Engineering Learning: Cross-Community Design, Development, and Implementation of Engineering Design Challenges at a Science Center

by

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Abstract

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The perception of engineering as intimidating contributes to a lack of diversity among aspiring engineers. My research develops a deeper understanding of tinkering spaces at public science centers as an accessible pathway towards engineering. I engage in cross-community collaborations with college engineering students, industry engineers, and informal science educators to design tinkering spaces, and I analyze the effect of these spaces on the learner experience. This dissertation explores these collaborators' processes of developing engineering design challenges as well as how these processes affect the students' and engineers' understanding of learning and engineering. A variety of observations, including ethnographic case studies of the cross-community design and a comparison of the visitor experience in the space with and without the cross-community design, are synthesized into practical guidelines for creating engineering tinkering spaces.

Focusing on visitors' design processes and perceptions, I find that (1) visitors are not just playing randomly, rather many are engineering deliberately; (2) visitors initially do not necessarily identify as engineers or understand engineering, and mostly associate engineering with building; and (3) constructing designs in these activities leads to the construction of identity and agency as engineers. In particular, the physical materials and the presence of other designs in the space play a key role in visitors' problem scoping, information gathering, and concept generation. Thus, the structure of these tinkering environments empowers visitors to engineer and to continue these experiences. The cross-community collaborators contribute uniquely to the design of the challenges: the educators contribute methods for accessible learning, while the industry engineers and engineering students contribute technical authenticity. Using a human-centered design process with science center visitors, the collaborators grow to view learning as a mutual experience involving contributions from the learners. Visitors at the collaborations' challenges engage in and identify broader engineering behaviors and are better able to connect the challenges to the real world when compared to visitors at challenges without cross-community design. These results provide the basis for guidelines to improve the perception of engineering through tinkering. My dissertation contributes to knowledge on the design of and learning in these tinkering spaces, particularly how learners' engineering design processes serve as a pathway towards becoming future engineers.

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Chapter 1

Introduction: Making Engineering Accessible and Authentic in a Science Center

The Ingenuity Lab at the Lawrence Hall of Science is a novel learning space for families of all ages to tinker with intriguing materials and take on engineering design challenges relevant to their lives. Yet, upon peeking in and hearing the word "engineering," many visitors immediately respond with "Oh, my kid is too young for this" or "I have a girl; I don't think she'll be interested in this." Perceptions like these have contributed to the perpetuation of a disappointingly low number of aspiring engineers and a lack of diversity among engineers. This research addresses a persistent challenge: how to present engineering as an accessible subject to a broad set of learners in a museum setting. In this dissertation, I aim to understand what visitors are doing and gaining from Ingenuity Lab experiences as well as how cross-community collaborations can design these experiences and how the participants (designers and visitors) may be impacted. Two main activities comprise my dissertation research: (1) the cross-community collaborations to design challenges at the Ingenuity Lab and (2) the collaborations' impact on the visitor experience. The study of these two activities will respectively answer my research questions:

(1) How do the diverse collaboration members — college engineering students, industry engineers, and informal science educators — negotiate the ideation process, and what are their roles and contributions in designing engineering learning programs through a cross-community collaboration?
(2) What is the potential impact of the cross-community collaboration model on visitor experience and persistence in engineering?

By studying the processes to create successful Ingenuity Lab design challenges and the experiences of visitors at the Ingenuity Lab, I seek to develop a deeper understanding of tinkering and how it can serve as an accessible pathway towards engineering. Tinkering takes on many forms, especially as a form of play for children. I define tinkering as engaging with tools and materials, whether physical or virtual, in an open-ended environment where the learner drives the goals and processes to construct an entity. I hypothesize that through supporting these natural tinkering inclinations, learners can engage in and gain agency in engineering.

1.1 Rationale

Because engineering is not required in most schools, any change in the public perception of engineering must arise in other contexts. Science centers are alternative learning environments that can play key roles in dispelling the common perception of engineering as "hard" or "not for me" and thus increase broader participation in engineering.

Engineering education has potential to integrate science, math, humanities, and arts for effective education (Committee on K-12 Engineering Education, 2009). The need to emphasize engineering education is important as the U.S. pushes to improve STEM literacy for greater global innovation.

We need to understand how to create accessible opportunities for learning engineering. Many engineers attribute their careers to early interest in STEM, so opportunities should be presented to children early on. Particularly, these opportunities should engage children in ways that are relevant to their lives and potential future careers.

Interest, not performance, has been shown to be a greater predictor of choosing to concentrate in STEM (Tai et al., 2006; Maltese & Tai, 2011). A popular activity to pique interest in STEM is tinkering, and following the recent Maker and Do-It-Yourself Movement[1], science centers are now increasingly offering tinkering programs (Wang et al., 2013). In this dissertation, I research the design and impact of tinkering in an informal learning space, specifically in the design challenges at the Ingenuity Lab. Tinkering lets visitors engage in engineering practice through designing, building, and testing their own creations using a variety of materials with visitor-defined goals whereas traditional exhibits only allow a limited range of interactions because they are usually designed with specific learning goals. Thus, tinkering provides a unique opportunity for children to engage in engineering.

While tinkering offers a means for engaging in engineering, science centers still need authentic and current science and engineering content for their programs (Field & Powell, 2001). By updating exhibits with renewable, adaptable, and relevant content, science centers can help place science in a real life context and keep visitors engaged (Hodder, 2010) and aware of new trends in research and industry (Field & Powell, 2001). One method of providing authentic content is through collaborations with professional scientists and engineers. Scientists and engineers have a need to communicate their work to the public, increase public scientific and technological literacy to understand the fields' impact on society, and show that these careers are interesting (Pace et al., 2010; Field & Powell, 2001).

To address the persistent challenge of authentically presenting engineering as an accessible subject to a broad set of learners, this research will develop a set of design guidelines for the museum and engineering education fields. This research will help the many science centers implementing tinkering programs with guidelines for developing accessible and authentic engineering design activities that promote interest in the discipline. Focusing on the Ingenuity Lab at the Lawrence Hall of Science, I (1) implement and study a model of cross-community design of authentic engineering experiences and (2) analyze the consequent impact of the design processes on the visitor experience. Specifically, this research seeks to (a) determine the productive roles of designers and visitors and the impact of their roles, (b) provide documentation on indicators of engineering learning, and (c) develop guidelines for accessible and authentic engineering design challenges.

[1] The Maker Movement is led in part by MAKE Magazine, a magazine dedicated to Do-It-Yourself projects from electronics to crafts to cooking to art (Kuznetsov & Paulos, 2010; New York Hall of Science, 2010). The Maker Movement focuses on hobby projects where people "tweak, hack, and bend any technology" through creativity, ingenuity, and resourcefulness (MAKE, 2012).

In order to determine the roles, practices, and impacts of these experiences on the cross-community designers and the visitors, I focus on (a) their perceived experience with engineering design, (b) their engagement in engineering practice, (c) their agency and persistence in engaging with the activities, and (d) their past experience and potential future interest in engineering activities. A wide variety of observations, including focused ethnographic case studies of the cross-community design and a quasi-experimental set-up comparing the visitor experience in the space with and without the cross-community design, are synthesized into a collection of indicators of engineering learning and a set of practical guidelines.

1.2 Background

This dissertation reports on a study of an engineering design challenge program at the Lawrence Hall of Science (the Hall), a public science center part of the University of California, Berkeley. The research focuses on the roles, practices, and impacts on the cross-community designers and the visitors. The context is the Ingenuity Lab, an engineering design program open to the public on a drop-in basis during weekends. This dissertation builds on the current program by developing and implementing a cross-community collaboration model with engineering students, industry engineers, and informal educators to develop open-ended engineering design challenges.

The Ingenuity Lab began in Fall 2009, providing open-ended tinkering design challenges to about 800 visitors a month, with ages ranging from infant to elderly. The majority of children who visit are between the ages of three and twelve, usually consisting of even numbers of boys and girls. The Lab is held in a large classroom space, allowing visitors to come and go as they wish; the average stay time is just over 30 minutes. Each month, an engineering design challenge and theme is presented to visitors, along with appropriate materials. Past challenges have included *LEGO robotics*, where visitors use LEGOs, PicoCricket microcontrollers, sensors, motors, gears, and wheels to design their own robotic cars; *mechanical grabbers*, where visitors use sticks, rubber bands, wires, tubes, string, and sponges to create grabbers to pick up objects; *scribble machines*, where visitors use motors, batteries, glue sticks, cardboard, tubes, and markers to make vibrating machines that draw patterns; *cardboard automata*, where visitors use cardboard, foam, string, sticks, and paper to develop mechanical sculptures; and *boats*, where visitors use paper, pennies, foil, tape, balsa wood, and string to design boats that float and sail.

1.2.1 The Cross-Community Design Process

Previously, two educators developed the existing engineering design challenges at the Ingenuity Lab, but neither have any engineering experience. Because visitors are mostly unaware of the Ingenuity Lab's relevance to real world engineering (Wang et al., 2013), I hypothesize that the addition of local industry engineers and engineering students to the challenge development process can help provide content of engineering relevance, especially as related to the local community. I research this novel addition by studying two cross-community collaborations between college engineering students, industry engineers, and informal science educators to develop challenges representative of the industry engineers' practices. Specifically, engineers from Google and Meyer Sound participate as expert engineers and provide engineering content. All participants are volunteers and do not receive any incentive. These two challenges are developed and implemented with visitors, each serving as a monthly theme for the Ingenuity

Lab. College engineering student teams serve as amateur engineers and take ownership of the design process as a service learning[2] project. Informal educators guide and support the process to ensure its practicality. The novel design collaboration aims to translate the engineers' authentic practices into accessible practices for visitors at the Ingenuity Lab.

1.3 Research Questions

In this section, I discuss my goals, approaches, and hypotheses in answering my research questions. I repeat my research questions here for reference:

(1) How do the diverse collaboration members — college engineering students, industry engineers, and informal science educators — negotiate the ideation process, and what are their roles and contributions in designing engineering learning programs through a cross-community collaboration?

(2) What is the potential impact of the cross-community collaboration model on visitor experience and persistence in engineering?

For the first research question, I explore an exciting new direction of cross-disciplinary and cross-community collaboration in the development of educational programming. I focus on the various participants of the collaboration, not just the students, but also the educators and industry engineers. Brereton et al. (1996) identify the complex social processes that influence the outcome of design collaborations, and Bronstein (2003) identifies several features of interdisciplinary collaborations. I build on these studies to understand the two collaborations' social design processes, particularly the extended and cross-disciplinary processes of conducting background research, developing criteria for an Ingenuity Lab design challenge, brainstorming and selecting ideas, and implementing and refining the idea in the Ingenuity Lab. Because of the social nature of design, I implement ethnographic case studies of two collaborations to explore: What happens when these various collaboration members get together to design, develop, and implement an actual service for the community? What are the benefits and drawbacks of this collaboration? What do the various participants contribute, and how do they take ownership of the design process? What are their criteria for the challenge, and how are challenge ideas developed and selected? How did the process affect the collaborations' understanding of learning and their own engineering practices? How do participants value the experience with their various roles? Each case illuminates the physical, social, and personal factors that may influence such a collaboration.

Ethnography helps illuminate the cultural context of the design processes and backgrounds of the participants to understand how and why certain actions occur, in addition to how the design processes unfold. Specifically, the ethnographic case studies include data from pre- and post-surveys of collaboration members, videotaped observations of meetings, and artifacts from the

[2] Service learning is commonly used in humanities courses to increase civic engagement by implementing classroom learning with service in the community, but are increasingly being utilized effectively in engineering courses (Lima, Oakes, & Gruender, 2006; Tsang et al., 2001). In this case, engineering students are serving the public visitors and the science center.

design processes. Triangulated together, these data offer insight into the roles, practices, and impacts of the cross-community design collaborations.

The students participate in the project in a service learning capacity and are given the opportunity to implement the project as part of the Ingenuity Lab's actual programming. Because the engineers and educators are dedicated to full-time jobs, students are given the most ownership over the project. The industry engineers, however, volunteered for the collaboration and are thus interested in education, offering to serve as engineering experts and mentors for the project. The educators involved manage the space and the Ingenuity Lab program and serve as experts in education.

I hypothesize that the novel cross-community design will allow students to take ownership of the design of the challenge, heavily guided by the educators. Engineering education has been found to be much more effective for student retention and skill-building when students are engaged in project-based learning through design (Dym et al., 2005; Kolodner, 2002). Furthermore, authentic and consequential tasks enrich the learning experience for students (Brown & Campione, 1996; Edelson & Reiser, 2006). The students can apply engineering theory to a real-world context of engineering. They will feel proud that their design is implemented in the Ingenuity Lab and thus, the accountability of an actual service to the community compels students to take responsibility as reliable team members. The students also selected the project and thus are motivated about education. Engineers will provide mentorship and support in guiding the students, though some may become too busy. Through participation in this corporate social responsibility, engineers gain can competencies in leadership and communication (Fombrun, Gardberg, & Barnett, 2000). "Strategic philanthrophy" (Porter & Kramer, 2002) can also effectively increase company reputation and publicity, especially to the local community and potential employees. Educators will push the team towards more realistic activities and in turn, the educators will gain a better perspective on engineering as well as gain content and much-needed resources (Field & Powell, 2001) in the form of new activities for the Ingenuity Lab. The engineers and educators may have some disagreements in terms of what is practical for learning, but I hypothesize that this would be beneficial, as the final challenge idea would be informed by authentic engineering as well as practical constraints and accessibility. As an interdisciplinary collaboration, the participation of members from various fields provides teams with greater quality outcomes (Bronstein, 2003). Furthermore, students who work in interdisciplinary teams gain valuable experiences for their future engineering careers.

For the second question, I study the visitors to the Ingenuity Lab during three months of implementation of traditional challenges without cross-community collaboration and during the two months of implementation for each cross-community collaboration's design challenge. I compare the five different months through a quasi-experimental mixed methods analysis.

To determine visitors' engineering design processes and their perspectives on the Ingenuity Lab experience, I collect the average stay-time of visitors, visitor survey responses, and in-depth videotaped observations of visitors with pre- and post-interviews. The observations help identify engineering behaviors exhibited by visitors participating in the Ingenuity Lab challenges, and the surveys and interviews provide information about their positive and negative opinions about the program as well as their perspectives of engineering. I explore: How do visitors engage in engineering design? What are visitors' identities and perceptions with respect to engineering? What are their past experiences and potential future interest in these activities? Do visitors – both parents and children – gain agency and confidence in their abilities to engineer? What might they learn from the Ingenuity Lab experience? What are indicators of engineering learning, as related to the various engineering behaviors? Are visitors better able to identify the activities as authentic engineering and/or make connections to the real world in challenges developed by the cross-community collaborations?

I hypothesize that visitors to the cross-community collaboration challenges will consequently better attend to engineering practices such as problem scoping and discussing improvements when compared to visitors at the traditional challenges, perceive their experience as related to the real world and engineers, and experience agency and confidence in engineering tinkering activities regardless of age or background as shown by the New York Hall of Science (2013).

The development of design challenges in collaboration with the local industry is intended to contextualize tinkering in current research and industry topics from the local community, specifically in the two industries of software and audio represented by Google and Meyer Sound. This would provide the public with contextualized activities that are personally relevant (Linn, 2006; Kali, Fortus, & Ronen-Furhman, 2009) and help create a sense of identity within the community through participation in a relevant activity (diSessa and Cobb, 2004; Blikstein, 2004). Museum experiences that specify context "will provide greater impact and meaning than [those] that are decontextualized in nature" (Anderson et al., 2002). Framing learning contexts in relation to a larger, more meaningful context (in this case, engineering in the local community) may also lead to deeper learning (Engle, 2006). Within the context of real engineering, visitors may gain an increased awareness of how creative problem-solving and the design process apply to the STEM industry, and even identify themselves as engineers when engaging in these activities.

Visitors to these challenges may engage in a wider variety of engineering behaviors, though each challenge will be unique to the engineers' industry, and context will have a large influence on the experience. For example, the context of software may prompt visitors to engage in debugging, or identifying and fixing problems; visitors may be able to easily identify the connection to their everyday lives with technology; and the designs created may end up less tangible when compared to the other challenges.

Furthermore, collaboration in these challenges may deepen engagement in engineering behaviors; my previous study found visitors at the Hall's engineering design exhibits almost always work together as groups, and these groups exhibited more and deeper engineering behaviors than groups who did not collaborate (Wang & Walker, 2013). Engaging children and adults together can extend the learning experience to outside the museum, and contextualization of the design challenge within real-world engineering may prompt them to continue to discuss relevant topics in the community and how they relate to engineering. A positive affect may also contribute to the visitors' persistence and sustained engagement (Hidi & Renninger, 2006). Long-term interest would thus be associated with potential careers in engineering.

My dissertation research explores these hypotheses through the investigation of the design processes of the collaborations and implementations of the challenges at the Ingenuity Lab. Based on engineering behavior analyses of many in-depth visitor observations as well as aggregated perspectives on the experiences, I provide guidelines for designing tinkering programs that maximally convey the spirit of engineering while promoting deep and persistent interest in the discipline.

1.4 Overview

The following chapters of this dissertation contextualize this research with background in the literature as well as a theoretical framework. Chapter two provides a review of the existing literature on the main area of this dissertation, making and engineering, as well as the more specific focus on informal learning, interdisciplinary collaboration, and service learning. Chapter three provides a more in-depth overview of my theoretical framework for making and its connection to engineering through socio-cultural theories and constructionism.

Chapter four describes the methodology in detail, including the context, participants, data collection methods, data analysis methods, and the breakdown of the two research components: the cross-community collaboration and the visitor experience.

Chapters five, six, and seven explore the findings from the dissertation. Chapter five provides the analysis and results of the study of three traditional Ingenuity Lab challenges, without the cross-community collaboration. Chapter six describes the case studies of the two cross-community collaborations, specifically focusing on their design processes, and chapter seven focuses on the visitor impact of the collaborations' design and implementation of Ingenuity Lab challenges.

Finally, chapter eight provides a cross-analysis of all five challenges and concludes with a discussion of the research findings as well as areas for further research. By characterizing the nature of the cross-community design processes, I will develop empirically-grounded hypotheses about important elements of the design processes that serve as guidelines to foster productive visitor experiences.

Chapter 2

Literature Review: Engineering Design, Making and Informal Learning, and Interdisciplinary Collaboration and Service Learning

In order to ground my research in the existing literature, I review literature in the areas of engineering education, informal learning and making, interdisciplinary collaboration, and service learning.

The literature review begins with a discussion of engineering design because this dissertation focuses on education on the topic of engineering at both the elementary and post-secondary levels, with visitors as well as the college engineering students, industry engineers, and informal science educators engaging in engineering design. With increasing emphasis on using engineering design activities as a pedagogical method to learn science and mathematics, and even engineering practices (e.g., Common Core Standards), I focus on defining engineering: how engineering is related to and distinct from science, what constitutes engineering practice, and how to identify expert engineering design processes.

As the context of this research is an engineering making program at a science center, the literature review helps to distinguish informal environments as a unique learning environment with different variables and populations than classroom learning contexts. Further, many science centers are adopting "making" into their programming to attract visitors with a novel engagement, so I also review literature on the growing Maker Movement.

Finally, as the community and student involvement is the novel contribution of my research, I highlight existing studies on involving the community, especially content experts, in the development of education programs, along with related studies on interdisciplinary collaborations and service learning.

2.1 Engineering Design

Because both the designers and visitors are engaging in engineering design, I review literature in the areas of engineering design and engineering education.

2.1.1 The Nature of Science and the Nature of Engineering

To understand how to learn engineering, I take a look at literature that explores the nature of both science and engineering, because they often overlap and are often taught in conjunction.

Many researchers distinguish between the nature of science and the nature of engineering (e.g., Lewin, 1979; Kolodner, 2002). Lewin (1979) even pushes for engineering as its own field separated from science, taught with a distinct approach. However, more integrated approaches are now being implemented and advocated (Committee on K-12 Engineering Education, 2009; Kolodner, 2002).

Lewin (1979) describes science as accumulation of knowledge for its own sake, and Kolodner (2002) similarly describes it as aiming to better understand the world around us. Experiments in science are in closed and controlled systems (Lewin, 1979), breaking down the complex world into smaller isolated components that can be studied. Science involves a basic inquiry method, often cyclic, that involves a question to be asked, developing a method to investigate the question, conducting the experiment, predicting and observing outcomes, and interpreting findings to be communicated (Kolodner, 2002; Allen & Gutwill, 2009). Success in science means that these experiments are rigorous and replicable (Lewin, 1979).

On the other hand, Lewin (1979) describes engineering as creating something to solve a problem or need, and Koldoner (2002) explains that engineers aim to design artifacts that will allow control over the world around us. The product is driven by the goal and specifications, and the problem-solving takes place in an open system with complex, unknown factors (Lewin, 1979). Unique from science, engineering involves designing for use by people; using a human-centered design approach, specifications may even evolve after user research (Beckman & Barry, 2007). Engineering involves a cyclic method similar to science inquiry: an engineering design process involves identifying the problem, planning out a solution to the problem, building and testing the solution, reflecting on the test outcomes and refining the solution, and communicating the final product (Kolodner, 2002; Dym et al., 2005; Cunningham & Lachapelle, 2011; Committee on K-12 Engineering Education, 2009; Lehrer et al., 2000). Success in engineering is more open than in science, as it is determined by how well the design solution meets the criteria, but the complexity of the situation involves considering trade-offs, when it works or fails, and whether it fulfills the client's needs (Kolodner, 2002). Furthermore, construction skills and understanding of material properties are key to the ability to develop a design (Kolodner, 2002).

2.1.2 Science Inquiry and Engineering Design

The parallels between science and engineering, as described in the previous section, suggest that they can be integrated (Chiu & Linn, 2011). Both involve teamwork, collaboration, and the ability to communicate. Both also involve a cyclic feedback loop. Penner et al. (1997) integrate the two fields by viewing science as building, testing, and revising mental models of the world, which is achieved through building, testing, and revising physical artifacts. Chiu & Linn (2011) integrate similarly by considering design as inquiry.

However, I view the two cycles as distinct, while each informs the other in an ongoing process between exploring the world (science inquiry cycle) and transforming the world (engineering design cycle). Engineering design requires many kinds of knowledge about the world and thus requires science (Sadler, Coyle, & Schwartz, 2000). Kolodner (2002) and Dym et al. (2005) distinguish the two cycles as each informing the other in an ongoing and iterative fashion. Kolodner's *Learning By Design* curriculum (2002) employs the inquiry cycle to discover science principles that will help inform the design, while the engineering design cycle creates new questions to explore using the inquiry cycle. Dym et al. (2005) note that design thinking iterates through divergent-convergent questioning, with divergent thinking as generating concepts and designs (engineering design) and convergent thinking as understanding knowledge (science inquiry). Beckman and Barry (2007) similarly describe design thinking as cycling between concrete, abstract, analysis, and synthesis, where concrete observations are analyzed (science inquiry) and abstract ideas are synthesized (engineering design).

2.1.3 Aspects of Engineering Design

Design processes are used to solve open-ended problems and vary given the situation, problem, and approach, but roughly include the following steps: understand the problem, brainstorm multiple designs, explore the implications of the designs, choose a design and create it, test and evaluate the design, refine the design, and repeat.

Design is commonly considered the key component of engineering (Dym et al., 2005). Dym et al. (2005) define engineering design as “a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients’ objectives or users’ needs while satisfying a specified set of constraints.” However, children and even teachers are more likely to identify engineering with building and constructing (Cunningham & Lachapelle, 2011). People often overlook the problem-solving and design processes involved in the practice of engineering (Cunningham & Lachapelle, 2011). For instance, the critical phases of “analyzing the problem, exploring the space of possible solutions, and deciding when a good enough solution has been achieved” are often neglected (Lehrer et al., 2000). Another aspect often overlooked is the human-centered and socially embedded component of engineering. Consumers should be aware of how engineering impacts products, structures, and systems that they engage with everyday, and engineers must understand how their products, structures, and systems are used by people (Hollands & Wickens, 1999).

Engaging in an iterative design process helps increase engineering understanding (Cunningham & Lachapelle, 2011). The iterative design process, with its built-in feedback, serves as a framework for engineering activities in learning environments as well as a tool for teaching engineering (Committee on K-12 Engineering Education, 2009; Cunningham, 2009). The design process involves engaging in open-ended problems, reflecting the complexity of real engineering problems (Lehrer et al., 2000; Sheppard & Jenison, 1997; Dym et al., 2005). Working through these types of problems provides “valuable opportunities to generate multiple design possibilities, explore their implications, settle on a provisional plan, carry out the plan, evaluate the outcome, and then perhaps carry out one or more repetitions of these phases as cycles of revision” (Lehrer et al., 2000). This longer iterative design process is another key component emphasized in engineering, as solutions can constantly be improved and refined (Committee on K-12 Engineering Education, 2009). The extended process allows opportunities to self-assess, critique, revise, and reflect through such phases as observing, framing problems, exploring solutions, evaluating alternatives, and communicating ideas (Lee, 2009). It further allows time to think, reflect, make mistakes, learn from others, and see other people’s ideas (Papert, 1991). Through planning, analysis, and reflection in interacting with users and iterating tangible designs, learners iterate and refine their abstract ideas and knowledge. These several phases of design allow learners to continually develop and evaluate hypotheses as they work towards the design goal (Resnick, Berg, & Eisenberg, 2000). Collaboration further enables learners to iteratively refine their ideas and knowledge to converge toward conceptual change with shared meaning and understanding (Roschelle, 1992).

Reflection, in particular, is a key component of learning and design. Reflection prompts learners to monitor their own learning and to make connections between their ideas (Linn, 2006). Similarly, Schön (1983) describes good design processes as reflective. The iterative process is a continuous process of learning, where the designer continues to reflect on the process to monitor and improve the practice of design (Schön, 1983). Schön (1992) also characterizes this reflective process as a conversation in which the designer is always in transaction with the design situation, responding to the situation and creating the situation. The design situation consists of the context, users, task, materials, and prototypes. He further outlines the transaction as *see-move-see*, where the designer *sees* a situation and materials, *moves* to create a design, and *sees* the feedback in how well the solution works. The designer can continue and *move* to modify the design, and again, *see* what happens, repeating multiple times. The distinct steps of *see-move-see* break down the complex process into smaller design problems that the designer can focus on and respond to, where each step brings the designer closer to a suitable solution for the larger design problem.

Schön (1992) also states that the "designer not only designs with the mind but with the body and senses." Engaging the physical is relevant to both design and play. Papert (1980) and Resnick (2002) state that children engaging in productive play with materials through design can lead to meaningful learning experiences. In both design and play, children explore possibilities and experiment, learning new concepts with each small problem and solution (Resnick, 2006). Embodied design (Abrahamson, 2009) similarly identifies the use of artifacts as a means to learn, where certain abstract concepts are embodied by the physical gestures.

I now summarize several aspects of engineering design extracted from the literature, which I have refined as involving: a design goal, open-ended problems, systems thinking, iterations, failures, collaboration and communication, materials and a design space, and human-centered design:

Design goal. The design goal defines the criteria to determine the performance of a solution (Dym et al., 2005). This involves identifying the needs of the situation (Next Generation Science Standards, 2014), where the desired artifact or service determines what will be designed. Oftentimes, sub-goals emerge from interaction in the design situation (Schön, 1992).

Open-ended problems. Engineering problems are open-ended and complex, with many undetermined factors (Dym et al., 2005; Committee on K-12 Engineering Education, 2009; Eckert et al., 2010; Lehrer et al., 2000). The engineer must be able to define and break down the problem as best as possible to determine the constraints in achieving the design goal (Next Generation Science Standards, 2014). Multiple solutions are thus possible (Eckert et al., 2010; Next Generation Science Standards, 2014) and creativity is essential in developing solutions (Committee on K-12 Engineering Education, 2009).

Systems thinking. In considering the open-ended problems, the complex factors are not necessarily separable. Thus, good engineers must be able to consider the entire situation as a system, taking into account factors influencing other factors, trade-offs, prioritization of criteria, and social and environmental impacts (Committee on K-12 Engineering Education, 2009; Next Generation Science Standards, 2014).

Iterations. Design processes are iterative (Norman, 2002), often with goals and unintended consequences emerging from the iterations (Schön, 1992). Because multiple solutions are possible and there is no one right solution, iterations are key to refining and developing the best solution (Lehrer et al., 2000; Cunningham & Lachapelle, 2011). Testing out the solution provides feedback on how designs can be improved (Next Generation Science Standards, 2014).

Failures. Learning from failure is key to improved designs (Kolodner, 2002; Sadler, Coyle, & Schwartz, 2000). Without knowing what does not work, it is hard to determine what will work consistently and robustly. Difficulties help refine the outcome.

Collaboration and communication. Engineers work with clients, as well as with other engineers, designers, scientists, etc. (Next Generation Science Standards, 2014). Thus, communication with the clients and the design team is extremely important (Eckert et al., 2010; Committee on K-12 Engineering Education, 2009; Kolodner, 2002; Kumar & Hsiao, 2007). Furthermore, the nature of design itself is social (Bucciarelli, 1994; Schön, 1992; Beckman & Barry, 2007; Dym et al., 2005). The ability to collaborate and communicate, including leading, working with clients, and setting up and solving problems, is one of the essential and under-taught professional skills that engineers need (Kumar & Hsiao, 2007).

Materials and the design space. The materials and design space present the constraints of the design problem (Eckert et al., 2010). However, they also present opportunities (Eckert et al., 2010; Schön, 1992). Materials can be interpreted and used differently by different people (Schön, 1992). Materials also serve as physical manifestations of ideas (Sadler, Coyle, & Schwartz, 2000), with which designers and engineers can communicate (Schön, 1992; Bamberger, 1991).

Human-centered design. Finally, an essential and often neglected component of engineering is that engineers design artifacts and services for people to use (Next Generation Science Standards, 2014). Thus, it is important that people can understand how to use these artifacts and services (Norman, 2002). The designer must consider human factors (Hollands & Wickens, 1999) and think through the use to find possible mistakes and abuses in how people may want to use the product (Norman, 2002).

2.1.4 Expert Engineering Design Processes

Engineering and design are everywhere. Any problem-solving or goal-oriented design can be interpreted as some sort of engineering. When a child tinkers with LEGO blocks, s/he engages in engineering behaviors in solving mini-problems s/he encounters, such as not being able to fit the right blocks together. Through solving the mini-problems, s/he engages in systems thinking, iterates, fails, and eventually aims for some goal (e.g., get the blocks to fit together). S/he may collaborate or communicate with others to get help, and s/he explores the design space by manipulating the materials, the LEGO blocks. Finally, when s/he finishes her/his LEGO creation, s/he has created a design for her/himself, one that s/he can use and play with. Making and creating things appears open-ended and unstructured, and may not appear to have any educational value. However, Resnick (2006) explains that these activities engage the learners in systematic behaviors naturally in achieving a goal.

Does this then mean that anyone is a designer or engineer? Norman (2002) would argue that it's not easy to do *good* design. Schön (1992) also investigates the nature of knowledge involved in design, and would argue that an expert designer is different than a novice designer. An expert's design knowledge is intuitive, but inarticulate except when in the process of design, what Schön calls "knowing-in-action." He and Norman also explain that professionals spend more time planning, as well as thinking through the use and possible mistakes. However, the primitive behaviors of engineering found in children can still be educationally productive, and educators can build on these primitive behaviors to foster expert design behaviors.

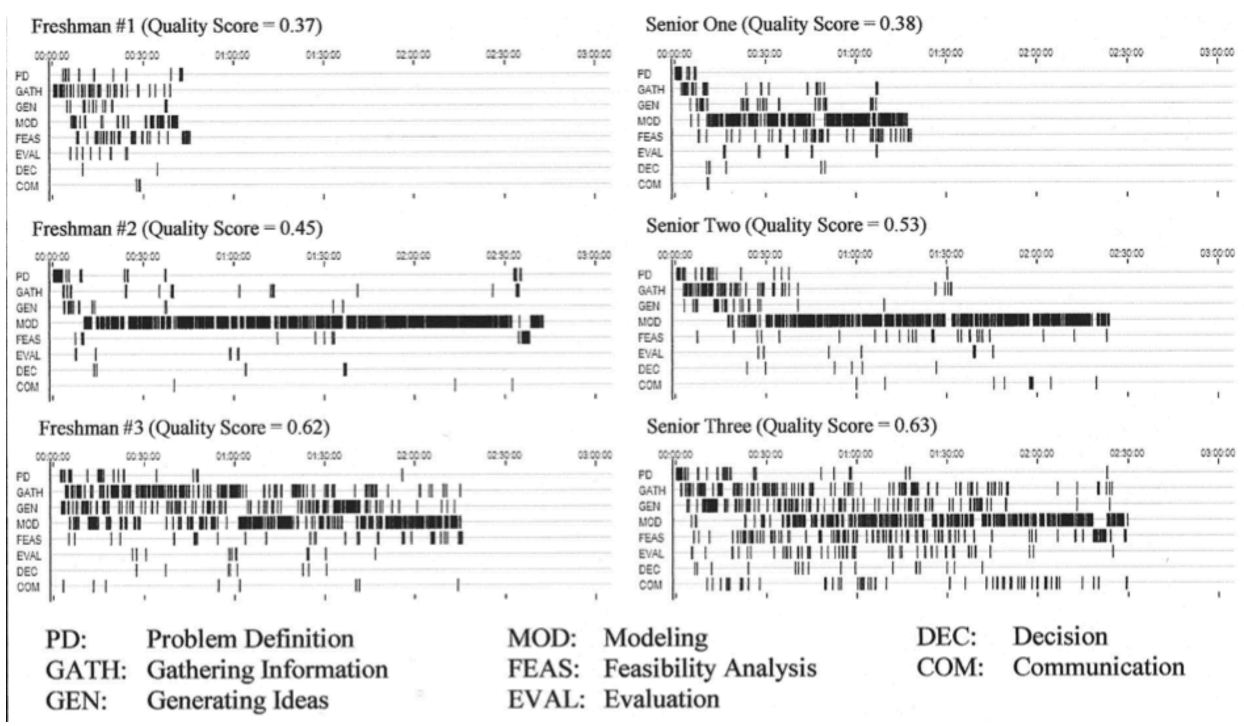


Figure 2.1: Examples of various timelines with quality scores indicated, representing the quality of the design solution (Borgford-Parnell, Deibel, & Atman, 2010). Note that the timelines with greater quality scores have more frequent transitions between design activities, extended engagement in broader behaviors particularly in Problem Scoping (PD, GATH), and a stronger *cascade* pattern.

In order to determine the engineering design processes of the visitors, this dissertation draws on studies by Atman et al. (1999, 2007), in which the authors compare the design processes of freshmen and senior engineering students and expert engineers. The participants engaged in open-ended problem solving in a lab environment to design a playground, and could stay for up to three hours. I similarly study participants in an open-ended problem-solving context where participants determine the duration. Atman et al. develop timelines of the problem-solving that focus on the participants' design processes in terms of problem scoping, developing alternative solutions, project realization, frequency of transitions between activities and duration of activities, and solution quality (Figure 2.1). The timelines indicate the duration and frequency of each activity in the design process. Similar to Schön (1992) and Norman (2002), Atman et al. find that when compared to students, experts spent more time on the problem overall, especially in the area of problem scoping. Experts also gathered more information across categories and made more transitions between activities. Most importantly, experts' design processes portrayed a *cascade* pattern in which they began in the problem scoping stage and transitioned within that stage for a while, then progressed to developing alternative solutions in which they transitioned for a while, and throughout the process, transitioned back to problem scoping and to project realization (see Figure 2.2).

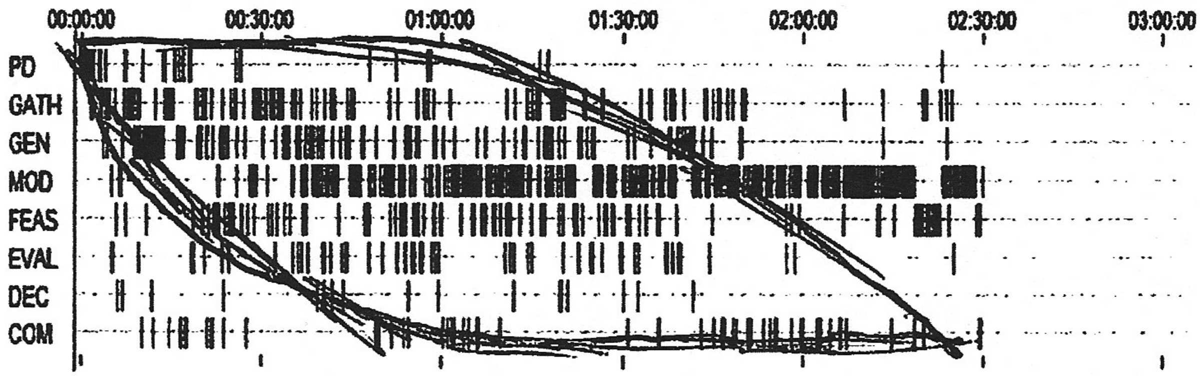


Figure 2.2: Example of an expert *cascade* pattern indicated by a hand-drawn mark over a representative timeline (Borgford-Parnell, Deibel, & Atman, 2010). The *cascade* pattern, or "Ideal Project Envelope," begins in Problem Scoping, transitioning between Problem Definition (PD) and Information Gathering (GATH); then progresses to Developing Alternative Solutions, transitioning between Generation of Ideas (GEN), Modeling (MOD), Feasibility of Analysis (FEAS), and Evaluation (EVAL); and throughout the process transitions to Problem Scoping and Project Realization, which includes Decision (DEC) and Communication (COM). Note the progression from the upper left to the bottom right.

2.2 Making and Informal Learning

To understand the experiences of the visitor in the Ingenuity Lab environment, I now review some literature on learning by doing in the context of making and tinkering as well as literature on informal learning environments.

2.2.1 Learning by Doing: Design, Making, and Tinkering

The idea of open-ended, hands-on, personal learning is not new. Over a century ago during the early 1900s, John Dewey advocated more lab-like environments that represent the open-ended and complex real world, stating that "school should be less about preparation for life and more like life itself" (Bransford, Brown, & Cocking, 2000). Around the same time, Maria Montessori developed a successful child-centered approach that involved hands-on activities and open-ended play (Lillard, 1972). In the mid-1900s, Jean Piaget and other constructivist theorists argued that children's learning must build on their personal knowledge (diSessa, 2005). Open-ended and hands-on learning through play allows for ownership, provides realistic situations, and offers accessible opportunities to revisit the same ideas at deeper levels, in line with Jerome Bruner's spiral curriculum (1966). Papert (1980) also advocated learning through creating public entities rather than receiving traditional instruction.

Recently, a rekindling of hobbyists has ignited a trend of do-it-yourself (DIY) projects and making that appears to offer these hands-on learning opportunities. The Maker Movement is a growing culture in which people engage in personal projects, “tinkering, hacking, creating and reusing materials and technology” through creativity, ingenuity, and resourcefulness (MAKE, 2012; Kuznetsov & Paulos, 2010; New York Hall of Science, 2010). The Maker Movement is led in part by MAKE Magazine, a magazine dedicated to Do-It-Yourself projects from electronics to crafts to cooking to art (MAKE, 2012). Making is not only personally motivating and socially engaging, it is also accessible to a diverse audience. Making encourages experimentation safely; learners make mistakes but still retain their confidence and identity to pursue their interests (New York Hall of Science, 2010).

Moreover, the maker activities not only offer learning opportunities, but also offer natural opportunities to engage in accessible and authentic engineering design practices. By engaging in open-ended and complex projects, makers are naturally inclined to employ many of the same skills and tactics that engineers use to solve their problems and achieve their goals (Resnick, 2006). Thus, making may be an excellent means for learning engineering.

Design challenges in particular can provide opportunities to make and engineer. In the last decades, the popularity of tinkering and design challenges has grown, especially with the Maker Movement (Kuznetsov & Paulos, 2010; Comunian, 2011; Gross & Do, 2009; Turner, 2011; New York Hall of Science, 2010). Design challenges have been increasingly implemented in both formal and informal learning environments, through curricula such as *Engineering is Elementary* and programs such as the *Tinkering Studio* at the Exploratorium.

The renewed interest in DIY projects (Kuznetsov & Paulos, 2010) and design challenges has brought about questions of how these activities can be educationally productive (New York Hall of Science, 2010). The constructionist perspective is to view these activities as design. Papert (1991), Resnick (2006), and Bamberger (1991) emphasize the process of constructing entities as the driver of meaningful learning. Resnick and Silverman (2005) contend that the “best learning experiences [...] come when [learners] are actively engaged in designing and creating things, especially things that are meaningful to them or others around them,” and Dym et al. (2005) claim that “design is both a mechanism for learning and in itself a learning process.” Beckman & Barry (2007) also liken the design process to the learning process. Lewin (1979) exclaims the importance of educating engineers through design experiences, drawing out rather than forcing in concepts.

Design is also particularly effective in education because it fosters ownership (Brown & Campione, 1996) and is accessible to many types of learners (Beckman & Barry, 2007; Papert, 1991; Resnick, 2006). Open-ended design activities give students responsibility for structuring their own activities (Edelson & Reiser, 2006) and creating their own artifacts through various possible paths (Papert, 1991). Consequently, design can foster experiences that are much more meaningful than other types of activities.

Resnick (2006) further states that design is a type of play: “In design activities, as in play, children test the boundaries, experiment with ideas, explore what’s possible. As children design and create, they also learn new concepts.” Wellington (1990) also advocates that play does not need to be distinct from learning. In fact, learning is oftentimes most successful when it’s fun and involves play. Salen and Zimmerman (2005) assert that play can be meaningful, and meanings are created by the player's actions. Meaningful play, they explain, emerges through the interactions between player actions and system outcomes, in which the player and system influence each other. Salen and Zimmerman (2005) also differentiate meaningful play as having actions and outcomes that are discernable and integrated into the larger context of the game. In design, the designer's actions create a product, which is then tested in an environment that provides feedback on how the designer should next proceed (Schön, 1992). Similarly, engineers design in an infinite solution space, then test to explore possibilities. Thus, design offers an opportunity for meaningful play and productivity.

Other aspects of play and design relevant to learning are building with materials and learning by doing. Seymour Papert (1980) emphasizes the idea of the child as a builder. Personal construction through building with concrete materials or with abstract concepts leads to the construction of knowledge structures in what Papert coined *constructionism* (1987). He builds on the Piagetian model of children as builders of their own knowledge, and highlights that children learn many things without being "taught" and even describes the classroom as an artificial learning environment (1980). Papert advocates *bricolage*, trying things out through play. The manipulatives and tools used in building are an important part of the process of learning and thinking (Goodwin, 1994; Hutchins, 1995) and must be chosen carefully (Uttal, Scudder, & DeLoache, 1997). Using material objects and tools, learners experiment and engage with the physical through an education of the senses (Montessori, 1912). Learning by doing and experiential learning are also emphasized by Dewey (1916) and Kolb and Fry (1975). These researchers emphasize that students should actively take part in their own learning and make discoveries firsthand.

In this tinkering type of play, what exactly is learned? STEM content serves as a guide (Resnick & Silverman, 2005; Papert, 1991), as the context (Chiu & Linn, 2011), and as the means for designing (New York Hall of Science, 2010). The Maker Faire Report focuses on STEM as the process, pushing that STEM is not the end goal (New York Hall of Science, 2010). However, STEM content is still an outcome of engaging in designing. Through the processes of critical thinking, problem solving, and collaboration, design supports deep engagement with STEM content and powerful ideas. For instance, feedback is a powerful idea encountered in most design activities, and is a part of engineering, biology, the social sciences, etc. (Resnick & Silverman, 2005).

These tinkering activities can further take advantage of the self-directed, self-motivated, and natural aspects of making and connect the activity to STEM concepts through contextualization within real engineering. Engineering is a natural tendency for children, as shown in design's association with play (Salen & Zimmerman, 2005; Resnick, 2006; Schön, 1992), and tinkering and play may lead to future interest in engineering for young children (Habashi et al., 2008). My previous research found that science center visitors often exhibit behaviors of engineers when participating in engineering design challenges (Wang et al., 2013). However, visitors do not usually draw explicit connections between what they are doing and the work of professional engineers unless attention is specifically drawn to the connection. This was mitigated with emphasis on the engineering design process and facilitation by engineering students (wearing "Ask me, I'm an engineer" buttons). Thus, I hypothesize that the collaboration with industry engineers and engineering students would not only effectively draw attention to the connections between visitor actions and those of engineers, but also increase awareness of scientific and engineering careers as well as understanding of what the local engineering industry does.

Tinkering engineering activities and design problems also provide context to learn and put into action many important skills for the 21st century (Partnership for the 21st Century, 2009; Committee on K-12 Engineering Education, 2009). It is critical to provide real-world design problems in learning environments to bolster social skills, content-based skills, and problem-solving skills (Kali, Fortus, & Ronen-Furhman, 2009; Lehrer et al., 2000; Campbell, Perlman, & Hadley , 2002). Designing and building with materials in these contexts also provides opportunities to engage in hands-on construction and three-dimensional manipulation (Museum of Science, n.d.; Papert, 1991).

As noted above, design provides a powerful and motivating context for learning. But, there is a dearth in the literature on effective practices. However, the few papers focusing on design in K-12 engineering seem to show its effectiveness. Cunningham and Lachapelle (2011) summarize the results from six years of *Engineering is Elementary*, an engineering design curriculum for elementary schools, and find that it has improved interest, engagement, and performance in science and engineering in both students and teachers. Sadler, Coyle, & Schwartz (2000) show that after engaging in design challenges, middle school students' science skills increased, though they evaluated solely the ability to design science experiments. Kolodner (2002) finds that students participating in *Learning By Design* engaged in collaboration, communication, decision-making, and design of investigations much more like experts when compared to other similar students. Penner et al. (1997) demonstrate that students who designed physical models better understood science models, though their instruments seemed biased towards these students. These studies focus mostly on pre- and post-assessments of science concepts and skills; further studies are needed to evaluate the learning of engineering, particularly learners' engineering processes while they engage in design activities. However, with respect to some engineering habits of mind, researchers believe that design provides opportunities for students to exercise engineering habits of mind; students can test their preconceptions (Sadler, Coyle, & Schwartz, 2000), creatively develop unique solutions through multiple paths (Eckert et al. 2010; Committee on K-12 Engineering Education, 2009; Papert, 1991; Resnick, 2006), engage in systems thinking (Committee on K-12 Engineering Education, 2009), iteratively refine their design and thinking (Cunningham & Lachapelle, 2011), learn from failure (Bamberger, 1991; Schön, 1992), collaborate and communicate (Eckert et al., 2010; Kolodner, 2002; Kumar & Hsiao, 2007), manipulate and reflect with materials (Sadler, Coyle, & Schwartz, 2000; Schön, 1992; Bamberger, 1991; Edelson & Reiser, 2006), and ethically and civically design for people (Tsang et al., 2001). Therefore, though the results are still slim, it seems that tinkering design activities are educational for engineering.

