Engineering Approaches to Problem Solving and Design in Secondary School Science: Teachers as Design Coaches

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Abstract

This position paper examines the integration of engineering and science in secondary education by synthesizing literature drawn from bodies of literature in engineering education, science education, learning sciences, design cognition, and engineering studies. This paper argues that realizing the vision of the Framework requires a clear understanding of its dimensions, a strive for authenticity, a vision of students as reflective decision-makers, and the development of teachers as design coaches. Promising models of teaching are discussed with evidence supporting student learning and engagement and recommendations for further scaffolding. The paper also describes epistemic, disciplinary practices in engineering and compares these practices to the depictions of engineering practices in the classroom. Recommendations are provided on how to support disciplinary core ideas in engineering design. In classrooms where three-dimensional learning is happening, students and teachers take roles that are more than receiving and delivering knowledge; they are part of a classroom learning community where students are reflective decision-makers and teachers are design coaches.

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Introduction

In *A Framework for K-12 Science Education*, engineering is included along with natural sciences recognizing the intertwined relationship between science and engineering as well as the need for students to understand the human-made world (NRC, 2012). Such an integrative approach is necessary to promote effective transfer of learning so students are able to use science and engineering in daily decision-making and discourse; see value in science and engineering; and are equipped with the necessary skills for the careers they wish to pursue. The charge for educators is to promote three-dimensional learning so that disciplinary core ideas, disciplinary practices, and cross-cutting concepts are woven together to reflect authentic scientific investigations and engineering design in the classroom.

Accomplishing such integration in K-12 education may appear like a tall order calling for significant changes to how science is taught in the classroom. But the push for three-dimensional learning is necessary to avoid misrepresentation of scientific investigations in the classroom being presented in fragmented ways, far removed from a reflection of authentic science (Chinn & Malhotra, 2002). Much can be learned and applied from science education research especially in regards to teaching the nature of science in K-12 education. Dagher and Erduran (2017) argue that the scientific enterprise is complex and the nature of science taught in the classroom must address this complexity (Dagher & Erduran, 2017). They argue for the inclusion of social and cultural dimensions of science and its values beyond its specific practices such as experimentation. We see evidence of sub-optimal learning from focusing simply on experimentation articulated in the America's Lab Report (Chinn & Malhotra, 2002; NRC, 2006). The challenge is that authentic science and engineering are messy, and attaining such the learning goals is challenging. The tension between maintaining authenticity to epistemic practices and the need to meet specific performance objectives in a time-constrained classroom environment must be recognized. However, the trade-offs should be evaluated based on student outcomes and evidence from research shows levels of authenticity is possible within the classroom (Goldstein, Omar, Purzer, Adams, in press) and such practices can be applied to engineering education.

The body of research on the integration of science and engineering in K-12 education is fairly recent, dating back to the last two decades (Hynes, Mathis, Purzer, Rynearson, & Siverling, 2017; Mendoza Diaz & Cox, 2012). Yet, there are promising examples of teaching models that work in the classroom providing evidence of increased student learning, reflective decision-making, argumentation, and engagement. Hence, meeting the vision of the Framework is realistic. Yet, there are a number of challenges and opportunities to accomplishing this goal. In particular, this paper argues that realizing the vision of the Framework requires a clear understanding of its dimensions, striving for authenticity, envisioning students as reflective decision-makers, and the development of teachers as design coaches. Moreover, changes are

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necessary in the practices of not just the teachers, but all involved: those who study teaching and learning, those who prepare teachers, those who develop curricula and projects, and those who teach in the classroom. These changes in practices must be fueled with a vision of students developing as reflective decision-makers. This paper outlines three main areas of understanding and practice that need attention and modification in order to meet the goals of the Framework.

First, we must clarify the confusion arising from multiple means of talking about design in the research literature and the Framework, namely design as a pedagogy, design as disciplinary practice, and design as a disciplinary core idea. By juxtaposing these three conceptualizations of design, this paper clarifies the distinction between practices and ideas as well as the appropriate methods for teaching them. Second, this paper argues for the use of authentic design experiences that promote three-dimensional learning in the classroom. Much has been written in science education about the discrepancies between school science and real science. Curricula and design projects must endeavor authenticity so students can develop informed design practices and become reflective decision-makers. Finally, teacher education needs to address teacher beliefs along with pedagogical content knowledge. To facilitate three-dimensional learning, teachers must be supported in developing competencies as coaches in the classroom with abilities to elicit, recognize, and respond to student thinking as well as address students' social and emotional needs.

Is engineering design a pedagogy, a disciplinary practice, or a disciplinary core idea?
Educators and researchers approach and conceptualize engineering design in various ways. Sometimes their perspectives reflect design as a pedagogy, sometimes as a disciplinary practice or a core idea, and yet sometimes with a mix of these perspectives. These distinctions are often not recognized, a cause of confusion in the discourse of research and teaching practice. Hence, it is important to outline the nuanced differences in these three perspectives.

The differences in perspectives are associated with three research movements that occurred in the past twenty years. The first research movement in the United States, has started to emerge in late 1900s. These studies came from the learning sciences and have embraced design as a pedagogical approach. The teaching models developed during this movement presents design-based learning as an alternative to scripted inquiry-based learning (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kolodner et al., 2003). Although all promote science learning through design, these approaches have taken different names such as learning by design, design-based learning, design-based science. These models and associated curricula built on these perspectives, view design as a pedagogical approach and focus on disciplinary core ideas in physical, life, and earth sciences.

