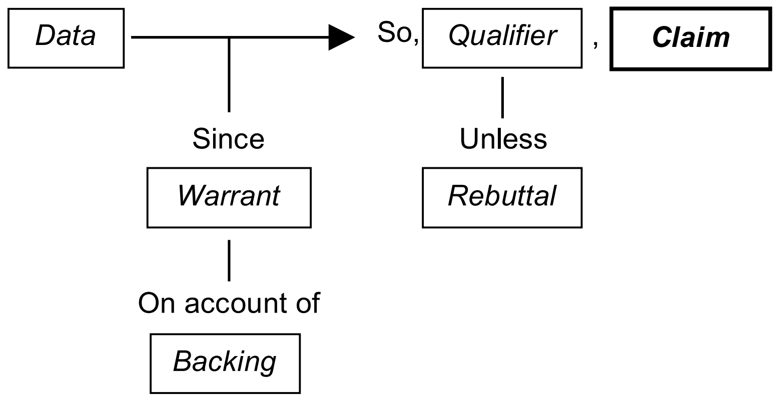

Figure 1. Toulmin's Argument Pattern [26]. Adapted from *The Uses of Argument* (p. 97), by S. E. Toulmin.

The *Framework for Quality K-12 Engineering Education* is meant to assist with developing or evaluating K-12 engineering education initiatives including standards, assessments, and curricula [27]. The curricular unit used in this study was designed and developed with guidance from both the STEM integration framework [24] and The *Framework for Quality K-12 Engineering Education* [27]. The latter framework identifies nine key characteristics of quality pre-college engineering; the first of these characteristics, the *Process of Design* (POD), is most pertinent to this study. POD has six sub-indicators which represent the fundamental characteristics of design processes: *problem, background, plan, implement, test,* and *evaluate*. POD can be broken into two stages: problem scoping and solution generation. The problem scoping stage is composed of identifying the problem, criteria, and constraints and acquiring background information in preparation for proposed solution generation (POD sub-indicators - Problem and Background). The solution generation stage is composed of the four remaining POD sub-indicators. The first phase of the solution generation is planning (POD-Plan); in the planning phase, students construct a plan for their design solution by developing and evaluating pros and cons of several possible solutions before selecting one viable plan. The second phase is implement (POD-Implement); here, students construct prototypes or models. The third phase is test (POD-Test); students test their products or processes to determine if their designs meet the criteria and constraints identified in the problem scoping stage. The final phase of the solution generation stage is evaluate (POD-Evaluate); students evaluate their design solution by determining its strengths and weaknesses in relation to the engineering problem's identified criteria and constraints. After evaluating their design solution, students decide whether to redesign.

The conceptual and theoretical frameworks described above guided us while we sought to answer the following research question: *While generating and justifying solutions to an engineering design problem in an engineering design-based STEM integration unit, what STEM content does a team of elementary school students discuss?*

Methodology

This research follows the naturalistic inquiry methodology [28], [29] with three conceptual and theoretical frameworks: the *STEM integration framework* [24], *Toulmin's Argument Pattern* [26], and *A Framework for Quality K-12 Engineering* [27]. The content of these has already been described; in this section, descriptions of how we used them in the research will occur. But first, we will describe the data sources.

Project

This study was conducted as part of a federally funded, five-year curriculum and teacher professional development project. One of the goals of this project was for teacher teams to iteratively develop, implement, and improve engineering design-based STEM integration curricular units with assistance from the project team and guidance from the STEM integration framework [24]. For this study, the curriculum was developed by two elementary school teachers as part of this larger project.

