Exploring patterns of collaborative practices at interactive engineering challenge exhibits

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Introduction

This work was part of *Designing Our Tomorrow—Mobilizing the Next Generation of Engineers,* a five-year (2018–2023) project led by the Oregon Museum of Science and Industry (OMSI) with the support of the National Science Foundation (NSF, DRL-1811617) and project partners (Adelante Mujeres, the Biomimicry Institute, and the Fleet Science Center).

Designing Our Tomorrow (DOT) capitalizes on museum exhibits as unique family learning environments to foster intergenerational participation in engineering activities. The project targets girls ages 9–14 and their groups, and includes processes to ensure the inclusion and influence of members of Latino communities. For more details about the multiple strands of DOT Study 1, please refer to *The study of collaborative practices at interactive engineering challenge exhibits— background and methods* (a.k.a. the DOT Background and Methods paper; Shagott, et al. 2021).

One of the goals of DOT Study 1 was to further practitioners' understanding of how exhibit features elicit changes to family engineering design practices during design challenge activities. An increased understanding of what practices groups engage in at exhibits, and how exhibit features can influence engagement in those practices can provide valuable insights for the development and design of educational experiences such as facilitated activities at exhibits, floor demonstrations, and activities developed for after school and summer programs. To this end, this work explored how family groups engage in different engineering practices at exhibits, what patterns of practices are commonly observed, and how these patterns differ from exhibit to exhibit. This paper provides a qualitative description of some of the patterns of family engineering design practices documented at three design challenge exhibits.

We recognize the influences that personal experience, physical setting, and cultural norms play in exhibit interactions and learning (Falk & Dierking, 2013). Therefore, visitor interactions with exhibits are viewed through a sociocultural lens and situated within an ecological framework that can simultaneously hold multiple theories on people, places, and culture (NRC, 2009). A detailed discussion of the study's theoretical orientation can be found in Shagott, et al. (2021).

We created the Collaborative Practices at Interactive Engineering Challenge Exhibits (C-PIECE) Framework and referenced it as a basis for this analysis. As described in *The C-PIECE Framework: Documenting group engineering practices at design challenge exhibits* (Randol, et al. 2021), the final framework divides 37 engineering practices between two proficiencies: *Defining a Problem* and *Improving a Design*. Within each proficiency, each practice is labeled as Beginning, Intermediate, or Informed to reflect our ranking of the sophistication of that practice informed by prior theory and recent evidence. While engagement in any of these practices can be part of an engineering process, we posit that use of Informed practices indicates richer and more thoughtful engagement. By better understanding how these practices may be associated with each other and to the context in which learners engage, we can provide insights for improving experiences that support the use of more Informed practices. We provide the framework used in the data collection in Table 1. The final version of this framework and operational definitions for the practices (revised after analysis) can be seen in Appendices A and B.

Table 1. The Framework used for research data collection.

Framework for DOT Engineering Practices

Defining a Problem

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

Improving a Design

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

The purpose of this research was to explore associations between engineering practices included in the C-PIECE framework. In this work, we took particular interest in practices under the *Defining a Problem* proficiency. Practices under *Defining a Problem* have great potential to influence the entire exhibit interaction and early observations indicated that visitor groups did not engage frequently in these practices at the informed level, therefore they were seen as an opportunity ripe for study. Through observations, interviews, and video analysis, the DOT research team investigated the following questions:

- What patterns of engineering design practices are commonly seen during exhibit interactions?
- Which relationships between engineering design practices are potentially meaningful for design challenge exhibit development and facilitation?
- How can engagement in certain engineering design practices relate or lead to engagement in other practices?

We believe that a deeper understanding of the relationships between practices can help exhibit developers and educators to leverage the practices that visitors appear to engage in commonly to help support engagement in less frequent and higher proficiency practices.

Methods

Data Collection

Following recent recommendations in the informal STEM field, this research used multiple culturally-responsive strategies (e.g. Garibay and Teasdale, 2019; OMSI, 2016; Kirkhart and Hopson, 2010) during data collection and analysis. Such strategies included prioritizing broadening participation in engineering, privileging underrepresented voices in engineering—those of girls and members of Latino communities, and striving for multicultural validity. Furthermore, efforts to strengthen—and reduce threats to—all five dimensions of multicultural validity as described by Kirkhart and Hopson (2010) were implemented. Our culturally responsive research strategies 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 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.

We conducted data collection in English and Spanish at OMSI in Portland, Oregon with both general visitors and groups from Adelante Mujeres, an Oregon-based nonprofit focused on empowering Latina women and girls. We gathered information from participating groups that engaged with one of three selected engineering exhibit components, two of which are from the *Designing Our World* exhibit (DRL-1322306), an NSF-funded project aimed at engaging girls and their groups with experiences focused on the social, personally relevant, and altruistic aspects of engineering. We used an observation instrument and took open-ended notes, video recorded exhibit interactions, administered surveys, and conducted interviews with groups about their experiences with the engineering activities. For more details about our methodology, please refer to the DOT Background and Methods paper (Shagott, et al., 2021).

Observation instrument

We created a one-page form to gather observation data (Appendix C). The goal was to create a user-friendly observation tool to document visitors' engineering design practices. The form prompted observers to record the size and make-up of a family group, the date, the time of day, and the name of the exhibit. Once a visitor interacted with the exhibit, we recorded the time, tracked the number of unique designs that the focal group created (called the design version), and noted which of nine observable operational indicators the group engaged in during any given design version. Some of these indicators were defined using the same words as the engineering practices (e.g. *Describes what happened*), and others were behaviors observed during coding to imply more complex practices. *Attempts the challenge*, for instance, is not an engineering practice from the framework, but it is an observable indicator. During coding, we documented *Attempts the challenge* in association with other indicators such as *Modifies design* to code for practices that were also directly observable. For example, if the group *Attempts the challenge, Modifies design*, then *Attempts the challenge* again, this series of actions was coded as *Completes multiple iterations*, an Informed level of engineering practice found in the C-PIECE Framework.

The observation form also prompted observers to take open notes about what visitors said and did. These observation data were reviewed and coded by exhibit for the presence or absence of 36 of the 37 engineering practices. We anticipated that 18 of the practices would be captured consistently across groups since the instrument was designed to record those practices explicitly. While not the intended focus of the observation instrument, an additional 18 practices had the potential to be captured through the open notes section.

