The C-PIECE Framework:

Documenting group engineering practices elicited by design challenge exhibits

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Abstract

This paper describes the Collaborative Practices at Interactive Engineering Challenge Exhibits (C-PIECE) Framework, a new engineering design practices framework for informal exhibit settings. It outlines the development of instruments to document these practices, and presents findings from a study of visitor use of engineering practices at design challenge exhibits. The work was conducted as part of *The study of collaborative practices at interactive engineering challenge exhibits (the C-PIECE Study),* and addresses two aims, 1) develop indicators and methods of measurement of engineering design practices exercised by visitor groups within an engineering exhibit context, and 2) speculate on those practices' associations with the exercise of beginning, intermediate, and informed engineering proficiency levels within an exhibit context. The framework is intended to be used to inform the development of informal engineering education experiences, not to assess individual performance.

Introduction

The Collaborative Practices at Interactive Engineering Challenge Exhibits (C-PIECE) Framework is a new, theory-derived framework for studying engineering design practices in exhibit settings. This paper outlines the development of instruments to document these practices, presents findings from a study of visitors' use of engineering practices at design challenge exhibits, and examines how the framework and instruments might be used by others in the informal education field. The framework is intended to be used to inform the development of informal engineering education experiences, not to assess individual performance.

The research described here is part of Designing Our Tomorrow—Mobilizing the Next Generation of Engineers (DOT), a multi-year (2018-2024) project led by the Oregon Museum of Science and Industry (OMSI) with the support of the National Science Foundation and project partners (Adelante Mujeres, the Biomimicry Institute, and the Fleet Science Center). The DOT project seeks to promote and strengthen family engagement and engineering design via compelling exhibit-based design challenges to help solve human problems. DOT capitalizes on museum exhibits as unique family learning environments in the interest of fostering intergenerational participation and investment in engineering activities. The project focuses on girls ages 9 to 14 and their families and will deliver a 2000-square-foot traveling exhibit co-developed and presented in Spanish and English. The development of the exhibition was informed by this research study, titled *The study of collaborative practices at interactive engineering challenge exhibits* (the C-PIECE Study) which examined collaborative engineering design behaviors at exhibits.

This research is focused on 1) developing indicators and methods of measurement of engineering design practices exercised by visitor groups learning within an engineering exhibit context and 2) speculating on how those practices fit within a framework of beginning, intermediate, and informed levels of engineering proficiencies. In this research, we define engineering practices as strategies, approaches, or a series of actions that are part of engaging in engineering. Since this research was conducted at interactive exhibits within a science center, the findings are most applicable to similar informal designed environments. The research employed a Research Advisory Committee (RAC) composed of three members with research expertise in museum education, engineering education, and measurement. The RAC helped guide the research team in conducting rigorous, reliable, valid, and culturally responsive research. At several points during the project, RAC members were asked to review research activities and provide recommendations. For more information on the DOT project and theoretical orientations, as well as details on the C-PIECE Study methodology, please refer to *The study of collaborative practices at interactive engineering challenge exhibits—background and methods* (Shagott, et al. 2021).

Developing the C-PIECE Framework

Building on prior work

The purpose of this research was to adapt constructs of engineering proficiencies for nuanced use within an exhibit context. This required looking into the current literature including documents such as Next Generation Science Standards (NGSS), American Society for Engineering Education's (ASEE) Framework for P-12 Engineering Learning; and the Informed Design

Teaching and Learning Matrix. The NGSS are a set of research-based content standards which set the expectations for K-12 students in the classroom (NGSS Lead States, 2013). While not intended as a comprehensive set of standards for engineering education, the NGSS Framework for K-12 Science Education integrates engineering design, providing performance expectations for engineering design practices such as defining problems, specifying criteria, building and testing prototypes, and generating multiple solutions, by grade level. The ASEE Framework for P-12 Engineering Learning (Strimel, et al., 2020) focuses specifically on engineering literacy goals. The ASEE Framework defines engineering practices as “the combination of skills and knowledge that enable a student to authentically act or behave like an engineering-literate individual” and presents four general categories of practices: Engineering Design, Material Processing, Quantitative Analysis, and Professionalism. Like the NGSS Framework, learning goals are separated by grade level. The Informed Design Teaching and Learning Matrix (Matrix) developed by Crismond and Adams (2012), is a framework of design practices, instructional goals, and teaching strategies associated with engineering education for learners K-16. Stemming from an information processing perspective (Adams & Atman, 1999; Axton et al., 1997; Goel, 1989), Crismond and Adams developed the emergent educational theory of informed design. This theory is represented in the evidence-based Matrix which includes behavioral constructs associated with phases of design that indicate beginning and informed learning approaches. This Matrix includes engineering-related proficiencies such as understanding the challenge, experimenting, and iterating. The Matrix also articulates characteristics of the classroom environment that elicit or afford these design practices.

Given the Matrix's clear statement of behaviors and environmental characteristics associated with levels of demonstrated engineering proficiencies, we decided to build heavily on the work of Crismond and Adams (2012) to study, through a sociocultural lens (Nagel, 2012; Grabinger, et al. 2007), how exhibits can support, afford, and elicit engineering design practices in families. This lens acknowledges the influences that personal experience and cultural norms play in exhibit interactions and learning (Falk & Dierking, 2013). Therefore, in this study group interactions with exhibits can be situated within an ecological framework that can simultaneously hold multiple theories on people, places, and culture (NRC, 2009). Furthermore, a sociocultural perspective recognizes that physical environments influence learning, even in everyday settings (NRC, 2009) and support situated learning which emphasizes learning within authentic contexts. Prior research and development on engineering interpretation in informal education (Cardella, et al., 2013; Heimlich, et al., 2014; Museum of Science, 2012; Wang, 2014) suggests that it is not likely to see all of the engineering proficiencies described in classroom-based standards like the Matrix in an exhibit setting.

