The study of collaborative practices at interactive engineering challenge exhibits—background and methods

(The C-PIECE Study)

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Abstract
This paper provides detailed descriptions of the goals, theoretical perspectives, context, and methods used in *A study of collaborative practices at interactive engineering challenge exhibits (the C-PIECE Study)*, the first of two studies in the Designing Our Tomorrow (DOT) research program. The C-PIECE Study supported foundational and exploratory lines of inquiry related to engineering practices used by families engaging with design challenge exhibits. This paper describes the study background and methods as an anchor to four other products that detail these four specific lines of inquiry and findings.

Introduction

DOT project goals
Designing Our Tomorrow—Mobilizing the Next Generation of Engineers (DOT) is a multi-deliverable project funded by the National Science Foundation (NSF, DRL-1811617). The project focuses on promoting and strengthening engineering education in an informal museum environment for girls 9-14 and their families.

DOT capitalizes on exhibits as unique family learning environments to foster family participation in engineering. The project utilizes culturally responsive co-development and research strategies to provide challenges that highlight the altruistic and collaborative aspects of engineering.

The DOT project contains two research studies: *The study of collaborative practices at interactive engineering challenge exhibits* (the C-PIECE Study) and *A study of facilitating family engineering design practices at exhibits* (Study 2). These studies contribute to theoretical and practical conversations in engineering education. Data from the C-PIECE Study were used to inform the development of a 2,500 square foot traveling, bilingual Spanish/English exhibition of exhibits. The exhibits will engage visitors in biomimicry where they can learn from nature's strategies to design solutions and associated professional development for informal science educators.

The C-PIECE Study, the focus of this paper, supported foundational and exploratory lines of inquiry related to engineering practices used by groups engaging with design challenge exhibits and informed the DOT project's design and development research.

This paper describes the context and methods that are cornerstone to the investigation, and serves as an anchor for four other products based on this first research study (Herran et al., 2021; Randol et al., 2021a; Randol et al., 2021b; Randol et al., 2021c).

Links to these products, as well as other deliverables related to the C-PIECE Study, will be made available on the DOT website (www.engineerourtomorrow.com).

Within this paper, we will describe the context and methods of the C-PIECE Study by referencing the rationale, prior work, and approaches that fuel the overall DOT project. We will then describe the goals of the DOT research program and discuss details specific to the C-PIECE Study, including our connections with prior work, questions, protocols, and data management. The language used in this paper reflects the context in which the paper was written—a project still in progress. As such, the verb tenses may change accordingly; future tense when describing project events that have not yet taken place, past tense when describing project events that have already taken place, and present tense to discuss project actions that are taking place during the writing of this paper.

DOT project rationale

Need to broaden participation in engineering

As a global community, there are many local and regional problems that can benefit from engineering practices. For instance, many of the United Nations' Sustainable Development Goals (UNSDGs), which relate to some of the most pressing issues of our time (e.g. hunger and clean energy), require engineering knowledge and skills (United Nations, n.d.). Addressing UNSDGs requires community members to participate by identifying challenges in their daily lives and designing solutions that benefit both themselves and others.

One UNSDG pertains to gender equality, namely ensuring that women and girls enjoy the same rights as men. In order to increase gender equality related to engineering, it is important that adults support girls' engineering identities (National Academy of Engineering [NAE], 2008; National Research Council [NRC], 2009; University of Wisconsin–Milwaukee, 2008; WGBH, 2005). To this end, it is important to show girls not only the social and altruistic aspects of engineering (Eccles, 2006; Fadigan & Hammrich, 2004; Jenkens & Pell, 2006; NAE, 2009;

Weisgram & Bigler, 2006), but also how engineering affects their lives (Fadigan & Hammrich, 2004; Liston et al., 2007).

To support the need to broaden participation in engineering, the DOT project targets girls 9 - 14 years old and their families by applying an equity approach that frames engineering practices as authentic, everyday activities (Philip & Azevedo, 2017).

Need to better understand engineering learning experiences at exhibits
An increasing number of federally funded projects have focused on encouraging youth and families to learn about engineering (e.g., GRADIENT, Cardella et al., 2013; Engineering is Elementary, Cunningham & Lachapelle, 2014; and Head Start on Engineering, Pattison et al., 2016). This trend, paired with the increasing popularity of design challenge-based engineering learning experiences (those that allow participants to explore and apply the engineering design process to create solutions for a given problem) at science centers (e.g. Wang, 2014), provides evidence that engineering education outside of the classroom setting is important.

The Oregon Museum of Science and Industry (OMSI) in Portland, Oregon accordingly explored design challenge development as part of NSF-funded *Designing Our World* (DRL-1322306), a project aimed at engaging girls authentically in STEM using exhibit experiences. We discovered that open-ended activities that provided no initial guidance confused and overwhelmed visitors. However, including an example of how to proceed created an opening for visitors to engage in activities of greater complexity.

The DOT project aims to improve the practices elicited by an exhibit while also encouraging awareness of participation in engineering, collaboration among family members, and satisfaction with the overall experience.

DOT project strategy
Following recent recommendations in the informal STEM field, this research uses multiple culturally-responsive strategies (e.g. Garibay and Teasdale, 2019; Kirkhart and Hopson, 2010; OMSI, 2016). Such strategies include prioritizing broadening participation in engineering, privileging underrepresented voices in engineering—those of girls and members of Latino communities, and striving for multicultural validity.

Our team recognizes that power dynamics exist between researchers and participants and we approach our relationships with empathy and compassion (OMSI, 2016). We actively value broad participation in engineering by recognizing that participants contribute assets and funds of knowledge to the engineering education research (Bevan et al., 2018). We define engineering approaches broadly, as problem-solving processes and sets of activities that everyone does, or can do, in their everyday lives (Bevan et al., 2018). And we recognize that culture plays a central role in learning and education (Bevan et al., 2018).

Since Spanish is the second most spoken language in the US and the Latino population is growing in our region, this project is designed to privilege voices from Latino communities through codevelopment and partnering with an organization that is led by and serves Latinas and their families, staffing project leadership positions with members of Latino communities, working with the public in Spanish and English throughout research processes, and engaging members of Latino communities as participants in the research study.

Our culturally responsive strategies include efforts to strengthen—and reduce threats to—all five dimensions of multicultural validity (Kirkhart and Hopson, 2010). To support methodological validity, we have ensured that members of Latino communities are involved in all aspects of the research. To reduce threats to interpersonal validity, we work to cultivate trust with participants and our organizational partners. To support theoretical validity, we have approached this project from a sociocultural perspective (Cobb & Bowers, 1999) that recognizes learning is co-created within personal, social, and physical contexts. Through the use of multiple methods to capture the wisdom of participants—naturalistic observation; video recording; interviews; and surveys, we support experiential validity. By adopting a perspective that engineering is not an end, but a means for community members to achieve their goals (NSF, 2008; Bevin et al., 2018), this research supports consequential validity.

DOT project theoretical perspectives

Theoretical perspectives in science museum and exhibit experiences
The theoretical perspectives informing the DOT project follow those described in *Learning Science in Informal Environments People, Places, and Pursuits* (LSIE) (NRC, 2009), a summary of trends related to learning and education theory in informal science education. The LSIE summary provides aspirational goals, common language to describe the trends, and recommendations for further research and development. Exhibit-related projects at OMSI have followed these trends over the past two decades through NSF-funded design and development research projects. DOT is likewise building on this accumulated knowledge and innovation to help girls and their families engage in engineering practices to achieve their goals. We acknowledge that it is a coarse comparison to assume engineering education in museums is similar to science education in museums. However, because engineering education in museums is nascent it is logical, if not necessary, to draw in part on material from informal science education.

Ecological framework

The authors of the LSIE synthesis recommend situating informal science education experiences within an ecological framework (a framework that focuses on the relationship of a person to their social and physical environments) that can simultaneously hold multiple theories on people, places, and culture (NRC, 2009). This framework is congruent with the perspective used in DOT. As a rich, designed, real-world physical and social environment, this project manages many variables and potential theoretical explanations surrounding all of its project deliverables.

Ecological construct of affordances
An important ecological construct for the DOT project is the construct of affordances. An affordance is the functional fit between environment and behavior (Gibson, 1979). As a cross-disciplinary project team creating a designed environment, we find the term "affordance" useful for describing the qualities of an environment for inviting certain behaviors (Gibson, 1979; Norman, 1988). OMSI and other science museums commonly use this term in their research (e.g. Cardiel, et al., 2016; Achiam, et al., 2014; Gariby, 2014; Bertschi, et al., 2008) to describe the characteristics of an exhibit that supports visitor interactions and learning behaviors. In the context of the DOT project, the term is frequently used to

reference exhibit characteristics that support engineering design practices among girls 9-14 years old and their families.

Sociocultural and cognitive lenses

The LSIE authors determined that sociocultural and cognitive lenses on learning are predominant and useful in the research and development of informal science education experiences (NRC, 2009); both lenses include some recognition of the roles physical environments serve in learning, including everyday settings (NRC, 2009). The DOT project acknowledges the presence of culture in all educational activities. The project identifies groups, rather than individuals, as learners (Bell, et al., 2006; Astor-Jack, et al., 2007) and communities as beneficiaries of impact (NSF, 2008; Bevin et al., 2018). The OMSI research group uses multiple data collection methods, including methods of naturalistic observation and self-report, to capture information through both sociocultural and cognitive lenses.

Notions of co-constructed learning
As a museum exhibit project, DOT will leverage notions of co-constructed learning found within theories of sociocultural and cognitive lenses. The project may benefit from working with broad explanatory frames like social-constructivism (Vygotsky, 1978) and distributed cognition (Achiam et al., 2014). Likewise, narrower concepts like scaffolding (Andre, 2017) or communities of practice (Lave & Wenger, 1991) may provide useful underpinnings. While each of these notions is distinct, we will leverage them in the overall project to better understand how to reinforce the advantages of intergenerational, family learning to exercise informed engineering practices and awareness of engineering.

Theoretical perspectives commonly associated with design challenges

Although there is significant variation across engineering design challenges, certain characteristics are widely shared. For instance, Householder and Hailey (2012) suggest that design challenges are open-ended with an ill-structured problem requiring the use of science and math to create a human-built solution to the stated problem. Design challenges are often associated with problem-based learning (PBL) theoretical perspectives (e.g. Porath & Lordan, 2009). A review of research by Haugen et al. (2018) on design challenges using PBL frames found that design challenges can positively influence understanding and retention of science content and increase motivation, interest, and confidence with regard to solving engineering problems.