Interview Protocol

We conducted guided interviews with visitor groups immediately after they interacted with an exhibit. We asked visitors to describe what the exhibit was about, what they did at the exhibit, the steps they took, and the role(s) they played (Appendix D). These questions were intended to complement the observation data and provide insights into what the visitor was thinking. We used a Spanish version of this instrument with visitors who opted for an interview in Spanish. The interview data were reviewed and coded, by exhibit, for the presence or absence of each of the 37 engineering practices.

Video Recording

Exhibit interactions were video recorded, and we coded those videos to obtain a more detailed look at the use of engineering practices. We also developed a code book that included documentation of 29 engineering-related behaviors; these behaviors were mapped onto 18 practices from the C-PIECE Framework.

For more information about the development of the C-PIECE Framework, and which practices were captured by which instruments, please refer to Randol et al. (2021).

Sample Sizes

The survey, observation, and interview data used in the following analyses span 71 family groups, 22 of which preferred communicating in Spanish. We analyzed videos for 31 English-speaking and 18 Spanish-speaking groups. The remaining 22 groups did not undergo video analysis because the recordings were not of sufficient quality to analyze the participants' interactions with the exhibits.

Exhibit Descriptions

We collected data at three engineering design challenge exhibits, each of which are briefly described below. For additional details and images of the exhibits and copy panels, please refer to the DOT Background and Methods paper (Shagott, et al., 2021).

The *Catch the Wind* exhibit challenges visitors to assemble and test a wind turbine using a hub, a variety of K'Nex® pieces, and plastic blades of different shapes. Visitors test their designs by putting them in front of a vertical air blower.

The *Build a Boat* exhibit allows visitors to assemble a functioning boat that they can then test in a tank of water. Exhibit copy prompts visitors to consider the different real world needs of people in the design of their boat. The building station includes hull pieces in different shapes and sizes, three shapes of sails, and cargo. The water-filled testing tank has an air blower at one end to provide propulsion, and obstacles and a finish line make the activity engaging.

The *LEGO® Drop* exhibit challenged visitors to use materials such as pipe cleaners, pieces of pool noodles, paper, and string to protect a LEGO® crate from being damaged in a fall. This activity was framed within the context of a very real challenge: providing supplies to remote areas via airdrop. Visitors built their crate using supplies. Finally, they tested their design from three different drop heights.

Analysis

We used data collected from observations, interviews, and video recordings to answer three questions:

1. As educational interventions, in what ways can exhibits elicit different inferred levels of engineering design proficiencies?
2. What patterns of engineering design practices are commonly seen during exhibit interactions?
3. How does engagement in certain engineering design practices relate or lead to engagement in other practices?

The observation, interview, and video data shed light on the participants' experiences at the exhibits, provided valuable insights into how participants approached challenges, and helped to reveal common patterns of visitor practices and ways certain exhibit affordances impacted visitor engineering practices.

We entered all of the data into a spreadsheet and coded them for the presence or absence of each practice. We looked at relevant items from each method: if the practice was present, the method by which it was captured ('o' for observation, 'i' for interview, or 'v' for video) was recorded in the spreadsheet. If the practice was not captured, the spreadsheet cell was left blank. Each cell in the spreadsheet therefore documented which methods captured a single practice for one group; values ranged from empty, if the practice was not captured for that group, to 'oiv' if the practice was captured by all three methods for that group.

For each exhibit, we also counted how many groups were captured engaging in each of the practices by method (observation, interview, video); we furthermore counted the total number of unique groups that engaged in that practice. These values were then summed to yield information about the total number of groups engaging in each practice by method across the exhibits. Finally, we generated descriptive statistics from the data.

As described in the DOT Context and Methods paper (Shagott, et al., 2021), we developed a codebook for reviewing the video recorded interactions using NVivo 11 software. We applied two types of codes when reviewing the videos: *Macro* and *Micro*. Macro codes were intended to provide an impression of the type of practices present during an interaction. Micro codes were intended to deepen our understanding of the practices by identifying exactly when and at what frequency each of the indicators were present during an interaction. We coded 18 videos, nine in English and nine in Spanish. Each video was coded independently by two researchers who then discussed discrepancies and came to consensus on the final coding. After we completed coding the videos, we analyzed the codes to describe emerging patterns. We then used these patterns as guides to run *node cluster* reports, an exploratory technique that allowed us to visualize patterns by grouping codes that share similar attributes. These node cluster reports helped us to better understand how the codes were associated with one another and how these coded interactions appeared to relate to *Defining the problem.*

In an effort to better understand and visualize connections between engineering practices at exhibits, we examined our data from several perspectives. One approach was to group engineering practices from the C-PIECE Framework into sets based on the purpose of those practices within the engineering processes. Anchored in common models of the engineering process and informed by analysis of the data collected, seven sets were identified by the research team. In the results section, data are presented in these engineering practice sets.

Engineering Practice Sets

Defining a problem proficiency

- Orientation set - These practices relate to determining what to do and what resources are available or how the activity works.
- Design preparation set - These practices are associated with making initial decisions about the design and how to achieve a goal.
- Goal orientation set - These practices relate to how users define a problem or challenge.

Improving a design proficiency

- Testing practices set - These practices are associated with determining whether a design performs in a way that meets the goal.
- Interpretation set - These practices relate to the performance of a design.
- Goal assessment set - These practices relate to determination how well, or whether, the design meets the goal.
- Design modification set - These practices are in reaction to the performance of a design and relate to attempts to make improvements

Results

The results of data analysis are presented in three sections: 1) use of practices at exhibits and 2) common patterns of engineering practices.

Use of Practices at Exhibits

The data describing the use of practices at exhibits is presented in two parts: 1) Defining a problem proficiency and 2) Improving a design proficiency. Within each part, the data are presented by practice sets. Each chart shows the number of unique groups that demonstrated each practice at least once. Practices are organized and color-coded by proficiency level: Beginning in yellow, Intermediate in blue, and Informed in green.

Defining a problem proficiency

Orientation set

The Orientation practice set included practices that were observed most frequently as visitors were orienting themselves to the exhibit, figuring out how the exhibit works, and determining what they were supposed to do or accomplish. These Orientation practices include *Reading or listening to information provided, Watching others*, and *Exploring resources*. The fact that most groups engaged in these practices prior to starting their first design contributed to a large number of groups coded as *Prematurely attempts challenge* or *Delays design decisions*. On the contrary, only eighteen groups were coded through the observation as *Immediately attempts the challenge* (Figure 1).