2.2.2 Informal Learning

Design challenges in classrooms and afterschool programs have been found to be effective in promoting understanding of science and engineering (see, for example, Cunningham & Lachapelle, 2011; Kolodner, 2002; and Sadler, Coyle, & Schwartz, 2000). However, despite the growing popularity of design challenges in informal drop-in settings (e.g., *Tinkering Studio* at the

Exploratorium; *Challenge Zone* at the Ontario Science Centre; *Engineering Studio* at the Science Museum of Minnesota; *Lemelson Center* at the Smithsonian; *The Works* in Minnesota; *Design Challenges* at the Museum of Science, Boston; and *Engineer It* at the Oregon Museum for Science and Industry), these environments have not been well-studied. This dissertation intends to provide a study of this type of environment, specifically the *Ingenuity Lab* at the Lawrence Hall of Science.

Most learning happens outside of school, with Americans spending over 80% of their waking hours out of school (Stevens & Bransford, 2007). Nearly half of the public's understanding of science comes from free-choice, informal learning outside of school (Falk, 2002). This free-choice learning is often more effective, as it is lifelong learning that is intrinsically motivated and thus personally meaningful (Falk & Dierking, 2000) and the learner must be willing to be actively involved in the activity (Merriam, Cafferella, & Baumgartner, 2007). These informal environments contrast with the artificial, forced environment of classrooms (Papert, 1980). Furthermore, learning is continuous, dynamic, and organic, and much of what people know comes from real world experiences (Rennie & Stocklmayer, 2003). As such, the personalized experience of informal learning environments and museums is ideal for bridging these real world experiences.

Although informal learning environments vary greatly, Fenichel and Schweingruber (2010) outline five common commitments of these environments: engage participants in multiple ways, encourage direct interaction with natural and designed worlds, provide science as dynamic and from multiple perspectives, build on participants' prior knowledge and interests, and allow participants choice and control of the learning. They further emphasize the desire to make the interactions challenging, but not frustrating, and open-ended, but still offering opportunities for success.

Table 2.1: Falk and Dierking's (2000) Contextual Model of Learning in museums.

Personal context	**Socio-cultural context**	**Physical context**
• Visit motivation and expectations • Prior knowledge • Prior experiences • Prior interests • Choice and control	• Within group social mediation • Mediation by others outside the immediate social group	• Advance organizers • Orientation to the physical space • Architecture and large-scale environment • Design and exposure to exhibits and programs • Subsequent reinforcing events and experiences outside the museum

Because the visitors and environments are so diverse, learning is complex in museums. Falk and Dierking (2000) delineate the Contextual Model of Learning, emphasizing the complexity of learning and the various contexts that influence learning in a museum. The three area contexts are personal, socio-cultural, and physical, and the factors are outlined in Table 2.1. All of these factors and contexts are interwoven through time and must be considered holistically as a series of overlapping and related processes (Falk & Dierking, 2000). Learning is complex and difficult to assess in museum environments because "it requires knowing something about who is visiting, why they are visiting and with whom, what they are doing before and after the exhibit, what they see and do in the museum, and how all these factors interact and interrelate" (Falk & Dierking, 2000).

For the personal context, motivation is particularly important because science center visitors choose which activities to participate in and can choose to leave at any time. The learners that come through are also of all ages and extremely diverse in prior knowledge, experiences, and interests.

The socio-cultural context is important because visitors tend to visit in diverse groups with varying backgrounds (Falk & Dierking, 2000). Parents come to science centers with children to spend time together, have fun, and learn (National Research Council, 2009). Thus, maker spaces and design challenges at science centers often involve intergenerational collaboration. Many studies show that the involvement of parents in science centers improves children's experiences and deepens children's ideas (Crowley et al., 2001; Crowley & Galco, 2001; Gleason & Schauble, 1999; Hall & Schaverien, 2001). Parents can act as educators, co-learners, or passive observers (Schauble et al., 2002). The extension of the learning experience beyond the visit through conversations and support is important for science centers because the visits are often short and infrequent. Children can develop "islands of expertise," which begin with an initial interest from a single experience and develop into deep knowledge through family support (Crowley & Jacobs, 2002; Palmquist & Crowley, 2007). Therefore, parents can help sustain children's efforts, increase their competence (Barron, 2006), and positively reinforce their identities (National Research Council, 2009; Hall & Brassard, 2008).

Finally, the physical context is key to tinkering spaces. The specific building materials as well as the set-up of the space affords the types of design solutions and design processes that visitors can engage in.

Learning is influenced by people (both the individual and other people), the tools and materials, the environment, the history, and the context. In informal learning centers, this is particularly important, as there is no classroom full of regular students; instead, the environment consists of a huge variety of learners in background, age, and knowledge, many of which may only visit once. For engineering learning contexts, the influence from the situation of the learner and environment is also critical because each individual brings in his or her own unique perspectives to create innovative designs, shaped by the surrounding environment.

2.3 Interdisciplinary Collaboration and Service Learning

Finally, I now review literature on collaborations across disciplines and communities, as well as literature on service learning to contextualize the experiences of the engineering students creating design challenges for the Ingenuity Lab environment. I study the cross-community team designing the challenge, including the engineers and engineering students as co-designers who deconstruct their engineering practices for visitors as well as the educators who ensure the feasibility of the challenge.

2.3.1 Interdisciplinary Collaboration

A review of the literature shows that interdisciplinary collaboration among students, engineers, and educators can be mutually beneficial, and can especially achieve the need to inform and bring awareness to the public of current science and engineering research and technologies (Field & Powell, 2001).

With half of the public understanding of science coming from informal learning (Falk, 2002), broad-reaching and widespread informal science centers are well positioned to inform the public of current science and engineering. Science centers need both content and fiscal funding to create visitor experiences that are relevant, integrated, and dynamic. At the same time, they ideally need to have an adaptable learning environment with updatable content (Field & Powell, 2001). In order to achieve these goals, science centers strive to communicate current science and engineering research to the public (Field & Powell, 2001) and can do so through collaborations with professional scientists and engineers. Scientists and engineers are also motivated to increase public understanding by raising awareness of their work (Pace et al., 2010; Feinstein, 2005; Davies, 2008; Tisdal, 2011) and to inspire youth to pursue STEM activities and careers (Tisdal, 2011). However, despite the strong support for science-educator collaborations (e.g., Morrow, 2002; Crone, 2010; Field & Powell, 2001; Davis, 2004; Hodder, 2010; Selvakumar & Storksdieck, 2012; Feinstein, 2005), these collaborations can often be difficult for science centers because of the scarce resources required to keep these non-profits constantly updated (Powell & Field, 2001; Davis, 2004; Tisdal, 2011), a negative peer professional image of scientists and engineers who take time out to help these educational programs (Pace et al., 2010), and the challenge to translate the scientists' and engineers' practices to something accessible and understandable to a quickly passing visitor (Davies, 2008).

One approach called Portal to the Public aims to overcome some of these obstacles and provides a framework for science centers and museums to engage with scientists, engineers, and researchers (Selvakumar & Storksdieck, 2013). The framework, they emphasize, is not a "one-size-fits-all" approach, but rather acknowledges the idiosyncrasies of each setting. Professional development is key to Portal to the Public; science researchers are trained by museum educators and are then given opportunities to translate their current research for museum audiences. A key challenge in such endeavors is that there is often a large technical knowledge gap between the understanding of experts and novices, and design teams for these activities must learn to recognize that not all simplifications are problematic (Davis et al., 2013).

The approach of this dissertation research further incorporates the participation of students for a semester-long project. The engagement of professionals and students provides an avenue for the education of the public that overcomes the other above obstacles by providing a service learning (Lima, Oakes, & Gruender, 2006) project for students to undertake substantially, minimizing the time required by the professionals and educators while engaging students in an authentic and consequential engineering task.

Because of the interdisciplinary cross-community nature of this approach, I now look at some literature on interdisciplinary collaborations. Design is a social process (Bucciarelli, 1994), so why are most educational activities designed only by educators? In designing educational programs, Field & Powell (2001) similarly emphasize the need for interdisciplinarity through an iterative process between informal educators, professionals, and the public. Coordination between informal educators and partnerships with the professional science and engineering communities are vital to sustain such efforts to provide relevant, integrated, and dynamic science center programs.

Interdisciplinary teams that capture diverse perspectives from different fields of study and cultural backgrounds have a high potential to design creative learning activities for students, but there are challenges to such collaborative approaches. For example, for middle school teachers, interdisciplinary teams represent a change from their independent classrooms, and without follow-up support for the educators, collaborative activities are not likely to achieve sustained educational outcomes (Flowers, Mertens, & Mulhall, 2000). In industry, interdisciplinary teams also provide valuable insights, and the challenges are similar (Edmondson & Nembhard, 2009). In most cases, individual participants do not have the conceptual background needed to easily understand specialized topics in other disciplines, and skill is needed for enabling rapid learning in these situations (Pennington, 2011).

Bronstein (2003) provides a model for interdisciplinary collaboration, describing components that lead to the success of such collaborations. Her model was developed specifically for social workers but is applicable to the field of education with its similar focus on service to society. The key components are (1) *interdependence* such that team members depend on other members with unique expertise and maximize creativity through integrative teamwork, (2) *newly created professional activities* such that specific outcomes are created that cannot be created independently, (3) *flexibility* such that members compromise and react creatively to disagreement and unexpected issues, (4) *collective ownership of goals* such that there is a shared responsibility among team members through the joint design, definition, development, and achievement of shared goals, and (5) *reflection on process* such that self-evaluation and feedback are formalized as part of the collaboration efforts.

A design team composed of both engineers and scientists working together with educators to create novel learning activities is particularly valuable because these experts have been trained to think about natural and engineered systems in the world in different ways, and the educators would benefit from co-designing with these high-level engineers and scientists. For example, scientists are trained to examine phenomena through hypothesis testing (Tang et al., 2010), engineers are trained to develop technologies that solve problems (Jonassen, Strobel, & Lee, 2006), and educators are trained to present material to audiences to increase their subject-matter understanding (Stigler & Hiebert, 1999). The combination of these different thought patterns in a collaborative environment can provide great synergy to bring real-world engineering and science to educational settings.

Thus, by bringing in these interdisciplinary collaborators, *interdependence* and *newly created professional activities* have been set up according to Bronstein's model (2003). It is therefore important to ensure that the team members further engage in *flexibility*, *collective ownership of goals*, and *reflection* to successfully create novel learning activities.

Previous studies show that these science-educator collaborations can be beneficial to learners in many ways: the public gains positive attitudes towards science and engineering (Greco, 2011), view the technical fields as more approachable and relevant (Pace et al., 2010), are more aware of previously unknown careers, and retain science concepts (Tisdal, 2011). Next, I explore literature on how these collaborations can benefit the engineers and technical professionals involved in the design, as well as their organizations. In the following section on Service Learning, I review literature on how these collaborations benefit the students on the design teams.

As a mutually beneficial partnership, both the engineers and educators would complement each other's talents and expertise. In essence, the collaboration would be a mutual professional development (Morrow, 2002), with engineers gaining communication skills while sharing their work with the public and educators gaining programs contextualized in the technical fields while maintaining educational values (Selvakumar & Storksdieck, 2013). Past collaborations have found that engineers and scientists enjoy the experience and increase communication skills (Selvakumar & Storksdieck, 2013; Feinstein, 2005; Pace et al., 2010). Furthermore, scientists can increase their exposure to new ideas that may help in their own professional work and gain professional recognition (Pace et al., 2010). In an evaluation of Portal to the Public, scientists also reported that the collaborative experience was fun, rewarding, and satisfying, and that they could apply the skills gained to other settings; scientists appreciated the opportunity to communicate work to the public (Tisdal, 2011). In a review of corporate social responsibility, in which employees volunteer for and companies support community service, Fombrun, Gardberg, and Barnett (2000) claim that employees gain a "broader repertoire of cultural, relational, and self-leadership competencies."

Furthermore, these collaborations not only benefit the scientists or engineers, but also their organizations. Research centers are required by many funding agencies to engage in public outreach (e.g., grants from the National Science Foundation; Pace et al., 2010; Feinstein, 2005). Many scientists also feel that it is their duty to educate the public (Pace et al., 2010). Thus, with opportunities to collaborate with science centers, research centers can engage in broad-reaching impact through education. Companies are also looking to add "social responsibility" aspects to their brands (Peters & Mullen, 2009; Bhattacharya, Korschun, & Sen, 2008; Cooper & Wagman, 2009; Koo & Cooper, 2011; Lindgreen & Swaen, 2010; Weeden, 2011). In implementing "strategic philanthropy" (Porter & Kramer, 2002) with a science center, these companies can promote their image and brand through supporting education, increase company visibility through exposure as a potential employer to engineering students and to young visitors and their parents, and improve employee morale through participation in a good cause and mentoring engineering students. By exposing employees to the community, companies can increase employees' understanding and awareness of direct and indirect stakeholders' needs and perspectives (Fombrun, Gardberg, & Barnett, 2000). Additionally, previous research on industry and museum collaborations shows the benefits of such collaborations (e.g., Kraus, 2000; Knerr, 2000). For instance, there are more and more corporate museums whose aim is to educate the public about the company (Rennie & Stocklmayer, 2003) to improve the acceptability of these companies' technologies (Knerr, 2000).

Literature on previous such science-educator collaborations have explored how scientists have viewed their role in outreach as a one-way communication, in which they are transmitting important knowledge to the learners with minimal contribution from or personalization for the learners, contrary to educators' models of learning (Davies, 2008; McCallie et al., 2009; Feinstein, 2005). These outreach programs usually consist of face-to-face transmission of knowledge through table-top activities or talks. One program that further involved scientists in the design of exhibits and activities found that scientists abstractly described the communication as one-way, but they tended to describe specific past experiences in communication of science as a more context-dependent and individualized experience for the learner (Feinstein, 2005); this finding is promising and suggests that these scientists may have explicit criteria for what they abstractly believe general education and communication should consist of, while they employ different criteria implicitly in the actual educational situation that better reflect educators' model of learning.

New methods besides face-to-face transmission of knowledge are needed for communicating advances in science and technology to the general public (Suleski & Ibaraki, 2010), and tinkering and design challenges offer a great opportunity.

2.3.2 Service Learning

I view the participation of students in the design teams as service learning, and now review literature in that field. Shuman, Besterfield-Sacre, & McGourty (2005) provide a thorough review of many successful pedagogical paths for implementation of professional skills in engineering academic programs, emphasizing the use of service learning in combination with engineering design projects to teach and reinforce outcome combinations. In the last few decades there has been a great deal of emphasis on developing the professional skill sets in the engineering curriculum (Pulko & Parikh, 2003). These "soft" skills – proficiencies such as leadership, management, teamwork, decision-making, and communication – are important attributes of a successful engineer. Engineering students often graduate weak in these essential skills (Nguyen, 1998; Selinger, 2004). Instead, these professional and leadership skills are usually learned the hard way: through experience in the workplace as a professional engineer (Kumar & Hsiao, 2007). Traditional engineering curricula and lecture formats need to be revised to enhance these professional skills, as "the quality of future engineers depends very much on the quality of engineering education" (Nguyen, 1998).

Service learning fosters these skills by incorporating real-world experiences into the engineering curriculum while providing a valuable service for an entity such as a nonprofit organization or a disadvantaged community (Lima, Oakes, & Gruender, 2006). This provides students with an opportunity to actively utilize their design and engineering skills in a real world experience (Amadei, 2003). The National Academy of Engineering has found that academic programs that engage students in team exercises and design challenges that connect to real-world problems are most successful in retaining its engineers (National Academy of Engineering, 2005). It has been shown that students engaged in such experiential learning opportunities have better retention of technical knowledge and are better able to apply what they have learned in college courses to real life situations after graduation (Shuman, Besterfield-Sacre, & McGourty, 2005; Duffy, 2000; Morton, 1996; Jeffers, Safferman, & Safferman, 2004; Eyler & Giles, 1999). These benefits of service learning are also reflected in the ABET criteria for engineering accreditation at colleges (ABET, 2012; Tsang et al., 2001; Coyle, Jamieson, & Oakes, 2005).

In particular, first-year courses that incorporate service learning serve to expose students to engineering practice early on, and can have a positive influence on the education of young engineers (National Research Council, 1995). In contrast, the National Science Board (2007) noted that students usually "develop little identity as engineers in their first two years of college because they take math and science courses and have little exposure to the engineering practice." Studies have demonstrated the implementation and subsequent success of first-year design or cornerstone courses, such as service learning, for student retention and building practical skills (Dym et al., 2005; Marra, Palmer, & Litzinger, 2000; Cronk, Hall, & Nelson, 2009).

Moreover, service learning and professional skill development has been shown to have a positive impact on women engineers and may improve recruitment and retention of women into the field of engineering at the undergraduate level (National Research Council, 1995; Atwood, Patten, & Pruitt, 2010; Selinger, 2004; ABET, 2012; Dym et al., 2005). Additionally, the collaboration studied in this dissertation involves students with professional engineers, thus connecting the students to practicing experts as mentors. Mentoring is known to increase retention and persistence of women and minorities, especially in the STEM fields (e.g., Noe, 1988; Kahveci, Southerland, & Gilmer, 2006; Chesler & Chesler, 2002).

Findings from a previous collaboration with students from a first-year engineering design project course serving as facilitators at the Lawrence Hall of Science demonstrated that teaching others is an effective method of solidifying understanding, facilitating engineering design challenges can increase student self-rating on several crucial ABET standards (especially in soft skills such as communication, teamwork, and leadership), and women student engineers especially benefited from the experience, suggesting such a collaboration's potential to recruit and retain women in engineering (Shelby et al., 2013).

2.4 Summary

In this chapter, I have reviewed literature relevant to my dissertation research, particularly literature in the areas of engineering education, informal learning and making, interdisciplinary collaboration, and service learning. In the next chapter, I use the education literature to ground my research in the learning theories, particularly socio-cultural theory and constructionism, as both context (individual, physical, and social) and the act of constructing are the basis for the Ingenuity Lab program.

Chapter 3

Theoretical Framework: Socio-cultural Theory and Constructionism

My research is grounded in learning theories from the socio-cultural and situated perspectives as well as the constructionist and learner-centered perspectives. These theories serve to provide (1) dimensions of learning to focus on in my study, (2) a pedagogical philosophy of learning to guide the design of the engineering learning program, and (3) a hypothesis on the connection between perceived and actual engineering practices. Here, I provide an overview of these learning theories, and in the following sections, I critically review these theories.

Learning theorists have argued the importance of various factors from the external to internal that influence learning. The socio-cultural and situated perspectives (e.g., Greeno, Collins, & Resnick, 1996; Vygotsky, 1978; Engle, 2006; Lave & Wenger, 1991) emphasize the external social and physical factors that affect learning: social interaction with others (Chi, 2009; Greeno, Collins, & Resnick, 1996; Vygotsky, 1978) and within a community of practice (Lave & Wenger, 1991; Engle, 2006) and physical artifacts, content, and settings of the environment (Hutchins, 1995). The constructionist and learner-centered perspectives emphasize internal factors and posit that individual learners enter learning situations with their own prior knowledge and build on this knowledge for meaningful learning (e.g., Papert, 1991; diSessa, 2008; Chiu & Linn, 2011; Linn, 2006). These various factors – the social, physical, and personal – interplay dynamically in a learning situation (Falk & Storksdieck, 2005). I draw from these theories of learning to guide my study. In particular, my empirical methods will systematically attend to the social, physical, and personal contexts of learners.

A pedagogical philosophy follows from the situated and constructionist theories. Open-ended learning environments in which learners can construct entities through play and design with others can foster opportunities for meaningful social interaction (Blud, 1990; Diamond, 1986) and productive construction with materials (Anderson et al., 2002), while too much open-endedness may be unproductive without some guidance (Chiu & Linn, 2011; Linn, 2006). Social interaction allows learners to build on each other's ideas (Chi, 2009; Vygotsky, 1978; Dewey, 1916; Roschelle, 1992; Okada & Simon, 1997; Mercer, 2008; Cohen, 1994) and constructing entities leads to knowledge construction (Papert, 1991; Resnick, 2006). The transactive design process engages the learner in constructing entities as a designer in a constant dialogue between the design situation and the design materials (Schön, 1992), as well as with others in the environment.

Many formal learning environments, such as classrooms and afterschool programs, have used open-ended design activities over extended durations and focus mostly on science learning (e.g., Kolodner, 2002; Penner et al., 1997; Sadler, Coyle, & Schwartz, 2000), but I intend to study the new trend of tinkering in informal drop-in environments as a means to engage in engineering practice, where learners of all ages and backgrounds participate for varying durations, from 15 minutes to over two hours, and where a single interaction may spark life-long interest in engineering. Furthermore, I focus on the process in which the designers engage to create these learning experiences. These learning environments are in contrast to typical science center exhibits. Rather than constraining the actions of users with a limited number of variables and an intended goal, open-ended spaces allow opportunities for transactive engagement (Tatter, 2008; Stroud, 2010; Salen & Zimmerman, 2005). Users tinker with a variety of materials to construct their own creations and achieve personally defined goals, thus constructing knowledge (Papert, 1991). Tinkering and design are natural tendencies for children, as design is commonly associated with play (Resnick, 2006); science centers can foster and sustain these tendencies. Providing opportunities for open-ended design and tinkering is a theoretically-grounded approach to designing a science center learning environment.

3.1 Dimensions of Learning: A Continuum from the External to Internal

Learning theorists emphasize the importance of various factors in learning, from the community and people with whom learners interact to the physical environment and artifacts to learners' personal prior knowledge and background. In this section, I review the work of several researchers along this multi-dimensional continuum.

Focusing on the social factors, Falk and Dierking (2000), along with Wellington (1990), argue that conversation and social activities are key to knowledge construction and learning; social groups build on each other's knowledge and reflect on the various perspectives, with each of these short moments important for the larger learning experiences. Lave (1996) highlights both teachers and learners as participants that are interdependent learners in a constantly changing community of practice. Her study of apprenticeship, an ideal learning environment, shows that these environments are learner-centered whereas schools are mostly teacher-centered. However, Lave focuses on learning as a long-term process over years; in contrast, learning must be happening in more short-term and one-time engagements, especially in museums and science centers dedicated to education. Engle (2006) and Tran (2006) note that short-term engagements form part of the larger long-term experience, and Azevedo (2011) also highlights the importance of "relationships between local, short-term activities and those of an extended nature." Brown and Campione (1996) implement Lave's theories and create a classroom community of learning through social interaction, but these authors, along with Lave, neglect the learning that can happen individually and in short moments. Engle (2006) also studies the social interactions in these communities of learning, but details the interactions at a micro level as opposed to Brown and Campione's more macro study of the community and of the systems design of the learning environment. Engle's work shows how the teacher, through dialogue, creates intercontextuality by framing the learning activity, a short-term event, with the past and future to integrate into a long-term experience. Falk and Dierking (2000) look at communities of learning in informal environments and emphasize the importance of the social context, which, like Engle proposes, can reinforce past experiences to create more personal, shared experiences and build on prior knowledge through knowledge integration (Chiu & Linn, 2011). For this dissertation, it's important to note that the social factor is also important to design, as design is frequently considered a social activity (Bucciarelli, 1994; Beckman & Barry, 2007; Dym et al., 2005; Schön, 1992; Eckert et al., 2010; Committee on K-12 Engineering Education, 2009; Kolodner, 2002; Kumar & Hsiao, 2007; New York Hall of Science, 2010).

This focus mostly on dialogue neglects other factors that may influence learning and framing of activities, including the context of learning and the physical environment. Azevedo (2011), as mentioned previously, investigates the many smaller activities that comprise a larger complex context, which plays a key role in influencing interest and practice. Many other researchers similarly emphasize that learning outcomes are better and more memorable when the learning content is better integrated with personal contexts as well as real contexts, with all its complexity (Billig, 2000; Braund & Reiss, 2006; Wollins, Jenson, & Ulzheimer, 1992; Engle, 2006; and Schauble & Bartlett, 1997). The context provides mediation via not only social interactions, but also physical artifacts (Schauble & Bartlett, 1997), which should be appropriately chosen to foster desired processes (Resnick & Silverman, 2005). Further, context can not only be the driving factor for persistence in an activity (Azevedo, 2011), it can be the inspiration and motivation to initially engage in an activity (New York Hall of Science, 2010). Azevedo boldly claims that context is more important than the content of a pursued practice. On the other hand, other researchers argue for the importance of content and process: Brown and Campione (1996) argue that content provides the core of what students learn while constructionists like Papert (1991) and Resnick and Silverman (2005) argue that the process provides skills as tools for thinking, which are more powerful than the content learned.

Papert, Resnick, Silverman, and other researchers emphasize the internal factors of personal knowledge and ideas rather than external factors of social contexts. Many researchers claim that building on personal interests is key to meaningful learning (Billig, 2000; Braund & Reiss, 2006; Wollins, Jensen, & Ulzheimer, 1992; Resnick & Silverman, 2005; Resnick, 2006; and Kali, Fortus, & Ronen-Furhman, 2009). Chiu and Linn (2011) consider the personal factors; scaffolded knowledge integration involves adding, sorting, evaluating, distinguishing, and refining individual ideas, but with support through social or contextual scaffolding. Rather than considering the importance of conversations as a mediator, constructionists like Papert (1991), Resnick (2006), and Bamberger (1991) consider actively doing activities and constructing entities as the driver of meaningful learning. Active learning is typically learner-motivated, thus building on personal interests (National Research Council, 2009; Falk & Dierking, 2000). Papert (1991) proposes that everything is understood by being constructed; constructing entities is productive and allows for multiple styles of engagement, resulting in knowledge that is concrete, personal, and less detached while traditional instructionist methods are rote and authoritarian, resulting in knowledge that is abstract, impersonal, and detached. Resnick (2006) similarly advocates that play in open-ended environments with construction materials leads to creativity and active engagement in meaningful and systematic processes through productive design. Bamberger (1991) discusses two kinds of knowledge: “hand knowledge” and “symbolic knowledge” that result from, respectively, active engagement with concrete artifacts and traditional abstract teaching methods. Unlike Papert, who discusses the superiority of “hand knowledge,” Bamberger values both types of knowledge and explores how to confront and develop these multiple representations by reflecting and learning about similarities and differences between the representations. Papert, Resnick, and Bamberger, however, would agree that traditional instruction is abstract and symbolic, and often excludes certain types of learners through neglect of personal knowledge and ideas.

The entire continuum of perspectives – from social to physical to personal – all focus on learner-centered approaches, in contrast to traditional teaching which is teacher-centered, emphasizing content as opposed to processes and where all students learn the same thing (Kumar & Hsiao, 2007). The social and situated perspectives focus on the learner as working with others in a specific context; the cognitivist perspectives focus on the learner as bringing in his/her own personal knowledge and interests. Informal environments are naturally learner-centered (National Research Council, 2009). Falk and Storksdieck (2005) and the National Research Council (2009) consider an ecological framework of these various factors that influence learning in informal environments: the social, physical, and personal. The social factor, or culture-centric perspective, emphasizes the community and social interactions. The physical factor, or place-centric perspective, emphasizes the context, the activities, and the physical artifacts. The personal factor, or people-centric perspective, emphasizes the prior knowledge and intuitive ideas of the individual. These three factors provide a lens through which to view the processes of the design teams and the visitors at the Ingenuity Lab.

3.2 Pedagogical Philosophy: A Continuum from Open-Ended to Structured Learning Environments

The design of successful learning environments involves the same processes as engineering a good solution. Brown and Campione (1996) state that the design of learning environments should be thought of as a system of parts, where each part is dependent on others. Thus, designing learning environments should be considered as a whole. They (also see Allen & Gutwill, 2009; Schauble & Bartlett, 1997; Kali, Fortus, & Ronen-Furhman, 2009; Edelson & Reiser, 2006) emphasize the importance of research-driven designs with continued formative evaluation in an iterative process. Like engineering a good solution, design environments must be based on good science and be continually tested and refined.

While most of the above researchers have focused on formal learning environments, a few (Allen & Gutwill, 2009; Schauble & Bartlett, 1997) consider informal learning environments from a similar perspective. Schauble and Bartlett (1997) study a science center and describe an entire exhibit design process, an area understudied by researchers. Their paper provides an excellent insight into the process, highlighting their three levels of design: theories from learning sciences to inform the design, learning research in content areas to inform the development, and forms of mediation and teaching to inform the implementation. Bitgood (1994) explains several approaches to designing museum exhibits: content-based, aesthetic, hedonistic, realistic, hands-on, social, or individual-difference. The latter three reflect the three factors of learning described in the previous section: hands-on reflects the physical factors, social reflects the social factors, and individual-difference reflects the personal factors. Hein similarly divides exhibit design approaches as a continuum between didactic, discovery, constructivist, and behaviorist (National Research Council, 2009). The discovery and constructivist approaches are similar to the hands-on and individual-difference approaches; however, Hein neglects the social potential of exhibits.

Two extremes of hands-on learning environments are to offer open-ended activities or structured activities. Proponents of open-ended activities tend to focus on the process over the content (e.g., Resnick, 2006; Resnick & Silverman, 2005; Papert, 1991; Schauble & Bartlett, 1997; New York Hall of Science, 2011), the authenticity offered by the environment (Braund & Reiss, 2006; Wellington, 1990), and personalization of learning (Resnick & Silverman, 2005). Open-ended environments provide opportunities to engage in processes that encounter and use powerful ideas; Papert (1991) defines powerful ideas as "tools to think with over a lifetime." Moreover, open-ended means that each learner can engage differently, but all learners still encounter and use the same underlying ideas (Resnick & Silverman, 2005). Schauble and Bartlett (1997) also emphasize the development of thinking rather than content. Brown and Campione (1996) state that "the idea that all children of a certain age in the same grade should acquire the same body of knowledge at the same time … is one of the reasons that contemporary school activities are to a large part inauthentic." Authenticity is one of the key contributions of informal learning environments (Braund & Reiss, 2006; Wellington, 1990). Learning environments in engineering should provide experiences similar to the activities of professional scientists and engineers, and these experiences are open-ended and self-directed (Braund & Reiss, 2006). Finally, open-ended allows for personalization for each learner to engage differently, as mentioned earlier, and thus provides each learner the opportunity to experience ownership of his/her learning process and product. From a constructionist perspective, Resnick and Silverman (2005) also advocate that appropriate manipulables offer a wide diversity of use for personalization.

On the other hand, how do we ensure that students are learning the desired content or even process if it's just an open-ended, free-for-all environment? Proponents of structured activities propose that some guidance is needed to support the learning process (Allen & Gutwill, 2009; Chiu & Linn, 2011), to scaffold complex practices (Edelson & Reiser, 2006), to selectively provide areas of focus (Edelson & Reiser, 2006: Resnick & Silverman, 2005), and to help foster transfer (Kolodner, 2002). By structuring activities, the process can be properly directed, the context can be simplified, and the practices can be ritualized (Kolodner, 2002). Resnick & Silverman (2005) argue that guidance through providing the right tools can promote specific desired interactions.

Bruner's spiral curriculum offers a balance to the two extremes (Bruner, 1966). The spiral revisits the same concepts, but with an opportunity to dive deeper at each revisit. Thus, the open-ended personalization and accessibility is retained while certain contents and processes can be ritualized. The beginning of the spiral is easier and more structured, but learners also have the opportunity to begin at a deeper, more open-ended level. Other researchers have embraced similar methods to the spiral curriculum for both in-school and out-of-school environments (e.g., Brown & Campione, 1996; Wellington, 1990; Schauble & Bartlett, 1997; Kali, Fortus, & Ronen-Furhman, 2009).

In summary, the design of the learning environment shapes the learning processes. Design creates meaning (Salen & Zimmerman, 2005). Although Salen and Zimmerman focus on game design, much of what they discuss is pertinent to the design of all meaningful environments; they describe how the particular design can heavily impact the player experience. To promote constructionist learning, balancing structure with open-endedness by providing the right tools and guidance is unique to each environment, activity, and learner. The approach of the environment – along the multi-dimensional continuum from open-ended to structured – should be considered carefully, and, as described previously, should be informed by research and continued formative evaluation.

3.2.1 Design Principles

Following from above, the continuum from open-ended to structured and the factors from social to physical to personal provide many dimensions to consider in designing a learning activity. Wellington (1990) states that science centers "contribute almost exclusively to *knowledge that* and rarely contribute directly to a knowledge of how and why phenomena occur." I believe the new tinkering programs at science centers are changing this by offering learners a spark of interest to wonder how or why something happens and providing an environment to explore how or why. The literature provides several guiding design principles along the many dimensions informed by both research and practice to help these tinkering programs contribute to knowledge of how and why. Figure 3.1 summarizes these design principles, and the rest of this section elaborates on each of the design principles.

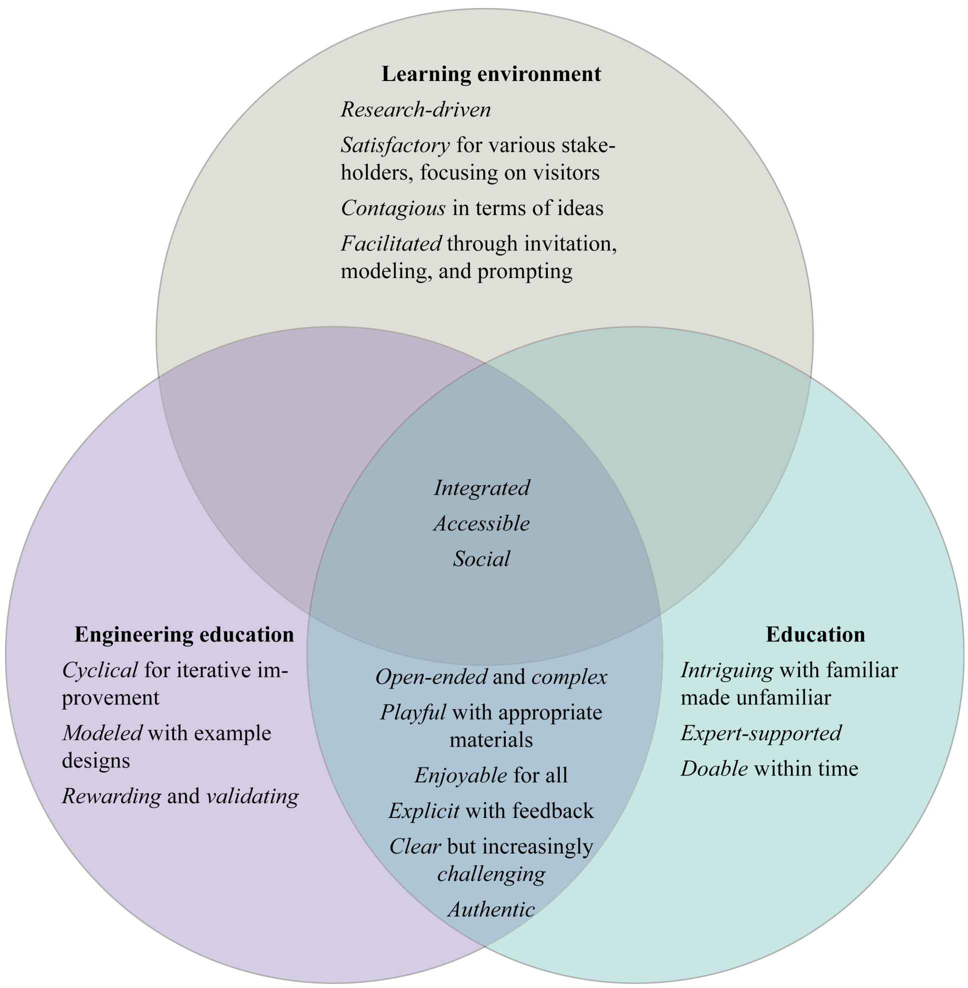


Figure 3.1: Design principles for the learning environment, education, and engineering education, with the crossover of design principles indicated by the overlap in the Venn diagram. Each of these three research perspectives contributes to the design of a tinkering environment. The learning environment perspective focuses on things in the environment that shape learning and how to create a space to achieve certain goals; the education perspective contributes learning theories on how to distinguish and build on ideas and how to support deeper learning; and the engineering education perspective provides guidance for structuring design processes.

Informal Learning Environment Design Principles.

1. *Research-driven*. The learning environment design should be research-driven (based on research in the learning sciences, informal learning, and content area) and iterated with formative evaluation, both qualitative and quantitative (Allen & Gutwill, 2009; Edelson & Reiser, 2006; Schauble & Bartlett, 1997; Brown & Campione, 1996; Bitgood, 1994; Kali, Fortus, & Ronen-Furhman, 2009; Resnick & Silverman, 2005).
2. *Integrated*. Design trade-offs include creating an experience that is generalizable (Allen & Gutwill, 2009) versus content-specific (Bitgood, 1994).
3. *Satisfactory*. Reconcile the various stakeholders – the designer, scientist/content specialists, educator, and visitor – but the visitor is most important (Bitgood, 1994; Schauble & Bartlett, 1997).
4. *Accessible*. Allow for accessibility through various paths and means of support (Allen & Gutwill, 2009; Schauble & Bartlett, 1997; Bitgood, 1994; New York Hall of Science, 2010). Allow for adaptation of the learning environment design for these various paths (Kali, Fortus, & Ronen-Furhman, 2009).
5. *Social*. Encourage collaboration across generations (New York Hall of Science, 2010; Falk & Dierking, 2000).
6. *Contagious*. Foster cross-pollination and spreading of ideas (New York Hall of Science, 2010).
7. *Facilitated*. Use facilitators to invite and encourage visitors to engage, model possible behaviors, and ask what-if questions (New York Hall of Science, 2010).

Educational Design Principles.

1. *Accessible and challenging*. Design the activity to be appropriate and accessible for a broad range through funneling and increasing depth (Schauble & Bartlett, 1997; Brown & Campione, 1996), building on knowledge (Schauble & Bartlett, 1997; Allen & Gutwill, 2009), and multiple paths (Resnick & Silverman, 2005; Resnick, 2006; Brown & Campione, 1996). Funneling and spiral begin with personal, large, and easy, and progresses to deeper, more complex, more abstract (Brown & Campione, 1996; Wellington, 1990; Schauble & Bartlett, 1997; Kali, Fortus, & Ronen-Furhman, 2009).
2. *Open-ended*. Allow for choice and personalization through multiple paths, building on prior interests and knowledge (Wollins, Jensen, & Ulzheimer, 1992; New York Hall of Science, 2010; Schauble & Bartlett, 1997; Brown & Campione, 1996; Kali, Fortus, & Ronen-Furhman, 2009).
3. *Integrated*. Integrate and interconnect the content across contexts and domains (Engle, 2006; Schauble & Bartlett, 1997; Braund & Reiss, 2006; Kali, Fortus, & Ronen-Furhman, 2009; Wollins, Jensen, & Ulzheimer, 1992; Kolodner, 2002).
4. *Playful*. Provide a meaningful context and materials for personal interest and ownership (Braund & Reiss, 2006; Edelson & Reiser, 2006; Kali, Fortus, & Ronen-Furhman, 2009; Resnick & Silverman, 2005; Brown & Campione, 1996; Chiu & Linn, 2011). Encourage play with various materials, situations, solutions, and contexts, and encourage documentation and reflection on the experience (Schauble & Bartlett, 1997; Kali, Fortus, & Ronen-Furhman, 2009; Resnick & Silverman, 2005; Brown & Campione, 1996; Edelson & Reiser, 2006).

5. *Intriguing*. Make the familiar intriguing and unexpected (Schauble & Bartlett, 1997; Resnick, 2006; Wollins, Jensen, & Ulzheimer, 1992; Chiu & Linn, 2011).
6. *Clear*. Present complex, but not overwhelming, design problems and challenges with a consequential task (Schauble & Bartlett, 1997; Edelson & Reiser, 2006; Allen & Gutwill, 2009; Brown & Campione, 1996; Kali, Fortus, & Ronen-Furhman, 2009; Resnick, 2006). Reduce complexity through scaffolding and blackboxes to make the activity as simple as possible (Allen & Gutwill, 2009; Edelson & Reiser, 2006; Resnick & Silverman, 2005; New York Hall of Science, 2010; Kali, Fortus, & Ronen-Furhman, 2009; Brown & Campione, 1996).
7. *Authentic*. Make implicit elements and powerful ideas of authentic practices explicit (Edelson & Reiser, 2006; Resnick & Silverman, 2005).
8. *Social*. Foster cooperative play, sharing of ideas, and social interaction (Schauble & Bartlett, 1997; Allen & Gutwill, 2009; Braund & Reiss, 2006; Kali, Fortus, & Ronen-Furhman, 2009; Brown & Campione, 1996; Engle, 2006; Chiu & Linn, 2011).
9. *Enjoyable*. The activity should be intrinsically enjoyable (Allen & Gutwill, 2009; Braund & Reiss, 2006; Wellington, 1990; Papert, 1991; Resnick, 2006).
10. *Explicit*. Make feedback explicit (Kali, Fortus, & Ronen-Furhman, 2009; Salen & Zimmerman, 2005).
11. *Expert-supported*. Provide access to domain specific expertise (Brown & Campione, 1996).
12. *Doable*. Support learning goals such that the activity is doable within the time frame (Allen & Gutwill, 2009; Brown & Campione, 1996).

Engineering Education Design Principles.

1. *Integrated*. Integrate the activity with STEM and other content areas (Committee on K-12 Engineering Education, 2009; Billig, 2000).
2. *Cyclical*. Allow for multiple short iterations and improvements through large possible ranges in performance (Kolodner, 2002; Sadler, Coyle, & Schwartz, 2000).
3. *Open-ended and complex*. Have an open-ended and complex systems environment to allow learners to engage with design trade-offs and prioritization of goals (Committee on K-12 Engineering Education, 2009).
4. *Playful*. Provide materials that invite inquiry and play and that can be used diversely (New York Hall of Science, 2010; Schauble & Bartlett, 1997; Kali, Fortus, & Ronen-Furhman, 2009; Resnick, 2006; Resnick & Silverman, 2005; Brown & Campione, 1996; Billig, 2000).
5. *Enjoyable*. The activity should be something *you* enjoy making (Resnick & Silverman, 2005).
6. *Clear, but challenging*. Make the design problem clear and easily understood, yet challenging and requiring application of technical skills (Sadler, Coyle, & Schwartz, 2000; Schauble & Bartlett, 1997; Edelson & Reiser, 2006; Allen & Gutwill, 2009; Kali, Fortus, & Ronen-Furhman, 2009; Billig, 2000; Bitgood, 1994).
7. *Modeled*. Offer initial prototype designs as starting points or inspiration (Sadler, Coyle, & Schwartz, 2000).
8. *Explicit*. The challenge should have explicit feedback through tests against nature (reliable and non-subjective; Sadler, Coyle, & Schwartz, 2000) and support easy methods to document and share test results to get feedback from others (Kali, Fortus, & Ronen-

Furhman, 2009; Chiu & Linn, 2011; Norman, 2002; Sadler, Coyle, & Schwartz, 2000; Billig, 2000; New York Hall of Science, 2010; Bitgood, 1994).

9. *Authentic*. Allow learners to understand the practices of engineering (Edelson & Reiser, 2006). Integrate the activity with careers of real engineers (Billig, 2000).
10. *Accessible and open-ended*. Nurture accessibility and ownership through individually-guided design activities (Billig, 2000; Brown & Campione, 1996; Edelson & Reiser, 2006; New York Hall of Science, 2010).
11. *Social*. Encourage collaboration, interaction, partnerships, and communication (Billig, 2000; Schauble & Bartlett, 1997; Allen & Gutwill, 2009; Braund & Reiss, 2006; Kali, Fortus, & Ronen-Furhman, 2009; Brown & Campione, 1996; Engle, 2006; Chiu & Linn, 2011).
12. *Rewarding and validating*. Acknowledge, celebrate, and validate the learners' work (Billig, 2000).

3.3 Hypothesis

Lastly, my theoretical framework structures my hypothesis on the connection between perceived and actual engineering practices for both the visitors and the designers. The perceived engineering practices represent a *formal epistemology* (Sandoval, 2005) in what is believed about professional engineers and the actual engineering practices represent *practical epistemology* (Sandoval, 2005) in the actions in which the visitors and the designers engage. The designers must deconstruct their perceived formal engineering practices for visitors, and in the process, the designers engage in actual engineering practices; the visitors actually engage in these practices deconstructed by the designers and do so coming in with their own perception of formal engineering practices.

In previous studies, scientists serving as collaborators in outreach have attempted to translate their own formal practices through a one-way communication from scientist to learner with little or no contribution from the learner (Davies, 2008; Feinstein, 2005). However, rather than contributing through a specific exhibit, talk, or a brief table-top activity, the collaborators in this dissertation are designing an extended experience in which the learners construct their own design solutions to an open-ended challenge. Does involving the engineers and engineering students in the design process, particularly the design of an engineering tinkering challenge, promote a different perception of communication?

I hypothesize that the engineers and engineering students serving as co-designers will consequently not view visitor learning as a one-way communication, but rather as a mutual learning experience in which the learners also contribute to the experience (McCallie et al., 2009). I seek to understand the designers' processes to deconstruct their engineering practices for visitors and whether the perception is reflected in their criteria for a "good" engineering tinkering activity. I explore how the designers explicitly identify engineers' practices along with how they implement engineering design activities representing the engineers' practices by comparing the explicitly identified criteria for the challenges with the final implementation of the challenges. Despite possible gaps between the explicit criteria and implementation, I hypothesize the explicit criteria only represents the formal perceived practice and may not fully capture the actual practices while the implementation will represent the practical and actual engineering practices. Analogously, in deconstructing formal engineering practices, some of the formal engineering practices may be lost in translation in the explicit criteria but retained implicitly.

My research aims to bridge the gap between perceived formal and actual practical engineering. Visitors may perceive the tinkering activities as "play" yet perceive engineering as difficult and abstract. However, I hypothesize that by engaging successfully in the engineering tinkering practices developed through the collaboration and by highlighting the connection to real engineers through grounding the practices in authentic, local engineering topics, the perceived formal practice of engineering can then be aligned with the actual practice of engineering. Visitors would instead perceive engineering as accessible through "play" in authentic practices.

Subsequently, I argue beyond the constructionist theories of Papert (1991), Resnick (2006), and Bamberger (1991) in that doing and constructing things does not only lead to the construction of knowledge, it also leads to the construction of agency in the learner's ability to do things and identity as a doer of these kinds of activities. With the alignment of the perceived formal practice of engineering with these engineering tinkering practices, learners can create an identity as a person who engineers. Developing agency and identity is key in informal settings, which often involve only a short, one-time experience that is not long enough for deep and extended construction of knowledge. Instead, this one-time experience gives learners the tools and confidence to pursue similar practices beyond this moment. Miles (1987) states that informal environments "are not places for communicating a lot of factual information to a lay public, but they do present opportunities for awakening people's interest in a subject, so affecting their educational desires."