Drew (2020) analyzed the principles of PBL approaches and found that they are congruent with theories of situated learning and situated cognition (Hung, 2002). While PBL research is often conducted in classrooms, situated learning and situated cognition emphasize learning within authentic contexts, and in some cases may help bridge PBL with the sociocultural and cognitive lenses commonly used in museums.

The emergent educational theory of informed design

Building on work founded in information processing theory (Adams & Atman, 1999; Axton et al., 1997; Goel, 1989), Crismond and Adams (2012) developed the emergent educational theory of informed design. These authors established a framework of learning trajectories, instructional goals, and teaching strategies associated with engineering termed the Informed Design Teaching and Learning Matrix (Crismond & Adams, 2012), which is referred to in this paper as the *Matrix*. The evidence-based strategies in the Matrix include engineering-related processes such as understanding the challenge, experimenting, and iterating. Additionally, the Matrix provides expectations of how learners' behaviors change as they transition from beginning designers—in terms of engineering familiarity and comfort—to more informed designers. For example, a beginning designer might understand the challenge as a problem to *solve*, and an informed designer might understand the challenge as a problem to *frame*. Similarly, a beginning designer might approach revisions to solutions in a haphazard way, and an informed designer might approach revisions in a managed and iterative way (Crismond & Adams, 2012). Crismond and Adams (2012) also suggest ways that teachers and classroom environments can support a learner moving from beginning to informed, making this approach well-positioned for study within the sociocultural perspective commonly used in museum research (e.g. NRC, 2009).

Although informed design is well-suited to the context of informal education, the idea of learning progressions, or a sequence of skills that an individual learner develops over time (Crismond and Adams, 2012; National Research Council, 2007; Duschl, 2019), is not. The sociocultural context of museums requires that learning be studied not through the assessment, but understanding of the informed design strategies that can be supported by the tools used for experiential learning.

To this end, this study led to the development of the *C-PIECE framework: Collaborative practices at interactive engineering challenge exhibits* to articulate the strategies used by social groups whose members may have different developmental levels, educational histories, or experiences. Proficiency levels within the framework are not assumed to be moved through in a linear fashion or persist throughout an interaction.

To our knowledge, DOT is the first informal education project to transfer the Matrix to an exhibit setting for the purpose of researching and developing an integrated approach to engineering practices, design challenges, and exhibit components that will exercise participants' more informed engineering design practices.

Overarching goals of the DOT research program

As part of DOT's overarching goals to strengthen family engineering learning by elevating the effectiveness and impact of engineering design challenge exhibits, we took a closer look at the family engineering design practices elicited by engineering design challenge exhibits. We sought to better understand engineering design practices, their relationships to exhibit features, and their relationship to levels of engineering proficiencies.

To this end, we gathered evidence related to the overall guiding question, "What can we better understand about fostering engineering design practices associated with more informed levels of engineering proficiencies by improving engineering design challenge exhibits and facilitation for families?"

We used qualitative approaches to create a framework that can be used to inform various aspects of exhibit-based engineering challenges.

As a research and development group located within a science museum, our work generally integrates research and practice through design and development research. This type of research can benefit other professionals who use evidence to inform their work (e.g. researchers, practitioners, and those who hold both roles simultaneously). We have shared, and plan to continue to share, the findings from the DOT project with partners, including those who engaged girls and families with the project, and other colleagues associated with informal engineering education.

C-PIECE Study contributors

The research took place in Portland, Oregon and included participants primarily living in or visiting the region; we communicated with one another and the participants in English and/or Spanish. Our research team included persons identifying as female or male who had grown up in the United States or elsewhere. Our academic backgrounds include education, policy, and natural, physical, and social sciences. Our diverse professional identities include researchers, exhibit developers, and educators. To maintain continuity between this research and the other aspects of the DOT project, we consulted with partners, advisors, and members from other DOT project teams to obtain input when appropriate.

We worked with a Research Advisory Committee (RAC) composed of three members with research expertise in museum education, engineering education, and measurement. We consulted with RAC members via several meetings focused on conducting rigorous, reliable, valid, and culturally responsive research.

We also used an expert review process to strengthen the validity of the materials, approaches, and constructs developed as part of this study. In this process, individuals and small groups with expertise in a variety of areas—informal education with Latina girls, engineering education, informal science education, biomimicry education, engineering education research, informal STEM education research, and museum research—reviewed and commented on our work.

C-PIECE Study research process

This study was not conducted in an entirely linear fashion; it involved concurrent reading, consultations, efforts, reflections, and revisions (a C-PIECE Study process map appears in Appendix A.2 and on the DOT project website, www.engineerourtomorrow.com). This study roughly followed a process of:

- Refine questions and approach (Pilot)
- Create the draft C-PIECE framework
- Create operational definitions of practices and design initial methods
- Select exhibits for study
- Iteratively use and improve methods and framework
    - Engage participants in data collection methods
    - Review methods and findings with collaborators
- Refine analysis questions and approach

- Manage and code data generated by methods
- Analyze data
- Interpret results; revise methods and the C-PIECE framework
- Disseminate findings and recommendations, including C-PIECE framework

This paper provides descriptions of the C-PIECE Study process activities from Refine questions and approach (Pilot) to Iteratively use and improve instruments. The other four C-PIECE Study products present four lines of inquiry from the study process and cover the activities: Refine analysis questions and approach, Manage and code data generated by methods, Analyze data, Interpret results; revising methods and the C-PIECE framework, and Disseminate findings and recommendations.

C-PIECE Study planning and piloting

Additional literature review

As part of the C-PIECE Study, we gathered updated information about engineering proficiencies by reviewing material from journals, books, and credible websites. We reviewed material about qualitative research approaches to develop protocols and instruments (tools used to collect data; e.g. interview, survey), including material on validity.

We also explored sources for material on engineering proficiencies, learning processes, and instruments. We collected and reviewed publications from both English and Spanish databases, including, but not limited to: EBSCO, Journal of Science Education Research, American Society for Engineering Education Papers on Engineering Education Repository (ASEE PEER), Web of Science, ProQuest Education Database, previous OMSI projects, NSF Award Database, Research Gate, EBSCO-en Español, and Revista Educación en Ingeniería.

Our culturally responsive research strategy included having informed conversations with museum visitors who spoke English and/or Spanish to learn what words they would use to describe engineering proficiencies, processes, and learning. We then applied these conversations to instrument development later in the project.

Adapting the formal education Matrix to support informal education
We selected nine models of engineering to inform our adaptation of the Matrix into a new format for informal engineering education (Barriault & Pearson, 2010; Bevanet al., 2014; Crismond & Adams, 2012; Dorie et al., 2014; Ehsan et al., 2018; Lussenhop et al. 2015; Museum of Science, 2012; Paulsen & Burke, 2017; Wang, 2013). From these models, we identified three key proficiencies—*understanding the challenge*, *testing*, and *iteration*. Individual practices from each model were grouped by similarity under one of these three proficiencies. For clarity and alignment with the language used in the exhibit design and facilitation, we used the wording *defining a problem* rather than *understanding the challenge.*

Based on additional research and conversations with the RAC, we learned that there was a relationship among all three proficiencies; practices associated with *testing* and *iteration* supported *defining a problem*. This additional research resulted in our collapsing the testing and iteration proficiencies into a larger proficiency referred to as *improving a design* (Kelley, 2010; Cunningham & Carlsen, 2014).

Lists of key practices within the *defining a problem* and *improving a design* proficiencies were drawn from the literature and then reviewed by the project team to exclude redundancies. Each practice was then assigned to a level of proficiency (beginning, intermediate, or informed) based on how it either corresponded to levels in the *Matrix* or was described in the primary publication.

The literature and our conversations with the RAC also prompted us to narrow our research focus to one proficiency—*defining a problem*. This decision was made in part because this proficiency was largely described within the context of formal education in the literature we reviewed. As a result, we were left with questions as to how museum visitors engage in this process. As museum professionals, we recognized that the *defining a problem* proficiency can apply directly to the exhibit development process and facilitation by informal science educators. Given that DOT is engineering focused, and a defining characteristic of engineering is the formulation of solutions to problems (Epistemic Practices of Engineering for Education, 2017), the focus on *defining a problem* seemed too relevant and compelling to be overlooked.

From this research, we produced a rough draft of the C-PIECE framework--our adaptation of the Informed Design Teaching and Learning Matrix (Crismond & Adams, 2012). The framework is organized by proficiency (*defining a problem* and *improving a design*) with practices for each grouped by similarity and divided into the levels of proficiency—beginning, intermediate, and informed. The draft framework was refined based on conversations with the RAC and the expert review process, and it was used to inform the development of the initial instruments used in this study, which then informed further refinements of the framework and the instruments. See Randol et al. (2021b) for greater detail on the development of the C-PIECE framework now available for use by informal education professionals.

Long-term potential of adapting the Matrix for use in informal education

Our strategy to adapt the Matrix involved retaining a practical focus that could, over the long-term, yield understandings of engineering learning for informal education that somewhat parallel those informed by the Matrix in formal education. For example, this research-based adaptation could potentially help informal education practitioners do the following:

- Identify family practices at informal engineering education experiences that are associated with engineering proficiencies and levels of engineering proficiencies
- Identify exhibit characteristics that seem to afford the practices during exhibit experiences
- Connect the practices with measures of families' awareness of engaging in engineering processes at exhibit experiences
- Develop and situate practitioner theories about engineering learning and education through unfacilitated and facilitated exhibit experiences
- Develop engineering exhibit experiences
- Develop facilitation strategies at engineering exhibits
- Evaluate the designs of engineering exhibit experiences

The aim was to develop a foundational tool for informal education professionals in the form of an evidence-based framework of practices that are associated with the defining a problem proficiency and feasible for families to exercise through exhibit experiences. The development of this framework is the foundation of the C-PIECE Study and the primary resource that we are contributing to the field.

An overarching question informed by piloting and planning
Informed by the C-PIECE Study pilot activities, along with recommendations from the RAC, the C-PIECE Study investigation focused on the following overarching research question: *What can we better understand about fostering engineering design practices associated with more informed levels of engineering proficiencies by improving engineering design challenge exhibits and facilitation for families?*

C-PIECE Study objective, questions, and approach

C-PIECE Study objective
The purpose of the C-PIECE Study was to develop theory-based tools to guide ways that engineering design challenge exhibits can elicit more informed engineering design practices associated with defining engineering problems and awareness of participation in engineering (Paulson & Bransfield, 2009; WPI, 2007). The culmination of the study was the creation and refinement of credible and trustworthy instruments and protocols to measure visitor experience outcomes at engineering exhibits and the development of the C-PEICE Framework to assist informal education professionals with designing, facilitating, evaluating and researching engineering design challenge experiences (Randol et al., 2021c).