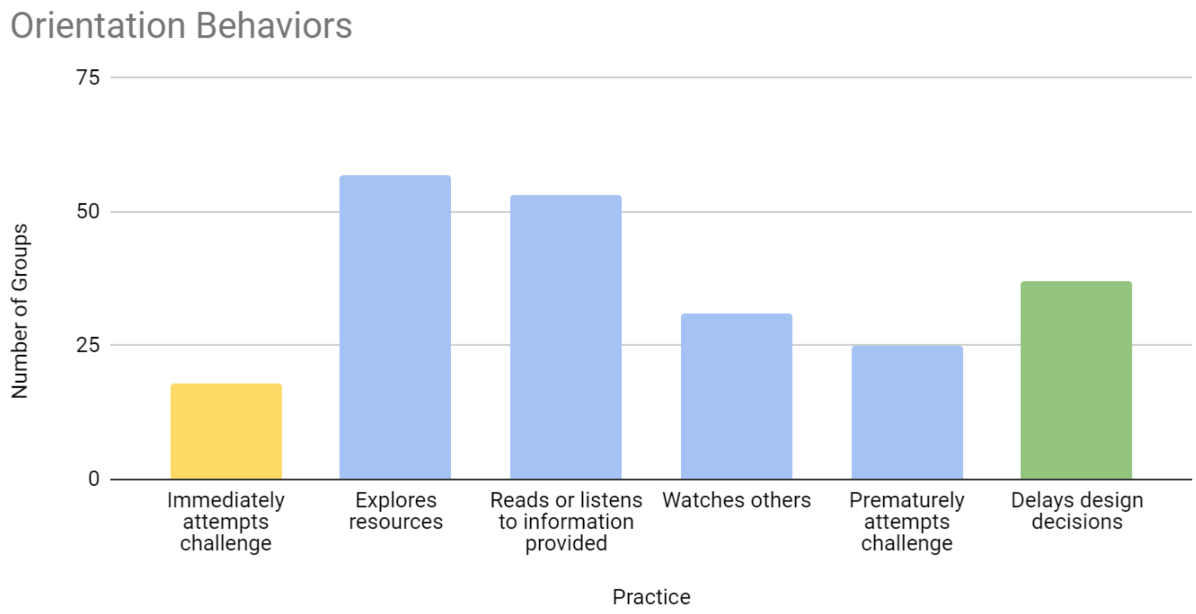

Figure 1. Frequency of Framework practices in the Orientation set of the Defining a problem proficiency. Practices are color-coded by proficiency level: Beginning in yellow, Intermediate in blue, and Informed in green.

Design preparation set

While most groups delayed design decisions by orienting themselves to the exhibit, considerably fewer engaged in practices related to Design preparation such as brainstorming or making plans with others in their group (Figure 2). In roughly one third of the groups, group members talked about the different materials available and the trade-offs of using those materials for a design. In a similar number of groups, individuals within the group assumed a specific role or task to do as part of the process. In some cases the role was explicit (e.g. a child asking an adult to hold something steady or tie two pieces together). In other cases, individuals took on a role without explicit direction (e.g. an adult taking on the role of providing materials to a child working on a design).

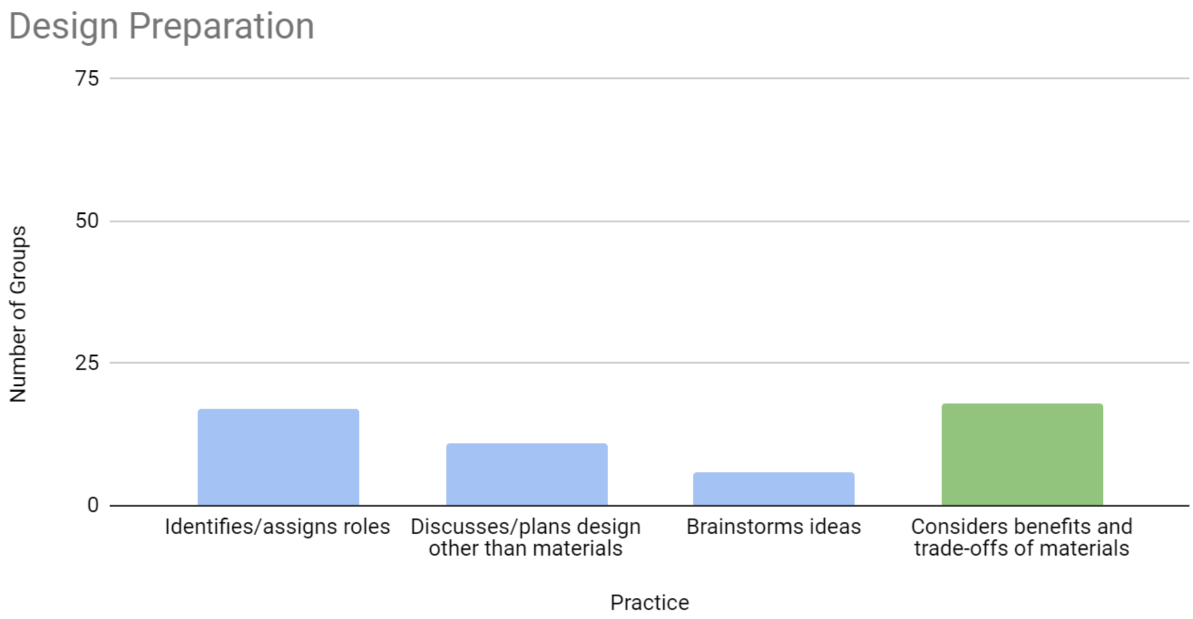

Figure 2. Frequency of Framework practices in the Design preparation set of the Defining a problem proficiency. Practices are color-coded by proficiency level: Intermediate in blue, and Informed in green.

Goal orientation set

Interview responses provided insights into the Goal orientation of the groups, which were coded as *Perceiving the goal as straight forward* if members of the group reported what they were trying to do or accomplish simply as a goal to be met or coded as *Defining the problem within context* if they included descriptions of associated constraints, conditions, or context. According to the interviews, most groups (63%; 46 out of 73) demonstrated a straightforward perception of the goal. This finding is supported by the fact that very few groups engaged in the practice *Restating the goal* (only three groups across all methods) or discussing the process with others in their group to clarify how they should approach the ideation, construction or testing of their design; what constitutes success; or the conditions of testing (only two groups across all methods). The most frequently observed practice related to Goal orientation was *Relating the content to prior experiences* (Figure 3). For example, several adults at the *Catch the Wind* exhibit reminded the children of wind farms that they had seen while traveling.

