
AC 2012-4186: LEARNING SCIENCES GUIDED HIGH SCHOOL ENGINEERING CURRICULUM DEVELOPMENT

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Ms. Cheryl Farmer, UTeachEngineering

Cheryl Farmer is the founding Program Manager and Project Director of UTeachEngineering. Funded through a five-year, \$12.5 million Math and Science Partnership grant from the National Science Foundation, UTeachEngineering offers a well-designed, well-rounded, design-based high school engineering course that can be implemented at low cost in virtually any setting, as well as a variety of professional development programs for pre-service and in-service teachers who want to add engineering to their teaching portfolio. Prior to co-founding UTeachEngineering, Farmer spent several years managing programs for both K-12 and higher education. Before entering higher education, Farmer worked as a project manager

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Learning Sciences Guided High School Engineering Curriculum Development

Engineering education is increasingly appearing in high school courses—as either a stand-alone course or a component of a science course. In either context, engineering modules are tasked with multiple goals. In particular, as synthesized in the National Research Council’s¹³ review of K-12 engineering education, it is expected that engineering education will: 1.) focus on design and problem solving; 2.) incorporate appropriate STEM concepts and 3.) “promote engineering habits of mind.” High school engineering curriculum invariably addresses these goals (with differing emphases) through a project-based approach¹¹, in which students are given problems—or challenges—that motivate the exploration of the desired engineering concepts as well as the relevant math and science concepts. In engineering education, this is typically called Challenge-Based Instruction (CBI).

CBI courses contextualize student exploration of the desired content within a broader challenge. This contextualization supports the introduction, application, exploration, refinement and assessment of math, science, and engineering concepts^{5,15,18}. This paper reports upon the efforts of an NSF-funded project to develop a yearlong high school engineering course that uses a CBI approach to integrating math, science, and engineering learning goals. The team that designed this course, comprising university engineering faculty, clinical engineering faculty (professionals with experience as both practicing engineers and secondary classroom teachers), engineering research fellows, and learning sciences faculty, discovered that the CBI approach provided a guiding philosophy—that of contextualizing all student work within a challenge—but not the level of specificity required to develop a course with a consistent pedagogical approach across units and engineering domains. We resolved this challenge by adapting design approaches found in the learning sciences and science education research to create a set of principles to guide our work. The current paper explains and exemplifies the most important of these principles, including:

1. Contextualizing all student work within STEM design challenges
2. Using a standardized engineering design process and employing it as an instructional framework
3. Engaging students in meaningful (if simplified) versions of the practices of engineers
4. Ensuring that desired science and math concepts are necessary for students’ successful completion of the design projects.

Context

We exemplify these key course design principles in the context of the second unit in our yearlong course: *Pinholes to Pixels: The Evolution of Imagery*. In this unit, students design and build a pinhole camera that can take a picture that satisfies customer specifications.

The *Pinholes to Pixels* unit begins with student exploration of a camera obscura—a large, light tight chamber (*i.e.*, 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 1 illustrates this functionality.

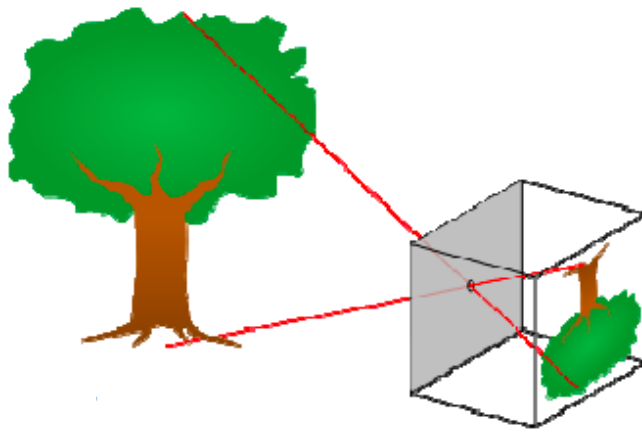


Figure 1: Functionality of the camera obscura

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

In the following sections we discuss the four most prominent design principles guiding our curricular work. For each principle, we explain the intent and learning theories behind the principle, and reify it within the context of the *Pinholes to Pixels* unit.

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

There exists a growing movement in both collegiate^{9,20} and pre-collegiate¹³ engineering education to contextualize student exploration of engineering, math and science concepts within a challenge—to implement Challenge-Based Instruction. However, the CBI approach is agnostic with respect to the challenge type. In fact, in reviewing the literature we identified three different challenge types: problem-based challenges in which students are posed problems that can only be solved through the application of novel concepts; design-based challenges in which students engage the design work of engineers without explicit emphasis on the underlying math and science concepts; and what we call STEM-design challenges in which students are posed with a design challenge that can only be completed through the purposeful application of engineering principles and relevant math and science concepts².

Thus, our first decision was in the type of challenge that would be utilized throughout the yearlong course. In keeping with the National Research Council's¹³ synthesis of the research on K-12 engineering education research, we chose to focus on STEM-design challenges. This decision reflects our commitment both to apply relevant math and science concepts *and* to enable students to engage 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 this 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 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; there are no extraneous assignments or lectures. In addition, we designed the challenge to facilitate student exploration of the desired science and math concepts, as described in the remaining principles.

