Students' Use of Evidence-Based Reasoning in K-12 Engineering: A Case Study (Fundamental)

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It is well known that the United States is concerned about the low numbers of students prepared for careers in science, technology, engineering, and mathematics (STEM), which is necessary to remain internationally competitive[1,2]. As a result, improving STEM education in precollege settings has become a focal point because not only can it prepare students for these careers of the future, may also increase the STEM literacy of all students[3]. Part of this effort to increase K-12 STEM education is a movement to provide standards that are STEM-focused and include engineering design, which is already underway at the state and national levels[4–8].

Although policy and standards may help increase the number of students interested in STEM, additional efforts are needed to equip students with the technical and professional skills required by those careers. Regardless of the STEM career, employers want employees who can solve problems, think critically, communicate, work in teams, collaborate effectively, and have technical skills[9]. This means that K-12 teachers need to help students develop professional skills, as well as teach STEM content knowledge. The research presented here concerns the professional practice of using evidence to support idea generation and decision making within engineering, commonly called argumentation.

While there are a number of professional practices that students need to engage in and learn, argumentation in particular has drawn the attention of K-12 educators in many disciplines, including English language arts, history, and STEM[10]. As humans, arguments are embedded in our daily lives. Children develop basic argumentation skills very early and may hone them with age and practice[11]. The educational system can assist students in developing argumentation skills[10] through multiple forms of communication (e.g., writing, oral presentations) while also developing critical thinking. The incorporation of argumentation skills into curricula can foster students' ability to solve problems, reason with evidence, and develop content knowledge in all areas of education and daily life activities[11,12]. In addition, curricula that allow students to construct an understanding of arguments through experiences provide opportunities to develop social and communication skills needed by STEM and other professionals[13,14].

Although argumentation can be used in many academic domains, research has been done specifically about argumentation in K-12 science education and undergraduate engineering education. Argumentation is seen as essential to scientific discourse because it provides a framework for students to make claims supported by evidence and reasoning related to scientific theory[15–17]. Using arguments also allows students to act as scientists through deep discussions and writing research papers that persuade others of the significance of their findings and work[11,18]. Positive outcomes are also seen in the scant literature regarding argumentation in engineering education, though these studies focus on the learning of undergraduate students. This research has suggested that argumentation improves students' ability to think critically[19] and solve engineering problems[20].

Currently, almost no research regarding argumentation in K-12 engineering education exists. With the increasingly common expectation that engineering be included in K-12 education, this is a gap that needs to be addressed. Thus, this study is designed to explore how student-generated arguments emerge within engineering lessons of an integrated STEM unit. For the purpose of this research, we will be using the phrase *evidence-based reasoning* (EBR) rather than the commonly used term *argumentation* in order to clearly distinguish between argumentation in engineering versus science contexts. A more thorough explanation of each of these terms and why this distinction is needed is addressed in the next section of the paper. Thus, the following questions were used to guide this research:

- *When students are engaging in an engineering design challenge within a STEM integration unit, where in their process does EBR naturally occur?*
- *For what purposes are students using EBR when participating in engineering process of design within a STEM integration unit?*

Theoretical Frameworks

This study employed two theoretical frameworks. This first framework supports a model of STEM integration[21] in which engineering design is the central component to which the other disciplines are applied; this framework underlies the development and implementation of the curriculum used in this study. The second theoretical framework relates to argumentation and evidence-based reasoning, which is the student practice that is the focus of this study.

The STEM integration framework provides the scheme that situates engineering design within K-12 education[21]. STEM integration is the cohesive merging of science, technology, engineering, and mathematics content with the intent of deepening students' understanding of each discipline[22]. Moore et al.[21] suggest that engineering challenges that require the application and development of science and mathematics may serve as a model for creating STEM integration lessons. Moreover, it is an interdisciplinary approach that provides the foundation for bringing together each of the four disciplines[23]. This framework supports the integration of STEM through engineering design, which influenced the design and implementation of the curriculum used in this study.

