Engineering Everywhere: Bridging Formal and Informal STEM Education (Works in Progress)

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Sharlene Yang is the director of Partnerships for the Engineering is Elementary project. In this position she is working with organizations and individuals across the country to help them support implementation of elementary engineering with area schools and teachers. She also led the efforts and initiatives of EiE professional development team, which now reach approximately 300 teachers a year. Yang has been active with STEM education for the past fifteen years; prior to her work with EiE, Yang has over a decade of experience as both a science educator and researcher that includes teaching biology to at-risk and underserved populations, environmental outreach education, and research in biopsychology. Yang has focused much of her work with EiE on creating and conducting professional development that not only teaches content, but models strong science pedagogy so that teachers can experience for themselves the power of inquiry-based and open-ended learning. In her work with partners, she hopes to bring these methods to science education PD providers nationwide. Sharlene received her B.A. in Biology and Psychology from Cornell University, her M.S. in Biopsychology from the University of Michigan, and her M.A.T. in Science Education from Tufts University.

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Works in Progress
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As interest in STEM education has increased, engineering design challenges have been used in different types of educational settings to engage student learning. As a way to help others design and create engaging engineering activities for their particular audiences, we compare and contrast factors that influenced the structure of two engineering education programs: *Engineering is Elementary*® (EiE), a formal engineering curriculum for the elementary classroom and Design Challenges, an informal hands-on engineering design challenge exhibit at a science museum in northeast United States.

To best illustrate the factors that influenced how the lessons and activities of these two programs were designed, we will begin by first detailing the learning goals and resulting criteria that both engineering programs aimed to reach and the constraints presented by the different learning environments (formal classroom versus museum exhibit floor) in which they were implemented. We will then describe two engineering challenges focusing on harnessing wind energy—one created for implementation in the formal classroom and another used at the informal hands-on museum exhibit—to explain and give examples of how the two programs worked within different constraints to achieve similar learning goals.

Criteria and Activity Design

Both Design Challenges and EiE have created 20 engineering design challenges that aim to reach five main engineering education learning goals. The chart below outlines these learning goals and the criteria that the programs set so their activities would meet these goals:

Learning Goals	Informal and Formal Activities' Criteria
Learners will engage in the Engineering Design Process.	The activities will lead learners through an iterative process (with distinct steps).
Learners will have a positive engineering experience.	The activities are learner-driven through inquiry.
	The activities are project-based and hands-on.
Learners will complete a challenge that is analogous to those completed by professional engineers.	The activities center on a problem defined by criteria and constraints.
	The activities have multiple solutions.
	The activities' solutions must be testable by measurable criteria.
Learners will gain a broader understanding of the types of problems engineers work creatively to solve.	The activities are set in a context.
	The engineering challenges represent many different fields of engineering.
Students will understand that everyone can engineer.	The activities are deliberately created to be gender-neutral.
	The activities are accessible by diverse audiences.

Constraints and Activity Design

Even though both the Design Challenges and EiE programs have similar learning goals, the environments where the activities are implemented—the elementary school classroom versus the museum exhibit floor—present different constraints on their design. The following are the factors that each program needed to consider and the different constraints that each learning environment imposed on activity design:

Factor	Constraints on Informal Activity	Constraints on Formal Activity
Activity preparation time	10 – 15 minutes (both classroom teachers and museum instructors require a short preparation time)	
Materials Budget	Low	
Age range of learners	2-80 years old	One grade of students
Number of learners	~100 visitors drop in per hour	25-30 students in a classroom
Special learning environment expectations	Museum visitors expect a unique, “wow” factor No prior science knowledge needed	Must meet content standards and be able to integrate across curricula
Implementation time	20 minutes per visitor	45-60 minutes per session; multiple sessions
Facilitation of activity	Self-guided	Teacher-facilitated with scaffolding

Engineering Design Activities—Two Examples

So how do these two programs meet similar criteria under mostly different constraints? To illustrate this, we will describe two engineering Design Challenges that focus on harnessing the wind’s energy to do work— *Ships Ahoy*, the informal museum activity, and *Catching the Wind: Designing Windmills*, the formal classroom curriculum.

