Argumentation in K-12 Engineering Education: A Review of the Literature (Fundamental)

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While individual engineers address problems differently, one trait all engineers share is reliance on argumentation skills to make claims about their designs and solutions. Engineers understand the need to persuasively communicate the attributes of their designs and solutions to a wide range of stakeholders—from team members, to clients, to financiers, to the general public (Gainsburg, Fox, & Solan, 2016; Jarzebowicz & Wardzinski, 2005; Latour, 1987; Madhavan, 2015). Moreover, engineers' arguments must address a range of (sometimes competing) factors, such as safety, cost, and environmental impacts.

Along with the centrality of argumentation within engineering practice, there is additional motivation for integrating argumentation into engineering education: Argumentation instruction is shown to improve student outcomes. A large body of research in the related discipline of science (Erduran, Ozdem, & Park, 2015) has suggested that argumentation improves diverse students' conceptual understandings. In recognition that argumentation is a promising approach to teaching engineering, the National Research Council (NRC, 2012) contended that students should master "constructing a convincing argument that supports or refutes claims" for solutions about the designed world – a recommendation that was adopted by the *Next Generation Science Standards* (NGSS Lead States, 2013, p. 63).

Although argumentation can help both students and engineers achieve positive outcomes (Gouran, 1995; Zohar & Nemet, 2002), it's not always a simple skill for students to master (Wilson-Lopez & Garlick, 2017). Consequently, we argue that there is a need for more research related to best practices for supporting K-12 students in engaging in engineering argumentation. The purpose of this review is to identify how argumentation education is being implemented in K-12 classrooms, as well as areas of strength and opportunities for growth in its implementation.

Theoretical Framework

In this section, we will explicate the constructivist theories that we relied on in order to shape this review. In particular, this research was informed by sociocultural theories (Lave & Wenger, 1991; Wertsch, 1998), which contend that teachers in each content area rely on unique, sociohistorically-derived tools to construct discipline-specific claims (Villa, Kephart, Gates, Thiry, & Hug, 2013). In accordance with this theoretical framework, Knorr-Cetina (1999) asserted that each discipline constitutes its own "epistemic culture."

Across different academic content areas, researchers and practitioners alike (Goldman et al., 2016; Osborne, Simon, Christodoulou, Howell-Richardson, & Richardson, 2013) agree that argumentation is a promising approach for engaging students in epistemic practices. By using argumentation to frame activities, K-12 teachers avoid "final form" instruction (Duschl, 1990), where concepts and findings are presented as unquestionable facts or formulas that lack the context of the history of their conception. Contrary to this typical epistemic culture, students who take part in argumentation can construct and validate claims, establish the relationship between claims and data, and evaluate contradictory alternatives. Essentially, through argumentation, students learn epistemic practices, which are sociohistorically situated within disciplinary contexts.

Like Sampson and Clark (2008), in this literature review we make the distinction between *arguments*, or the verbal, written, visual, and/or mathematical products that students develop in order to justify their claims; and *argumentation*, or the ways in which claims are constructed. While different content areas have established unique methods of validating discipline-specific sorts of claims, scholars most commonly use Toulmin's (1958) argumentation pattern to describe and analyze students' arguments across disciplines (Litman & Greenleaf, 2017; Ryu & Sandoval, 2012). Toulmin's pattern includes *claims*, or the contentions that one wishes to prove; *evidence*, or support for the claim; *warrants* that demonstrate how the evidence sufficiently supports the claim; and *rebuttals* to given or anticipated counterarguments that offer competing information and/or alternative claims. In the engineering community, claims may include assertions regarding whether testing procedures and processes are appropriate and thorough enough; arguments regarding whether a particular design decision is justifiable; and contentions regarding where, how, when, and with whom overall solutions should be adopted (Vinck, 2003; Winsor, 2003).

While the term *argument* refers to justified claims, the term *argumentation* refers to the process of constructing and justifying those claims (Sampson & Clark, 2008). In engineering, for example, this process frequently involves testing and revising prototypes; developing and/or applying mathematical models; and showing how design ideas meet criteria and constraints- while simultaneously engaging in dialogue and debate with other engineers (Buciarelli, 1994; Downey, 1998; Vincenti, 1990).