I propose that characteristics of authentic engineering practices are fundamental to tinkering, connecting the perceived formal with the actual engineering practices. Characteristics of engineering include engaging in iterative design through planning, designing, building, testing, and refining; learning from failure to improve the next design; systems thinking and dealing with trade-offs; and being adaptable in approaching design problems with multiple solutions (Dym et al., 2005; Lewin, 1979; Nguyen, 1998; Committee on K-12 Engineering Education, 2009; National Academy of Engineering, 2005; ABET, 2012; Next Generation Science Standards, 2014). Based on this proposition and the learning theories, I hypothesize that the cross-community collaboration grounds the accessible tinkering activities in authentic engineering. Thus, providing opportunities for tinkering creates access to authentic engineering practices. With careful design of the learning environment, these practices can be sustained through (a) an encouraging memory of the experience to lead to interest (Wollins, Jensen, & Ulzheimer, 1992), (b) relevant engineering context within which to use powerful ideas (Papert, 1991) and gain new knowledge (Brown & Campione, 1996), (c) doing the design and tinkering to foster agency and identity (Falk & Dierking, 2000; Lave, 1996), and (d) a positive affect engaging in the experience to promote a constructive perception, attitude, and disposition (Wellington, 1990) towards engineering for repeat engagement (Hidi & Renninger, 2006) (see Figure 3.2).

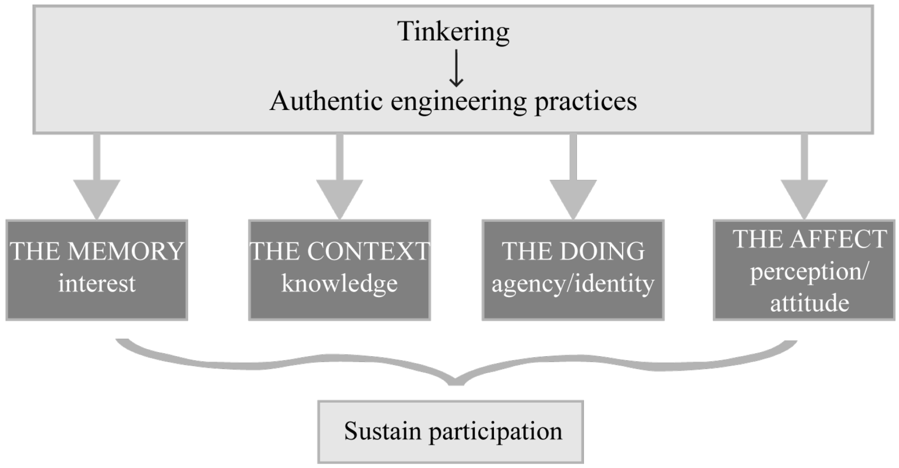


Figure 3.2: Hypothesis of how the learning environment will sustain participation in engineering. The process of tinkering engages learners in authentic engineering practices. These engineering practices can then be sustained through an encouraging memory, a relevant context, active doing, and a positive affect during tinkering that foster interest, knowledge, agency and identity, and a positive perception and attitude in engineering.

Furthermore, informal learning environments, in particular museums and science centers, are well-suited to bridge perceived formal and actual engineering design practices, with the concept of engineering design serving as the perceived formal practice and the science center experience serving as the actual practice. I pull together several variables (modified from Museum of Science, Boston, 2011 and Exploratorium, 2012) that contribute to successful science center experiences in which families are engaged, interested, enjoying the activity, and inspired to pursue the activities outside of the science center. In Table 3.1, I map the variables to several characteristics of engineering design.

Table 3.1: Variables of science center experiences that are conducive to characteristics of engineering design, with each row representing a natural mapping.

Variables of science center experiences	Characteristics of engineering design
Cross-generational: engages multiple and diverse generations collaboratively	Collaboration and communication, diversity of teams
Extended time and depth: holds families long enough to engage deeply	Complex problems that take time to solve
Informal: is open-ended and minimally structured	Complex problems that are ill-structured
Flexibility: allows for freedom and choice	Any solution is possible
Facilitation: guides families through proper practices	More knowledgeable experts can serve as references to the team
Materials, set-up, and framing: offers an expandable experience	Infinite possible resources and solutions within the constraints

3.4 Summary

Thus, the theoretical framework in this dissertation provides (1) grounding for the various dimensions of learning that play into the Ingenuity Lab experience – social, physical, and personal, (2) a pedagogical philosophy of learning through constructing and designing as well as guidance on the design of these types of learning environments that considers the various dimensions of learning and balances the trade-off between open-ended and structured environments, and (3) a hypothesis that both the designers and visitors will engage in engineering through constructionist, mutual learning that bridges the gap between their perceived and actual practices of engineering and leads to agency and identity as engineers. This theoretical framework and the collective cases from the data will inform my design guidelines for these informal engineering experiences.

Chapter 4

Methodology: Ethnographic Case Studies and Quasi-Experimental Comparative Case Studies

4.1 Setting and Subjects

The context of this study is the design and implementation of activities for an engineering design program at a science center – the Ingenuity Lab at the Lawrence Hall of Science. The cross-community design collaborations consisted of informal educators from the Ingenuity Lab, engineering students and their instructor from the University of California, Berkeley, and local engineers from industry (Google and Meyer Sound).

The Ingenuity Lab was an existing program open to the public on a drop-in basis during weekends. The rationale for the program was to build on the popularity of simple construction activities and to provide a more goal-oriented engineering experience. The program provided open-ended and tinkering design challenges. About 800 visitors participated each month, with ages ranging from infant to elderly. The majority of children who visited were between the ages of three and twelve. The program was held in a large classroom space, allowing visitors to come and go as they wished; the average stay time was just over 30 minutes. Each month, an engineering design challenge and theme was presented to visitors, along with appropriate materials. The existing challenges were designed by science center educators, who often adapted previous educational activities. Science center staff, college engineering students, and community volunteers facilitated and guided visitors as they developed solutions to the challenge.

Three of the existing engineering design challenges at the drop-in program were studied along with two new challenges designed by cross-community design collaborations. Each challenge was implemented for one month. The existing traditional challenges studied were Marble Machines, Spinning Tops, and Cars. The two final outcome challenges, Engineer the World and Sound Engineering, were developed with the cross-community design collaborations. Table 4.1 provides descriptions of the challenges.

The two parts of this dissertation focus on 1) the two cross-community design collaborations and 2) the visitors to the Ingenuity Lab. Figure 4.1 shows the overall methods and participants. Part 1 looks at the collaboration model, in particular the processes and roles that the collaborations engaged in via focused ethnographic case studies. Part 2 looks at the impact of the model to determine its success, in particular the visitor experience in the activities, their perceptions of the experience as related to engineering, and their agency in these types of activities. Part 2 studies these visitors through quasi-experimental comparative case studies at the five challenges.

Table 4.1: Descriptions and examples of each challenge. Descriptions modified from the science center website (The Lawrence Hall of Science, 2013).

Challenge	**Description**	**Example**
Marble Machines	Using a pegboard and simple materials like rubber, PVC pipes, funnels, and tubes, design a marble rollercoaster.	
Spinning Tops	Design the longest spinning top by selecting the size of plates, number of plates, and its height. Staff help spin your top with an electronic hand mixer. See how your design compares to others on the data graph.	
Cars	Design, build, and test a robotic LEGO car by putting together the right gears and wheels and learning how to connect the microcontroller to the appropriate sensors and actuators. Time your car on the racetrack.	

Engineer the World	Design your own paper prototype for a website or mobile app, then implement it on the computer with help from staff. *This challenge was developed in collaboration with a team of engineering students and practicing engineers from a local software engineering company.*	
Sound Engineering	Create and change sound by making a loudspeaker or instrument using recycled materials, coils of wire, magnets, and rubber bands. Staff assist in testing speakers. *This challenge was developed in collaboration with a team of engineering students and practicing engineers from a local audio engineering company.*	

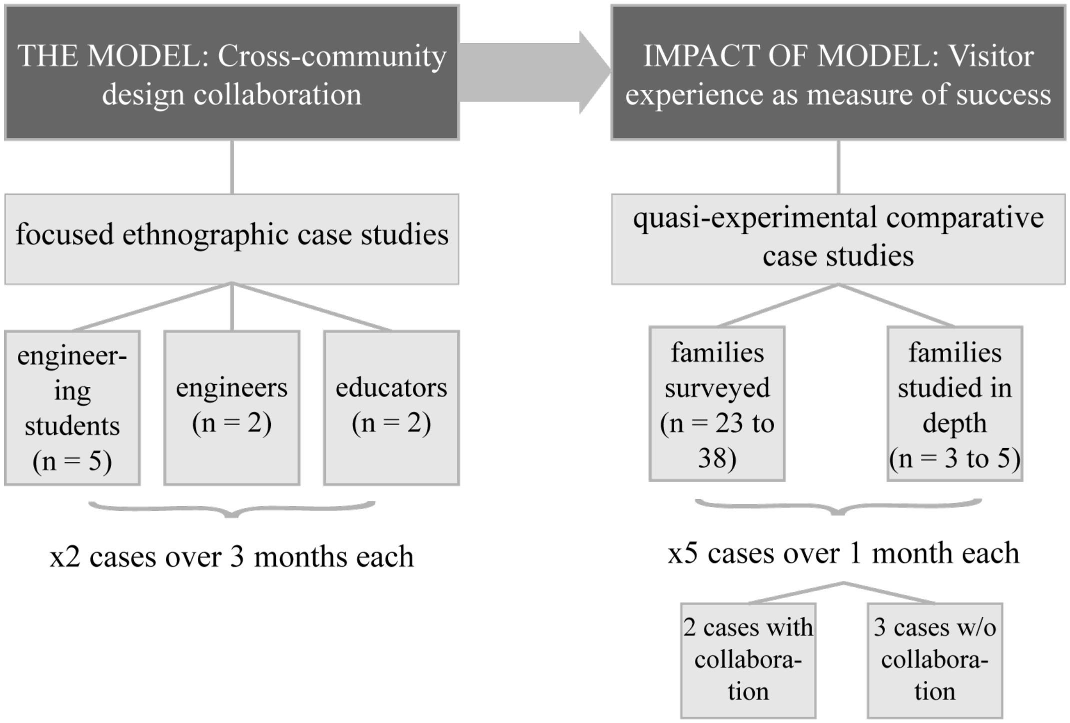


Figure 4.1: Methods to evaluate research questions and participants. The cross-community collaborations were studied through two separate focused ethnographic case studies, each collaboration consisting of five engineering students, two engineers, and two educators (one of which was myself as participant-observer). The visitor experience was studied across five challenges for five months through quasi-experimental comparative case studies; each case was a challenge implemented for one month. Two cases were the two challenges developed by the cross-community collaborations and three cases were existing traditional challenges without the collaborations. Each case consisted of surveys of 23-38 family groups and in-depth observations and interviews with 3-5 family groups.

4.1.1 Design Collaborations

Two cross-community design collaborations were facilitated as part of this research. Because the existing challenges were created by science center educators with no science or engineering background, I aimed to further include experts in these areas to create design challenges with strong connections to science and engineering. Each of the two collaborations included practicing industry engineers and technical professionals as well as undergraduate engineering students from UC Berkeley. The rationale for including the engineering students was to involve them in a real-world project in which they carry out the design processes that the full-time practicing professionals could not fully dedicate time towards.

The first collaboration created Engineer the World and consisted of two engineers from the software engineering company Google, five sophomore-year students (one bioengineering, one electrical engineering and computer science, one civil and environmental engineering, one industrial engineering and operations research, and one physics), and two educators from the science center, including myself as an embedded education researcher. Three out of the five students had previously volunteered in the Ingenuity Lab, while the program was new to the other two students and the two engineers. The students were recruited through an engineering education outreach club, participating voluntarily through the outreach club and for course credit during Fall 2012. The engineers were recruited through my personal contacts. The roles and expectations were communicated in initial recruitment documents, with emphasis on time commitment, purpose, and tasks. An initial meeting with all members introduced the projects and expectations.

The second collaboration created the Sound Engineering challenge and consisted of an engineer and a technical support specialist from the sound reinforcement engineering company Meyer Sound, five junior and senior-year engineering students (three mechanical engineering, one bioengineering, and one electrical engineering and computer science), and two educators (the engineering design instructor and myself as the embedded education researcher). The three junior students had taken a previous course that included a project at the Ingenuity Lab and its related exhibits, while none of the other students and engineers had any prior experience with the science center. The students individually selected this collaboration for their product development engineering course project during Spring 2013. The engineer and technical support specialist were recruited through Meyer Sound, an existing partner of the Lawrence Hall of Science. The roles and expectations for these two were communicated in an initial recruitment document, with emphasis on time commitment, purpose, and tasks. The roles and expectations for the students were mostly set by the course but also in initial recruitment documents.

All participants volunteered and agreed to participate, and no incentive was provided to any of the participants from the research, course, or employers. Both collaborations met five times over a semester (3 months) in 1-3 hour blocks (see Figures 4.2-4.3). Students carried out the bulk of the project with engineers serving as mentors and educators serving as advisors. The engineers gave feedback and suggestions to students during the whole-group meetings. The student teams also met separately in many additional meetings during the design process, further carrying out brainstorming and prototyping independently of the engineers and educators. The first two months consisted of background research, brainstorming, and prototyping while the last month was implementation of the challenge in the Ingenuity Lab, including refinement through feedback. I used the collaboration meetings to perform formative assessments during the design processes to help structure the overall process. The Sound Engineering collaboration's process was further structured by the associated course, with deadlines and constraints built in for the students' course project.

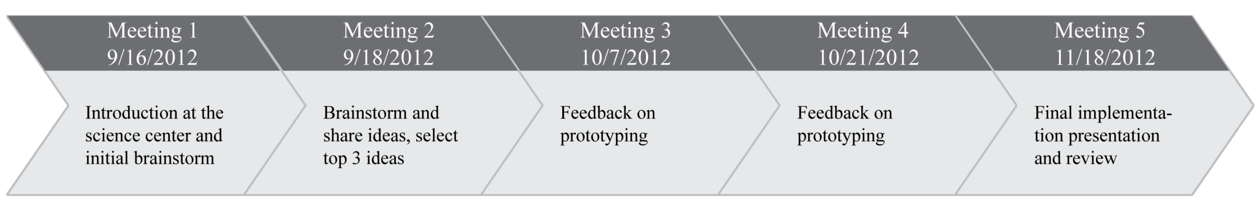


Figure 4.2: Meetings during the design process for the Engineer the World collaboration, spanning September – November 2012, with implementation during November. This process was structured by the science center educators.

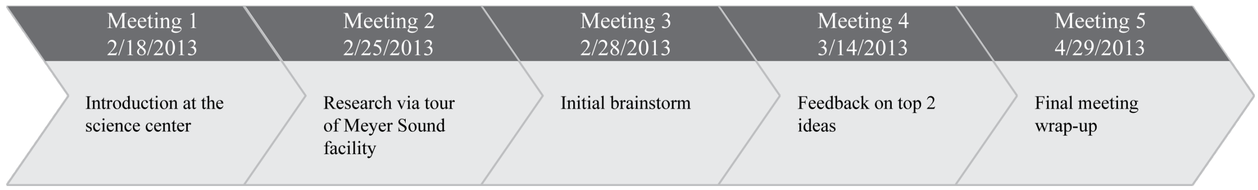


Figure 4.3: Meetings during the design process for the Sound Engineering collaboration, spanning February – April 2013, with implementation during April. Unlike the Engineer the World collaboration, this collaboration's process was heavily structured by the product development engineering course, with concept selection and prototyping happening individually as assignments for the course without the industry engineers.

4.1.2 Visitors

Over 4,412 visitors came to the Ingenuity Lab during these five months studied. A survey was available on a computer near the exit, and visitor groups were asked to take the survey as they left. A total of 148 visitor groups responded to the surveys during the five challenges, with an average of 1.5 children per group and children's ages ranging from 1-17 at an average age of 7. Surveys were usually answered by parents, with frequent input from children in the group. See Table 4.2 for a breakdown of survey responses and visitor attendance by challenge.

Table 4.2: Survey responses from visitor groups and attendance (counting all individuals per group), by challenge.

Challenge	**Survey responses (average of 1.5 children per group)**	**Average age of children in surveys**	**Total visitors**	**Average visitors per day**
Marble Machines	35	6.8 ± 3.4	1073	107
Spinning Tops	23	6.3 ± 2.4	891	111
Cars	38	7.2 ± 2.5	951	119
Engineer the World	26	7.2 ± 2.4	611	72
Sound Engineering	26	7.5 ± 2.9	886	98

Visitors to the museum who came during observation periods were asked to participate in the videotaped observation and interview as they walked in (and they were excluded from the survey part of the study). Most visitors (> 90%) agreed to participate, totaling 22 groups across the five challenges included in this dissertation. The only selection criterion was that there should be at least one child who was greater than 6 years old such that such that the child could speak better about his/her experience for a productive interview. All observed groups included at least one child and one adult (see Table 4.3).

Table 4.3: Participants and stay-time for each in-depth video observation. Primary active participants are bolded. Average stay-time for all visitors for the month of the challenge is included. (y.o. = years old; M = male and F = female.)

	Family 1	Family 2	Family 3	Family 4	Family 5
Marble Machines Average stay-time: 29 ± 10 minutes	**8 y.o. M** & adult M	**8 y.o. F** & adult F	**10 y.o. M**, **14 y.o. M**, & adult F	**6 y.o. F**, **9 y.o. F**, adult F, & adult F	**9 y.o. M**, 3 younger siblings, adult F, & adult M
	39 min.	16 min.	78 min.	75 min.	18 min.
Spinning Tops Average stay-time: 26 ± 10 minutes	**10 y.o. M** & adult F	6 y.o. F, **8 y.o. F**, & adult F	**6 y.o. M**, **7 y.o. F**, adult F, & adult F	**6 y.o. M**, toddler F, & adult F	
	43 min.	24 min.	33 min.	44 min.	
Cars Average stay-time: 53 ± 13 minutes	**8 y.o. M** & adult F	**9 y.o. F** & adult M	5 y.o. F, **7 y.o. M**, baby F, adult M, & adult F	**9 y.o. F**, **14 y.o. M**, adult M, & adult F	5 y.o. M, **9 y.o M**, adult M, & adult F
	61 min.	13 min.	42 min.	22 min.	65 min.
Engineer the World Average stay-time: 33 ± 13 minutes	**8 y.o. M**, **11 y.o. F**, & adult M	**7 y.o. M**, **8 y.o. F**, & adult F	**12 y.o. M**, **12 y.o. M**, & adult F		
	60 min.	41 min.	45 min.		
Sound Engineering Average stay-time: 31 ± 14 minutes	**11 y.o. M**, **13 y.o. F**, & adult F	**6 y.o. M**, **8 y.o. M**, **adult M**, & adult F	**8 y.o. F**, **13 y.o. F**, adult M, & adult F	4 y.o. M, 6 y.o. M, **7 y.o. M**, adult M, & adult F	**7 y.o. M**, **9 y.o. M**, adult M, adult M, adult F, & adult F
	57 min.	35 min.	13 min.	20 min.	33 min.

4.2 Data Collection Methods and Instruments

My theoretical framework informs what kinds of data to collect on the learners — the students, engineers, educators, and visitors. In particular, the framework highlights the various contexts that influence learning: social, physical, and personal. For the social context, I collected observations of these participants' engagement with others via video and field notes. For the physical context, I noted the layout and objects in the physical spaces where the collaborative design processes occurred and the Ingenuity Lab space where visitors engaged, as well as background information on the spaces via work samples, artifacts, video, and field notes. Finally, for the personal context, I collected qualitative pre- and post- surveys and interviews with participants to understand their personal history, perceptions, and aspirations.

4.2.1 Design Collaborations

To evaluate the first research question – *How do the diverse collaboration members — college engineering students, industry engineers, and informal science educators — negotiate the ideation process, and what are their roles and contributions in designing engineering learning programs through a cross-community collaboration?* – I implemented focused ethnographic case studies of the cross-community design collaboration model as a participant-observer (Kluckhohn, 1940) as one of the educators in Figure 4.1.

As participant-observer, I helped coordinate communication between the students and industry engineers, mostly organizing meetings and setting agenda for the meetings. For example, for the introduction meeting, my agenda items included an introduction to the Ingenuity Lab and Lawrence Hall of Science, engagement in the Ingenuity Lab challenge for that month, discussing criteria for a "good" challenge, and brainstorming possible challenge ideas based on the engineers' work. Other meetings were determined more formatively by the ongoing design process. I also acted as a client as an educator from the Lawrence Hall of Science, but as a researcher, I was very hands-off in the idea development and selection phases and more involved during implementation. I aimed to understand the collaborations' design processes and their perceptions of learning and engineering.

Data collected include qualitative pre-surveys, post-surveys, observations of design meetings via video-recording and field notes, and work samples, including design notebooks, prototyping results, assignments, and final presentations and write-ups. Videotaped observations were conducted during all meetings of the engineering students and engineers, and artifacts pertaining to the design processes were collected from the students after the collaboration.

To measure progress on the dimensions of learning and engineering, I created pre- and post-survey instruments. Surveys were given at the beginning of and after the collaboration experience. Pre- and post-survey questions are included in Table 4.4. Pre- and post-survey questions covered participants' background, perceptions of engineering, expectations and contributions, reflections on implementation with visitors, and perceived impact of the experience on themselves as engineers. Collaboration members were also given an opportunity to express any other comments or questions anonymously in the surveys. The post-survey further included questions to rank agreement with various statements on the impact of the experience (Table 4.5).

Table 4.4: Pre- and post- survey open-ended questions given to the design collaboration members, including the engineering students, industry engineers, and informal educators. Similar questions to assess pre- to post- changes are included in the same row.

Pre-survey	Post-survey
	• What was valuable about this Ingenuity Lab collaboration design experience?
• What do you hope to contribute?	• How did you contribute to the challenge design?
• What do you hope to get out of this project?	• Did the collaboration design experience meet your expectations? Why or why not?
• How do you define engineering?	• How do you define engineering? How do you think your challenge teaches engineering?
• What are attributes and characteristics of a good engineer?	• What characteristics and attributes define a good engineer?
• What are your strengths and weaknesses as an engineer?	• What are your strengths and weaknesses as an engineer?
• Please list your criteria for a good engineering learning activity.	• Please list your criteria for a good engineering learning activity.
• What about engineering do you think engineers should teach to visitors (children and adults) who aren't familiar with engineering?	• What do you think visitors have learned from your challenge?
	• Describe a typical successful interaction at your Ingenuity Lab challenge. What methods have you found to be most effective in engaging with visitors?
	• What have you found most interesting about how visitors engage with your challenge?
	• What are the key elements to your Ingenuity Lab challenge?
• Briefly describe your engineering experiences.	
• Why did you decide to be an engineer?	
	• How could this collaboration experience be improved?
• Any other comments/questions?	• Any other comments?

Table 4.5: Post-survey Likert questions, ranking from 1-5 from disagree to agree, given to design collaboration members.

Please indicate your agreement with the following statements. This experience has ...
... improved my communication skills.
... increased my sense of responsibility as an engineer.
... improved my confidence in engineering.
... increased my awareness of community needs.
... shown me I can make a difference as an engineer.
... deepened my understanding of engineering.

4.2.2 Visitors

To evaluate the second research question – *What is the potential impact of the cross-community collaboration model on visitor experience and persistence in engineering?* – I implemented quasi-experimental comparative case studies to measure the impact of the collaboration model by comparing the cases without the collaboration to the cases with the collaboration (see Figure 4.1).

Five different challenges, each implemented for a month, were studied; three challenges were traditional challenges without the collaboration and two represented the practices of industry engineers as the outcome of the collaborations (see Table 4.1). Because this naturalistic study sought to understand visitors in the environment, minimal disturbance to the experience was desired and data collection methods reflect this (and thus, no randomized controlled trials; Allen, 2002); visitors were approached as they entered the Ingenuity Lab space and asked to participate. Those who did not participate in the observation and interview study were asked to take a short post-survey anonymously on a computer near the exit after their engagement in the Ingenuity Lab.

Data collected consist of qualitative post-surveys with 148 groups as well as in-depth observations (videotaped and with field notes) and pre- and post-interviews with 22 groups totaling 34 active participants for all five challenges. Time and attendance of all visitors to the challenge were also recorded with attendance samples taken once every five minutes during open hours in order to determine the total attendance and average duration of visits.

The short post-survey was developed in collaboration with the Ingenuity Lab staff (see Table 4.6). Questions covered age, visitors' Ingenuity Lab experience, their perceptions of and identity with engineering, past and future experiences with similar activities, as well as general comments.

Table 4.6: Survey questions that visitors anonymously responded to on a computer after the activity experience and as they exited the Lab.

Post-survey questions
How old is/are your child(ren)?
What was your favorite part of the Ingenuity Lab today?
What surprised you about this challenge?
What did you do today that made you feel like an engineer?
Have you been to any previous challenges? [If so, what?]
Have you ever done a project similar to the one you just did? If so, what?
Do you hope to continue doing activities like these? If so, how?
Would you consider becoming a museum member based on your experience in the Ingenuity Lab?
What did you NOT like? Any other suggestions/comments/concerns?

Naturalistic observations and interviews were carried out with 22 groups. Observation field notes covered demographics including age and gender, engagement, affect, engineering behaviors, design iterations, and social interactions. The entire duration of each group's activities was video-recorded. The camera followed the active participant(s). Some groups included multiple participants who actively engaged in the activity and created designs, so the video included all participants simultaneously, if possible. Interviews were conducted with the active participants before and after participation in the challenge while in the Ingenuity Lab. Pre- and post-interviews covered visitors' understanding of and identity with engineering, and post-interviews further probed visitors' design processes, their perception of the challenge's relation to the real world, and past and future experiences with similar activities. See Appendix A for the full interview protocol.

4.3 Analysis and Interpretation Methods

I interpreted the data from both activities through my hypothesis from my theoretical framework (see Figure 3.2 in Chapter 3, Section 3.3). Particularly, I inferred (a) the positive memory of participants' experience as correlated with interest in engineering activities; (b) the context of the experience as indicative of the potential content of knowledge gained; (c) the constructive doing of the experience as fostering agency and identity in engineering; and (d) participants' affect in the experience as indication of their perception, attitude, and disposition towards engineering. By characterizing the nature of the cross-community design processes, I develop empirically-grounded hypotheses about important elements of the design processes that serve as guidelines to foster productive visitor experiences.

4.3.1 Design Collaborations

I studied the roles of the collaboration participants with respect to their perceptions of engineering (pre-surveys and post-surveys), their values and how the values are negotiated in the design process (observations and surveys), and their design goals (observations, surveys, and work samples). I also tracked the groups' ideation trajectories and how they translate industry engineers' authentic practices into accessible engineering practices for visitors. Specifically, I looked at whose ideas are adopted (observations and work samples), how the ideas evolve (observations and work samples), and occasions of debate about ideas (observations).

For analysis, data from artifacts were triangulated with the survey and meeting data to create progressions of the design processes, focusing on the development of criteria for the design challenges, the ideation processes, design goals and objectives, and the collaborations' beliefs about engineering and learning. Progressions were developed on matrices, with each column chronologically representing a meeting or entry in the design notebook. Each column includes an overall meeting summary, criteria, goals, ideas, and contributions separated by each member. The progressions highlight how each member participated with respect to the ideas contributed and how criteria for the activities were developed across time. Natural history narratives were developed for each member to understand each of their roles.

The ideas and criteria were thematically extracted from the progressions in an emergent analysis to understand the trajectory and evolution throughout the design processes as well as the participants' roles throughout time. In particular, the ideas were listed chronologically, then the most similar ideas were categorized into 7-8 main themes. These themes were color coded in a chronological display to visualize how the ideas progressed through time in terms of brainstorming, selection, and refinement of ideas. The criteria were similarly analyzed, but with an extra dimension of attributing criteria to individual members; this was represented in a matrix format with each row representing a date and each column representing an individual's contributed criteria for that date. In this way, criteria could be associated with certain chronological events and/or specific individuals. Explicit criteria identified and agreed upon by the whole collaboration were distinguished from implicit criteria that emerged through notes and informal conversations. All these criteria were further used to assess the final design challenges through visitor survey data and observations in order to learn what criteria were and were not ultimately achieved.

4.3.2 Visitors

Data were collected from all five Ingenuity Lab challenges to compare each challenge and find any correlations or patterns between challenges, especially with respect to any differences between the challenges developed with and without the cross-community collaboration. Data include time tracking, survey responses, and observations with interviews. Specifically, I focused on the visitor experience in terms of their perceived experience with engineering design, especially with regards to accessibility and agency (interviews and surveys); attendance to engineering practices (observations, interviews, and surveys); engagement and persistence in the challenges (observations); and potential consequences for long-term interest and sustaining participation (interviews and surveys).

To track the number and duration of visitors with minimal disturbance, a simple one-box model (Jacob, 1999) was implemented (usually used for estimating the lifetime of molecules in a container, with flow in and out). I sampled the number of people in the room at any one time, roughly every five minutes, and noted the number of people who left during these intervals. From that, I took the average number of people at any one time and divided by the rate of visitors leaving to get an estimated average stay time. The total of all the people who left equals the total number of people who came through.

Survey responses were analyzed for age, number of children per group, and whether visitors had been to previous challenges and/or planned to continue similar activities. Qualitative responses to "What surprised you about this challenge?," "What did you do today that made you feel like an engineer?," and general comments were coded in an emergent analysis, with the first pass identifying common themes and the second pass solidifying and condensing the themes into codes. These items were studied to understand how visitors' expectations, experiences, identities, and perceptions of the relation to engineering vary across challenges. General comments were analyzed to identify key aspects of each challenge. Confidence and agency were assessed through visitors' previous and intended future engagement in these types of activities, particularly what they intend to do and how.

The main method for analyzing the observation data was video analysis. Videos were coded for and segmented into engineering design behaviors (see Table 4.7). Three researchers used ELAN[3] to capture the timestamp of start and end times for each behavior and to annotate the behavior along with specific notes about what happened. All three researchers worked individually coding videos, overlapping on five (23% of) videos, one from each challenge that

[3] ELAN is a tool for annotating video and audio resources (Max Planck Institute for Psycholinguistics, 2014).

represented a fairly typical complete interaction. The researchers met weekly after each video was coded to ensure consistency and to refine the behaviors. Discrepancies were resolved through discussion. Percentage agreement on coding the timespans of all behaviors in these videos was 91% (see Appendix B for percentage agreement calculation).

The behaviors in Table 4.7 began as a list adapted from the Museum of Science, Boston's *Engineering is Elementary* Engineering Design Process (Museum of Science, n.d.). As the videos were coded, the three researchers discussed behaviors they observed and the list was refined weekly to identify all prominent engineering behaviors. New behaviors emerged (e.g., *Looks at/compares with other designs*) and other behaviors were combined (e.g., *Manipulates variables to achieve goal* and *Modifies design to make improvements* were combined). These behaviors were further cross-linked with the design activities in Atman et al. (2007), such that comparisons could be made with the expert engineers. These design activites are Identify Need, Problem Definition, Gather Information, Generate Ideas, Modeling, Feasibility Analysis, Evaluation, Decision, Communication, and Implementation (see Table 4.7). Table 4.7 shows how the behaviors follow the same general trend from the stage of (1) Problem Scoping to (2) Developing Alternative Solutions to (3) Project Realization. The last two behaviors in the table are an exception to the order and could be either Problem Scoping or Developing Alternative Solutions, depending on context. The largest difference between the context in this study and that of Atman et al. (1999, 2007) is that the participants here have materials to build and implement designs; Implement was ultimately not included as a design activity for Atman et al.'s participants. Thus, in this study, I place Feasibility Analysis and Evaluation after Implementation, rather than after Modeling as in Atman et al. (1999, 2007).

Drawing from Atman et al. (1999; 2007), timelines highlighting behaviors were developed for each participant. I sought to identify (1) the frequency and duration of behaviors, (2) the number and rate of transitions between behaviors, and (3) the overall pattern and whether it fit the *cascade* pattern of experts identified by Atman et al. (2007; see Figures 2.1-2.2 in Chapter 2, Section 2.1.4). The timeline was triangulated with field notes and interviews that contained further details of the behaviors that could not be identified solely in the videos.

Because the last two behaviors, *Discusses how this activity relates to the real world* and *Looks at/compares with other designs*, can occur anytime throughout the process and are not part of the preserved order of Atman et al.'s (1999, 2007) timelines, I excluded them from the cascade pattern analysis. Using the timelines for all participants across the five challenges, two researchers determined whether a cascade pattern falling from left to right on the timeline was identifiable, independently rating the cascade as high (1), medium (0.5), or low (0) and then discussing to resolve discrepancies. For instance, some confusion arose from timelines with multiple iterations that made the whole timeline look flat; this was resolved by identifying each iteration as a cascade.

Table 4.7: Coded engineering design behaviors and examples as related to design activities. Design activities are Identify Need, Problem Definition, Gather Information, Generate Ideas, Modeling, Feasibility Analysis, Evaluation, Decision, Communication, and Implementation (Atman et al., 1999 and 2007). Atman et al. (1999, 2007) show that expert engineers cascade from (1) Problem Scoping to (2) Developing Alternative Solutions to (3) Project Realization, with small transitions within and between each. (1) Problem Scoping includes Identify Need, Problem Definition, Gather Information; (2) Developing Alternative Solutions includes Generate Ideas, Modeling, Feasibility Analysis, Evaluation; and (3) Project Realization includes Decision, Communication, Implementation. Note that these are visitor groups, so the primary child often interacts with other children and adults in conversations; thus, quotes come from all group members.

Engineering Design Behavior	Examples	Design Activity
Describes/identifies a problem to be solved	Provided with the challenge or describes the challenge; Encounters a problem or obstacle. *"How do you connect this [the gears] so that the wheels go?"*	Identify need/ Problem definition (1)
Expresses a design goal	States a goal or asks how to achieve a goal. *"I wanna make it* really *low."* *"How do you make them into links?"*	Identify need (1)
Considers one or more options for achieving goal	Explanation of what can be done; Describes options for achieving goal. *"So we'll probably have to tape this, or paper clip."* *"You can talk about yourself. You can do things that you like, or where you live, sports you play."*	Gather information (1)/ Generate ideas (2)
Sketches design	Draws design on paper.	Modeling (2)
Explores/selects appropriate materials/tools from available options	Explores, selects, or tinkers with materials; Looks for material; Asks about materials. *"What does this do?"* *"[This] has 10 times as many. Which one do you want to use?"*	Gather information (1)/ Modeling (2)
Makes causal inference/predictions about how design will perform	Traces out a test; Considers how design will perform. *"If it's lighter, will it go faster?"*	Modeling (2)
Builds or modifies design	Builds or constructs object with a purpose; Modifies or adjusts design.	Implementation (3)
Tests design	Tries out design with specific test.	Feasibility analysis (2)
Analyzes what happens and what can be improved from the tests	Discusses what happens during test; Considers options for improvement. *"Oh look, it kinda slows it down, huh?"*	Evaluation (2)/ Decision (3)
Discusses how this activity relates to the real world, engineers, etc.	Makes connections to personal lives or engineering. *"Just like that guitar. Strings, they like to break."*	Gather information (1)/ Evaluation (2)
Looks at/compares with other designs	Checks out designs that other people have made. *"See, mom, look at this one. This chain over here doesn't fall off."*	Gather information (1)/ Generate ideas (2)/ Evaluation (2)

To further understand visitors' behaviors and perceptions, I analyzed each observed visitor's pre- and post-interviews. These interviews were studied to identify visitors' perception of and identity with engineering, confidence and agency in these types of activities, awareness of the activity's relation to the real world, and intentions behind their design processes (see Table 4.8). The responses were analyzed using an emergent, bottom-up analysis, as with the qualitative survey questions. In terms of the perception of engineering, responses to "What do you think engineers do?" were coded for action verbs (do), context (what), and other. Pre- and post-responses to this question were compared for changes. Identity with engineering was classified from responses to "Do you feel like you're an engineer?" (pre-interview) and "Do you feel like what you did was engineering?" (post-interview), and visitors' justifications were analyzed. Visitors' confidence and agency were interpreted through analysis of visitors' previous similar experiences and visitors' intentions to continue these activities. Their awareness of the real world relation was extracted from whether they identified the relation and what product or experience they identified. Finally, to further understand visitors' processes, responses to "How did you choose what to make?" and "What were you trying to do with it?" were coded to identify the various approaches to design as well as visitors' design goals that were not explicitly stated during the observation.

Table 4.8: Dimensions of analysis of interview data to understand visitor behavior and perceptions, with interview questions and specific areas that were coded in an emergent analysis.

Dimensions	Interview Questions	Coded For
Perception of Engineering	(Pre/Post) What do you think engineers do?	Action verbs (do) Context (what) Other
Identity with Engineering	(Pre) Do you feel like you're an engineer?	Yes/No
	(Post) Do you feel like what you did was engineering?	Yes/No Justifications: What they did that was engineering
Confidence and Agency in Engineering	(Post) Have you done something like this before? How is it similar?	Yes/No Justifications: What they did that was similar
	(Post) Do you think you'll continue doing activities like this? What would you want to do?	Yes/No Future activities
Awareness of Activity's Real-World Connection	(Post) How is what you did here related to the real world or anything you've seen before?	Yes/No awareness What product or experience is related
Intentions Behind Design Process	(Post) How did you choose what to make? Did you look at other designs/projects?	Reason for design Yes/No looking at other designs Purpose of looking at other designs
	(Post) What were you trying to do with it [design goal]? Did it do what you wanted it to do?	Goal Yes/No in achieving goal

4.4 Limitations

Limitations to these methods include problems associated with participant-observer studies as well as naturalistic studies. As participant-observer, I had the potential to influence the study and change the natural history of the collaboration. Specifically, I encountered logistical problems around scheduling and ensuring the collaboration followed through to fulfill the needs of the Lawrence Hall of Science. In terms of resolving these issues, some meetings just had to be scheduled due to time constraints and exclude some members (and some excluded from this study who were from the industry side eventually dropped out). I also had to take some initiative in getting logistical items done to ensure the Lawrence Hall of Science's needs were met. I did attempt to be a more passive observer to not influence the study by not responding to questions with how things should be done; however, because of my more authoritative coaching role and my position at the Lawrence Hall of Science, the student teams tended to be more easily persuaded by my suggestions. To not persuade the students, I attempted to give facts (e.g., things made by visitors are not taken home) rather than interpretations (e.g., taking things home is not important). On the other hand, I did not observe some of the behind-the-scenes meetings that the students independently initiated and therefore missed some moments in the design processes.

Furthermore, the collaboration members in this study were all self-selected; thus, the results may be more positive than if the members were randomly selected. However, many of these students who self-selected had previous engagement with the Ingenuity Lab and consequently chose to return and deepen their experience: three of the students from Engineer the World had previously volunteered with the Ingenuity Lab and three of the students from Sound Engineering had participated as a requirement for a prior mandatory course. Thus, ultimately, change will not necessarily be apparent from before to after the experience..

In terms of the naturalistic studies of the visitors, visitors entering the space are self-selected in choosing to come to the Lawrence Hall of Science and the Ingenuity Lab. Visitors also chose whether or not to participate in the study. Thus, some excluded are families who would not or could not come to the Lawrence Hall of Science, and there may be some who came and chose to participate only because of the positive experience and some who did not participate because of their time or logistical constraints; the visitors selected were therefore not randomly selected. The survey response rate is low and the number of observed visitors is small; therefore, the data is not necessarily representative of the larger population. However, there are at least 20 surveys per challenge, thus mitigating any outliers, and in-depth observations help elucidate what these typical experiences are like. I do note that during observations, videos could not always capture all participants simultaneously; thus, some gaps in observation are noted if there is more than one primary participant per group. Furthermore, as a naturalistic observation, no probing was implemented and behaviors were observed while non-spoken thoughts could not be observed.

4.5 Summary

By observing, interviewing, and surveying the visitors in the natural environment of the Ingenuity Lab, I aim to better understand how they engage and engineer in this type of open-ended tinkering environment. By observing and surveying the two cross-community collaborations, I hope to understand the roles of the various members and how they contribute to the process of creating and implementing Ingenuity Lab challenges. I compare the visitor experiences in three traditional Ingenuity Lab challenges with the visitor experiences in the collaborations' two newly created Ingenuity Lab challenges and synthesize the findings into guidelines for these engineering spaces.

Chapter 5

Three Traditional Challenges: Ingenuity Lab Visitor Experience without the Cross-Community Collaboration

This chapter provides a baseline analysis of the Ingenuity Lab visitor experience at three traditional engineering design challenges. These challenges are Marble Machines, Spinning Tops, and Cars, which had each been implemented in the lab for at least one month prior to the months studied. Table 5.1 provides an overview of the features of each challenge. Survey, observation, and interview findings from visitors at these three challenges are discussed in this chapter. I aim to develop a deeper understanding of what visitors are doing in these challenges in order to determine how to create learning opportunities in these environments as accessible pathways towards engineering. Particularly, on the surface, visitors may seem to be just playing and having fun, but I anticipate that there may be deliberate choices in their actions and design processes. I also anticipate that visitors may not identify as engineers in these challenges without cross-community collaborations. However, I believe the visitors would gain agency and confidence in these types of activities, without necessarily identifying it as engineering.

I discover that families overall enjoy the experience and find the Ingenuity Lab challenges accessible, especially noting the persistence of their children in getting their designs to "work," the simplicity of the materials, and the collaboration and sharing that occurs. Observations indicate that visitors primarily engage in building, and surveys confirm that most visitors identify this as the primary activity of engineering. Visitors were not observed to relate their experiences to engineering in the real world (see Table 5.1 for examples), and thus do not connect their perception of formal engineering with their actual experiences in engineering. The next chapters explore the cross-community design processes and their impact on the Ingenuity Lab visitor experience to determine whether visitors to the cross-community challenges identify further important activities of engineering such as problem identification, information gathering, considering various ideas, and assessing ideas, and relate their experiences to engineering in the real world.

Table 5.1: The features of the three challenges without cross-community collaboration, specifically the goals, materials, set-up, ability to compare designs, familiarity, real world connections, and science and engineering concepts.

	Marble Machines	**Spinning Tops**	**Cars**
Goal	To make the marble travel through the design without falling off.	To get the top to spin for as long as possible.	To design and build a motorized car that runs on its own.
Materials	Pegboards (3 ½ feet tall), pegs, tubes, rubber strips, funnels, half pipes, wooden blocks, containers, clothespins, string, tape, bells, marbles.	Paper plates of three sizes, pencils, rubber bands, wooden spools, crayons.	LEGOs, LEGO gears, PicoCricket microcontrollers, cables.

Set-up	Eight pegboards were placed upright in a circle in the center open area of the room, with both sides of the pegboards available for designs to be built onto. Materials were placed in the middle of the circle of pegboards. All materials, including marbles, could be accessed at anytime, and visitors tested their designs by dropping marbles whenever they wanted.	The materials were placed at the center of the room, and visitors took materials to tables around the room to design and build their tops. Testing took place at the front of the room, where facilitators helped spin and time the tops on the ground using kitchen hand mixers.	Visitors received a PicoCricket when they entered the room; LEGO materials were at all tables throughout the room. A track was set up for testing the cars on one side of the room along the floor, where facilitators assisted.
Ability to compare designs	Because the eight pegboards were all next to each other, visitors could easily see what other visitors were making or left behind.	There was a graph aggregating the data from visitors throughout the day, plotting time of spin vs. height of plates, with size of plates indicated on each data point; this was projected on a large screen visible to the whole room. A leaderboard of top spin times with height and size of plates was also visible on a board. Visitors could also observe what other visitors were designing in the space.	Visitors could observe what other visitos were designing in the space on the separate tables.
Familiarity	Marbles are a common toy that many children may have played with; the basic building materials also include many toy components that kids may have encountered.	Tops are a common toy. Visitors may also be familiar with other spin toys, spinning mechanisms, or spinning experiences. The materials are also common household materials.	LEGOs are a very common construction toy. However, many visitors had not used the PicoCricket or other electronic components with LEGOs before. Visitors are familiar with vehicles in the real world and as toys.
Real world connections	Engineered products that are related include water slides, roller coasters, rain gutters, storm drains, and pinball machines. Some connections from nature include waterfalls and streams.	Engineered products are spinning toys, rotating mechanisms like blenders, chairs, doors, fans, wheels. Actions include figure skating, gymnastics, and skateboarding spins and tumbles. Connections with nature include tornadoes and whirlpools.	Vehicles, bicycles, clocks.
Science / engineering concepts	Energy (potential and kinetic), stability, construction, experimentation.	Stability, rotational motion, angular momentum, experimentation.	Friction, gearing, motors, construction, experimentation.

5.1 Engineering Perception and Identity

Visitors' engineering perception and identity were explored to determine if they felt engineering was accessible in terms of the formal perception and the actual practice of engineering. The survey responses to "What did you do today that made you feel like an engineer?" indicate visitors' perceptions of engineering as related to the challenge; visitors were surprisingly able to connect their experiences to engineering. Surveys were usually answered by parents, with frequent input from children. However, the majority by far (37 of 88 responses; 42%) indicated that building or making made them feel like engineers (see Figure 5.1), a common oversimplified perception of engineering (Cunningham & Lachapelle, 2011). Only one explicitly stated optimizing, while others indicated the content of the challenge (26), refining (8), and creating a working design (6). Survey comments highlighted iteration and refinement (see Table 5.2). Other common responses mentioned problem-solving, science concepts, testing, materials, variables, goals, planning and thinking, ideas, experimenting, recording data, personalization, designing, inventing, creativity, comparing, and tinkering. None discussed teamwork, despite the mention of teamwork and collaboration in response to the other questions. Thus, visitors were able to identify some more accessible and obvious features of engineering.

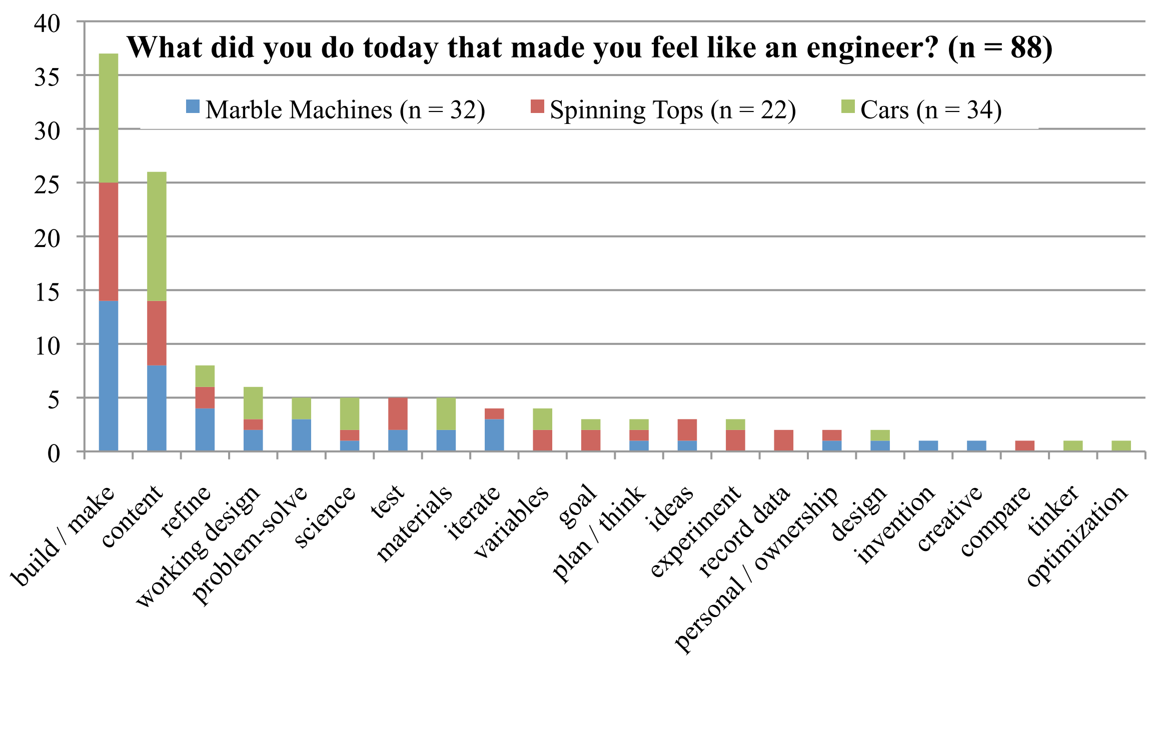


Figure 5.1: Coded survey responses to "What did you do today that made you feel like an engineer?" by challenge.

