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Designing for STEM Integration

Abstract

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Keywords

curriculum design

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Designing for STEM Integration

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Abstract

We are increasingly seeing an emphasis on STEM integration in high school classrooms such that students will learn and apply relevant math and science content while simultaneously developing engineering habits of mind. However, research in both science education and engineering education suggests that this goal of truly integrating STEM is rife with challenges. As such, this paper reports upon the efforts of an NSF-funded project to translate the lessons learned in science classrooms—in which the science learning goals are contextualized within engineering challenges—to engineering classrooms—in which the engineering practices are an additional, and important, learning goal. In particular, this paper identifies design principles for facilitating student application of math and science concepts while they engage in the practices of engineering. We explain the intent and learning theories behind each principle. In addition, we reify each goal by illustrating its application in our yearlong engineering course.

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Engineering education is increasingly appearing in high schools—as both stand-alone courses and as components of science, mathematics, and career-tech courses. In all contexts, engineering modules are tasked with multiple goals. In particular, as synthesized in the National Academies (National Academy of Engineering & National Research Council, 2009) review of K-12 engineering education, it is expected that engineering education will: (1) focus on design and problem solving; (2) incorporate appropriate science, technology, engineering, and mathematics (STEM) concepts; and (3) “promote engineering habits of mind.” A similar trend is seen in the recent framework for K-12 science education standards (National Research Council, 2011). As such, we see that K-12 classrooms are increasingly asked to integrate STEM learning goals by contextualizing student work in science, math, and engineering around engineering design challenges. Science education has demonstrated the efficacy of design challenges that contextualize student exploration and learning of science and math concepts (Fortus, Dershimer, Krajcik, Marx & Mamlok-Naaman, 2004; Kanter, 2010; Kolodner et al., 2003). However, this work occurs in the context of science classrooms in which the goal is learning the science and not “promoting engineering habits of mind” or engaging students in the practices of engineering. Moreover, the different goals of science and engineering—from understanding how or why a natural phenomenon occurs to fulfilling a design specification—can result in significant challenges when students move between them (e.g., Crismond, 2001; Leonard, 2005; Schauble, Klopfer & Raghavan, 1991). For example, Berland and Busch (2012) explore how students use science when focused on solving an engineering design challenge. In this case, the students touched upon the science concepts without exploring them in-depth, possibly because they were able to design and build the specified product successfully without developing an in-depth understanding of the relevant science concepts. This work suggests that the goal of truly integrating STEM is challenging.

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Moreover, work like Project Lead the Way and Infinity Project, which have extensive pre-collegiate engineering curricula, have little research regarding “how, or if, these curricula help students develop the ‘habits of mind’ that the NAE identifies ...” (Chandler, Fontenot & Tate, 2011, p. 44). In fact, one of the major recommendations emerging out of the National Academies synthesis of K-12 engineering education was a call for increased focus on and clarity about the integration of engineering, math, science, and technology education (National Academy of Engineering & National Research Council, 2009). Thus, we see that little is known about how to develop a curriculum that successfully integrates STEM content by using engineering challenges to contextualize student application of relevant math and science content, while simultaneously developing engineering habits of mind.

This paper reports upon the efforts of an NSF-funded project to translate the lessons learned in science classrooms—in which the science learning goals are contextualized within engineering challenges—to engineering classrooms—in which the engineering practices are an additional, and important, learning goal. In particular, this paper identifies instructional design principles for facilitating student engagement with engineering, math, and science learning goals. These instructional design principles were developed as part of the UTeach*Engineering* team’s effort to develop a yearlong high school engineering course: *Engineer Your World*. The course is designed to work in a range of public and private high schools, as an upper-level (junior or senior) elective or a science course. The team that designed this course consists of university engineering faculty, clinical engineering faculty (professionals with experience as both practicing engineers and secondary classroom teachers), engineering research fellows, and learning sciences faculty.

Instructional Design Principles

In the following sections we discuss the instructional design principles guiding our curricular work. The instructional design principles represent a synthesis and translation of best practices found in the science education and learning sciences literature. They include:

1. Contextualize all student work within STEM-design challenges.
2. Specify specific course and unit learning goals.
3. Employ a standardized engineering design process as an instructional framework.
4. Engage students in sensible forms of engineering practices from day one.
5. Ensure that all science and math concepts, and technology tools employed are necessary for students’ successful completion of the STEM-design projects.
6. Attend to the constraints of high school and school district systems.