- *Ships Ahoy*, an example of an informal museum activity

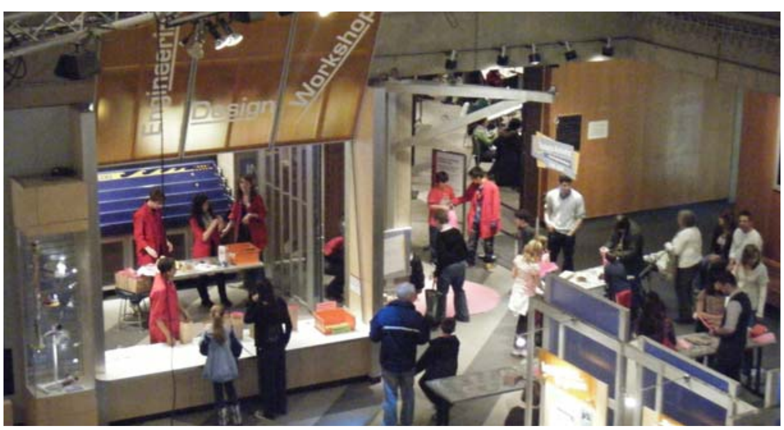

Image 1. Photo of Design Challenges exhibit space.

As outlined in the previous chart, the informal museum program is mostly constrained by the large volume of visitors/learners it must reach in a very short amount of time. Design Challenges is structured as a drop-in program on the museum floor that is open for two-hour sessions, once or twice a day. This exhibit has a 900 sq. ft., permanent space on the museum floor. It consists of an enclosed area that houses activity materials in organized bins, a counter area where museum staff introduce the engineering challenge and relevant activity materials are laid out, and a large monitor that projects the results of the daily design challenge. Tables set up in the surrounding exhibit space are used as an area where guests can create their designs. (See Image 1.)

On average, the program's facilitators interact with 100 guests per hour with school age visitors consisting of about 52% girls and 48% boys. The activities are recommended for students in grades 4-10 as well as for small family groups of all ages. Although the average time visitors spend at this program is 20 minutes, family groups often stay at the exhibit for the entire two-hour session participating in the engineering design process. Staff members who facilitate the museum program are formally educated as engineers and scientists (or in the process of being educated) and represent a culturally diverse group of individuals including those from underrepresented groups in STEM fields. Staff members use an inquiry-based teaching method to help facilitate the activity, particularly with guests having difficulty achieving a successful design.

Ships Ahoy is a design challenge where visitors use simple, colorful, and recycled materials to design and build a model vessel to achieve the optimal use of wind power. Guests are introduced to the goals, materials, and constraints of the activity at the counter of the Engineering Design Workshop through a short story. This short story sets the context for the design challenge and in the case of *Ships Ahoy*, the facilitators use the story to explain to the visitors are engineers that need to help people on an island by either designing a hull and sail configuration for a ship that will do one of two things: (1) get the ship there as quickly as possible or (2) allow the ship to bring over as many supplies as possible.

Participants then choose from a selection of pre-cut materials to design their ship's hull and sails so that it moves across the water track without sinking. Guests test their invention on an elaborate, custom-built, 9-foot long, four-lane, wind-powered, water-filled track, and observe what happens to their creation when the wind blows (fans turn on). For vessels that make it successfully across the track without sinking, a time is measured and displayed on the track. As an added challenge, guests can also improve their designs by either redesigning their hull and sail combination to either move the vessel faster down the water track or carry more "supplies" in the form of glass beads. Visitors with the record for the fastest time of the day or most supplies successfully transported name their team and then can post their record on a large monitor visible to the public. By posting the records of the day guests are inspired to re-design and re-test their invention in an attempt to achieve the record. Although competition is inherent in this activity, the focus for guests is to improve their own design and not to focus solely on the record of the day. Guests are encouraged to work with a partner to support and develop collaboration rather than competition.