C-PIECE Study questions
We had four research questions specific to engineering awareness or practices and measurement. Three were related to engineering practices, and one was related to engineering awareness.

Practice-related questions

- What practices associated with defining engineering problems can we observe and document (measure) among families engaging with engineering design challenge exhibits?
- What are the relationships among these practices?
- What are the relationships among these practices and engineering design challenge exhibit features?

Awareness-related question

- What are the relationships among engineering awareness and engineering design challenge exhibit features?

C-PIECE Study approach

Prior to developing instruments to measure engineering practices, we conducted a review of the literature to identify 1) instruments in use for measuring the *defining a problem* proficiency within an informal education context; 2) instruments in use for measuring the *improving a design* proficiency within an informal education context.

Definitions of proficiencies

Defining a problem

Two of the most promising items found in the literature review for instruments related to *defining a problem* included the Museum of Science's Design Challenges Observation Instrument (Museum of Science, 2012) and the related Facilitation Research for Engineering Design Education (FREDE) report (Lussenhop et al., 2015), which included an "Ask/Imagine/Plan" phase that encompasses indicators, or behaviors associated with understanding the challenge. Both provided information that informed the development of the instruments related to *defining a problem.* While the FREDE report documented the time spent in an engineering design phase, along with more qualitative data, the Design Challenges Observation Instrument looked for several observable behaviors such as reading or listening to information provided, relating content to prior experiences, and brainstorming ideas. In their study, *Capturing the Engineering Behaviors of Young Children Interacting with a Parent*, Dorie, Cardella, and Svarovsky (2014) included a section titled "Problem Scoping," which included identifying constraints, restating the goal, and familiarizing oneself with the materials.

Improving a design

As noted above, *improving a design* is a proficiency encompassing both testing and iteration (Kelley, 2010; Cunningham & Carlsen, 2014). Elements of *improving a design* have been identified in different ways within the literature. For example, testing was found in Crismond and Adams (2012) within an identified proficiency of Conducting Tests and Experiments. The FREDE instrument captured the number of designs tested, and Dorie et al. (2014) included an indicator for assessing goal completion. Likewise, the Design Challenges Observation Instrument (Museum of Science, 2012) included behaviors such as testing prototypes, observing testing, identifying what happened, identifying the pros/cons of a design, and comparing the results to one's own past performance.

As with testing, iteration was found in Crismond and Adams (2012), specifically within the two engineering proficiencies of Troubleshoot and Revise/Iterate. Likewise, the FREDE instrument looked at iteration by including both the number of designs tested and the amount of time spent in the create/build phase. Dorie et al. (2014) similarly investigated iteration through the use of codes, which included increasing efficiency, iteration based on feedback, and optimization. Additionally, indicators for iteration behaviors found in Museum of Science (2012) included practices such as Makes Needed Improvements to Help Prototype Reach Goal, Brainstorms Ways to Make Successful Prototype Better, Makes Aesthetic Improvements, and Reevaluates the Goal.

From this literature, we were able to identify practices—strategies, approaches, or series of actions that are part of engaging in an engineering proficiency—related to the proficiencies of *defining a problem* and *improving a design*. This helped the team to better understand the types of practices that could reasonably be observed, and led to the creation of operational definitions for each—providing a shared understanding of what each practice might look like during a group's interaction with a design challenge.

Engineering awareness

Although engineering awareness construct was not the focus of this study, it was a topic that we were interested in better understanding. Because engineering awareness is a term that may be interpreted in many different ways, it was important to develop a clear definition that provides context. We view engineering awareness as metacognitive knowledge that A) connects the ability to engage in engineering practices to knowing what those practices are, B) provides understanding that the practices are part of a problem-solving process, and C) leads to the recognition that the practices and processes are associated with the socially constructed term engineering (Randol et al., 2021c). As discussed in Randol et al. (2021c), for the purpose of this study, engineering awareness is comprised in part by the facets of recognizing that one uses a set of practices and strategies, that they are part of a problem-solving process, and that the practices, strategies, and process are part of doing engineering.

General C-PIECE research protocol

With a clear idea of the constructs used in research on individual learning progressions, we were ready to see what the constructs looked like with groups in a sociocultural context focused on proficiency levels. To start, we collected data from visitors with four methods: 1) an observation instrument, 2) a survey, 3) an interview guide, and 4) a video-taping protocol. We explored different aspects of the visitor experience outcomes (visitor satisfaction, engineering awareness, intergenerational communication, and engineering proficiencies) through these different methods, as described below.

During data collection, we met participants in the museum lobby and accompanied them to the exhibit under observation. Upon arrival at the exhibit, a researcher explained both the informed consent and photo release documents, providing adults with paper copies, which they were asked to sign. After consent had been provided, the video camera was turned on, and researchers started to make written observations. Once participants had finished interacting with the exhibit, they were asked to participate in an interview and then complete a survey.

Observation

The observation tool was designed to capture group engineering-related practices from the draft C-PIECE framework and the order in which they occurred (Appendix B.1). The observation instrument required us to take open notes, tally the number of versions of a solution the group designed, and record instances of seven engineering-related behaviors, in particular.

The observation instrument was also designed to document intergenerational communication. In the pilot study, we included a holistic measure of intergenerational communication that had been used by Pattison et al. (2018) to document the extent to which members within a group were talking to one another about the exhibit. Our initial analysis showed that this approach did not yield the insights about intergenerational communication that we had hoped to capture. In final data collection, we used a modified version of the social engagement tool developed by the Science Learning Activation Lab (Moore, Bathgate, Chung, & Cannady, 2011) to document intergenerational communication.

Visitor survey

A two-page (one sheet, front and back) written survey was given to groups after their exhibit interaction (Appendix B.2). The first four questions were related to the exhibit experience: one question pertained to satisfaction with the exhibit experience (modified from Packer, 2004), and three questions explored facets of engineering awareness. The order of the three awareness-related questions was varied across survey versions to eliminate ordering influences of the questions. Four demographic items were included at the end of the survey to gather information about the ages and gender make-up of the group, the individuals' races/ethnicities, and the language(s) they spoke at home. We used a Spanish version of this instrument when collecting data from families who preferred to communicate in Spanish (Appendix B.3).

Interview

Guided interviews (Appendix B.4) were conducted with groups after they had completed their survey. These interviews were primarily used to better understand the practices and proficiencies used by groups when interacting with the exhibit. To this end, interviewers asked members of the group to describe what the exhibit was about, what they did at the exhibit, the steps they took, and the role(s) they played. We used a Spanish version of this instrument when collecting data from groups who preferred to communicate in Spanish (Appendix B.5).

Video-recording protocol

Intended to measure the proficiency of *defining a problem* and intergenerational communication, the video-protocol primarily focused on creating a descriptive understanding of *defining a problem* and its relationship with the practices associated with *improving a design*.

Prior to collecting the video data, we posted signs throughout OMSI informing visitors that video recordings would be taking place at certain exhibits. Stanchions were then placed around the exhibit of interest to help ensure that visitors not participating in the study did not interfere with study participants' interactions or the video-recording process.

We positioned ourselves and the video-recording equipment outside of the stanchions and away from museum traffic. Video recording started after participants provided written consent and entered the stanchioned area and continued until they were finished interacting with the exhibit; video recordings were four to 33 minutes, with most videos under 20 minutes.

After the data collection was complete, the video files were downloaded from the camera's memory card onto a secure server and placed on a back-up hard drive.

Selecting exhibits

Prior to implementing the protocols described above, we had to identify which of the available exhibits best suited the requirements of the data collection and also possessed characteristics important to elicit engineering-related behaviors. In this section, we discuss both the process of selecting the exhibits used in this research and the suitability of the chosen exhibits.

Exhibit selection criteria

The criteria we used to select the engineering activities and exhibits for this study were informed by a literature review on design challenges and the draft *C-PIECE framework: Collaborative practices at interactive engineering challenge exhibits*. We attempted to select activities that presented an explicit goal or challenge, had multiple outcomes, had no one "right" answer, provided clear feedback for success, and provided opportunities for creating and improving designs and improving approaches to designs. Likewise, we prioritized exhibits that had enough space for multiple people to work simultaneously and allowed group members to watch others prior to engaging. Additionally, we sought out exhibits that could be cordoned off to create one entrance and exit with clear lines of sight for observation and video recording. Although the selection criteria did not include exhibit content, because the DOT exhibition content is focused on biomimicry and OMSI did not have biomimicry exhibits at the time, exhibits with a connection to sustainability were preferred.

Exhibits

We applied the exhibit selection criteria to activities throughout OMSI, piloting those that fit the best to test their suitability for use in real-world data collection. We ultimately selected three exhibit components—*Catch the Wind, LEGO® Drop,* and *Build a Boat.* Both *Catch the Wind* and *Build a Boat* from are part of a permanent exhibit developed by OMSI as part of an NSF-funded project, Designing Our World (DRL-1322306), aimed at engaging girls and their families with experiences that focused on the social, personally relevant, and altruistic aspects of engineering.

The *LEGO® Drop* exhibit is one of several hands-on exhibits developed by OMSI's Center for Innovation team aimed at providing visitors opportunities to design, create, and test solutions related to society's grand challenges.

The signage at the *Build a Boat* exhibit was vague in the guidance that it provided to visitors (Appendix G.1). Specifically, it did not present a defined problem for visitors to solve. The exhibit contained two spaces: a building station (Figure 1) and a testing tank (Figure 2). The physical layout of each provided space for multiple people to interact simultaneously with the exhibit.

Figure 1. Visitors at the *Build a Boat* exhibit.

The building station offered hull pieces in different shapes and sizes, two sizes of sails, and cargo to complete the design. Groups could also test their design in the testing tank (Figure 2).

Figure 2. Visitors testing their boats at the *Build a Boat* exhibit.

The testing tank contained water, an air blower, obstacles, and a finish line to provide visitors with an opportunity to test their design. Furthermore, the exhibit could be cordoned off to create one entrance and exit, and it had lines of sight for observation and video recording. For additional details about this exhibit, see the annotated image in Appendix G.1.

Catch the Wind

The *Catch the Wind* exhibit gave visitors an opportunity to create and test a variety of designs to solve the problem of generating energy from wind power. This real-world problem with a strong connection to sustainability was communicated to visitors through the text of the exhibit's signage.

This exhibit was group friendly and allowed multiple visitors to interact with the exhibit at the same time (Figure 3).

Figure 3. Visitors interacting with the *Catch the Wind* exhibit.