In this paper, we explain the intent and learning theories behind each principle. In addition, we reify each goal by illustrating its application in our yearlong engineering course. We begin by briefly describing the curriculum we designed following these principles.

Curriculum

This paper reports on the instructional design principles guiding our redesign of *Engineer Your World*. The redesign effort focused on two goals: (1) ensuring that the course be usable in a wide range of public high schools that have a range of resources, class schedules and sizes, and student interests, and (2) translating and applying design strategies found in the science education and learning sciences work. To accomplish the first goal, in consultation with stakeholders (i.e., teachers and administrators from local districts), we identified the following criteria that guided our curriculum development:

- The course must be affordable.
- The course should start with an engaging, short unit that will pique interest without teaching substantial content as the course roster is not stable at the beginning of the year.
- Lessons should allow for, but not require, teachers to review (and possibly teach) prerequisite math and science content knowledge.
- The course should accommodate a variety of physical and technological configurations (i.e., cross platform technology, activities that can be done with or without daily access to computers, etc.)
- The course should fit a variety of class sizes.
- The course materials should be available electronically.
- The materials should support teachers with a range of backgrounds—they should not assume expertise in engineering or higher-level math and science.

In addition, the stakeholders suggested that the course needed to be flexible such so teachers could adapt the course to fit particular student needs and interests while ensuring that students would be introduced to and engage with the necessary engineering practices. To that end we developed a course framework that supports modularity and teacher flexibility (see Figure 1). This framework identifies the key objectives that each unit is expected to introduce such that experienced teachers can design completely new units to use in place of a provided unit. That is, the framework helps teachers and designers determine which learning objectives they must focus on if they revise an existing unit or design a new one.

In this paper, we exemplify the instructional design principles by describing their use in the second unit in the course—the *Pinholes to Pixels* unit. As seen in Figure 1, this unit is expected to introduce many of the central

Unit Number	1	2	3	4	5	6
Engineering's Societal Impacts						
Greatest Achievements		o	o	o	●	o
Grand Challenges		o	o	o	o	●
Innovation and design evolution		●	o	o	o	o
The Practice of Engineering						
Engineering disciplines and careers		o	o	o	o	o
Engineering ethics and codes of practice		o	o	●	o	o
Safety considerations		o	o	o	o	●
Engineering standards and regulations		o	●	o	o	o
Legal aspects		o	o	o	o	●
The engineering design process						
The engineering design process		■	x	x	x	x
Design approaches (e.g., new design, design modification, redesign)		■	■	x	x	■
Systems thinking						
System context and top-down perspective		~	~	■	x	~
System decomposition		~	~	■	x	~
Activity diagram/concept of operations		~	~	■	x	■
Functional models		~	~	■	x	■
Systems Understanding & Quantification						
Requirements, customer needs, constraints		■	x	x	x	■
Instrumentation and experimentation		~	■	x	x	x
Using data to develop performance targets		~	■	x	x	x
Creativity						
Techniques for concept generation		■		x	x	x
Techniques for concept selection		~	~	■	x	x
Verification						
Design embodiment		■	x	x	x	x
Verifying performance		■	x	x	x	x
Communication						
Engineering notebooks (individual and team)	■	■	x	■	x	x
Formal documentation		■	x	x	x	x
Collaboration						
Teamwork	■	x	x	■	x	x
Common engineering tools and techniques						
Project management techniques	~	~	~	■	x	~
Risk analysis techniques	~	~	~	■	x	~
Software and technology tools	~	~	~	~	~	~
Application of math/science knowledge	~	~	~	~	~	~

● **Concept addressed in depth (unit project)** o- **Concept woven in as appropriate**
 ■ **Skill (or variant) first introduced** x – **Skill reinforced**
 ~ **Tool or skill introduced as needed for challenge (not scaffolded)**

Figure 1. Scaffolded course framework.

engineering practices including the engineering design process, data collection for verification, and maintaining an engineering notebook.

In the *Pinholes to Pixels* unit, students design and build a pinhole camera that will take a picture of a particular object. It is assumed that students entering the course have: (1) algebraic skills necessary to find slope and use

equations for lines; (2) geometry skills for using a coordinate grid and working with similar triangles; and (3) physics knowledge of light reflection and that light travels in straight lines. While these concepts are considered pre-requisite knowledge, the concepts are reviewed, as necessary, throughout the unit. The unit consists of 10 lessons that are taught over the course of 6–8

weeks. The lessons were organized into lesson sets grouping together broader learning goals; these lesson sets are described in greater detail in Table 1.