Each challenge had slightly unique visitor descriptions of engineering. By challenge (Figure 5.1), visitors to the Marble Machines challenge most frequently mentioned iterating, refining, and problem-solving as engineering in the surveys. Visitors encountered many mini-problems that they needed to solve or fix as they tested their marble tracks. Furthermore, these visitors also discussed being creative and inventing as engineering. Only one group mentioned engaging in science concepts. No groups mentioned having a goal or adjusting variables. Visitors to the Spinning Tops challenge most frequently mentioned building or making. However, unlike in the other challenges, visitors doing Spinning Tops pointed out more planning, testing, experimenting, adjusting variables, recording data, and comparing, all science skills that helped visitors interpret data to inform their designs. They also mentioned trying to achieve a goal. Also in contrast to other challenges, no visitors to this challenge mentioned materials or design. Finally, visitors to the Cars challenge most frequently described their engineering behaviors as the content of the challenge itself – building cars. However, many also mentioned refining their solution, creating a working design, understanding the science concepts of gears and drive trains, and selecting appropriate materials. Visitors to Cars most frequently mentioned science concepts.

Table 5.2: Comments highlighting iteration and refinement of designs.

Representative comments
"How well a 3.5 year old could do with trial and error"
"construct, run a trial, then adjust according to results of the trial."
"fixing the machine to make it work"
"I enjoyed watching my children make multiple attempts and not give up."

Consistent with the surveys, visitors who were observed and interviewed most commonly mentioned in pre-interviews that they thought engineers build, make, and create things. In terms of what things are made, visitors most frequently describe structures, vehicles, or machines, representing a very limited set of products produced by engineers. Four of 14 visitors mentioned they didn't know what engineers did, and three stated that engineers drive trains.

In post-interviews, there was no significant change. However, only two visitors continued to state that they didn't know what engineers did and two mentioned that engineers drive trains. Furthermore, fewer visitors described engineering as making structures, vehicles, or machines, and visitors newly mentioned electronics, technology, and materials for a broader set of engineered products. Also, while no visitors previously mentioned optimization, three in the post-interviews described engineering as involving optimization. More visitors also brought up helping people or the world in the post-interview. Thus, changes from pre- to post-interviews suggest that visitors had a slightly broader perception of engineering and were less unsure of what engineers do.

When asked in pre-interviews, "Do you feel like you're an engineer?," six out of the 14 visitors said no and only one said yes. When asked in post-interviews if they felt the activity was engineering, only two out of the 12 respondents said no while six said yes and four said maybe. Of the two who said no, one mentioned that she "didn't build trains" and the other had described engineering as "a little bit of everything." One visitor at Marble Machines brought up materials in stating the reason for why she felt the activity was engineering: "I made something and it was made out of different kinds of materials." Thus, the numbers from pre- to post- were inverted, indicating that the experience at the Ingenuity Lab engaged many who did not previously identify as engineers in what they recognized as an engineering activity. In particular, the physical materials may have played a role in their engagement; I explore this next.

5.2 Visitors Engineering

Visitor observations confirm that most visitors spent most of their time building, reflecting the large proportion of survey responses on how building made them feel like engineers. Timelines of the observations at all three Ingenuity Lab challenges show cascade patterns, with variations of strong and weak cascades within each challenge. The cascade indicates that visitors are acting like expert engineers by progressing from Problem Scoping to Developing Alternative Solutions to Project Realization with transitions within and between each of these stages (Atman et al., 2007; see Figure 2.2 in Chapter 2, Section 2.1.4) and are thus able to successfully monitor their design progress to transition appropriately, rather than just randomly playing. As shown in Figures 5.3-5.5, some timelines also show multiple iterations through multiple cascades, thus confirming visitors' identification of refinement of designs as engineering and showing their persistence, suggesting confidence in these activities. Timelines also show that all visitors who completed the activity tested their designs in order to determine whether their design worked. In particular, visitors spent, by average in all challenges, most of their time in the behaviors *Explores/selects appropriate materials/tools*, *Builds or modifies design*, and *Tests design* (see Figure 5.2). This shows that visitors spent the majority of their time with the physical materials.

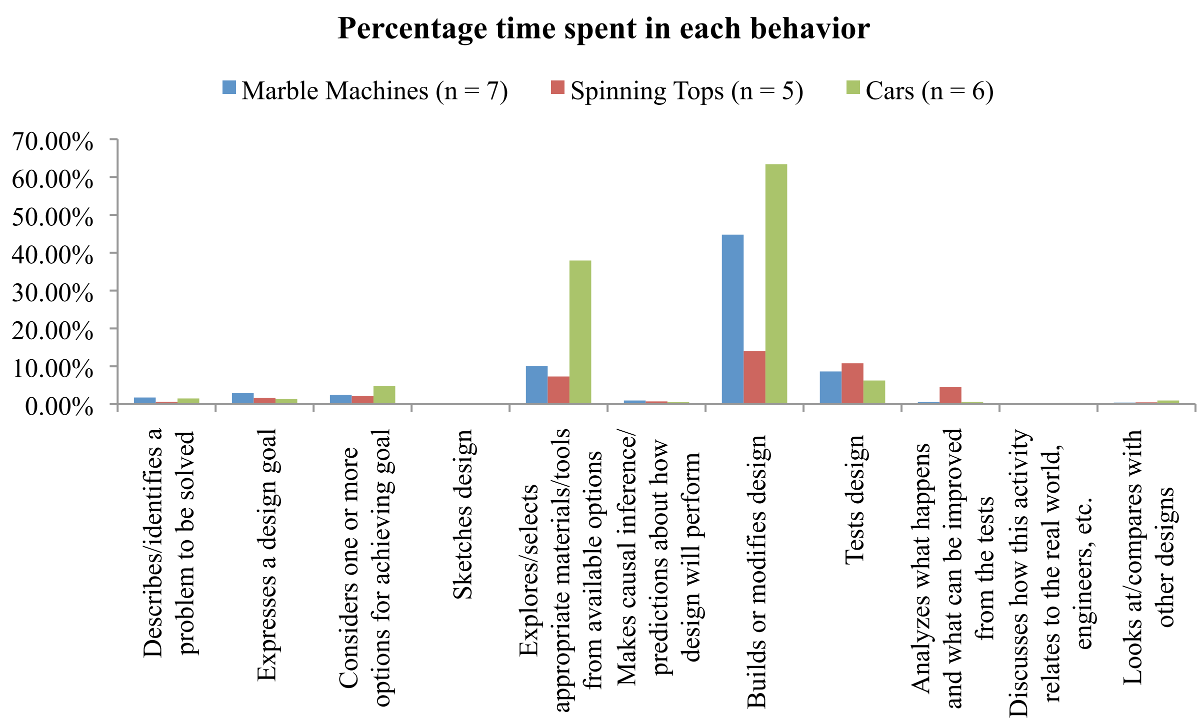


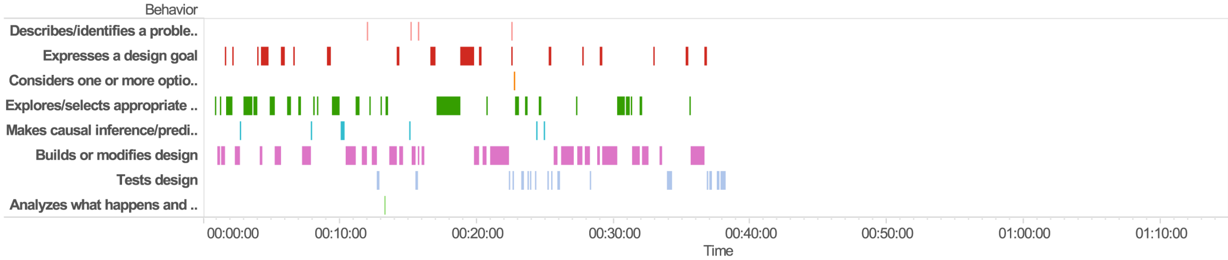
Figure 5.2. The average percentage time spent in each engineering design behavior, by challenge. The three most dominant behaviors for the three challenges are *Explores/selects appropriate materials/tools*, *Builds or modifies design*, and *Tests design*. No visitors engaged in *Sketches design* or *Discusses how this activity relates to the real world, experiences, etc*.

By challenge, Marble Machines timelines (Figure 5.3) loosely show the cascade pattern, with a mean rating of 0.36 on the 0-1 scale for the cascade. The design processes frequently transition among *Explores/selects appropriate materials/tools*, *Builds or modifies design*, and *Tests design* throughout. The majority of time is spent in these behaviors, which, without the problem scoping behaviors, results in a flat pattern, suggesting that visitors are not necessarily planning their designs ahead of time. *Explores/selects appropriate materials/tools* and *Builds or modifies design* occur most frequently here out of all challenges. The behavior *Tests design* occurs early relative to other challenges and also occurs the most frequently out of all challenges at an average of 36 times per visitor, likely due to the ease of testing. Observations show that these visitors had the greatest frequency and percentage time spent in *Describes/identifies a problem to be solved*; this suggests that the design challenge provided opportunities to explore the problem space, with ease of testing and feedback from testing helping to identify problems. Four of seven groups looked at other designs, and no groups discussed the real world relation of the challenge possibly because the challenge materials looked like toys. This is not surprising given that the content of the challenge is more abstractly related to the real world (e.g., rain gutters, roller coasters).

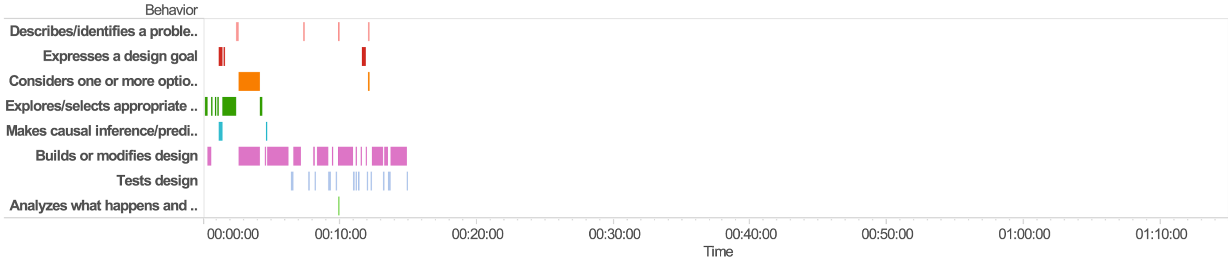
Spinning Tops timelines (Figure 5.4) show behaviors are more spaced out with shorter durations; however, the cascade pattern is fairly obvious with a mean rating of 0.60, indicating that visitors here may be better monitoring their design progress to transition behaviors like experts. *Tests design* occurs less frequently and tends to occur towards the end, but the largest percentage time was spent in this behavior as facilitators helped visitors test for the longest spin time. Compared to other challenges, these visitors spent a greater percentage of time and more frequently exhibited *Analyzes what happens and what can be improved*, almost with the same frequency as *Tests design*; this means that on average, they discussed the results almost after every test, possibly because of the help of the facilitator. The ratio of *Tests design* to *Analyzes what happens and what can be improved* was the greatest of all challenges. Only one participant was observed to look at another design, and no one discussed the relationship to the real world, probably because the abstract concept of spin is more difficult to connect in this context.

Cars timelines (Figure 5.5) portray a fairly flat pattern and have the lowest mean rating of 0.25 for the cascade, with almost a reverse cascade in some instances (e.g., Cars 27 and 29 in Figure 5.5). Visitors in Cars spent the most time of all challenges transitioning between *Explores/selects appropriate materials/tools* (38% of time) and *Builds or modifies design* (63% of time), with some exhibiting short bursts of *Tests design* throughout while others tested towards the end. These simple LEGO bricks provided a variety of ways to build, and thus may have provoked this tinkering pattern of transitioning between exploring and building. *Describes/identifies a problem*, *Expresses a design goal*, and *Considers options for achieving goal* are more prevalent in the latter half of timelines, emerging from the exploratory behaviors and contributing to the reverse cascade pattern. Two participants who did not finish only exhibited *Explores/selects appropriate materials/tools* and *Builds or modifies design*, giving up before they could test and obtain feedback from the test. Two groups compared designs and three groups discussed the activity's relation to the real world.

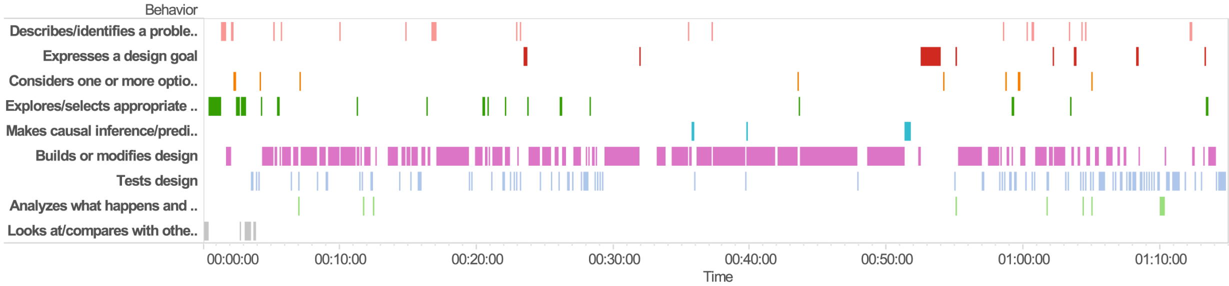
Marble Machines 4 (cascade = 0)



Marble Machines 7 (cascade = 0.5)



Marble Machines 10-1 (cascade = 0.5)



Marble Machines 10-2 (cascade = 0.5)

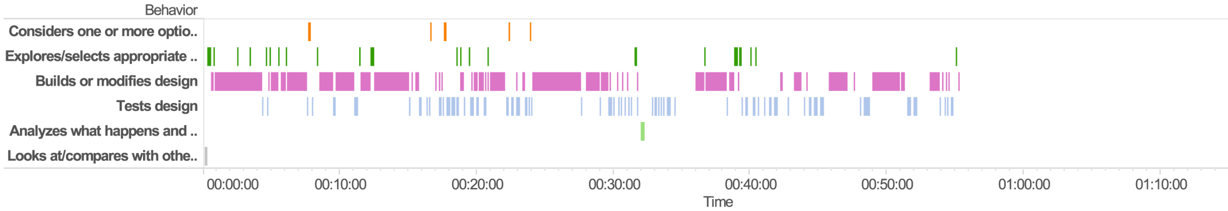


Figure 5.3: Timelines of participants at Marble Machines. The average cascade rating for these timelines is 0.36, with individual ratings labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

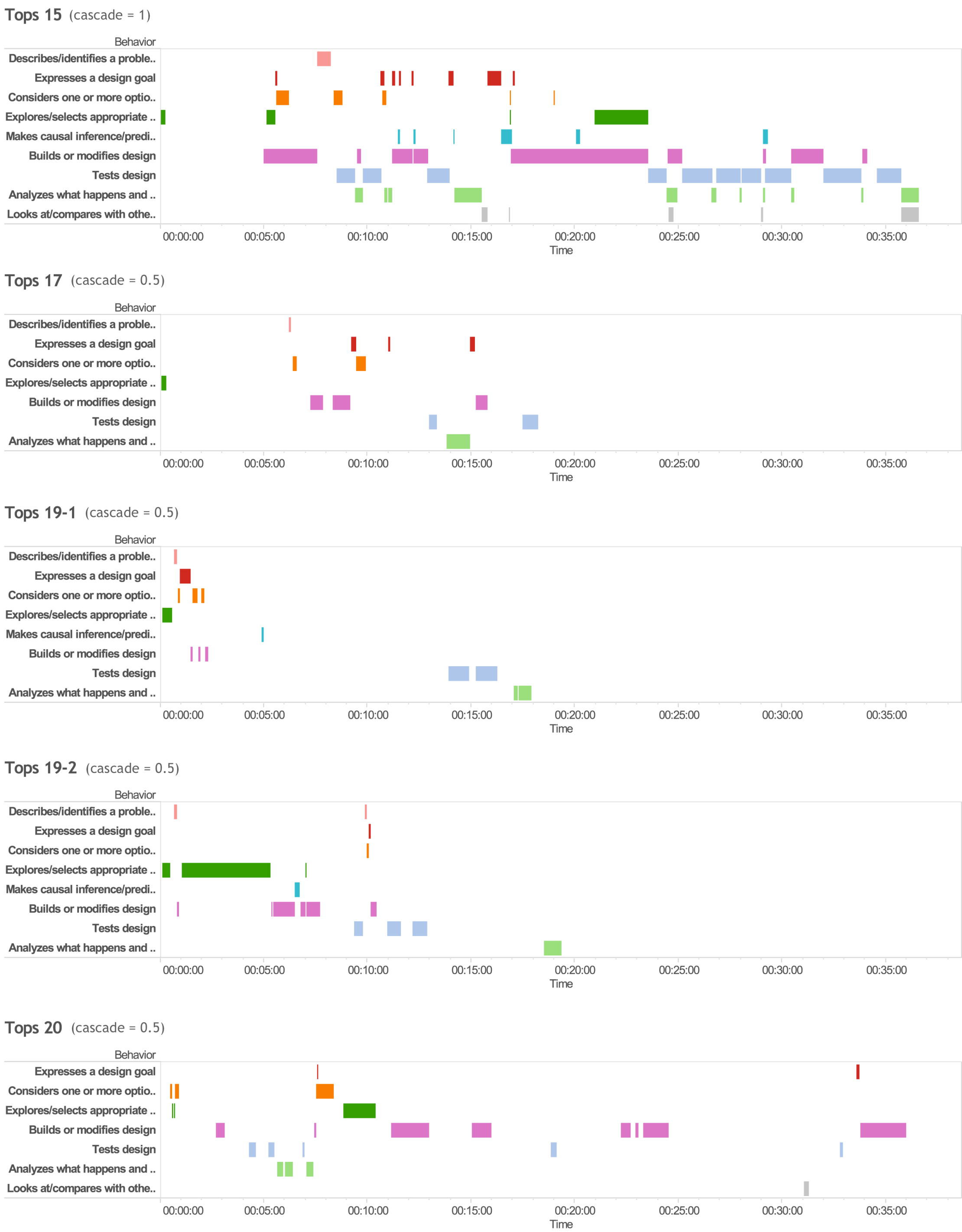


Figure 5.4: Timelines of participants at Spinning Tops. The average cascade rating for these timelines is 0.60, with individual ratings labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

Figure 5.5: Timelines of participants at Cars. The average cascade rating for these timelines is the lowest of all challenges at 0.25. Individual cascade ratings are labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

5.2.1 Interviews

Analysis of the interviews provides further insight into the visitors' design processes. When asked how they chose their design, visitors in these three challenges most frequently mentioned a goal (8 of 13 groups); two of five groups at Marble Machines and three of four at Spinning Tops also mentioned specific materials, two at Spinning Tops described using data from previous visitors' designs, and two at Marble Machines stated that they "just came up" with an idea. Because of the observed dominant time spent with physical materials, interview responses indicate that visitors may have come up with their ideas and goals through the exploration of materials, through which they deepened their understanding of the affordances and constraints of the material and thus the design space. Further, by setting their own goals, the visitors were very persistent to get their designs to achieve their goal and continuously refined their designs, as indicated by the multiple cascades and as mentioned in surveys. This persistence also demonstrates visitors' confidence and the accessibility of the challenges as visitors felt they could achieve the goals.

Because of the presence of other visitors in the space working on their own designs, observed visitors were asked whether they looked at these other designs. Four of five groups at Marble Machines indicated that they looked at other designs, while half from Spinning Tops (2 of 4) and from Cars (2 of 4) stated so. Marble Machines and Spinning Tops visitors mentioned getting ideas about materials from these other designs, while Marble Machines and Cars visitors mentioned gaining ideas for designs and wanting to modify or improve upon the other designs. One visitor from Cars described his decision to not look at other designs: "Just trying to create my own design, nothing like anybody else."

In terms of the goals, similar goals emerged within each challenge, despite the lack of a clear, explicit goal for the space. Furthermore, these goals were rarely stated during the experience, but visitors were easily able to describe their goal when prompted afterwards. For instance, Marble Machines visitors mentioned trying to get the marble to follow a path without falling, get the marble to the finish, and achieve special tricks such as following loops or making sounds. Spinning Tops visitors wanted to have their tops spin for a long time and achieve stability; the goal was more explicit here as there was a leaderboard of top spin times that many visitors aimed to surpass. Finally, most Cars visitors mentioned that they wanted their car to be able to run, and some had more advanced goals of making the car run fast or climb an incline.

By engaging in multiple iterations to achieve their goals, many visitors (7 of 13) across the challenges also spontaneously identified that they wanted to achieve the "best" or better solution, indicating their awareness of an optimal rather than a single correct solution. Specifically, visitors recognized the need to modify or adjust their designs as well as trade-offs and specific problems that prevented them from achieving their goals.

Interestingly, none of the visitors from Cars stated that they achieved their goals, despite the popularity of the challenge by attendance and the significantly longer average stay-time of 53 minutes (compared to 25 and 28 minutes for the other two challenges). In particular, many visitors in Cars identified specific trade-offs or problems with their solution, possibly because none achieved their goals.

When asked if what they did was related to anything from the real world, less than half of visitors in post-interviews identified related products or experiences. Two out of five (40%) Marble Machines visitors identified roller coasters, storm drains, water slides, and ramps. One out of four (25%) Spinning Tops visitors identified spinning tops toys. And, two out of four (50%) Cars visitors mentioned previous science camps and competitions. No observed visitors explicitly discussed the real world relation while engaging in the challenge.

5.3 Surprise at the Accessibility of Engineering: Gaining Confidence and Agency

Visitor comments indicated several characteristics of the program that they appreciated and enjoyed (see Figure 5.6), particularly the hands-on interaction, feedback, and guidance. These three components contributed to the accessibility of the challenge, providing opportunities for the visitors to gain confidence and agency in these activities. Figure 5.6 shows that the most frequently discussed aspect was the hands-on component that involved building, making, designing, and creating something that works as intended (22 of 96 responses). Other appreciated aspects included feedback determining how well the design works through testing, experimenting, and competing (20); challenging or difficult parts of the activity that visitors persisted in overcoming (17); and how much fun they had (9). An important characteristic mentioned across all three challenges is the guidance through facilitation (9). Because the program was so open-ended, the facilitator interaction was extremely important in shaping the experience. One comment below describes the facilitator interactions:

> *"The college age docents that assisted the kids with the experiments were awesome. [T]hey treated the children with genuine respect, as though challenging the little scientists within."*

Further characteristics mentioned were the creative aspects, the simplicity and easiness of the challenge, an explicit goal, the variety and simplicity of the materials, and the open-ended self-discovery and exploratory pace as well as the multiple solutions that could be achieved. Recognition of the successes was also important for visitors; one visitor said their favorite part was "*Getting on the leaderboard - for both kids!*" See Figure 5.6 for the list of characteristics.

Finally, an important connection established in the comments, but only in one visitor group, was the connection to the visitors' personal lives: "*it was great for us to recognize the importance of the height. we have a lot of spins toy at home. but we have never been curious of the secret for spinning. Thanks!*"

In terms of experiences resulting from these challenges' characteristics, survey responses showed that parents were most surprised at their children's abilities to sustain interest, successfully create a working design (after many iterations), and learn concepts. Many were also surprised at the simplicity of the challenge and materials. Respondents further indicated surprise at the multiple paths and solutions to achieve the challenge and their accessibility. Teamwork was a final surprise; parents liked that their children worked collaboratively with each other and with the whole family across generations. Parents also appreciated that the children had to share materials and ideas. See Table 5.3 for quotes.

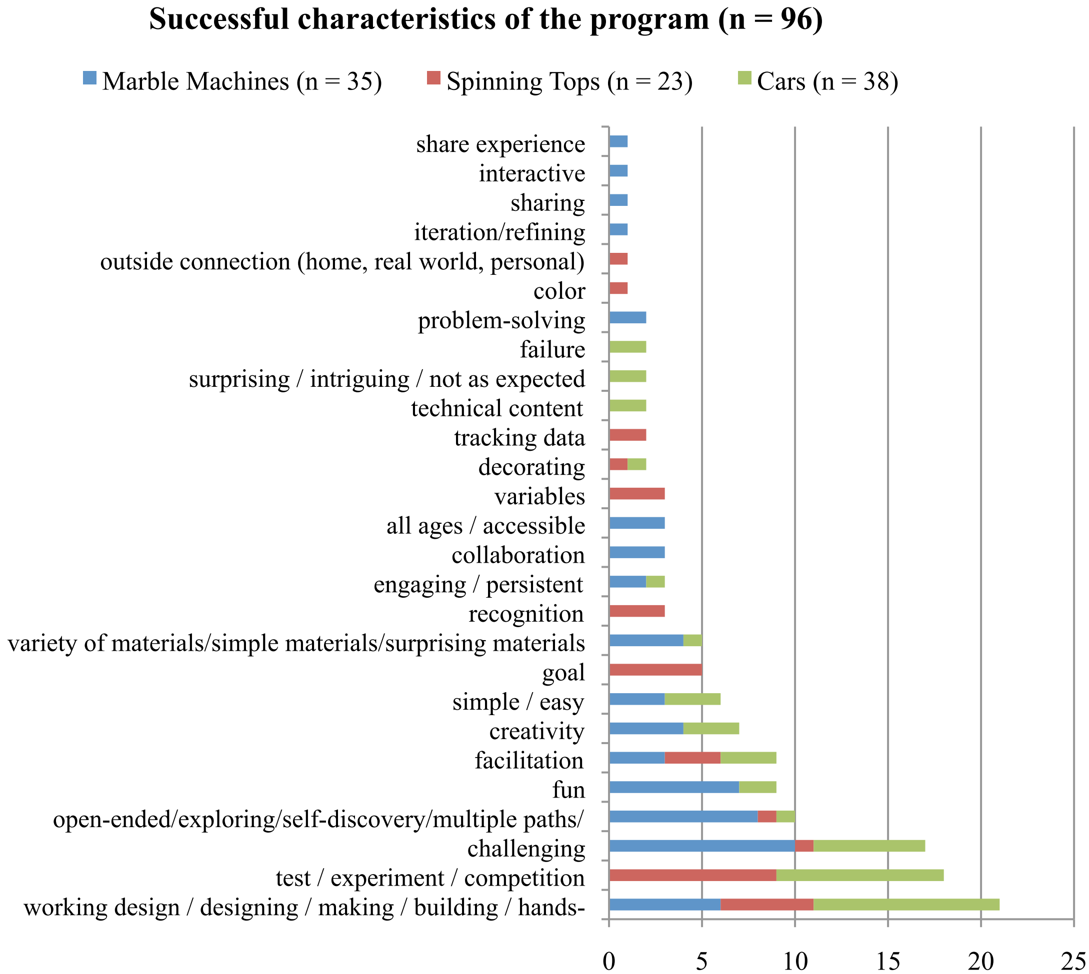


Figure 5.6: Successful characteristics of the program that visitors mentioned in the survey responses.

By challenge, visitors indicated that Marble Machines was very challenging, but fun. They enjoyed the simple materials as well as the self-discovery, self-paced, and open-ended, yet accessible, problem-solving of the challenge. The children especially persisted in the challenge through problem-solving in small iterations. Spinning Tops was most unique in its more established data collection and projection by graphing the duration of the spin versus the plate size and height; visitors appreciated this, noting the use of the graph to inform the design and recognize their design results. Finally, Cars was frequently discussed as a hands-on activity in which visitors were most surprised at their ability to get the car to work. They also mentioned the encounters with failure in this challenge; however, they approached the failure as an opportunity to problem-solve.

Table 5.3: Quotes of visitors' surprise about the activities.

	Representative comments
Agency and persistence to make something "work"	*"kids stayed very focused"*
	"my six year old is better at it than i am"
	"That the kids could be creative, curious and problem solve"
	"kids kept working they were extremely engaged"
	"Entering data was great -- really captured the 7 year old, who kept trying to improve his time."
	"[…] you could actually make a working top."
	"[…] the cars were simpler to make than i expected."
	"How innovative kids can be on their own without adult help."
	"[Our favorite part was] seeing our vehicles fail."
	"our girls were able to stick with it with just a little help"
Simplicity of materials and challenge	*"even though it was simple but it still took a little bit of effort"*
	"Variety of materials"
	"materials that i would not expect to be used for the challenge were available"
	"lots of fun materials. "
	"The creativity of objects to design the marble maze"
	"The mixer!"
Accessible, multiple paths and solutions	*"the open-ended structure"*
	"The marble tracks are fun and there are so many ways to build them"
	"interactive, self pace, self discovery - then photo at the end."
	"there were so many different ways of doing things"
	"Total freedom to use anything."
	"easy for all ages."
	"free discovery/exploration"
Teamwork	*"interaction with the kids and getting them to think it through"*
	"forcing my child to share"
	"working all together"
	"work together to make somethin"

The surveys, observations, and interviews show that the large majority of children and parents identified engaging in the Ingenuity Lab as a positive experience. Of particular interest is that the parents indicated in surveys that they were surprised at the accessibility of the challenges and their children's persistence in refining their designs to get it to "work" without giving up. The observations and interviews demonstrate that children were extremely persistent in trying to achieve their goals, spending a large amount of time building, testing, and refining with the physical materials; the social and physical factors, in particular the other visitors, facilitators, and materials, may have fostered the persistence and long stay-times, leading to potential gains in confidence and agency. With these positive experiences, both the children and parents further identified the activities as engineering in their survey and interview responses. The next section discusses findings on the visitors' previous and future engagement with such engineering activities to determine whether the positive experiences may encourage further engineering experiences.

5.3.1 Continuing the Experience

To identify if visitors are returning to the Ingenuity Lab (thus implying they previously had a positive experience that brought them back) and how the experience may be affecting them, post-surveys asked visitors if they had previously attended any Ingenuity Lab challenges and if so, which challenges they attended. Survey responses show that 73% of groups (n = 77) had not previously been to any challenges. Of the 21 returning groups, 19 indicated how many challenges they had been to; two had been to five previous challenges while nine returned after only one challenge (Figure 5.7).

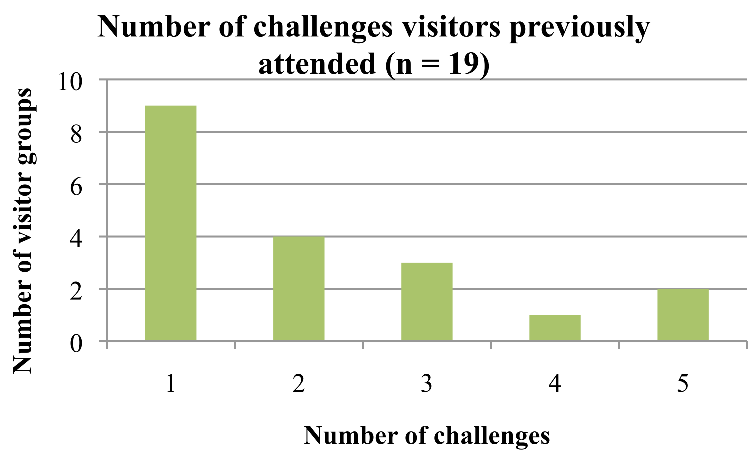


Figure 5.7: The number of challenges returning visitors previously attended, according to survey responses.

When asked about the specific challenge, most visitors had never been involved with activities like the design challenge prior to their experience at the Ingenuity Lab. Surveys indicate that 40 out of 62, or 65%, said they had not done anything like this before. Even more (56 of 77, or 73%) of surveyed visitors had not previously been to any Ingenuity Lab challenges. On the other hand, almost all visitors (51 of 54, or 94%) said that they would continue doing similar activities, with fifteen saying that they would come back to the Ingenuity Lab, and ten saying that they would do these activities at home with their children. Furthermore, survey responses indicate that only five visitor groups would not purchase a museum membership because of the Ingenuity Lab, with two mentioning that they were not local but would "definitely" become members if they were. Overall, visitors indicate positive experiences with a desire to return, if they were not already returning visitors.

Interviewed visitors responded similarly about their past and future experiences with these types of activities. Over half of these visitors (8 of 15) stated that they had not done something like this before, but all stated that they would continue to do these kinds of activities afterwards.

Visitors mentioned that in the future, they would like to do something similar (either improve upon their designs or have different constraints or materials), do something different, or come back. Interestingly, in post-interviews, these visitors identified a very broad range of activities that they had previously done or wanted to do that was similar to the Ingenuity Lab challenges, mentioning things like making "spy gadgets," food, and videos, suggesting a broader interpretation of engineering than building structures.

Thus, almost all visitors indicated that they would like to continue these types of activities in the future, in addition to identifying the Ingenuity Lab experience as positive and related to engineering. The desire to continue suggests that the positive experience in actual engineering practices may have not only added value to these activities, but further confirms that it may have increased confidence and agency in engineering. For example, one 11-year-old male at Marble Machines mentioned that the activity "built confidence, helps [me] understand engineering better." A parent of 8- and 10-year-olds at Cars noted: "[O]ur girls were able to stick with it with just a little help." One 8-year-old female at Spinning Tops mentioned the value of engineering at the Ingenuity Lab: "I was making something that could be used instead of playing on the computer or watching TV."

Further, not only did the children enjoy the experience and gain confidence by participating in the Ingenuity Lab challenges, but the parents also enjoyed seeing their children persist, important as parents often are the decision-makers for their children. One parent of 6- and 7-year-olds at Spinning Tops stated: "This is the first time my children have been challenged in this way!" and "I just wish science was incorporated into school - it seems like there is nothing left but reading, writing, and math." Further, because the Ingenuity Lab challenges engaged children in collaborative experiences with the entire family or group, parents were able to work together with their children so that they were not just encouraging the children, but learning with them. As described before, surveys show that parents are inspired to come back to the space and continue to do these activities with their kids at home. Parent involvement and encouragement is very important in fostering what is accepted or routine for children (Barron et al., 2009; Zimmerman, Perin, & Bell, 2010; Astor-Jack et al., 2007); thus, the Ingenuity Lab promotes engineering as an accepted and encouraged activity for the whole family, increasing the likelihood for the family to continue these activities in the future.

5.4 Discussion

Overall, families were very satisfied with the program. The Ingenuity Lab was a new experience for most visitors, and most observed visitors did not identify as engineers before the experience. Surprisingly, many identified the Ingenuity Lab challenges as engineering afterwards and most indicated that they wanted to continue such experiences. Thus, despite the lack of experience in these types of engineering activities, almost all visitors stated their desire to continue engineering, indicating their agency and confidence.

Results suggest that visitors wanted to continue because they found the experience surprisingly accessible, appreciating the variety of paths and solutions, the hands-on experience of building and feedback from testing with physical materials and solutions, and the guidance through facilitation. They found that all ages and backgrounds, including adults, could actively participate. Parents were very surprised that anyone can engineer; their children were able to learn technical concepts, design, and persist in building things "that work." Parents were surprised at the simplicity of the materials. Many parents hoped to pursue such activities by collecting similar materials for home and returning to the Ingenuity Lab. The regularly returning visitors and long stay times also portrayed the success of the program.

The largest surprise among families was parents' and children's new confidence in and agency to do engineering. Across the challenges, families engaged in and recognized their own engineering behaviors (though mostly building), gaining confidence and agency by doing. Families collaborated across generations and appreciated the opportunity to work together, finding their own path and own solution to the challenge. Key to their experience was learning to iterate and refine without giving up. In particular, children had goals that they most commonly described as the reason behind their design decisions. These implicit goals emerged through exploration with materials, and visitors often stated that they "just came up" with the goal or idea while messing around. Children were excited to get their design to "work"; the satisfaction of achieving the challenge empowered them to do engineering, and as exemplified by their long stay times and multiple iterations, they persisted without giving up.

Timelines show that many visitors exhibited a cascade pattern like expert engineers (Atman et al., 2007), suggesting that they are doing more than just playing and are able to self-monitor their design progress like experts to engage in appropriate design steps. Many even exhibited repeating cascades, indicating the multiple iterations of their designs.

However, unlike the experts, the visitors here spent less time problem scoping and more time in the physical: exploring materials, building, and testing, which are the top three behaviors by time spent for all. The increase in mention of materials in post-interviews corroborates data from observations. Also unique from the expert engineers, visitors looked at other designs for inspiration and ideas, explaining that they gained ideas for materials, wanted to build and improve upon these designs, or sought to make something different from the existing designs. The physical activities and the exploration of existing designs provided a critical means for visitors to identify problems and goals and gain inspiration differently than the experts (Atman et al., 2007). Tinkering with materials exposed them to the materials as constraints and potentials, with goals and ideas emerging from the process. Children utilized information from existing designs in the space, often engaging in conversation with others and asking about the materials, designs, and examples.

Thus, these visitors spent a lot of time exploring materials as a way to gather information and identify problems that influenced their designs. Furthermore, like experts, they transitioned frequently between the behaviors of problem identification and modeling or building in a reflective conversation (Schön, 1992) that co-evolved their understanding of the problem and the solution (Adams, 2001). In other words, they transitioned between exploring materials, building, and testing as a form of transitioning between information gathering and concept generation that experts engage in (Ennis & Gyeszly, 1991; Atman et al., 2007).

The social and physical characteristics of the learning environment led to varying engineering design behaviors among the challenges. Social aspects included the other designs, facilitators, family members, and other visitors while physical aspects included the materials and set-up. The Ingenuity Lab environment engaged visitors in getting their design to "work" for very long times with an average of 44 minutes per group (as compared to an average museum exhibit stay time of one to three minutes (Diamond, 1986; Randol, 2005)). All challenges had similar social and physical characteristics that visitors appreciated, though each characteristic was present in each challenge in varying degrees.

Marble Machines engaged visitors in a very open-ended and self-paced exploratory challenge in which visitors encountered many mini-problems, and thus, continually refined and iterated their designs in small increments through problem-solving. Marble Machines timelines show visitors were engaged in frequent testing throughout most of the process because the design could be tested by dropping a marble at any time. They also engaged in exploring materials the most frequently out of all challenges, going back and forth among selecting new materials, building, and testing. Visitors were very persistent in getting their design to work. Because the challenge was so open to personalization, visitors found this to be most accessible.

Spinning Tops, through its unique data graphing and sharing component, engaged visitors in persisting to achieve the goal of the longest spin time. Visitors also really valued the recognition of their design on the graph and on the leaderboard. Timelines show that Spinning Tops visitors almost regularly analyzed their design after each test, often with the graph, possibly due to the facilitation of all tests by staff or volunteers. They spent the greatest percentage of time analyzing their design compared to the other challenges. Furthermore, in using the graph to inform their own design, visitors recognized many science skills that they linked to engineering skills – planning, testing, adjusting variables, experimenting, recording data, and comparing.

Cars allowed visitors to successfully create their own working designs, a huge surprise for visitors who thought the activity would be too complex and difficult. Cars visitors were observed most greatly by time to explore materials and build since the building process was much more complex than other challenges. Visitors in the Cars challenge further mentioned science of the car's mechanisms they learned in order to design and build a working car.

Interestingly, Cars timelines demonstrate an anomaly of a reverse cascade and have the lowest mean cascade score. None of these observed participants reported that they achieved their goals even though the average stay-time was longest of all challenges. The unfamiliar materials and context – microcontrollers and gearing – prompted many visitors to begin transitioning between *Explores/selects appropriate materials/tools* and *Builds or modifies design*, then *Describes/Identifies problem* emerged through this process, thus producing a reverse-looking cascade. Furthermore, the persistence in exploration and aiming to get the car to "run" is intriguing in face of the failure to achieve their goals. Surveys indicate that visitors understood failure as a method of learning rather than as a result of their inability. Cars also included the only visitors who stopped before completing at least one iteration. Thus, the context of the challenge may have fostered extreme forms of participation: long and persistent participation or short and incomplete participation. With regards to the persistence, the multiple iterations and feedback from testing may have provided small steps of success that further encouraged visitors. The presence of other similar visitors with working designs may also have made them feel that success was possible. Deeper exploration of these visitors' processes can provide insight into these visitors' tremendous persistence.

Despite the success of the Ingenuity Lab to engage visitors in accessible engineering and to increase agency and confidence, visitors still had difficulty connecting their actions to their personal lives and to engineering in the real world. No observed visitor discussed the activity's relation to the real world, and only 38% of 13 interviewed visitor groups were able to identify relations when prompted. Thus, there was a gap between their perception of formal engineering and the actual practice of engineering in the Ingenuity Lab. Furthermore, visitors were still observed to primarily engage in exploring materials and building, and predominantly identified engineering as building. Thus, more can be done to engage visitors in ways such that they can understand the challenges' real world relation and significance to engineering as well as develop broader engineering behaviors beyond building, such as problem scoping and identification, making predictions, and analyzing solutions. In Chapters 6-7, I explore the engagement of practicing engineers and engineering students in the design of Ingenuity Lab challenges to determine whether these goals are achieved in the resulting challenges.

Chapter 6

Cross-Community Design: Two Cases

In this chapter, I describe the results from the two cross-community collaborations' design processes. The first cross-community collaboration involved students from an engineering outreach club, industry engineers from Google, and museum educators that created the Engineer the World challenge. The second cross-community collaboration involved students from a product development course, industry engineers from Meyer Sound, a museum educator, and the course instructor that created the Sound Engineering challenge. I detail the collaborations' goals, objectives, and criteria; the ideation processes; and the various roles of the members to understand how they produced the final design challenges. I also analyze the pre- and post-survey responses of all collaboration members with respect to their perceptions of learning, engineering, and the collaboration experience to determine how the experience may have impacted them and how their perceptions may have influenced the designs.

6.1 Design Processes: Interdisciplinarity Contributes Accessibility and Authenticity

Bronstein's (2003) interdisciplinary collaboration model offers five components that lead to the success of multidisciplinary collaborations: interdependence, newly created professional activities, flexibility, collective ownership of goals, and reflection on process. For the two collaborations in this dissertation, I look at how these components play out with respect to the overall design process. In particular, I focus on the ideation process and criteria developed as well as the collaborators' perceptions of engineering and learning. By the context of the collaboration, I note that interdependence is set up with the unique expertise of the college students, industry engineers, and educators that make up the collaboration and newly created professional activities is set up with the goal to develop a new engineering design challenge for the Ingenuity Lab. I intend to analyze the collaborations' design processes to determine how flexibility, collective ownership of goals, and reflection on process occur.

6.1.1 Objectives

The collaborations needed to establish a clear set of objectives, reflecting collective ownership of goals, in order to successfully work together. I analyze the collaboration meetings and documents and consider the whole progression of events to determine if and how this collective ownership was established.

To determine commitment to the goals, I looked at the participation level of the collaborators. Tables 6.1-6.2 below provide overviews of the design meetings for both collaborations. Not all participants were at every meeting due to scheduling difficulties. The Engineer the World collaboration lacked only one student from the first meeting and another from the second meeting; both of whom caught up with what was missed by talking to me. In the Sound Engineering collaboration, some engineers and students missed meetings throughout the process for scheduling reasons. The only needed information that the engineers missed was the introduction at the Ingenuity Lab, which they researched with URLs of the Ingenuity Lab I provided as well as their own time at the Lawrence Hall of Science. The students met frequently in the course (which met two times a week) as well as outside of the course, easily catching anything that was missed.

Table 6.1: Engineer the World collaboration design activity overview. The students, separately from the rest of the collaboration, prototyped the ideas between Meetings 2 and 3 and Meetings 3 and 4. The students also implemented and refined the challenge with Ingenuity Lab staff during the month of November.

	Summary	Conflicts	Outcome	Participants	Duration
Meeting 1 9/16/2012: Introduction, initial brainstorm	Educator of Ingenuity Lab provided introduction and overview of Ingenuity Lab; engineers and students participated in current Ingenuity Lab challenge; all discussed experiences and observations of the challenge, particularly focusing on criteria for a "good" challenge; engineers provided overview of their work at Google; the entire group brainstormed ideas for challenges	Only one conflict when discussing possible ideas: Educator brought up an idea around filtering with water, a student liked it, but an engineer did not understand and stated that they would "need to stretch far to connect to Google."	A list of criteria for a "good" challenge including emphasis on accessibility and authenticity; many ideas for challenges; all planned to individually brainstorm more ideas before next meeting	4 students (1 student not in attendance); 2 engineers; 2 educators	4 hours at the Hall
Meeting 2 9/18/2012: Brainstorm, idea selection	Each shared 1-3 of their favorite ideas; an educator aggregated these on a spreadsheet, then all members voted 5 ideas each	No conflict, but discussion of feasibility of use of AppInventor for programming Android apps	Top 3 voted ideas (social network profile, mobile app, programming scavenger hunt); these were discussed for the students to prototype with children before the next meeting	4 students (1 student, different from meeting 1, not in attendance); 2 engineers; 2 educators	1 hour videoconf erencing
Meeting 3 10/7/2012: Prototyping results, round 1	Students presented their 3 prototyped ideas and how children engaged with the ideas; discussed refinement suggestions from parents, children, and other collaboration members	No conflict, but engineer suggested, then student embraced, to combine ideas into one challenge	Refined profile idea as more general website idea; combined app idea with website idea; incorporated other refinement suggestions on materials	5 students; 2 engineers; 2 educators	1 hour at the Hall, videoconf erencing with engineers

Meeting 4 10/21/2012: Prototyping results, round 2	Students presented the refined idea of website/app building; educators made suggestions for more improvement with more technology integrated	No conflict, but educators wanted more on guidance and how challenge would be presented, as well as more technology integration	Needed to prototype more; intended to refine with more technical elements on computer (example websites and framework for HTML website)	5 students; 1 engineer; 2 educators	1 hour at the Hall, videoconferencing with engineer and an educator
Meeting 5 11/18/2012: Final presentation	Students discussed the final idea that was implemented and how visitors engaged in the challenge	No conflict	Students were proud and "thought it was pretty cool," felt the challenge "follows the mission of LHS"; engineers were impressed at "iteration speed" and how the challenge "support[ed] different ages"	5 students; 2 engineers; 2 educators	1 hour at the Hall

Table 6.2: Sound Engineering collaboration design activity overview. The students, separately from the rest of the collaboration, developed a mission statement, developed user needs, and brainstormed ideas before Meeting 3. The students also prototyped between Meetings 4 and 5 and implemented and refined the challenge with Ingenuity Lab staff during the month of April.