Design Principle 2: Use a standardized engineering design process and employ it 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 other CBI work in which students are supported in following the STAR-legacy cycle^{9,18}. This well-tested and proven cycle⁵ is most frequently used in the service of addressing *problems* rather than *STEM-design challenges*. As such, we found that we needed to adapt the STAR-legacy cycle to better reflect the process typically undertaken by engineers. The particular EDP created by the project team and used in this course is described by the project authors in a related paper³.

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 colleagues¹⁰ 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 effortlessly engage in it. 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 the details of the engineering practice.

The other half of this design principle, namely the commitment to employ the EDP as an instructional framework, reflects the design team’s intent 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 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 decision about what to do next, identification of the necessary artifacts, the ways in which these artifacts are useful, and the information that should and can be communicated by these artifacts becomes 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 use a 6-3-5 brainwriting strategy. Then, as students present their final 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 6-3-5 strategy and decision matrix and, over the course of the following units, these become ritualized tools that students use as they engage in the concept-generation and concept-selection steps of the EDP.

Design Principle 3: Engage students in meaningful versions of the practices of engineers.

Engaging students in a standardized EDP such that they have ritualized the enactment of particular engineering practices can be dangerous. As seen in the use of the Scientific Method in science classes, this standardization can quickly become a script that students perform without understanding the purpose of the practices²¹. That is, the artifacts can become pseudotransactional^{1,14,19} such that they are completed in the service of a grade, rather than to fulfill a communicative and sensemaking goal. Similarly, the processes can become a “classroom game”¹², rather than a purposeful activity in which the students engage.

We address this danger by ensuring that students engage in “meaningful” versions of these practices. By meaningful, we intend for the practices to be enacted only when and if they students experience them as necessary for the fulfillment of their STEM-design challenge. As such, 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 suggested that the two different artifacts provided the student-designers with similar 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 such that students now create an activity diagram and then

identify the questions they need to answer about each step without replicating the information from in activity diagram in a separate table.

This principle of engaging students in meaningful, or purposeful, 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 engineering practice before students engage in it, we create situations that enable students to recognize the importance of these practices. In fact, each EDP step is named and defined *after* students complete it for the first time. As such, students experience the EDP as a process that is useful to their design work rather than a process the teacher is asking them to follow. To that end, the *Pinholes to Pixels* unit concludes each lesson with a note to the teachers reminding them to name the step they just completed and add it 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 Curriculum materials).

We go through a similar process when introducing processes and artifacts that engineers frequently use. For example, as mentioned above, students use the 6-3-5 brainwriting technique during the concept-generation step of the *Pinholes to Pixels* unit. Rather than describe this process and assign students to use it, teachers offer students the opportunity to experience a need for it. 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 6-3-5 method as a technique that could enable them to explore more solutions. 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 met¹⁶. That is, we learn when we are motivated to do so—when we realize that our current knowledge is insufficient to accomplish the desired ends⁷. 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's¹⁷ finding that individuals learn from direct instruction best after engaging with the content themselves.

Design Principle 4: Ensure that science and math concepts 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 the project. That is, we do not ask students to perform calculations or discuss scientific concepts unless doing so is clearly and immediately applicable to their work on their designs. This principle is drawn from Edelson’s⁷ 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, emphases added).

As such, in this high school course, we carefully select our math and science learning goals to ensure that we identify concepts that will clearly and directly support student fulfillment of the STEM-design challenge. For example, 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 2) and how 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, and/or the focal length). These geometry concepts are therefore discussed and emphasized as the students work on designing and building their pinhole cameras.

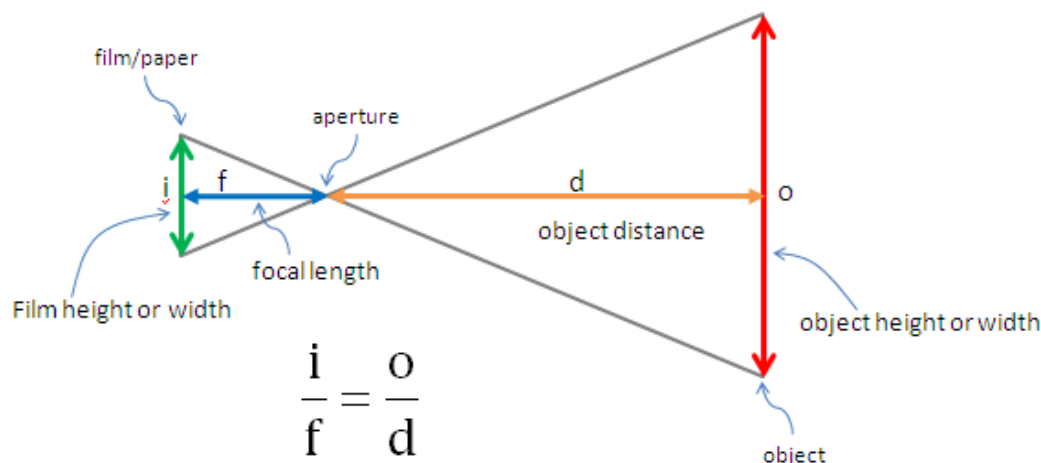


Figure 2: Depicting the optics of how the pinhole camera works

Beyond influencing our 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 four principles described and exemplified in this article were created through the application of learning sciences theories of how people learn⁴ to the context of STEM-design challenges. These theories have been reified in science classrooms across project-types and grades. For example, Kolodner et al.¹⁰ and Fortus et al.⁸ have both demonstrated the efficacy of using engineering contexts to teach science concepts. However, throughout this work, we see that 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. Crismond⁶ similarly found that high school students rarely spontaneously discuss underlying science concepts when engaged in design.