The second research movement is led by engineering educators, propelled by the publication of "Engineering in K-12 Education: Understanding the Status and Improving the Prospects" in 2009 (NRC, 2009) and similar other reports published on the status of engineering education in the US. These studies are typically motivated by the goal of changing the negative images of engineering, attracting more students into engineering, and the diversification of the engineering workforce (NRC, 2008). As a key example of this movement, the Boston Museum of Science has developed Engineering is Elementary units, which promotes design, positive views of engineers, and integration of engineering and science. Another two examples commonly used in secondary education are the Project Lead The Way (PLTW) engineering curriculum and Engineer Your World. These programs support engineering and computing skills, college readiness, and engage high school students in project-based learning using mathematics and science as tools of design (“Project Lead the Way,” n.d.). In these circular units and research studies, engineering is framed as a core content while design is promoted as a disciplinary practice. Similarly, design as a disciplinary practice and design as a pedagogy and an integrator is emphasized in the integrated STEM education efforts. Integrated STEM units typically build content knowledge in science and mathematics through a variety of pedagogical approaches including DBL. However, the integrated STEM approach also focuses on engineering design as a practice. The integrated STEM perspectives and curricula view design as a pedagogical approach but also promote design as a practice.

As we enter a third research movement, propelled by the Framework, we add to the mixture the notion that engineering design is also a core disciplinary idea. There is currently very little research that examines design as a core disciplinary idea (Hsu, Cardella, & Purzer, 2012). The body of literature that exists relevant to such exploration has been conducted with expert designers and undergraduate students. These studies are vital to the development of a foundation of research in K-12 education, as they focus on authentic design practices that naturally integrate multiple dimensions of the Framework.

Because of these differences in views of design in K-12 education, the following sections discuss prior literature under the headings of engineering design as pedagogy, engineering design as disciplinary practice, and engineering design a disciplinary core idea.

Engineering design as pedagogy

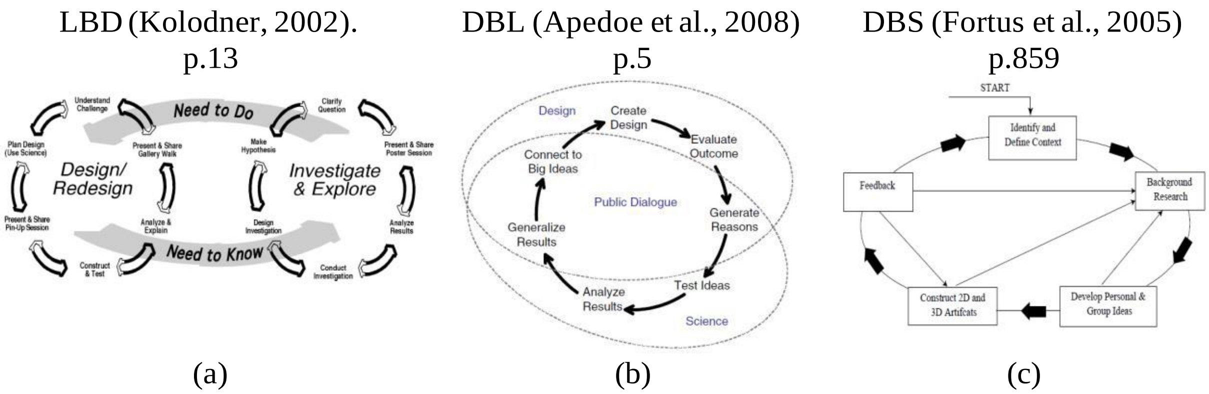
The Framework promotes the importance of teaching disciplinary practices along with disciplinary core ideas and the cross-cutting concepts, but it does not explicitly prescribe a specific pedagogical approach. Yet, there are a number of pedagogies that stimulate learning through design and hence implicitly embody aspects of the Framework. Among the most commonly known pedagogies of design are learning by design, design-based learning, and design-based science. These models of teaching have been studied with notable results on student learning and hence promise significant potential in supporting three-dimensional learning in the classroom. Three of these design-based pedagogies are described below.

Learning By Design ™ (LBD) is one of the first instructional models that uses scientific and engineering practices as a pedagogy (Hmelo, Holton, & Kolodner, 2000; Kolodner, 2002; Kolodner et al., 2003). LBD is developed by learning scientists and cognitive scientists at Georgia Institute of Technology based on theories of learning transfer and has been influenced by the design literature (Kolodner, 2002; Kolodner et al., 2003). While the model is developed at the intersection of problem-based learning and case-based reasoning, LBD is defined as a project-based inquiry approach to science education. In this approach, a design challenge provides a reason for learning the science content, and hence provides engagement in meaningful learning of science and design practices. LBD targets student learning of science concepts as students solve complex, ill-defined problems. The model promotes iteration, collaboration, and discourse through practices such as informed decision making, identifying and using evidence to make an argument, designing and running investigations, and communicating ideas and experimental results. The LBD curricula target middle school grades and take between three to ten weeks. The LBD cycle is composed of two connected cycles of inquiry: design–redesign and scientific investigation (See Figure 1a).

Design-Based Learning (DBL) was developed by learning scientists at the University of Pittsburgh (Apedoe & Schunn, 2013). With DBL, the model uses engineering design projects to inspire high school students about engineering as a career while also promoting scientific competencies by integrating scientific inquiry and engineering design (Apedoe, Reynolds, Ellefson, & Schunn, 2008). DBL helps make abstract science concepts more meaningful for students. For example, the Heating and Cooling Systems unit for high school takes about eight weeks and aims to promote student learning of challenging chemistry concepts such as atomic interactions, reactions, and energy transformations. There are a number of studies that compare DBL to scripted inquiry or traditional science education methods, and these studies find that students who learn concepts with DBL develop higher scientific content knowledge compared to others (Fortus et al., 2004; Kolodner, 2002; Kolodner et al., 2003; Mehalik, Doppelt, & Schuun, 2008). DBL is promoted as a project-based learning approach that promotes the need to learn disciplinary concepts while engaging students in the practices of science and design. At the center of the DBL model is public dialogue (See Figure 1b).