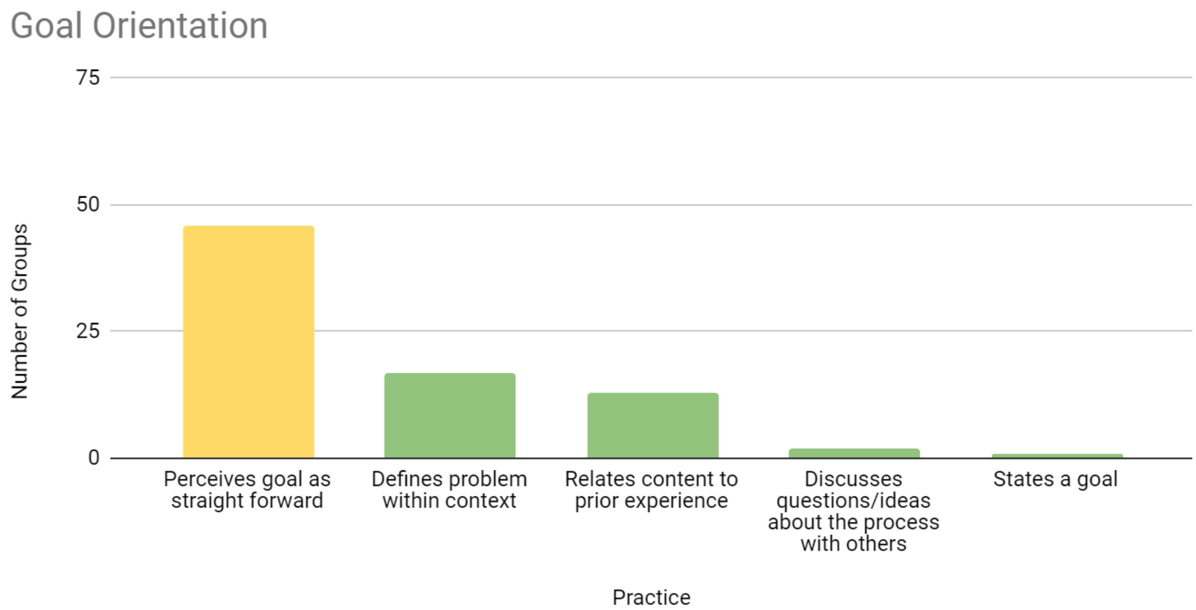

Figure 3. Frequency of Framework practices in the Goal orientation set of the Defining a problem proficiency. Practices are color-coded by proficiency level: Beginning in yellow and Informed in green.

Overall, practices observed least frequently for Defining a Problem included *Discusses questions/ideas about the process with others*, *Restates goal,* and *Brainstorms ideas*. While it is perhaps true that visitors use these practices less frequently, it is also likely that we missed instances of these practices during data collection. Because these practices are conversation-based rather than visibly observable, they were not an area of focus of the observation instrument. Also, while some related codes were included in the video analysis, these specific practices were not included. We have made changes to our data collection and coding protocols to better capture these practices in future studies.

Improving a design proficiency

Testing set

We found that the majority of groups exhibited practices that were at the informed level of Improving a Design (e.g. completing multiple iterations of their designs, conducting multiple tests, making improvements to their designs, adjusting testing conditions and continuing to test after they had completed a challenge) (Figure 4). While the visitors' designs typically improved over time, it was not evident from the data that the visitors were testing specific variables independently.

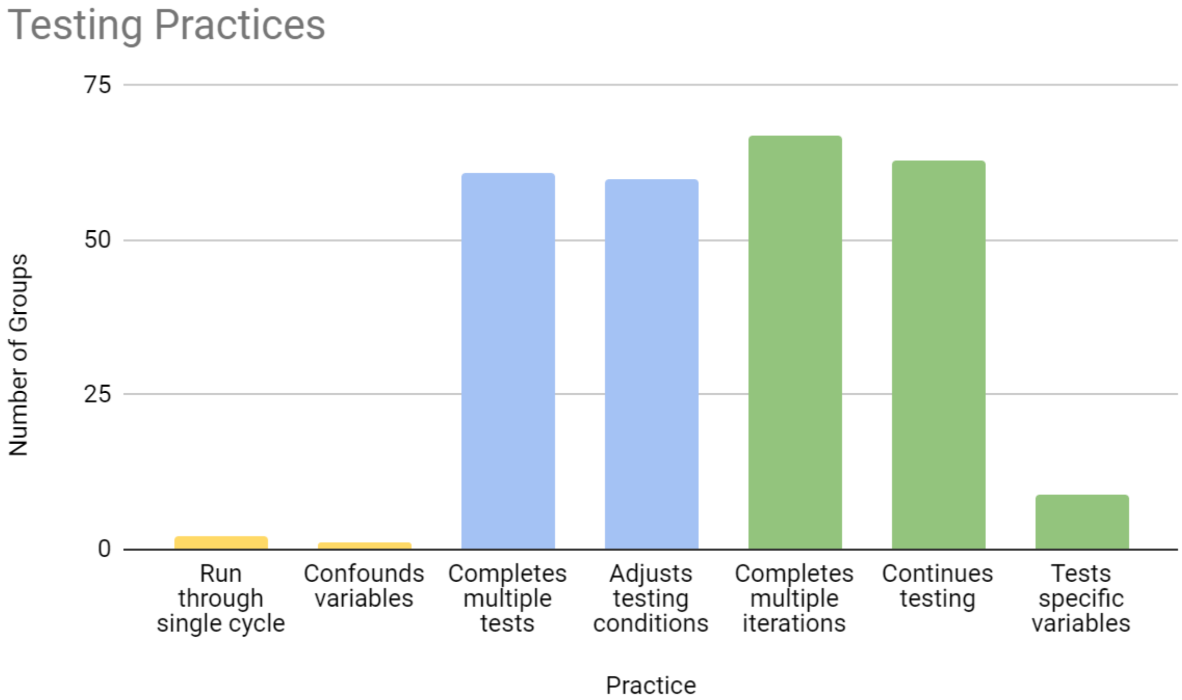

Figure 4. Frequency of Framework practices in the Testing set of the Improving a design proficiency. Practices are color-coded by proficiency level: Beginning in yellow, Intermediate in blue, and Informed in green.