The exhibit provided a stand with a hub, a variety of K'NEX® pieces, and different shaped plastic blades (see Appendix G.2 for an annotated image of the exhibit). The exhibit's layout and position allowed access to be restricted, and, at the same time, we were able to place ourselves in a position to observe the exhibit.

LEGO® Drop

The *LEGO® Drop* exhibit examined the real-world problem of delivering supplies (e.g. food, water, medicine) to remote areas. With explicit objectives and outcomes for success communicated through signage, the exhibit provided visitors an opportunity to create a variety of designs and solutions to a specific problem. The exhibit included an area containing different materials for building a solution (Figure 4) and a separate area with three towers for testing designs (Figure 5). The space around the exhibit allowed us to cordon off the exhibit with a single entry and exit. There was a clear line of sight for observation and video recording. For additional details about the exhibit, see the annotated image in Appendix G.3.

Figure 4. Visitors building at the *LEGO® Drop* exhibit.

The building station provided visitors with signage containing information about the challenge, as well as plastic containers filled with a myriad of materials (e.g. pipe cleaners, fabric, string). Because the station was organized around a table, multiple group members could build at the same time. Participants could then test their design in the testing area.

Figure 5. Visitors testing at the *LEGO® Drop* exhibit.

The *LEGO® Drop* testing area contained three drop zones of different heights. Each drop zone contained a platform upon which visitors could place their designs, and each was equipped with a lever that, when pushed, angled the platform and caused anything atop it to fall to the floor. With three drop zones available, multiple people could test their designs concurrently.

Exhibit comparison

While similar in characteristics, each exhibit afforded different goals. For example, the *LEGO® Drop* exhibit suggested a very clear goal: design an apparatus that allows cargo to be dropped without sustaining damage. Similarly, *Catch the Wind* suggested a clear goal of creating a turbine that would spin in the wind, simulating electricity-generating turbines. However, *Build a Boat* provided visitors with an opportunity to define their goal; one visitor might choose to build a boat for speed, and another might have the goal of building a boat to carry large loads of cargo. In both cases, the visitors would have interacted with the same exhibit, but they would have had different experiences with different anticipated outcomes.

In addition to affording different goals, the exhibits differed in the variety and types of materials available to visitors. The *Catch the Wind* exhibit provided visitors with three shapes of fan blades, K'NEX® pieces, and a stand; the *Build a Boat* exhibit provided three basic shapes that could be connected to create short or long boats (some had keels, some did not), three shapes of sails, and cargo; and the *LEGO® Drop* exhibit had seven different items available, including Popsicle® sticks and mesh fabric (see Appendix G.3 for a full list).

The exhibits also varied in the ways in which the provided materials could be used. Each item provided at the *Catch the Wind* exhibit was meant to serve a single purpose, and there were a finite number of ways that one could have reasonably attached the K'NEX® to the stand and connected the blades to the K'NEX®. The variability of the materials derived largely from the number, angle, shape, and configuration of the blades. The materials at the *Build a Boat* exhibit were also provided with an expected use (i.e. hull pieces for floatation, sails as a means of propulsion, and cargo to increase drag). The *LEGO® Drop* exhibit afforded visitors the most freedom in deciding how to use their materials. This exhibit challenged visitors to use seemingly unrelated items to build an apparatus to protect dropped cargo. Material usage and configuration were limited only by a visitor's design and the amount of materials on hand.

For all three exhibits, signage played a role in informing visitors about the problem to be solved. However, the illustrations on the signage at the *Catch the Wind* exhibit unintentionally communicated a specific blade configuration that was impossible to replicate with the material provided. While this situation caused frustration and confusion for some visitors, it did not seem to diminish the messaging around defining the problem of the exhibit's challenge.

All of the exhibits provided adequate room for multiple people to simultaneously interact with the exhibit. However, at *Build a Boat* some participants tested their designs on the side of the testing tank that positioned their backs toward the camera and obscured their interactions. We accordingly stanchioned off this side of the tank to discourage participants from testing their designs there.

Emerging instrument integrity

The integrity of this study was guided by a qualitative lens. While this research used some quantitative measurements, the study as a whole relied on a qualitative methodology. We accordingly conducted literature reviews to identify techniques to increase instrument integrity, specifically trustworthiness and validity.

Trustworthiness is used to refer to the overall study approach and qualitative data collection methods and findings of the project (Lincoln & Guba, 1985). Lincoln and Guba (1985) outline a set of four criteria for qualitative research, which they refer to, on the whole, as trustworthiness: 1) credibility, which involves establishing that the results of research are credible or believable from the perspective of the participants; 2) transferability, or the degree to which the results of qualitative research can be generalized or transferred to other, similar, contexts and settings; 3) dependability, which refers to the potential consistency with which the results could be repeated and result in similar findings; and 4) confirmability, or the degree to which results could be corroborated by others.

The notion of validity is concerned with the accuracy and truthfulness of scientific research and findings (Van Manen, 1990); it describes the soundness, quality, and rigor of a study, including the instruments used in data collection. In this study, the term validity is associated with the instruments used to examine exhibit experience outcomes; it alludes to a view focused on how well a test measures what it is supposed to measure, or construct validity. This study also uses the term validity to refer to multicultural validity—the accuracy and truthfulness of the methods, measures, and protocols to reflect and consider the lived experiences of participants (Kirkhart and Hopson, 2010).

According to Kirkhart and Hopson (2010), multicultural validity includes five dimensions—interpersonal, theoretical, experiential, consequential, and methodological. Kirkhart (1995) argues that multicultural validity is a critical consideration to research and that any threats to these dimensions can undermine broader conversations of trustworthiness and validity.

Several organizations (e.g. the American Educational Research Association, the American Evaluation Association, the National Council on Measurement in

Education) state that validity relies on evidence to construct an integrated argument focusing on what inferences can be validly made from an instrument. This unitary view is the idea that validity focuses on construct validity and potential sources of evidence to support inferences (Brown, 2010; Loughland & Vlies, 2016; Reeves & Marbach-Ad, 2016). This approach is consistent with Grack Nelson et al. (2018), who stress that measure validity is not a static and universal feature of an instrument but rather a process that is dependent upon the context in which it is developed and used, including the audience, setting, constructs, and inferences.

Based on our current understanding of the nuanced distinctions among multicultural validity, trustworthiness, and construct validity, we considered and reflected upon the five dimensions of multicultural validity (interpersonal, theoretical, experiential, consequential, and methodological), Lincoln and Guba's (1985) four criteria of trustworthiness, listed above, and a unitary (evidence-based) approach to construct validity. We applied these ideas throughout each step of the research from the creation of the research questions to the interpretation of the findings.

To help ensure the integrity of this study, we applied culturally responsive approaches to develop the instruments for this research. We used an iterative process of implementation followed by reflection, discussion, and instrument refinement that included input from participants, OMSI researchers, educators, and project team members, plus partners and content experts. OMSI educators and researchers participated in instrument implementation, completed debrief forms following data collection, and were part of guided discussions intended to contribute to the construct and content validity of the instruments and the trustworthiness of the methods used in the study.

Participants

Recruitment

Consistent with a sociocultural perspective on learning (Cobb & Bowers, 1999), the unit of analysis that we used was groups—at least two visitors that include one visitor age 18 or over and one visitor under the age of 18. As such, the participant recruitment plan employed two strategies to engage families with girls ages 9-14.

The first strategy utilized social media to invite members of the public to complete a screening questionnaire (see Appendix E for recruitment message). Those families who fell within the target audience were invited to schedule a time to visit OMSI and participate in the study. Recruitment using this method continued until we had collected at least 10 videos for each exhibit that met both the video and audio quality thresholds necessary for the data analysis.

The second strategy ensured that the research included representation from the Latino community. Based on recommendations from cultural advisors, the second strategy included snowball sampling techniques to recruit Spanish speaking families. To help with recruitment, we contacted two community partners who have connections within the Latino community: Adelante Mujeres and Metropolitan Family Services. Additionally, we posted flyers in locations where bilingual (Spanish and English) families were likely to visit and provided flyers (Appendix F) for distribution to Impact Northwest, a local community organization trusted by the Latino community. Lastly, individual team members used snowball sampling in their own personal and professional networks to recruit families. Recruitment of bilingual families continued until we had collected videos of at least five families with each exhibit that met both the video and audio quality thresholds necessary for the data analysis.

We collected data from 71 family groups, including 22 family groups that identify as bilingual (Spanish/English). All recruitment, consent, assent, and data collection documents and procedures were available in both Spanish and English. We followed OMSI guidelines for collecting, managing, and analyzing data in two languages (e.g. more than one researcher is fluent in Spanish and English, instrument development includes members of Latino communities, data is collected in participants' preferred language(s), and kept in the source language throughout analysis).

Informed Consent

Video data collection followed the posted-sign method of informed consent (Gutwill, 2003). Bilingual (Spanish and English) signage notifying visitors that they were being video recorded was placed at the entrance of the museum, next to the exhibit, and on the exhibit itself.

An informed consent document was provided to all participating families in either English (Appendix C) or Spanish (Appendix D), as preferred by the family. Prior to asking participants to sign an informed consent form, researchers discussed informed consent and highlighted the purpose and procedures of the research and explained potential risks associated with participation, the participants' rights, and expectations related to confidentiality. Participants were offered a copy of the consent document containing contact information for both the evaluation manager overseeing the research and the study's institutional review board.

Data collection

Consistent with a sociocultural perspective on learning (Cobb & Bowers, 1999), the unit of analysis that we used was groups. Families or family groups are defined as groups of at least two visitors that include one visitor age 18 or over and one visitor under the age of 18.

Data management

Engineering design practices video codebook

Four people on our research team—three with backgrounds as researchers and one with a background as an educator—analyzed and coded the videos. One of the researchers identifies as a White male; the other two identify as Latina, each representing a different nationality and culture. The educator identifies as a White female. While the members of the team differ in their research experience, they will henceforth be referred to as "researchers."

The focus of the video analysis was to obtain a descriptive understanding of *defining a problem* and its relationship with the proficiencies associated with *improving a design*. The video analysis took place in two phases: initial coding and focal coding (described below). To prepare the video data for analysis, we needed to create and refine a codebook of engineering practices.

Initial video coding of family engineering design practices

To create both an analytical framework and a shared understanding of the framework, we began initial coding by reviewing the videos. Two videos from each exhibit were chosen for the analysis. Guided by a video analysis sheet (Appendix H) and a draft of the C-PIECE framework, each researcher independently coded the videos by noting phrases from family interactions that were relevant to the analytic questions and examples of behavior for each observed indicator of practices within each engineering proficiency.