Curriculum

The *Survival Suit* engineering design-based STEM integration unit was developed for upper elementary science instruction. The overall flow of the unit is that it first introduces students to the engineering problem, then they learn specific science and mathematics content, and finally they generate solutions (design and redesign) to the challenge. The context of the unit is a dystopian future United States where the environment has changed to include only five types of habitats. The student engineers are challenged to design a suit that will allow people to survive and travel in these extreme environments. For example, two of the criteria are related to protecting humans from predators; the suit must provide camouflage with the environment, and it must be made of a strong material. During the science-focused lessons of the unit, students learn about how adaptations provide advantages for animals' survival, characteristics of the five habitats (including predator/prey relationships within each), and how to use measurements and data analysis of decimals in various experiments. For the initial design, each student team is assigned one habitat to design their suit for; another habitat is added in the redesign phase. Students do not actually create a whole survival suit. Instead, they design each suit component based on the science they have learned and the data they gathered from previous experiments related to the components. An important note about the *Survival Suit* unit is that while it did not explicitly teach the practice of EBR, it did contain prompts for students to explain their reasons and use data to justify their design decisions.

Setting and participants

The setting for this study is a school that is located within a Midwestern school district serving approximately 39,000 K-12 students. Seventy-five percent are students of color, and over 70% are eligible for the federal free and reduced-price lunch program. Because many of the students are from immigrant and refugee families, over 100 languages and dialects are spoken by students and their families. Within a school in this Midwestern district, we studied one 5th grade teacher's classroom. The primary data were audio recordings of one student team's discussions, though we also referenced the written *Survival Suit* curricular documents and video recordings of the whole class to help clarify the primary data. The student team consisted of four 5th grade boys; this team was recommended to us by the teacher as a team that would provide quality audio data.

Data analysis

We carried out three steps of data analysis. In the first step, we limited the audio data and accompanying transcripts to those in which students generated and justified solutions (i.e., used EBR) to the engineering design problem. This occurred during the solution generation stage of the process of design, which includes the phases of *plan*, *implement*, *test*, and *evaluate*, according to the definition in the *Framework for Quality K-12 Engineering Education* [27]. For the *Survival Suit* unit, students were not able to *implement*, *test*, and *evaluate* a full version of their suit, so they were limited to *planning* each component of the suit based on their science knowledge and previous test results. This limiting of data yielded audio and transcripts from two class periods for initial design plan and another period of redesign plan.

In the second step of data analysis, we identified instances of EBR in the transcripts using a revised version of *Toulmin's Argument Pattern* [26]. This revised version included two components, a *claim* and a *statement of support*. We defined a *claim* as any statement about a design idea or decision. A *statement of support* was any evidence or justification used to back up the *claim*. In sum, we identified instances of EBR that contained a design idea or decision and a supporting statement.

In the third step of data analysis, we performed open coding on these instances of EBR. Using our education and STEM backgrounds, two researchers identified the science, technology, engineering, and mathematics content categories that students discussed during the instances of EBR. Each instance of EBR contained at least two STEM content categories, one for the *claim* and one for the *statement of support*. Many instances were coded with more than two content categories if the *claims* and/or *statements of support* referenced multiple categories with one idea; several examples in the next section demonstrate this. The next section also contains the final codebook of the STEM content categories that emerged from one student team's instances of EBR.

Results

STEM content categories

We identified nine STEM content categories that the four elementary school students discussed while generating and justifying engineering solutions (i.e., while practicing evidence-based reasoning). These content categories are described in Figure 2. Only one content category is needed for each of the disciplines of science, mathematics, and technology. However, the discipline of engineering is broken up into six categories: *design*, *material type*, *functionality*, *structure*, *ease of use*, and *aesthetics*. In the following paragraphs, we demonstrate most of these STEM content categories through examples from the student team's design discussions. In all of the examples, instances of EBR are *italicized*; other discourse is included for context.

STEM		Description
Discipline	**Category**	
Engineering	Design	Reference to the overall design
	Material type	Choice of material or other item to use for a design component
	Functionality	Function or purpose of the design or design component
	Structure	A way in which materials are put together in the design
	Ease of use	How easy it is for the end users to utilize the design prototype
	Aesthetics	How pretty or ugly a design is
Science		Typical K-12 science content knowledge
Mathematics		Typical K-12 mathematics content knowledge
Technology		Prior knowledge about existing technologies (i.e., "I saw another design in the real world similar to this and this is how it was done")

Figure 2. Descriptions of the STEM content categories that emerged from instances of EBR during one student team's design discussions in the *Survival Suit* unit.