Interpretation set

After testing a design, most groups engaged in Interpretation. Roughly one quarter of the groups described what had happened (Figure 5). That is, they described and summarized the result of attempting the challenge (e.g. "It sunk."). About one third of groups explained their results (Figure 5), proposing or discussing ideas about the underlying mechanisms explaining their performance (e.g. "It sunk because there was too much weight in the front."). Many groups also focused on figuring out why their design did not work by diagnosing issues.

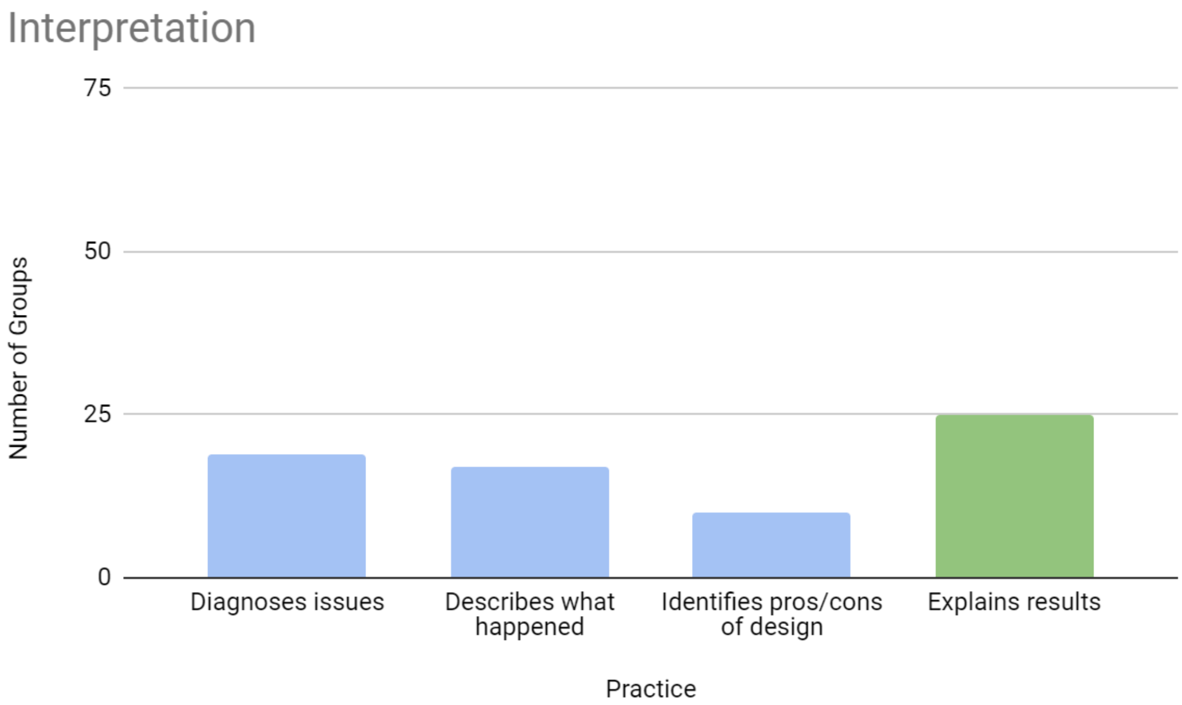

Figure 5. Frequency of Framework practices in the Interpretation set of the Improving a design proficiency. Practices are color-coded by proficiency level: Intermediate in blue, and Informed in green.

Roughly half of the groups compared the performance of their design with previous iterations (Figure 6), and nearly all groups used a qualitative measure to gauge their success. For example, the design was "faster" or it "passed" or "failed." Groups that used a subjective measure (e.g. their design was "cool") typically included a very young child. We documented only one example of a quantitative measure: a visitor noted the distance that their boat traveled before sinking. This dearth of quantitative measurements is not surprising since none of the exhibits studied provided quantitative feedback.

Goal assessment set

We also found that roughly 15 groups reevaluated their goal. This practice was coded from the video and typically occurred after the group completed a challenge and a new challenge or goal was defined.

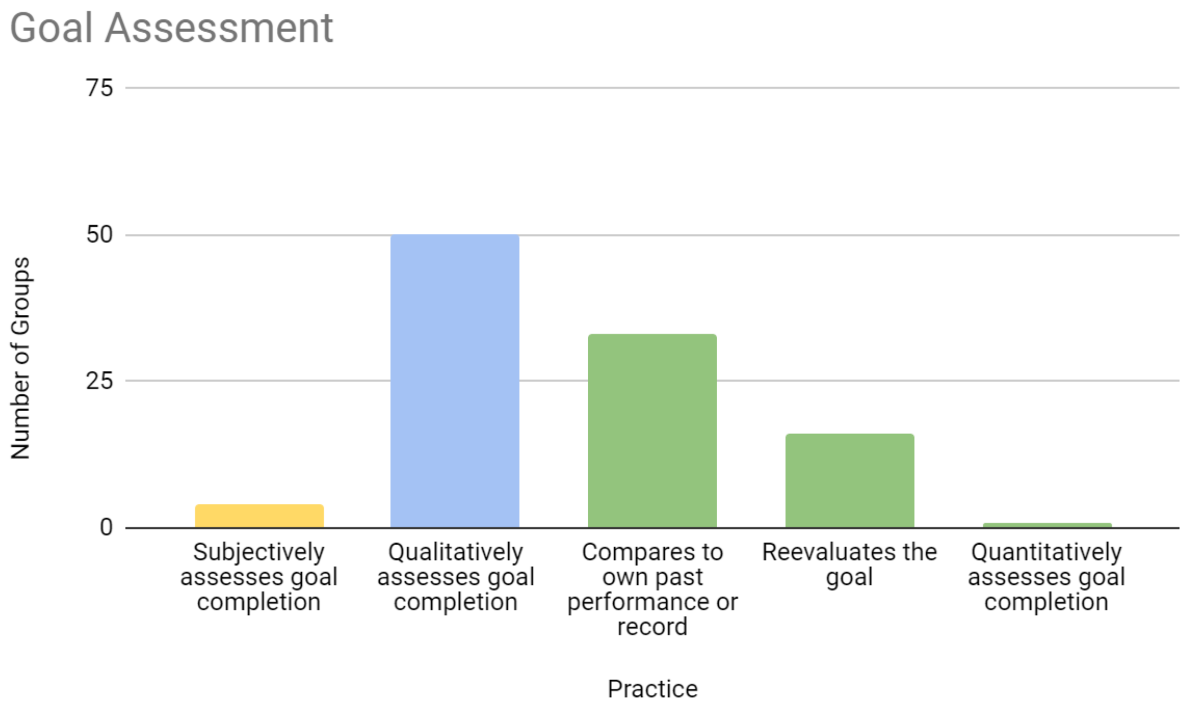

Figure 6. Frequency of Framework practices in the Goal Assessment set of the Improving a design proficiency. Practices are color-coded by proficiency level: Beginning in yellow, Intermediate in blue, and Informed in green.