We concluded that the Matrix had to be adapted to be useful for exhibit experiences, which are relatively quick, unstructured, and involve multiple learners and multiple visitor agendas (Allen et al., 2007; Falk, et al., 1998; Falk & Dierking, 2000; Griffin, 1994; NRC, 2009;). An adapted version needed to refer to fewer steps in a design cycle and use language (both Spanish and English) familiar to visitors. Therefore, we conducted a systematic study to adapt the Matrix. We used existing research from the field of informal science and engineering education; consultations with researchers, informal science educators, and community educators; and input from learners in the form of observations and interviews to simplify and adapt the Matrix into the C-PIECE Framework to guide the development of measures of engineering design proficiencies for use with visitor groups during exhibit experiences.

Creating the initial C-PIECE Framework

The first step to adapting the Matrix to an exhibit setting was to conduct a thorough literature review of existing research and measures relating to engineering proficiencies. We systematically collected and reviewed publications from both English- and Spanish-language databases, including, but not limited to: EBSCO (which includes the Journal of Engineering Education), Journal of Science and Education and Research, ASEE Papers on Engineering Education Repository (PEER), Web of Science, ProQuest Education Database, previous OMSI projects, NSF Award Database, Research Gate, EBSCO-en Español, and Revista Educación en Ingeniería. We selected nine descriptions of practices associated with engineering design (Barriault & Pearson, 2010; Bevan, et al., 2015; Crismond & Adams, 2012; Dorie, et al., 2014; Ehsan, et al., 2018; Lussenhop, et al., 2015; Museum of Science, 2012; Paulsen & Burke, 2017; Wang, 2013) to serve as a basis for the development of the C-PIECE Framework. Individual practices from each source were grouped by similarity and categorized under one of three key proficiencies—Understanding the Problem, Testing, and Iteration. We believed this set of practices could both be observed and measured in an exhibit setting and could provide rich insights into the sophistication of visitor engineering design approaches. Appendix A contains a list of the practices organized by their proficiency and source.

Understanding the Problem proficiency A review of the literature identified several practices related to Understanding the Problem. The Museum of Science (MOS) Design Challenges Observation Instrument (MOS, 2012) and the related Facilitation Research for Engineering Design Education (FREDE) report (Lussenhop, et al., 2015) include an Ask/Imagine/Plan phase that encompasses indicators related to Understanding the Problem. While the FREDE instrument documented time spent in the 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, et al. (2014) created a section titled Problem Scoping that included identifying constraints, restating the goal, and becoming familiar with materials. Finally, practices provided in the Matrix by Crismond and Adams (2012) for Understanding the Challenge include a range of practices from perceiving the challenge as straightforward and attempting it prematurely (Beginning) to exploring the problem and delaying design decisions (Informed).

Practices associated with considering or developing solutions (Atman, et. al, 2003; Atman et. al, 2007) such as Explores resources, Brainstorms ideas, and Discusses questions/ideas about the process with others, were categorized within the Understanding the Problem proficiency. We felt it was appropriate to include these practices as they support how the visitors define and refine what they are trying to do, especially in an exhibit setting where visitors are often approaching a challenge for the first time with little or no context, and may not spend a great deal of time focused on a single design challenge. Including these practices as part of Understanding the Problem is consistent with Lussenhop, et al.'s decision to include Imagine and Plan as part of their Understanding the problem phase (2015). The decision is also supported by work of

Watkins, et al. (2014) who found that some students, practicing engineering design at a novice level, engage in planning their design simultaneously with problem scoping, but prior to testing and iterating; we suspected that visitors may do the same.

Testing proficiency In the Matrix, Crismond and Adams (2012) identify a proficiency labeled Conducting Tests and Experiments; within this proficiency, the practice of conducting valid experiments to learn about materials and systems would be considered an informed practice while the practice of confounding variables and doing very few tests would be considered a beginning practice. The FREDE instrument noted the number of designs tested; Dorie et al. (2014) included a general design evaluation phase that includes assessing goal completion based on outcomes of a test. The Design Challenges Observation Instrument (MOS, 2012) lists five behaviors under their Test phase: testing prototypes, observing testing, identifying what happened, identifying pros/cons of design, and comparing results to their own past performance or record.

Iteration proficiency Iteration is a category focused specifically on troubleshooting and improving during design activities. Nearly all of the sources that we examined included practices related to iteration. Ehsan et al. (2018) define four actions involved in design-based troubleshooting: Observing, Diagnosing, Explaining, and Fixing. From the FREDE instrument, both the number of designs tested and the time in the create/build phase were included in the iteration category. Dorie et al. (2014) listed the codes: increasing efficiency, iteration based on feedback, and optimization under the heading Revision. The Design Challenges Observation Instrument has an Improve phase that includes: makes needed improvements to help prototype reach goal, brainstorms ways to make successful prototype better, makes aesthetic improvements, and reevaluates the goal. Like the FREDE report, the Design Challenges Observation Instrument also codes for the number of designs tested. Finally, elements from Crismond and Adams' Matrix proficiencies titled Troubleshoot and Revise/Iterate were included in the C-PIECE construct of Iteration. Within these proficiencies, Crismond and Adams (2012) contrast the beginning approaches of haphazard, unfocused, non-analytical design with the informed approaches of focus on problematic subsystems, improvements based on feedback, and multiple iterations.

