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Engineering Explorations: Connecting K-12 Classroom Learning and Field Trip Experiences through Engineering Design

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At MOXI, Skinner's current role in education research focuses on training informal STEM facilitators and engaging visitors in the practices of science and engineering. He is the principal investigator on two collaborative NSF grants and one sub-award with UC Santa Barbara, where he is also pursuing doctoral work in education research.

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Engineering Explorations: Connecting K-12 classroom learning and field trip experiences through engineering design

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Abstract

Interactive science centers are in a unique position to provide opportunities for engineering education through K-12 field trip programs. However, field trip programs are often disconnected from students' classroom learning, and many K-12 teachers lack the engineering education background to make that connection. Engineering Explorations is a 3-year project funded by the National Science Foundation (NSF) program Research in the Formation of Engineers (RFE) (EEC-1824856 and EEC-1824859). The primary goal of this project is to develop and test engineering education modules that link K-12 students' classroom learning to field trip experiences in an interactive science museum, increasing student learning and extending the field trip experiences. Each Engineering Explorations module consists of one 50-minute field trip program completed at an interactive science center and curriculum for three 50-minute lessons to be implemented by the classroom teacher before (2 lessons) and after (1 lesson) the field trip program. Our paper will present both development and research outcomes.

Development accomplishments. To date, we have developed and tested 3 field trip programs with over 5,000 K-12 students and full curriculum modules with a subset of these classrooms. We have 4 additional curriculum modules in various stages of development. Each of the field trip programs engage students in an engineering design challenge, from designing an object that hovers in a rising column of air to designing a patch for a greenhouse on the moon to modifying a structure to reduce swaying during an earthquake. The classroom activities provide opportunities for students to develop science and engineering ideas that augment the engineering design challenge and to reflect on the field trip experience.

Research accomplishments. Our research has focused on using an iterative design process to inform design principles used to develop the engineering field trip programs and curriculum modules. We present design principles for coordinating classroom and field trip programs, for accommodating different grade levels, and for engaging diverse audiences.

Introduction

In an effort to provide students with a foundation, "to better engage in and aspire to solve the major societal and environmental challenges they will face in decades ahead," the Next Generation Science Standards (NGSS) [1], include engineering design at all levels of K-12 education. However, research has consistently shown that elementary teachers are not confident teaching science, especially physical science, and generally have little knowledge of engineering

[2]. As such, K-12 teachers need support implementing these new standards around engineering. Interactive science centers and other "informal science environments" (a term used to refer to out-of-school learning environments that provide rich opportunities for science and engineering learning) can share the responsibility of providing educational and compelling engineering experiences for youth. Ideally, the learning in such environments would complement the education that students receive in formal school settings and the curricular goals of districts and states. Partnerships between institutions from multiple education sectors can be effective in bringing different perspectives and resources to create engaging engineering learning opportunities [3].

Engineering Explorations is a 3-year National Science Foundation funded project that leverages partners from multiple education sectors (K-12 schools, interactive science centers, higher education, and afterschool programs) to provide engineering learning experiences for youth and increase local teachers' capacity to deliver high quality engineering learning opportunities. The primary development outcome goal of the Engineering Explorations project is to develop and test a set of 9 Engineering Explorations modules that link K-12 students' school-based experiences to field trip experiences in a local interactive science center. Each Engineering Explorations module consists of one 50-minute field trip program completed at an interactive science center and curriculum for three 50-minute lessons to be implemented by the classroom teacher. Two are implemented before the field trip and one is implemented after the field trip program. The lesson plans for school teachers to complete before and after the field trip include "educative" materials [4] to help teachers develop their capacity to introduce engineering in their classrooms. All activities are aligned with the Next Generation Science Standards (NGSS).

The primary Research Practice Partnership (RPP) [5] is between MOXI, The Wolf Museum of Exploration + Innovation (MOXI), and researchers at University of California, Santa Barbara (UCSB). See [6] for an overview of the multiple interacting programs and related research this partnership has produced. Our work follows a design-based implementation research model [7-9], which is "a systematic but flexible methodology aimed to improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings" [10].