Design modification set

We found that visitors tended to focus on improving the performance of their designs: nearly all visitor groups made needed improvements to their design when their first attempt at the challenge was unsuccessful (Figure 7). Very few groups appeared to make changes to their design without considering how those changes would affect performance. Practices related to Design modifications that were observed least frequently included *Brainstorms ways to make successful prototype better, Optimizes design and materials,* and *Focuses on problematic subsystems*. It should be noted that these practices were either not specifically coded for (*Brainstorms ways to make successful*) or may not have been operationally defined in such a way that they were reflected in the coding (*Optimizes design and materials, Focuses on problematic subsystems)*. Changes were made to the instruments and to operational definitions after Study 1 addressed these issues.

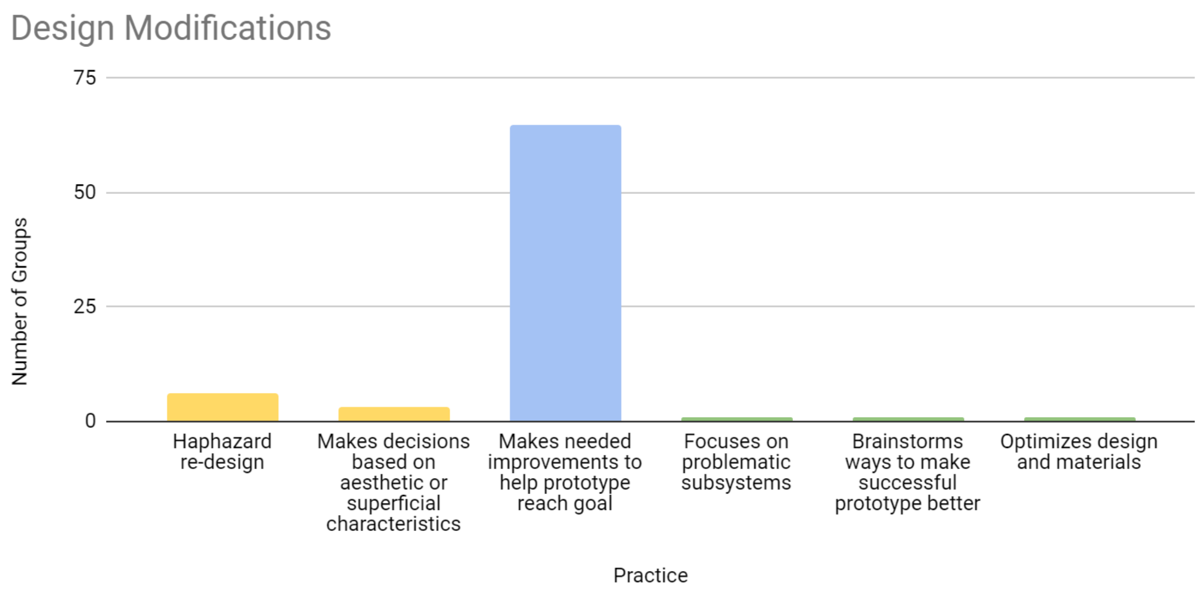

Figure 7. Frequency of Framework practices in the Design Modification set of the Improving a design proficiency. Practices are color-coded by proficiency level: Beginning in yellow, Intermediate in blue, and Informed in green.

Leveraging Patterns of Engineering Practices

The data presented above suggest that both the frequency and proficiency level of the practices that visitor groups exercise vary greatly across practice sets. For example, a majority of groups engaged in Intermediate and Informed level practices for Orientation, Testing, and Design Modification sets while a majority of groups engaged in Beginning level practices for the Goal Orientation set. Less than a third of groups engaged in practices in the Interpretation and Design Preparation sets; however, the groups that did engage in these practices were doing so at an Intermediate or Informed level.

One strategy for increasing the use of Informed level practices is to better understand how certain practices are associated with each other; that is, understanding which practices are often seen together or how one practice may be associated with another in the engineering process. The relationships between practices may help exhibit developers support less frequently seen Informed practices by making more explicit connections to and leveraging the practices that groups are already exercising.

In the following section, we describe how three practices—*Explores resources; Makes needed improvements to help prototype reach goal*; and *Qualitatively assesses goal* *completion*—serve meaningful roles in the engineering process and might be leveraged to support more frequent engagement in Informed engineering practices.

Explores Resources

Defining parts of the practice *Explores resource*s are looking at, touching, discussing and/or comparing materials. The Framework has an additional two practices that specifically involve discussing materials: the *Considers trade-offs of materials* practice in the *Defining a Problem* proficiency at the Informed level and the *Optimizes design and materials* practice in the *Improving a design* proficiency at the Informed level. The similarity in the activity of discussing materials that is part of *Explores resources* and the discussion of materials in *Considers trade-offs of materials* and *Optimizes design and materials* provides an opportunity to build on practices visitors already engage in to scaffold the use of Informed practices that are less frequently seen.

Explores resources is one practice in the Orientation set in which groups discovered what an activity was about, how the exhibit worked, and what resources were available. In exploring resources, groups were frequently seen identifying and discussing the type of materials available, their properties, and the potential uses of specific materials. Orientation set practices often led directly to Design preparation set practices where group members continued to discuss aspects of materials as they created their design: the colors and shapes of the materials and how these properties might influence their design performance, and even comparisons of materials. Similarly, materials were often discussed in the Design modification set as group members made changes and adjustments to their designs after testing.

Visitor groups were frequently observed discussing materials during orientation as part of the *Explores resources* practice as well as during the Design preparation and Design modification sets. We posit that exhibit developers can design exhibit environments to leverage the commonly seen discussion of materials to scaffold a higher percentage of visitor groups to *Consider trade-offs of materials* and *Optimize design and materials*. The variety of materials available and their placement in the exhibit space could support more discussion of the design prior to testing. Making differences between similar design elements noticeable (e.g. turbine blades are color-coded by shape) could help elicit more comparisons between material choices.