Based on feedback from members of the RAC, gaps in the literature (Adams, et al., 2003; Crismond & Adams, 2012), and the link between the engineering proficiency of understanding the problem and the visitor experience of understanding the exhibit challenge, we decided to focus data collection and analysis on practices in the category, understanding the problem. To clarify the language that was used in the project, make it applicable to the exhibit development process, and to capture the nature of free-choice learning, we use the term Defining a Problem to refer to this proficiency. Drawing from language in the Engineering Design Cycle (MOS, 2009) and Engineering is Elementary (Cunningham & Hester, 2007), which both include an Improve step, for the purposes of this study, we decided to label a second proficiency Improving a Design, which includes Testing and Iteration.

In the literature, specific engineering design practices are associated with the different proficiencies (Barriault & Pearson, 2010; Bevan, et al., 2015; Crismond & Adams, 2012; Dorie, et al., 2014; Ehsan, et al., 2018; Lussenhop, et al., 2015; Museum of Science, 2012; Paulsen &

Burke, 2017; Wang, et al., 2013). 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 corresponded to levels in the Matrix or was described in the primary publication. The result was the first draft of the C-PIECE Framework. The operational definitions for each of the practices in this first draft of the framework were refined, and data collection instruments were created in Spanish and English. Operational definitions for each of the final 37 practices are in Appendix B; a visualization of the framework can be seen in Figure 1.

The C-PIECE Framework was developed to show more detail on evidence-based engineering design practices at exhibits than we found in the nine engineering process sources we drew upon. Also, the C-PIECE Framework was created to inform the development of informal engineering design experiences; it is not intended to assess individual performance. In fact, the C-PIECE Framework is constructed with evidence from groups' use of exhibits, not individuals. While in formal engineering education, levels of proficiency are often seen as progressive or sequential, in exhibit contexts the exercise of practices is more dependent on the practices an exhibit affords groups. Although practices in the C-PIECE Framework are categorized by level, it was expected to see groups exercise practices in multiple levels of proficiencies during their experience. The C-PIECE Framework allows exhibit developers, designers, researchers, and evaluators to see the levels of practices that an exhibit affords; if an exhibit does not afford Intermediate and Informed practices, then the exhibit professionals have an opportunity to revise their activities to stretch more practices.

Evolving the C-PIECE Framework through design and development research

The draft C-PIECE Framework was vetted and refined through iterative conversations with the RAC, piloting of associated instruments with girls and their families, additional literature review, and via the expert review process described below in an effort to provide a useful tool for informal engineering education efforts. The final published framework includes 37 engineering-related practices along with their operational definitions (Appendix B). The practices are listed under two proficiencies (Defining a Problem and Improving a Design) and categorized across three levels of proficiency (Beginning, Intermediate, and Informed). The C-PIECE Framework is now ready for broad use, though we envision it will evolve through further research and development by our team and others.

[Figure 1 Here]

Method

Approach

This research followed recommendations in the field of informal science, technology, engineering, and math (STEM) education by using multiple culturally-responsive strategies (e.g. Garibay & Teasdale, 2019; Kirkhart & Hopson, 2010; OMSI, 2016) to reduce threats to and strengthen all five dimensions of multicultural validity (Kirkhart & Hopson, 2010). To support methodological validity, the team ensured that members of Latino communities were involved in all aspects of the research including instrument creation, translation, data collection, analysis, and dissemination. To reduce threats to interpersonal validity, the research team strived to develop trust with participants and organizational partners by fostering an environment that welcomed their insights. To support theoretical validity, the research team approached this project from a sociocultural perspective (Cobb & Bowers, 1999) that recognizes learning is co-created within personal, social, and physical contexts. The researchers supported experiential validity through the use of multiple English and Spanish language methods to capture the wisdom and preferred language of participants—naturalistic observation, video recording, interviews, and surveys. By adopting a perspective that engineering is not an end, but a means for community members to achieve their goals (Bevin et al., 2018; NSF, 2008) and by recognizing that culture plays a central role in learning and education (Bevan et al., 2018), research supported consequential validity. For a detailed description of the approaches and strategies employed in the research, please see Shagott, et al. (2021).

Data Collection Instruments

As part of the C-PIECE Study, we developed and iteratively tested instruments to document engineering practices in the C-PIECE Framework. Instruments based on the C-PIECE Framework were developed and refined through an iterative process of piloting the instruments followed by reflection and discussion of the data. OMSI educators and researchers participated in the development of instruments by reviewing and commenting on drafts, completing debrief forms following data collection, and taking part in guided discussions intended to contribute to the construct and content validity of the instruments and the trustworthiness of the methods used in the study.

For this research—documenting group engineering practices elicited by design challenge exhibits—we used three methods for gathering data from visitors: 1) naturalistic observations, 2) interviews, and 3) video recorded observations. The unit of data collection and analysis was a visitor group, which was defined as an intergenerational group of two or more people who came to the museum together. While many of these visiting groups were "families," we did not presume a relationship between individuals and refer to all of them simply as groups.

Naturalistic Observation Protocol

We set out to create a user-friendly observation tool to document visitors' engineering design practices while engaging with the exhibits. To that end, we created a one-page form to gather observation data (Appendix C). The form prompted observers to record the size and make-up of the group, the date, the time of day, and the exhibit where data were being collected. Once a visitor interacted with the exhibit, observers 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 are defined using the same words as the engineering practices (e.g. Describes what happened), and others are observable behaviors that are used during coding to imply more complex practices. Attempts the challenge, for instance, is not an engineering practice from the framework—it is an observable indicator. During coding, documentation of Attempts the challenge was used in association with other indicators, such as Modifies design, to code for practices that could not be observed as a single behavior. 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.