The second theoretical framework is rooted in Toulmin's Argument Pattern (TAP)[24]. The premise of this framework is that the validity of an argument depends on its logical form. Therefore, the process of constructing a rational argument, which is generally known as *argumentation*, requires reaching conclusions through logical reasoning. The TAP model identifies six major elements of an argument: *claims, data, warrants, backing, modal qualifiers,* and *rebuttals*. According to Toulmin[24], the most basic argument contains a *claim*, *data*, and *warrants*, while more complex arguments will also include other elements. This generic form of argument can be applied to many different fields. For example, Toulmin[24] references mathematics, science, philosophy, and law, among others.

This general TAP model has been interpreted in various ways in the field of science education, though there are similarities between these models of *scientific argumentation*[12,16,25]. All models involve a *claim*, which is a conclusion or assertion about natural phenomena that answers the initial question. These claims are supported by *data* or *evidence*, which usually refers to measurements and observations gathered during a scientific investigation. Finally, these models of *scientific argumentation* include reasoning that links the claim and evidence, often with reference to scientific theories and laws. This reasoning element has been called *explanation*[12], *justification*[16], and *rationale*[25], to name a few. Additional elements of *scientific argumentation* are found in some of the models, but these three components are common to all.

A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas[8], the report upon which the Next Generation Science Standards (NGSS) are based[26], also stresses the importance of argumentation. One of the eight essential practices it emphasizes is engaging in argument from evidence, and it describes what this practice means in a science versus an engineering context. In science, argument is used to make and support claims about natural phenomena; in engineering, it is used to develop the best possible solutions to engineering problems[8]. In engineering, the solution chosen is often one of many valid solutions, whereas in science, there is not an expectation that there are many possible answers to a scientific question[6]. Conclusions reached in science are ideally independent of context, whereas the entire purpose of engineering is to design a solution that meets the needs of a particular client. Both scientists and engineers base their arguments on evidence, but the underlying reasoning is often different. Engineering designs certainly take into account the principles of science and mathematics, but they also take have to consider design criteria (e.g., performance, safety, aesthetics) and constraints (e.g., client’s requirements, limited budget, materials available)[6,8]. It is evident that engaging in argument from evidence is an important practice in science and engineering, but the arguments look quite different.

We have chosen to use a different term, *evidence-based reasoning*, to describe arguments in engineering contexts. While the general TAP model of developing a logical argument applies to both engineering and science, there is a clear distinction between how each field needs to transform this model to meet its needs. *Scientific argumentation* makes claims about natural phenomena and supports them with evidence and reasoning related to scientific theories and laws. Arguments in engineering are related to design decisions, and these arguments are supported by evidence and reasoning related to scientific and mathematical principles, the criteria by which the solution will be judged, the constraints that limit possible solutions, and external factors related to the context for which the solution will be used. Furthermore, engineers seek to come to consensus when working on a problem. Due to the collaborative nature of engineering, the word argument might highlight an adversarial stance in teams which, we believe, could misrepresent the field of engineering to K-12 students. Moreover, since this study considers engineering as it is embedded in science classrooms, argumentation has specific connotations to science educators and the K-12 students who have been practicing argumentation in science classes. Finally, throughout this study and our work with teachers, it has become apparent that we need to differentiate the practice in engineering as it did not always occur in the same manner as scientific argumentation in the classroom. Evidence-based reasoning is a more general term than argumentation and is better representative of how engineers use evidence to support the decisions they make as they work.

Methodology

This research used an exploratory case study design to investigate students' use of evidence-based reasoning (EBR) while engaging in engineering activities within an integrated STEM curricular unit. A case study was selected as it allows for an in-depth investigation to understand the complexities of a system[27] and a holistic view of a real situation[28]. By using a case study, the researchers gleaned unique insight into where and how students naturally use EBR within the engineering lessons of the STEM integration unit.

Participants

The study followed one science teacher's seventh grade classes through the implementation of a three week integrated STEM unit during the spring of 2015. The class with the highest percentage of students who agreed to participate in the study was selected for this research. This class was divided into five teams, each containing three to four students. To gain deeper insight into students' use of EBR, one team (case) was selected for further examination. The criterion for selection was the team with the most audio and video data available. In this case, the team chosen was a group of four 7th grade girls: Ally, Becky, Colleen, and Danielle (pseudonyms).