Design-Based Science (DBS) is a pedagogical approach developed by science education researchers at the University of Michigan (Fortus et al., 2004; Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005). DBS is promoted as an inquiry-based approach to learning science that uses design-based teaching. Developed for high school students, DBS puts science at the core of the curriculum as students tackle real-world, ill-defined problems. DBS uses design as a vehicle for learning science (Fortus et al., 2004). Focused on the creation of artifacts, DBS pedagogy aims to help develop modeling and representational abilities of students related to science. DBS also includes multiple learning cycles to support learning transfer by presenting concepts in multiple contexts, supporting meaningful learning through problem solving, and engaging students in metacognitive reflection (Fortus et al., 2005). DBS model's focus on student-created artifacts and models promotes a sense of ownership and hence serve as a motivator. Fortus and colleagues have assessed student learning through science knowledge tests as well as through evaluations of student artifacts, with findings that students had substantial learning gains in their scientific knowledge (Fortus et al., 2004, 2005). The process model of DBS starts by defining the problem context and emphasizes background research, collaboration, and feedback (See Figure 1c).

Each of the three approaches have many commonalities with their focus on learning of science concepts and emphasis on public dialogue around a designed artifact. What is unique about the LBD and DBL models with respect to the Framework is that they explicitly represent both scientific and engineering practices in their process models. This connection in the visualization of the DBS model is implicit although its learning outcomes are also oriented towards science concepts (See Figure 1).



LBD (Kolodner, 2002). p.13

DBL (Apedoe et al., 2008) p.5

DBS (Fortus et al., 2005) p.859

(a) (b) (c)

Figure 1. Comparisons of pedagogical models that use design as a vehicle for learning

Engineering Design as a Disciplinary Practice

One of the dimensions of the Framework is scientific and engineering practices, suggesting that students must engage in these practices in the classroom. One confusion arises with regards to the pedagogical approaches described earlier, as these models are inspired by science and design practices. So, we might ask, would students engage in and develop disciplinary practices if teachers were to use one of the design-based pedagogies? Couldn't these modes of instructional models described earlier also be argued as approaches to teaching design as a disciplinary practice? The pedagogical models would promote disciplinary practices in science and engineering, but with some limitation. This is because these models do not represent the epistemological underpinnings of each field, especially engineering design. We need to ask if these pedagogical models should be presented to the students as representations of disciplinary practices. With inquiry-based learning, the earlier reform efforts in science education faced this dilemma too. Today's parallel is design-based learning.

Design is undoubtedly a disciplinary practice for engineering (Dym, Agogino, Eris, Frey, & Leifer, 2005). As one of the three dimensions of learning, the design practice should be represented authentically. The simplistic narratives of engineering defines the discipline as applications of science and mathematics (Pawley, 2009), emphasizing its analytic, evidence-driven nature. The design-based pedagogical models reflect these aspects. But engineering practice also involves the satisfaction of end users and working with constraints that are economic, societal, legal, environmental, or contextual (Cunningham & Kelly, 2017a; Figueiredo, 2008; Svarovsky, 2011). In fact, similarly science is not simply an evidence-driven discipline – decision-making in science also involves values and moral judgement (Bell & Lederman, 2003). While design-based pedagogies emphasize evidence, public discourse, and collaborative learning, they do not typically require a client, a deep understanding of the user, and the consideration of non-technical factors such as cost. There are a number of teaching models that represent design authenticity by engaging a user or a client.

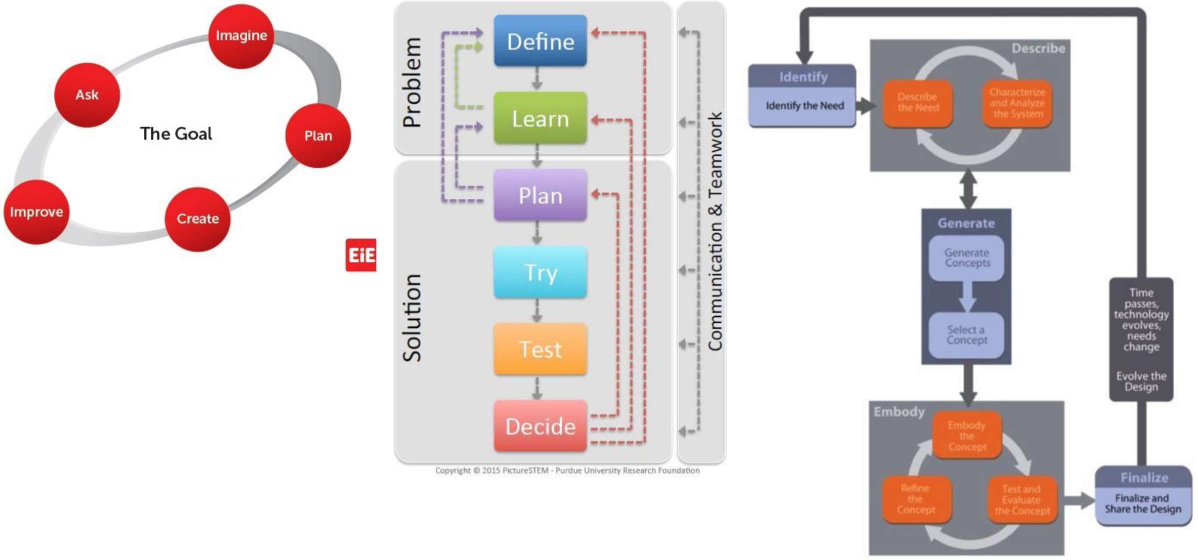
At the elementary level, designing for book characters and animals has been particularly effective in supporting student engagement and learning. Novel Engineering, is one approach that highlights an understanding of and care for users at the core of instruction. Developed by researchers at Tufts University, Novel Engineering integrates characters from books and novels as the users of the solutions students develop. The students spend early stages of the project in developing an understanding of the problem context and the needs of the user, develop criteria and constraints, and based on these insights and understandings develop prototypes that can be tested and evaluated. Another elementary level model is PictureSTEM, integrated STEM units, developed by researchers at the University of Minnesota and Purdue University. These units also include clients and users, although simulated, they are effective in engaging students in authentic disciplinary practices and supporting argumentation and learning(Mathis, Siverling, Glancy, Guzey, & Moore, 2016). At the secondary level, educators have also successfully engaged stakeholders in design with the collaboration of science and mathematics teachers. Goldstein and colleagues have worked with a local homebuilder to challenge middle school students in designing a sustainable neighborhood (Goldstein, Loy & Purzer, 2017). At the conclusion of this project, one of the student teams is built at the neighbor after further design involving the students and the builders. Students show gains in their abilities to answer questions that require the application of science concepts to design scenarios (Chao et al., 2017; Goldstein, Omar, Purzer, &Adams, in press).