The observation form also prompts observers to take open notes about what visitors say and do during their time at the exhibit. These observation data were reviewed and coded by exhibit for the presence or absence of each of 36 of the 38 engineering design practices from the study version of the framework (Appendix D). We anticipated that 18 of the practices would be captured consistently across groups since the observation instrument was designed to record those practices explicitly; an additional 18 practices had the potential to be captured through the open notes section. Two practices from the framework (Perceives goal as straightforward and Defines problem within context) could not be captured via observation. Table 1 lists which practices were captured with each method (observation, interview or video-recording). An X denotes that the practice was captured by the method itself, an N indicates that the practice was captured in observer notes related to that method, and -- shows that a practice was not captured by that method.

[Table 1 near here]

Interview Protocol

We conducted guided interviews with groups after they had completed their exhibit experience. Interviewers 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 E). The questions were intended to provide information that complemented the observation data and to provide insights into what the visitor was thinking and doing that could not be directly observed. We used a Spanish version of this instrument with visitors who preferred to communicate in Spanish. The interview data were reviewed and coded by exhibit for the presence or absence of each of 37 engineering practices.

Video Recording Protocol

Exhibit interactions were video recorded. We developed a code book that included documentation of 29 engineering-related behaviors; these behaviors were mapped onto 18 practices from the C-PIECE Framework. Videos were coded for the presence or absence of the behaviors using the codebook to obtain a more detailed look at the use of engineering practices.

Expert Review

We used an expert review process to strengthen the validity of the materials, approaches, and constructs we developed. Individuals and small groups with expertise in a variety of areas—informal education with Latina girls, engineering education, engineering design, informal STEM education, biomimicry education, engineering education research, informal STEM education research, and museum research—reviewed and commented on our work. Candidates for the review process were selected based on their areas of expertise and their experience in that area. The panel of 15 individuals had an average of over 15 years experience in their respective fields.

The review process included one 30-minute meeting (face-to-face when possible, otherwise via video call) to orient the experts to the DOT project, explain the review process and its purpose, and to introduce them to the tools and materials being developed. Following the orientation meeting, materials were sent via email for review. All experts received a copy of the draft C-PIECE Framework as well as a list of the operational definitions of each of the engineering design practices. Depending upon their area of expertise, some of the experts also received exhibit-specific examples of the indicators and/or data collection instruments. Finally, all of the experts received a set of questions that asked them to reflect on the completeness and clarity of the indicators, the operational definitions, and the appropriateness for their use at exhibits and with different audiences. Many experts furthermore received additional questions related to their specific experience (e.g. work with girls, measure development).

We asked the experts for general comments and suggestions for improvement. These questions served as a guide for a one-hour discussion that took place approximately one week after the initial introduction. Several of these discussions led to identification of additional literature on the topic (Atman, et al., 2007; Childress & Rhodes, 2008; CMC, 2008; Moore, et al., 2014). These sources were reviewed and practices identified in the new sources were compared with the existing list to ensure that there were no new practices to be added. We collected notes from these conversations and the experts' responses; we reviewed these data and used them to further refine the C-PIECE Framework and instruments.

Data collection

Data collection was conducted in the public spaces at OMSI. Researchers gathered information from participating groups that engaged with one of three engineering design exhibit components from the Designing Our World exhibition (Shagott, et al., 2021). They used an observation instrument and took open-ended notes, video-recorded exhibit interactions, and conducted interviews with groups about their experiences with the engineering activities. All groups knew they were participating in a study that included video recording and they had provided written consent prior to engaging with the exhibits (Shagott, et al., 2021).

Exhibits

We collected data at three engineering design challenge exhibits at OMSI, which are briefly described below. For additional details and images, please refer to Shagott, et al. (2021).

The Catch the Wind exhibit challenged visitors to assemble and test a wind turbine using a hub, a variety of K'Nex® pieces, and plastic blades of different shapes to explore generating energy from wind power—a real-world concept with a strong connection to sustainability.

The Build a Boat exhibit allowed visitors to assemble a functioning boat that they could then test in a tank of water. Exhibit copy prompted visitors to consider the different real world needs of people in the design of their boat. The building station included: hull pieces in different shapes and sizes, three shapes of sails, and cargo. The water-filled testing tank had an air blower at one end to provide propulsion; obstacles and a finish line made 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, then they tested their design from three different drop heights.

Participants

Data were collected from 71 groups, including 22 groups that opted for data collection in Spanish. For the 71 groups recruited to participate in the study, we analyzed all of their survey and observation data; 31 English-speaking and 18 bilingual/Spanish-speaking groups were included in the video analysis. The remaining groups were omitted from the analysis because their video recordings were not of sufficient quality to analyze the participants' interactions with the exhibits. For more information on the participant pool, see Shagott, et al. (2021).

Results

This study explored the extent to which visitors engaged in the engineering design practices identified in the C-PIECE Framework as they interacted with design challenge exhibits. We sought to determine whether exhibits could afford a variety of engineering practices across a range of proficiency levels, and whether the instruments developed could capture those practices. We did not attempt to assess the participants' engineering knowledge or abilities. Instead, we focused on the presence or absence of engineering-related practices as measured by the suite of instruments. By determining whether the range of practices in the C-PIECE Framework can reasonably be expected in exhibit interactions and whether the instruments and methods developed can capture those practices we could establish that the C-PIECE Framework and methods were viable means of studying engineering design practices afforded by exhibits and potentially inform the development of new design challenge exhibits, such as those being developed as part of DOT.

The objectives of our work were two-fold: 1) to determine whether design challenge exhibits could afford the engineering practices listed in the C-PIECE Framework and 2) to assess the usefulness of the data collection instruments and methods for capturing group engineering design practices elicited by exhibit experiences. If certain practices were not captured via the data collection, one could conclude that either the instruments failed to capture those practices, or that the exhibits did not afford them. These findings could help further refine and improve the framework and instruments.

Modifications were made to the framework following data analyses, resulting in the version presented in Figure 1. The data below are presented using the version of the framework prior to those final changes, so certain terms and labels will not match exactly. The version of the framework used for analysis, referred to as the study version, can be found in Appendix D.