The project reported here is one of the few curriculum development endeavors in which the theories of learning have been applied to a yearlong engineering course, rather than to a component of a science or math class. As such, the current context provides an exciting opportunity to explore the challenges associated with teaching science through design challenges^{6,8,10}. 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 design challenges and 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 NRC's call for engineering education to promote engineering habits of mind through challenges that incorporate relevant science and math concepts. 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).

Acknowledgements

This research was funded by the National Science Foundation under Grant DUE-0831811 to the University of Texas at Austin. The opinions expressed herein are those of the authors and not necessarily those of the NSF. For additional information about UTeachEngineering curricula and research see <http://www.uteachengineering.org/>.

References

1. Berland, L. K., & Hammer, D. (2012). Framing for scientific argumentation. *Journal of Research in Science Teaching*, 49(1), 68–94.

2. Berland, L. K. Martin, T. H., Ko, P., Peacock, S., and Rudolf, J. (under review). Student Learning in Challenge-Based Engineering Curricula. *Journal of Pre-collegiate Engineering Education*.
3. Guerra, et al. (under review). A Unique Approach to Characterizing the Engineering Design Process
4. Bransford, J., Brown, A. L., & Cocking, R. R. (1999). *How people learn : Brain, mind, experience, and school*. Washington, D.C.: National Academy Press.
5. Cordray, D. S., Harris, T. R., & Klein, S. (2009). A Research Synthesis of the Effectiveness, Replicability, and Generality of the VaNTH Challenge-based Instructional Modules in Bioengineering. *Journal of Engineering Education*, 98(4), 335-348.
6. Crismond, D. (2001). Learning and Using Science Ideas When Doing Investigate-and-Redesign Tasks: A Study of Naive, Novice, and Expert Designers Doing Constrained and Scaffolded Design Work. *Journal of Research in Science Teaching*, 38(7), 791-820.
7. Edelson, D. C. (2001). Learning-for-use: A framework for integrating content and process learning in the design of inquiry activities. *Journal of Research in Science Teaching*, 38, 355-385.
8. Fortus, D., Dershimer, R. C., Krajcik, J., Marx, R. W., & Mamlok-Naaman, R. (2004). Design-Based Science and Student Learning. *Journal of Research in Science Teaching*, 41(10), 1081-1110.
9. Klein, S. S., & Harris, A. H. (2007). A User's Guide to the Legacy Cycle. *Journal of Education and Human Development*, 1(1).
10. Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., Puntambekar, S., et al. (2003). Problem-Based Learning Meets Case-Based Reasoning in the Middle-School Science Classroom: Putting Learning by Design Into Practice. *Journal of the Learning Sciences*, 12(4), 495-547.
11. Krajcik, J., & Czerniak, C. M. (2007). *Teaching science in elementary and middle school classrooms: A project-based approach* (Vol. 3). New York, NY: Lawrence Erlbaum Associates.
12. Lemke, J. L. (1990). *Talking science: Language, learning, and values*. Norwood, NJ: Ablex Publishing.
13. National Academy of Engineering & National Research Council (2009). *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*. (L. Katehi & M. Feder, Eds.). Washington DC: National Academies Press.
14. Petraglia, J. (1995). Spinning like a kite: A closer look at the pseudotransactional function of writing. *Journal of Advanced Composition*, 15, 19-33.
15. Roselli, R. J., & Brophy, S. P. (2006). Effectiveness of challenge-based instruction in biomechanics. *Journal of Engineering Education*, 95(4), 311-324.
16. Schank, R. C. (1999). *Dynamic Memory Revisited* (2nd ed.). Chapter 3. Cambridge University Press.
17. Schwartz, D. L., & Bransford, J. (1998). A time for telling. *Cognition and Instruction*, 16(4), 475-522.
18. Schwartz, D. L., Brophy, S., Lin, X., & Bransford, J. D. (1999). Software for Managing Complex Learning: Examples from an Educational Psychology Course. *Educational Technology Research and Development*, 47(2), 39-59.
19. Spinuzzi, C. (1996). Pseudotransactionality, activity theory, and professional writing instruction. *Technical Communication Quarterly*, 5(3), 295-308.
20. Tate, D., Chandler, J., Fontenot, A. D., & Talkmitt, S. (2010). Matching pedagogical intent with engineering design process models for precollege education. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 24, 379-395.
21. Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, 92(5), 941-967.