Pinholes to Pixels begins with student exploration of a camera obscura—a large, light-tight chamber (e.g., a cardboard box) with a tiny hole on one side through which outside light shines to project a miniature, upside-down, color image of the exterior scene. This technology led to early cameras (similar to the pinhole cameras students create in this unit). Figure 2 illustrates this functionality.

After exploring this technology, students are introduced to their challenge of recording an image for posterity. Over the course of this unit, students in the engineering course: identify particular needs that their pinhole cameras must fulfill; brainstorm possible designs; develop a mathematical model of the relationships between the camera size, aperture size, target object size, and distance between camera and target object; and build, test, and refine their cameras.

Design Principle 1: Contextualize all student work within STEM-design challenges

There exists a growing movement in both collegiate and pre-collegiate engineering education to contextualize student exploration of engineering, math, and science concepts within a challenge—to implement Challenge-Based Instruction (e.g., Cordray, Harris & Klein, 2009). When reviewing the literature we identified three different types

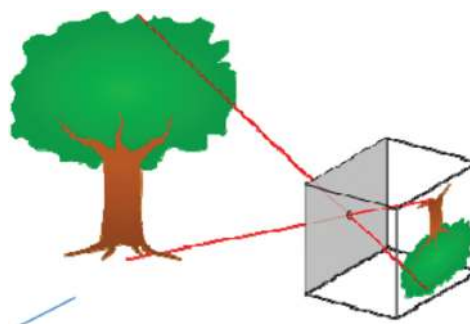


Figure 2. Functionality of the camera obscura.

of challenges used within the Challenge-Based Instructional model (Berland & McKenna, 2012):

- Problem-based challenges in which students are posed problems that can only be solved through the application of novel concepts. Problem-based challenges focus students on traditional, complex science and math questions that do not require design (e.g., Cordray et al., 2009; Klein & Harris, 2007; Linsenmeier, Harris & Olds, 2002; Martin, Rivale & Diller, 2007)
- Engineering design-based challenges which focus on engaging students in the design work of engineers such that the science and math concepts that underlie the challenge are not the primary focus; clearly students must work with those concepts in order to

Table 1
Unit Plan for *From Pinholes to Pixels*

Lesson Set 1: Understanding and Characterizing (3–5 days)	
Description	Lessons
The students are introduced to the topic from the scientific viewpoint to understand how science and technology exist in parallel with the evolution of societal needs and that engineers are the people who apply scientific knowledge to solve societal needs.	1. We need Engineers and Engineers Need Us 2. Describing the Need 3. Characterize and Analyze the System
Lesson Set 2: Creating and Selecting a Concept (3 days)	
Description	Lessons
The students use design requirements and customer needs information to create and select a design. The goal is to model the decision making process as a structured, purposeful process rather than choices due to personal preferences.	4. Generating Concepts 5. Selecting the Concept
Lesson Set 3: Building, Verifying and Refining (6–10 days)	
Description	Lessons
Students build and use their cameras, evaluating the success based upon how they met the design requirements. The emphasis of this set of activities is the plan to measure and test for those requirements.	6. Embody the Concept 7. Test, Evaluate and Refine 8. Finalize and Share the Design
Lesson Set 4: Evolving Over Time (2 days)	
Description	Lessons
Students set their work in the larger context of current technology by completing a parallel activity involving research on the grand achievement of imagery. Students also reflect on their learning.	9. Historical Timeline Presentations 10. Reflect on the Engineering Design Process

complete a design challenge, but this is not an instructional focus (e.g., Hirsch et al., 2001; Project Lead the Way, n.d.; Tate, Chandler, Fontenot, & Talkmitt, 2010).

- STEM-design challenges in which students are posed a design challenge that can only be completed when relevant math and science concepts are applied. These concepts are seen as learning goals in STEM-design challenges (e.g., Coyle, Jamieson & Sommers, 1997; Fortus et al., 2004; Kanter, 2010; Kolodner et al., 2003).

While each of these challenge-types overlap significantly in practice, they place different emphases on the various learning goals. That is, problem-based challenges typically emphasize science and math learning goals, while design-based challenges foreground engineering goals and STEM-design challenges are targeting both.