Description of Unit

The unit implemented was designed for a middle school life science course[29]. The instructional material combined the learning of topics from cellular biology, biochemistry, biotechnology, and engineering design through a series of STEM integration activities that allowed students to use various aspects of engineering to solve a problem. In this integrated STEM unit, students explored cells, DNA, biotechnology, and surface area to complete an engineering design challenge. The engineering challenge allowed students to take part in one aspect of health by improving a process used in the development of medicines. The schedule of the lessons and a summary are provided in Table 1. For the purpose of this study, the only lesson examined for EBR was the last lesson, the engineering challenge. During the first five lessons, students learned about the engineering problem and gathered background information through science inquiry lessons in order to prepare for designing a solution.

The teacher did not explicitly teach the practice of argumentation, scientific or related to engineering, prior to the lesson, nor during the lesson. However, the teacher did ask students to elaborate on any answers they provided both on paper and during class discussions. These requests for elaboration were not purposeful attempts to elicit scientific argumentation or engineering evidence-based reasoning; rather, they were an attempt to help students articulate their understanding and thinking.

Table 1: Overview of the unit

Lesson	Days	Summary
The Client	1	Introduction to the client and examine what it is the client wants
Balloon Animal Cells	1	Review cell structures, identify the location of DNA in the cell, and clarify the engineering problem using a model
The Client's Protocol	3	Extract DNA from cells based on the client's current protocol, calculate baseline data, and describe characteristics of DNA
Maximizing Access	2	Use models to explain the relationship between the exterior and interior cells within a tissue and describe how this influences the number of cells available to extract DNA from
Competition	2	Investigate how different environmental factors affect how fast enzymes work and consider how this might be used to slow down the destruction of DNA
The Engineering Challenge	7	Design a process to improve the yield of DNA, test and evaluate the success of the design, redesign to improve the efficiency of the extraction, and make final recommendations to the client

Data Sources

Several forms of data were collected for this study. The primary sources of data were seven days of video and five hours of audio recordings of the target team during the last lesson, which were transcribed. Other data included student artifacts. Data that contained information that went beyond the target team, such as whole class discussions and multiple team discussions, were examined to provide context and clarification for what was occurring within the teams but were not analyzed for EBR.

Although conversational data was collected for each of the seven days of the engineering challenge lesson, two of them were excluded. The fourth day of the engineering lesson was excluded due to low attendance within the team as a result of a school field trip. The fifth day was excluded due to low quality of both the video and audio recordings. As a result, conversations were not captured for these days, which have implications that will be discussed later in this paper.

Data Analysis

Content analysis methods were selected to examine the data as it is a systematic way of analyzing a body of recorded communication that may include videos, pictures, symbols, and written text[30]. This method allowed the researchers to take a close look at one case to gain an understanding of the use of EBR during engineering design within a STEM integration unit using students' written and oral documentation.

Analyzing the data for this research was completed in three phases. The first step was to identify instances of students using EBR. Toulmin's Argumentation Pattern (TAP) was used to identify instances of EBR within students' written and oral communication[24]. As this research was focused on identifying where in the engineering design process EBR naturally occurred and how students were using EBR, but not the robustness or completeness of the EBR, a broader definition of the TAP model was used. Written and oral communication that included a *claim* in an engineering context, which was a suggestion or decision related to the engineering design, plus at least one other element of an argument (*data, warrants, backing, modal qualifiers,* or *rebuttals*) was coded as EBR for this paper.

Coding for EBR occurred within two types of data: student conversations and worksheets. Conversational instances of EBR were identified in terms of episodes since they reflect the back-and-forth dynamics of conversation. As such, some episodes contain multiple interweaving instances of reasoning from evidence, but because of this interrelated nature, each episode was coded as one instance of EBR. When coding worksheets for EBR, each individual instance of EBR was coded separately since worksheets are a form of written communication in which the student records information without feedback from others. Thus, a single worksheet may have multiple codes. Data were presented to other researchers for verification of each EBR instance coded.