Even with these models that represent authentic engineering design practices, simply involving users is not sufficient. The classroom activities also need to be guided by research on informed design practices (Crismond, Gellert, Cain, & Wright, 2013; Crismond & Adams, 2012). These studies emphasize reflective decision-making in the social dimensions of design found in form of team interactions and the designer’s interactions with the users, clients, and other stakeholders. Among these researchers, Crismond and Adams describe informed design practices and misuses of design by synthesizing studies of expert and novice designers. Hence, it is not simply that students follow a design process but also engage in informed and authentic design practices. According to Crismond and Adams (Crismond, 2013; Crismond et al., 2013; Crismond & Adams, 2012), beginning designers:

- start building first before understanding the challenge, and rather than gathering information to scope the problems, they make premature decisions.
- develop only one or few solutions and fixate on a solution early on without considering alternatives and fully weighing trade-offs.
- draw or build superficial models and prototypes that are not testable and do not lend themselves to investigation.
- skip research, run few experiments, and when they do they conduct confounded experiments changing multiple variables at once with unfocused diagnostics.
- have difficulty evaluating alternative solutions and articulating design decisions, they make decisions without weighting benefits and trade-offs based on multiple confounded criteria

At the core of these design mishabits is the belief that design problems are well-defined problems with a correct answer and lack of reflective, iterative design practices. Design problems are typically ill-defined and hence involve: a need for problem framing, ambiguity in the process, a possibility of multiple solutions, and complexity in solution evaluation (Crismond & Adams, 2012; Jonassen, Strobel, & Lee, 2006). Similarly, studies of first-year engineering students show variations in student comfort with ill-defined problems (Dringenberg, 2015). In Dringenberg’s study, students who were not conformable with ill-structured problems wanted to eliminate ambiguity and relied on the perspectives of the individuals external to the team (i.e. the course instructor). Students with more advanced understandings embraced ambiguity and internalized multiple perspectives within their teams and external to their team as part of their personal growth. As the framework argues, three-dimensional learning needs to promote such mature views and practices necessary to solve ill-defined problems.

When it comes to the assessment of student understanding of the design practices, researchers have typically used think-aloud protocols. A series of renown design-think-aloud studies were conducted to compare practices of engineering students with the practices of design experts (Atman et al., 2007). Examples of think-aloud research is also evident in K-12 settings but these typically involve an approach along with an assessment protocol (Alemdar, Lingle, Wind, & Moore, 2017; Hsu et al., 2012). Repeatedly these studies indicate that problem scoping and information gathering are major weaknesses of students. They suggest educators can help students review and discuss differences in expert designer's approaches to design as compared to novice designers' processes and reflect on their own design processes. The literature also includes a number of design process models educators have adopted as part of curriculum (See Figure 2). These models should be used carefully to reflect diversity in the processes and the importance of iteration and reflection.



Engineering is Elementary ("Engineering is Elementary," n.d.)

PictureSTEM ("PictureSTEM," n.d.)

Engineer Your World ("Engineer Your World," n.d.)

Figure 2. Representations of engineering design process models in K-12 curricula

Engineering Design as a Core Disciplinary Idea

The Framework outlines two disciplinary core ideas associated with engineering and technology. ETS1, engineering design, articulates the disciplinary core idea as "specialized knowledge about criteria and constraints, modeling and analysis, and optimization and trade-offs" (NRC, 2012, p. 204). ETS2 focuses on the knowledge of the links among engineering, technology, science, and society. The relationship between engineering, technology, science, and society have been historically examined as part of science, technology, society (STS) education (Bell & Lederman, 2003; Pedretti, 1999; Sadler, 2004; Sadler & Zeidler, 2005). What is less studied is ways students develop understanding of the value and meaning of specialized knowledge about engineering design. Hence, in this paper, I focus on the synthesis of the literature on ETS1.

The studies that frame engineering as a disciplinary core idea would examine students' and teachers' conceptions of design and engineering. Hence, these studies ask: Do students understand how engineering problems are defined and delimited? Do students understand how prototypes and mathematical models are used to develop, test, and refine alternative solutions? Do students understand optimization and trade-offs? Do students understand the purpose of specialized tools and methods necessary to make decisions and optimize design solutions? To what extent are teachers familiar with these core ideas? The following sections, organized by disciplinary core ideas, discuss prior studies that has addressed these questions with regards to aspects of engineering design as a disciplinary core idea.

Defining and Delimiting an Engineering Problem

In particular, prior research agrees that student have difficulties in understanding criteria and constraints, which are aspects of defining and delimiting problems. Hsu and colleagues examined elementary students' understanding of design by asking students to evaluate the design process of a cartoon character. Their study showed that while students were familiar with the importance of building and re-designing, even before formal engineering education, they did not recognize the importance of asking questions and the need to understand the problem (Hsu et al., 2012). Similarly, Hudson and colleagues found middle school teachers had difficulty with disciplinary core ideas of design, especially defining criteria and constraints. However, among high school students, Berland et al (2014) found that students understood the importance of problem definition as well as generating multiple solutions (Berland, Steingut, & Ko, 2014).