In keeping with the goal of creating opportunities for students to employ both engineering practices and science/math concepts while engaged in design work, the curriculum development team chose to focus on STEM-design challenges. This decision reflects our commitment to enabling students to apply relevant math and science concepts while engaging in core engineering practices.

By organizing units around STEM-design challenges, we are indicating that all challenges will require students to design a product and purposefully apply relevant math and science concepts. The outcome of the students' design work can vary according to the engineering domain being emphasized in each unit. For example, across the units in this course students are engaging in paper-design, design, and production of the requested product (as they are in the *Pinholes to Pixels* unit), design and creation of a model, and process design.

In selecting the particular design challenges used in the unit, we attend to four criteria:

1. The challenge must have multiple plausible solutions so as to create opportunities for students to solve the problems creatively rather than to execute their teacher's plan.
2. The challenge will require students to consider the problem from multiple engineering disciplines and, throughout the course, different challenges will emphasize different disciplines. This will ensure that students experience the interdisciplinary nature of engineering and will introduce students to a range of possible foci for their professional trajectory.
3. The challenge must address a societal need as this has been shown to attract individuals from populations that are typically underrepresented in engineering (Busch-Vishniac, 2004).
4. The challenge will directly draw upon math and or science concepts such that students have an opportunity to apply domain specific knowledge to their engineering design work.

In the *Pinholes to Pixels* unit, *all* student work and discussions are focused on understanding, designing, and building a pinhole camera to customer specifications. This means that the students are constantly engaged in solving the STEM-design challenge, and there are no extraneous assignments or lectures. This particular challenge has many points at which students will be able to design a solution creatively rather than drive towards a single answer. For example, the material used to construct the camera can vary from group to group, as can their strategies for aiming the camera and loading the film without exposing it to unwanted light. In addition, this topic explicitly connects to mechanical and chemical engineering, and is introduced as a historical solution to the societal need of capturing images for posterity. Finally, we designed the challenge to facilitate student exploration of particular science and math concepts, as described in several of the remaining principles.

Design Principle 2: Specify Specific Course and Unit Learning Goals

As described by Wiggins and McTighe (1998), curriculum development frequently reflects one of two possible problems: “aimless coverage of content, [or] isolated activities that are merely engaging (at best)” (p. 56). In neither case are students substantively engaging in knowledge construction. Thus, in developing *Engineer Your World*, we engaged in a learning-goals driven approach (Krajcik, McNeill & Reiser, 2008). That is, we worked to specify learning goals before designing specific lessons—so that we could ensure that the lessons would address those goals. This approach mirrors engineering practices of specifying a need before designing a solution and reflects a trend in education to engage in “backwards design” (Ainsworth, 2004; Wiggins & McTighe, 1998) in which goals and assessments are identified *before* lessons are designed.

Given that there existed no stable set of national standards for engineering courses at the time of the course development, the first step in our design process was to identify the objectives or “enduring understandings” (Wiggins & McTighe, 1998) we expected students in our course to develop. We developed the list of objectives by synthesizing national (National Academy of Engineering & National Research Council, 2009) and state (Texas Education Agency, 2011) policy documents, as well as the expertise of engineering professors on our team and criteria developed by the Accreditation Board for Engineering and Technology. These objectives include statements of the types of engineering practices in which we expected students in our course to engage, such as:

1. Information gathering (constraints, requirements, customer needs).
2. Creation of functional models, including input/output.
3. Data acquisition, analysis, and representation to develop performance targets.

4. Formal documentation.
5. Application of domain-specific math/science knowledge.

Note that we have provided a subset of the objectives here, to illustrate the types of objectives included in the curriculum. The complete list is beyond the scope of this paper and can be found in (Farmer, Allen, Berland, Crawford & Guerra, 2012).

In addition, a subset of the course objectives highlighted the concepts that are fundamental to engineering, such as:

1. Impacts of innovation on society.
2. Safety considerations with respect to the system, the engineer, and the user.
3. Legal aspects including intellectual property, patents, and trademarks.