Data Analyses

Based on our analyses, we sought to answer the following questions:

- Did the methods capture the anticipated engineering practices at least once?
- How often did each method capture each anticipated practice across groups and exhibits?
- Were any of the practices not captured or captured only rarely?

We first identified specifically which items from each method could be used to capture each practice; that is, which interview questions, video codes, and observation codes were associated with each practice. For example, the interview question “What were you trying to do/accomplish?” was linked to the practices, Perceives goal as straightforward and Defines problem within context. The observation form included an open notes field; these notes were reviewed looking for indicators of all of the practices, rather than any one specific practice. Therefore, while it was possible to capture a practice, it was not necessarily expected. Tables 2 -

4 below list which methods had items that might capture each practice. Practices captured via observation notes are marked with an 'N'.

[Table 2 near here]

All data sources were then reviewed and coded for the presence or absence of each practice by group and method. For each practice, coders 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 a spreadsheet. If the practice was not captured, the cell was left blank. Each cell in the spreadsheet documented which methods captured at least one 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 counted how many groups were captured engaging in each of the practices by method; we also 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, as captured by each data collection method, across exhibits. Finally, we generated descriptive statistics from the data. Note that observation and interview data were collected from 71 groups; video data were analyzed from 49 groups.

Practices by Method

As can be seen in Tables 3 and 4, all but one of the practices in the C-PIECE Framework were captured at least once by one of the methods and each data collection method was able to capture different practices. This result was promising for two reasons: 1) the data demonstrate that the exhibits afford a wide range of engineering design practices, and 2) the instruments worked as intended.

The only practice not captured was Few or no tests of prototype, a beginning level practice under Improving a Design. We believe that we failed to capture this practice not because of a deficiency in the instruments but rather because this practice would be rarely observed at exhibits like these that had gone through an extensive evaluation process during their development. High counts of practices such as Completes multiple tests, Continues testing, and Completes multiple iterations and very low counts of Runs through single cycle suggest that the exhibits are designed to elicit the testing of designs from groups.

While every other practice was captured, it is clear that some practices were observed much more frequently than others. The following practices were observed in fewer than 10 groups: Brainstorms ideas, Discusses questions/ideas about the process with others, Restates goal, Confounds variables, Focuses on problematic subsystems, Brainstorms ways to make successful prototype better, Subjectively assesses goal completion, Makes decisions based on aesthetic or superficial characteristics, Haphazard re-design, Runs through single cycle, Tests specific variables, Optimizes design and materials, and Quantitatively assesses goal completion. We speculate that the counts are low for different practices for different reasons. Some beginning practices, such as Runs through single cycle, Confounds variables, Makes decisions based on aesthetic or superficial characteristics, Haphazard re-design, and Subjectively assesses goal completion, were rarely seen among groups that engaged in related Intermediate or Informed level practices. Quantitatively assesses goal completion was only seen once, which was not surprising since none of the three exhibits studied provided participants with quantitative feedback. This practice is an affordance that could be added to the exhibits to increase engagement. The remaining practices were not coded for at all in the video recordings, and there were no items in the interviews or observations that were specifically developed to capture them. Therefore, while the counts on these practices are low, it is unclear whether most groups were not engaging in them or whether they were simply not being captured by the instruments.

[Tables 3 and 4 near here]

For most practices, the count of total unique groups can be accounted for by a single instrument, either observation or interview. For example, the observation captured a large number of groups exploring resources that were missed by the interview, and the interview captured groups perceiving the goal as straightforward, a practice not captured by the observation. This finding suggests that the observation and interview appear to be complementary as data collection instruments and can be used in tandem to capture a wide range of practices. There are, however, some practices for which one instrument captured some groups while another instrument captured others. These practices include Watches others, Considers benefits and trade-offs of materials, Diagnoses issues, Explains results, Relates content to prior experience, Identifies/assigns roles, and Reevaluates the goal. While there was inter-rater reliability within the coding of a single instrument, this result suggests that different instruments are inconsistently capturing these practices likely due to differences in how the practices were coded for different methods. Results of these analyses were used to further refine the C-PIECE Framework, operational definitions of the practices, and the data collection instruments as provided in this article.

Discussion

This study employed qualitative, culturally responsive research methods intended to realize multi-cultural and construct validity. Through foundational research (Institute of Education Sciences, 2013), this study contributes to knowledge of indicators and methods of measuring collaborative engineering design practices elicited by engineering exhibits, viewed with an intersection of levels of engineering proficiency (Crismond & Adams, 2012). The work confirmed that exhibits, as educational interventions, can elicit nuanced practices associated with engineering design and that those practices can be documented (i.e. measured). We adapted a plausible set of collaborative design practices at engineering exhibits from the theory-based Informed Design Teaching and Learning Matrix (Crismond & Adams, 2012), other research on engineering processes, and the research team’s experience with engineering design challenge exhibits into the C-PIECE Framework. The research team focused the adapted C-PIECE Framework on engineering design practices exercised at exhibits and speculated their association with Beginning, Intermediate, and Informed levels of the engineering proficiencies Defining a Problem and Improving a Design.

Using evidence gathered through naturalistic observation, interviews, and video-recordings of groups interacting with three different exhibits, the research team confirmed that these engineering design practices could be afforded by engineering exhibits. We further refined the C-PIECE Framework through a systematic review with stakeholders representing diverse perspectives in museum education, informal education, and engineering education. We continued conducting expert reviews and refinements until we no longer received comments that something was missing or did not make sense. Data analyses yielded information useful for further refining our instruments, protocols, and operational definitions. We are using the C-PIECE Framework for continued work on the DOT project and sharing it with the larger field of informal STEM education.