Recognizing the importance of understanding and scoping a problem before developing solutions is an area that differentiates experts from novice designers (Atman et al., 2007) and an area of challenge even for undergraduate students. Yet, there is research evidence that students can engage in problem scoping when presented with challenges that are meaningful. Watkins, Spenser, and Hammer (2014) found that when given opportunities, fourth grade students were able to engage in rich problem scoping including prioritizing criteria (Watkins, Spencer, & Hammer, 2014). In another study, McCormick and Hammer (2014) used book characters as users. They found that elementary students were able to attend to and articulate their fictional clients' needs (McCormick & Hammer, 2016). However, the authors also observed instances where the students focused on the teacher and what the teacher would like to see. Similar patterns exist among undergraduate students as well where students sought input and direction from the instructor (Dringenberg, 2015). Student problem scoping is best facilitated in projects with real clients (Svihla & Reeve, 2016).

Developing Possible Solutions

In engineering, modeling and analysis are especially important. Engineering models support negotiation and decisions and are critical components of the technical discourse (Dannels, 2009; Dannels & Martin, 2008; Darling & Dannels, 2003). According to Wendell (2017), engineers frequently interact with the manipulation of physical materials and symbolic representations while communicating with a range of linguistic modes that are oral, written, and schematic (Aurigemma, Chandrasekharan, Nersessian, & Newstetter, 2013; Johri, Roth, & Olds, 2013). In fact, prototypes and models are more than representations; they support engineering designers in communicating, reasoning and decision-making with special tools and vocabularies as part of a shared practice (Kittleson & Southerland, 2004). Prototypes serve different purposes such as, allowing the designer to visualize elements of a solution, conduct tests to evaluate the performance of a solution, build on and develop additional solutions, and communicate a solution to others.

When developing solutions and prototyping, students may be more concerned about form and physical appearance as opposed to function and structure (Hmelo et al., 2000). Curriculum needs to limit focus on physical appearance of prototypes (Hmelo et al., 2000) or the design performance (Apedoe & Schunn, 2013; González, Alegría, Barraza, & Villalobos, 2011) and rather should focus on the use and articulations of the design features specific to the design task, elaboration and justification. Svarovsky (2011) presents how engineering knowledge can be assessed by examining students' use of technical and professional vocabulary in their discourse and descriptions of their solutions with respect client needs (Svarovsky, 2011). Virtual prototypes also play an important role is supporting core disciplinary ideas. Chao and colleagues studied secondary school students' development of design prototypes using a computer-aided design software called, Energy3D ("Energy3D," n.d.). Chao and colleagues' study shows that representation, analysis, reflection relate to gains in student learning and that design tools such as computer-aided design software with data simulation capabilities are critical in engaging student simultaneously in design and scientific practices (Chao et al., 2017). They argue that design tools shape the knowledge development by integrating design and science practices (Chao et al., 2017) and hence support student understanding of disciplinary core ides in design.

Student also have challenges, especially at the elementary level, with data analysis and measurement (Glancy, Moore, Guzey, & Smith, 2017). Glancy and colleagues research with fifth grade students, in an integrated STEM unit, showed that students struggled in properly using measurement devices, associating quantitative data with the phenomenon being measured, and interpreting the significance of variation and error in the data they collected. Similarly, Berland and colleagues argue that high school students engaging in design have a better understanding of qualitative aspects of design such as data from interviewing with the user than the quantitative aspects of design (Berland et al., 2014). However, they find that students had difficulties in mathematically modeling and systematically comparing their design solutions. In other studies, student challenges depended on familiarity. Valtora and Berland conducted a discourse analysis, of high school students, who successfully applied mathematics and science concepts to their engineering design work when the concepts were familiar (Valtorta & Berland, 2015). However, when the concepts were not familiar to the students, explicit teacher prompting was necessary.

In authentic projects with a real client, it is likely that the performance of the design solution would depend on informed design practices. However, caution must be taken so the focus of a project is not solely delivering a prototype or an artifact. For example, Mentzer compared high students' design solutions when they had Internet access and information gathering with students who did not have access to internet. Students' solution quality did not differ based on time spent on information gathering in a playground design challenge (Mentzer, Huffman, & Thayer, 2014). Hence, simply having access to information was not sufficient. It is the arguments and the incorporation of user needs that determine the quality of a solution-- not simply its feasibility. Fortus and colleagues (2004), for example, evaluate early and late models as a way to judge student learning through prototypes (Fortus et al., 2004).

Optimizing the Design Solution

In the practice of engineering, optimization is an important and a challenging concept (Kelley, 2010). However, there are examples of studies that illustrate that elementary school children can engage in optimization (Purzer, Duncan-Wiles, & Strobel, 2013). Goldstein and others have examined students conceptions of "making trade-offs" in design by examining students' prioritization and re-prioritization of design strategies after undertaking a design activity (Goldstein, Purzer, Zielinski, & Adams, 2015; Purzer, Goldstein, Adams, Xie, & Nourian, 2015). They administered a survey, Conceptions of Design Test (CDT) as a pre- and post-test assessment in three middle schools with over 700 students. Results suggest that after a design activity, "balancing trade-offs" became a statistically more important concept to students, but that students still did not have a sophisticated understanding of the term suggesting the design terminology needs to be explicitly taught in the classroom.