	Summary	Conflicts	Outcome	Participants	Duration
Meeting 0 2/12/2013: Course project team launch	Student team was put together for class; engineer and Meyer Sound communications director joined for launch; engineer introduced his loudspeaker idea	No conflict	Students met each other as well as 2 from Meyer Sound and 1 educator (the other educator was the instructor for the course); engineer suggested loudspeaker idea	5 students; 1 engineer; 1 Meyer Sound communications director; 2 educators	1.5 hours at UC Berkeley
Meeting 1 2/18/2013: Introduction to Ingenuity Lab	Educator of Ingenuity Lab provided introduction and overview of Ingenuity Lab; students participated in current Ingenuity Lab challenge; all discussed experiences and observations of the challenge, particularly focusing on criteria for a "good" challenge	No conflict; students ask about any problems with "copying" among visitors and educator lets them discuss for themselves	Beginning set of criteria for "good" challenge, including modularity	5 students; 1 educator	2 hours at the Hall

Meeting 2 2/25/2013: Research on Meyer Sound	Engineer gave students and educator a tour of the Meyer Sound facilities, including their research, manufacturing, and completed products	No conflict	Students learned about the variety of Meyer Sound products and services, as well as some of the manufacturing and engineering processes	5 students; 1 engineer; 1 educator	1.5 hours at Meyer Sound
Meeting 3 2/28/2013: Brainstorm	Students presented their list of user needs/criteria; the entire group brainstormed ideas for challenges	No conflict; 1 engineer suggests focusing topic and starting simple; engineer also asks about learning interaction and value of memory, take-home object, dimensions of interaction	Many ideas for challenges	3 students; 2 engineers; 1 educator	1 hour at Meyer Sound
Meeting 4 3/14/2013: Feedback on top ideas	Students presented their top 2 ideas and how they wanted to combine the ideas; engineers provided suggestions for implementation	No conflict; educator questions feasibility of making instrument of varying frequencies with just rubberbands and household containers	Suggestions on materials for refining top 2 ideas (loudspeaker and instrument) from engineers; top 2 ideas were combined into one challenge	3 students; 3 engineers; 1 educator	1 hour phone call
Meeting 5 4/29/2013: Wrap-up	All discussed thoughts and feedback on the challenge, how challenge was received by visitors and ways to improve challenge; engineers discussed loudspeaker industry	No conflict, but discussion of whether a clean environment or cluttered environment was better	Students felt proud and they especially liked their project in comparison to others in the course; one student said "[This is] one of the best projects I've done at Cal"; students incorporated engineers' thoughts on loudspeaker industry into final presentation	5 students; 2 engineers; 1 educator	1 hour at Meyer Sound and phone call with 1 student

6.1.1.1 Engineer the World: Show What Engineering Is and "Engineering is for Everyone"

For the first collaboration that created Engineer the World, the objectives were established in the very first introduction meeting, initially asserted by the educators. The first meeting consisted of a short presentation by the museum educator on the Ingenuity Lab and its goals, along with the opportunity for discussion and questions (see Table 6.1). This educator stated that she wanted to "make explicit connections between the actions of participants and the work of professional engineers" in the program (authenticity) while the other educator stated that she wanted to "show that engineering is for everyone" (accessibility). After the presentation, the students and engineers participated in the current engineering design challenge for that month during the Ingenuity Lab's public open hours, followed by a discussion facilitated by one of the educators. The students and engineers named criteria for a "good" challenge based on their own experiences and observations of other visitors in the Ingenuity Lab. One educator continued to emphasize her goal to make the challenge accessible, especially to all ages and genders, with contributions from the entire group during the extended discussion on how to make engineering accessible without losing authenticity. For instance, the educator asked whether a young child who was just decorating rather than trying to achieve the challenge was learning anything, and a student replied that the child would still have "exposure" to the ideas while an engineer suggested that it could be a "positive motivator" because he/she would still be contributing to the project. Another student suggested accommodating different age groups by having the same challenge, "but tweak it a little bit to push their limits." An engineer mentioned, "The goal could be the kid should be able to do the whole thing himself." The engineer further mentioned that the challenge "needs to relate to kids in daily lives" to attract girls. Thus, the students and the engineers embraced the concept of accessibility, contributing many ideas for making the challenge accessible to all ages and genders. The educator further guided the collaboration to achieve engineering authenticity; the final portion of that meeting ended with the engineers' descriptions of their professional work and an initial group brainstorm of potential design challenges representing those practices.

The final meeting for this collaboration consisted of a short presentation by the students on their complete challenge followed by a discussion among the whole group. One of the students mentioned that the collaboration achieved accessibility through projecting children's websites on the wall; when other children saw these websites, they got more "enthusiastic because they realized if she can do it, then they can do it as well." Another student nicely summarized the achievement of the initial objectives on making the engineering content authentic:

"One of the things that I realized that was really helpful about this project is teaching them about what engineers really do, the whole design and then [actually] applying their ideas to actually making it happen, and I think we were really able to show that aspect [...] but I think also in engineering in general, regardless if programming is involved, there's always that same process where you have to come up with an idea, and then you have to think about what you do, and then ultimately lead to whatever goal that you want to achieve."

An engineer nodded and responded to the student, "It's a reflection of what actually happens in work life."

The objectives of accessibility and authenticity were initially established by the educators, but the whole collaboration, especially the students, embraced these objectives and emphasized them at this final meeting. Because the educators were the more authoritative figures of the collaboration, the young students and the engineers new to the Hall were more receptive to the goals of the educator; consequently, the students' and engineers' contributions may have been heavily biased by the educators. Furthermore, the accessibility and authenticity objectives were fairly general, and thus still open to interpretation. As a result, the collaboration members had the ability to carry out the design with their own interpretation, which may have strayed from the educators' initial intentions. However, collective ownership of goals was achieved with an initial assertion from the educators that was adopted by the rest of the group, with feedback from the educators throughout the process to ensure their intentions were met.

6.1.1.2 Sound Engineering: Evolved From Passive and Formal to Active, Personal, and Sustainable Learning

The students from the second collaboration that created Sound Engineering had developed a mission statement for their objective, which they collectively approved and submitted four times throughout the course project with feedback from the instructor. The initial mission statement (Table 6.3) portrayed the ultimate challenge as providing a passive one-way engagement for a "young audience": the students' goal was to "demonstrate and disseminate fundamental knowledge of engineering." After the initial user needs research with museum-goers and with the visitors at the Hall, the students refined their mission statement. The mission statement evolved to a more specific, and still one-way, communication of knowledge with a less personal description of the visitors, aiming to create a challenge that "demonstrated the fundamentals of sound engineering to the users." With further user research and prototyping of their idea, the third iteration of the mission statement began to show the students' understanding of learning as more than one-way, including hands-on interaction from the visitors; the students aimed to "design a hands-on engineering challenge" to "inspire users and teach the fundamentals of acoustics." The final mission statement, refined after implementation of the challenge at the Ingenuity Lab, continued this much more active learning interaction of the "hands-on engineering challenge" and also focused more on long-term learning goals in a more personal way to "inspire and teach children" with "sound" as a means, rather than an end-goal, reflecting the goals of the science center.

As can be seen from Table 6.3, their mission statement evolved in three distinct ways. First, it evolved from a more passive one-way to an active two-way engagement of learning, going from "demonstrate" to "inspire" and "teach" with "hands-on." Furthermore, the students' business proposition for the course included adjectives such as "interactive," "fun," "engaging," "active," and "hands-on," which are not captured by the initial goal to "demonstrate." Second, the mission statement initially referred to visitors more formally as a "young audience" and "users" but eventually referred to them in a more personal way as "children." Finally, the learning goal evolved from focus on the end-goal of learning specific concepts towards focus on the learning process for sustained interest. The goal began as disseminating "fundamental knowledge of engineering" which evolved to "fundamentals of sound engineering" then "fundamentals of acoustics," and ultimately evolved to "inspire and teach children through sound" with the content as a means to long-term learning and inspiration. Specifically, during the design process, the students conducted user research by engaging with visitors at the Ingenuity Lab and interviewing visitors of museums to better understand effective learning, sought feedback and contributions from the engineers, and incorporated input from the educators. Thus, through the entire collaborations' design process, the students' understanding of learning evolved productively and influenced the outcome at the Ingenuity Lab with more hands-on and personal learning to inspire children.

Table 6.3: Sound Engineering collaboration's evolving mission statement, as developed by the students for their course. Emphasis added.

2/12/2013	2/26/2013	3/21/2013	5/7/2013
To **demonstrate** and **disseminate fundamental knowledge** of engineering, **through sound** engineering, to a **young audience** and **inspire** them to pursue a STEM field.	A challenge at the Ingenuity Lab in the Lawrence Hall of Science which **demonstrates** the **fundamentals of sound engineering** to the **users**.	To **design** a **hands-on** engineering challenge for the Ingenuity Lab in the Lawrence Hall of Science in order to **inspire users** and **teach** the **fundamentals of acoustics**.	To **design** a **hands-on** engineering challenge for the Lawrence Hall of Science in order to **inspire** and **teach children** through sound

Towards the end of the collaboration, further objectives consider the other stakeholders and sustainability. A uniquely interesting objective from the industry stakeholders showed up in the final meeting with the industry engineers: the students stated in their final presentation that their goal was "to revitalize the dying art form of sound engineering." In the final meeting prior to the presentation, the industry professionals had discussed design in industry and how the loudspeaker industry, as a relatively new and small industry, with its proprietary designs results in a world where "not a lot of people know how to build a loudspeaker." An engineer stated that building loudspeakers is "one of these dying sciences." Thus, the students incorporated this goal of the industry partners into their objectives for a design challenge that engaged children in building loudspeakers. Sustainability was also brought up, influenced by the course lectures. The students thought of sustainability in the sense of sustaining the program financially, environmentally, and educationally: the final presentation included the goals of gaining donors, having visitors return, using materials that are reusable and recyclable, and promoting engineering careers for children. The design process thus shows that the collaboration and outcome were influenced by the students' own research on visitor learning, the engineers' perspectives, and the course lectures.

6.1.2 Criteria

Both collaborations, through their design processes, came up with criteria around what a "good" Ingenuity Lab challenge should be. Analysis of the overall progressions demonstrates that two sets of criteria were formed to achieve the collaborations' objectives – an explicit set and an implicit set. The explicit set emerged when the collaborations explicitly listed the project's needs, which they identified as a group, while the implicit set came about informally through conversations and personal notes (see Appendices C-D).

6.1.2.1 Engineer the World: Accessible and Authentic through Personalization, Creativity, and Facilitation

For Engineer the World, all but five of the 21 explicit and implicit criteria came from the industry engineers and educators (see Table 6.4). All explicit criteria were established in the very first meeting; these did not change throughout the design process, possibly because much of the criteria originated from these more authoritative figures and the overall timeline until implementation was short, less than three months. The museum educator presented an informal list of criteria during the initial part of the first meeting, but in the group discussion of criteria after their participation in the Ingenuity Lab challenge, the engineers contributed many. The educators contributed criteria for accessibility for all ages and genders, showing engineering is for everyone, as well as more pedagogical concerns such as making success attainable through small iterations, building on prior knowledge and interests, extending the activity with a take-home component, and making the activity museum-specific. One engineer from industry discussed criteria from observations of visitors: have a topic that's familiar, display example solutions, offer a decoration component for younger visitors, provide an exciting test for the solution, and have a flexible timescale. Another engineer from industry added from her own experience and passions about engineering education; she suggested the challenge should show that engineering involves helping people and is social, make the challenge personally relatable, and have appropriate guidance. The students each contributed at least one criterion: allow for individual and group work, be open-ended for various paths and solutions, have a variety of materials for creativity, and offer tiered levels of challenges for different ages. See Table 6.4 for the explicit criteria from this collaboration.

Five implicit criteria (also in Table 6.4) appeared in meeting conversations and student notes that were not mentioned during the initial discussion of criteria. These implicit criteria may have developed naturally in the space or were implied by other criteria; thus, these criteria were never explicitly articulated. During the introduction meeting, an educator mentioned that the challenge should be fun and interesting, rewarding, challenging, and based on the design cycle; an engineer also asked about long-term inspiration. The students individually wrote in their notebooks the educator's emphasis on the design-build-test cycle, but this did not appear in the explicit criteria later on. The criteria of fun reappeared during prototyping, when a student noted that the prototype challenge was "somewhat fun." Fun and interesting, rewarding, challenging, and based on the design cycle also reappeared at the end, when the students described the final challenge implementation, noting that they observed that these criteria were achieved. The design-build-test cycle represents the engineering authenticity that the collaboration strived for, and the collaboration noted their observation of visitors engaging in this process.

Overall criteria that appeared most frequently (see Appendix C) involved showing that engineering is for all ages and genders (7 of 9 collaborators mentioned), allowing for creativity and personalization with materials (7 of 9), connecting the challenge to personal and real-world contexts (6 of 9), and providing guidance through facilitation (5 of 9). Thus, the Engineer the World criteria heavily emphasized accessibility, focusing on the learner experience as a mutual experience between the learner, facilitator, and context while aiming to represent the authentic processes of the Google engineers.

Table 6.4: Criteria for engineering design challenges for both collaborations, including criteria both explicitly identified by all members of the collaboration and implicitly identified through informal discussions and personal notes. Parentheses indicate whether an educator (Ed), engineer (Eng), or student (S) contributed the criterion, with some criteria resulting from a combination of multiple contributions.

	Engineer the World	Sound Engineering
Explicit: Initial	• Allow for individual work and collaboration across generations (Ed/S) • Parents have some familiarity with the topic (Eng) • Lots of different outcomes and ways to engage (S) • Have examples for inspiration and allow for cross-pollination (Eng/Ed) • Use materials that allow for personalization, use familiar materials in unfamiliar ways (S) • Offer decorative components for young kids (Eng) • Be museum specific, but also have a take-home component (Ed) • Provide a flexible timescale - allow for many short iterations for improvement, make success attainable (Eng) • Should be exciting to test (Eng) • Show that engineering is broader, not just mechanical (Eng) • Be gender neutral (Ed) • Build on prior knowledge and interests (Ed) • Relate to kids' personal/daily lives (Eng) • Provide tiered levels of challenges for different ages (Ed/S) • Facilitate with varying intensity (S) • Have stations with instructions that are progressively more complex (Eng) • Have instructions to create a toolkit of fundamental elements to build with (Eng)	• Fun and informative (S) • Interactive in a "hands-on" fashion (S) • Allows individual user to create unique solutions (S) • Goal-oriented (S) • Allows user to cycle between testing and tuning their design (S) • Minimal wait time and fast feedback (S) • Applicable for a range of ages (Ed) • Gender neutral activity (Ed) • Rewards teamwork and collaboration (Ed) • Cheap, reusable supplies (S)
Explicit: Final	Same as above	• Fun and informative • Hands-On • Goal-oriented • Iterative Design • Fast Feedback • Allow for creativity • Gender and Age Neutral • Sustainable
Implicit	• Fun/interesting (Ed) • Challenging (Ed) • Rewarding (Ed) • Inspiring (Eng) • Goal/design oriented/challenge to be solved (Ed)	• Simple (S) • Challenging (S) • Rewarding (S) • Adequate materials (Eng) • Relate to personal/real-world (S) • Social (Ed) • Inspiring (S/Eng) • Guidance (S) • Modularized (S) • Unusual/novel (S) • Attractive and dynamic (S) • Take-home (S) • House-hold/familiar materials (S) • Spacious, clean (S/Eng) • Examples (S)

6.1.2.2 Sound Engineering: Accessible, Authentic, and Sustainable

Sound Engineering's criteria came almost exclusively from the students, with engineers pushing for specifications of the criteria; only five of the 25 criteria did not come from students. Explicit criteria, developed and submitted by the students as user needs for their course project, focused on goals of the activity for all stakeholders: visitors, engineers, and the Lawrence Hall of Science. These criteria also included specific methods to achieve authentic engineering experiences and accessible visitor engagement. The final explicit criteria were fun and informative, hands-on, goal-oriented, iterative design, fast feedback, allow for creativity, gender and age neutral, and sustainable (see Table 6.4). The group submission of the criteria indicates that all students agreed on the criteria, establishing collective ownership of goals. The students also presented these criteria to the engineers in Meeting 3 (see Table 6.2), and the engineers agreed, stating, "You've got it nailed."

Implicit criteria (also in Table 6.4) mostly focused on the visitor experience, particularly on what visitors want and how to keep them engaged. This represents understanding of the learning process as a mutual, rather than a one-way, experience (Davies, 2008; McCallie et al., 2009; Feinstein, 2005) in incorporating visitor needs and backgrounds. These criteria came from participating in and observing the Ingenuity Lab, as well as interviews with visitors. For example, the collaboration implied criteria for guidance, accessibility, attractiveness, and challenge.

The criteria evolved and had varying emphases throughout the design process (see Appendix D). In the pre-survey, students identified criteria for a "good" challenge as interactive and hands-on, fun, educational, and allowing for multiple solutions. Further criteria were identified in the first meeting at the Lawrence Hall of Science (see Table 6.2). These criteria were particular to the science center space and came from their own experiences and observations; they included guidance, personalization and creativity, fast feedback and design cycles, and modularity. For instance, the students noticed that visitors were often confused on what to do, so they suggested guidance. The students also noticed that visitors became impatient or bored when the testing station took too long, and they thus suggested fast feedback. An educator added collaboration and accommodating all ages and genders. The students further interviewed people on science center experiences and independently identified the same and more user needs: accommodating groups, appropriate for all ages and interests, and also attractive, dynamic, and unusual. Meeting 3 at the Meyer Sound facility with the engineers reemphasized modularity, and to assist with brainstorming, the engineers pushed to specify the existing criteria in more detail, prompting discussion on the importance of a take-home object versus the memory of the experience, the number of modes of interaction, as well as focus on a specific topic and age group. Before the next meeting, the students individually selected the top challenge ideas with their own criteria, which were very similar to each other; all five students independently used the criteria of educational and cheap, with no mention of age and gender. Lectures introduced the criterion of modularity from a sustainable perspective, and further observations of the Ingenuity Lab program during implementation really highlighted the need for better guidance. Ultimately, the collaboration's final explicit criteria only changed from their initial set of user needs by excluding collaboration. In the post-survey, the students identified all the final explicit criteria except gender and age neutral and sustainable.

Overall, the criteria of hands-on (6 of the 8 collaborators mentioned) and multiple solutions for personalization (all 5 students mentioned) were very prevalent throughout the process, emphasizing accessibility as a mutual learning experience similar to the Engineer the World collaboration. Other criteria were more commonly identified in the science center space: guidance, fast feedback, goal-oriented, and cheap and reusable materials. On the other hand, user interviews and the educators contributed the criteria of age and gender neutral as well as collaboration, and course lectures emphasized the concept of sustainability. See Appendix D for a matrix of assertions of all criteria by time and individual.

6.1.2.3 Final Idea: Did It Meet the Criteria?

I now look at the final challenges implemented by both collaborations in order to determine whether their criteria were actually met. The Engineer the World collaboration's final challenge was to create websites and mobile apps, while the Sound Engineering collaboration's final challenge was to develop something that produces sound. Analysis of the collaboration data as well as visitor comments show that the majority of the collaborations' criteria were met (see Tables 6.5-6.6). The following details how the criteria were met.

The final challenge implemented by Engineer the World combined two top ideas: creating a website and creating a mobile application. The visitor's design process flow was to first make a paper version of the website or app, then to go to the computer to implement a basic version of the website in HTML or a basic version of the app in App Inventor with heavy guidance from the facilitator. Table 6.5 shows visitor and collaborator comments that represent whether the criteria were met or not. According to visitor and collaborator comments, most of this collaboration's criteria were met. The criteria to be museum specific with a take-home component was somewhat met as visitors were able to email their websites to themselves, but the activity itself was not necessarily museum specific since they could do the activity elsewhere. Comments and observations show that criteria that were not met are: provide a flexible timescale with many short iterations, have stations with instructions that are progressively more complex, have instructions for a toolkit of fundamental elements, and challenging. The flexible timescale was not achieved because of the extended one-on-one facilitation time spent on the limited computers. Specifically, the nature of the coding implementation on the computer, an unfamiliar and new activity for most visitors, required more time and guidance than in other challenges, and the number of available computers limited the number of visitors who could work simultaneously. The stations and instructions were not implemented due to the limited resources and time from the collaboration members, and no visitor mentioned that the challenge was particularly challenging or difficult, as it was a very open-ended activity. Although these criteria were not met, the collaboration was satisfied that they engaged the visitors in at least one cycle of the design-build-test cycle; and because of the open-ended nature, the challenge was accessible yet still engaged visitors in authentic practices, including creativity.

Table 6.5: The Engineer the World collaboration's criteria and how the criteria were met, according to visitors and/or the collaborators from throughout the month of implementation. Each visitor group is represented by a letter in the parentheses (quotes come from 14 of 26 surveyed groups). Ages of children from the survey quotes are indicated in parentheses, with some surveyed groups including more than one child.

	Criteria	Was criterion met?	Comments
Explicit	Allow for individual work AND collaboration across generations	Yes	"*the kids did it by themselves*" (A: 8, 8) "*i was able to finished my design with great help*" (B: 8)
	Parents have some familiarity with the topic	Yes	Visitors are familiar with websites, computers, apps
	Be open-ended for lots of different outcomes/solutions to the challenge and lots of different ways to engage	Yes	4/26 visitors mention this criterion "*structure - free to interpretation*" (C: 3) "*opportunity for my kid to get creative and excited about turning his ideas on paper into something real*" (D: 5) "*creative and interesting handson activities*" (E: 5, 8) "*Make them to think new ideas and visualize fun things."* (F: 8, 11)
	Have examples for inspiration and allow for cross-pollination	Yes	"*so when I projected the website onto [over there], as the other kids saw what this child did, they were more enthusiastic about it because they realized that if she can do it, then they can do it as well*" (student) In one observation, the mom showed her son an example to get started, and he filled out his website with similar content.
	Use materials that allow for personalization, use familiar materials in unfamiliar ways	Yes	"*opportunity for my kid to get creative and excited about turning his ideas on paper into something real*" (D: 5) "*art project to learn about web design*" (A: 8, 8)
	Offer decorative components for young kids	Yes	Achieved with paper website building; "*making drawings and cutting out*" (G: 5, 7), with 5/26 visitors mentioning something similar
	Be museum specific, but also have a take-home component	Somewhat	Somewhat achieved "*wish there was a way to keep web site more easily*" (H: 9, 11)
	Provide a flexible timescale - allow for many short iterations for improvement, make success attainable	No	Not mentioned, though implementation timescale wasn't too flexible (depended on computer availability, and kids spent a while on computers)
	Should be exciting to test	Yes	"*opportunity for my kid to get creative and excited about turning his ideas on paper into something real*" (D: 5)
	Show that engineering is broader, not just mechanical	Yes	"*I learned about some online tools for developing apps*" (I: 8) "*engaged my little girl in coding*" (J: 4, 2) "*allowing youngsters to make programs,*" but also

			said nothing made them feel like engineer (K: 9) "*It allows kids to think about how to organize the information.* " (L: 5, 6) "*think the way to help users navigate information*" (L: 5, 6)
	Be gender neutral	Yes	"*Friendly and open people; loved the 'girl power*" & "*engaged my little girl in coding*" (J: 4, 2)
	Build on prior knowledge and interests	Yes	Achieved through kids making websites about themselves or their interests
	Relate to kids' personal/daily lives	Yes	"*connection to real world*" (C: 3)
	Provide tiered levels of challenges for different age groups	Yes	"*how accessible it was to my 4 year old*" (J: 4, 2) "*allowing youngsters to make programs*" (K: 9)
	Facilitate with varying intensity of help to increase accessibility	Yes	"*patience of staff*" (M: 6, 6, 7) "*all the great volunteers*" (D: 5)
	Have stations with instructions that are progressively more complex	No	Not implemented
	Have instructions to create a toolkit of fundamental elements to build with	No	Some signage, but mostly not implemented
Implicit	Fun/interesting	Yes	"*It was so fun*" (G: 5, 7) "*It was fun*" (N: 10)
	Goal/design oriented/challenge to be solved	Yes	"*Designing before building*" (I: 8)
	Challenging	Somewhat	Not noted in surveys
	Rewarding	Yes	"*opportunity for my kid to get creative and excited about turning his ideas on paper into something real*" (D: 5)
	Inspiring	Yes	23/26 survey responses said they want to continue the activities, and 1 "no" and 2 "maybes" "*yes!! want to come back next month*" (D: 5) "*yes, [will continue these activities] at home*" (J: 4, 2)

The Sound Engineering collaboration also similarly combined their top two ideas. They presented the final challenge as "make-your-own sound generating device," which could be a loudspeaker or instrument. The visitor design process was facilitated with some modularized pre-built components (e.g., the coils were pre-wound with designated turns) and involved reusing recycled materials. Loudspeakers were tested on computer and amplifier set-ups. Table 6.6 shows visitor and collaborator comments on the challenge, with respect to the collaboration's criteria. Most of the criteria were met, according to visitor comments and observations. The explicit criteria that were only somewhat met were fast feedback, which sometimes could be slow if there were not enough facilitators to help out, and gender and age neutral, which a visitor commented was not accessible to their 4-year-old. However, others with a child of the same age noted their positive experiences. Implicit criteria that were somewhat met were guidance, which had mixed visitor comments where one noted a greater need for guidance while another noted that it was the right mix of help and exploration; modularization, which one of the students noted in that not every component was pre-built, consequently allowing for more personalization; and attractive and dynamic space, which both a student and engineer noted was not achieved when the room was empty of visitors. The only criteria not met were two implicit criteria: having a take-home component and a spacious and clean environment, which an engineer noted was "too cluttered." These criteria were consequently not prioritized for the project – the take-home component was not absolutely necessary for implementation and its importance was mitigated in the discussion during Meeting 3 while the clutter was part of the space and beyond the control of the students.

Table 6.6: The Sound Engineering collaboration's criteria and how the criteria were met, according to visitors and/or the collaborators from throughout the month of implementation. Each visitor group is represented by a letter in the parentheses (quotes come from 14 of 26 surveyed groups). Ages and gender of children from the survey quotes are indicated in parentheses, with some surveyed groups including more than one child.

	Criteria	**Was criterion met?**	**Comments**
Explicit	Fun and informative	Yes	"*learn how to cause vibration to make music*" (A: 8F, 12F) "*that there are infinity options of sounds*" (B: 11F)
	Hands-On	Yes	4/26 visitors mention "*hands on activity to be creative*" (A: 8F, 12F) "*[our favorite part was] the interactivity*" (C: 3M, 5F)
	Goal-oriented	Yes	"*making something that would make sound*" (B: 11F)
	Iterative Design	Yes	"*I changed, revised, and edited the stuff I was making just like an engineer*" (B: 11F)
	Fast Feedback	Somewhat	Somewhat; one student notes that visitors get discouraged when testing is slow
	Allow for creativity	Yes	Students show unique designs made by visitors (double speaker, suspended by rubberbands, etc.) "*[their] way of looking and using the materials is different than mine*" (C: 10F, 10F)
	Gender and Age Neutral	Somewhat	Somewhat achieved for age (survey: average age 7.5 with s.d. 2.9, range 3-12) Achieved for gender (survey: 42% male, 58% female) "*it was too hard, and the staff gave an example but not enough instructions for a 4yo. Maybe you could have staff who specialize in early childhood?*" (D: 4M) "*nothing just the right mixture of help and letting them explore*" (C: 10F, 10F)
	Sustainable	Yes	Materials never ran out Visitors returned
Implicit	Simple	Yes	"*easy to understand*" (E: 5)
	Cyclical • Able to be improved upon • Testable/measure	Yes	"*I changed, revised, and edited the stuff I was making just like an engineer*" (B: 11F)

able/competition		
Challenging	Yes	"*its harder than it looks*" (F: 12F)
Rewarding	Yes	Achieved, when visitors get something to "work," 9/26 visitors talked about functionality "*that it actually makes music*" (G: 7F)
Adequate materials	Yes	"*Create my own instrument with only four materials*" (H: 9F)
Relate to personal/real-world	Yes	Challenge had familiar materials, speakers, instrument
Social	Yes	"*helped my daughter build a speaker*" (I: 5F)
Inspiring	Yes	All surveyed visitors responded "yes" to continue to do activities like these, with 2/19 mentioning returning to the Ingenuity Lab, others doing it at home or library
Guidance	Somewhat	Somewhat achieved; both students in observations and visitors note the need for better facilitation and clarifying signage "*instructions take it home*" (J: 5) "*it was too hard, and the staff gave an example but not enough instructions for a 4yo. Maybe you could have staff who specialize in early childhood?*" (D: 4M) "*just the right mixture of help and letting them explore*" (C: 10F, 10F) "*Had to ask what to do... we weren't stopped and gave clarification of the project to hold our attention*" (A: 8F, 12F)
Modularized	Somewhat	One student notes that some stuff is modularized (coils) while others are not (diaphragm, etc.)
Unusual/novel	Yes	6/26 visitors were surprised that their designs worked "*that it actually worked!*" (K: 7F, 11M)
Attractive and dynamic	Somewhat	One student notes this criterion was achieved when room was full, but not when empty
Take-home	No	"*you weren't able to keep your invention = (*" (L: 12F)
House-hold/familiar materials	Yes	4/26 mentioned, with 1 talking about wanting to do the challenge at home with recycled materials "*[I'm surprised] That it actually worked with recycled materials*" (M: 7F) "*Yes. Using different materials to make instruments [at home]*." (N: 4M)
Spacious clean	No	One engineer mentioned the space was too cluttered
Examples	Yes	"*examples [are my favorite part of the Ingenuity Lab today]*" (D: 4M)

6.1.2.4 Summary

Both collaborations developed explicit and implicit criteria. The implicit criteria were never established as a group; however, these implicit criteria still played important roles in the design and development of the challenge. The Engineer the World collaboration created a broader set of explicit criteria at the beginning of their design process, heavily guided by the engineers and educators, while the Sound Engineering students came up with their criteria more independently from the engineers and educators. However, both collaborations acknowledged the need to make the challenge accessible and authentic, and in particular understood the need to make the experience a mutual learning experience with contribution and interaction from visitors. The mutual learning experience was emphasized with the criteria of a hands-on experience, guidance from facilitators, catering to all ages and genders, allowing for personalization through multiple paths and solutions, connecting to personal and real world contexts, and providing feedback through quick iterations. Many of these were implicit criteria for Sound Engineering, while Engineer the World included many of these in their explicit criteria (see Table 6.4). However, both collaborations strived to achieve both their explicit and implicit criteria in their final design challenge to provide the public with a mutual learning experience, as evident in the refinement of the challenges. Both collaborations measured their prototypes against the criteria to help refine the challenge. For instance, after the initial prototyping, two students from Engineer the World noted that they needed to make the activity more connected to the children (an explicit criterion), so they decided to allow visitors to make the website or app on any of their own interests. An educator and two of the students from Sound Engineering noted the need for more guidance (an implicit criterion) in the challenge, so the students created more signage clarifying the materials and goals of the challenge.

Thus, as shown in the previous section, in order to translate their implicit engineering practices to explicit practices for visitors, the members of each collaboration negotiated a play between explicit and implicit criteria, prioritizing and emphasizing some, but compromising others as the context and implementation highlighted distinct needs. Not all criteria were explicit, and notably criteria acknowledging the mutual learning experience were mostly implied, many of which took precedence over the explicit criteria. Many of these criteria actually originated from the initial interaction in the Ingenuity Lab space, in which the collaborators observed and interviewed visitors. Therefore, in designing these activities, designers should engage with learners in-situ in a human-centered design process to recognize important implicit criteria that guide the design of the activity.

6.1.3 Ideation Process

The ideation processes for both collaborations were surprisingly smooth. The early establishment and agreement of criteria in the first meetings created collective ownership of goals in selecting ideas. In brainstorming, ideas initially were heavily influenced by the actual products of the engineering companies involved; however, ideas soon branched out even broader within the topic areas of computer science and sound. Ideas were contributed by all collaboration members. The Engineer the World collaboration collectively voted for the top ideas while the Sound Engineering collaboration individually selected their top three ideas and got user feedback before voting on the final. Coincidentally, both collaborations decided to combine their top two ideas into one challenge.

6.1.3.1 Engineer the World: Flexibly Incorporating Contributions and Feedback

The Engineer the World collaboration brainstormed over 70 very divergent and broad ideas (see Appendix E), with many inspired by the list of products from Google. As shown previously in Table 6.1, the entire collaboration first brainstormed ideas as two groups, then further brainstormed ideas individually. Ideas were narrowed to concepts around traffic, programming, paper prototypes, social networks, apps, and search queries. Eventually, the collaboration focused more on paper prototyping, then both educators pushed to bring in more technical activities and technology.

The top three ideas for Engineer the World were clearly preferred above the other ideas by the entire collaboration. Many of the ideas overlapped and were consequently combined. The top three ideas after combining were *create a social network or profile*, *create an app*, and *programming scavenger hunt*, which originally were contributed respectively by an engineer, a student and an educator, and an educator and an engineer. *Create a social network or profile* was selected by all but two members, *create an app* was selected by all members, and *programming scavenger hunt* was selected by all members. The students then prototyped these top three ideas, and in the following meeting, a student said, “I would hate to take only like one and leave the other two kind of untouched – is there a way to incorporate all three or do we have to pick one and just go with it?” As a result, the *create a social network or profile* and *create an app* ideas were combined for the challenge, while the *programming scavenger hunt* would be integrated into the next month’s challenge.

The final ideas evolved through the design process, with the students flexibly incorporating feedback from visitors, educators, and facilitators. Even though the students had divided the three ideas amongst the five of them for prototyping, they credited one student in particular with all three implementation ideas. Feedback from prototyping these ideas with visitors included the need to have appropriate materials for decorative components, guiding questions, connections to real life, considerations for privacy, and example websites. The meeting following the first prototyping session led the students to be flexible with their initial ideas and refine the *social network or profile* idea into a more general *website*. Because this first prototyping session also prompted the students to combine two of the ideas, the students carried out another round of prototyping, this time with a refined prototype of incorporating the *website* idea with the *app* idea. The students further demonstrated flexibility by integrating the visitors’ suggestions from prototyping; as a consequence of the visitors’ suggestions, the students refined the challenge to offer a greater variety of materials and developed hand-outs and signs with guiding questions, connections to real life, and example websites. In the follow-up meeting on the second prototyping session, an educator further pushed the students to integrate more guidance as well as more programming on computers. The students were again flexible with their idea and incorporated the educator’s feedback for implementation with more structure around the website and app design process. During implementation, the students reflected on the challenge with volunteer facilitators from their outreach organization and found that these facilitators also wanted more integration with technical concepts, such as programming. As a consequence, the collaboration flexibly added an in-line editor for HTML and App Inventor for making apps, along with a small activity to “program your parent” with paper flashcard commands.

In summary, likely because the collaboration established collective ownership of goals early on, there was very little disagreement throughout the process. Although the authority of the educators may have also led to less disagreement among the collaborators, the students demonstrated ownership over the process. For instance, one student stated afterwards in the survey that he "was the main builder of the shoebox design." Furthermore, as an embedded education researcher, I purposely passed control and ownership to the students by calling the challenge "your [the students'] challenge." The students were flexible in incorporating feedback from reflections with visitors, educators, and facilitators. In particular, their big theme goals were reaching all ages, attracting girls, fostering creativity, relating and connecting the activity, and representing the engineers' actual processes. The engineering students believed that they had successfully achieved their goals: children of all ages and genders felt like they could do the activity, especially after seeing other children's websites; visitors were given complete freedom to creatively design any type of website or app; visitors commented on the activity's real world connection; and children engaged in a similar process as engineers in designing a website or app.

6.1.3.2 Sound Engineering: Strong Collective Ownership of Goals

The Sound Engineering collaboration brainstormed over 110 ideas (see Appendix F). Students individually brainstormed ideas, then came together with the engineers and educator to brainstorm more ideas. Some common ideas covered loudspeaker design, sound visualization, instruments, speaker placement, acoustics of spaces, sound filters, and microphones. Other unique ideas included sound analysis, ears, electronic sound, and natural sound effects.

Though the Sound Engineering students individually selected their top ideas with their own set of criteria, their top three ideas were nearly identical because of their early-established collective ownership of criteria. All five had *making an instrument* as the top idea, *making a speaker* as the second top idea, and the third top idea varied among the students. The *speaker* idea originated from one of the engineers, who mentioned this idea to the students the very first time he met them. The *instrument* idea was individually contributed by four of the five students. The students' criteria were very similar; all had educational as well as low-cost and sustainable, four had goal-oriented, personalizable, fun, and interactive, and two had ease-of-use and creative. Because of the 100% agreement on the top two ideas, the students decided to combine these two for implementation. This strong agreement and the implied agreement on the group assignments for the mission statement and user needs suggest a very strong collective ownership of goals for the students.

The refinement and evolution of the ideas mostly involved execution. The students originally wanted to modularize most of the speaker components as preassembled, but ended up only modularizing coils by pre-winding wires to various numbers of turns. Furthermore, the students' early testing of the speakers found that position was a huge factor for volume, ceramic magnets as opposed to more powerful magnets were sufficient, and the coils needed to be more robust for reuse. During early implementation, the instructor and educator suggested the need for more guidance, including diagrams, signage, and facilitation. An engineer also emphasized the need for a better structure for the former (the tube for the voice-coil) of the speaker, improved room environment and acoustics, an educational display of a speaker and cross-section, more information on magnetism, and an introduction including safety. As a consequence of the prototyping and feedback from the educators and engineer, the student team flexibly modified their original challenge; only ceramic magnets were provided to visitors, coils were glued and widened, and more diagrams and signage were developed.

A pervasive theme throughout the design process was modularity, initially brought up by one of the students in the first meeting. The student emphasized modularity with preassembled modules of the design to ease the visitor's process of putting together and taking apart components for iterative design, thus providing control of the learning situation to the visitor and promoting hands-on mutual learning. This idea of modularity was reintroduced at the first meeting with the engineers (Meeting 3), where the same student mentioned that modularity would "scaffold parts of a whole system" for versatility in design and quick iterations. Lectures throughout the semester also reinforced the concept of modularity to achieve other criteria: another student connected the concept of modular architecture from lecture, noting that "kids can swap out pieces and learn how the sound changes" while another related to the lecture topics of sustainability and manufacturing and mentioned how modularity facilitates reuse. Overall, the students mentioned that modularity of components helps make the design easy to assemble, easy to take apart, easy to customize, easy to modify, and easy to reuse. Thus, modularity helps them to achieve half of their criteria: iterative design through easily disassembling and modifying, creativity through scaffolding components for a variety of designs, accessibility for a wide variety of ages through easy assembly, and sustainability through ease of reuse.

Other common themes were the concept of DIY, or do-it-yourself, and synthesis of various ideas. Students heavily emphasized DIY in the sense that the challenge would be a hands-on interaction for the visitors, in which they could create their own design, rather than following a prescriptive method. Specifically, they referenced the top two ideas as "DIY speakers" and "DIY instruments." Again, this aligns with their objective to provide a hands-on interactive challenge. One student mentioned synthesis in the first brainstorming meeting with the engineers: "If we synthesize 2-3 ideas into one exhibit, then that'd be really awesome." Another noted in the post-survey that he came up with the idea to merge the top two ideas of speaker and instruments, while another student also mentioned the idea to combine ideas in Meeting 4, the concept selection meeting. The students were therefore in agreement about the concepts of DIY and synthesizing ideas, reinforcing their collective ownership of goals.

Sustainability was also important. During the final presentation, an engineer asked the students what they would change given infinite resources. Interestingly, they responded that they would do the same because the materials are familiar household items that are accessible, available to do at home, and sustainable through reusing recycled materials. Thus, the concept of sustainability, initially prompted by the students' observation of the Ingenuity Lab space and reinforced by the class lectures, became a part of their objectives, further strengthening their collective ownership of goals.

6.1.4 Collaboration Roles

The roles of the students, engineers, and educators were similar in both collaborations, and the interplay of the roles shows the interdependence of the collaboration members. The students participated in a creative role, taking on the bulk of the design process through brainstorming, testing, implementing, and refining the challenge (see Tables 6.1-6.2). They flexibly carried out these processes with help from the industry engineers in a mentor role and from educators in a logistical role, and further integrated feedback from visitors. The engineers brought up questions in meetings that really probed and defined the criteria, pinning down the nuances and forcing the collaboration to reflect on what was necessary or not. For example, an engineer from Sound Engineering suggested that the students focus on one topic and a more specific age group. Thus, they helped refine the criteria by pushing for specification as in real engineering practices and turned the design process into a more authentic learning experience. The educators were very strict with the timeline and logistics, as the challenge was scheduled to be delivered to the public for a set month. In particular, one educator pushed very persistently to have the materials ready sooner, which meant that the challenge idea needed to be decided earlier. The educators from the science center also played a greater role in the implementation than did the engineers. Their experience with the program along with the goals of the science center led them to emphasize certain criteria: accommodating a wide age range, appealing to both boys and girls, and fostering collaboration across generations. Both the engineers and educators were also more critical of ideas, providing different perspectives and feedback for the student teams, and forcing them to think flexibly. For example, one engineer from Meyer Sound asked whether it was more important to have a physical take-home component to the challenge, or if the memory of the experience was enough (see Appendix D). The Sound Engineering students then ensued in a discussion of the importance of multi-modal sensory experiences and concluded that taking home a physical object was not as important as the experience, thus prioritizing their goals and ideas. The engineers and educators in both collaborations also provided guidance with suggestions on how to proceed with ideas. As a whole, the students were in greatest control of the design process, though the educators heavily guided and enforced logistical constraints while the engineers had least control but still guided the students and contributed key ideas. Consequently, the educators contributed educational accessibility while the engineers and students contributed engineering authenticity.

The most blatant difference between the two collaborations was the students' participation. The Engineer the World students participated voluntarily through an outreach club and were all sophomores while the Sound Engineering students participated for their course project and were all juniors and seniors. Consequently, the Engineer the World students participated in more of a learning role with heavy guidance and instruction from the educators concerning which parts of the design process to carry out and when. On the other hand, the Sound Engineering students viewed this as their engineering project and took much greater ownership of the design process, taking initiative on much of the brainstorming, idea selection, prototyping, and even some of the implementation. See Table 6.7 for an overview of the key components of these two collaborations' processes. This difference was even slightly reflected in the engineers, where in surveys, the engineers in Engineer the World noted their direct contributions to the final challenge while the engineers in Sound Engineering talked more about their mentoring role for the students in the collaboration. However, the educators were most familiar with the science center context and thus more heavily guided the implementation and refinement portions of the design processes for both collaborations.

Further differences rose from the initial components of the processes (Table 6.7) and the content of the engineers' work. Engineer the World emphasized showing that engineering is broad, specifically wanting to engage visitors in Google's process for software engineering. The educators in particular pushed to show engineering as authentic through representation of Google engineers' practices and to make engineering accessible to all ages and genders. The engineers also focused on the authentic side of engineering, particularly the broadness of the field and the creativity involved. Consequently, this collaboration focused much more on creativity in the final challenge, with the final design challenge emphasizing the design process from planning through sketches to implementation on the computer. In contrast, Sound Engineering sought to represent the engineers' practices with hands-on interactivity through DIY. As this was the more student-led collaboration and it was part of the students' course, the students also emphasized the concepts of modularity and sustainability from the course lectures. The engineers and educators agreed with the students' objectives, only asking for more specification on the objectives. As a consequence, the collaboration focused on physical materials, particularly reusable and recycled materials. They also aimed to make the challenge accessible through some modularized components to ease the build and refine steps of the design process.

Table 6.7: Overview of the key components and decisions of the two collaborations' design processes.

	Engineer the World	Sound Engineering
Overall process	Structured by educator (myself as participant-observer)	Structured by course project, somewhat by educator (myself as participant-observer)
Background research	Introduction and engagement at Ingenuity Lab (whole group)	Introduction and engagement at Ingenuity Lab (students only)
Criteria development	Criteria developed initially as whole group, then maintained constant → emphasized creativity, reach all ages/genders, Google process	Criteria developed by students, evolved slightly → emphasized modularity, DIY, sustainability
Engineering company research	Description of Google products from engineers → goals to show what engineers do, engineering is for everyone, show connection to real world, have kid do him/herself	Tour of Meyer Sound → goal to inspire interest in STEM through sound, interactive, fun, informative
Idea development	Ideas all brainstormed as group, then individually	Idea initially proposed by engineer, before any research/brainstorming; ideas then brainstormed individually, then as group
Idea selection	Group selection of ideas → combined top two	Students selected ideas → combined top two
Prototyping	Prototyped with guidance from educators → combined into one challenge, social profile turned into more general website	Prototyped with class from course → modularized only some components
Implementation and refinement	During implementation, incorporated feedback from facilitators, visitors, educators → added more technical elements	During implementation, incorporated feedback from visitors, educators → added more guidance through signage
Outcome engineering learning foci	Open-ended for creativity, sketch and build for design process	Physical and hands-on through recyclable/reuseable materials, modularity for design process

6.2 Surveys: Perceptions of Learning, Engineering, and the Experience

6.2.1 Understanding of Education as a Mutual Learning Experience

The processes used to create the learning experiences reflect the collaborations' perceptions of learning. Both collaborations heavily emphasized accessibility and authenticity, in particular achieving accessibility through a mutual learning experience involving guidance, personalization, and flexibility in ways to engage in a variety of solutions. They shared the goal of engaging visitors in authentic engineering; in pre-surveys, Engineer the World emphasized teaching communication and teamwork as important parts of engineering, while Sound Engineering focused on the process of developing useful solutions. For instance, Engineer the World responses include:

"I believe that engineers should teach these people that engineering is not just building new contraptions. It is a skill which people can apply to a number of jobs."

"Engineers need to teach other non-engineers that engineering is not just about problem solving but collaboration and communication of ideas among multiple individuals."

"How it involves lots of creativity (not just doing certain protocols over and over again) and applying what you know to a different problem each time"

While Sound Engineering responses include:

"The pulling in of knowledge to develop something meaningful."

"We should teach engineering to be the discipline of translating scientific knowledge to usable consumer products."

In pre-surveys, particularly engineers from both collaborations stressed showing the accessibility and broadness of engineering, including the various "career opportunities."

As a result of the implementation of criteria around accessibility and authenticity, visitors engaged in mutual learning experiences. In post-surveys, collaborators report that visitors learned about the accessibility of the engineering topics as well as basic technical concepts for each challenge. An Engineer the World student said that visitors "have learned that anyone can learn to program," and a Sound Engineering student described that visitors learned "[h]ow to build speakers, how easy it is to demonstrate basic science principles, that technology is not necessarily complicated, and plenty of acoustics principles." In particular, visitor experiences in both challenges depended heavily on facilitation. The Engineer the World collaboration spoke about using facilitation to show visitors that making websites and apps is accessible and doable and to connect the topic to familiar ideas, culminating in a rewarding outcome in the final implementation of visitors' designs. An engineer from industry said, "I've realized that parents can sometimes judge too quickly if their child can or cannot do something, so I think the facilitators can recognize these types of parents and try to get them to re-evaluate the situation again and not assume that the challenge is too hard for their children." While the Engineer the World collaboration focused on implementation, the Sound Engineering collaboration described facilitation through timely and friendly interaction with visitors; the success of visitors depended mostly on testing and refining through feedback from both the tests and the discussion of results with facilitators. They emphasized accessibility through multiple paths and solutions through the testing and refining steps of design. Thus, both collaborations noted how the challenges were accessible to visitors through a mutual feedback process, in which facilitators played a key role.