Makes needed improvements to help prototype reach goal

Most groups demonstrated intermediate and informed levels of proficiency at Testing set practices to determine if their design met their intended goal (e.g. a boat floated in the water tank). When the designs did not perform as expected, the majority of groups modified their designs which was coded as *Makes needed improvements to help* *prototype reach goal.* It is clear from the data that groups readily decided whether their design met their criteria for success and, if not, made changes to improve it. While the modifications and continued testing are seen frequently, the diagnosis of issues and discussions around how to improve the design (*Brainstorms ways to make a successful prototype better* and *Optimizes design and materials*) are not as frequently observed.

The frequency of *Makes needed improvements to help prototype reach goal* provides opportunities to scaffold visitors to engage in practices such as *Diagnoses Issues* and practices in the *Design modification* set more frequently. *Diagnoses issues*, a practice that involves speculating why a design did not perform as expected after testing, is included in the Interpretation practice set at the Intermediate level of the *Improving a design* proficiency. We found that, when seen, group members discussed potential issues with their designs and why they did not perform as expected (e.g. "The boat had too much cargo in the back;" "The boat was too big"). In a few instances, groups anticipated problems as they iterated on their designs and diagnosed potential issues related to their materials or designs prior to testing. While we did not observe a particularly high frequency of the *Diagnoses issues* practice, the practice is closely related to, and when seen, led to design modifications (*Makes needed improvements to help prototype reach goal)*. This connection provides opportunities for groups to discuss re-design approaches through practices such as *Brainstorms ways to make a successful prototype better* and *Optimizes design and materials* where they might discuss exchanging materials, brainstorming solutions, either removing a design from testing or keeping a design modification and performing additional tests. Developers and designers can leverage the commonly used practice of *Makes needed improvements to help prototype reach goal* to elicit more frequent exercise of *Diagnose issues* and the practices in the *Design modification* practice set—all of which involve group communication. Challenges that require collaboration between group members may encourage more communication about what they want to do, how they want to do it, how successful a test was and what they need to do to improve.

Qualitatively assesses goal completion

Most groups demonstrated some form of Goal assessment; most frequently, this was *Qualitatively assesses goal*. The fact that groups assessed goal completion suggested that they had a goal in mind; however, instances of the practice *States a goal* are rather rare. Through video analysis we became aware of two important aspects related to the *States a goal* practice, specifically discussing criteria (i.e. conditions for success) for the goal and constraints (i.e. conditions under which the testing takes place). Although only a few groups identified criteria and constraints, this practice, when present, proved to be important for *Defining a Problem*. Once we recognized the importance of *Identifies criteria and constraints*, it was added as an additional practice in the Goal orientation set at the Informed level of the Defining a problem proficiency.

Criteria were sometimes defined within the exhibit text (e.g. "The LEGO® crate needs to hit the ground without breaking"). Regardless of whether criteria were explicit, visitors often defined their own criteria, sometimes revising the criteria for success as they engaged further with the exhibit. Groups at the *Build a Boat* exhibit often began with defining success as "the boat floats." Once they succeeded, a new criterion was often imposed: get their boat across the finish line. (Another often followed: cross the finish line with cargo.) At the *Catch the Wind* exhibit, one family wanted to have several wind turbines spinning at the same time.

Some of the constraints identified were self-imposed. In other cases, constraints manifested because of limitations associated with the materials or exhibit itself (e.g. limited places to attach materials). One example of an exhibit-related constraint that appeared frustrating to visitors was at the *Catch the Wind* exhibit: the hubs that served as a base for the turbine blades had only eight attachment points. As a result, it was impossible to create a design with three evenly spaced blades (the configuration illustrated on the exhibit).

Identifying criteria and constraints also played a role in transitions from practices in the Goal assessment set to additional cycles of building, testing and iterating a design. If groups were successful in their design, some applied new criteria and constraints as they redefined their goal.

While groups practiced Goal assessment practices frequently, they only rarely articulated their goal explicitly, or described the criteria for success or design constraints related to that goal. We suggest exhibit developers and designers can incorporate exhibit features to leverage visitors' implicit definition of a goal and frequent practice of *Qualitatively assesses goal* to scaffold a higher percentage of visitor groups to *Identify criteria and constraints* and *State a goal.* Opportunities to better support Goal Orientation practices by groups so that they make their goals, criteria and constraints explicit might include challenges that require collaboration, or by including copy or images that encourage groups to discuss what they hope to achieve and what success looks like.

Implications and Next Steps

We have used qualitative, culturally responsive research methods to explore how family groups engage in different engineering practices at exhibits and how these patterns differ from exhibit to exhibit. Using evidence gathered through naturalistic observation, interviews, and coded video recordings, we have explored how practices from the *C-PIECE framework* are related to one another. Furthermore, we identified three frequently observed practices: *Explores resources; Makes needed improvements to* *help prototype reach goal*; and *Qualitatively assesses goal completion* that might be leveraged to support engagement in more informed engineering practices.

Our data suggest that certain engineering practices occur together in many groups' interactions with exhibits. We speculate that these relationships are meaningful with respect to how groups engage in the engineering process, and we encourage further study during the design and development research for the DOT exhibit. Additionally, we believe that exhibit developers and designers can design exhibit features to leverage behaviors that are occurring frequently and scaffold visitors to some of the behaviors that are occurring less frequently. We provide these three examples for exhibit developers and designers to try to design exhibit features that:

1. Leverage the Intermediate practice of *Exploring resources* and scaffold a higher percentage of visitor groups to exercise the Informed practices of *Consider trade-offs of materials* and *Optimize design and materials*.

2. Leverage the *Makes needed improvements to help prototype reach goal* practice to scaffold a higher frequency of informed practices such as *Diagnosis of issues*, *Brainstorms ways to make a successful prototype better* and *Optimizes design and materials*.

3. Leverage the high frequency of visitors' implicit definition of a goal and frequent practice of *Qualitatively assesses goal* to scaffold a higher percentage of visitor groups to *Identify criteria and constraints* and *State a goal*.