Identifying these learning objectives was a key step in understanding the engineering practices on which this course would focus. However, as described in numerous documents about educating with a focus on state standards, objectives at this level lack the detail necessary to guide lesson development. In particular, these descriptions of practices and concepts do not provide a specific description of what it means to enact or understand them. Thus, we “unwrapped” (Ainsworth, 2004) the objectives into learning goals that describe the student actions that would be evidence of their growing understandings (Krajcik et al., 2008). For example, in the *Pinholes to Pixels* unit, objectives 1 and 2 above (that students would engage in information gathering and creation of functional models) were translated into three learning goals:

- 1a. Students describe why customer needs are important in the design process.
- 1b. Students create a list of customer needs and product features.
- 2a. Students use their mathematical models to determine the appropriate camera dimensions necessary to take a picture of a specified size and exposure.

We similarly translated the hoped-for engineering concepts into learning goals. For example, the expectation that students would explore the impact of engineering on society (goal 6, above) was reflected in the *Pinholes to Pixels* unit as the goal: “Students will connect changes in technology and society to the evolution of imagery and identify examples of innovation, new design and redesign.”

Note that while one course objective was for students to “apply domain-specific math/science knowledge” (goal 5, above), we did not further specify particular math and science learning objectives at the level of the yearlong course a priori, as we did with the engineering objectives. Instead, as each challenge was selected and designed, we identified the math and science content that the challenge built upon and created unit specific learning goals tied directly to that content. For example, students in the

Pinholes to Pixels unit are expected to “use their mathematical models to determine the appropriate camera dimensions necessary to take a picture of a specified size and exposure.” This approach of not specifying math and science objectives a priori means that the target math and science goals are tied to the challenges rather than identified at the outset of the course development. This reflects our focus on engineering—the course is designed to address pre-specified engineering objectives, but is flexible with respect to the particular math and science content addressed. In addition, it provides designers with the most flexibility with respect to identifying challenges that meet the criteria described in Design Principle #1 because they are not targeting specific math and science goals from the outset.

After identifying the learning goals for each unit, we developed the actual lessons and activities. As part of this process, we identified the student artifacts and activities that would serve as opportunities for teachers to assess each learning goal. For example, in *Pinholes to Pixels*, the identification of customer needs is assessed in Lesson 5 in which students identify potential customer needs and organize the customer’s requested functionality. This information is stored in the students’ engineering notebooks which guides the students’ design work and offers an assessment opportunity.

Design Principle 3: Employ a Standardized Engineering Design Process as an Instructional Framework

In addition to focusing all student work on fulfilling STEM-design challenges, we developed the units such that student work follows a standardized engineering design process (EDP). The intent behind this principle is similar to other Challenge-Based Instruction, in which students are supported in following particular work processes or cycles, such as the STAR-legacy cycle (Klein & Harris, 2007). This particularly well-tested and proven cycle is most frequently used in the service of addressing *problems* rather than *STEM-design challenges*. We therefore found that we needed to adapt the STAR-legacy cycle to reflect the process typically undertaken by engineers better.

To this end, the project team combined a benchmarking analysis of the EDPs used in existing engineering curriculum with the needs and expertise of this particular team to create the *Engineer Your World* EDP, depicted in Figure 3 (see Guerra, Allen, Berland, Crawford & Farmer, 2012 for additional information regarding the design of our EDP). As seen in Figure 3, our EDP identifies five “super-steps” (i.e., identify, describe, generate, embody and finalize). In addition, we identified the sub-steps within each of the super-steps (i.e., the super-step “describe” consists of describing the project need qualitatively as well as characterizing and analyzing the system more quantitatively). This organizational structure of super-steps and sub-steps enabled the team to highlight key points of