Both collaborations' survey responses on their challenges' key elements reflected their understanding of learning as a mutual process involving contributions from and personalization for the learner. The Engineer the World collaboration was specific about the key elements of their challenge in addition to facilitation; the challenge focused on the steps of design and implementation of a website through a hands-on experience with a rewarding outcome. The Sound Engineering collaboration also focused on iterations of design of a speaker or instrument, but emphasized more general education features such as fun, inspiring, customizable, simple, hands-on, collaborative, creative, sustainable, and goal-oriented. They also talked about a rewarding outcome through a "wow moment."

6.2.2 Engineering Involves Much More Than Technical Skills or Intellectual Ability

Pre- and post-surveys do not show much change in perception of engineering for either collaboration. For the definition of engineering, surveys show slight differences between each collaboration. The Engineer the World collaboration defined engineering as applying math and science to solve problems to help society, and the Sound Engineering collaboration defined it as using prior knowledge and science to design and build products to benefit society. The Engineer the World students mentioned efficiency and optimization while none in the other collaboration do, and the Sound Engineering collaboration discussed developing a product or service while no one in the other collaboration does. Both collaborations strongly emphasized the problem-solving process and societal impact in the pre- and post-surveys. One engineer mentioned the process: "Engineering has a strong emphasis on process and this presentation taught that lesson quite well; that there is a process to which scientific creations can be accomplished." Creating such solutions is the rewarding motivator in engineering. Both collaborations also mentioned creativity as part of the definition of engineering. Although they noted that technical knowledge was needed, they emphasized the process, societal impact, and creativity.

In terms of how well the collaborations thought their final challenge taught engineering, both matched their definitions of engineering to the visitor experience in the challenge. Engineer the World mentioned that visitors were given the basics and freedom to creatively design something in software development, an area not necessarily encountered by most visitors, thus reaching the collaborations' goals to emphasize creativity and the broadness of engineering. One engineering student said, "The challenge teaches engineering by giving students the building blocks of creation, from which they can progress their own designs." Sound Engineering noted in the post-survey that their challenge gave some science background, then allowed visitors to apply that knowledge to solve a problem and engineer a design through a process. One engineer from industry said, "The lab activities were examples of converting an electrical or mechanical energy into sound in air. Working with the available materials to create a system to do either, requires solving several problems, engineering a solution." Thus, Sound Engineering focused on the design process, particularly refinement and iteration, through modularizing components. In summary, Engineer the World emphasized creativity while Sound Engineering emphasized process.

More interesting details about the collaborations' perceptions of engineering came from responses to the survey question: "What are attributes and characteristics of a good engineer?" Although there was not much difference in the responses between the pre- and post-surveys, very few people mentioned technical skills and no engineers from industry mentioned technical skills. In fact, most attributes mentioned were hardworking, determination, curiosity, willingness to learn, and creativity. These types of attributes are in line with the malleable mindset (Dweck, 2006), in which intelligence is not something people are born with, but rather achieved through hard work and perseverance. This finding is surprising given that a common perception is that engineering is difficult and requires innate technical ability (Sinkele & Mupinga, 2011; Yaşar et al., 2006). Uniquely, Engineer the World heavily emphasized creativity, and Sound Engineering heavily emphasized communication in the pre-survey and problem-solving in the post-survey.

The collaborations' self-identified strengths and weaknesses in engineering actually show that they felt their weaknesses were these previously named attributes of a good engineer, though the pre- and post-surveys show little change before and after the collaboration design experience. Both collaborations named analytical as a strength and non-creativity and narrow-mindedness as weaknesses. However, both student groups did increasingly identify communication and teamwork as strengths. Engineer the World students initially named communication as a weakness in the pre-survey, and in the post-survey, they further mentioned their need to be more flexible and open-minded. Some Sound Engineering students did mention communication as a strength in the pre-survey, but similar to the other collaboration, named weaknesses such as lack of flexibility, non-creativity, and procrastination. The industry engineers from both collaborations named technical skills as their weaknesses; one engineer from Sound Engineering even said his weakness was "differential equations" while an engineer from Engineer the World said her weaknesses included "algorithms" and "low level systems." This further negates the concept that one must be innately good at technical skills to be an engineer.

6.2.3 Engineering Students and Industry Engineers Value the Experience, Feeling Like They Contributed Substantially to a Consequential Task and They Gained Professional Skills and Real World Experience

In reflections on the surveys, both collaborations reported their own contributions as well as the values they gained from the experience. The Engineer the World students noted in pre-surveys that they hoped to contribute ideas and teaching experience, and in post-surveys, said that they contributed ideas and feedback to improve the challenge. The Sound Engineering students reported in pre-surveys that they wanted to contribute their skills and knowledge (both technical and professional), but in post-surveys emphasized their ideas and contributions to the design phases. Engineers from Engineer the World wanted to contribute to the challenge itself and "encourage young people […] to understand what a career in engineering can entail" while engineers from Sound Engineering focused more on mentoring the students "through the phases of developing the LHS activity."

In terms of benefitting from the collaboration design experience, both collaborations noted in pre-surveys that they wanted to experience the design process of creating a challenge. The students from Engineer the World mentioned in particular that they wanted to expand their mentoring and teaching skills with children, while students from Sound Engineering talked about creating an effective solution that will inspire children. Students from both collaborations discussed their hope to gain professional skills, particularly communication and collaboration skills, through working on a team that included clients and industry engineers. The educator hoped for logistical gains in pre-surveys, such as a documented challenge activity and engaging visitors in authentic design practices. The engineers from Engineer the World wanted to build new relationships while the engineers from Sound Engineering mentioned wanting to gain new ideas and perspectives.

Table 6.8: Student designers reflecting on the experience.

Quotes
"The design experience went beyond my expectations. It fully immersed me in all phases of the design cycle and allowed me to iterate alternate designs multiple times."
"[The experience was] Very important, it taught me how to work under deadlines when we actually have something to implement, rather than an arbitrary deadline just because something is due."
"I felt this project gave me more experience working with stakeholders outside of group members and classroom faculty."
"It gave me the opportunity to collaborate as a group and create something from scratch, much like what engineers do in the field."
"I think we all felt vested in the design experience not just for the class, but also to produce a great and worthwhile exhibit at the LHS."
"We were able to use creativity in analyzing a topic and developed our effective solution to solve the problem. Thinking like this will help prepare us for the thinking that engineers do."
"It allowed me to know that sometimes I have to consistently change my plan in order to improve customer satisfaction."

In post-surveys, all engineering students and practitioners stated that the experience met or exceeded their expectations, with both collaborations emphasizing the actual implementation of their design challenges as the valuable component. They emphasized that the collaboration design experience allowed them to increase professional skills, gain real world experience, and have an impact on the public, which could all be attributed to the actual implementation with the public. The engineering students cited increased understanding of design processes and the greater real-world relevance (see Table 6.8). Engineer the World focused more on education and teaching, while Sound Engineering focused more on implementation of their design. Engineer the World students noted that they were able to work together and create something from scratch, similar to engineers' actual practices. They discussed collaborating with those from different backgrounds and needing to come to a consensus to implement the challenge, learning how to teach engineering, and seeing their impact on education. Both industry engineers from Engineer the World were surprised that the challenge was able to cater to a wide range of ages. Sound Engineering emphasized the value of participating in the design cycle in full form, especially the implementation. The students further mentioned the value of working with various stakeholders and diverse people, performing under real deadlines, having interactions outside of the university, and brainstorming with industry engineers. The engineers from industry found the experience rewarding because they were able to reach out to the public and teach them about their jobs; an engineer from Sound Engineering noted the value of having a real impact on education. Finally, the educators gained from the expertise of the students and engineers and added to their repertoire of engineering education activities.

In terms of skills, students from both collaborations mention gaining engineering skills, particularly professional skills. Two students from Engineer the World explicitly stated that they were prepared for what engineers do, five mentioned engineering skills, and four mentioned professional skills (e.g., collaboration, communication, teamwork, flexibility). Three students from Sound Engineering mentioned collaboration in a multidisciplinary team with people from outside the class, two mentioned engaging in the design cycle, and one mentioned time management.

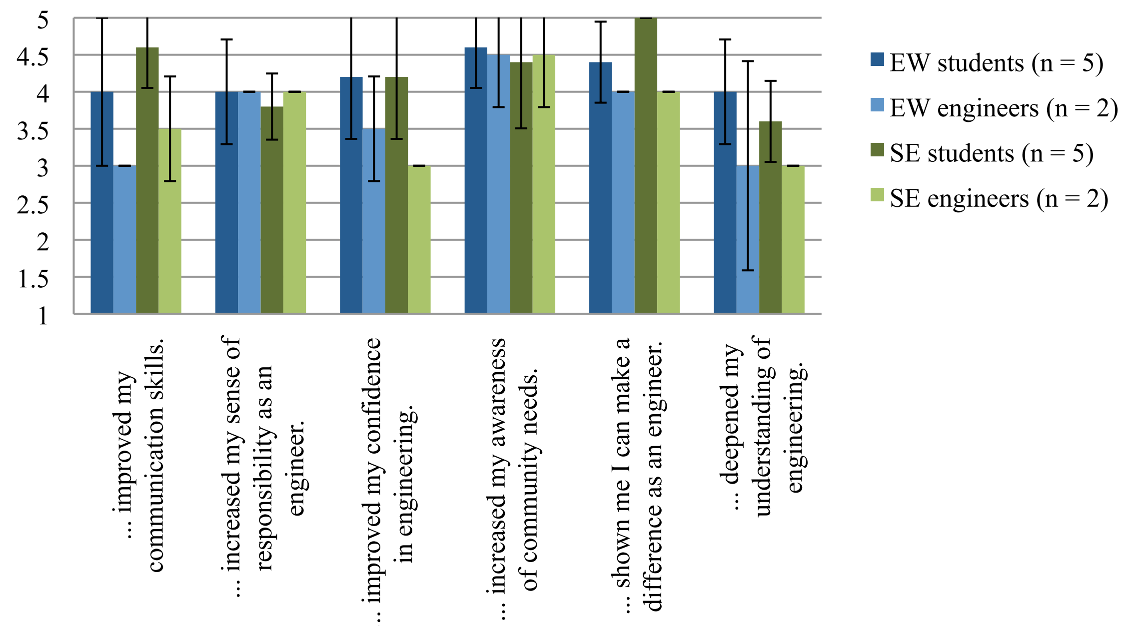


Figure 6.1: Post-survey self-ratings on the collaboration experience (1-5 Likert scale, with 5 as strongest agreement and 1 as strongest disagreement). EW = Engineer the World and SE = Sound Engineering.

Not surprisingly, the students generally rated their gains higher than did the engineers from industry in the self-rating questions on post-surveys (Figure 6.1). Students rated that the experience improved their communication skills, confidence in engineering, and understanding of engineering. All five students from Sound Engineering rated a 5 on the 1-5 Likert scale, strongly agreeing that the experience had shown them that they could make a difference as an engineer. The Engineer the World students also rated this highly at an average of 4.4. The average responses for both the students and engineers were highest for making a difference as an engineer and increasing their awareness of community needs. These are particularly valuable because of the relatively low emphasis on ethics and social responsibility in engineering curricula (Bucciarelli, 2008), and indicate that engaging in and reflecting on such experiences can help increase engineers' understanding of their impact on the public and world. Through these experiences, they can recognize that the products and services they create should engage the users in mutual learning experiences in which the user and engineer both learn and contribute.

Thus, both the actual implementation with the public and the connections with practicing engineers from industry were valued by the students. These kinds of connections can be motivating (Magleby, Sorensen, & Todd, 1991) and appear to strongly motivate the students in these two collaborations. The frequent mention of the rewarding experience outside of their university with the public and the explicit statements about the preparation for professional engineering practice confirms previous research on the benefits of such external experiences (Stevens et al., 2008), and further indicate an increased understanding of their actual impact on the world.

6.3 Discussion

6.3.1 Design Processes

The multidisciplinary make-up of the collaborations allowed the various members to contribute their own expertise to the design processes. The educators, focused on logistics and learning, contributed accessibility. The engineering students and the industry engineers, taking on the bulk of the creative work and engineering tasks, contributed authenticity. The collaborators were flexible in these various roles and accommodated contributions from all members. The educators pushed deadlines and industry engineers pushed for more specification on criteria, all while working flexibly around each other's tight schedules and course timelines and consequently engaging the student teams in real engineering practices for an authentic learning experience. Furthermore, as in authentic engineering practice, flexibility was needed to prioritize criteria, as the constraints of the design situation (mostly logistical) meant that some criteria were excluded and others were implied in the situation.

Because criteria and goals were agreed upon early on in the processes, both collaborations established collective ownership of goals, contributing to a smooth ideation process. The collaborations constantly reflected on the criteria in selecting and refining their ideas, and with agreement on the criteria, almost zero disagreement played out as they flexibly incorporated feedback from the engineers, educators, and visitors. Instead, both collaborations interestingly decided to combine their top two ideas for the final design challenge in order to ensure everyone's contributions were acknowledged and implemented.

Differences between the two collaborations' design processes included the roles of the students and engineers as well as the focus for engineering learning. The Engineer the World students were younger and much less vocal in meetings; they were also participating voluntarily rather than as part of a course. Instead, as part of the education outreach club, these students were much more focused on education and teaching while the Sound Engineering students focused much more on the design process emphasized by their course. Thus, the Engineer the World students were more heavily guided by other collaboration members, and the collaboration's engineers contributed more directly to the final challenge than did Sound Engineering's engineers. The educators and engineers heavily guided the criteria development process, and the collaboration ended up with a very broad set of criteria with the goal to show the public what engineering is and that "engineering is for everyone." The Engineer the World collaboration consequently focused on the authentic design-build-test process and engineering as involving creativity for accessibility. On the other hand, the Sound Engineering students were all junior and senior students and selected this collaboration for their course project; these students independently conducted much of the design work as part of their course requirements, but also had greater initiative and confidence than the other students. Thus, these students came up with their own criteria and asked for feedback from the engineers and educators; their explicit criteria were much narrower, but there were many implicit criteria that resurfaced throughout the design process and overlapped with the other collaboration's criteria. They focused on the engineering learning experience as being hands-on and interactive through physical recycled materials and accessible through modularization of design components. This collaboration also uniquely emphasized sustainability from their course lectures. Overall, the two collaborations' combined explicit and implicit criteria overlapped quite a bit, as both aimed to achieve accessibility and authenticity.

6.3.2 Beliefs About Learning

Accessibility and authenticity were thus emphasized throughout the design processes, and were achieved through such criteria as personalization, creativity, and facilitation, importantly acknowledging learning as a mutual experience. Many of these criteria emerged through the human-centered design process, in which the collaborations engaged in-situ with the public in the science center context in order to understand their needs. Thus, this human-centered process guided the collaborations towards accessibility and authenticity. For example, the evolution of the Sound Engineering collaboration's mission statement reflects their changing perception as they engaged with visitors; the statement evolved from portraying learning as passive to active and inclusive. This perception of learning is further corroborated by the collaborations' survey responses. In describing what should be learned and what was learned in the design challenges, both collaborations emphasized accessibility, especially through facilitation and guidance to personalize the experience. Therefore, contrary to some science and engineering experts' perception of communication of knowledge as one-way (Davies, 2008; McCallie et al., 2009; Feinstein, 2005), these collaborations grew to acknowledge such learning experiences as mutual, with contributions and interactions from learners.

6.3.3 Beliefs About Engineering

An interesting finding emerged from the collaborations' beliefs about engineering. There was no substantial change in their beliefs from the pre- to post-surveys; but, both collaborations, rather than emphasizing technical knowledge and intellectual ability as key to engineering, instead emphasized the entire engineering process, societal impact, and creativity. Furthermore, when asked about attributes of good engineers, the engineering students and practitioners much more frequently cited hardworking, determination, curiosity, willingness to learn, and creativity than technical math and science ability, consistent with previous findings on engineers' self-perceptions (National Academy of Engineering, 2008). No engineers from industry named technical ability, and two of the engineers even noted that their weaknesses were specific technical abilities. Thus, these perceptions about engineering align with Dweck's (2006) theories of malleable intelligence and growth mindset, and underscore the need to change the public perception of engineering to show its accessibility. The National Academy of Engineering's Changing the Conversation report (National Academy of Engineering, 2008) has emphasized attracting new engineers by showing engineering as a creative endeavor and one that helps society; however, the findings here suggest that it is also important to emphasize that engineering is accessible to all through hard work, determination, and curiosity and is not a "hard" unknown that the public may perceive (Sinkele & Mupinga, 2011; Yaşar et al., 2006). Both collaborations noted in particular that the visitors engaging in their challenge did find engineering accessible, and many children even persisted through many failed attempts and iterations to the surprise of their parents, ultimately finding the experience very rewarding in achieving something that "works." Thus, such collaborations as these may open the way to attract diverse future engineers through persistence and curiosity.

6.3.4 Reflections

Both collaborations reflected on their process and experience, which Schön (1983) claimed is vital to professional creativity. Reflections on the process included personal observations and group discussions about the challenge, important for improvement as the challenge was implemented with the public. Reflections in post-surveys show that the collaboration participants, especially the students, were able to understand the importance of engineering in society and its impact on the world. The students valued the experience, and particularly valued the opportunity to contribute substantially to a real challenge that was implemented with the public, noting their personal increase in professional skills and real-world experience. The consequential task also held the students responsible and accountable, and they remarked the value of working with various people and stakeholders, especially with those from outside their classroom.

6.3.5 Future Work

Future work should explore more of these types of cross-community collaborations to better understand the interactions behind the design processes. In particular, it would be interesting to further explore the collaborators' thoughts on learning and engineering. Interviews, rather than surveys, may provide more information, as the conversation allows the interviewer to probe as needed. These interviews can specifically cover the topics of educational accessibility and engineering authenticity, asking the participants what their criteria are for each, as well as how they believe they worked to achieve these criteria and whether their challenge does or does not achieve these criteria. The interviews can elucidate each participant's priority of criteria. Furthermore, the interviews can investigate the roles and contributions of each member, as the members only provided brief and superficial descriptions in the surveys.

6.4 Summary

Through the collaborative design experience, these students engaged in authentic engineering design, working flexibly on a team and reflecting on the process to achieve and prioritize criteria within the constraints of their situation. The human-centered design process allowed the collaborations to dig in and understand the needs of all stakeholders, especially the visitors. Engaging in design as a learning process (Beckman & Barry, 2007; Dym et al., 2005) allowed the students to not only learn from the authentic experience, but also from the industry engineers, educators, and visitors. One student stated:

"I was very impressed, actually, despite the coordination of everyone, at LHS, our team, Meyer Sound. I thought we achieved a lot and out of all the other teams in ME110, that's the class we're in, I feel like we actually accomplished the most because not only did we design a feasible model for our project, we actually executed it and it was successful in the field. And all the teams in ME110 just didn't get the opportunity, so I thought this was one of the best projects I've ever worked on at Cal."

This chapter investigated the design processes of the collaborations involving engineering students and engineers from industry, showing that each member contributed with his/her own expertise to the process. Through the experiences, both collaborations gained a deeper understanding of learning as a mutual process and reinforced their perceptions of engineering. In the next chapter, I explore the outcome of these collaborations – the engineering design challenges and their impacts on visitors.

Chapter 7

Two Outcome Challenges of the Cross-Community Collaborations: Impact on the Ingenuity Lab Visitor Experience

Table 7.1: The features of the two challenges, specifically the goals, materials, set-up, ability to compare designs, familiarity, real world connections, and science and engineering concepts.

	Engineer the World	**Sound Engineering**
Goal	To create a website or mobile app.	To design and build something that makes sound.
Materials	Paper, markers, computers.	Cups, plates, bowls, jars, cardboard, cones, tongue depressors, rubber bands, magnets, coils of wire, tape, and other recycled materials.
Set-up	Visitors first created paper prototypes of their website or app at tables around the room, then went to the testing station in the middle of the room to build and test their website or app. The testing station had four computers, each with a facilitator to help the visitor.	Visitors designed and built their speakers or instruments at tables around the room. The speakers could be tested at the testing station at the back, where facilitators helped visitors test their speakers by connecting to the sound output of the computer.
Ability to compare designs	Visitors were shown example paper prototypes in the introduction and could see paper prototypes that others were making around the room. Some of the final built websites were projected on a large screen visible to the whole room.	A table at the center of the room displayed tens of example instruments and speakers made by others. Visitors could also observe designs being made by others in the room.
Familiarity	Websites and apps are well known to adults and many, but not all, the children. Children are familiar with paper and markers.	Visitors are familiar with instruments and speakers. Visitors are also familiar with most of the materials, as they are many household or recycled materials.
Real world connections	Websites on computers, mobile apps on tablets and phones.	Musical instruments, audio speakers, headphones, megaphones, cones, music.
Science / engineering concepts	Programming, designing and planning, testing.	Vibrations, frequency, electricity and magnetism, materials, experimentation.

The cross-community collaborations provided novel resources and perspectives for the Ingenuity Lab visitor experience. In particular, the involvement of the engineering students and the industry engineers provided engineering authenticity in addition to the educational accessibility pushed by the educators. The interaction among the diverse members of the cross-community design collaborations also reinforced the concepts that learning should be a mutual experience and that engineering involves more than technical skills, including creativity, persistence, determination, curiosity, and willingness to learn. This chapter provides an overview of the outcome of the collaborations, two Ingenuity Lab design challenges, and compares them to the three traditional Ingenuity Lab challenges described in Chapter 5 in order to determine the potential impact of the collaborations on the visitor experience. Specifically, I explore if the collaboration grounded the tinkering activities in authentic engineering to connect the actual practice of tinkering with the formal perception of engineering. Table 7.1 provides an overview of the features of the two outcome challenges, Engineer the World and Sound Engineering. In this chapter, I show that through the authenticity advocated by the engineering students and practitioners, visitors engaged in mutual engineering learning, more frequently connected the challenges to the real world, and exhibited broader engineering behaviors when compared to visitors at the traditional challenges.

7.1 Visitors Engineering

As stated in Chapter 4, over 4000 individual visitors participated in one of the five challenges, 148 visitor groups returned surveys, and 22 groups were observed. Most visitors (> 90%) agreed to participate in observations, totaling 22 groups with 34 active participants across the five challenges included in this dissertation. The only selection criterion was that there should be at least one child who was greater than 6 years old such that the interview could be conducted effectively. All observed groups included at least one child and one adult (see Chapter 4, Table 4.3). Of the 22 groups, 3 visited Engineer the World and 5 visited Sound Engineering (Table 4.3).

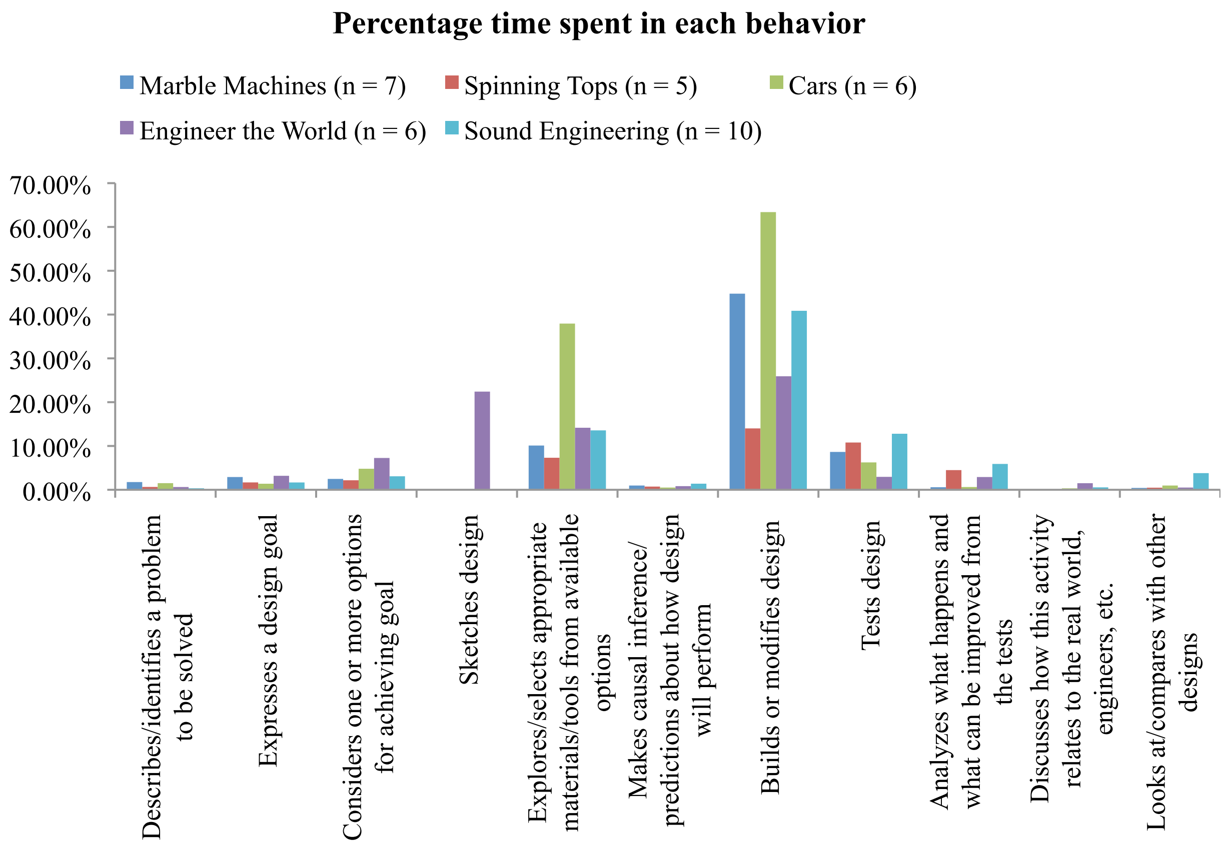


Figure 7.1: Percentage time spent in each behavior, by challenge. Visitors were from Marble Machines (5 groups, totaling 7 active participants), Spinning Tops (4 groups, totaling 5 active participants), Cars (5 groups, totaling 6 active participants), Engineer the World (3 groups, totaling 6 active participants), and Sound Engineering (5 groups, totaling 10 active participants).

As the outcome of the collaborations' design processes, visitors engaged in engineering practices in these tinkering design challenges. Design timelines (Figures 7.2-7.3) for each observed active participant indicate the times, durations, and frequencies of engineering design behaviors in each interaction. When compared to visitor timelines in the traditional challenges not developed through cross-community design, visitors at these two challenges spent more percentage time in these behaviors: *Considers options for achieving goal, Sketches design* ($p < 0.01$ for frequency and percentage time), *Makes causal inference/predictions* ($p < 0.10$ for percentage time), *Analyzes what happens and what can be improved* ($p < 0.01$ for frequency and percentage time), *Discusses how this activity relates to the real world* ($p < 0.01$ for frequency and percentage time), and *Looks at/compares with other designs* ($p < 0.10$ for percentage time). See Figure 7.1 for the breakdown by challenge. Thus, these visitors engaged in more planning and evaluation than in the traditional challenges, in which visitors exhibited mostly building and testing.

In particular, these two challenges developed with the collaborations engaged visitors in more discussion about the real-world relevance (see Figure 7.1). Consequently, the collaborations' push for accessibility and authenticity came through, as many visitors noted the accessibility through guidance and open-endedness and engaged in a broader set of engineering behaviors, noting their experiences' relationship to the real world. When prompted about the relationship, visitors at Engineer the World noted real websites and visitors at Sound Engineering described speakers, headphones, radio, music, instruments, and even cones.

In terms of their design processes, all Engineer the World timelines (Figure 7.2) demonstrate a strong average cascade pattern with the highest mean rating of 0.83 on the 0-1 scale (each timeline was rated as a high (1), medium (0.5), or low (0) cascade; see Chapter 4, Section 4.3.2). The cascade pattern, found in expert engineers, occurs when the interaction progresses from Problem Scoping to Developing Alternative Solutions to Project Realization, with frequent transitions between behaviors; this is indicated by a cascade from the top left to the bottom right of the timeline (see Figure 2.2 in Chapter 2, Section 2.1.4 for an example of the original cascade from Atman et al., 2007). The high cascade suggests that Engineer the World may have helped structure the experience in a way that visitors were able to better monitor their progress and determine which design behaviors were appropriate for their stages of progress. However, the Engineer the World timelines show little repetition of the cascade, indicating a single iteration. Because they were told to sketch before implementing, only participants at this challenge exhibited *Sketches design*, spending almost just as much time in this behavior (22%) as *Builds or modifies design* (26%); however, none return to it after implementing their website on the computer, likely because of the long time spent on implementation. As a result of the sketching requirement, these visitors were the only ones who sketched consistently, indicating that sketching out a plan may not be an intuitive step in creating designs. The lack of return to sketching also suggests that it is not intuitive. These visitors spent a relatively large percentage of time and frequency in Problem Scoping, particularly *Expresses a design goal* and *Considers one or more options for achieving goal*, mostly with facilitator guidance (Figure 7.2). The latter portion of the timeline, when visitors implemented their website, varied by facilitator during this one-on-one time. Half of participants looked at other prototype and real websites. And, with the more obvious relation to real websites, all groups discussed the activity's real world relation.

Sound Engineering timelines (Figure 7.3) have a mean rating of 0.59 for the cascade pattern, with four visitors exhibiting strong cascades. Many show repeated cascades indicating multiple iterations in design. Specifically, those who made an instrument exhibited a flatter cascade and transitioned more frequently between *Explores/selects appropriate materials/tools*, *Builds or modifies design*, and *Tests design* throughout, with most time spent in *Builds or modifies design*. Similar to Marble Machines, these visitors could test their instrument designs easily and instantaneously. Others who designed the speaker spent most time in *Explores/selects appropriate materials/tools* then *Builds or modifies design*, with few transitions between. *Tests design* for speakers was not as frequent throughout because of the need to test with a facilitator at a specific station. Overall, the greatest time (41%) was spent in *Builds or modifies design*. These visitors exhibited *Analyzes what happens and what can be improved* consistently after tests and most frequently of all challenges (see Table 7.4), likely due to the facilitated tests. All groups looked at other designs and three groups discussed the relation to the real world, as sound was something all were familiar with as consumers.

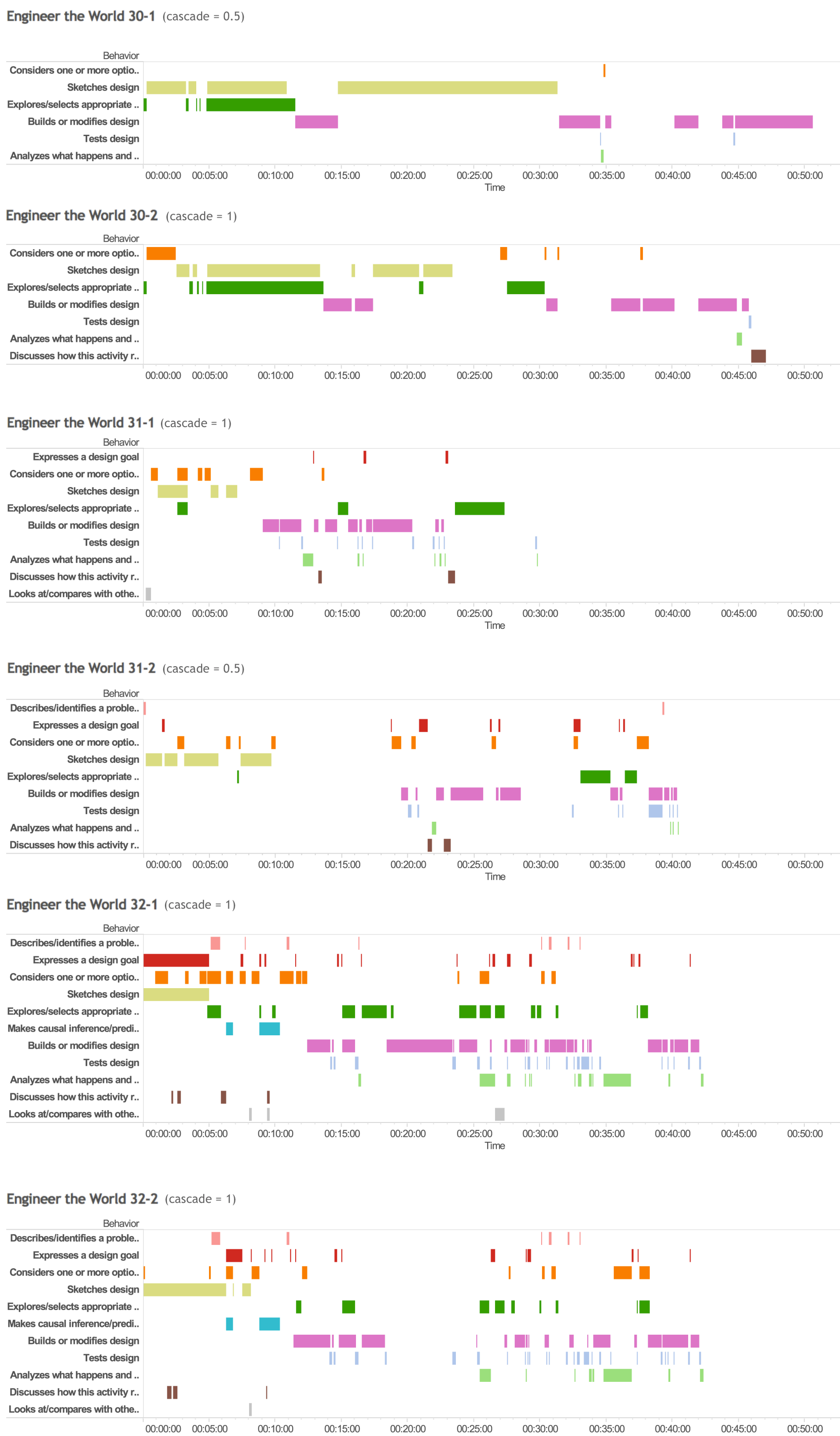
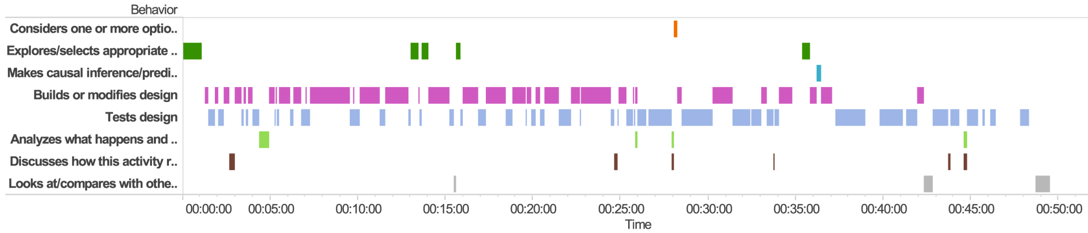
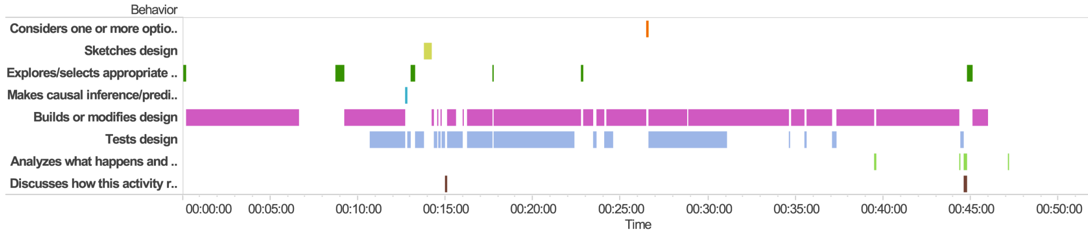


Figure 7.2: Timelines of participants at Engineer the World. The average cascade rating for these timelines is the highest of all challenges at 0.83. Individual cascade ratings are labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

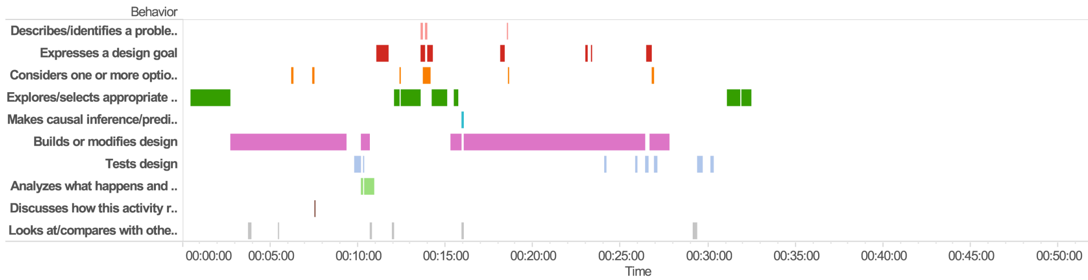
Sound 39-1 (cascade = 0.5)



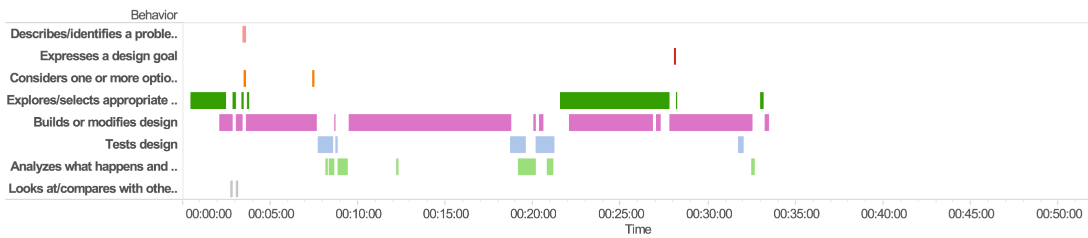
Sound 39-2 (cascade = 0)



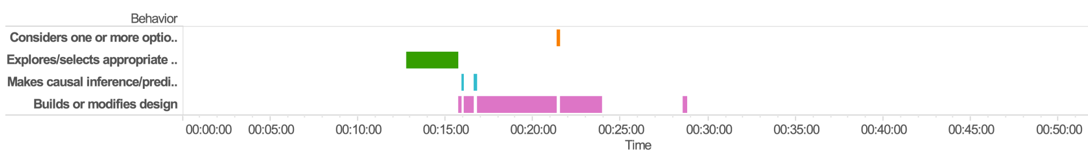
Sound 40-1 (cascade = 1)



Sound 40-2 (cascade = 0.5)



Sound 40-3 (cascade = 0.5)



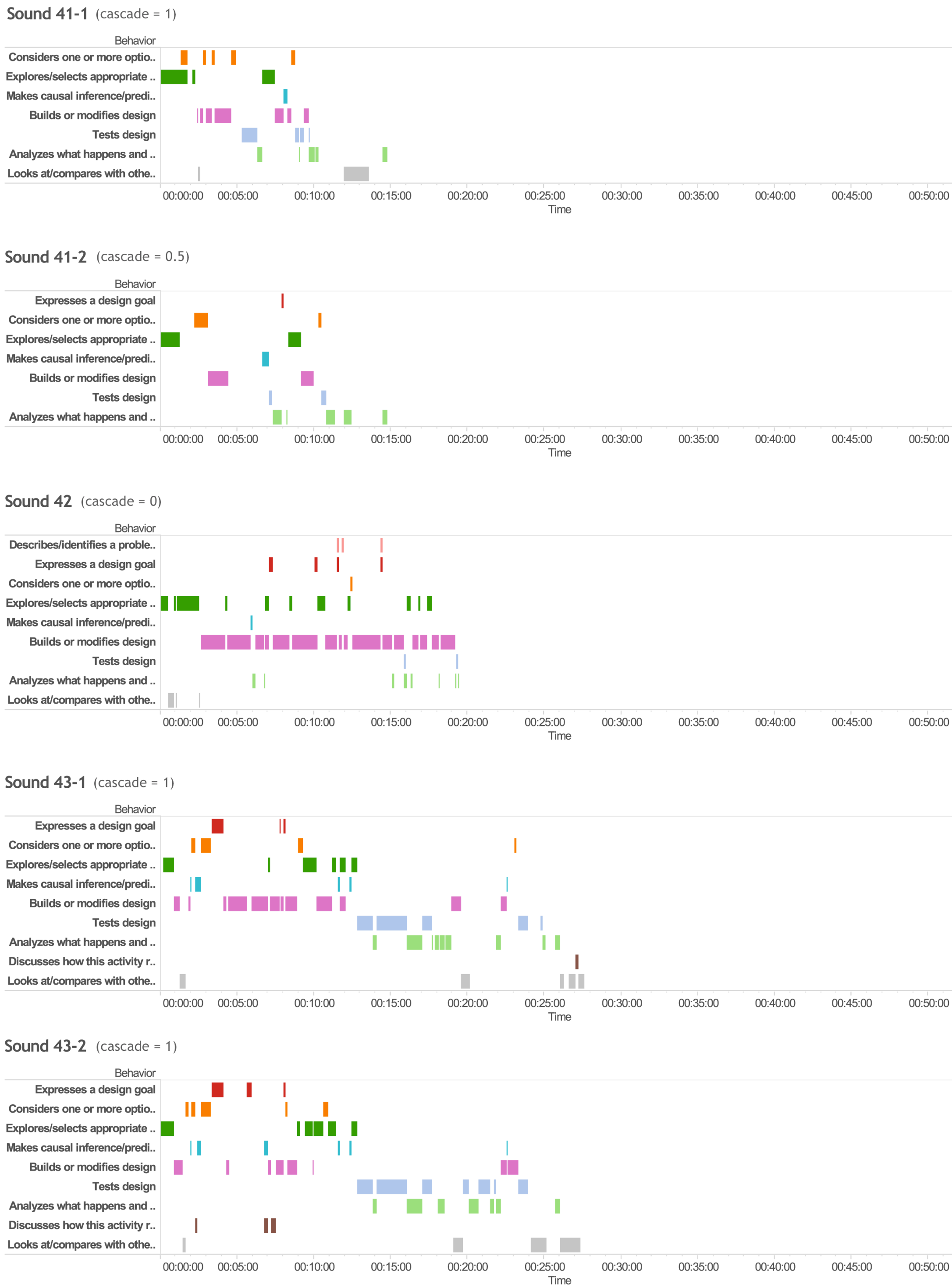


Figure 7.3: Timelines of participants at Sound Engineering. Numbers 39, 42, 40-3, and 40-1 beginning at 12 minutes and 40-2 beginning at 22 minutes engaged in the instrument design while Numbers 41, 43, and the beginning parts of 40-1 and 40-2 engaged in the speaker design. The average cascade rating for these timelines is 0.59, with individual ratings labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

7.1.1 Interviews

Pre- and post-interviews were conducted with all 22 observed groups, totaling 34 active participants across groups. As stated in Chapter 4, the primary active participants in these groups ranged in age from 6 to 14, with the average age 9 ± 2 years old. Engineer the World observed participants were slightly older at an average of 10 ± 2 years old and Sound Engineering participants were an average of 9 ± 3 years old. Thus, ages across the five different challenges are relatively comparable.

The interviews provide deeper understanding of the visitors' design processes. When asked how they chose what to make, two of the three groups at Engineer the World mentioned personal motivations and the other mentioned a goal; they felt that the project allowed for a lot of creativity. On the other hand, visitors at Sound Engineering frequently responded that the materials (4 of 5 groups) and the goal (3 of 5) were the reasons for their design choices; these visitors had a more common goal to make sound. Further reasons included motivation from an example from real life, trial and error, and the goal to make a unique design. When asked specifically about their goals, Engineer the World visitors named a wide range of goals: to finish, to get it to work on the computer, to have fun, to make something funny, to explain about themselves, and to post videos and reviews. Sound Engineering visitors had much more consistent goals, such as getting the speaker to work or play louder and making an instrument that makes sound.

Visitors from both challenges showed persistence and motivation. Engineer the World visitors spent more time planning, in particular sketching their designs. Their persistence and long times spent in the activity can be attributed to the accessibility of drawing the designs and then one-on-one guidance from facilitators as visitors implemented their designs on the computers. Facilitators at Sound Engineering guided visitors through the testing processes; thus visitors spent more time discussing, and consequently identified a problem, trade-off, or need to modify when asked about their goals during post-interviews. Consequently, Sound Engineering visitors often persisted through multiple iterations to refine their solutions, unlike Engineer the World visitors, who only completed one long iteration.

While half from Engineer the World and all from Sound Engineering were observed to look at other designs, only one of three groups from Engineer the World and three of five groups from Sound Engineering mentioned in interviews that they looked at other designs, possibly because they may not have been aware of their own observations of others or they may have thought that they did not copy these other groups. The Engineer the World setup at the Ingenuity Lab may have fostered less sharing of designs, as visitors worked on individual computers; visitors also talked about the personalization and uniqueness of their designs, which may have reduced their need to look at other designs. Sound Engineering had a unique setup in which example and previous visitor designs were left behind on a center table. Over half of these visitors mentioned in interviews that they got inspiration and ideas from these other designs while others wanted to make their design different or modify these existing designs, similar to visitors from the three traditional challenges designed without the cross-community collaborations. One visitor in

Sound Engineering further mentioned using an example from the real world rather than a physical example in the Ingenuity Lab.

7.2 Engineering Perception and Identity

Also similar to visitors at Marble Machines, Spinning Tops, and Cars, visitors from Engineer the World and Sound Engineering mostly described building or the content of the challenge in survey responses to "What did you do today that made you feel like an engineer?" (see Figure 7.4; surveys are usually parents responding with input from the children). Specifically, Engineer the World visitors most frequently mentioned the content of making websites or apps, followed by building and making, then designing. Visitors at this challenge mentioned design, plan, and personalization and ownership at a much greater percentage compared to all other challenges. They were also the only ones to mention programming. However, unlike visitors at other challenges, these visitors did not mention refining, having a successful outcome, or science concepts.