Our findings, including how different exhibit features afford different engineering design practices (See *Exhibit Features and Visitor Groups' Engineering Design Practices*; Herran, et al, 2021), are already being applied in exhibit development for the DOT travelling exhibition and will also inform the development of associated educational programs and professional development. Furthermore, exhibit evaluation and a second research study examining how facilitation impacts engineering practices at exhibits will draw upon the instruments and measures developed in DOT Study 1.

While these findings are of immediate value for design and development research associated with the DOT project, they also have great potential to inform the practices of exhibit developers in the broader field of informal science education who are working to create or improve design challenge exhibits. An increased understanding of what practices groups engage in at exhibits, how those practices are associated with each other, and how exhibit features can influence engagement in those practices can provide valuable insights for how exhibit experiences could be designed to support the use of more Informed engineering practices. Furthermore, these results can help inform and guide the development of a wide range of educational experiences such as facilitated activities at exhibits, floor demonstrations, and activities developed for after school and summer programs. We invite informal education professionals to use this framework as a starting point for discussions and theoretical exploration around the topic of family engineering practices in museums.

Appendix A: DOT Engineering Practices 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

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Oregon Museum of Science and Industry
Designing our Tomorrow, June 2021 version

Appendix B : DOT Engineering Practices Operational Definitions

C-PIECE Framework

Collaborative Practices at Interactive Engineering Challenge Exhibits

General definitions

Proficiency: Overarching collection of practices.

Practice: A strategy, approach, or series of actions that are part of engaging in an engineering proficiency.

Practice set: a group of practices that share the same purpose within the engineering processes.

Operational definitions of practices related to *Defining a Problem* proficiency

Beginning

Immediately attempts challenge: Group creates and/or tests a design prior to watching others, exploring resources, reading panels.

Perceives goal as straight forward: Group reports the problem or challenge solely as a goal to be met.

Intermediate

Brainstorms ideas: Group makes suggestions for a design.

Discusses/plans design other than materials: Group talks about or report considering intended form, function and behavior of their design prior to or during construction.

Explores resources: Group learns about what resources are available and how they work. This may include looking at, touching, discussing and/or comparing materials without assembling or placing them, figuring out how the exhibit works or responds to input (pushing buttons, turning knobs, carefully observing), examining models, prototypes, existing designs left by other visitors, sketches or other artifacts that suggest ideas for a design.

Identifies/assigns roles: Group identifies and/or takes responsibility for specific tasks related to the challenge/problems.

Prematurely attempts the challenge: Group creates and/or tests a design after briefly watching others, exploring resources or reading panels.

Reads/listens to information provided: Group appears to focus on text panels, points to or references the text, reads text aloud.

Watches others: Group observes other groups or individuals participating in the activity or working with materials. Watching others can occur while participating in other behaviors.

Informed

Considers benefits and trade-offs of materials: Group reports or discusses alternative materials and associated potential differences.

Defines problem within context: Group describes the challenge as a goal with associated constraints, conditions, context, etc.

Delays design decisions: Group watches others, explores resources and reads panels for an extended length of time, or discusses processes, ideas or goal prior to creating a design.

Discusses questions/ideas about the process with others*:* Group members talk about how they should approach the ideation, construction or testing of their design.

Identifies/describes criteria or constraints: Group members talk about what needs to be done to accomplish a goal, measures of success of a test or restrictions for the design.

Relates content to prior experience: Group associates the current task or design to something they have experienced in the past.

States a goal: Group uses their own words to articulate, define, restate, reiterate or clarify challenge or goal.

C-PIECE Framework

Collaborative Practices at Interactive Engineering Challenge Exhibits

Operational definitions of practices related to *Improving a Design* proficiency

Beginning

Applies casual modifications: Group makes changes, often several at once, to their design with little or no evidence of consideration of how the changes will affect performance or are based on earlier tests.

Confounds variables: Group changes more than one aspect of their design between tests.

Runs through single cycle: Group builds and tests one design with few or no modifications.

Subjectively assesses goal completion: Group defines success in terms of a personally relevant measure.

Makes decisions based on aesthetic or superficial characteristics: The group creates or makes changes to a design based solely on how it looks.

Intermediate

Adjusts testing conditions: Individual(s) in the focal group appear to systematically change the conditions under which they are conducting tests.

Applies directed modifications: Group makes changes that improve the performance of a design to address issues to help it achieve the goal.

Completes multiple tests: Group repeats testing of a single design.

Describes what happened: Group summarizes or describes the result of attempting the challenge.

Diagnoses issues: Group reports or talks about figuring out why the design did not perform well.

Identifies pros/cons of design: Group talks about what seems to be working well and what seems to be a problem with their design; includes comparisons and trade-offs of design elements and materials.

Qualitatively assesses goal completion: Group defines success in terms relative to a general standard or previous performance.

Informed

Brainstorms ways to make successful prototype better: Group propose ideas to improve the performance of a design that has achieved the challenge.

Compares to own past performance or record: Group reports or talks about results of a test in terms of previous trials.

Completes multiple iterations: Group tests a design after each of several modifications: cycles of modify, test, observe.

Continues testing: Group continues to improve and test a design after the goal was successfully achieved. ***Explains results:*** Group proposes and/or discusses ideas about underlying mechanisms for performance of a design.

Focuses on problematic subsystems: Group identifies aspects of their design that are not functioning well and modify those while leaving other parts alone.

Tests specific variables: Group makes one specific change to their design and retests.

Optimizes design and materials: Group makes changes based on feedback to continue to improve a design after the goal is met.

Quantitatively assesses goal completion: Group defines success in terms of a numerical standard.

Others (behaviors that were part of the observation instrument as indicators of more complex practices)

Attempts the challenge: Group puts their design 'to the test' by trying it out to see if it meets the challenge or goal.

Completes the challenge: Group tests whether the current design iteration successfully meets the criteria of the goal or challenge presented.

Modifies/manipulates design: Group makes a change about the design they are working with. This includes minor modifications or refinements, repositioning parts, etc. as well as major modifications.

Appendix C: DOT Study 1 Observation Form

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:

Reads

Watches others

Explores materials

Discusses goal/process

Modifies/manipulates design

Suggests a goal

Attempts a challenge

Completes a challenge

Adjusts testing conditions

Notes:

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

Appendix D: DOT Learners Study 1 Interview Form

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?

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

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

How did you decide where to start/what to do first?"[use their language for: building/designing/placing objects?

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 that change affect what happened?”

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

Would you say that you were doing engineering at this activity?

if yes, ask What about this activity was engineering?

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