Examples related to suit covering materials

The first two examples, which are shown in Figures 3 and 4, are student conversations about the survival suit covering material design decision. For the suit covering design component, the students needed to consider material properties related to strength (i.e., resistance to puncture), flexibility (i.e., ability to stretch), and thermal insulation. During the science-focused lessons of the unit, which occurred before students began generating design ideas, the students had performed several experiments to test these properties with various materials. They were then able to refer to this information while generating and justifying their design ideas and decisions. Figure 3 is an excerpt from a student discussion during the initial design planning phase, and the dialogue in Figure 4 occurred near the end of the redesign planning phase when students were recording their final design decisions.

Sean:	Amphibian skin, should we do that? Do we agree?
Samuel:	What's amphibian skin? What's amphibian skin?
Sebastian:	I don't really know.
Sean:	*Yoga mat. It was second strong. Cause if you have leather, you're not going to be able to move much. Your arms are gonna be like that, your legs are gonna be like that, and you're gonna be like this, walking like a penguin*.

Material Type	**Functionality**	**Ease of Use**	**Science**

Figure 3. Student conversation about suit covering material choice during the initial design planning phase. Bolded words represent the STEM content categories coded.

<table>
<tr><td>Sebastian:</td><td colspan="3">(reading off what team had already written) "We chose amphibian skin because," wait, wait. Because it stretched 3 cm, and the leather stretched 2.5 cm. Wait, let me see it again.</td></tr>
<tr><td>Samuel:</td><td colspan="3">Stretches 2.5 cm.</td></tr>
<tr><td>Sebastian:</td><td colspan="3">And we chose amphibian skin because it stretches, because it stretched more, it stretches more than leather by 5 cm.</td></tr>
<tr><td>Material Type</td><td>Functionality</td><td>Science</td><td>Mathematics</td></tr>
</table>

Figure 4. Student conversation about suit covering material choice during the redesign planning phase. Bolded words represent the STEM content categories coded.

For much of the initial design and redesign, the student team debated between two suit covering material choices, leather and amphibian skin. (Amphibian skin was represented by yoga mat material.) In the strength test, the leather had performed the best with the amphibian skin performing second best. In the flexibility test, the amphibian skin had stretched more than the leather. During their design discussions, the students used this information to justify their design ideas and decision about which suit covering material to use. (The students also discussed the thermal properties of these two materials, but their conversations about strength and flexibility were much more prevalent.) In both instances of EBR shown in Figures 3 and 4, the design idea/decision was coded as *material type*, since the students were debating which material to use. Both examples demonstrate justifications related to *functionality* and *science*. These instances of EBR were coded as *functionality* because the justifications related to how well the design would work. The instances were coded as *science* because the students used information related to properties of materials, which is typical K-12 physical science content knowledge.

The two examples were both coded with a fourth STEM content category, though those differed. In the example in Figure 3, Sean was not just thinking about *functionality* broadly, but he was specifically considering the design's *ease of use*. He argued against choosing leather by saying, "Cause if you have leather, you're not going to be able to move much"; this demonstrates that he was thinking about how easy it would be for the end user to use the survival suit. In Figure 4, the instance of EBR was coded with the STEM content category *mathematics*. After their initial design, the students had received feedback from the teacher to include their previously collected data in their redesign justification. In this example, not only was Sebastian referring to the raw data that amphibian skin stretched 3 cm and leather 2.5 cm, but he also referred to the mathematical difference of those results. His stated difference, 5 cm, was not a correct subtraction. However, it still represents an attempt at mathematical operations with decimals, which is standards-based *mathematics* at the upper elementary level.