We began designing each Engineering Exploration module by developing the field trip activity. Since not all students who participate in the field trip activity do the pre- and post-field trip classroom activities, the field trip programs are designed as standalone programs so that classrooms that attend the MOXI field trip without having completed the pre-visit activities can still participate in an engineering design challenge. Each of these challenges is based on a real-world problem that engages students in the process of engineering design. After developing the field trip lesson, we considered the engineering and science activities that would benefit students in developing a deeper understanding of science and engineering ideas during the field trip program. Figure 1 depicts the framework that guides our module development. The first school classroom activity engages students in a science investigation, through which they collect data and make observations. In this activity, students also draw their initial conceptual models of the phenomena being investigated. In the second in-class activity, students complete an engineering design task. Their designs are informed by the data and observations made during the earlier science activity. During these two pre-field trip classroom activities, they also become familiar with some of the materials they will use during the field trip and develop skills related to manipulating these materials. During the field trip program at MOXI, students then engage in a more complex engineering design challenge. After the field trip, they return to their classrooms and extend their learning through reflection on the activities, the engineering design process, and additional data analysis, which includes revising their conceptual models of the phenomena being investigated.

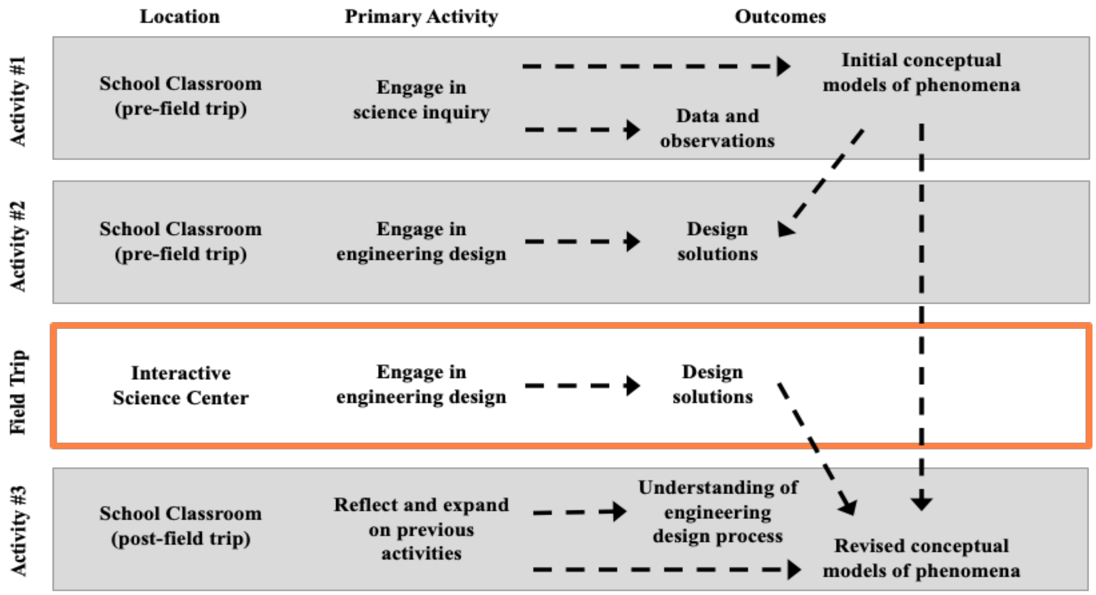

Figure 1. Engineering Explorations curriculum module framework.

Implementation and Data Collection

In 2018-2019, the Engineering Explorations field trip programs were implemented a total of 116 times, directly impacting 2,615 elementary school children in grades K-6. In 2019-2020 the field trips were implemented 120 times before testing was halted in March 2020 due to the COVID-19 global pandemic. In total, the field trip program has been tested with over 5,000 children from over 50 schools across 19 school districts in four counties. The full modules have been tested in 29 classrooms (18 classrooms in year 1 and 11 classrooms in year 2) and with 4 classes through an afterschool program for girls.

To ensure representation of the broad range of demographics served by the interactive science center, we recruited diverse schools and afterschool programs to test the curriculum modules. In year 1, we worked with two schools and an afterschool program. The first school reported that 40% of the students were classified as English Language Learners and 62% qualified for free and reduced lunch and the school was classified as a Title 1 school. At the second school, 9% were classified as English Language Learners and 11% qualified for free and reduced lunch. The afterschool program served girls in the local area; 70% were eligible for free and reduced lunch and 69% from underrepresented ethnic groups. In year two, we worked with a third school who reported 17.5% of their students were classified as English Language Learners and 51.8% qualified for free and reduced lunch. We also continued working with the same afterschool program in year two.