Students can apply their knowledge and understanding of wind power, buoyancy, displacement, friction, and lift to their sailboat design, but no previous knowledge of these science concepts is necessary. Guests are encouraged to re-design and re-test as many times as they have time for. When guests have finished participating in the design challenge they are asked to support re-cycling and re-using by dismantling their creation and returning the materials. For their effort they receive a design challenge specific magnet.

- *Catching the Wind: Designing Windmills*, an example of the formal classroom curriculum
  In contrast, the formal classroom curriculum is mostly constrained by teachers' need to meet state and national content standards. As engineering is not yet a part of most states' elementary school standards, teachers will not be motivated to teach engineering in the classroom unless it reinforces skills in science, English language arts or mathematics. The EiE curriculum is designed to integrate engineering and technology concepts and skills with elementary science topics in grades 1-5.[1]

  The EiE curriculum consists of 20 engineering units; each unit is paired with a different science topic or topics that are commonly taught in elementary school. The lessons assume that the students are studying or have already studied the science concepts that are then utilized in the engineering lessons. Over a series of 45-50 minute lessons taught over 8-10 class periods, students learn about a relevant field of engineering and the engineering design process.

  They are engaged in activities that give them the opportunity to ask questions about the challenge, find answers and collect data through experimentation, and use that data to inform design choices while solving the design challenge. Through facilitated discussion, students get a chance to practice using relevant science and engineering vocabulary as a way to reflect on their engineering experience and process their results. Each unit Teacher Guide provides the relevant science and engineering background information for the teacher as well as detailed lesson plans that emphasize student-centered, inquiry-based learning.

  Catching the Wind is an engineering unit where students use their knowledge of wind energy, creativity, and the Engineering Design Process to design blades for a windmill that will harness the wind's energy to do work. As with all EiE units, *Catching the Wind* is divided into four lessons:
    - Lesson 1 is a storybook that features children from a variety of cultures and backgrounds and introduces students to a five-step Engineering Design Process (EDP) and an engineering problem. Students are then challenged to solve a problem similar to that faced by the storybook character. In the case of *Catching the Wind*, this unit begins with a storybook about a boy in Denmark who applies his knowledge of wind and weather and the EDP to solve a mechanical engineering problem—designing a wind-powered paddle that will aerate his cousin's fish pond. The students will then be invited to complete a similar challenge—to design the blades for a windmill that will use the wind's energy to lift a cup of weights.[2]
    - Lesson 2 is an activity that gives students an opportunity to broaden their knowledge of a specific field of engineering. Since *Catching the Wind* focuses on solving a mechanical engineering design challenge, in this lesson, students get the opportunity to think like mechanical engineers by evaluating four common machines (a mechanical pencil, a can opener, a glue stick and a manual egg beater) and examining the direction of the action on each machine and the direction of reaction of the machine. Students then engage in a discussion of the advantages and disadvantages of using the machine.[2]

- Lesson 3 begins the engineering design challenge by first explicitly reviewing the steps of the Engineering Design Process—Ask, Imagine, Plan, Create, and Improve. Students then engage in the first step of the EDP by asking questions to clarify the criteria and constraints of the engineering problem they are being asked to solve. In the case of *Catching the Wind,* students answer the question, "What properties of a sail affect how well it catches the wind?" by exploring by designing sails in different shapes and sizes out of materials such as index cards, tissue paper, plastic bag, aluminum foil, popsicle sticks, and tape. By testing their sails on a fan-powered track, they determine which properties of a sail (material, shape, size, etc.) affect how well it is able harness the wind's energy. [2]
- Lesson 4 continues to lead students through the Engineering Design Process to solve their challenge by scaffolding them through the EDP with teacher-facilitated instruction and handouts that specifically take them through each step of the process. In *Catching the Wind*, students discuss their data and observations about the properties of sails then apply this knowledge to the design of their windmill by utilizing the remaining steps of the EDP. They imagine different kinds of windmill blades, plan one idea in detail, create and test the design, and then improve their blades based on testing results. The success of the windmills designs are evaluated on a windmill's ability to use the wind's energy (from a box fan) to lift a cup of weights attached to the rotor's axel—the more weights that the windmill can lift, the more successful the design. [2]