The second phase of the analysis was to identify where in the engineering challenge these instances of EBR occurred, which addresses the first research question. To accomplish this, the instances coded as EBR were mapped to the *Framework for Implementing Quality K-12 Engineering Education*[31], which defines the characteristics of K-12 engineering. This framework identifies nine key indicators that define engineering in K-12. The first of the indicators is the *Process of Design*, which is subdivided into *Problem, Background, Plan, Implement*, *Test* and *Evaluate*. Instances identified as EBR were coded based on where they occurred within the *Process of Design.* Given that the focus of this study was just the engineering design challenge portion of the unit, instances of EBR that occurred during the *Process of Design* were given one of three codes: *Plan, Implement & Test,* or *Evaluate*. *Implement* and *Test* were combined because these steps were difficult to distinguish as they were done concurrently by students due to the nature of the design challenge. The iteration aspect of the design process was also accounted for; these three codes were also noted as occurring in the initial design phase or within the redesign phase.

The third step was to take a close look at how students utilized EBR when participating in engineering process of design, which was done to address the second research question. This was done using emergent coding[32]. Each instance of EBR was given a code that described the purpose for which EBR was being used (e.g., providing reasoning for suggested designs during brainstorming). These codes were then categorized into themes.

Findings and Discussion

The findings for this case are presented in the following section. First, we begin with general findings about the instances of EBR that were identified in the case study. Next, we describe how EBR aligns with engineering process of design. Then, we describe trends that emerged, revealing how these four students used EBR within the engineering design challenge of the STEM unit.

Evidence-based reasoning: General findings

After reviewing the target team's data, a total of 30 instances of EBR were identified from the five days that were analyzed within the engineering design lesson. Nine of these instances occurred during group conversations, while 21 were found in student worksheets. Almost all of the group conversations involved two or more individuals engaging in interweaving EBR, though there were two instances where a single person presented a possible decision backed with evidence with no comments made by other team members. Most of the instances of EBR in worksheets were found in students' individual worksheets; these were more commonly assigned by the teacher. However, five instances of EBR were found in the group worksheet in which the student team had to describe their design plans. An interesting note is that three students clearly used EBR in their individual worksheets and while contributing to group conversations. However, while one student filled out worksheets and made statements in group conversations, she did not provide reasoning or evidence to support claims

Evidence-based reasoning: Location within the engineering process of design

To determine where EBR was being used within the design challenge, each of the 30 instances of EBR were mapped to steps within the design process. The distribution of EBR within the engineering process of design varied between the different steps students were engaged in (see Figure 1). The majority (53%) of the arguments were found within the initial planning of the design, while 27% occurred during the evaluation of the redesign. The remaining instances of EBR (20%) were spread across the other three areas of the design process: Design-Implement/Test, Redesign-Plan, and Redesign-Implement/Test. No instances of EBR were found during the evaluation of the first design iteration due to low attendance of the students within the target team. It is possible that if all students had been present, more EBR may have occurred. In addition, the redesign-plan day may have also contained instances of students using EBR; however, these were not recorded due to technical difficulty, which meant that the only data source gathered from this day was the group redesign planning worksheet.

The appearance of EBR codes also varied between the different types of communication. Conversational EBR episodes were well spread throughout the process of design, occurring in five of the six steps coded. The majority were found in the initial planning, while the rest were distributed more evenly throughout. However, individual writing tasks generated student use of EBR extensively during the initial planning of the design and during the final evaluation of the redesign, slightly during redesign planning, and not at all during the other steps. These instances correspond to prompts found within the worksheets provided to students. Yet, when students were not provided documentation that requested additional information, no EBR was present. In sum, while both forms of communication showed evidence of students using EBR, it more consistently appeared throughout the process of design through team conversations.