Because the argumentation skills used by practicing engineers further represent a promising approach to K-12 engineering education, the first purpose of this literature review was to categorize and describe how arguments and argumentation have been utilized in existing research literature, in order to extrapolate the assumptions and values that drive epistemic cultures of engineering as they are enacted in pre-workforce settings. The second purpose of this literature review was to identify areas of strengths and areas for growth in research and practice in engineering argumentation.

Therefore, our research questions are as follows:

1. How are engineering-related arguments operationalized in K-12 educational settings? This question leads to the following sub-questions: What sorts of claims do educators ask students to make, and how are these claims warranted with specific types of evidence?

2. How is engineering-related argumentation operationalized in K-12 educational settings? This question included the following sub-question: What pedagogical practices or processes preceded or supported students' production of arguments? By answering this question, we sought to identify epistemic practices that exhibit the ways in which knowledge is constructed within engineering.

Method

Scholars (Borrego, Foster, & Froyd, 2014) contend that development a quality literature review requires researchers to assemble a team with appropriate interdisciplinary experience. Our team includes researchers in literacy education; engineering education; science education; and literature reviews and university librarianship. Argumentation is traditionally taught in English and composition classrooms and is often absorbed under the umbrella of literacy education. Thus, we sought out several researchers with advanced degrees in literacy education whose scholarship focused specifically on argumentation. The two engineering education researchers have both been employed in engineering firms and have attained or are working towards advanced degrees in engineering education. Since many of the articles we located on engineering argumentation had been published in science education journals, we solicited a science educator/researcher as another team member. Finally, a university librarian, with expertise and experience in database searches and data management, oversaw and advised the search process.

Eliminating Abstracts and Full-Text Articles

First, we specified search parameters (Appendix A) to locate articles. Once articles were located, we uploaded them to Rayyan, a web-based application designed for use in literature reviews. Rayyan helped the research team identify and eliminate duplicate articles. Two authors—one with expertise in engineering education and one with expertise in literacy education—read the remaining documents. We mutually agreed that an article/manuscript should be excluded from the literature review when it did not meet one or more of the following inclusion criteria:

1. Study is in English.
2. Study is peer-reviewed (dissertation, article, monograph, etc.).
3. Focal research participants are K-12 students in or outside of classroom settings.
4. Study is empirical (qualitative, quantitative, or mixed methods). Empirical studies need to meet the following criteria: (a) state a research question, purpose, or hypothesis; (b) include a methods section with explicit mention of methods of data sources and data analysis; and (c) include results or findings that stem from the analysis. With this criterion in mind, theoretical papers and thought pieces are excluded from this study.
5. Participants in the study must develop or use evidence-based claims.
6. The evidence-based claims must relate to the designed world (e.g. devices or processes created by humans).
7. Meta-analyses or literature reviews should be excluded.

Based on these criteria, we identified 83 studies that were included in the review.

Coding Studies

We used constant comparative analytic methods (Corbin & Strauss, 2014) to develop a coding scheme to analyze the claims made by students, as well as the evidence they produced to support them. The purpose of this coding process was to answer RQ1 in relation to arguments. Next, we developed a coding scheme to delineate the types of supports teachers provided to students to help them develop their arguments. The purpose of this coding process was to answer RQ2 in relation to argumentation, or the process of developing arguments. Table 1 demonstrates exemplars of codes that were developed in this way.

Table 1. *Codes related to studies.*

Research Question One *How are engineering-related arguments operationalized in K-12 educational settings?*		Research Question Two *How is engineering-related argumentation operationalized in K-12 educational settings?*		
Types of Claims	Types of Evidence	Physical Practices	Social Practices	Literacy Practices
•**Adoption:** A design or design element (which somebody else has created) should or should not be adopted in a particular context. •**Design:** A design or design element, which the student(s) generates, should or should not be adopted. •**Evaluation:** A design or design element, which has already been implemented, should or should not have been implemented. •**Outcome:** A design elements or design led to a particular positive or negative outcome.	•Analogy. •Authority. •Cost. •Environment. •Ethics. •Evidence from tests. •Human users. •Originality. •Regulations. •Safety/health. •Scientific principles.	•Experiments (manipulated variables but not designs). •Observations (observations of natural designs) •Tests (planned, manipulated tests of designs)	•Interviews. •Role play. •Small-group discussion. •Whole-class discussion.	•Internet searches. •Peer or teacher feedback on written drafts. •Read scenarios that introduce the problem. •Read texts with different perspectives. •Writing scaffolds such as graphic organizers or written prompts.