We collected field observations and audio and video recordings of the classroom activities in year 1 and a subset of the field trips to MOXI, as well as samples of student work. We administered questionnaires to teachers who brought their students to the stand-alone field trip. Teachers who implemented the pre- and post-field trip activities in their classrooms were interviewed and surveyed.

Engineering Explorations has both research and development goals. Below we describe the progress we have made on both sets of goals in the first two years of the project.

Development Accomplishments

We have developed and implemented three new field trip programs at MOXI. For two of these, we have also completed and tested the full modules (field trip programs + classroom activity curricula). Four other Engineering Exploration modules are in various stages of development. Below we discuss the three field trip programs that have been developed and tested and then discuss the two modules that include classroom activity curricula.

Field trip programs

Each MOXI Engineering Explorations field trip program is 50 minutes long and offered to schools as an additional experience to exploring the museum and investigating the exhibits. Field trip programs take place in the “Exploration Lab,” MOXI’s classroom space, and engage students in the three aspects of engineering design described by the NGSS:

- NGSS-ETS1.A Define and delimit engineering problems
- NGSS-ETS1.B Design solutions to engineering problems
- NGSS-ETS1.C Optimize design solutions.

In addition, depending on the grade level, this field trip also aligns with California Science Standards [11] (which are derived from the NGSS): 4-PS3-2 (4th grade) and MS-PS3-3 (6th grade).

Engineering Exploration 1 Riding the Rising Air	**Engineering Exploration 2 Greenhouse on the Moon**	**Engineering Exploration 3 Earthquake!**
Fire scientists need data to predict the movement of wildfires. Students design and build vehicles capable of hovering a sensor in the rising air above a wildfire. MOXI’s wind column exhibit provides a simulation of rising air in which students test and	Lunar astronauts need help! Students design a patch for a damaged lunar greenhouse in a futuristic moon colony. The patch must optimize the amount of light and heat available for plant growth within the constraints of the limited	Earthquake engineers use a variety of structural methods to shift a building’s natural frequencies of vibration out of the range of earthquake frequencies. Using MOXI’s variable frequency shaker tables, students iteratively design, build, and test modifications to model skyscraper structures to

iteratively revise and improve their designs.	materials available to the lunar colony.	minimize the amount they sway in a simulated earthquake.

Table 1. Overview of field trip programs.

Engineering Exploration 1: Riding the Rising Air. This MOXI field trip program begins with students making observations and inferences from an image of smoke rising from a wildfire burning near a city. Student inferences help to develop a storyline, which leads to the definition of an authentic problem and the presentation of an engineering design challenge: Design and build a vehicle using simple materials, that can hover in the rising air above a wildfire while carrying a lightweight sensor the size and weight of a metal washer. Students collaboratively identify goals for success (criteria) and limitations (constraints) to delimit the problem. Materials are presented to teams of students, who engage in the engineering design process to design, build, and test a vehicle that satisfies the goals for success (criteria). Students use MOXI's wind column exhibit as a model of the wildfire scenario to test their vehicles in a column of rising air. [12]

Engineering Exploration 2: Greenhouse on the Moon. Students begin by making observations of infrared camera images of hot and cold objects covered with different materials. These observations lead them to the conclusion that some materials block visible light and transmit heat while other materials transmit visible light and block heat. A story emerges that a greenhouse supplying food to a lunar colony has been damaged and is in need of repair. Students are challenged to design a repair solution using a model of the sun's infrared and visible radiation spectrum (heat lamp), measuring tools (lux meter and infrared thermometer), and a sample of the limited materials available to lunar colonists to make the repair (e.g., acrylic sheet, plastic trash bag, colored plexiglass filters, translucent paper). Students collaboratively identify goals for success (criteria) and limitations (constraints) to delimit the problem. Students work in teams to iteratively design and test combinations of materials that optimize the amount of transmitted visible light needed to grow plants while adequately reducing the intense infrared radiation from the sun to prevent overheating of the greenhouse. Time is an important constraint, as the colonists' food supply will not last long without a functioning greenhouse in the harsh lunar conditions. [13]

Engineering Exploration 3: Earthquake! Students begin by making observations of three different scale models of skyscrapers oscillating on MOXI's variable frequency shaker tables. A storyline emerges, which leads to the definition of an authentic problem and the presentation of an engineering design challenge: Design and build modifications to the skyscrapers that minimize swaying under different conditions of ground movement. Students collaboratively identify goals for success (criteria) and limitations (constraints) to delimit the problem. Materials are presented to teams of students, who engage in the engineering design process to design, build, and test modifications to the model skyscrapers that satisfy the criteria.