After these videos were coded, each researcher summarized the data on the video analysis form, describing interactions, behaviors, and/or indicators related to the engineering proficiencies. Based on this summary, each researcher wrote an explanation describing how the family in the video "defined a problem." The corresponding interview and survey were reviewed, and the summary was updated to include observations not noted in the coding of the video. Once this process was completed for each video, the findings were discussed. From these discussions, two types of codes were created: Macro and Micro. Macro codes were intended to provide an impression of the type of indicators present during an interaction. Micro codes were intended to deepen our understanding of the interactions by identifying exactly when and at what frequency each of the indicators were present.

Focal video coding of family engineering design practices

The first part of focal video coding involved developing a focal codebook based on the initial Micro codes and a draft of the C-PIECE framework for information about engineering practices. The initial codes were tested by each researcher on two videos. The focal coding was reviewed and the focal codebook and the data file were updated with the changes.

The focal codes were used for another round of coding. Three researchers coded videos of families speaking English: one researcher coded 18 videos, two other researchers each coded nine videos, and the third researcher coded three videos. The videos of Spanish-speaking families were also coded by three researchers: two coded nine videos each and a third researcher coded three. The coding was compared across videos, and areas of disagreement were discussed until the coders arrived at a resolution. The remainder of the videos were coded using the Macro codes developed during the initial coding phase.

Although video data were collected from 71 groups, only 49 videos were analyzed and coded (from 31 English-speaking and 22 bilingual groups). The remaining videos were omitted from the analysis because the video recordings were not of the requisite quality for analysis.

Engineering design practice by method

To better understand the data available for the practices listed in the draft C-PIECE framework within each proficiency (*defining a problem*; *improving a design*), we created a document mapping each indicator of the practices and its proficiency level (beginning, intermediate, and informed) to each of the methods for which data could be collected (observation, interview, video).

We first took an inventory of the presence of indicators found in the C-PIECE framework; we created a Microsoft Excel document containing a worksheet for each of the three exhibits: *Catch the Wind, LEGO® Drop,* and *Build a Boat*. Each worksheet contained a row for each indicator and a column for each of the groups who interacted with the exhibit during data collection. For each group, we indicated the presence of the indicator in data from each of the three data-collection methods: observation notes, interview responses, and the video code reports. Across the three exhibits, we found a total of 36, 37, and 29 practice indicators identified via observation, interviews, and video, respectively.

By identifying which practice indicators were present for each mode of data collection across videos, this inventory provides a reasonable expectation of practice indicators that are identifiable using the instruments developed in this study. This understanding can be used by others to better understand the practices elicited by their own exhibits, and also be used as a starting point for researchers to consider how to collect practice indicator data and what findings to expect.

Analysis and beyond

After the surveys, interviews, observations, and videos were coded and the video codebooks were updated, the data were analyzed and interpreted. As mentioned previously, the data analyses and in-depth examinations of the study's findings reside in four other papers developed through this research. To provide a glimpse of the study's findings, we use the following and final section to briefly summarize the papers in which those findings are discussed.

C-PIECE Study findings and summary

In support of local and global problem-solving efforts (e.g. UNSDGs), the overall goal of the DOT project is to continue strengthening family engineering learning and capacities by elevating the effectiveness and impact of engineering design challenge exhibits. In turn, the overarching goal of the DOT research program is to take a closer look at family engineering design practices elicited by engineering design challenge exhibits to better understand engineering design practices, their relationships to exhibit features, and their relationships to levels of engineering proficiencies. Inspired by research in formal education that looks at levels of engineering proficiencies (Crismond & Adams, 2012), we aimed to provide museum professionals with evidence-based strategies for creating educational engineering experiences that afford more informed engineering design practices. These research findings will specifically inform DOT exhibit development, design, evaluation, and facilitation. The findings from this research can also benefit other professionals who use evidence to inform their work in engineering education—researchers, practitioners, and those who operate in both roles simultaneously.

We addressed this overarching question by studying related literature, collaborating with partners and other stakeholders in engineering education, collecting observational and self-report data from families interacting with exhibits, consulting with an RAC, and reviewing the findings with collaborators.

Considerations

As with all research, this study required us to optimize the study's components to satisfy financial, temporal, and geographic constraints. While these optimizations were made in a thoughtful and educated manner, they introduced elements that could have influenced the interpretation of the findings. Conversely, however, these optimizations also helped to define the context of the study.

This foundational and early stage research took place at a science museum, a setting that may elicit expectations regarding how visitors interact and approach exhibits. Similarly, the participants were recruited, which may have influenced both the depth and the length of their interactions with the exhibits (Pattison & Shagott, 2015). While we are confident in our methods and findings, we note that visitors' behaviors observed in other contexts may vary slightly from those seen in this study.

Contributions to knowledge

Using qualitative and culturally responsive research methods intended to support multi-cultural and construct validity, we generated knowledge while we:

1) Defined and developed theory-based instruments, protocols, and methods to determine practices associated with engineering proficiencies that could

be observed and documented (measured) at engineering design challenge exhibits.

2) Speculated about relationships between the documented engineering design practices and levels of engineering proficiencies—beginning, intermediate, and informed

3) Speculated about relationships between some of the engineering design practices and exhibits' features

4) Speculated about relationships between facets of engineering awareness and features of design challenge exhibits

5) Monitored the concurrent presence of intergenerational communication and visitor satisfaction during family engagement

Paper describing the C-PIECE framework

To develop the C-PIECE framework, we tested the premise that exhibits, as educational interventions, can elicit different design practices associated with engineering learning that can be documented (i.e. measured). We developed a plausible set of family design practices at engineering exhibits inspired the Matrix (Crismond & Adams, 2012), informed by a literature review that included the review of nine models of engineering (Barriault & Pearson, 2010; Bevanet al., 2014; Crismond & Adams, 2012; Dorie et al., 2014; Ehsan et al., 2018; Lussenhop et al. 2015; Museum of Science, 2012; Paulsen & Burke, 2017; Wang, 2013), and utilized OMSI staff's experience with engineering design challenge exhibits. We focused the C-PIECE framework on design practices used in engineering learning and speculated about their association with beginning, intermediate, and informed levels of two engineering proficiencies: *defining a problem* and *improving a design*. For details on the development of the C-PIECE framework, see Randol et al. (2021b).

Using evidence gathered through naturalistic observation and video recordings of families interacting with three different exhibits, we confirmed that these family learning practices could be afforded by engineering exhibits. We further refined the C-PIECE framework by consulting stakeholders with diverse perspectives in community education, museum education, informal education, and engineering education. We continued to iterate with testing and stakeholder reviews and refinements until we did not receive any more comments that something was missing or did not make sense.

Exploratory studies

The material that we collected via naturalistic observations, surveys, interviews, and video recordings allowed us to explore (Institute of Educational Sciences, 2013) three additional strands of inquiry :

1. What relationships do we observe between engineering practices?

2. What relationships do we observe between engineering practices and exhibit features?

3. What relationships do we observe between families' engineering awareness and exhibit features?

Paper exploring relationships between engineering practices

The paper, *Exploring patterns of collaborative practices at interactive engineering at challenge exhibits* (Randol et al., 2021a and on www.engineerourtomorrow.com), describes relationships between engineering design practices in the C-PIECE framework. This paper explores associations between engineering practices found in the C-PIECE framework—particularly practices under the *Defining a Problem* proficiency. These practices were chosen because they have great potential to influence the entire exhibit interaction, but early observations indicated that visitor groups did not engage frequently in these practices at the informed level. This paper examines patterns of engineering design practices commonly seen during exhibit interactions, the relationships that may be most useful to design challenge developers and facilitators, and how certain design practices support the engagement in other practices.

Brief exploring relationships between engineering practices and exhibit features

The brief, *Exhibit Features and Visitor Groups' Engineering Design Practices* (Herran et al., 2021 and on www.engineerourtomorrow.com), broadly describes exhibit features that may influence groups' engineering practices associated with the engineering proficiency *defining a problem and improving a design*. Using a research brief approach with graphics and weblinks, the information is accessible for practitioner review, action, and reflection.

Some of the findings discussed suggest that engineering design challenge exhibit features—the type and location of design challenge materials, the type and location of exhibit copy, and the location of the design challenge building and testing areas—could be integrated into an exhibit in ways that intentionally exercise families' engineering practices when they interact with an exhibit.

Paper exploring engineering awareness

The paper, *Engineering Awareness at Design Challenge Exhibits* (Randol et al., 2021c), describes instruments and measures used to capture facets of engineering awareness, and a discussion on how this approach can contribute to understanding of relationships between facets of engineering awareness and possible next steps in design and development research.

While the study found that visitors demonstrated facets of awareness of doing engineering practices, it is less clear that they were aware that these practices are associated with the process of engineering. In close-ended survey responses, participants overwhelmingly reported that they were doing engineering at exhibits. However, in open-ended responses from the interview, most groups simply implied or named specific engineering design practices rather than use the term engineering.

The variation in data regarding engineering practices by exhibit, along with some of the variations observed in facets of engineering awareness, suggest differences in how exhibits encourage respondents to engage in, and recognize their engagement as, engineering practices.

Use of this knowledge and approach

Through this study of family learning practices afforded by engineering design challenge exhibits, we have created tools, data, and speculations that have immediate value for design and development research and are currently being used on the DOT project. We believe that a broad range of museum professionals—including designers, developers, educators, and evaluators—who are interested in better understanding engineering learning at exhibits can benefit from the products of this research:

- The C-PIECE framework provides research-based understanding of indicators related to the engineering proficiencies of *defining a problem* and *improving a design*. Researchers can use it as a starting point for theoretical exploration around the topic of family engineering practices in museums, designers can use it to inform decisions regarding exhibit affordances, and educators can use the framework to support learners' exercise of engineering design practices.

- This paper and four other products describe and discuss different aspects of this research study. These papers can help guide those who wish to embark on similar research and development and provide insights and discussions useful for theoretical and practical models that connect engineering learning outcomes with engineering education interventions.

- A set of methodological protocols, instruments, and codebooks—including naturalistic observation, surveys, interviews, and video-recording—provides researchers with a set of tools that can be used either as is, or as a starting point to further advance the research of engineering learning at exhibits.

Our desire is to share the findings from this study with all who are interested in engineering learning outcomes and engineering education experiences. As such, products created by these researchers are currently available through the www.engineerourtomorrow.com website, workshops, and personal communications. Additional dissemination of our work will utilize conferences, social media and publications.