Example related to foot adaptation

Another design component that the student team had to consider was to choose a foot adaptation that would allow the end user to walk in the tundra environment; this environment was the habitat assigned to this student team for their initial design. During a prior science lesson, students had tested out different foot shapes (e.g., rabbit, eagle) by pressing them into various earth materials (e.g., snow, sand, dirt) and measuring how far into the material they sank. Because this student team had been assigned the tundra, they had several design conversations about what type of foot shape would be able to walk in snow and dirt. While most of these conversations included justifications related to their prior data collection, Figure 5 shows one instance where they refer to other options.

Aide:	Why did you pick rabbit feet?
Sean:	*Because there's not human feet.*
Aide:	You got a better answer than that. Let me see.
	(unrelated background conversation)
Sean:	Hey, *our feet can last in snow. I see my footprints outside*.
Samuel:	*That's your shoes, bro.*

Material Type	**Functionality**	**Technology**

Figure 5. Student conversation about foot adaptation choice during the initial design planning phase. This excerpt contains two instances of EBR; the first is represented in *italics* and the second in *underlined italics*. Bolded words represent the STEM content categories coded.

In this example, Sean pointed out that the reason the team chose rabbit feet for their foot adaptation was because human feet were not available as an option, even though those would work because "our feet can last in snow." In this instance of EBR, Sean justified his desire to use human feet with his prior experience of being able to successfully walk on snow. Samuel countered with a second instance of EBR, which is represented in *underlined italics*. In this instance of EBR, the design idea is implicit, since Samuel did not explicitly state that he disagreed with Sean's idea to use human feet. However, Samuel's disagreement is clear with his rationale of "that's your shoes"; he reminded Sean that he does not actually walk outside with his human feet. After this conversation, Sean agreed with the rest of the team that the rabbit foot was the best design choice for the foot adaptation component.

These instances of EBR were both coded *material type* because the students discussed which foot type to use for the foot adaptation component of the survival suit design. The first instance of EBR stated by Sean was also coded *functionality* because he explicitly referred to his knowledge that human feet would work in the snowy conditions. The second instance of EBR was coded *technology*, since Samuel justified his counterargument by referring to an existing technology, shoes. He used his prior knowledge about existing technologies to point out a flaw in his teammate's argument that human feet would be the best option for the survival suit.

Example related to colors and camouflage

In addition to the choice of the survival suit covering material, students also had to choose which color(s) to make the exterior of their suit. Throughout the initial design and redesign processes, the student team discussed which colors would blend in with the colors of their assigned habitats (i.e., tundra and prairie) best. Figure 6 shows an excerpt from one of these discussions.

Sebastian:	*What if I draw the dark green?*
Samuel:	That's ugly.
Sebastian:	*Yeah. It might look ugly but it's going to camouflage.*

Material Type	**Functionality**	**Science**	**Aesthetics**

Figure 6. Student conversation about suit covering color during the initial design planning phase. Bolded words represent the STEM content categories coded.

Facing a protest from Samuel, Sebastian defended the design decision to use dark green as part of the suit covering color with the justification, “It might look ugly but it’s going to camouflage.” In this instance of EBR, the design choice of dark green falls into the *material type* category because choosing colors was part of the suit covering material choice. Sebastian explained his design choice in two ways. First, he countered Samuel’s rebuttal by acknowledging that the dark green “might look ugly.” This is an example of the STEM content category *aesthetics*, since it refers to the aesthetically pleasing appearance (or lack thereof) of the design idea. Second, Sebastian pointed out “but it [the dark green] is going to camouflage.” Here, he referred to the *functionality* of the design in terms of how well the colors match the background environment. This instance of EBR is also an example of *science* content because it demonstrates that Sebastian knew about the climate and colors of the team’s assigned habitat, the tundra.

Other STEM content categories

The previous four excerpts from the student team’s design conversations demonstrate seven of the nine STEM content categories that emerged in this study. *Design* is the first content category that has not yet been addressed. An instance of EBR was coded *design* whenever the students referred to the entire design rather than one component of it (e.g., suit covering material, foot adaptation). The few instances of EBR with *design* tended to have vague justifications, with the students talking about how their design “is good” or “will work.” The second of the STEM content categories not yet mentioned is *structure*. In the *Survival Suit* unit, most of the structural components of the suit design were outside the scope of the students’ design solution. For each design component, students chose one of several options. For example, the students ultimately chose to use amphibian skin (i.e., yoga mat) for their suit covering material. However, they had little say in how those materials and components fit together. The one item that they were able to make structural decisions about was how the colors fit together. In a couple of instances of EBR, the students discussed what sort of pattern the colors of their suit should take, and these instances were examples of the *structure* STEM content category.