Additional field trip programs under development focus on energy, electricity, and light through a challenge to design an efficient home lighting circuit; energy, electricity, and aerodynamics through a challenge to design wind turbine blades that optimize energy output; and forces and motion through separate challenges to create a balanced kinetic sculpture and to create a cardboard structure capable of supporting weight.

Classroom Activities

For each Engineering Explorations module, we developed a set of 3 classroom activities: two completed prior to the field trip and one completed after. The activities were designed to supplement the field trip experience and extend the learning. The two pre-field trip classroom activities provided opportunities for the students to gain familiarity with the science phenomena and the engineering process prior to their visit to MOXI. The post-field trip classroom activity allowed for students to reflect on their process and, in the case of EE2, incorporate mathematical reasoning with their field trip observations to make more evidence-based decisions about optimizing their solutions.

Engineering Exploration 1: Riding the Rising Air. In the first classroom activity, students conduct an investigation of parachutes of different canopy sizes to understand the relationship between surface area and rate of fall of an object. In the second classroom activity, students build upon their investigation in the first classroom activity and design, test, and optimize a vehicle made using only a piece of paper and tape that can carry a metal washer and, when dropped, fall as slowly as possible. In the post-field trip classroom activity, students reconstruct a classmate's field trip vehicle from a drawing and compare how the vehicle behaves in the classroom drop test to how it acted in the MOXI rising air column exhibit. Through this comparison they begin to develop an understanding of balanced and unbalanced forces.

Engineering Exploration 2: Greenhouse on the Moon. In the first classroom activity, students explore how light travels through different colored filters and create a chart that compares different colors as seen through blue and red filters. In the second classroom activity, they use their color chart to decode (reverse engineer) the colors of a Rubik's Cube image hidden behind red and blue filters and then design and develop a secret message that can only be read by using the correct colored filter. In the post-field trip classroom activity, students explore various solutions that may have been proposed during the MOXI field trip and optimize these solutions along the variables of light transmitted, infrared radiation transmitted, and cost. Through this process, they begin to develop an understanding of energy conservation and transmission of radiation.

Engineering Exploration 3: Earthquake! In the first classroom activity, students investigate the structural strength of different geometrical shapes. In the second classroom activity, they design and build a structure, using only a piece of paper and tape, that can support the weight of a book. In the post-field trip classroom activity, students analyze seismographs and reflect on their field trip observations. Through this exercise they begin to understand the relationship between structure and oscillation.

Research accomplishments

As we encountered challenges during our developmental work, we used data collected to develop design principles that would help move our project forward and help other teams facing similar engineering curriculum design challenges.

Integrating classroom and field trip activities

The different goals and constraints of schools and informal institutions like interactive science centers makes developing curriculum that link students' school experience with field trips challenging. Schools are held accountable to state and national content standards and days are typically scheduled in fifty-minute increments. Extensive interviews with teachers and discussion with the MOXI project team staff provided insight into designing curricula that suited the goals of both types of institutions. Our research led to the development of design principles and guidance for curriculum development (Table 2). This development process and further details on the design principles is described in more detail in [6].

Design Principles
1. Design field trips as a stand-alone activity. 2. Field trip activity provides opportunities to engage with tools/exhibits unique to the interactive science center that can be used with a minimal learning curve. 3. Design field trips to be implemented similarly across a wide range of grade levels with differentiation where necessary. 4. Design pre- and post-field trip classroom activities to require only materials that are commonly available and easy to access. 5. Align pre- and post-field trip classroom activities with grade level literacy and math standards. 6. Design pre-field trip classroom activities so that science investigations precede engineering design challenges. 7. Design pre-field trip classroom activity engineering design challenge to follow the same general design process as field trip engineering design challenge. 8. Integrate building conceptual models of phenomena in pre- and post-field trip classroom activities.

Table 2. Design principles for integrating classroom and field trip activities.