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Appendix A - C-PIECE framework

A.1 C-PIECE framework

C-PIECE Framework

Collaborative Practices at Interactive Engineering Challenge Exhibits

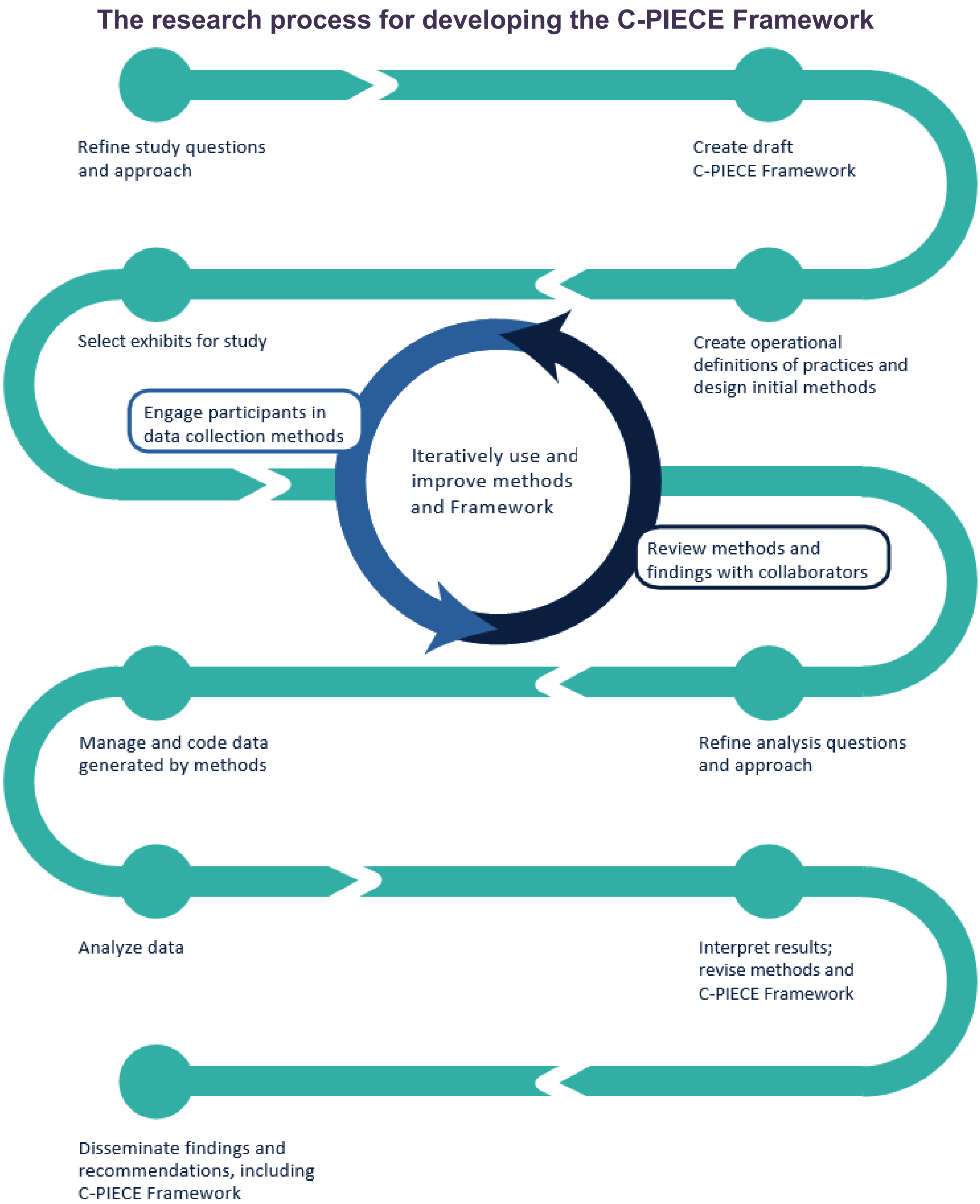
Defining a Problem

	Beginning	Intermediate	Informed
Orientation	• Immediately attempts challenge	• Reads or listens to information provided • Explores resources • Watches others • Prematurely attempts challenge	• Delays design decisions
Design Preparation		• Discusses/plans design other than materials • Brainstorms ideas • Identifies/assigns roles	• Considers benefits and trade-offs of materials
Goal Orientation	• Perceives goal as straight forward		• Discusses questions/ideas about the process with others • Identifies/describes criteria or constraints • Relates content to prior experience • States a goal • Defines problem within context

Improving a Design

	Beginning	Intermediate	Informed
Testing	• Runs through single cycle • Confounds variables	• Adjusts testing conditions • Completes multiple tests	• Tests specific variables • Completes multiple iterations • Continues testing
Interpretation		• Identifies pros/cons of design • Diagnoses issues • Describes what happened	• Explains results
Goal Assessment	• Subjectively assesses goal completion	• Qualitatively assesses goal completion	• Compares to own past performance or record • Quantitatively assesses goal completion
Design Modification	• Applies casual modifications • Makes decisions based on aesthetic or superficial characteristics	• Applies directed modifications	• Focuses on problematic subsystems • Brainstorms ways to make successful prototype better • Optimizes design and materials

A.2 C-PIECE framework Research Map



Appendix B - Instruments used in research

B.1 Observation Instrument

DoT Learners Study 1- Cycle 3 Observation Form

OMSI

Date: ____________________ Observer: ________________ Time start:_______ Time end:_______

Group Number: _____ Activity: __________________________ Total Time:______________

Age/Gender: 2-4_____ 5-8____ 9-11____ 12-14 ____ 15-18____ 19-25 ____ 26-35____ 36-49____ 50-65_____ 66+_____

Design Version:

Notes: brief description of group members and each design; time when new members of the group arrive or others leave, how resources are explored, what modifications are made

Reads/listens to information

Watches others

Explores resources

Modifies/manipulates design

Attempts the challenge

Completes the challenge

Adjusts testing conditions

Social interactions: Adult Peers ____ Child Peers ____ Intergenerational ____ with Facilitator ____

4. Extensive, ongoing interactions 3. Cursory, ongoing interactions 2. Minimal interactions 1.None,but others were present 0.Not present

v 6.25..19

B.2 English Visitor Survey Instrument

OMSI
Everyday Encounters with Science

OMSI is interested in learning more about your group's experience with exhibits. Your feedback is very valuable to us and we appreciate your time. Please answer the questions as thoughtfully and honestly as you can. All of your responses will be confidential. Thank you!

Think about the experience your group just had at the exhibit.

1. *How* *<u>satisfied</u>* *were you with your group's exhibit experience? (Please circle one response for each item.)*

	Not at all satisfied		Not very satisfied	In the middle	Satisfied		Very Satisfied
a. I feel my family benefited greatly from my experience with the exhibit today.	1	2	3	4	5	6	7
b. We found the exhibit experience to be very worthwhile.	1	2	3	4	5	6	7
c. The experience was as good as we had hoped.	1	2	3	4	5	6	7
d. I would highly recommend this exhibit to a friend.	1	2	3	4	5	6	7
e. Overall, we were very satisfied with the exhibit experience.	1	2	3	4	5	6	7

2. *During your time at the exhibit, how often do you think those in your group were:*

	Never	A little bit of the time	Some of the time	Most of the time	The whole time
a. Having fun	☐	☐	☐	☐	☐
b. Doing science	☐	☐	☐	☐	☐
c. Feeling successful	☐	☐	☐	☐	☐
d. Working together	☐	☐	☐	☐	☐
e. Doing engineering	☐	☐	☐	☐	☐
f. Feeling frustrated	☐	☐	☐	☐	☐

3. *Circle the* ***<u>three</u>*** *activities below that you think are* *<u>most important</u>* *in the work that Engineers do.*

Defining problems or goals	Making improvements to designs
Telling stories	Building things
Making plans	Doing Math/calculations
Writing reports	Testing things

Please see next page

For staff use only: Survey #________ Date________ Researcher initials________ Form B

B.3 Spanish Visitor Survey Instrument

OMSI
Everyday Encounters with Science

OMSI está interesado en aprender más sobre su experiencia con nuestras exhibiciones. Su opinión es valiosa y apreciamos su tiempo. Por favor considere las siguientes preguntas y provea la respuesta más detallada posible. Todas sus respuestas son anónimas. ¡Gracias!

Piense en la experiencia que su grupo tuvo en esta exhibición.

1. *Mientras usted estaba usando la exhibición, que tan seguido la personas en su grupo hicieron los siguiente:*

	Nunca	Una o dos veces	Unas pocas veces	Varias veces	Muchas veces
a. Definir un problema u objetivo	☐	☐	☐	☐	☐
b. Hacer un plan	☐	☐	☐	☐	☐
c. Construir algo	☐	☐	☐	☐	☐
d. Probar algo	☐	☐	☐	☐	☐
e. Hacer mejoras	☐	☐	☐	☐	☐
f. Completar un desafío	☐	☐	☐	☐	☐

2. *¿Cuán satisfecho está con su experiencia en la exhibición? (Por favor encierre su respuesta en un circulo para cada afirmación).*

	Completamente en desacuerdo		Desacuerdo	En el medio	Acuerdo		Completamente de acuerdo
a. Siento que me he beneficiado al visitar esta exhibición hoy.	1	2	3	4	5	6	7
b. Mi experiencia en la exhibición valió la pena.	1	2	3	4	5	6	7
c. Mi experiencia fue tan buena como esperaba.	1	2	3	4	5	6	7
d. Recomendaría altamente esta exhibición a un amigo (a).	1	2	3	4	5	6	7
e. En general, estoy muy satisfecho (a) con mi experiencia en la exhibición.	1	2	3	4	5	6	7

3. *Durante su tiempo en la exhibición, que tan seguido pensó usted que las personas en su grupo estaban:*

	Nuca	Un poco del tiempo	Algunas veces	La mayoría del tiempo	Todo el tiempo
a. Divirtiéndose	☐	☐	☐	☐	☐
b. Haciendo ciencia	☐	☐	☐	☐	☐
c. Sintiéndose exitosos	☐	☐	☐	☐	☐
d. Trabajando juntos	☐	☐	☐	☐	☐
e. Haciendo ingeniería	☐	☐	☐	☐	☐
f. Sintiéndose frustrados	☐	☐	☐	☐	☐

Continua en la siguiente página.

For staff use only: Survey #________ Date________ Researcher initials________ Form A

4. *Circule tres actividades que piensa que son las partes más importantes del trabajo que los ingenieros(as) hacen*

Definir problemas u objetivos	Hacer mejoras a diseños
Contar historias	Construir cosas
Hacer planes	Usar matemáticas o cálculo
Escribir reportes	Probar cosas

Por favor díganos más acerca de usted y su familia (sus respuestas son completamente anónimas).