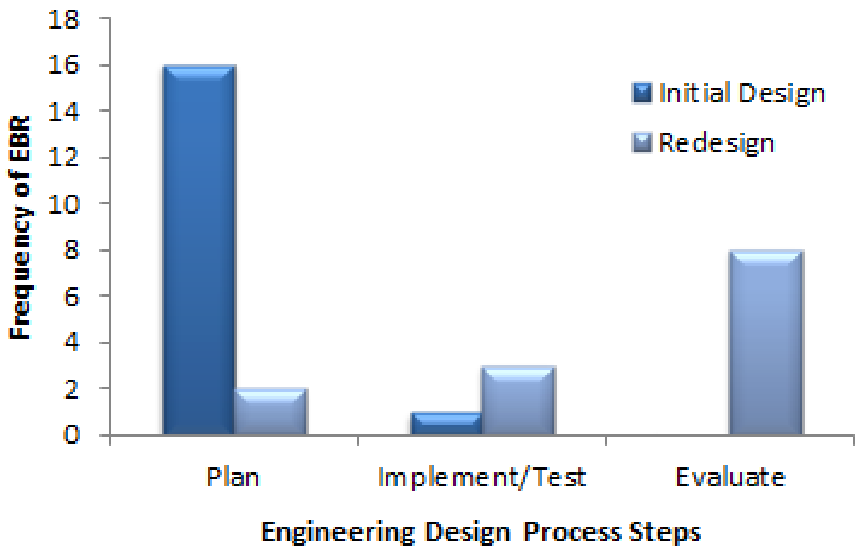

Figure 1. Distribution of augments within the engineering process of design

Use of evidence-based reasoning in engineering

Students in the target team used EBR in four different ways. The first was through brainstorming activities. Students were provided worksheets that required them to consider what elements of the DNA extraction they would change to improve the client's protocol. Figure 2 displays the response of one student. Though the worksheet did not explicitly ask students to generate an explanation from evidence, elements of EBR were present.

Individual Brainstorming – (worksheet)
Cut up the sample with cells into tinier objects or mash them up. *Pros:* more surface area with cells *Cons:* could damage some useful cells
Heat up the sample before extracting. Our recent experiment shows it helped. *Pros:* slows down enzymes that might destroy DNA *Cons:* extra time used up, heat could damage cells
Pop the cell. The DNA is in the cell and nucleus so if we pop it, it will all be there. *Pros:* fast, easy, simple *Cons:* damage cell, enzymes could get and destroy the DNA first

Figure 2. Colleen's brainstorming worksheet responses for the initial prototype

In this excerpt, Colleen brainstormed possible changes that could be made to improve the client's current DNA extraction protocol. She provided three claims, in this case suggestions for possible design solutions, while also providing reasoning for each. The first idea she presented identifies a solution, that cutting or mashing the sample will improve the process, followed by her justification that it will increase the surface area. Her second idea identified a solution that heat may also be an option for improving the protocol as it reduces enzyme activity. The evidence provided to support this idea is based on her experience in a lab completed prior to this lesson, where the students explored how different environments may alter enzyme activity. Colleen's third idea attempted to identify a solution to accessing the DNA. She claimed that popping the cells will be needed because DNA is located with a cell's nuclease.

The second way the target team utilized EBR was negotiating the prototype design. The initial brainstorm was used as a stepping stone for presenting and persuading their teammates that their ideas should be implemented into the prototype design. The following excerpt provides an example of how three of the four students began to negotiate whether smashing or cutting their sample into thin slices would be a better choice for extracting DNA.

Ally: Ok, so one of my ideas was instead of smashing the strawberry, or whatever we are using, we could cut it up into a bunch of really, really thin slices. Cells would be ruined or smashed…but since we are not smashing, it would be less surface area.

Becky: But, we can't put the cells back.

Colleen: It is better to do it that way because if we do, if we are smashing we're going to have less cells.

Becky: How would we have less cells?

Colleen: Because we kill them.

Becky: No, like…the cells need to be broken open so we can get to the DNA.

In this example, Ally provided a foundation for the development of the use of EBR by presenting an alternative plan for how to deal with increasing the surface area of the sample. Becky was not convinced that cutting was the most efficient way. However, Colleen agreed that slicing was the best course of action and attempted to provide more information to her team. They did not resolve the issue at this point and returned to it during a later conversation.

Colleen: I think we should cut it [the sample] because smashing it would kill the cells.

Becky: I don't understand how that would like kill the cells though.

Colleen: Because if you smash a cell, it would like pop it open and it dies.

Becky: Yeah, but it's going to die anyway.

Colleen:	If we do it the smashing way, it will give the enzymes more time to get to the cell, the DNA and destroy it. Because what the enzymes do is destroy the DNA.
Becky:	Hey, but how does smashing it give it more time than cutting it?
Colleen:	Cuz smashing it would like be feeding it I guess. And cutting it really small where like the inside of those might still be cells
Becky:	But the cells are going to die anyway.
Colleen:	But cutting they'll die slower. That sounds horrible.
Ally:	We're smashing them.