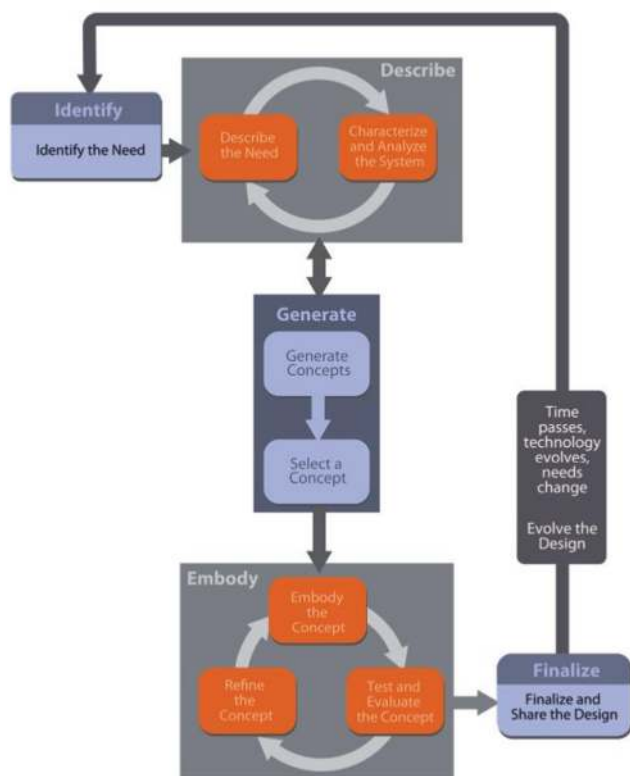


Figure 3. *Engineer Your World* Engineering Design Process.

iteration between steps of the EDP while still fulfilling the need for students to make progress in high school classrooms.

The commitment to use a standardized EDP—that is, one that is consistent across the yearlong course—is motivated by a desire to enable core engineering practices to become “ritualized” for the students. As Kolodner and colleagues (2003) describe in their work on middle-school students learning through design activities, ritualization means that each student activity—in our case, the phases of the EDP and the processes and artifacts that are associated with them—are defined in such a way that students and teacher would come to be able to engage in it effortlessly. In effect, ritualization makes the expectations for any activity clear and succinct (p. 513).

As such, this ritualization enables students to focus on the novel aspects of their work—the particular challenge and content at hand—rather than on the details of the engineering practice.

The other half of this instructional design principle, namely, the commitment to employ the EDP as an instructional framework, reflects the curriculum development team’s expectation that lessons be organized around the steps of the EDP such that all classroom work be contextualized within an EDP phase. That is, students are never researching, calculating, testing, brainstorming, building, or performing other activities unless these activities are in the service of the EDP. This specification

reemphasizes the expectation that all student work be contextualized within a design challenge—in this case, we expect that students and their teachers are consistently thinking of how their work fits within the EDP and, therefore, how it will help them complete their STEM-design challenge.

Our commitment to the second half of this instructional design principle manifests in that there is almost a one-to-one relationship between unit lessons and EDP phases. That is, the majority of lessons tackle a single step in the EDP. In addition, each major section of the EDP has particular processes that students follow, and artifacts that students learn to construct and use throughout their work in the course. As such, the decisions about what to do next, identification of the necessary artifacts, the ways in which these artifacts are used, and the information that should and can be communicated by these artifacts become background knowledge for the students—the artifacts and processes become a piece of the ritualized EDP. For example, during the concept generation phase of the *Pinholes to Pixels* unit, students are introduced to brainstorming techniques. Then, as students present their designs, the teacher records the criteria they used to make their design decisions in a decision matrix. The class then reflects on the utility of the particular brainstorming techniques they used and the decision matrix and, over the course of the following units, these strategies become ritualized tools that students use throughout future STEM-design challenges.

Design Principle 4: Engage Students in Sensible Forms of Engineering Practices From Day One

Engaging students in a standardized EDP such that they have ritualized the enactment of particular engineering practices can be dangerous. As seen with the typical enactment of “inquiry” approaches in science classrooms (i.e., providing students with a question and methods for answering that question, asking students to collect and analyze the data as they draw pre-determined conclusions), this standardization can quickly become a script that students perform without understanding the purpose of the practices (Windschitl, Thompson & Braaten, 2008). That is, the artifacts can become pseudotransactional (Berland & Hammer, 2011; Spinuzzi, 1996) or a “classroom game” (Lemke, 1990), such that the work is completed in the service of a grade, rather than a communicative and sense-making goal. We address this danger by ensuring that students engage in “meaningful” versions of these practices. In other words, the practices will be enacted only when and if the purpose of the practice—the ways in which it will help students fulfill their STEM-design challenge—has been communicated to the students. In this way, engagement in these practices becomes purposeful.

To illustrate this point, we note that early drafts of the *Pinholes to Pixels* unit required that students both (1) create

an activity diagram (i.e., a type of functional model representing the sequence of actions undertaken by a user, thereby focusing on what the product must accomplish rather than how it will do so) identifying all actions that the camera must perform and (2) list all of those actions in a table that identified questions related to each one. Reviews of this lesson and discussions with pilot teachers suggested that the two different artifacts provided the student-designers with the same information. As such, the curriculum design team determined that the combination of artifacts was redundant and that students were likely to perceive the second one (in this case, the table) as unnecessary—or without purpose. Redesigns of this lesson addressed this concern—and enacted the principle of meaningful student action—by combining the artifacts so that students continue to be provided the activity diagram and work to transform it into a useful table that will guide their design work.