Constraints Determine Methods Used to Meet Criteria

From the museum activity and classroom curriculum examples described above, Design Challenges and EiE use different methods to reach achieve similar learning goals even though they must work within different constraints. These methods are summarized here:

- Learning Goal 1—Learners will engage in the engineering design process.
  Criteria—The activities will lead learners through an iterative process (with distinct steps).

  Because Design Challenges must facilitate the museum activity with such a large volume of diverse visitors in a short period of time, the activities are set up to encourage the iterative process in implicit ways. Museum staff are trained to facilitate the activities by encouraging guests to improve their designs by using the language of the EDP.[3] For example, to encourage a hesitant visitor, they might say, "imagine some more ideas, pick one to plan out, and then create it." At the testing station, a staff person might ask a visitor, "What do you think you can improve to make your vessel go faster?" In addition, publicly posting the "best" scores (highest, slowest, most treasure) sets up the museum engineering activities to encourage visitors to re-design their engineering solutions so that they can beat the "best" score.

  Because EiE is a classroom curriculum that is taught to approximately 25 students at one time in a structured environment, the Engineering Design Process (Ask, Imagine, Plan, Create and Improve) is able to be explicitly scaffolded in every unit through teacher facilitation and handouts that guide students through each step of the EDP. As a part of the Improve step, students must identify both the parts of their design that worked best and need improvement, then draw up a new plan of their re-design before creating and testing. Therefore, through improving, students are able to experience the iterative nature of engineering.[1]

- Learning Goal 2—Learners will have a positive engineering experience.
  Criteria—The activities are learner-driven through inquiry, project-based and hands-on.

  Both Design Challenges and EiE center their lessons and activities on an open-ended engineering challenge that requires hands-on manipulation of materials to create a technological solution. Visitors and students must explore possible materials and ask questions about how things work in order to achieve their engineering goal.

  In the informal museum environment, the design challenge is created to be straight-forward using familiar, easily manipulated materials (such as sheet foam, plastic rods, plastic containers, fabric pieces pre-cut into different shapes and sizes rather than complicated electronic parts) so that visitors can immediately take ownership of the activity and figure out a solution on their own. For visitors who struggle, Design Challenges staff are trained to help them through guided inquiry facilitation methods. For example, in the activity, *Ships Ahoy*, visitors often will add large hulls and sails to their vessels to harness more wind, but during testing, end up sinking their boat from excess weight. To troubleshoot this situation, a staff person would ask the visitor, "What do you notice? Why do you think your boat is sinking? What do you think you can change to make it stop sinking?" and then encourage the visitor to try again.[3]

  To keep classroom activities learner-driven, the EiE curriculum lesson plans and handouts are written in the same inquiry-based vein, but with more with careful attention to building foundational knowledge. For example, in *Catching the Wind*, the unit starts with students thinking about things that they already know catch the wind (like kites and sails) and connecting this prior knowledge to a hands-on exploration where they test different materials to see if they are good wind catchers. It is only after the students have had experience with the materials and a deeper understanding of wind's ability to move things are they allowed to design a windmill. Paying careful attention to the way that an engineering challenge is introduced through layers of foundational knowledge makes it more likely that the students will be able to work independently to create successful engineering designs.[4]

- Learning Goal 3—Learners will complete a challenge that is analogous to those completed by professional engineers.
  Criteria—The activities will center on a problem defined by criteria and constraints and have multiple solutions. The solutions must be testable by measurable criteria.