Another approach to supporting student understanding of optimization is provided by Purzer, Duncan and Strobel (2013) suggesting students' ability to engage in optimization and trade-offs can be supported by presenting challenges with two competing criteria such as cost and effectiveness supported by repeated cycles of iteration. With a modified version of the egg-drop challenge with a simulated client, they promote student understanding of optimization by using metacognitive prompts. As one student writes, "I am thinking that our project was successful but our cost was too high. ... Our cost was 5× higher than the other highest costing project… To change, we for sure, will lower the cost by using fewer materials"(p. 38). In this example, through iterative, focused testing and diagnostics, students determined what to improve and redesigned focusing on improving effectiveness, redesigned in an effort to reduce cost, or attempted to improve both. The use of specialized tools such as weighted-decision matrix and pros/cons evaluations, can also make design trade-off decisions explicit and engage students in the understanding of optimization. Moreover, Purzer and colleagues examined students' design moves and written reflections and found that high school students made explicit connections to science concepts when engaged in trade-off decisions (Purzer et al., 2015).

Three-dimensional Learning Necessitates Authentic Design Projects, Students as Reflective Designers, and Teachers as Design Coaches

Characteristics of Authentic Design projects

In the practice of engineering design in elementary and secondary classrooms, educators have taken variety of approaches, which vary based on their authenticity. Among the most traditional ones are the build-test challenges such as building a catapult to move an object from one table to another, building the tallest tower with pasta and marshmallows, and building bridges that can hold the highest load. Even the earlier National Science Education Standards include the infamous egg-drop design challenge, prompting students to design "a container for an egg so that the egg would drop 15 feet and not break" (NRC, 1996)(p.163). These challenges promote engineering design but often as a linear process with test-and-trial cycles. In these type of problems, solutions are limited and often obvious, problems are well-scripted, and criteria are straightforward. On the other side of the spectrum, there are practices of design in classrooms where challenges are presented to the students by a real client, problems have multiple dimensions not only including technical and scientific requirements but also economic, environmental, and social constraints, and there are variety of solutions students can explore (Goldstein, Loy & Purzer, 2017). These type of design projects promote engineering practices that value user needs and client wants, the importance of justifying design decisions with technical evidence and experiments, and complexity of solving problems with technical, social, economic, environmental constraints and implications. In between these two examples of teaching practices, there are examples of projects, which utilizes simulated clients, giving the students the opportunity to explore the needs of a user (Moore et al., 2015; Moore, Guzey, & Brown, 2014).

So which one of these methods promote three-dimensional learning? In a three-dimensional learning, students are immersed into practices of scientists and engineers, exploring and applying disciplinary core ideas, and with opportunities to make connections across areas of disciplinary content through cross-cutting concepts. Such deep engagement in scientific and design practices cannot be accomplished with build-test challenges. Three-dimensional learning requires and necessitates solving problems with authentic purposes and users that students either have access to or can relate to.

Authentic practices also support deeper student learning (Svihla, Petrosino, & Diller, 2012). For example, Mathis and colleagues found that argumentation was strongest when students presented their solutions to a client (Mathis, Siverling, Glancy, & Moore, 2017) . Similarly, Svarovsky's study further suggests that students build more sophisticated connections when they engage in activities that are client-focused work (Svarovsky, 2011). Authenticity also naturally integrates cross-disciplinary ideas such as systems and hence all parts of the three-dimensions of the framework. Goldstein and colleagues present a middle school design project that involves a real client and compare student learning outcomes to a structured, shorter version of the project implemented at a nearby school. They show evidence that student learning was evident in both school but the project with a real client resulted in higher learning gains (Goldstein, Omar, , Purzer, & Adams, in press). Moreover, the authors argue that there are many other aspects of learning in the authentic group, such as communication, that their analysis did not cover. Authentic experiences are also engaging especially for students who are at risk of losing interest in STEM (Hernandez et al., 2014). These experiences provide students with meaningful learning, while promoting value in science and engineering.

Alternative perspectives exist, however. For example, Chalbalengula and colleagues compared nine engineering programs, based on their coverage of science and engineering practices, offered to elementary, middle, and high schools (Chabalengula, 2017). They found variations in the practices arguing that , "in order for students to conduct investigations, analyze and interpret data or construct scientific explanations and design engineering solutions, there must be good science questions asked, and well defined engineering problems" (p. 319). Yet, engineering problems are inherently ill-defined. Moreover, the Framework calls for meaningful experiences that are authentic to scientific and engineering practices in the real world.

In summary, to promote three-dimensional learning, it is necessary for students to engage in challenges that are authentic or that simulate such authenticity. Such projects would:

- involve a user that the students can interact with or a user that they can relate to.
- present problems with a variety of possible solutions
- involve criteria and constraints that are not only technical (associated with a disciplinary core idea) but also address aspects such as economic, societal, or environmental.

Students as Reflective Designers

Reflective, collaborative decision-making is a critical part of engineering design (Daly, Adams, & Bodner, 2012). Similarly, in student design practices, reflective decision-making occurs repeatedly as well (Wendell, Wright, & Paugh, 2017). In their analysis of elementary student's discourse patterns Wendell and colleagues identified six elements of reflective decision-making that occurred when students were articulating alternative solutions, evaluating pros and cons of alternative solutions, intentionally selecting a solution, retelling the performance of a solution, analyzing a solution with evidence, and purposefully choosing improvements. In Wendell and colleagues' study, reflective decision-making practices among elementary students was evident even when the teacher was not experienced. In fact, reflective decision-making starts at early stages of design, while defining and scoping the problem and is promoted with discourse that is oral, written, and schematic.

There has been a number of studies of students discourse practices that illustrate that students engage in reflective design through oral discourse. According to Wilson and colleagues certain design and discourse practices are important for quality solutions (Wilson, Smith, & Householder, 2014). These include: 1) rereading, annotating, and sharing/summarizing understandings of the problem statement (defining problem); 2) prioritizing which aspects of the problem most need to be addressed (delimiting problems); 3) identifying gaps in information (reflecting) 4) using strategies such as asking questions, making inferences, and consulting different source types (gathering information); 5) keeping track of ideas generated (generating ideas); and 6) responding to feedback (reflective practice). These practices agree with the position of Crismond and Adams (2012) in their model of informed design practice. However, the classroom context play a role in both supporting and hindering effective discourse.