Our findings suggest that the exhibits studied afford a wide variety of engineering-related practices and that the practices included in the C-PIECE Framework can be captured using different methods. We also note that while video coding provides a very rich look at what visitors are doing at an exhibit, it is possible to capture the full range of engineering design practices with a combination of naturalistic observation and interview which require fewer resources than video-recording. Detailed information, including what practices are observed most and least frequently, is already being applied in the development and evaluation of the DOT traveling exhibition and will serve as a foundation for the associated educational programs and professional development

While the findings of this research are of immediate value for the design and development of DOT, they can also be used to inform work beyond this project. For example, this work helps expand Crismond and Adams Emergent Education Theory of Informed Action to an exhibit and group setting. Researchers can include the C-PIECE Framework in discussions and explorations around the topic of collaborative engineering design practices in museums. We have identified potential for further research with the C-PIECE Framework. For example, our team applied theories of knowledge and skill acquisition (Anderson & Krathwohl, 2001; Jideani & Jideani, 2012; Krathwohl, 2002) to explore how groups engaging in design challenge exhibits describe and characterize what they are doing, and the extent to which they report that the practices and strategies they are exercising are part of an engineering process (Randol, Herran et al., 2021). We have conducted analyses to better understand associations between engineering practices included in the C-PIECE framework such as how engagement in certain engineering design practices relates or leads to engagement in other practices at exhibits (Randol, Benne et al., 2021). We also encourage further study of the practices' association with proficiency levels and continued improvement of the multi-cultural validity of the C-PIECE Framework. Researchers will find the C-PIECE Framework is compatible with prior research on engineering education processes already mentioned in this paper and can use the Framework to further their interests in those sources. To support future research, we provided additional background on the theoretical orientations informing the C-PIECE Framework in Shagott et al. (2021).

Practitioners will benefit by using the C-PIECE Framework to plan and evaluate their engineering activities in ways that help them focus or stretch groups' exercise of engineering practices. A C-PIECE user orientation for practitioners is provided in *Exhibit Features and Visitor Groups' Engineering Design Practices* (Herrán et al., 2021). The instruments and protocols in this study are ready to be used and adapted by exhibit developers, evaluators, and researchers in the field. The indicators and methods developed in this research are intended to be useful for establishing and studying outcomes. The findings derived from monitoring the indicators are intended to help professionals understand exhibit characteristics that afford engineering design practices. We provide practitioners with a story of how we assessed three exhibits using the C-PIECE Framework to document the practices we observed, the design features that seemed to afford those practices, and the practices we did not observe (Herran et al., 2021). The C-PIECE Framework provides multiple lenses on engineering design challenge activities so that practitioners can adapt the Framework to their goals and inquiries.

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Declaration of Interest

In accordance with Taylor & Francis policy and my ethical obligation as researchers, We are reporting that I have no financial and/or business interests in, do not receive funding from, nor am a consultant to any company that may be affected by the research reported in the enclosed paper.

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About the Authors

Scott Randol, PhD, is Participatory Research and Evaluation Manager at Oregon Museum of Science and Industry (OMSI) in Portland, Oregon. He has worked in informal STEM education institutions as an evaluator, researcher, and educator in Math and Science Education for over 25 years. His work focuses on inspiring people of all ages and backgrounds to be more engaged in learning about and understanding the world around them.

Marcie Benne, PhD, is the Director of Engagement Research and Advancement at OMSI. She studied engineering psychology at Georgia Institute of Technology and spent 20 years helping advance research and development projects in informal STEM education with particular attention to family learning at exhibits.

Carla Herrán is Research and Evaluation Associate at OMSI. She is a bi-lingual (Spanish/English) researcher and evaluator who is passionate about work that centers the voices of target audiences. She is currently applying content analysis to care-giver created narratives to study how the relevance of engineering practices at exhibits to visitors' everyday lives can be communicated. Carla is Co-PI on the DOT project.

Smirla Ramos-Montañez, PhD, is a bilingual (Spanish/English) and bicultural (Puerto Rican/American) researcher and evaluator focusing on culturally responsive studies related to informal STEM learning. During the last five years Dr. Ramos-Montañez has led and supported a variety of projects, including program and exhibit evaluation as well as STEM education research to provide accessible, culturally relevant, and engaging experiences for diverse audiences. Currently, she is working with Dr. Scott Pattison to better understand family interest pathways and how to foster long-term interest in the engineering design process.

Todd Shagott, PhD, is the Data Systems Analyst in the Engagement Research & Advancement division at Oregon Museum of Science and Industry. He considers his work to be at the intersection of research and informal education. This positioning provides the opportunity to bring insights that may bridge the disconnect between research and practice

Appendix A: Engineering-related Practices by Source

Engineering Proficiency	Practice	Sources
Understanding the Problem	Time in ask/imagine/plan phase[A] Problem scoping[C] ● Identify constraints ● Restate goal ● Look at feasibility of problem ● Add context ● Understanding goal (instructions) ● Familiarize w/ materials ● Identify/assign roles Define goal [I] Ask/Imagine/Plan[F] ● Reads or listens to information provided ● Looks at model and building station. ● Watch other people test ● Chooses specific sub-challenge (e.g. low vs. high bounce) ● Discusses questions/ideas about the process with staff ● Relates content to prior experience ● Brainstorms ideas ● Decides on one best possible solution ● Explores/compares materials and tools to use ● Discusses/plans design other than materials Perceived as straightforward; prematurely attempt/delay design decisions, explore problem[G] Identifying a problem[H]	[A] Facilitation Research for Engineering Design Education (Lussenhop, et. al, 2015) [B] Assessing Exhibits for Learning in Science Centers: A Practical Tool (Barriault & Pearson 2012) [C] Capturing the Design Thinking of Young Children Interacting with a Parent (Dorie, et. al, 2014) [D] Examining Children's Engineering Practices During an Engineering Activity in a Designed Learning Setting: A Focus on Troubleshooting (Ehsan, et. al, 2018) [E] Learning Through STEM-Rich Tinkering: Findings From a Jointly Negotiated Research Project Taken Up in Practice (Bevan, et. al, 2014) [F] MOS Design Challenges Observation Instrument (Museum of Science 2012) [G] The Informed Design