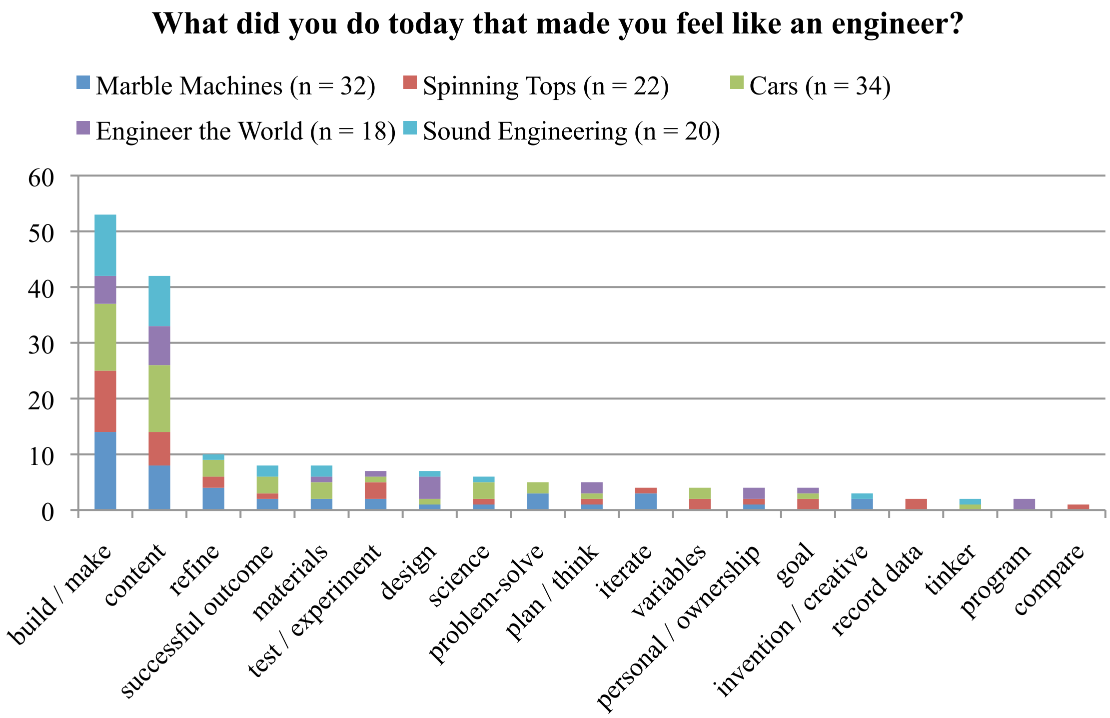


Figure 7.4: Coded visitor survey responses to "What did you do today that made you feel like an engineer?" by challenge.

Not surprisingly, surveyed Sound Engineering visitors mostly mentioned building or making, followed by the content of the challenge (see Figure 7.4). A slightly greater percentage of visitors here mentioned building and making, content, successful outcome, materials, and tinkering compared to other challenges. Unlike the other challenges, Sound Engineering visitors did not mention testing or planning, which is in contrast to observations that show Sound Engineering visitors spent the most time testing and the most time and frequency discussing test results. Unlike Engineer the World, there was no mention of personalization or ownership and no mention of goals.

Similar to survey responses, interviewed visitors mostly described engineers as making, building, or creating, specifically mentioning structures and vehicles in pre-interviews. These interviewed visitors gave similar responses to the interviewed visitors from Marble Machines, Spinning Tops, and Cars. However, unlike the visitors from these three traditional challenges, only one of the visitors from Engineer the World and Sound Engineering mentioned that they didn't know what engineers do. And, the visitors here further mentioned design (4 of 8 groups), improving (3), new ideas (3), mechanical (3), and various kinds of engineering (2).

Post-interviews show little change in visitors' responses. Coding of the responses demonstrates that making, building, and creating was still the dominant response, and other aspects, such as design, improving, mechanical, and different kinds of engineering, were actually less frequently mentioned than before. This may have been due to the visitors having already mentioned it in the pre-interviews, which were mostly less than an hour before, or the visitors may have felt that the actions of making and building in the Ingenuity Lab were reinforced as engineering. Specifically, visitors in Engineer the World mentioned more programming, planning, and regretting and less design and helping society while visitors in Sound Engineering mentioned more making and building, testing, programming, and wiring and less improving.

Interestingly, comments in interviews and surveys show that visitors at Engineer the World emphasized the concept of designing before building, or the excitement of turning their plans into a real website on the computer. One parent of a 5-year-old stated: "opportunity for my kid to get creative and excited about turning his ideas on paper into something real." Comments in interviews and surveys show that visitors at Sound Engineering heavily discussed the materials and example designs. An 8-year-old female mentioned "working with certain materials to have a result" made her feel like an engineer, and a 9-year-old female said that she was able to "[c]reate [her] own instrument with only four materials." One parent of two girls stated that "[their] way of looking and using the materials is different than mine." See Table 7.2 for further comments.

Table 7.2: Visitor survey comments on their experiences with engineering.

Engineer the World	**Sound Engineering**
"*Designing before building*"	"*Create my own instrument with only four materials*"
"*Make them to think new ideas and visualize fun things*."	"*[their] way of looking and using the materials is different than mine*"
"*It allows kids to think about how to organize the information*."	"*That it actually worked with recycled materials*"
"*think the way to help users navigate information*"	"*I piece[d] [my design] together from the example at the front with different materials*"

Furthermore, in post-interviews and surveys, visitors in both challenges newly mentioned the rewards of creating a functional product, something that "works." And visitors noted that there is not one correct solution or design. For example, one 11-year-old female observed, "there are infinity options of sounds."

When asked in pre-interviews whether they felt like an engineer, four of nine Engineer the World and Sound Engineering visitors said no, while only two said yes and three said maybe. In post-interviews, five of nine mentioned that they felt like what they did was engineering while only two said they did not feel it was engineering. These two stated that they did not fully complete their project, one saying that he "kinda made something" and the other saying that it "didn't exactly work." Similar to the traditional three challenges of Marble Machines, Spinning Tops, and Cars, the pre-post responses are inverted, thus indicating that the challenges engaged those without engineering experience or identity in what they identified as engineering activities. One 12-year-old in Engineer the World stated: "I feel more like an engineer now because we're making new things and new designs." Another 7-year-old in Sound Engineering described how their failures were engineering because "some engineering stuff doesn't work; [engineers have to] test it before they do real work."

Interviews show that most visitors in these two challenges recognized that the activity was related to engineering. In terms of relating the activity to specific real world products, 100% of the eight visitor groups from Engineer the World and Sound Engineering identified related products, while only five of 13 (38%) visitor groups from the traditional challenges, Marble Machines, Spinning Tops, and Cars, were able to identify related products. Thus, visitors at these two challenges were able to connect the tinkering activities to their everyday world, perhaps better connecting their actual engineering experience with the formal perception of engineering than those in the traditional challenges.

7.3 Surprise at Accessibility: Persistence through Confidence and Agency

As the content of these two challenges were more explicitly related to visitors' lives (i.e., websites and loudspeakers were products they regularly encounter), visitors were especially excited when they got their designs to "work." One adult visitor at Engineer the World wrote that s/he was surprised at "how accessible it was to my 4 year old" while one 7-year-old female at Sound Engineering stated that she was surprised "it actually worked with recycled materials." In other words, visitors were surprised that they could actually make these everyday products in an accessible experience. Furthermore, the visitors again noted the simplicity of the materials and the challenge, like in the traditional three challenges. Timelines from the observations show that Sound Engineering visitors, in particular, spent a great amount of time with the materials. They expressed appreciation of the simple and recycled materials in the survey comments. Compared to the traditional three challenges, visitors at Engineer the World and Sound Engineering did not mention the trial-and-error persistence as frequently and only one group mentioned collaboration, with a couple others praising the staff and volunteers. However, visitors in these two challenges further mentioned the rewarding aspect of creating something real, as related to their everyday lives. See Table 7.3 for sample comments.

Table 7.3: Survey quotes from visitors at Engineer the World and Sound Engineering.

	Representative comments
Agency and persistence to make something "work"	*"the kids did it by themselves"* *"I changed, revised, and edited the stuff I was making just like an engineer"* *"invented something new that functions"*
Simplicity of materials and challenge	*"making drawings and cutting out"* *"Create my own instrument with only four materials"* *"That it actually worked with recycled materials"*
Accessible, multiple paths and solutions	*"how accessible it was to my 4 year old // engaged my little girl in coding"* *"structure - free to interpretation"* *"creative and interesting handson activities"* *"the interactivity"* *"Different designs"* *"that there are infinity options of sounds"*
Teamwork	*"helped my [5-year-old] daughter build a speaker"* *"all the great volunteers"*
Rewarding	*"connection to real world"* *"opportunity for my kid to get creative and excited about turning his ideas on paper into something real"* *"That what I made was making nice sound."* *"that it actually makes music"*

In both challenges here, and in the three traditional challenges without cross-community collaboration described in Chapter 5, visitors frequently praised the facilitators – the staff and volunteers who assisted them in the Ingenuity Lab. They particularly felt that the facilitators were making the experience accessible to the children regardless of age or gender while still allowing the children to control the experience. One adult visitor stated that the experience was "just the right mixture of help and letting them explore," and another wrote in the survey: "Thank you for enthusiasm and answering child's questions!" One even noted: "Friendly and open people; loved the 'girl power.'"

Thus, as emphasized by the designers in both collaborations, guidance was extremely important in making the experience personal and accessible for visitors. The collaborations also both continually refined the challenge during implementation to improve guidance through facilitation and signage. In Engineer the World, facilitators mostly interacted in extended one-on-one time during implementation of the paper prototype onto the computer for a website, and in Sound Engineering, facilitators assisted with testing of the speakers. Both challenges included the increase of signage in the space to help clarify common confusions for visitors.

Among the overall successful characteristics (Figure 7.5) of these two challenges recognized by visitors are the hands-on aspect of creating something that works or is real, open-endedness for creativity and multiple solutions, fun, facilitation, accessibility, technical content, and examples of designs. Visitors at these two challenges mentioned the specific technical content much more frequently than at the three traditional challenges without industry collaboration. By challenge, visitors from Engineer the World mentioned creativity more than at any other challenge. Most visitors (58% of 26) also described drawing, designing, or programming as their favorite part of the Engineer the World challenge. They further mentioned the fun, technical content, and real world relationship. Visitors from Sound Engineering mentioned having a working design (62% of 26) more than visitors at any other challenge, making the speaker or instrument with recycled materials, testing and hearing their designs work, the open-endedness, and the technical content. They also found it very surprising that they could make different sounds with their designs. These visitors were the only ones to mention the example designs. See Appendix G for full comparisons across the challenges.

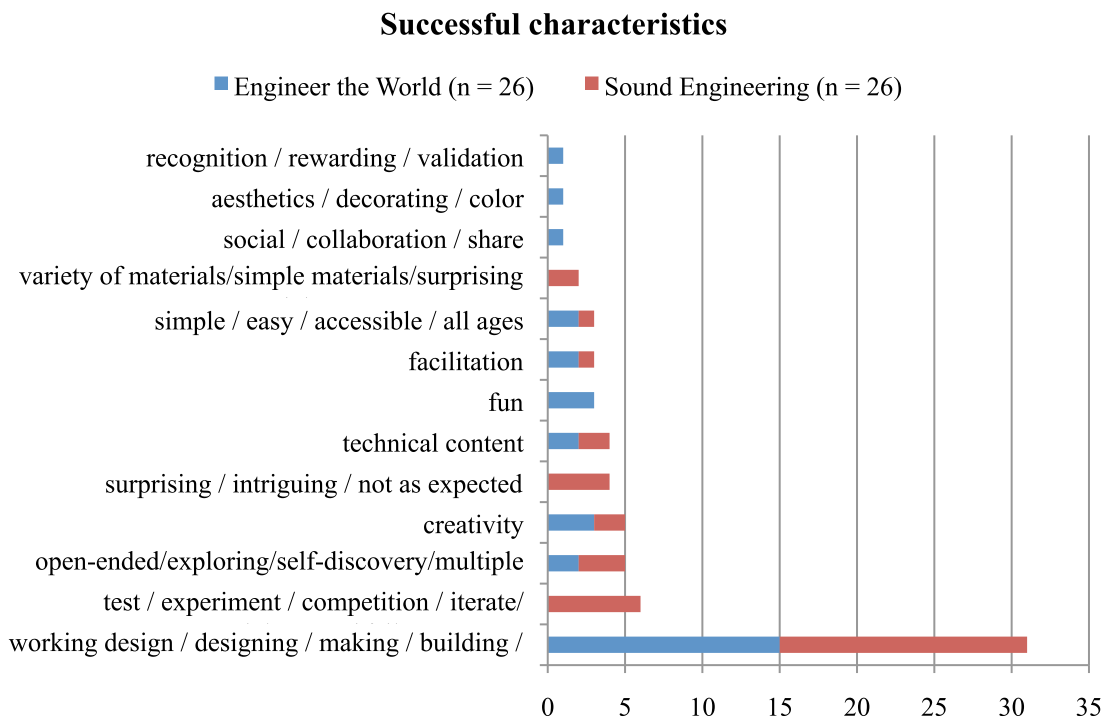


Figure 7.5: Coded visitor survey responses about the successful characteristics of the challenges.

7.3.1 Continuing the Experience

According to survey responses, a greater percentage of visitors at these two challenges had prior experience at the Ingenuity Lab compared to visitors at Marble Machines, Spinning Tops, and Cars. Half of respondents at these two challenges, 11 out of 19 at Engineer the World and 10 out of 23 at Sound Engineering, had previously attended at least one challenge while only 27% of 77 at the three traditional challenges did so. The difference in previous attendance between the three challenges and the two challenges is statistically significant ($F(1, 117) = 6.37$, $p = 0.01$)

However, when asked in surveys if they had previously done anything like the current challenge, 71% of 35 survey respondents said "no" while 62% of 65 from the previous three challenges without industry collaboration said "no." Thus, while half of the visitors had been to previous

Ingenuity Lab challenges, the Engineer the World and Sound Engineering challenges gave visitors a new engineering experience, potentially broadening their concept of engineering. Most of these visitors (88% of 32) responded that they want to continue these activities in the future, with the exception of two who said "maybe" and one who said "no."

Similarly, interviews show that most of the observed visitors had not done anything similar to the challenge. Half of the six at Engineer the World and six of the eight at Sound Engineering stated that they did the challenge as a new experience. And, all but one of the observed visitors stated that they wanted to continue these activities in the future. The one who said "no" participated in Sound Engineering and seemed disappointed that his design did not work as expected, as he had a very ambitious goal, and was anxious to finish the interview. Of the ones who did want to continue, six mentioned wanting to do something similar or make improvements on their designs, and a couple mentioned continuing the experiences at home or doing an unrelated project.

The children not only noted in interviews that they wanted to continue the experience, but some also described how the experience empowered them. One 12-year-old male at Engineer the World stated, "With [this] newfound information, we can do whatever we want." Further, parents were also inspired to continue the experience, as demonstrated in the surveys, by coming back to the Ingenuity Lab or continuing with their kids at home. This parent involvement is very important in fostering children's self-efficacy (Bandura et al., 2001), particularly what activities are routine or accepted, and the same enthusiasm shown by the children indicates that continuation of these types of engineering experiences is likely. Therefore, these Ingenuity Lab challenges have empowered those without prior engineering experience or identity through engagement in engineering.

7.4 Discussion

In order to determine if these two new challenges were successful, I review the goals of the two collaborations. Both collaborations aimed for authenticity and accessibility, with authenticity meaning that the engineers' practices were represented and accessibility meaning that visitors could engage in these practices. Specifically, the Engineer the World collaboration wanted to achieve engineering authenticity by showing that engineering is creative, broader than mechanical, and involves a design-build-test process. They strived for accessibility with the goals to reach all ages and genders and to make the experience personal. On the other hand, the Sound Engineering collaboration wanted to convey authenticity through revitalizing the "dying artform" of making loudspeakers and allowing for multiple solutions. Their goals for accessibility included making the experience hands-on and interactive and modularizing components to make the designs easy to build, take apart, and rebuild. This collaboration also had a long-term goal to get kids excited about sound engineering and wanted to make the challenge sustainable in terms of finances and environment.

Furthermore, I include my own criteria for success of the challenge, focusing on visitor experience and persistence. In particular, my criteria are visitor attendance and stay-times comparable to or better than the traditional challenges, positive enjoyment, persistence, and agency and confidence to continue.

For the collaboration's criteria and my own criteria, Engineer the World was a successful design challenge for the Ingenuity Lab. With respect to the collaboration's goals, the Engineer the World challenge ultimately engaged visitors in creativity and the entire design process, as noted by adults in surveys (12% of 26 survey responses, the greatest percentage across all challenges, mentioned creativity and personalization) and indicated by the high cascades of observed visitors (the highest average cascade of all challenges at 0.83, showing full engagement in behaviors and self-monitoring to engage in appropriate behaviors). An engineer and parents in surveys noted the challenge's ability to reach all ages and genders, thus achieving the accessibility goals. The content of website and app design was also not mechanical engineering, contributing a broader view of engineering than is typical. Accordingly, the collaboration's goals were met.

Considering my criteria for success, visitor attendance and stay-times were comparable to other challenges. The visitor attendance was slightly lower than the average across the five challenges; Engineer the World engaged an average of 72 visitors per day while the average for all five challenges was 101 visitors per day. The average stay-time at Engineer the World was 33 ± 13 minutes, the second longest stay time for all five challenges and just under the average for all challenges of 34 ± 12 minutes (see Table 4.3 in Chapter 4 for all the challenges' average stay-times). In terms of positive enjoyment, the majority of survey comments and children's comments in interviews were positive (see Appendix I for representative visitor comments in surveys and interviews). Observations show that visitors were persistent in this challenge; all timelines indicate a full iteration from planning and design to implementation. Finally, as described in the previous section, most visitors indicated a desire to continue (10 of 13 survey responses, with two indicating maybe, and all six interviewed children), likely as a consequence of agency and confidence resulting from the experience.

Sound Engineering was also a successful design challenge, even with the slightly different criteria of its collaboration members. The challenge achieved the collaboration's goals to revitalize the artform of making loudspeakers and to excite children; it engaged visitors in loudspeaker building, which observations and surveys indicate excited the children when the designs "worked." Survey and interview responses from both children and adults indicate that visitors were excited about the challenge content of sound and vibration (see Appendix I). The challenge was also interactive and hands-on, as noted by the frequent discussion of materials in both surveys and interviews (12% of 26 survey responses and all five interviewed groups). Observations of visitors and notes from the collaboration members show that visitors created a variety of designs, thus achieving the criterion of multiple solutions. The outcome of the collaboration was a challenge that emphasized the physical interaction through a multitude of recycled materials that were reused across visitors, consequently achieving both the goals of hands-on interaction and environmental sustainability. The materials were also partially pre-built into modular components to facilitate assembly, breakdown, customization, modification, and reuse. Therefore, the collaboration's goals were achieved.

In terms of my criteria for success, visitor attendance was just under the average for the five challenges at an average of 98 visitors per day. The average stay-time for Sound Engineering was also just below the average at 31 ± 14 minutes. Thus, the attendance and stay-time is comparable to the other challenges. Visitors in surveys and interviews also indicated positive enjoyment of the challenge (see Appendix I for representative comments). Persistence was shown by the multiple iterations of observed visitors. Finally, survey responses and children's interview responses suggest that the criterion of visitors continuing the activities was achieved; both adults and children mostly mention that they would like to do similar activities in the future (all 19 survey responses and six of seven interviewed children said they want to continue). Thus, the collaboration's goal of sustaining the challenge through continued engagement (and thus, financially) was also achieved.

The two outcome challenges developed by the collaborations, Engineer the World and Sound Engineering, each had unique content and goals. The goal of the Engineer the World challenge was to make a website or app, in particular, prototype the website or app on paper, then implement it on the computer with help from the facilitator. The goal of the Sound Engineering challenge was to make something that makes sound. Visitors could make a loudspeaker with the pre-built coils (of varying numbers of turns) and various recycled materials or go the acoustic route and make an instrument with the same materials.

The timeline patterns vary across challenges because of the unique context of each challenge, with different behaviors observed in different design situations, as found by Jin & Chusilp (2006). Table 7.4 shows the percentage time and average frequency spent in the 11 design behaviors across the five challenges. Engineer the World visitors were the only ones who sketched, as sketching was part of the challenge. Physical materials were not very important in the Engineer the World challenge; visitors spent almost just as much time sketching and planning as they did on building the website on the computer. However, all observed visitors only completed one full iteration of design, progressing from the sketching and planning to the implementation, which was heavily facilitated one-on-one. Because of the much more open-ended nature of the challenge, visitors found the challenge to foster creativity and allow for personalization. On surveys, parents reported drawing, designing, programming, creativity, fun, technical content, and the relationship to the real world as significant components of their experiences.

Timelines show that Sound Engineering visitors uniquely and consistently looked at other designs because of the presence of a table of examples. The creative use of simple materials was also very important as visitors spent the second most time of all challenges in exploring physical materials and frequently mentioned the materials in surveys and interviews. Unlike Engineer the World, these visitors often engaged in multiple iterations and continually refined their designs. Compared to all other challenges, visitors at Sound Engineering (children in interviews and parents in surveys) most commonly mentioned making a working design, in particular noting their excitement about hearing their speakers or instruments make sound.

Table 7.4: Similarities and differences across challenges, by behavior. Average frequency (f) and percentage of time spent (p) by challenge is noted with grey shading, with darker shades indicating greater frequency and percentage (see Appendix H for shading code). MM = Marble Machines (n = 7), ST = Spinning Tops (n = 5), C = Cars (n = 6), EW = Engineer the World (n = 6), and SE = Sound Engineering (n = 10).

Engineering Design Behavior	**Observations**	**MM (f, p)**	**ST (f, p)**	**C (f, p)**	**EW (f, p)**	**SE (f, p)**
Describes/identifies a problem to be solved	Not very common across all challenges; low frequency and short durations for all except Marble Machines and Cars.	6.43, 1.76%	0.93, 0.65%	4.27, 1.51%	1.58, 0.63%	0.60, 0.34%
Expresses a design goal	Uncommon across all challenges; low frequency and short durations except Marble Machines and Engineer the World.	6.14, 2.91%	2.53, 1.68%	3.66, 1.38%	5.16, 3.19%	1.80, 1.67%
Considers one or more options for achieving goal	Not very common across challenges, except Engineer the World. Also occurs more in collaborations.	3.90, 2.48%	2.66, 2.17%	4.77, 4.80%	9.50, 7.26%	2.40, 3.08%
Sketches design	Only Engineer the World engaged visitors in sketching regularly, but no visitor returned to this behavior after implementation.	0, 0%	0, 0%	0, 0%	4.08, 22.41 %	0.10, 0.10%
Explores/selects appropriate materials/tools from available options	Marble Machines, Cars, Engineer the World, and Sound Engineering engaged visitors heavily in this behavior using unfamiliar materials or familiar materials in unfamiliar ways.	14.95, 10.10 %	2.53, 7.31%	6.00, 37.94 %	6.25, 14.16 %	6.05, 13.56 %
Makes causal inference/predictions about how design will perform	Very uncommon across all challenges.	3.24, 0.97%	1.80, 0.73%	1.27, 0.51%	0.33, 0.83%	2.00, 1.39%
Builds or modifies design	Most common behavior across all challenges.	34.52, 44.77 %	7.60, 14.01 %	19.06, 63.39 %	12.00, 25.91 %	13.20, 40.86 %
Tests design	Occurred in all timelines with complete participation. Especially common in Marble Machines and Sound Engineering's instrument challenge, which let visitors test their designs in-situ; visitors transitioned frequently between *Builds or modifies design* and *Tests design*.	36.14, 8.64%	4.60, 10.79 %	16.67, 6.25%	10.08, 2.95%	9.65, 12.79 %
Analyzes what happens and what can be improved from the tests	Most frequent in Spinning Tops, Engineer the World, and Sound Engineering, which had facilitators assist in testing; Tops also had visitors graph and compare results.	2.38, 0.58%	3.93, 4.49%	0.55, 0.63%	4.33, 2.91%	5.35, 5.90%
Discusses how this activity relates to the real world, engineers, etc.	Cars, Engineer the World, and Sound Engineering visitors discussed more real world relevance of the challenges.	0, 0%	0, 0%	0.55, 0.33%	1.42, 1.50%	1.25, 0.55%
Looks at/compares with other designs	Sound Engineering, with a table of examples, was the only challenge where all groups looked at example designs. All other challenges only had 2-3 groups look at other designs.	1.10, 0.42%	0.80, 0.48%	1.22, 0.97%	0.50, 0.51%	2.35, 3.80%

In comparison, visitors at the three traditional challenges also exhibited unique trends. Marble Machines challenged visitors to design and build a working track for marbles. Spinning Tops had visitors create a top that could spin for as long as possible. The goal of Cars, as a much more complex challenge, was to build a working, motorized car. Marble Machines and Cars were similar to Sound Engineering and engaged visitors in physical, tangible materials. Marble Machines was easy to test, and therefore visitors tested frequently. Visitor design behaviors at Marble Machines, Cars, and Sound Engineering were strongest in exploring materials, building, and testing. Spinning Tops was unique in that the data from previous visitors' results were graphed publicly and a leaderboard kept track of top spin times; visitors here consequently did more comparing and analyzing of designs, relative to the frequency of testing (see Table 7.4). Sound Engineering visitors similarly analyzed their designs regularly, likely because both Sound Engineering and Spinning Tops challenges had facilitated tests. Engineer the World was most unique to the three traditional challenges and to Sound Engineering, as it was the only challenge that involved paper sketching and prototyping and involved virtual manipulatives on the computer; thus visitors here exhibited comparatively strong cascades with only a single iteration.

Overall, results suggest that the collaborations did have an impact on visitor perceptions, experiences, and persistence. Based on the baseline data of the traditional challenges, Marble Machines, Spinning Tops, and Cars, I hoped to see that visitors would make more connections to the real world, engage in broader engineering behaviors, and exhibit stronger cascade patterns in their design timelines. Observations, interviews, and surveys of visitors at Engineer the World and Sound Engineering show that these visitors more frequently made the connection to the real world ($p = 0.0017$; Table 7.5) and engaged in broader engineering behaviors when compared to visitors at Marble Machines, Spinning Tops, and Cars with no industry collaboration (see Table 7.5). In particular, visitors here were all able to identify related real world products when prompted, and many spontaneously discussed these products during their engagement in the challenge. They were especially excited when they could create a "working" or "real" version of the product on their own and indicated desire to continue these activities. Not only did the visitors note the real world relevance, but many also described the technical content of the challenges (see Appendix G).

In terms of engineering behaviors, these visitors spent significantly more time in planning, analysis, discussion, and comparison when compared to visitors at the traditional challenges not developed by the collaborations (see Table 7.5). Furthermore, the cascade patterns in the timelines are slightly stronger in these groups, indicating that these visitors may be better at self-monitoring their design progress to engage in appropriate behaviors at appropriate stages (the average cascade at challenges developed by the collaborations is 0.69 while the average cascade at the three traditional challenges is 0.39; $p = 0.016$). However, visitors here, similar to the visitors in the three challenges without the cross-community collaborations, continued to describe engineering as mostly building and making. Nevertheless, surveys and interviews show more mention of designing and planning for visitors at Engineer the World and more mention of materials and comparing designs for visitors at Sound Engineering, indicating some broader perceptions of engineering (see Figure 7.4).

Table 7.5: Unpaired t-tests comparing engineering design behaviors between traditional challenges not developed by a collaboration and challenges developed by collaborations (*p < 0.10 approaching significance; **p < 0.05 significant; ***p < 0.01 very significant).

Engineering Design Behavior	**Frequency**		**Percentage time**	
	traditional (n = 18)	collaboration (n = 16)	traditional (n = 18)	collaboration (n = 16)
Describes/identifies a problem to be solved	4.19**	1.31**	1.37%*	0.59%*
Expresses a design goal	4.31	3.88	2.06%	2.80%
Considers one or more options for achieving goal	3.85	5.69	3.17%	5.51%
Sketches design	0.00***	1.94***	0.00%***	9.68%***
Explores/selects appropriate materials/tools from available options	8.52	6.00	18.60%	12.75%
Makes causal inference/predictions about how design will perform	2.19	1.44	0.75%*	1.47%*
Builds or modifies design	21.89	13.69	42.43%	31.40%
Tests design	22.56	11.50	8.44%	9.08%
Analyzes what happens and what can be improved from the tests	2.20***	5.38***	1.68%***	5.03%***
Discusses how this activity relates to the real world, engineers, etc.	0.19***	1.50***	0.11%***	1.03%***
Looks at/compares with other designs	1.06	1.50	0.62%*	2.54%*

Not only was each challenge unique in context and background as described above, each experience of each visitor was unique. Thus, variance occurred not just across the challenges, but also within the challenges. It is therefore difficult to strongly support any findings about the differences between the challenges. Rather, this dissertation gathers findings across the different cases in order to illustrate certain features that may have contributed to engagement in certain engineering behaviors. Table 7.6 summarizes documentation on indicators of engineering learning, as illustrated by these cases.

Despite these differences, there were many similarities in the positive experiences of the visitors and characteristics of the challenges across all five challenges. Visitors in all five challenges gained confidence and agency; many who did not previously identify as engineers experienced these types of engineering activities for the first time (18 out of 31 interviewed children and 65 out of 96 surveyed groups) and nearly all children and parents stated their desire to continue these activities (25 out of 26 interviewed children and 79 out of 85 surveyed groups, with four unsure). Parents in particular specifically noted their surprise about the accessibility of getting the designs to work, the open-endedness for creativity, the simplicity of the materials, the fun, and the facilitation.

Table 7.6: Indicators of engineering learning, based on the 34 observed cases of visitors at the Ingenuity Lab.

Indicator	Meaning
Multiple iterations	When the learner engages in multiple iterations of refinement, he/she shows persistence in face of failure and understands that there is not one correct solution, but possible best solutions through identifying trade-offs and engaging in systems thinking. Progressively successful iterations imply that the decisions of refinement were justified by information from testing, which should happen throughout the process (Adams, 1999).
Expert cascade pattern	With an expert cascade pattern progressing from Problem Scoping to Developing Alternative Solutions to Project Realization, the learner is showing his/her ability to self-monitor his/her design progress, knowing which stage is appropriate when and not reaching a solution too quickly.
Sketching and planning	This leads to a stronger cascade pattern; sketching and planning indicates greater consideration of the problem and possible designs. This was a step neglected by almost all visitors who were not required to sketch.
Engaging with physical	Through exploring materials, building, and testing, the learner is engaging in novice engineering by using these activities as a means to problem scope, identify goals, identify constraints and potentials, explore possibilities, and synthesize and generate knowledge about the problem space (Adams & Atman, 1999). Through this process, the learner revises his/her own understanding of the problem and design.
Setting a goal	The learner understands engineering as goal-oriented. Setting a goal, as part of problem scoping, is the first step towards planning in problem-solving, and the goal reflects the learner's understanding of the problem as complex, open-ended, and constrained.
Looking at other designs	This indicates that the learner is exploring existing solutions as a means to gain inspiration and improve upon others' designs. This is a form of collaboration.
Transitioning between behaviors	Transitioning between exploring materials, building, and testing suggests transitioning between information gathering and concept generation.
Collaborating	Through collaboration, including asking for help, the learner recognizes his/her own limitations and the value of working with others. He/she learns teamwork and communication, particularly how to work with others and the different roles and strengths of each team member.
Curiosity, determination, willingness to learn	This is very important for a successful engineer, and indicates that the learner has the ability to learn something new. Engineers must constantly keep up and learn the latest research and technology.
Unique solutions	Creating a unique solution indicates the ability to think outside the box and to not be afraid of failure or being different.

7.5 Summary

For visitors, the plan or goal usually just emerged, often from engaging with the materials. But in these two challenges, particularly in Engineer the World, visitors spent more time on a plan before starting to build. Visitors also engaged in more discussion about the outcome of their designs; thus, they exhibited more scoping and more refinement. Facilitators, who provided a direction or goal, frequently guided both of these behaviors. During implementation of the challenges, the two collaborations found that more guidance was needed in the form of facilitation and signage to create better mutual learning experiences. Consequently, guidance is key to these experiences in open-ended environments; Linn (1980) found that free choice is not necessarily productive unless goals are clear to students. Furthermore, design, by nature, is constraint-based. For instance, Sound Engineering was constrained to simple, recycled materials, but visitors developed a wide variety of creative solutions. This guidance provided the appropriate direction for visitors to accessibly engage in tinkering activities grounded in authentic engineering; they connected the activities to the real world relevance, bridging their practices of engineering with the formal perception of engineering. The challenges empowered visitors to engineer. In the next and final chapter, I propose guidelines to design accessible and authentic engineering experiences for this type of open-ended space. I further summarize my findings, discuss the research questions, acknowledge limitations, and suggest implications from my dissertation.

Chapter 8

Conclusions: Empowerment through Engineering Design Experiences

Through research on two cross-community collaborations and five Ingenuity Lab challenges, my dissertation explored how grounding the tinkering activities of the challenges in authentic engineering may have connected the perceived formal (real-world engineering) and the actual practical (tinkering) engineering (Sandoval, 2005). I hypothesized that with the collaborations, the formal and practical engineering would be aligned. As a result of the alignment, doing and constructing in the tinkering activities would not only lead to construction of knowledge (Papert, 1991; Resnick, 2006; Bamberger, 1991) but also lead to the construction of identity and agency in engineering. By investigating the social, physical, and personal factors of learning, I sought to understand what learners are doing in these tinkering activities to inform how to create successful learning opportunities that serve as accessible pathways towards engineering. In particular, I wanted to explore how the collaborations engaged in the design process to create these learning activities and connect the activities to authentic engineering, as well as how they may have impacted the visitor experience. In this final chapter, I provide a summary with a cross-analysis of the five Ingenuity Lab challenges, explore the research questions and findings on the collaborations and their impacts on visitor experience, acknowledge the limitations of this dissertation research, and end with the implications, design guidelines, and some final words.

8.1 Comparison of the Traditional and Cross-Community Ingenuity Lab Challenges

In summary, analysis of the three traditional challenges shows that many visitors were demonstrating behaviors like expert engineers, suggesting that they are able to self-monitor their progress deliberately and expertly. By engaging in engineering design, visitors constructed entities, thus constructing knowledge (Papert, 1991; Resnick, 2006; Bamberger, 1991), and data show that they further constructed identities and agency as someone who can engage in these types of design challenges, supporting my hypothesis in Chapter 3, Section 3.3. However, visitors infrequently connected the activities to the real world or engineering careers, indicating a gap between their actual practice at the Ingenuity Lab and their perception of formal engineering. They also mostly engaged in and identified building as engineering, a limited perspective of engineering. To determine if these issues could be improved with cross-community collaborations, this research explored the development of new challenges with industry engineers and college engineering students. The cross-community collaborations emphasized engineering authenticity, in addition to accessibility, aligning the visitors' actions with the real world and engineering careers. Results show that visitors further engaged in and identified broader engineering behaviors, and they successfully identified the activity as relevant to the real world or engineering careers. Thus, cross-community collaboration can successfully ground tinkering at science centers in authentic engineering practice.

In comparison, the Engineer the World challenge was very unique to the three traditional challenges. The collaborators emphasized creativity and design, and the resulting challenge reflected this; the challenge engaged visitors in planning through sketching for an average of over 22% of their time, and all six observed visitors sketched consistently while sketching was absent in all other observed visitors at the traditional challenges. With the greater time spent in sketching, these visitors also spent less time building and testing compared to those in the traditional challenges, except for Spinning Tops visitors, who spent even less time building. Thus, the collaboration emphasized the full design process, and visitors did engage in the full process from planning to implementation. However, unlike in the traditional challenges, these visitors engaged in only one iteration of design. For the real world relevance, visitors here discussed real websites.

The Sound Engineering challenge was more similar to the traditional challenges. The collaboration emphasized interactivity and guidance; the collaborators facilitated these through the structure of the challenge by modularizing components for design, including signage that detailed what to do, and offering test stations that were facilitated. Similar to the three traditional challenges, these visitors spent most of their time exploring materials, building, and testing. In surveys and interviews, they frequently mentioned the simplicity and accessibility of materials, similar to comments on Marble Machines and Spinning Tops. Like the Spinning Tops challenge, the tests were facilitated and visitors frequently analyzed their designs after testing. The environment of this challenge also had a designated area for example designs; visitors were observed to spend much more time looking at and using these other designs, which helped inspire them, when compared to the traditional challenges. For the real world relevance at this challenge, visitors named a variety of products, including speakers, headphones, radio, music, instruments, and cones.

Across the challenges (see Appendix G), surveys (responses from parents frequently with input from children) show that visitors most commonly (36% of 148) mention creating something hands-on, in particular creating a working design, when discussing their favorite or most surprising part. Others describe feedback from testing, experimenting, and trial and error (18%); the challenge or difficulty encountered (12%); the open-ended discovery and multiple solutions (10%); the creativity involved (8%); how fun it was (8%); the positive experience with facilitators (8%); and the accessibility or simplicity of the challenge (7%). Surveys show that visitors did perceive the activities as related to engineering, most commonly indicating building, making, designing, problem-solving, refining, technical concepts, selecting materials, testing, and iterating.

Analysis of observations show that like the experts in Atman et al. (2007; see Figure 8.1), many visitors exhibited a cascade pattern in their design timelines, progressing from Problem Scoping to Developing Alternative Solutions to Project Realization and transitioning frequently within and between these stages. The cascade pattern suggests that these visitors, while they are only novice engineers, are able to assess the state of their design process and have a sense for what behaviors are appropriate during the process; they are able to self-monitor their design progress similar to expert engineers engaging in design. Furthermore, the longer time spent in these activities indicates an extended process that allowed learners to self-assess, critique, revise, and reflect to iterate and refine their ideas (Lee, 2009; Resnick, Berg, & Eisenberg, 2000) and their solutions while learning from mistakes and from others (Papert, 1991). The observation data show many variations within challenges, and some visitor timelines had no indication of a cascade pattern while others exhibited very strong cascade patterns. For some timelines, repeating cascades are visible, indicating multiple iterations of refinement that are characteristic of expert engineering design (Adams, 2001). The multiple iterations suggest the persistence of the learner in achieving a working solution and his/her ability to integrate information from previous iterations. In general, the easier it was to test the design, the more iterations occurred, since the ease of testing gave quick and frequent feedback about the success or failure of the design. The variation of timelines is not surprising given the diversity in visitor backgrounds and the strong influence of facilitators on the visitors' design processes. However, one-way ANOVA of the means of the cascades shows that Spinning Tops, Engineer the World, and Sound Engineering engaged the observed visitors in stronger cascade patterns while Cars visitors exhibited much weaker cascades ($F(4, 29) = 2.99$, $p = 0.035$). Thus, the nature of the design task and the materials at each challenge may have led to particular patterns in visitor behavior.

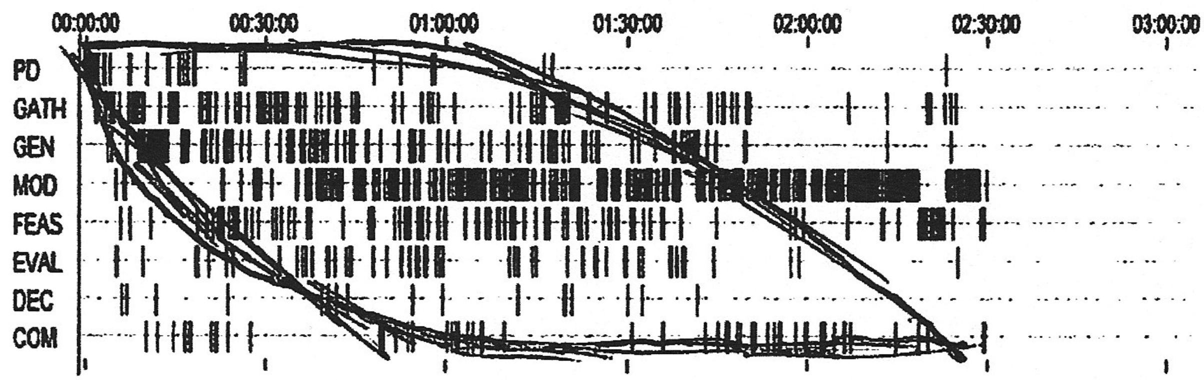


Figure 8.1: (Reproduced from Chapter 2.) Example of an expert *cascade* pattern indicated by a hand-drawn mark over a representative timeline (Borgford-Parnell, Deibel, & Atman, 2010). The *cascade* pattern, or "Ideal Project Envelope," begins in Problem Scoping, transitioning between Problem Definition (PD) and Information Gathering (GATH); then progresses to Developing Alternative Solutions, transitioning between Generation of Ideas (GEN), Modeling (MOD), Feasibility of Analysis (FEAS), and Evaluation (EVAL); and throughout the process transitions to Problem Scoping and Project Realization, which includes Decision (DEC) and Communication (COM). Note the progression from the upper left to the bottom right.

Unlike the experts, visitors spent less time problem scoping. The problem was not necessarily defined; some challenges had more specific goals (e.g., achieve longest spin time in Tops), while others were broader (e.g., make a website in Engineer the World). Visitors instead spent most time modeling and implementing: exploring and selecting materials, building, and testing, which are the top three behaviors by time spent for all except Engineer the World. Because of its unique requirement to sketch before implementation, Engineer the World participants spent relatively more time in the planning behaviors.

The interviews provide further insight into the design processes of visitors. Most visitors (57% of 21 observed groups) mentioned that their goal steered their design choices. However, 43% of these visitors mentioned specific physical materials that inspired their designs through constraints and affordances. Four visitor groups (19%) remarked that their idea "just came" as they explored materials; thus, their goal emerged from this process, explaining the large amount of time spent in the *Explores/selects appropriate materials/tools* behavior. Other visitor explanations for design choices include trial and error, inspiration from other people or examples, and wanting to make something unique. Over half of the visitors (12 of 20 groups) noted that they looked at other designs, with many mentioning gaining inspiration and ideas, some mentioning wanting to modify and build upon those designs, and others mentioning specific materials they noticed.

Interestingly, during observations, visitors rarely explicitly stated their goals; however, when prompted during interviews, they could identify their goals. Importantly, 11 of 21 visitor groups identified trying to achieve the "best" or better solution. Many pointed out the need to modify their designs for improvement (3), as well as trade-offs between various designs or specific problems that prevented them from achieving their goal (5). Thus, these implicit goals prompted visitors to engage in systems thinking and critical analysis, key engineering abilities. The only visitors who noted that they were not able to achieve their goals was one from Sound Engineering and all from Cars; this is interesting given that Cars was one of the most popular challenges with the greatest average attendance and stay-time (53 minutes versus 25-33 minutes for the four other challenges).

In terms of problem scoping across the challenges, these interviews reveal that children identified problems and obtained information while tinkering with materials, gaining inspiration from this process; children also utilized information from existing designs in the space and examples from the real world, often engaging in conversation with others and asking about the materials, designs, and examples. These processes suggest primitive forms of information gathering that similarly inspires experts (Ennis & Gyeszly, 1991); the visitors gathered information mostly on the design context, while experts further consider users, clients, environmental and social impact, etc. Thus, these behaviors of engaging with the tangible can serve as stepping stones towards expert engineering actions.

Therefore, in contrast to expert engineers in Atman et al. (2007), these visitors engaged heavily in tangible activities as a form of problem scoping. Without the foresight of expert engineers familiar with the domain and materials, the visitors spent a lot of time exploring materials, but in a way to gather information and identify problems that influenced their designs. Through co-evolutionary design (Maher & Tang, 2003; Dorst & Cross, 2001), they refined the problem while exploring materials in a reflective conversation between the materials, design situation, and design outcome (Schön, 1992). Thus, they transitioned frequently between exploring materials, building, and testing, where the physical materials helped scaffold them to transition opportunistically between information gathering and concept generation like experts (Ennis & Gyeszly, 1991; Atman et al., 2007). However, the experts in Atman et al. (2007) did not implement their designs and consequently did not engage in any building, only modeling. Through transitions and iterations, the visitors' understanding of the problem and solution further evolved (Adams, 2001). These findings are similar to early analyses from ongoing work on parent-child dyads in informal engineering learning environments (Cardella et al., 2013).

Further, these visitors were strongly influenced by other designs, a behavior unreported by Atman et al. (2007). This behavior emerged through the video coding process. Contrary to experts in the isolated lab, these visitors worked in a non-isolated context and were able to see others' evolving and final designs. Consequently, visitors copied and improved upon others' designs, or made a design unique from others.

In addition, when interviewed visitors described engineering, they focused less on structures, vehicles, trains, mechanical items, and machines after the experience than before (11 of 22 groups before and 6 of 21 groups after identified these items). Instead, they focused more on new things and ideas, creating a functional or useful product, and even the importance of materials (5 of 22 groups before and 7 of 21 groups after identified these items). Thus, the experience may have broadened their perspective on the content of engineering, though they still mostly identified the activities of engineering as building.

8.1.1 The Uniqueness of Each Challenge

In terms of variations across challenges, the timeline patterns vary because of the complex context of each challenge (see Table 7.4 from Chapter 7). Each design situation fostered different behaviors, confirming findings from Jin & Chusilp (2006).

Marble Machines provided an open-ended context where visitors could progress at their own pace and the design was easy to test. Materials were available in the center, and visitors built their designs next to others. Visitors were observed to engage in frequent testing throughout most of the process because the design could be tested by dropping a marble at any time. With the accessibility of the materials and ease of testing, they also showed the most frequency in exploring materials, building, and testing throughout, with many transitions between these behaviors. Thus, they engaged in solving mini-problems by iteratively refining in small increments, and exhibited persistence in problem-solving with the multiple iterations. The cascade pattern for observed visitors was somewhat observable at an average of 0.36 on a 0-1 scale, with no visitors exhibiting a high cascade of 1. Thus, these visitors are not necessarily assessing the state of their design in a way that shows an understanding of what design behaviors may be appropriate and may be less deliberate in their design approach. About half the observed visitors looked at other designs. Visitors commonly stated that the challenge was particularly accessible through the openness and multiple solutions along with the easy, simple materials. They also mentioned iteration, problem-solving, creativity, sharing, and persistence as key features they enjoyed.

Spinning Tops engaged visitors in creating their own tops, testing the tops with guidance from staff in a different location from where they built their designs, then plotting the results of their test on a cumulative graph that was visibly projected. There was also a leaderboard of the longest spin times, which included the variables of height of plates and size of plates, the same variables plotted on the graph. Thus, data was shared from previous visitors, motivating visitors to incorporate this information and persist in achieving the goal of longest spin time. The goal was the clearest of all challenges. Visitors also mentioned in surveys that they valued recognition of their designs on the graph and leaderboard. Compared to other challenges, visitors here spent the most amount of time testing and were observed to almost regularly analyze their design after each test, possibly due to the facilitation of all tests by staff or volunteers. The cascade pattern was moderately high at 0.60, and no low cascade pattern was observed. Unique from the other challenges, these visitors recognized many science and engineering skills, specifically planning, testing, adjusting variables, experimenting, recording data, and comparing, possibly because of the more explicit goal and variables affecting the outcome. They also mentioned aesthetics of the design and made connections to their own spin toys.

Cars probably engaged visitors in the most complex and difficult challenge, challenging visitors to put together motorized LEGO cars from scratch and have it run autonomously down a track. In particular, none of the observed visitors stated that they achieved their goal, and many surveyed visitors mentioned failure as a productive part of their experience. Visitors showed extreme persistence in getting their car to “run,” engaging in multiple iterations. Surveys indicate that visitors understood failure as a method of learning rather than as a result of their inability. As indication of the persistence, visitors were observed to spend significantly more time exploring materials and building since the process was much more complex than other challenges and the materials offered a variety of ways to build. Timelines also show that problem scoping tended to occur towards the end of iterations, often emerging from the *Explores/selects appropriate materials/tools* and *Builds or modifies design* behaviors; this created a reverse cascade pattern, suggesting that exploration of the materials, which were simple yet versatile, helped them to explore and understand the design space. Consequently, the average cascade pattern was the lowest of all challenges at 0.25. Survey responses indicate that visitors were commonly surprised at their ability to get their cars to finally work and they learned specific concepts around car mechanisms (e.g., gearing).