Limitations: Our study is limited for at least two reasons. First, our study is limited due to the search terms that we used. Many scholars do not use terms consistently when describing similar phenomena. For example, Osborne and Patterson (2011) contended that scholars often conflate the terms *argument* and *explanation,* even though they are two distinct genres. Thus, because we did not use the term *explanation* in our search terms, and because did not use other terms relevant to engineering and to argumentation, we may have missed relevant studies on engineering argumentation. Second, our study is limited in the sense that we analyzed studies on engineering argumentation, rather than observed teachers' practices ourselves. Thus, teachers may have engaged in multiple practices that were not adequately described or reported by the authors. Thus, we offer this study as a snapshot of how researchers are describing and recommending engineering argumentation, rather than as an accurate portrayal of how teachers and students enact engineering argumentation in school settings or out-of-school settings.

Findings

Research Question 1: To answer this research question, we sought to identify the types of claims and evidence that K-12 students made in relation to the designed world. Generally speaking, we observed that K-12 students were very rarely asked to argue on behalf or against their own designs of procedures or devices; instead, they frequently *evaluated* existing solutions by identifying their strengths and weaknesses (coded as *evaluation*), or they argued whether or not a design should be adopted in a particular context (coded as *adoption*). For example, in many studies (e.g., Christenson, Rundgren, Hoglund, 2012; Marttunen & Laurinen, 2007; Monaghan, 2015; Shoulders, 2012), K-12 students argued that certain genetically modified organisms should or should not be used in a given context (coded as *adoption)* and/or argued whether or not these GMOS were ultimately more beneficial or harmful to society (coded as *evaluation*). In many other studies (e.g., Gilabert, Garcia-Mila, & Fenton, 2013; Weible, 2014; Wu & Tsai, 2007), K-12 students argued whether or not a local nuclear power plant should be adopted (coded as *adoption*) in addition to the strengths and weaknesses of nuclear energy (coded as *evaluation*). Across numerous studies, K-12 most commonly used *scientific principles, environmental consequences*, and factors related to *health and safety* (e.g., radiation poisoning) to justify their claims regarding the designed world. For example, middle school students who sought to evaluate whether or not wind energy should be used in their region (Gilabert, Garcia-Mila, & Fenton, 2013) argued that windmill farms do not produce carbon dioxide and this would help reduce the greenhouse effect (coded as *environment*) and that "thermal power stations run by fossil fuels affect people's health" (coded as *safety/health*).

The least frequent categories in students' arguments included justifications of *originality* (you should adopt this design because it is creative or innovative), *human users* (evidence related to human preferences, aesthetics or behaviors), and *regulations* (e.g., this design meets regulations in policy or law). Overall, then, this literature review suggests that K-12 students in the studies did engage in thinking about ethics, cost, science, environmental impacts, health, and other important factors related to the design world as they sought to justify their arguments. However, they could more fully be taught to consider the human dimensions of engineering, such as whether or not people would be interested in their design or would use it as intended, as well as the legal dimensions of engineering, such as adherence to laws and regulations.

Research Question 2: To answer this research question, we sought to identify the argumentation-related practices in which students engaged before, during, and after they created their oral or written arguments. Teachers focused on argumentation in relation to three areas: physical practices, social practices, and literacy practices. The most common argumentation practices included small-group discussion and whole-class discussions, which were included in a majority of studies. This finding suggests that teachers recognized that engineering is a social endeavor requiring discussion and debate among people with different insights and perspectives.

By and large, teachers also recognized the important of literacy to engineering, in the sense that they provided students with a variety of textual supports (reading or writing) in order to help them produce high-quality oral or written arguments. For example, across many studies (Agell, Soria, & Carrio, 2015; Basche, Genareo, Leshem, Kissell, & Pauley, 2016; Knight & McNeill, 2015; Mathis, Siverling, Glancy, & Moore, 2015), teachers provided their students with texts that outlined the pros and cons of different designs, and/or texts that introduced different facets of the problem, in order to support their thinking in relation to the design. Across many other studies (e.g., Dawson & Carson, 2017; Khishfe, Alshaya, BouJaoude, Mansour, Alrudiyan, 2017; Yang, Lin, She, & Huang, 2015), teachers provided their students with writing scaffolds, such as graphic organizers or writing frames, before asking them to write their arguments.