This principle of engaging students in meaningful versions of the engineering practices is also apparent in how we introduce the EDP and associated processes and artifacts. The EDP is introduced in the *Pinholes to Pixels* unit, the second unit of this yearlong course. Rather than defining each step in the process and describing its associated artifacts before students engage in it, we create situations that enable students to recognize the importance of these steps and artifacts. In fact, the teacher names and defines EDP *after* students complete it for the first time. Thus, students experience the EDP as a process that is useful to their design work rather than as a process the teacher is asking them to follow. To that end, each lesson in the *Pinholes to Pixels* unit concludes with a note to the teachers reminding them to name the step they just completed and add it to the class's developing representation of this process:

At each step, we will be adding to the list of engineering design process steps. Have the class come up with a description of the step that was completed in this lesson, in their own words. Add this term to the list of design steps that you are creating on the wall in the classroom. Each time you add a new step review the entire process thus far (project course materials).

We have a similar approach to introducing processes and artifacts that engineers frequently use. For example, as mentioned above, students use prescribed brainstorming techniques during the concept-generation step of the *Pinholes to Pixels* unit. Rather than describing the desired techniques and assigning students to use them, teachers work to create a situation in which students experience a need for them. In particular, after a discussion about the value of having a range of design ideas from which a design team can select, student pairs begin brainstorming how they will fulfill the needs identified in their activity

diagram. Experience shows us, the curriculum designers, that this brainstorming will result in student teams quickly coalescing around the idea of the most vocal participant, rather than discussing a range of possibilities. Thus, after a few minutes of the pair brainstorming, the teacher interrupts to ask how many ideas each pair discussed. Referring back to the recently agreed-upon need to select from a range of design options, the teacher introduces the target brainstorming techniques as a tool for fulfilling that goal. The students then enact this technique and reflect on its efficacy.

This approach of allowing students to try to fulfill a goal before providing them with tools to do so draws from theories that individuals learn when their expectations are not met (Schank, 1999). That is, we learn when we are motivated to do so—when we realize that our current knowledge is insufficient to accomplish the desired ends. In addition, the approach of having the teacher present information—such as naming/defining an EDP phase or suggesting a useful process—after students have experienced its need is consistent with Schwartz and Bransford's (1998) finding that individuals learn from direct instruction best after engaging with the content themselves.

Design Principle 5: Ensure All Science and Math Concepts, and Technology Tools Employed are Necessary for Students' Successful Completion of the Stem-Design Projects

As with the engineering practices, we work to ensure that the science and math concepts addressed in each STEM-design challenge are necessary for the students' successful completion of their projects. That is, we do not ask students to perform calculations or to discuss scientific concepts unless doing so is clearly and immediately applicable to their work on their designs. This principle draws from Edelson's (2001) Learning-for-Use design framework that explains, among other things, that learning must be (and can only be) *initiated by the learner...* [and that] learning *how to use* conceptual knowledge must be part of the learning process, if the knowledge is to be useful" (p. 357, emphasis added).

As such, in this high school course, we carefully selected our math and science learning goals to ensure that we identified concepts that would clearly and directly support student fulfillment of the STEM-design challenge. For example, as seen in Berland and Busch (2012), it is possible—nay, likely—to construct a pinhole camera without ever discussing the optics principles behind why it works. Since this information is not essential to solving the STEM-design challenge, optics are not an explicit learning goal of the unit. In contrast, it is impossible to select a camera size, focal length, and aperture size without understanding similar triangles (see Figure 4) and the way in which changes to one triangle (e.g., the height of the object to be photographed) will impact the others (e.g., the necessary height of the film, the distance from the object,