In this episode, Becky was not convinced that slicing the sample was going to make a difference. Colleen continued her attempt to persuade Becky by bringing in more information about the role of enzymes. By the end of the conversation, Ally has made up her mind that smashing was the preferred choice. Though it is not clear if Colleen agreed with the decision, the team accepted this and moved on.

In the examples above, the students were also using evidence in an attempt to understand and clarify what others are thinking, which brings us to the third way students used EBR. EBR development often revolved around points of misunderstandings. In the two excerpts above, Becky and Colleen had a different understanding of the best way to increase the surface area of the sample while also considering the devastating effect enzymes have on DNA. Both Becky and Colleen clearly understood that smashing the cell would kill the cell. Colleen also realized that enzymes destroy the DNA but failed to recognize that to get the DNA out of the cell, it must be destroyed. Becky appeared to understand this fact, but she did not explain her evidence to the other students. By asking questions and challenging each other's claims, they unveiled areas that students were struggling to understand and attempted to clarify these misunderstandings for their teammates, which elicited EBR.

Finally, students used EBR to explain answers to teacher-prompted questions. During the final phase of the engineering process of design, the teacher created a set of worksheets to help students reflect on the engineering process and evaluate their design. In their written responses, students made claims about their design decisions and frequently supported those design choices with additional information. For instance, when trying to explain where they improved the most between the first and second iteration of their prototype, Ally wrote "We improved cost," while Colleen said they "improved the most on saving money because we used less materials." In addition, in an assessment, students were asked to evaluate and make recommendations to a client based on a given set of data of which only two students presented answers that included elements of EBR that went beyond a claim. Becky's response was "B, it got the most DNA percent." To the same question, Colleen's response was "I would recommend her to use Protocol B because they got the most DNA out of the blood sample. Protocol B had 0.5% more than the others." This suggests that students may use EBR to explain their reasoning for answers they provide, though many need to be developed further.

Conclusion

This case provides initial insight into where EBR may occur within the engineering challenge of a STEM integration unit. The most common locations of EBR were found within the planning and evaluation phases of the engineering process of design. Many of these instances were found on student worksheets, which had prompted them to explain their design choices. Instances of EBR found in student conversations were spread more evenly through the planning, implement & test, and evaluate phases. This is not to say that all students contribute equally nor present quality information, but it does suggest that when students participate in engineering activities that encourage them to discuss their design choices, it results in students using EBR.

In addition, this study illuminates some of the different ways students naturally used EBR. In this case, students used EBR in four ways: brainstorming, negotiating, clarifying, and answering teacher-generated prompts. Students' use of brainstorming predominantly occurred during the planning of their design; this phase also included negotiating the best solution. The EBR offered within these brainstorm and negotiation instances was generally linked to both science and mathematics. Moreover, students used EBR to clarify differences in each other's understanding, which seemed to be initiated due to confusion about a design choice, following through with the implementation of the design, and when design ideas conflicted. Finally, evidence of EBR was found when students responded to teacher prompts. Although teacher prompts, both verbal and written, are pedagogical strategies used to engage students in the engineering design process, they can be applied to many situations. While it is evident that brainstorming, negotiating, and clarification activities done by the students elicited EBR, more research needs to be done to identify how EBR might be carried out in other steps of engineering design.

Since this case study represents findings from one team of students during one STEM integration unit, these findings are not generalizable to other teams or other curricula. This study only captured how EBR emerged through four students' oral conversations and writing during an engineering design activity. More research needs to be done to study the use of EBR by other teams engaging in this curriculum. Additionally, further studies examining how students use EBR in different engineering units are needed.

Another area in which future research needs to be done is with respect to the quality of EBR used by students. This study considered EBR more broadly in terms of when and how students used it during an engineering design challenge. However, it was beyond the scope of this research to deeply analyze the instances of EBR. Future research should do a more detailed analysis of students' use of EBR to explore its quality. This research could include explorations into what kinds of evidence and reasoning students use to defend their design decisions, including whether students tend to use science and mathematics concepts, engineering problem considerations (e.g., criteria, constraints, factors related to the context of the problem), or both. This research would help further our understanding of how EBR may be used to link the disciplines of science, technology, engineering, and mathematics.

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