For example, competition for academic or social status with limited use of collaboration strategies impacted group decision-making dominated by overpowering members (Wendell, Wright, & Paugh, 2017). Unnoticed design failure, or unfocused diagnostics as Crismond and

Adams (2012) calls it, lead to poor evaluations when students are not attentive to design criteria and constraints in their discourse. Finally, Wendell and colleagues point to the importance of using specific, technical vocabulary as they illustrate student use of ambiguous pronouns such as "it" and "this" as they describe their design ideas.

Students also engage in reflective practice with schematics. When designing, students spend significant amount of their time modeling (i.e., building prototypes). During prototyping, they also focus highly on the performance of their solution. While in real world performance is important, engineers also expect failure as a critical part of the process especially when developing novel solutions for novel contexts they are exploring.

Students engage in reflective practice with writing too. Purzer examined instances where high school student made connections to science while designing by analyzing their written reflections (Purzer et al., 2015). They found a connection between students' trade-off decisions and science connections. Educators have also used engineering notebooks and design diaries to promote student reflection. These notebooks are typically structured focusing on specific stages of design such as problem scoping, experimentation, and testing (Kolodner, 2002). To promote reflective design practices (Schön, 1987), educators have implemented strategies for reflection on action and reflection in action. Reflection in action method is used as part of the in Energy3d software, which enables students to write reflections while designing ("Energy3D," n.d.). Reflection on action has been elicited with metacognitive prompts asking students to review test results and make decisions towards design revisions (Purzer et al., 2013). In other instructional practices, students are asked to write memos to clients (Mathis et al., 2016). As opposed to writing a research report, memos are addressed a client (Papadouris, 2012). By writing a memo, students communicate their solutions to an external person in writing, making their thinking visible.

With these multiple modes of communication, Nathan et al (2013) argue for the importance of cohesion of central concepts in engineering across a range of representations, activities, and social structures necessary for the seamless integration of science and engineering (Nathan et al., 2013). In addition, it is important to cover in these modes of engagement that critical features of engineering design include both quantitative predictive elements, (mathematical rigor) and qualitative elements (descriptions of functions and concern for stakeholder needs) (Asunda & Hill, 2007).

Teacher as Design Coaches

Supporting student learning in three-dimensional learning puts additional demands on teachers in multiple ways. First, many teachers do not have formal training on three-dimensional teaching and the integration of engineering and science (Yaşar, Baker, & Robinson-Kurpius, 2006). Another issue is that the three-dimensional approach require a different type of teaching including monitoring, guiding student ideas, dealing with unanticipated directions students take, and parsing out creative ideas from those that are off. In the design literature, this type of a teaching role is called design coaching (Adams & Siddiqui, 2015). Associating the role of the

teacher with the role of a coach, this paper argues that we must support teachers as design coaches.

Adams and colleagues studied coaching behaviors of experienced design educators in multiple design disciplines including engineering and industrial design. They reviewed video recordings of design review and critique sessions. Their analysis showed that design coaches engaged in four common ways of coaching. First, design coaches elicited student articulation by directing the learners' attention to discussing aspects of their design solutions and plans and to expressing their reasoning. Second, when necessary design coaches took control of the review to help students make conceptual connections and recognize their design fallacies. Third, they created teaching moments by conveying explicit knowledge associated with design habits and strategies. And finally, at times the coaches let the students "figure out" their own results by suggesting that they test and see the outcomes themselves to reflect on (Adams, Forin, Chua, & Radcliffe, 2016).

Design coaching as an approach is associated with an epistemological beliefs about design that is iterative and reflective. Before engaging teachers in three-dimensional teaching, we must elicit their epistemological beliefs about engineering and science and understand how these beliefs can be reflected in their teaching practices. Encompassing the social and creative aspects of engineering, Cunningham and Kelley (2017) describe four practices of engineering (Cunningham & Kelly, 2017b). According to their synthesis, engineering, 1) occurs in a social context as engineering is done with people and by people, 2) uses data and evidence to make decisions, 3) uses specialized tools and strategies for problem solving, and 4) develops solutions through creativity and innovation. For example, an aspect of evidence-based decision-making and creativity in engineering design is that failure expected. In fact, in engineering failure is modeled and anticipated.

Teachers' knowledge and beliefs about engineering may be at odds with the disciplinary practices. Lottero-Perdue and Parry (2017) found with a study of more than 250 elementary school teachers, that failure had a negative connotation and that the terms mistake and failure were considered anonymous (Lottero-Perdue & Parry, 2017). They argue that, while in educational settings, failure refer to errors such as making a mathematical miscalculations, in engineering design failure is an intentional part of testing, gathering feedback, and innovating. In another study, Sengupta-Irving &Mercado (2017) presents result of a seminar offered to secondary science, mathematics, engineering, and technology teachers (Sengupta-Irving & Mercado, 2017). They found changes in teachers' perceptions of engineering as teachers redefined failure as an important part of science and engineering. Throughout the seminar, teachers also recognized the economic and business aspects of engineering. However, these same group of teacher also communicated science and engineering in ways that reflected misrepresentations of both disciplines. For example, teachers described engineering as creative and non-algorithmic and science as cookbook-like and certain. In an effort to integrate science and engineering through three-dimensional learning, educators often approach the discussion as "science versus engineering" as opposed to "science and engineering." However, this approach for differentiation create the challenge of deciding which practices to focus on-- science or engineering? The practices and values that are common to both disciplines must be emphasized for a smooth integration and cohesion. For example, representations (e.g., sketching, graphing), discourse, evidence-based reasoning, and creativity are critical practices in both science and engineering (Johri et al, 2013; Wilson et al, 2014).