Differentiating engineering design activities for younger and older students

A second challenge we faced was adapting the field trip engineering design challenge activities for a range of age levels. Unlike elementary school classroom teachers, who are tasked with teaching a broad range of content to a single grade level, facilitators of field trip programs at interactive science centers implement a limited set of programs for students from a wide range of grade levels, sometimes in back-to-back sessions. Thus, we were tasked with creating curricular activities for the field trips that were easily adaptable for younger and older students, without extensive extra training for the facilitators. As presented in greater detail in [14, 15], we identified that differentiation occurred primarily along three NGSS Science and Engineering Practices:

- Practice 3: Planning and carrying out investigations
- Practice 4: Analyzing and interpreting data
- Practice 8: Obtaining, Evaluating, and Communicating Information

We found that for each field trip program, focusing differentiation on these three NGSS Science and Engineering Practices best supported grade level math and literacy standards for younger and older students while keeping the engineering design challenges consistent.

Assessment and Evaluation

Collected data were also used to assess the curricula and inform iterative development. Teachers reported that students on field trips were engaged in learning important engineering design concepts and developing identities as engineers. The teacher questionnaire responses returned from both the stand-alone field trip and the Engineering Explorations curriculum module experiences show that the majority of the teachers were satisfied with the quality and effectiveness of their experiences with the curriculum and field trip activities. Teachers reported that students learned important science and engineering concepts and processes such as writing down predictions, making observations, constructing solutions to problems, testing and re-testing designs, combining solutions to get optimum results, solving problems, and collaborating and communicating information in teams. One 4th grade teacher stated, “They learned how to draw plans and think like engineers. The students were given a lot of autonomy in finding ways to experiment and test their thinking! They had a great experience testing their wonderings and were offered amazing tools and resources to deepen understanding.”

Further, the teachers reported that the curriculum modules allowed for students to make connections between the science concepts they learned in the classroom activities and the field trip engineering design challenge. One 6th grade teacher described, “I saw my students take the knowledge they learned from [the pre-field trip activities] and applied them to create a lunar [green]house... I did like that this was a hands-on activity and that it was a way to apply what they had learned in class. Also, they had to work together to solve a problem.”

Teachers also developed their own understanding of engineering design. The vast majority of teachers whose students participated in the full experience reported that they themselves learned about the engineering design process and were able to use what they learned in their own classrooms. These teachers also suggested types of support they would need in order to implement the full Engineering Explorations curriculum module in their classrooms: Provide video examples to support implementation, reduce materials required for activities, provide additional structure and step-by-step instructions, make further connections to the “real world,” make connections to actual scientists and engineers, and provide additional opportunities for assessment. These suggestions are influencing the ongoing iterative development.

Discussion

The evaluation and research on this project indicate that the field trips and curriculum for classroom activities lead to positive engineering experiences for K-12 students and learning opportunities for both teachers and students. Indeed, a significant finding was that the teachers participating in this program learned about science and engineering instruction just from observing research and development staff implementing classroom activities with their students and developed confidence in themselves as engineering and science teachers. Furthermore, they realized the value of incorporating engineering design at their grade level and observed that their students were capable of and enjoyed engaging with engineering design challenges.

Our research accomplishments have implications beyond engineering education. Research indicates that field trips in general are not well integrated into the school curriculum. Curriculum developers and teachers can use the design principles to develop classroom activities that connect with field trips to other informal science institutions such as zoos, aquaria, and natural history museums. Such institutions also challenged to differentiate field trip activities across a range of ages. The strategy of focusing differentiation on specific NGSS Science and Engineering Practices to best support grade level math and literacy standards for younger and older students can inform curriculum design at other informal science institutions.

Conclusion

Over 5,000 children in grades K-12 attended Engineering Explorations field trip programs at MOXI. These students developed an understanding of engineering design and engaged in solving an engineering design challenge. In addition, the teachers who brought their students on field trips reported that the activities led to an increase in their own understanding of engineering education. In a survey, one teacher said students learned, “problem solving and how to use failing as a learning tool,” while another wrote, “problem solving takes going back and retrying, refitting, over and over again to get it right, or what you want it to be. Along the way you learn regardless.” Teachers especially liked the portion of the lessons where students were constructing, testing, and revising their designs, as this both engaged students and helped them learn through trial and error, like engineers do. Interactive science centers are in a unique position to provide opportunities for engineering education through K-12 field trip programs. Early experiences in engineering and science have been shown to be important for developing an interest in STEM and motivation for pursuing STEM careers. The Engineering Explorations curriculum modules provide opportunities for students and teachers alike to be introduced to engineering design.

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