1. *¿Cuál es la composición por edad y género de su grupo? (por favor, marque dentro de cada caja si es necesario)*

	0-8	*9-11*	*12-14*	*15-17*	*18 o mas*
Masculino					
Femenino					
Otro					

La siguiente información nos ayuda a determinar si estamos obteniendo la opinión de un grupo representativo de visitantes de OMSI.

2. ¿se identifica usted de origen hispano, latino o español? (Por favor marque uno o más cuadros.)

☐ No, no soy de origen hispano, latino o español ☐ Si, puertorriqueño

☐ Sí, mexicano, mexicano americano, chicano ☐ Si, cubano

☐ Yes, another Hispanic, Latino or Spanish origin (please indicate)__________________________

3. ¿Cuál es la raza con la que se identifica? (Por favor marque uno o más cuadros)

☐ Nativo Americano o nativo de Alaska ☐ Negra, Africana Americana o negroide ☐ Blanca

☐ India asiática ☐ China ☐ Japonesa ☐ Coreana ☐ Filipina ☐ Vietnamita

☐ Otra asiática (por favor indique)______________

☐ Nativa de Hawái ☐ Samoana ☐ Guameña ☐ Otra de las islas del Pacifico (por favor indique)______________

☐ Alguna otra raza (Por favor indique)________________________ ☐ No estoy seguro

4. ¿Qué idioma(s) habla en su casa? ____

¡Gracias por su ayuda!

B.4 English Interview Instrument

DoT Learners Study 1- Cycle 3 Interview Form **Date:________**

Group # _____

"Hi, my name is ______________ and this is ________; We work here at OMSI and we're talking to people about their experiences with these activities and would love to hear from your group. Would you all be willing to take a few minutes to answer some questions? It should only take a few minutes, there are not right and wrong answers. Your participation is voluntary and you can stop at any time."

What would you tell a friend this activity is about?

What were you trying to do/accomplish?

So, you were trying to [restate the goal they described]; is that it?

How did you decide what to do/what the goal was?

Tell me a little about what you did while at the activity. *Record language used for understanding the challenge, testing and iteration.*
Prompt: What steps did you take or process did you go through to accomplish your goal/[restate their goal]?

Was there anything you did or thought about before you started [use their language for: building/designing/placing objects?

v. 6.25-2019

1

Skip this section if no changes were made

Did you make any changes to your design? What kinds of changes did you make?

Why did you [describe change 1]?

What sorts of things did you consider when [making change 1]?

Repeat for each change they mention.

What did you do after making those changes?

How did you know when to stop changing your design?

How did you know when you had successfully accomplished your goal/were done?

How did you support your group during this activity/ process? *Ask each participant in the group*

v. 6.25-2019

2

B.5 Spanish Interview Instrument

Formulario de Entrevista del Estudio de Aprendizaje 1

Grupo # _____

"Hola, mi nombre es _______________ y él/ella es _________. Trabajamos aquí en OMSI, y estamos hablando con distintas personas sobre sus experiencias con estas actividades. Nos encantaría saber lo que piensa. ¿Tiene tiempo para responder algunas preguntas?

Si un amigo o amiga les preguntara de qué se trata esta actividad, ¿qué le dirían?

¿Qué estaba/estaban intentando lograr?

Entonces, tenía/tenían que [repetir el objetivo descrito], ¿correcto?

¿Cómo supo/supieron qué hacer o cuál era el objetivo?

Cuénteme/cuéntenme un poco sobre lo que hizo/hicieron en esta actividad. *[Registrar el lenguaje utilizado para comprender la actividad, las pruebas y las repeticiones]*

¿Qué pasos tomó o qué proceso siguió para lograr su objetivo? *[Repetir el objetivo que mencionó/mencionaron]*

¿Hubo algo que hizo/hicieron o que pensó/pensaron antes de comenzar a [construir/diseñar/colocar] objetos? *[Repetir lenguaje utilizado por los visitantes]*

v. 2-19-2019

Fecha_______ Iniciales_______

Omitir esta sección si no se hicieron cambios

Noté que hizo/hicieron algunas modificaciones en su diseño. ¿Qué tipo de cambios hizo/hicieron?

¿Por qué hizo/hicieron esa modificación? *[Describir cambio Nº1]*

¿Qué tipo de cosas consideró/consideraron cuando hizo/hicieron ese cambio? *[Describir cambio Nº1]*

[Repetir para cada modificación que mencionen]

¿Qué hizo/hicieron después de hacer esos cambios?

¿Cómo supo/supieron cuándo dejar de modificar su diseño?

¿Cómo supo/supieron cuándo había/habían logrado alcanzar el objetivo exitosamente? En otras palabras, ¿cuándo supo/supieron que había/habían terminado?

¿Cómo apoyó usted personalmente a los demás participantes del grupo en este proceso? [*Preguntar a cada participante del grupo]*

v. 2-19-2019 Fecha________ Iniciales________

Appendix C - English language consent document

Consent

Note: The following is a sample informed consent and the actual consent form sign used may be different. A copy of the final informed consent form will be sent for approval when it is ready.

Purpose: OMSI is [purpose, e.g. conducting a research study] about [topic, e.g. engineering]. We would like to gather information about what people know or feel about [this topic] in order to [goal, e.g. learn about identity formation].

Procedure

OMSI is asking you to participate in [research activity, e.g. a focus group]. To record the information gathered, OMSI will use [method, e.g. videotaping, observing, writing down notes].

If you agree to this, please write your initials next to the activity below:

____ ☐ [activity, e.g. take part in a focus group]

____ ☐ [activity, e.g. be recorded by a video camera]

____ ☐ [additional lines as needed]

Risks/ Discomforts

If being recorded, you could lose some privacy. Other than this risk, there are no known additional risks for participating.

Benefits

You may feel empowered by helping OMSI create better exhibits and program experiences.

AGREEMENT TO PARTICIPATE

Your signature does not waive any legal right. If you agree, please sign this form.

I am 18 years of age or older and agree to participate in these evaluation procedures.

Questions

If you have any questions regarding this study, please contact [OMSI Evaluation Manager, email and phone]. If you have complaints or questions about your rights, you may also contact Heartland Institutional Review Board - 866.618.HIRB - director@heartlandirb.org

Rights

Participation is voluntary. You can refuse or discontinue participation at any time without penalty or loss of benefits.

Confidentiality

We will keep your data confidential to the fullest extent allowable by law. To do this, we will keep the data in locked file cabinets and on secure servers that only qualified project staff can access. The ethics board that reviewed this study may also have access to records for auditing purposes.

Alternatives

Participation is voluntary; there is no penalty if you choose not to participate.

Financial Considerations

You will not be paid or have to pay for participating in this research. [We may offer free passes to OMSI as a token of appreciation

____

Date Signature

Appendix D - Spanish language consent document

FORMULARIO DE CONSENTIMIENTO

OMSI
Everyday Encounters with Science

Propósito

Este formulario contiene información que le ayudará a decidir si desea ser parte de este estudio o no. Por favor lea este documento cuidadosamente y contáctese con el Museo de Ciencias e Industria de Oregón (OMSI por sus siglas en inglés) si tiene preguntas.

Proyecto

Diseñando Nuestro mañana (Designing Our Tomorrow) es un proyecto de investigación fundado por el National Science Foundation. El propósito de esta actividad de investigación es aprender de los participantes en particular de familias con jóvenes de edades 9-14 a través de sus interacciones con exhibiciones específicas. Como participante, nos gustaría que nos ayudara a probar exhibiciones o actividades localizadas en el Turbine Hall en OMSI.

Procedimiento

OMSI le pide que participe con su grupo familiar interactuando con exhibiciones y / o actividades seleccionadas y proporcione comentarios para ayudar a guiar el trabajo de OMSI. La participación es voluntaria, y no hay penalización si decide no asistir o responder una pregunta. Al firmar este formulario de consentimiento, acepta participar en este estudio y dejar que OMSI utilice sus comentarios y sugerencias para ayudar con la planificación del proyecto y el desarrollo de la exhibición.

Grabaciones de video

Su grupo será grabado para apoyar un análisis posterior. Por favor, no participe en el estudio si no desea ser grabado. Si participa, la información registrada se mantendrá segura y confidencial durante cinco años después del estudio y luego será destruida.

Riesgos/Inconvenientes

Al ser grabado, podría perder algo de privacidad. Aparte de este riesgo, no hay riesgos adicionales conocidos para participar.

Beneficios

Podrá sentirse orgulloso al ayudar a OMSI a crear una exhibición y un programa.

Confidencialidad

Mantendremos la confidencialidad de sus datos en la medida máxima permitida por la ley. Para hacer esto, mantendremos los datos obtenidos de su grupo en una ubicación protegida y en servidores seguros a los que sólo el personal cualificado del proyecto tendrá acceso. La junta de ética que revisó este estudio también podrá tener acceso a la información con propósitos de auditoría.

Consideraciones financieras

No se le compensará ni tendrá que pagar por participar en este estudio. Puede existir la oportunidad de obtener pases gratis a OMSI como muestra de nuestro agradecimiento.

Derechos

La participación es voluntaria. Usted puede rechazar responder ciertas preguntas o suspender su participación en cualquier momento.

Preguntas:

Si tiene cualquier pregunta relacionada con este proyecto, el grupo focal o sus derechos, por favor contáctese con **Marcie Benne** a mbenne@omsi.edu ó **503.797.4612.**

ACUERDO DE PARTICIPACIÓN

Su firma no suspende sus derechos legales. Si usted está de acuerdo en participar, por favor firme este formulario.
Firma del Participante: Soy mayor de 18 años de edad y estoy de acuerdo en participar en este estudio.

Fecha	Nombre	Firma

Appendix E - English language recruitment message

Help OMSI create better exhibits and programs

OMSI's Research and Evaluation Division is seeking families to give feedback on exhibits, programs and activities over the coming year. Families will be selected based on the needs of the project and if selected will get free admission to OMSI on the day of their participation as well as four individual passes to return to OMSI at their convenience.

If you are interested in participating, please complete the survey here:

English:http://omsi.participants.sgizmo.com/s3/

Spanish: http://omsi.participantes.sgizmo.com/s3/

Thank you for your time; please contact us at visitorstudies@omsi.edu or 503-797 4000 ext 4537 if you have any questions.

Appendix F - Spanish language recruitment flyer

OMSI
Everyday Encounters with Science

Ayude a OMSI a crear mejores exhibiciones y programas

La División de Investigación y Evaluación de OMSI está buscando familias para probar nuevas exhibiciones, programas y actividades. Las familias participantes obtendrán **entrada gratuita a OMSI** el día que participen en el estudio, así como **cuatro pases válidos por aproximadamente un año** para regresar a OMSI a su conveniencia.