		Teaching and Learning Matrix (Crismond & Adams 2012)
Testing	Number of testing conditions[A] Design evaluation[C] ● Assess goal completion Testing [H,I] Experiment [I] Test[F] ● Tests prototype ● Observes testing ● Identifies what happened ● Identifies pros/cons of design ● Compares to own past performance or record Few or no tests, confounded variables, focus on problematic subsystems, discuss solutions[G]	[H] Design Squad Global Summative Evaluation Report (Paulsen & Burke 2017) [I] Ingenuity Lab: Making and Engineering through Design Challenges at a Science Center (Wang, 2013)
Iteration	Number of designs tested[A] Time in create/build phase[A] Revision[C] ● Increase efficiency by making a physical change[C] ● Iterate based on feedback (verbal or physical) [C] ● Optimization[C] Design-Based Troubleshooting[D] ● Observing ● Diagnosing ● Explaining ● Fixing Improve[F] ● Makes needed improvements to help prototype reach goal ● Brainstorms ways to make successful prototype better (small changes to improve working design) ● Makes aesthetic improvements ● Reevaluates the goal	

	Number of designs tested [F] Iterate, Refine, Optimize [I] Haphazard re-design, single run through cycle/multiple iterations, systematic changes based on feedback[G]	
General	Spending time, seeking and responding to feedback, persisting, requesting or offering help, taking risks, making connections, offering explanations, striving to understand [E] Total time[F]	
Beginner	Initiation behaviors: watching others, completing the activity[B]	
Intermediate	Transition behaviors: repeating the activity, positive affect[B]	
Informed	Breakthrough behaviors: referring to past experiences, seeking/sharing information, testing variables, making connections[B]	

Appendix B: C-PIECE 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: C-PIECE Study Observation Form

DoT Learners Study 1- Cycle 3 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:	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

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Appendix D: C-PIECE Framework (Study Version)

DOT Indicator Matrix 4-25-2019

Defining a Problem

Beginner	Intermediate	Informed
Prematurely attempts challenge	Reads or listens to information provided	Explores problem
Perceives goal as straight forward	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	Restates goal
	Identify/assign roles	Delays design decisions

Optimizing

Beginner	Intermediate	Informed
Confounds variables	Qualitative assessment of goal completion	Focuses on problematic subsystems
Subjective assessment of goal completion	Identifies what happened	Brainstorms ways to make successful prototype better
Makes decisions based on aesthetic or superficial characteristics	Diagnoses issues	Optimization of design and materials
Few or no tests of prototype	Identifies pros/cons of design	Compares to own past performance or record
Haphazard re-design	Makes needed improvements to help prototype reach goal	Explains results
Single run through cycle	Observes performance	Tests specific variables
	Completes multiple tests	Quantitative assessment of goal completion
	Adjusts testing conditions	Reevaluates the goal
		Completes multiple iterations
		Continued testing

Appendix E: DOT Learners C-PIECE Study Interview Form

DoT Learners Study 1 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?

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]?

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

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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?

Tables (with captions)

Table 1. Defining a Problem practices captured by method as indicated by X or N (-- not captured by this method)

Practice	**Observation**	**Interview**	**Video**
Immediately attempts challenge	X	X	X
Perceives goal as straight forward	--	X	X
Reads or listens to information provided	X	X	X
Explores resources	X	X	X
Discusses/plans design other than materials	N	X	--
Brainstorms ideas	N	X	--
Watches others	X	X	X
Identifies/assigns roles	N	X	X
Prematurely attempts challenge	X	--	X
Defines problem within context	--	X	X

Considers benefits and trade-offs of materials	N	X	X
Discusses questions/ideas about the process with others	N	X	--
Relates content to prior experience	N	X	X
States a goal	N	X	X
Delays design decisions	X	X	X

Table 2. Improving a Design practices captured by method as indicated by X or N (-- not captured by this method)

Improving a Design Practices			
Confounds variables	X	X	--
Subjectively assesses goal completion	N	X	--
Makes decisions based on aesthetic or superficial	N	X	--

characteristics			
Few or no tests of prototype	X	X	--
Haphazard re-design	X	X	--
Runs through single cycle	X	X	--
Qualitatively assesses goal completion	N	X	X
Describes what happened	N	X	--
Diagnoses issues	N	X	X
Identifies pros/cons of design	N	X	--
Makes needed improvements to help prototype reach goal	X	X	--
Adjusts testing conditions	X	X	--
Completes multiple tests	X	X	X
Focuses on problematic subsystems	X	X	--
Brainstorms ways to make successful prototype better	N	X	--

Optimizes design and materials	X	X	--
Compares to own past performance or record	N	X	--
Explains results	N	X	X
Tests specific variables	X	X	--
Quantitatively assesses goal completion	N	X	X
Reevaluates the goal	N	X	X
Completes multiple iterations	X	X	--
Continues testing	X	X	--

Table 3. Frequency of Defining a Problem practices captured by method

Defining a Problem Practices	**Total Unique Groups**	**Observation**	**Interview**	**Video**
Immediately attempts challenge	18	11	1	8
Perceives goal as straightforward	56	N/A	51	23