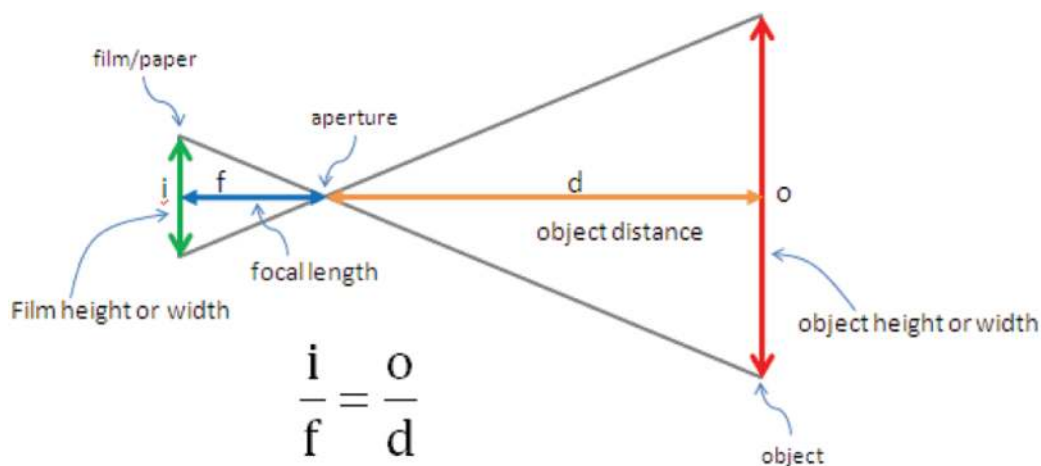


Figure 4. Depicting the use of similar triangles in the pinhole cameras.

and/or the focal length). These concepts are therefore discussed and emphasized as the students work on designing and building their pinhole cameras.

Beyond influencing the selection of the science and math concepts that our units will address, this principle also guides when and how we introduce these concepts. That is, similar to the introduction of engineering practices, we only introduce math and science concepts after students have felt a need for the information—after they have realized that they will be unable to complete their design without applying the particular concept. This realization is how the learning is “initiated by the learner.” For example, we do not introduce students to the similar triangles that will guide their design until they have discovered that they are unable to identify the necessary camera size, focal length, and aperture size without applying these concepts.

Discussion

The five principles described and exemplified in this article are the result of applying learning sciences theories of how people learn (*cf.* Bransford, Brown & Cocking, 1999) to STEM-design challenges. These theories have been reified in science classrooms across project-types and grades. For example, Kolodner et al. (2003) and Fortus et al. (2004) have both demonstrated the efficacy of using engineering challenges to teach science concepts. However, we suggest that the successes with using engineering challenges to teach science are limited in their applicability to engineering classrooms for two reasons:

1. Throughout this work, we see that learning science through engineering is challenging. For example, the teacher’s pedagogical approach and the classroom culture have a large effect on the degree to which students connect their design work to the desired science concepts.
2. Learning goals in engineering classrooms emphasize “engineering habits of mind” (National Academy of

Engineering & National Research Council, 2009) and engineering practices (National Research Council, 2011). These are not an emphasis in science classrooms. We therefore know little about whether and how students develop these particular practices in the context of an engineering challenge designed to apply particular science and math content. Moreover, given the epistemic differences between the fields—from learning how or why in science to developing a product to meet a specification in engineering—it is possible that the two kinds of learning goals (science content and engineering practices) will be in tension for students (Berland & Busch, 2012; Schauble et al., 1991).

Thus, the project reported here works to translate the lessons learned in the context of science classrooms to engineering classrooms, in which the learning goals foreground engineering practices rather than science or math practices and content. In addition to guiding curriculum development in engineering classrooms, we see this curriculum development endeavor as providing an exciting opportunity to explore the challenges associated with teaching science through design challenges. In particular, the engineering context offers the flexibility to address only those math and science concepts that are directly in the path of the design work. This is seen in the *Pinholes to Pixels* unit in which we decided not to pursue learning goals around the scientific principles governing the camera obscura (since successful designs could be easily identified and constructed without that background), but rather to emphasize the relevant and useful geometry.

This ability to select math and science concepts for their utility rather than their presence on a list of standards puts this project in a unique position to explore the ways in which students learn and apply math and science concepts while engaged in an engineering design challenge. As such, this context provides a prime opportunity to explore the challenges reported in related work and to explore the

feasibility of the National Academies' call for an integrated approach to STEM education (National Academy of Engineering & National Research Council, 2009; National Research Council, 2011). Future research will examine classroom enactments of the high school curriculum described here, focusing on understanding both *whether* students apply math and science concepts to their design work and *why* they do so (or not).

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