In sum, these results show that the students on this team used content knowledge from all four STEM disciplines during instances of EBR. In terms of engineering, the students talked about six content categories: *design*, *material type*, *functionality*, *structure*, *ease of use*, and *aesthetics*. They also frequently referred to *science* content knowledge during EBR, justifying their design ideas and decisions with their knowledge about animal adaptations, habitats, and properties of materials. Similarly, they used *mathematics* related to measurement and data analysis to better justify some of their design decisions. In a few instances, the students also talked about experiences they had with existing real-world *technologies*. The students used information from all four STEM disciplines to generate and justify solutions to an engineering design problem.

Discussion and implications

These results provide preliminary evidence of elementary students’ ability to integrate content knowledge from all four STEM disciplines while they generated and justified their design ideas and decisions during an engineering design-based STEM integration unit. The four students on the team frequently applied science and mathematics content knowledge that they had learned in earlier lessons, as well as some knowledge from their previous experiences with technology, to the solution of an engineering problem. This is in contrast to previous research that found limited student use of unit-based science and mathematics concepts as justifications for engineering design decisions (e.g., [18]). One possible reason for why the students in this study readily applied their science and mathematics knowledge during solution generation is that the engineering challenge essentially required it. This finding supports other research suggesting that during curriculum development, engineering challenges should be carefully aligned with the desired science and mathematics content [19], [20].

The students also considered several content categories within engineering, including one that was not part of the original engineering challenge. Based on the design components that students had to make decisions about (e.g., suit covering material, foot adaptation), it was not surprising to see students reference the overall *design*, the *material types* they had to choose from, the *structure* of the exterior color pattern, and the *functionality* they predicted each component would have. Because of the nature of the design challenge, the students thought about *functionality* in a general sense (i.e., does this component serve the purpose it is supposed to) and specific to how easy they thought it would be for the end user to use the suit (i.e., *ease of use*). The engineering content category that was unexpected was *aesthetics*; this category was surprising because the engineering challenge specifically included instructions that although the survival suit's appearance needed to blend in with the surrounding environment, it did not need to be visually pleasing. Even with that instruction, one student brought up *aesthetics* twice during the design conversations. This finding suggests that even when students are given the specific criteria and constraints of an engineering problem, they may consider additional factors.

This study also adds to the body of literature about EBR in pre-college engineering education. While previous research has been done about how teachers build design justifications into their classrooms [22], when students use EBR during the process of design [21], and what prompts students to use EBR during design discussions [23], this is the first to explore *what* students discuss when they practice EBR. In this *Survival Suit* curriculum, the teacher emphasized the use of data and evidence to support design decisions, even though he did not use the term EBR. This seemed to help this student team justify their design decisions with detailed, unit-based science and mathematics content knowledge. Taken together, these studies suggest the benefits of EBR in design-based STEM integration units, particularly with regard to helping students integrate content knowledge across and within the STEM disciplines. Ultimately, being able to make connections across the STEM disciplines can help deepen student understanding of each discipline and improve their ability to solve complex problems [4].

This study has shown promising preliminary results for EBR and engineering design-based STEM integration curriculum, especially in terms of students' ability to integrate information from all four STEM disciplines. A major limitation of this study is that it only included one student team from one curriculum. Hence, future work should expand the data sources to include multiple student teams and various curricula to see if other STEM content categories arise in different design-based STEM integration units with other students. Additionally, analyzing the use of the STEM content categories quantitatively could provide a better sense of how often students use the different categories. Ultimately, continued research about EBR will allow us to create better scaffolds, lessons, and curricula to help students justify their design ideas and decisions.

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