Reads or listens to information provided	64	58	37	21
Explores resources	65	63	13	1
Discusses/plans design other than materials	11	4	7	N/A
Brainstorms ideas	6	2	5	N/A
Watches others	50	34	10	20
Identifies/assign roles	17	2	10	9
Prematurely attempts challenge	26	26	1	14
Defines problem within context	24	0	17	9
Considers benefits and trade-offs of materials	19	3	10	9
Discusses questions/ideas about the process with others	2	2	0	N/A
Relates content to prior experience	29	7	15	15
States a goal	3	1	1	1

Delays design decisions	66	64	2	15

Table 4. Frequency of Improving a Design practices captured by method

Improving a Design Practices	Total Unique Groups	Observation	Interview	Video
Confounds variables	1	1	0	N/A
Subjectively assesses goal completion	7	0	7	N/A
Makes decisions based on aesthetic or superficial characteristics	7	2	5	N/A
Few or no tests of prototype	0	0	0	N/A
Haphazard re-design	6	2	4	N/A
Runs through single cycle	2	0	2	N/A
Qualitatively assesses goal completion	54	2	48	9
Describes what happened	17	3	15	N/A

Diagnoses issues	19	8	5	8
Identifies pros/cons of design	11	2	10	N/A
Makes needed improvements to help prototype reach goal	71	67	36	N/A
Adjusts testing conditions	61	57	25	N/A
Completes multiple tests	62	58	14	6
Focuses on problematic subsystems	1	1	1	N/A
Brainstorms ways to make successful prototype better	1	0	1	N/A
Optimizes design and materials	1	1	1	N/A
Compares to own past performance or record	34	6	31	N/A
Explains results	25	5	10	15
Tests specific variables	9	6	7	N/A
Quantitatively assesses goal completion	1	0	0	1

Reevaluates the goal	16	2	10	8
Completes multiple iterations	73	73	23	N/A
Continues testing	68	68	1	N/A

Figures

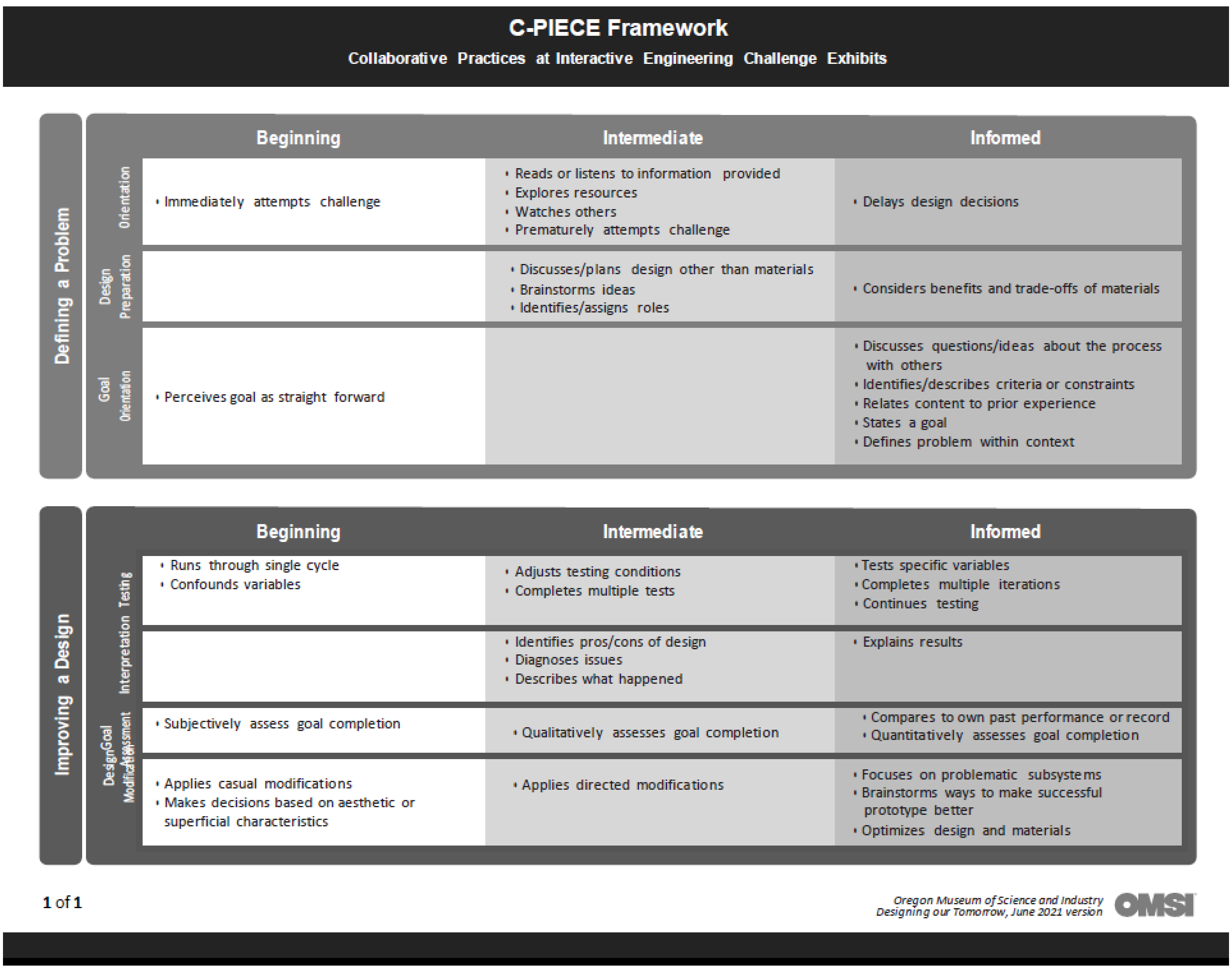

Figure 1. *C-PIECE Framework of Engineering Practices*