Sengupta-Irving &Mercado (2017) also found that teachers described the students who are successful in science to be high achieving, perfectionists, and bright, while describing students successful in engineering to be low achieving, hardworking, but not ‘‘book smart’’(Sengupta-Irving & Mercado, 2017). Other studies also show implicit biases of teachers towards students with low socio-economic status with regards to enrollment in science and engineering courses (Nathan, Atwood, Prevost, Phelps, & Tran, 2011). Sengupta-Irving and Mercado warn educators that these misconceptions can cause problems in two distinct ways. First, these misconceptions impact student understanding of the disciplines and must be challenged. Second, and more importantly, these are potential threats to equity with implications for who achieves in science or engineering. Hence, the issue of teacher beliefs must be examined up front.

Another challenge for teachers is managing the demands of authentic design while promoting student learning. At times teacher expectations for classroom management might interfere with design practices when students are expected to follow norms of classroom management and avoid risk in disturbing team. Johnson, Wendell, and Watkins (2017) argue that a “responsive approach to teaching” is necessary through which teachers attend to student thinking and adopt their instructional plans. In their study with interviews of teachers with at least two years of experience with Novel Engineering, teachers noticed their students in framing and interpreting the design problem, engaging with the engineering design process, exhibiting informed design behaviors, and communicating in diverse ways. The authors also report challenges faced by the teachers. Less experienced teachers focused more on social dynamics in student teams and students’ engineering solutions as opposed to student thinking (McCormick, Wendell, & O’Connell, 2014; Moore et al., 2015).

Three-dimensional learning requires teachers to adopt teaching approaches so they can notice student thinking, respond to student thinking, and adapt approaches as student thinking evolves. Responsive teaching is a foundation for design coaching. The design projects provided a rich learning environment. In such settings, the teacher can notice many things that are cognitive, interpersonal, and emotional such as student decision-making, use of academic language, misconceptions about science concepts, gender dynamics, collaboration, emotion, etc. Dalvi and Wendell used student videos capturing their work, talk, and interactions and compared noticing and responding behaviors or pre-service elementary teachers, engineers, and STEM educators. They found that all three groups had similar responding patterns (i.e., suggestions what teachers can do) (Dalvi & Wendell, 2017). However, pre-service elementary teachers were weaker in noticing students’ science ideas and engineering practices compared to engineers and STEM educators. They suggest that teachers need practice developing competencies in responsive teaching, so they can elicit student thinking, notices and interprets student thinking, and responds.

Three-dimensional teaching as a practice is new to teachers, but the development of new pedagogical content knowledge can be anchored on practices that excel in. Judson and colleagues analyzed middle school teacher lesson plans and found teachers were more comfortable writing lesson focusing on data analysis and design comparisons than those focusing on problem scoping including defining design criteria and constraints (Judson, Ernzen, Krause, Middleton, & Culbertson, 2016). Similarly, Wendell’s study with preservice elementary teachers showed that when engaged in design, pre-service teachers were comfortable in idea generation and feasibility analysis of potential solutions. However, these pre-service teachers engaged in little problem scoping, information gathering, modeling their design solutions, and testing design solutions (Wendell, 2014). Teacher education and professional development efforts can anchor on teachers' initial strengths and gradually build on competencies in areas that need deeper attention.

Challenges in teacher professional development associated with curricular resource are noted in the literature (Daugherty & Custer, 2012; Reid & Feldhaus, 2007). Daugherty and Custer studied professional development in secondary school education and found a heavy focus on process (practices) rather than content, mainly due to unclarity on core ideas for secondary level engineering. They also found heavy emphasis on modeling and prototyping at the expense of reflection and analysis.

In response to these challenges, Baker and colleagues provide strategies that supported teacher change in their teaching practices. These include: sharing successes and failures in their first implementations, discussing possible changes, receiving feedback, and reading and discussing research on the infusing of engineering in the classroom (Baker, Yasar-Purzer, Kurpius, Krause, & Roberts, 2007). A focus on technical and tinkering self-efficacy especially among female teachers is important (Baker et al., 2007). Similar to the design process, which is iterate, reflective, and comfortable with failure, teacher practices need to value that a change towards three-dimensional teaching require iteration, reflection, and planning for failure along the way.

Conclusions

With a focus on three-dimensional learning, K-12 students have the opportunity to engage in authentic problems, develop abilities to make evidence-based decisions, develop competencies and confidence in problem-solving, and see value of science and engineering in relationship to their everyday life. Meeting the promise of the Framework might seem challenging. Yet, studies show even at early ages children have intuitive abilities to design (Hsu et al., 2012). However, three issues needs to be addressed for success in implementing the vision of the Framework in the classroom.

First, educators must recognize that engineering design is used in multiple means in practice and in the Framework: as a pedagogy, disciplinary practice, and a disciplinary core idea. The comparison of these three conceptualizations of design is necessary to clarify practices and ideas as well as the appropriate methods for teaching them. Second, students need experiences with authentic design in the classroom through curricula and design projects so they can develop informed design practices and become reflective decision-makers. Finally, teacher education and the need to address teacher beliefs along with pedagogical content knowledge must be addressed. Teachers must be supported in developing competencies as design coaches in the classroom with abilities to elicit, notice, and respond to student thinking as well as students' social and emotional needs.

In summary, this paper argues that realizing the vision of the Framework requires a clear understanding of its dimensions, a strive for authenticity, and the development of students as reflective decision-makers and teachers as design coaches. In classrooms where students have the opportunity to experience authentic scientific investigations and engineering design, students and teachers take roles that are more than receiving and conveying information. In three-dimensional learning settings, students act as designers and reflective decision-makers and teachers act as design coaches.

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