Physical practices, such as tests and observations, appeared in reviewed articles less frequently than literacy practices and social practices. Moreover, many of these physical practices were designed to teach scientific principles, rather than to evaluate a particular engineering design. For example, the middle school students in McNeill's (2009) study conducted experiments in which they combined alka-seltzer and water in an open container to determine whether mass changes, in order to learn about chemistry, prior to designing their own soaps. This finding suggests that students could more frequently directly engage in tests of prototypes or models of their designs, and use these tests as evidence to support their claims—for example, test an egg drop device prior to arguing why their egg drop device should be adopted (Chen, Wang, Lu, Lin, & Hong, 2016)—in addition to the more common practice of conducting experiments and observations related to scientific principles.

Discussion and Implications

All in all, the K-12 students in the studies we reviewed engaged in similar argumentation practices to those used by professional engineers. However, in most studies, students did not construct arguments in relation to their own proposed designs. In order to engage students more fully in the engineering design process, these findings suggest that students might argue for or against their own designs more frequently, using tests of design prototypes to support their claims. Because many engineers spend a lot of time in testing specifically, the findings from this study suggest that designing and conducting controlled tests of design prototypes may be one way to bolster argumentation instruction in K-12 engineering.

Most notable, however, was the fact that K-12 engineering educators appeared to focus intensely on scientific principles and outcomes (e.g., radiation's effects on health) as a core justification of designs, rather than focusing on other factors that must be taken into account by engineers, such as specifications outlined in regulations. Therefore, for engineering instruction to more completely prepare students for the kinds of arguments encountered by practicing engineers, students should be encouraged to consider a range of factors simultaneously (e.g., scientific principles, preferences and behaviors of human users, regulations) instead of focusing on whether or not their design will work according to scientific principles. An emphasis on scientific principles likely occurred because the majority of the articles on engineering argumentation were published in science education journals (e.g., *Journal of Research in Science Teaching*) rather than engineering education journals. Educational materials and approaches, which are more specific to engineering, might focus more fully on the range of evidence and ideas that engineers must consider when arguing on behalf of a particular design.

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Appendix A
Search Strings

Database: Education Source on EBSCO Host
Date of Search: 8/17/17
Search String: argument* AND (((DE "engineering education") OR (DE "science education")))
Date Published: 20000101-20170731
Number of results: 565

Database: ERIC on EBSCO Host
Date of Search: 8/17/17
Search String: (((DE "persuasive discourse") OR (argument*))) AND (((DE "engineering education") OR (DE "science education")))
Date Published: 20000101-20170731
Number of results: 552
Note: * Included “persuasive discourse” as a descriptor as per scope note in ERIC Thesaurus

Database: Academic Search Premier EBSCO Host
Date of Search: 8/17/17
Search String: argument* AND (((DE "engineering education") OR (DE "Science Education")))
Date Published: 20000101-20171231
Number of results: 327

Database: Scopus
Date of Search: 8/17/17
Search String: TITLE-ABS-KEY (argument* AND ("engineering education" OR "science education")) AND PUBYEAR > 1999
Number of results: 647

Database: Engineering Village
Date of Search: 8/10/17
Search String: (((argument* AND ({engineering education} OR {teaching} OR {computer science education} OR {education} OR {further education} OR {electrical engineering education} OR {control engineering education} OR {physics education} OR {electronic engineering education} OR {telecommunication engineering education}))) AND ((2017 OR 2016 OR 2015 OR 2014 OR 2013 OR 2012 OR 2011 OR 2010 OR 2009 OR 2008 OR 2007 OR 2006 OR 2005 OR 2004 OR 2003 OR 2002 OR 2001 OR 2000) WN YR))
Number of results: 1095

Database: Digital Dissertations
Date of Search: 7/11/17

Search String: argument* AND (((DE "engineering education") OR (DE "science education")))
Date Published: 2000-2017
Number of Results: 211