  In Design Challenges' *Ships Ahoy* activity, visitors are presented with a very clear problem—they must help people on an island by either designing a ship's sails and hull configuration to create a fast ship or by creating a ship that can carry a lot of supplies to the island without sinking. Even though the possible solutions are constrained by the materials available, the challenges are constructed use a variety of materials that encourage many designs, but not so many that the variables become overwhelming. In the case of *Ships Ahoy*, students are allowed to choose their boat sails from pre-cut pieces in various shapes and sizes. The success of their designs is determined by quantifiable data—the time it takes to travel down the water track (the faster, the better) or the number of glass bead "supplies" their vessel can carry (the more, the better). Other museum-based design challenges are structured in a similar way.

In EiE's *Catching the Wind* unit, the students must design a windmill that harnesses the wind's energy to lift a cup of weights. The students' designs are constrained by materials available and similar to the museum exhibit activity, students have a limited variety of different materials to choose from. Since the students can make windmill blades from different types of materials, in different sizes, and attach more or fewer blades to the rotor, there are multiple successful solutions to this engineering problem. The success of their design is measured by the number of weights they are able to lift—the more weights, the better the design.

- Learning Goal 4—Learners will gain a broader understanding of the types of problems engineers work creatively to solve.
  Criteria— The engineering challenge is set in a context. The engineering challenges represent different fields of engineering such as bioengineering, environmental engineering, materials engineering, etc.

  It important for learners to understand that engineering centers on solving problems by designing a technological solution and these problems often stem from a societal need. If we want museum visitors and students to understand that engineers are problem solvers, it is important to set engineering challenges in a real life context.[4] Design Challenges does this by introducing each of their challenges with a short narrative. In *Ships Ahoy*, visitors are introduced to the activity through a story about how they are engineers helping to design the hull and sails configurations for one of two kinds of ships that will travel to an island to help people after a storm—one that will be able to travel quickly to bring help or another that will be able to transport a lot of supplies without sinking. Because of this story, visitors will begin to understand that engineers are problem solvers that help people by creating technologies.

  The EiE curriculum also sets a context by introducing every engineering unit through a storybook. In the case of *Catching the Wind*, the unit opens with a story about a boy who needs to help his cousin aerate her fish pond. He does this by designing a wind-powered paddle that churns the water in the pond—a clear example of engineering a technology to help meet a need.

  In addition, both of these programs have developed 20 different engineering units or activities that span across many fields of engineering, from environmental engineering to bioengineering to materials engineering. Since all the challenges are set in a context, a repeat museum visitor to Design Challenges or a student that is exposed to multiple EiE units will, over time, understand that engineers are problem solvers and designers of all sorts of technology.[4,5]

- Learning Goal 5—Learners will understand that everyone can engineer.
  Criteria— The activities are deliberately created to be gender-neutral and accessible by diverse audiences.

  Because engineering is currently a male-dominated profession, both programs are particularly cognizant about creating engineering experiences that will engage girls through Design Challenges that are more female-friendly (i.e. not as building oriented) and by using a wide range of everyday, colorful materials that are familiar and appealing to most children. In addition, both programs, in their own ways, try to provide diverse engineering role models for students and museum guests. The EiE curriculum uses the storybook to introduce the engineering design challenge, but also purposefully writes characters into the story that a diverse population of students can relate too.[4] For example, half of the protagonists are girls and half are boys; characters that are engineers are also split evenly across genders; since the stories take place all over the world, the characters are ethnically diverse as well. On the museum floor, the informal engineering education program is facilitated by a diverse staff that includes underrepresented groups in the STEM fields so they actually serve as the role models for visitors who participate in the activities.[5]

Conclusion

In summary, engineering activities can be used in many different kinds of educational settings. However, because informal and formal learning environments present different constraints, different methods may need to be used to achieve similar learning goals. Although this paper is being submitted as a work in progress, we hope this preliminary examination of engineering education in these two educational settings will further understanding about the pieces critical to successful engineering design activities so that others will be able to create richer STEM learning experiences in their own educational environments, whether in the classroom or out.

References:

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