Para más detalles:

- **Actividades:** las actividades están localizadas en OMSI y dirigidas a familias que tengan **por lo menos un niño/a de 9-14 años.** Nuestro equipo necesita que usted y su familia prueben una actividad. Mientras se realiza esta actividad usted y su familia serán grabados con el propósito de ayudar al estudio. Luego le haremos unas preguntas y le daremos una encuesta. Este proceso puede durar de 20 a 50 minutos por familia
- **Fecha y hora:** lunes 5 y 12 de agosto a partir de 11am a 5pm y miércoles 7 de agosto a partir de las 3-6pm.
- **Logísticas:** Personal de OMSI le recibirá y dará la bienvenida. Por favor recuerde el número de su parqueo.
- Como agradecimiento cada familia que participe recibirá **4 pases de admisión general** con una validez de 10 a 12 meses para que puedan regresar nuevamente.

Contacto: Si está interesado en participar **llame o envíe un mensaje** de texto a este número (503) 451-0201

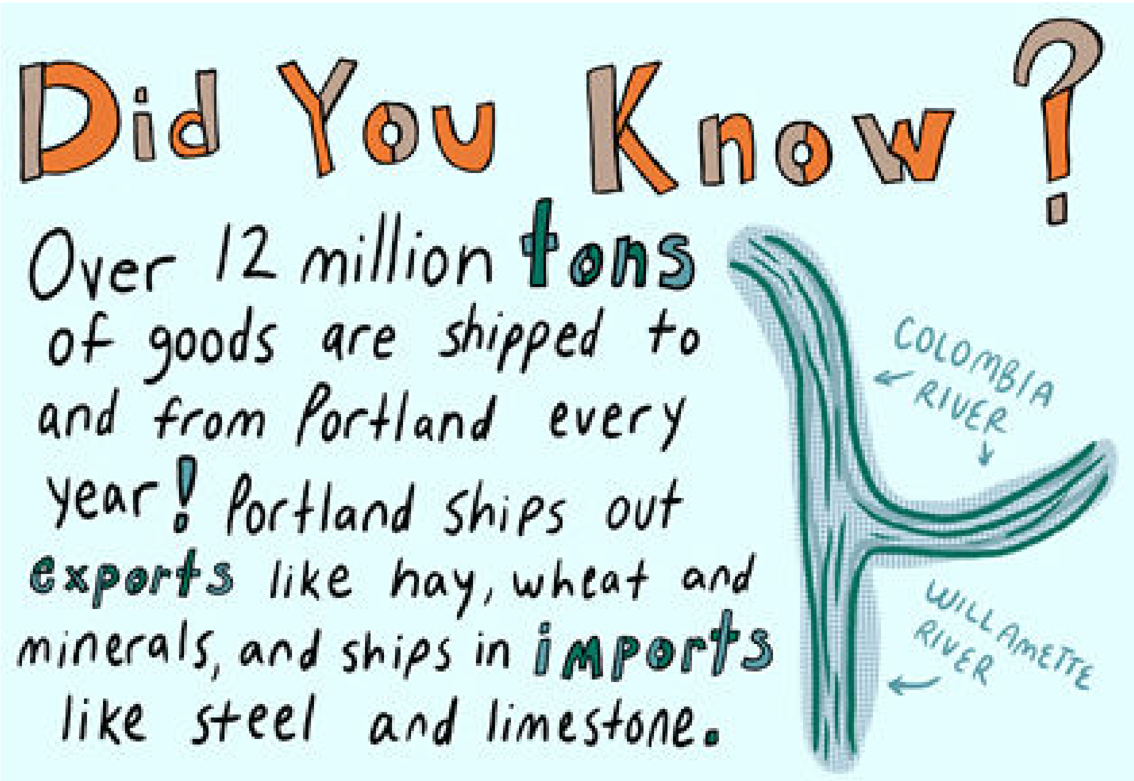
Si lo desea puede completar la encuesta aquí: http://omsi.participantes.sgizmo.com/s3/

Gracias por su tiempo.
Si necesita información adicional por favor contáctenos a visitorstudies@omsi.edu

Appendix G – Exhibit Descriptions

G.1 Build a Boat

Build a Boat exhibit copy



G.2 Catch the Wind

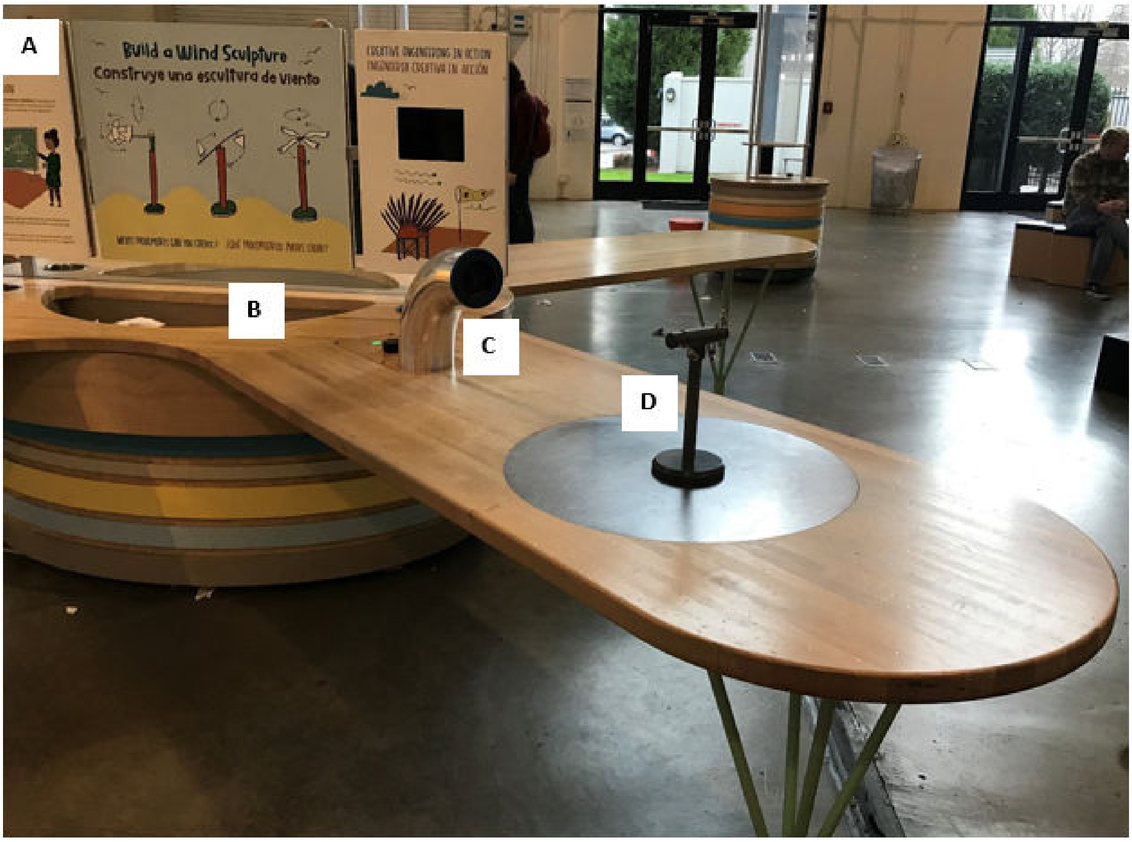


Exhibit Description

Visitors try to create a wind turbine by connecting K’NEX® pieces and plastic blades to a stand. Visitors test their turbine creations by placing them in front of the blower and turning it on.

A. Exhibit Copy
B. Bin to hold materials
    a. K’NEX® pieces to connect with the hub of stand
    b. Plastic blades for the turbines
        i. 3 shapes, each a different color
C. Blower with adjustable speed to provide “wind” to turn the turbine
D. Stand to hold blades to create a turbine. There were several available.

G.3 LEGO® Drop

Exhibit Description

Visitors build a breakable crate from LEGO® blocks. They then use the materials to create a protective container for the crate. Visitors test their designs by dropping them from towers of different heights.

A. Inspiration screen with slide showoff how to slow things down
B. Materials table with LEGO® blocks to build breakable crate and items to make protection:
    a. Pipe Cleaners
    b. String
    c. Mesh Fabric
    d. Nylon Fabric
    e. Foam Pieces
    f. Cardboard Squares
    g. Popsicle® Sticks
C. Towers of different heights from which crates are dropped
D. Crate landing area
E. Instructions

Appendix H - Initial Coding Video Analysis Sheet

Video #:__________ **Exhibit:___________________________**

Researcher Initials:____________

What behaviors and indicators did you observe in this video related to the "Defining a Problem" proficiency?

Example:

Explore resources – Family walked over to the material table and sorted through the sails while comparing the shape of the sails

What behaviors and indicators did you observe in this video related to the "Optimizing" proficiency? Did you think any of these behaviors or indicators were critical to helping visitors define a problem? If so, which ones?

Were there any behaviors and indicators you think were important that aren't a part of our documents? If so, which ones? Why did you think they were important?

Video Summary:

Example: Family of four worked on Build a Boat. Family started the interaction by looking at all of the materials in the material table. They compared the shapes of the sails. Two family members picked a square sail and two family members picked a triangle sail. They attached the sail to the boat and raced each other. The boat with the square sail won the race and the family started new designs only with square sails.

Memo of reflection from initial review of videos:

<u>Reflect on the following research questions:</u>

1) Descriptive understanding of "Defining a Problem" – what characterizes how families are defining a problem during their interaction with exhibits? What types of behaviors and indicators are present during these interactions?

2) Descriptive understanding of the relationship between iteration/testing ("optimizing") and "defining a problem engineering proficiencies – what behaviors and indicators of iteration/testing contribute to families defining a problem.

3) Explanatory understanding of factors that may influence behaviors and indicators associated with engineering proficiencies.

4) Ideas for exhibit design, the design challenge framework, and practicable strategies-how can the data influence the deliverables of the project?

5) Methodological – how do the instruments contribute to the descriptive understanding of the engineering proficiencies?

<u>Answer the following questions:</u>

1) How are families defining a problem during their interaction with the exhibits? Do you see any patterns or themes emerging?

2) Based on the videos you coded, what would you say is the current relationship between optimizing a defining problem?

3) What exhibit affordances or contextual factors do you think are influencing the way that families define a problem?

4) If you were to narrow indicators for both "Defining a Problem" and "Optimizing" (based on this initial review) which indicators would you choose and why?

5) Is there anything that stands out at the moment that you see as helpful or important for the rest of the project deliverables?

6) Any thoughts on validation of the indicators you selected?