Engineer the World was uniquely structured in such a way that visitors sketched their designs before implementing on the computer with help from a facilitator one-on-one. As a result, these visitors were the only ones who sketched consistently, indicating that sketching out a plan may not be an intuitive step in creating designs. Furthermore, the challenge was completely open-ended, and visitors could make a website or app on any topic of their choosing. Thus, unlike the other challenges, visitors stated a very wide range of goals. Furthermore, with the one-on-one facilitation and with the extended facilitated time implementing the designs on the computer, visitors spent more time planning and were observed to engage in only one iteration. Visitors here exhibited the highest average cascade of 0.83, and no visitor showed a low cascade. This suggests that Engineer the World may have helped structure the experience in a way that visitors were able to better monitor their progress and determine which design behaviors were appropriate for their stages of progress. In describing their experiences in surveys, visitors commonly referenced programming and websites, personal and real world connections, designing before implementing, creativity, and hands-on interactivity. Visitors were especially excited about turning their ideas into something real.

Finally, Sound Engineering provided simple, recycled materials for visitors to construct loudspeakers and instruments that make sound, and a table in the middle of the room exhibited example designs from previous visitors. Loudspeakers were tested at computer stations with help from facilitators. Visitors in surveys and interviews emphasized the materials and the example designs as their favorite or surprising components. Visitors were surprised and excited to get their design to make “real” sound or music from such basic materials. Observations show that they consistently looked at other designs because of the presence of a table of examples. And, visitors spent most of their time building and engaged in analyzing the designs most frequently of all challenges, possibly due to the facilitation of the loudspeaker test. The average cascade rating in the timelines was moderately high at 0.59, and the timelines show that visitors frequently engaged in multiple iterations in persisting to improve their designs.

Constant across all challenge contexts was the open-endedness. All challenges allowed for open access to the materials and self-paced progressions through designs. The environment also allowed for visitors in various design stages to work next to each other, and guidance was available through facilitation. Observations show that with the variance in materials, the constancy of the open-endedness, the ability to observe others, and the guidance of facilitators, these contexts provided opportunities for a range of engineering design behaviors similar to experts.

8.2 Discussion of Research Questions

The aim of this dissertation is to understand the productive roles of designers and visitors at the Ingenuity Lab and the impact of their roles. In particular, this dissertation studied the involvement of college engineering students and industry engineers as designers of science center maker activities within the existing framework of the Ingenuity Lab, a novel form of collaboration for science center educators. I wanted to determine if and how this cross-community collaboration may have impacted the visitor experience, and I aimed to understand the benefits to the collaborators. Through this research, I developed documentation on indicators of engineering learning (see Chapter 7, Section 7.4) and will detail guidelines for accessible and authentic design challenges in the next section. First, I review and discuss my research questions.

How do the diverse collaboration members — college engineering students, industry engineers, and informal science educators — negotiate the ideation process, and what are their roles and contributions in designing engineering learning programs through a cross-community collaboration?

For this research question, my analysis of observation, survey, and artifact data from the two collaborations (each included five engineering students, two industry engineers, and two educators) shows that

(1) the college students took ownership of the design processes through service learning to develop authentic engineering experiences for visitors,
(2) the industry engineers acted as mentors and contributed authenticity with their engineering expertise, and
(3) the educators ensured accessibility in maintaining logistical needs.

Through these contributions, the various members shaped the criteria and ultimately the final design challenge. They established collective ownership of goals early on in the design process, and all contributed criteria and ideas towards the goals. In particular, the goals for both overlapped around engineering authenticity and educational accessibility. The social dynamics played out slightly differently for the two collaborations. For the Engineer the World collaboration, the engineers and educators played substantial roles in shaping the design process, and students were especially flexible in incorporating contributions from all members. Uniquely, the students from this collaboration focused more on teaching and outreach, and the collaboration ultimately developed a very broad set of criteria. The final challenge highlighted creativity, which was initially emphasized by one of the engineers as an authentic part of engineering, in addition to accessibility of engineering to all ages and genders that both the engineers and educators emphasized. The Sound Engineering collaboration's engineers and educators played a smaller role in shaping the design process. By pedagogical design, the students were encouraged to take ownership of the decision-making process for their course project. They came up with criteria and ideas initially on their own, agreeing upon and submitting them as course assignments, then asked the rest of the collaboration members for feedback. The whole collaboration tended to emphasize design processes for the visitor experience, and the students distinctly stressed sustainability and modularity of the design challenge. Modularity, specifically, covered a majority of the collaboration's criteria, from simplicity to quick iterations to sustainability.

Interestingly, both collaborations had very smooth team processes. There was no major dissent or issue, likely because the criteria and goals were agreed upon by the whole group from the beginning. All members contributed ideas and helped select ideas. Both collaborations also combined their top two ideas into the final design challenge. Using a human-centered design process and engagement with visitors at the science center, the multidisciplinary collaborators grew to acknowledge learning as a mutual experience involving interaction and contributions from the learners. Thus, each group worked together towards their goals of authenticity and accessibility to create mutual learning experiences for the visitors, specifically incorporating feedback from educators and visitors to integrate more guidance through facilitation and signage. Guidance helped to personalize the experience for the visitors. This implies the importance of engaging learning environment and curriculum designers with the learners in-situ. The college students rated that, as a result, they had increased awareness of community needs and were able to make a difference as engineers. The overall collaboration members' perceptions of engineering were reinforced, highlighting engineering as much more than a technical profession and stressing the accessibility and rewards of the field through determination, curiosity, and creativity. The authenticity of the experience played a key role for the collaborators; all members especially valued the experience because of the implemented outcome and public impact of their collaboration.

What is the potential impact of the cross-community collaboration model on visitor experience and persistence in engineering?

Analysis of survey data from 148 visitor groups (parents responding with input from children) and observation and interview data from 22 visitor groups (with focus on children) across the five challenges suggest that visitors to the challenges developed by the collaborations engaged in broader engineering behaviors, identified a slightly broader description of engineering, and were able to connect the challenge to its real world counterpart when compared to the visitors in the three traditional challenges. The collaborators' beliefs about learning fostered accessible and personal experiences for the visitors. Almost all visitors across all five challenges perceived the experience as accessible and that they engaged in engineering design, mostly identifying engineering as building. However, I note broader descriptions of engineering for the two challenges developed with the collaborations: Engineer the World visitors mentioned slightly more about designing before building and Sound Engineering visitors placed a stronger emphasis on the materials. Observations confirm that most visitors across the five challenges engaged in engineering design and in various design behaviors. Most time was spent with tangible objects in exploring materials, building, and testing, which was in agreement with visitors' stated perceptions of engineering. Visitors at the two collaborations' challenges exhibited higher average cascades than did visitors at the three traditional challenges, indicating greater expert-like engineering processes, particularly more planning, analyzing, and discussion, especially more discussion about the real world relevance of the challenges. Thus, reflecting visitors' broader descriptions about engineering in the collaborations' challenges, visitors at those challenges engaged in broader engineering behaviors. The cross-community collaboration challenges appear to have further engaged visitors in broader engineering behaviors and these visitors consistently noted the real world relevance, supporting the hypothesis that this collaboration successfully connects the actual practices in the Ingenuity Lab with the formal perception of engineering.

Despite the differences named above, visitors across the challenges showed similarity in their positive perceptions, their agency and persistence, and their past and potential future interest in these activities. Almost all observed visitors engaged fully in engineering design as a positive experience; the only visitors who did not engage fully were two at the Cars challenge. However, the other visitors at Cars showed extreme persistence in the face of failure. Across the five challenges, visitors showed persistence in getting their design to "work." Visitors across challenges also exhibited expert-like engineering processes, suggesting that visitors in these challenges exhibit agency in engineering and are not just playing around, but self-aware and deliberate about their design behaviors. Though most visitors did not have prior experience in these types of activities and few initially identified as engineers, almost all surveyed and interviewed stated that they wanted to continue these experiences afterwards (93% of 85 survey responses, with 5% saying "maybe"; 25 of 26 interviewed). Thus, they identified the engineering experience as positive, gaining confidence and agency through doing the activity and feeling empowered to continue; this supports my hypothesis that constructionism not only leads to construction of knowledge, but it also leads to construction of identity and agency. In particular, the two new challenges developed by the collaborations further connected the visitors' identity and agency with real engineering.

8.3 Limitations and Opportunities

Although my findings are promising, the limitations of the research must be considered. Visitors were self-selected in observations and surveys, as they had to agree to participate. However, visitors were randomly asked to participate as the first ones to enter the Ingenuity Lab during research periods and most (> 90%) agreed to participate. Though this was not a controlled study and causality cannot be drawn, I aimed to prioritize studying visitors naturally in the science center environment and to not disturb real learning as it happened. Furthermore, as a naturalistic observation, no probing was implemented and behaviors were observed while non-spoken thoughts could not be observed. Specifically for visitor observations, videos could not always capture all participants simultaneously; thus, some gaps in observation are noted. And, the small sample size and the variety in backgrounds and context, including the individual facilitator influence, mean that the cases are not necessarily representative of the larger population. Therefore, these cases need to be considered with all the background and context details.

In terms of analysis of the visitor data, I did not observe any expert engineers engaging in the Ingenuity Lab challenges as visitors; thus, these findings should be considered in light of the differences between this study context and that of Atman et al. (2007). The greatest difference is the presence of physical materials to build with in the live and publicly accessible Ingenuity Lab program while Atman et al. (2007) only considered experts' paper-and-pencil planned designs in an isolated lab setting. However, this research provides a better understanding of the ways in which these expert patterns might be created by the various design contexts, contributing as a step towards optimally designing contexts for engineering learning. I saw that, overall, visitors engaged in little problem scoping in comparison to the experts in Atman et al. (2007) and instead heavily engaged in the physical and tangible; visitors also frequently utilized other designs in the space. Thus, future studies should compare the visitors, generally with no engineering experience and therefore novice engineers, with expert engineers in this type of space. Cross-comparison studies should explore how people of varying engineering expertise may engage in this type of live environment with physical materials and other designs to determine if they also exhibit more exploration of materials and building and if they utilize these other designs as a means of problem scoping. Perhaps, then, exploring materials and designs may be a pathway towards expert engineering processes. In order to optimally design contexts for learning, further studies should investigate various engineering learning environments to see if other informal environments show a similar pattern in their engineering-related learning contexts and to provide further examples of engineering patterns shaped by the various contexts and participants.

The collaborations also include participants that are self-selected. The students from Engineer the World volunteered to participate as part of their outreach club and the students from Sound Engineering chose this project for their course. Many of the students actually had prior experience with the Ingenuity Lab or Lawrence Hall of Science, choosing to further their experiences. All engineers also volunteered their own time to participate. Because of the self-selection and possibly because of prior experience, these students and engineers possess desirable values and characteristics of people who engage, which may have resulted in the minimal change between their pre- and post-surveys. Thus, the more important findings from this study may be characterizing the types of engineers that seek to engage in these types of activities and that appreciate different values from diverse team members, representative of successful professional engineers. My conclusion is that these are the types of engineers that the education system should foster to improve the function of engineering teams and therefore their design outcomes. The involvement of these engineers in K-12 learning helps to portray a positive perception of engineering to the public. Experiences like the cross-community collaborations in this study may further foster these types of engineers by engaging other students and the public who would otherwise not be engaged.

Interestingly, there were no power issues or debate for either collaboration, which is not particularly representative of most teamwork in engineering. There may have been ameliorating features that reduced the likelihood of contention, particularly the first meetings which set up an initial discussion of criteria and consequently an overall goal. And, because I was a participant-observer in the process, I potentially biased the process, whose structure may have appeared fixed. I did attempt to stay unbiased in terms of content and idea development. Also, the self-selection of the members means that they were internally motivated to participate and contribute, mitigating any potential issues resulting from unbalanced contribution from members. However, dissent is oftentimes valuable and contributes critical, diverse perspectives. It may be that the final concepts for the design challenges were not the best solutions since the perspectives were not as diverse as they could have been.

8.4 Implications

With the collaborations, all participants benefitted – the students, engineers, museum educators, and visitors. From my hypothesis on sustaining participation through the grounding of activities in authenticity (see Chapter 3, Section 3.3, Figure 3.2), I infer (a) the positive memory of the participants' experience as correlated with interest in engineering activities; (b) the context of the experience as indicative of the potential content of knowledge gained; (c) the constructive doing of the experience as fostering agency and identity in engineering; and (d) the participants' affect in the experience as indication of their perception, attitude, and disposition towards engineering. I now look at each of these with respect to the participants in this research.

First, all members of the collaboration and most visitors commented on the experience as positive. Nearly all visitors stated that they wanted to continue the activities. Thus, both the members of the collaboration and the visitors may be gaining interest in engineering. Second, for these participants, the context really shaped the experiences and concepts learned. For the collaborations, the further engagement of industry engineers with expertise, the educators serving as clients, and the actual implementation with the public helped to provide an authentic engineering design experience for the students. For the visitors, the context of each challenge shaped the engineering behaviors and the concepts learned, with learning from failure and persistence a dominant theme in all challenges, most notably in Cars. For instance, Marble Machines visitors came to better understand the need to constantly adjust and optimize their designs, Spinning Tops visitors consistently used data about variables to inform their design, Cars visitors learned about gearing mechanisms in making their cars run straight, Engineer the World visitors engaged in programming websites, and Sound Engineering visitors noted concepts about how vibrations make sound and the variety of ways to produce sound. Third, the collaborations' participation in the design processes and the visitors' participation in the challenges helped to develop agency and identity in engineering. Though the collaboration members had little change before and after concerning their perceptions of engineering or their engineering skills, the experience seemed to reinforce their agency and identity. And as described previously, few visitors identified as engineers before, but after the experience, almost all identified the activity as engineering and stated that they wanted to continue the experience. Parents were surprised at the accessibility of the activities and the children persisted in achieving their goals. Thus, the accessibility and doing of the activity fostered agency and identity with engineering. Finally, very little negative affect was observed among the collaborations or visitors. In the final meetings for both collaborations, the students particularly remarked how rewarding and enjoyable the experience was and appeared proud of their accomplishments. Surveys also show very positive feedback from all collaboration members, thus indicating a positive attitude and disposition towards the experience. All observed visitors showed intrigue and interest, excitement, or pleasure while engaging in the challenges. In terms of negative affect, only one at Cars showed displeasure and two from Marble Machines showed frustration. Therefore, visitors are presumed to have a positive perception, attitude, and disposition towards these types of engineering activities.

Through the collaborative, open-ended engineering design context, results from surveys and interviews suggest that engaging children and adults together may be extending the learning experience to outside the museum, and contextualization of the design challenge within real-world engineering may be prompting them to continue to discuss relevant topics in the community and how they relate to engineering. As evidenced by observations, parents and children often conversed about the activity and worked together; many even mentioned how they can continue the activities at home. Parent influence is strong and their positive involvement is likely to lead them to extend these activities and continue these conversations at home (Barron et al., 2009; Zimmerman, Perin, & Bell, 2010; Astor-Jack et al., 2007; Parsons, Adler, & Kaczala, 1982). Surveys and observations show that both children and parents have positive experiences at the Ingenuity Lab. Surveys show that many visitors chose to become museum members because of the Ingenuity Lab program and almost all indicated their desire to continue similar activities. Results indicate that children, parents, and other family members want to learn and work together at these activities, which are accessible through multiple pathways and simple materials. Parents felt the whole family could successfully engineer. The two collaborations designed challenges that expanded on the traditional challenges with authentic content; visitors at the challenges developed by collaborations were able to make more connections to the real world and engineering and engaged in broader engineering behaviors. The further engagement of the community engineering students and industry engineers in these public engagement activities can expand and diversify not only the content, but also the audiences and the models of learning (McCallie et al., 2009).

Similarly, the college engineering students' confidence and agency were reinforced by their participation in the authentic design experience. Particularly, they valued the ability to work with real clients and with real engineers outside of the classroom, and the actual implementation of their final design challenges at the Ingenuity Lab made the experience worthwhile. The students were particularly proud of their achievements in these projects.

Thus, the significance of these types of cross-community partnerships is that they align the engineering company's goals with students' needs for authentic learning experiences and science museums' needs for resources. With less government funding for science museums, partnerships with industry will become increasingly important (Knerr, 2000). This cross-community collaboration model strategically supports these companies' social and economic goals, thus increasing the company's reputational gain (Fombrun, Gardberg, & Barnett, 2000) while helping to achieve the museum's mission to educate and foster learning.

The findings on the engineering students' and practitioners' beliefs about learning and engineering provide implications for engineering education. Following a human-centered design approach, the students and educators first observed similar activities at other museums and worked with the industry sponsors, consequently identifying key features of the design challenge that would otherwise have been overlooked. As a consequence of the collaboration, the engineering students and practitioners identified the social implications of their engineering roles. A key takeaway is that in designing these learning activities, it is important to involve the engineers with the users in-situ to help develop important criteria that serve to create products and services that engage the users in mutual learning experiences in which the user and engineer both learn and contribute.

Another implication comes from the collaborations' perspectives on engineering. The engineering students and practitioners noted that engineering involves much more than technical skills or intellectual ability, contrary to popular public conceptions of engineering (Sinkele & Mupinga, 2011; Yaşar et al., 2006). In the surveys, students and engineers noted that the attributes of good engineers were mostly non-technical, including hardworking, determination, curiosity, willingness to learn, and creativity, which are attributes of a malleable intelligence and growth mindset (Dweck, 2006). As Dweck (2006) has shown, the malleable intelligence and growth mindset is important for many subject areas; however, it is of particular importance in engineering, which the public commonly perceives as hard and inaccessible (Sinkele & Mupinga, 2011; Yaşar et al., 2006), potentially contributing to the low numbers of aspiring engineers. In order to help change the negative perception of engineering, it is therefore important to not only show what engineering really entails – creativity and benefitting society (National Academy of Engineering, 2008) – but also to show that through hard work, determination, and willingness to learn, engineering is accessible to all and is rewarding. Particularly, this research has shown that the grounding of accessible tinkering activities in authentic engineering provides an opportunity for successful engineering learning. Broader and general community STEM outreach should work to portray engineering as accessible and rewarding through the growth mindset perspective. Future research should explore this finding more in depth, implementing cross-sectional longitudinal studies to determine if the finding on the perception of engineering is consistent across engineering students and engineers and whether fostering a malleable mindset (Dweck, 2006) can improve engagement in and perceptions of engineering.

Through the collaborative design process, the co-design collaborations deconstructed their engineering practices to engage visitors in accessible and authentic learning experiences to construct their own engineering practices. By engaging engineering students and practicing engineers in not only the implementation, but the *design* of the activities within the Ingenuity Lab framework, the collaboration benefitted (1) the visitors by engaging them in mutual learning experiences through broader and rewarding engineering design practices, (2) the students by providing experience in authentic, consequential projects (Brown & Campione, 1996), (3) the engineers and their organizations by increasing morale and portraying their impact through corporate social responsibility (Fombrun, Gardberg, & Barnett, 2000), and (4) the educators at the science center by providing content and much-needed resources (Field & Powell, 2001).

8.5 Design Guidelines

Not only was each challenge unique in context and background, each experience of each visitor was also unique. Thus, my recommendations for design guidelines are drawn from the research case studies as a collective. Design is inherently constraint-based, so some constraint is needed to foster creative engineering experiences that are both accessible and authentic. My theoretical framework further contributes to the guidelines. Constructionism advocates the active doing and constructing of entities and the personal relevance of the activity (e.g., Papert, 1991); socio-cultural theories emphasize the importance of other people and the physical environment (e.g., Lave, 1996; Hutchins, 1995; Falk & Dierking, 2000). The combination of these theories provides a framework for tinkering design activities: the experience should be open-ended and self-driven, yet still guided by others and the structure of the environment (Guidelines 1-2); the environment should provide a variety of materials to allow for multiple paths and solutions (Guidelines 1, 3) and for varying levels of participants (Guideline 6); guidance should be offered through appropriate facilitation (Guideline 2), example designs (Guideline 4), and environmental structure that fosters multiple iterations (Guideline 5); collaboration should be supported for social learning (Guideline 6); and the activity should be personally meaningful, grounded in a relevant context (Guideline 7). The guidelines, extracted from the uniqueness of each Ingenuity Lab challenge visitor experience and based on my theoretical framework, help to foster an open-ended context with constraints that facilitate desired engineering behaviors. The following elaborates on each of the guidelines.

1. *Allow for multiple paths and solutions*. Families found the challenges more accessible for a wide variety of ages and backgrounds when they were more open-ended, allowing them to design their own unique solutions and pursue their own path at their own pace. The creativity allowed by the openness inspired visitors to make unique designs and take ownership in personalizing their experience; many noted in interviews that they purposely made a design unique to existing designs.
2. *Make the goal clear and offer guidance at key moments*. Though visitors did like the openness, sometimes they were confused on what to do. Thus, with a clear goal like in Spinning Tops, visitors were more persistent in achieving the goal, and with guidance through facilitation, they broadened their ideas of the possibilities. Furthermore, observations of challenges with greater facilitation (Spinning Tops, Engineer the World, Sound Engineering) show that visitors discussed possibilities and analyzed their solutions more than in challenges with less facilitation built in to the process, thus engaging visitors in more problem scoping and analysis.
3. *Utilize a variety of everyday accessible materials*. Visitors most commonly indicated that they enjoyed the hands-on component of the challenges. They were surprised at the simplicity of the materials and appreciated the variety of the basic materials that they could use to design something so powerful, particularly with Sound Engineering's recycled, everyday materials. Simple and familiar materials used in unfamiliar ways prompted visitors to gather information through transitioning between exploring the materials and building, thus deepening their understanding of the problem and solution in an iterative, reflective conversation.
4. *Offer example designs*. Example designs gave visitors ideas for inspiration and materials, and visitors wanted to build upon, improve, or make a design unique to the existing designs. Visitors also found the challenge more accessible because they could see others complete the challenge.
5. *Foster multiple iterations of refinement through feedback*. Visitors were extremely engaged in getting small problems fixed – going through engineering design in testing, experimenting, improving, and problem-solving. By creating opportunities for small successes, visitors can persist and achieve success, thus gaining confidence in their ability to engineer. In particular, offering easy-to-do tests (like in Marble Machines) and facilitated test stations that provided

feedback on the designs (like in Spinning Tops and Sound Engineering) fostered more iterations, persistence, and expert-like engineering design processes.

6. *Support collaboration through varying levels of open-endedness*. Families really enjoyed working together, which allowed children to learn to share physical objects as well as ideas. More open-ended challenges can allow a diverse group to collaborate and each individual to uniquely contribute to the design.
7. *Provide challenges that engage visitors in developing real world products*. Visitors in the two challenges developed by the cross-community collaborations engaged in more conversations about the real world connections, and all were able to identify real world products when prompted. Visitors were especially excited when they were able to make something that "works" that they had seen or used in their personal lives. Thus, visitors could better identify the relevance of engineering in their lives.

8.6 Final Words

The cross-community design process presents a novel and sustainable way to incorporate real-world engineering with making. The interdisciplinary members of the design collaborations developed new activities that incorporated accessibility from the educators and authenticity from the engineers and students. The collaborations developed implicit and explicit criteria that guided the design of their tinkering challenges to engage visitors in a mutual learning experience, rather than a one-way communication (Davies, 2008; McCallie et al., 2009; Feinstein, 2005). The process of identifying criteria not only helped them gain a deeper understanding of learning, it also helped to create collective ownership of goals (Bronstein, 2003) that fostered a smooth and dissent-free ideation process, as the final ideas were selected and refined flexibly with the agreed-upon criteria. Through the criteria development and ideation processes, the design collaborations deconstructed their engineering practices in order for visitors to construct their own engineering practices. Visitors' design process timelines portray cascade patterns, indicating that visitors are not just playing, but able to monitor their progress to engage in appropriate design behaviors like experts. Real-world contexts supplemented the collaboration challenges, and visitors were exposed to the work of engineers, potentially increasing their understanding of engineering in the world and as a career. The cross-community design correlates with increases in visitors' awareness of the real-world relevance and increases in their engagement in broader engineering behaviors, not just building and testing. With the alignment of the formal authentic engineering and the practical tinkering, the activities contributed to the construction of visitors' engineering identity and agency and empowered them to continue these activities. All collaboration members also acknowledged that engineering involves important skills beyond technical skills and emphasized engineering's impact on society, with the collaboration experience reinforcing their perception of engineering. The designers – both the engineers and students – reflected on how they enjoyed the experience. An engineer stated: "It was nice to see our impact in the field of education." One graduating student said: "It was one of my most valuable experiences in my undergraduate engineering career."

Overall, the learner experiences in this open-ended design environment were heavily shaped by the structure, particularly by the materials and the guidance through facilitation. Therefore, not only did the personal factors play into the visitor experiences, but so did the physical and social factors. The personal factors varied across visitors, but most had no engineering experience or identity. The materials fostered a means to identify problems and solutions like expert engineers, and guidance personalized the experience for accessibility. Thus, the visitors not only engaged in a reflective conversation (Schön, 1992) among the materials, context, and design problem, but also in a reflective conversation with the facilitators and their own families in a mutual learning experience that was accessible to all in the family. Families therefore learned and worked together across generations and learned from other visitors working around them. Furthermore, the open-ended, self-paced nature of the context and the easy-to-do tests provided opportunities for feedback to iteratively refine their designs. Visitors were observed to frequently transition between a variety of engineering behaviors and engage in multiple iterations like expert engineers. These multiple iterations further indicate that visitors are not usually getting it right the first time, but they are also not giving up. Their persistence suggests that they understood failure as a part of the process, implying new confidence and agency in engineering. Though there are these cross-cutting features across the challenges, each context and each experience was still unique. The structure and context of each challenge provided opportunities to engage in engineering design in different forms.

This dissertation research aims to develop a deeper understanding of tinkering as an accessible pathway towards engineering. My research shows that in the Ingenuity Lab, (1) visitors are not just playing, rather many are deliberately engineering and designing; (2) visitors are not all able to identify engineering initially and mostly identify engineering as building, persisting this concept even after the Ingenuity Lab experience; and (3) visitors gain confidence and agency in engineering without connecting to real world engineering in the three traditional challenges whereas visitors gain similar confidence and agency and connect to real world engineering in the two collaboration challenges. Because many visitors do not initially identify as engineers and do not have engineering experience, but almost all state their desire to continue, the Ingenuity Lab experience empowered the visitors with accessible engineering experiences. The cross-community collaborations further grounded these experiences in authentic engineering.

The cross-community collaborators provided future engineers with opportunities to engage in engineering and empowered them to continue, and the visitors exhibited primitive forms of engineering at these design challenges, utilizing the materials to problem scope as a pathway towards becoming future engineers. It is amazing how children can walk up to an array of materials with little idea of what they want to do, but after tinkering with the materials, they come up with an idea and a goal emerges from their exploration of the design space. If given the right environment and materials, children have the ability to engage in engineering design and problem-solving. These popular tinkering engineering activities do have educational merit; they can teach aspects of the nature of engineering and influence parents to further these experiences. Following the guidelines enumerated in the previous section, this type of space may be replicated to empower the next generation of engineers. One future engineer at the Ingenuity Lab told me: "At some point in our lives, we build things and we're all kind of engineers – some stay on, some branch off."

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Appendices

Appendix A: Visitor pre- and post-interviews. Personal Meaning Mapping is a method used by Falk, Moussouri, & Coulson (1998) in museum setting interviews.

Visitor Pre-Interview

Script: *Hi, my name is ______. I'm talking to people and observing what they do here at the Ingenuity Lab to find out what they thought about these activities. Is it OK if I ask you some questions and if I observe and videotape what you do at the Ingenuity Lab? The questions will take about five minutes before and ten minutes after. While you're in the Ingenuity Lab, you should totally ignore us and enjoy yourself. You can stop at any time.*

1. **Personal Meaning Mapping**: Please write and draw anything that you think of when you see the word below.

Engineering

2. What do you think engineers do?

3. Do you feel like you’re an engineer? [Have you engineered things before?]

Visitor Post-Interview

1. Could you show me your design(s)? How did you choose what to make? Did you look at other designs/projects? [Have you built things like these before?]

2. What were you trying to do with it [design goal]? Did it do what you wanted it to do?

3. (If worked with others) How did other people help you? Did you help anyone else?

4. How is what you did here related to the real world or anything you've seen before?

5. Have you done something like this before? How is it similar?

6. Do you think you'll continue doing activities like this? What would you want to do? / Do you feel like you can engineer other things?

7. **PMM**: *Now we're going to go back to what we did before you started your project here. We're going to look again at what you said about "engineering."*

8. What do engineers do? Did you feel like what you did was engineering? Why/why not?

Appendix B: Formula for calculating percentage agreement on each engineering design behavior, which is the sum of agreement on where the behavior does not occur plus the agreement on where the behavior does occur. The average percentage agreement of all behaviors for an observation represents the percentage agreement on a video observation.

$$Agree = \frac{T - t}{T} + \frac{t_o}{T}$$

T = total timespan of video observation
t = union of timespans of behavior occurences for all researchers
t_o = intersection of timespans of behavior occurrences for all researchers

Appendix C: Implicit and explicit criteria development for the Engineer the World collaboration. An "x" mark indicates the presence of the person, but no contribution in terms of criteria. Each color represents a criterion asserted by the individual, by column.

	Student 1	Student 2	Student 3	Student 4	Student 5	Engineer 1	Engineer 2	Educator 1	Educator 2
9/16/2012 Intro meeting part I (before engaging in challenge)	show engineering for everyone	x		have kids engage in engineering; creativity	x	x	long-term impact	all ages; fun & rewarding experience; design process, failure is part of process; environment & materials - 1) examples, 2) go to next level, collaborate, 3) reflective conversation; draw connection to engineering; selection of materials for a lot of possibilities	show engineering is for everyone
9/16/2012 Intro meeting part II (after engaging in challenge)	different age group levels; how to help women go into engineering	variety of materials; personalize; take home; incentive to stay and finish		individual thinking & groupwork; guidance from facilitator; what attracts girls to engineering	many different outcomes	familiarity with problem (for parents); examples are helpful; younger kids interested in decorative; interesting/exciting to test; flexible timescale	fundamental instructions with goal to have kid be able to do whole thing himself; expose different fields of engineering; relate to kids' daily lives/something they personally need; show social side of helping; different stations with steps	wide age range; cross-generational; appeal to both boys and girls	different ways to engage in process; ways to make it more attractive to younger; cross-pollination of ideas; small iterations; prior knowledge & interests; make success attainable; museum-specific; take-home component
9/18/2012 Idea selection	x		x	foster individual thinking	x	emphasizes need for creativity	Presents ideas for general features that can	real world connection; mentions want to incorporat	reminds of criteria and also concrete test to

							make real world connection	e technology; likes everyone being thoughtful of age	evaluate visitor designs
10/6/2012 Prototyping	somewhat fun; able to solve problems; have questions to guide; connect Hall to website; caters to all ages; individual & group	need to make activity more connected; have better facilitation questions; take home; familiarity; decorative; prior knowledge /interests; collaboration; facilitation; challenge too long?							
10/7/2012 Prototyping 1 meeting	mentions need to have flexible timescale as constraint	needs facilitation						asks engineers to write about how they create apps/websites; emphasizes need to figure out materials;	varying difficulty for different ages
10/21/2012 Prototyping 2 meeting	x	x	not sure what materials to give kids - but "entirely freeform" in their design	x	x	asks about "freeform" being good or if people need guidance		asks about how it can relate to kid who doesn't use computer, or parents don't want to be involved with social networks	pushes to link with science/engineering
11/18/2012 Final meeting	Challenge shows how Google makes website/apps: "follows mission of LHS - use materials they could access at home, computers"; make interesting with flashy HTML, AppInvent or	Challenge is like what engineers do - design idea and then make it actually happen - not just computer science, but engineering in general	putting website on projector, other kids saw and got more "enthusiastic because they realized if she can do it, then they can do it as well"; takes pride in what they built	wanted more programming; freeform website was challenge - not much guidance	x	says "amazing iteration speed"; asks about age and flexibility in designs, harder concepts to grasp	asks about age and parent involvement, skill/time	x	parent perception of kid's ability to engage

Appendix D: Implicit and explicit criteria development for the Sound Engineering collaboration. An "x" mark indicates the presence of the person, but no contribution in terms of criteria. Each color represents a criterion asserted by the individual, by column.

	Student 1	Student 2	Student 3	Student 4	Student 5	Engineer 1	Engineer 2	Educator
2/18/2013 Intro student meeting Part I (before engaging in challenge)	broad solutions; take-home,	copying	copy and personalize	x	"that's [copying] how real-world engineering works"			
2/18/2013 Intro student meeting Part II (after engaging in challenge)	broad range of parent involvement; personalize; fast feedback, measurement	relate to personal interest; hands-on vs technical; modularize; room for creativity; relate challenge to real-world application	instructions and facilitator important; goal-oriented for rebuilding & retesting,	hands-on; competition	relate to personal interest; instructions and facilitator; concrete examples; goal-oriented; hands-on; cheaper and enough supplies			all ages, gender neutral; collaboration
2/19/2013 User interviews (individual)	interactive; interesting; fun; all ages + something for parents; simple; relatable; unusual; instructions	awe; unfamiliar; something for adults; accomodates groups social; user control,	engaging; interactive; groups/social; attractive; educational	engaging; educational; attractive and dynamic,	educational; clean/organized/spacious; dynamic; all interests; feedback; novel			
2/26/2013 Class presentation	● Fun and informative ● Interactive in a "hands-on" fashion ● Allows individual user to create unique solutions ● Goal-oriented ● Allows user to cycle between testing and tuning their design ● Minimal wait time and fast feedback ● Applicable for a range of ages ● Gender neutral activity ● Rewards teamwork and collaboration ● Cheap, reusable supplies							
2/28/2013 Meeting with engineers	more modes of interaction; one solution may be discouraging; modular better; need to have challenge	relate to personal; interaction/memory, more modes of interaction; modular - to change one thing at a time, modules to scaffold parts of a whole system; not too expensive			competition	more important to take something physical home? interaction/memory?; more modes of interaction; What part of acoustics to demonstrate?; age range	what will they remember a year later?	modular
3/5/2013 Prototyping		instrument not technical enough?						

3/14/2013 Individual idea selection	engaging; educational; cheap; goal-oriented; personalization	engaging; fun; educational; customizable; goal-oriented; low-cost	engaging/interactive; educational; cost-effective; goal-oriented; personalization; fun; fast turnaround, testable	fun; customizable; ease-of-use; challenge scaleability; educational; multiple solutions; goal-oriented; cheap	fun; educational; child-doable; creative; hands-on; sustainable			
3/19/2013 Class lecture	modular - easily customizeable, variety			modular - easily customizeable, variety, easy to improve	modular - easily customizeable, variety			
3/21/2013 Class presentation	customer needs hierarchy: engaging, educational, goal/design oriented, personalizable, cheap • Fun • Goal-oriented • Interactive, "Hands On" • Personalized and unique solutions • User should cycle between testing and tuning their design • Fast feedback • Cheap, reusable supplies • Age and gender neutral							
4/5/2013 First day at LHS	children want to improve design, discouraged/lose interest when testing slow; facilitation			facilitation/parents				
4/9/2013 Class lecture			modular - easy to assemble, reuse/take apart		modular - easy to assemble			
4/11/2013 Class lecture				reuse --> sustainable				
4/21/2013 Observation at LHS	guidance - better signage, instructions				guidance - better signage, instructions, more charismatic volunteers			
4/27/2013 Observation / interviews at LHS					facilitators need to help; speaker may be limiting creativity			
4/29/2013 Final meeting with engineers					guidance - better signage/guidance,	need more on magnetism to understand speakers; modularity good	exposed to ideas they wouldn't otherwise see - help determine if it's a future path for the kid	

5/7/2013 Course final presentation	● Fun and informative ● Hands-On ● Goal-oriented ● Iterative Design ● Fast Feedback ● Allow for creativity ● Gender and Age Neutral ● Sustainable; hierarchy: Engaging Educational Goal Oriented / Design Oriented Personalization / Customization Environmentally and Financially Sustainable; selection criteria: 1. Engaging 2. Educational 3. Cost-effective 4. Goal-oriented 5. Personalizable 6. Fun Factor; Key features (*modularized, allow for creativity, elementary concepts, reusable), triple bottom line analysis - sustainable with reusing and recycling, make sure people continuing to come, donors donate, inspire, education, promote engineering; With infinite resources - they would do the same - materials are household/familiar, they can do at home and reuseable sustain"

Appendix E: Ideas for design challenges from the Engineer the World collaboration.

1. Tangible data storage
2. Projector
3. Stop motion animation
4. Cooking instructions
5. Navigation
6. Game to make own restaurant
7. Nonintrusive ads
8. Mitigating a problem
9. Build app
10. Bridge for cars
11. Make small parts into large parts
12. Materials for drawing
13. Personalized ads
14. Sifter/filter
15. Search
16. YouTube
17. Music
18. Movies
19. Draw app, then turn into video
20. Matchbox cars dealing with traffic
21. Traffic control
22. Water flow
23. Dealing with traffic to/from an island
24. Partner drawing instructions
25. Scavenger hunt
26. Person finder
27. Design own challenge
28. Design a lunchbox
29. Website/profile
30. Paper prototypes/wireframes
31. Mobile phones
32. Build your own game
33. Social networking
34. Product search
35. Image search
36. Design alarm clock
37. Interactive menu
38. Maps for school
39. Engineer your own playground
40. Automatic chauffeur
41. Obstacle course
42. Search vs. Google search
43. Accessibility for deaf/blind
44. Design a wallet from a person's information
45. Flipbook
46. Make your own "choose your own adventure"
47. Program your parent
48. Reverse engineering
49. Program for a scavenger hunt
50. Basic programming
51. Map/reduce programming
52. Design a tool
53. Google Now/pattern recognition
54. Create product from user need
55. Pixels in an image
56. Word ladders
57. Debug a program
58. Stations for search queries
59. Relate to jobs
60. Test/interview visitors
61. Condition/recursion book
62. Sharing/taking turns
63. Pop-up app
64. Shoebox website
65. Slits for shoebox website for newspaper/magazine
66. Guiding questions
67. Connect to real websites
68. Make activity connected to real world
69. More decoration components
70. Interview
71. Mechanical turk
72. Incorporate three ideas
73. Profiles
74. Turn desktop website into mobile website
75. What is the Internet
76. Mobile app inside website
77. Write basic HTML
78. Program in Scratch

Appendix F: Ideas for design challenges from the Sound Engineering collaboration.

1. Speaker
2. Non-Newtonian fluid
3. Doppler effect
4. Distorin/intelligibility
5. Microphone/speaker
6. Electrical filters
7. Altered speaker diaphragms
8. Competition
9. Modularity
10. Measure loudness of speaker
11. DIY instrument
12. Make electronic music
13. Microphone
14. Reverberation vs. intelligibility
15. Theater speaker placement
16. Speaker interaction
17. Resonance
18. Tuning speakers
19. Guitar bridge
20. Electrostatic speaker
21. Build tuning fork
22. Media over ears
23. Timing speakers
24. Acoustic manipulation of room
25. Anechoic chamber
26. Bite on pencil/sound output
27. Life size acoustic tube
28. Music play on different types of speakers
29. Distance drop-off rate of sound
30. Visualizing vibrations
31. Speaker and magnet distortion
32. DIY drums
33. Reverberation of structure
34. Vibration effects of sound
35. Synthesizer to modulate song
36. Sound wave on a bubble
37. Design a constellation audio system
38. Wind instrument
39. Digital filters
40. Water stream with speaker
41. Surface area reverberation with seashells
42. Minimum and maximum hearing frequencies
43. Sound through gas/liquid
44. Xylophone
45. Amplification/reflection – ear
46. Sound transmission
47. Amplification
48. Rub a glass
49. Frequency analysis of instrument
50. Shapes/enclosures
51. Speed of sound
52. Stethoscope
53. Sound directionality
54. Computer simulation of voice
55. Sound digitization through phones
56. Product teardown
57. Megaphone
58. Tissue box guitar
59. Building dampening
60. String instrument
61. Design an ampitheater
62. Construction/destruction
63. Waterproof speakers
64. Seashell
65. Soda bottle flute
66. Pitched drums
67. Make music on computer
68. Computer analysis of vocals
69. Water based pipe instrument
70. Resonance in fluid
71. Varying loudspeaker geometries
72. Best medium for sound
73. Tune instruments
74. Build synthesizer
75. Singing resonance
76. Echo
77. Identify a pitch
78. Compare sound to light
79. Electrical-mechanical speaker/amplifier
80. Music playback
81. Parabolic dishes
82. Automata kinetic sculpture with sound

83. Art with vibrations
84. Speaker to resonate
85. Speaker in water
86. Sound as physical phenomenon
87. Max/MSP
88. Combine instrument with speaker
89. Materials allow for multiple projects – variety and modifications
90. Viewing waveform
91. Frequency spectrum
92. Goal to play specific frequency
93. Make coils wider
94. Hot glue coils
95. Solder thicker wires onto headphones
96. Better introduction to challenge
97. Use more diagrams
98. Prewind coils
99. Color code coils
100. More signage with instructions, materials
101. Reuse materials
102. Show multiple examples
103. Better facilitation/guidance
104. Glue wire
105. Volunteers need to be reminded to help
106. Offer more types of coils
107. Better structure for former on speaker
108. Remove large magnets
109. Improve acoustics of room
110. Need information on safety
111. Have cutaway of actual speaker
112. Less clutter in the room
113. More on magnetism

Appendix G: Coded visitor survey comments on what they enjoyed about the experience, by challenge. The greatest percentage of responses for each coded category is highlighted.

	Marble Machines (n = 35)	**Spinning Tops (n = 23)**	**Cars (n = 38)**	**Engineer the World (n = 26)**	**Sound Engineering (n = 26)**
working design / designing / making / building / hands-on / interactive / drawing / programming	20.00%	21.74%	26.32%	57.69%	61.54%
test / experiment / competition / iterate/trial&error / fail	2.86%	39.13%	26.32%	0.00%	23.08%
challenging	28.57%	4.35%	15.79%	0.00%	3.85%
open-ended/exploring/self-discovery/multiple paths/solutions/self-paced	22.86%	4.35%	2.63%	7.69%	11.54%
creativity	11.43%	0.00%	7.89%	11.54%	7.69%
fun	20.00%	0.00%	5.26%	11.54%	0.00%
facilitation	8.57%	13.04%	7.89%	7.69%	3.85%
simple / easy / accessible / all ages	14.29%	0.00%	7.89%	7.69%	3.85%
technical content	2.86%	0.00%	5.26%	7.69%	7.69%
variety of materials/simple materials/surprising materials	11.43%	0.00%	2.63%	0.00%	7.69%
social / collaboration / share	14.29%	0.00%	0.00%	3.85%	0.00%
surprising / intriguing / not as expected	0.00%	0.00%	5.26%	0.00%	15.38%
goal	0.00%	21.74%	0.00%	0.00%	0.00%
variables	0.00%	21.74%	0.00%	0.00%	0.00%
aesthetics / decorating / color	0.00%	8.70%	2.63%	3.85%	0.00%
recognition / rewarding / validation	0.00%	13.04%	0.00%	3.85%	0.00%
engaging / persistent	5.71%	0.00%	2.63%	0.00%	0.00%
problem-solving	5.71%	0.00%	0.00%	0.00%	0.00%
tracking data	0.00%	8.70%	0.00%	0.00%	0.00%
outside connection (home, real world, personal)	0.00%	4.35%	0.00%	3.85%	0.00%
examples	0.00%	0.00%	0.00%	0.00%	3.85%

Appendix H: Formula for coding shaded representation of average frequency (f) and average percentage time spent (p) on each behavior. Shading ranges from 0 to 70, with 0 as white and 70 as the darkest grey.

$$shade(f,p) = \begin{cases} 0 & s = 0 \\ 10 & 0 < s \leq 2.5 \\ 20 & 2.5 < s \leq 5 \\ 30 & 5 < s \leq 10 \\ 40 & 10 < s \leq 20 \\ 50 & 20 < s \leq 40 \\ 60 & 40 < s \leq 80 \\ 70 & s > 80 \end{cases}$$

$$s = f + 100p$$

Appendix I: Representative quotes from surveys and interviews at each challenge. Surveys were usually answered by parents, though the children's ages are indicated. Interviews were answered by the child, with the child's age and gender indicated.

Challenge	**Quotes from visitors**
Marble Machines	Surveys • 7, 10 y.o.: "how hard it was. and how fun it was - we spent an hour on the challenge!" • 3, 3, 5 y.o.: "How well a 3.5 year old could do with trial and error" • 2 y.o.: "forcing my child to share" • 7 y.o.: "we really can't do this at home but will use everyday items to apply physics." • 6 y.o.: "The marble tracks are fun and there are so many ways to build them"; "my six year old is better at it than i am" • 5 y.o.: "materials that i would not expect to be used for the challenge were available" • 3 y.o.: "working all together" • 1, 2, 4, 5, 9 y.o.: "lots of fun materials. easy for all ages." • 3, 6, 9 y.o.: "That the kids could be creative, curious and problem solve"; "Building, problem solving and executing the final model" • 4, 8 y.o.: "problem solving when things didn't work" • 6, 8 y.o.: "the marbles everything....kids kept working they were extremely engaged" Interviews • 8F: "Engineers make things, like I was doing." "Yes [this was like engineering]. I made something and it was made out of different kinds of materials." Mom: "You solved problems when something wasn't working right – used block to keep marble from flying. • 8M: "[My goal was to] make the marble get to the finish - the container. It did do what I wanted to do. […] when messes happen, we fixed it." • 9M: "doesn't always work out as you expect it to." "Engineers decide what they want to make, then make it." "Yes [this was like engineering]. I made something that didn't copy anybody else. It takes tries - hard to get it right the first time." • 9M: "[The activity was] A little related - in Monterrey, [they had an exhibit where] water came down and had a platform that made it bounce into a little pool." "Yes, [I want to continue these activities and] build a little fountain when I grow up." • 8M: "The activity was] Like a roller coaster – loop." • 9M: "[The activity was] like a storm drain pipe." 11M: "like drain pipe, machine, slide, high to low level." 9M: "connect to high level to spin turbine [and make] electricity." • 14M: "Saw some designs [and] add[ed] modifications myself." 10M: "Build anything on my mind, idea that comes to me, put idea into it. I looked at some [other designs], looked interesting. It looks easy but hard to do." 14M: "Yes [I would continue these activities]. [It] built confidence, helps understand better engineering." • 6F: "Just tried things, looked at materials. Yes, other designs helped a bit." 9F: "Testing/online saw you could do a loop. [I also] kept trying to make a sound, so added bell. [Yes, I] looked at other [designs]. [I looked at] some materials they used [to] stop, [follow a] different path." • 6F: "I wanted the marble to go through the tube and down the basket." 9F: "[For the] loop, [I was] trying to make it cool, have sound stuff. Yes [it reached my goal], a small marble to makes the design better."
Spinning Tops	Surveys • 4 y.o.: "Inputting data and testing different ideas." • 5, 7, 9 y.o.: "Thinking about weight, height, and diameter" • 7, 5 y.o.: "Entering data was great -- really captured the 7 year old, who kept trying to improve his time. He would have loved to see the data update in real-time and track more variables!" (Daddy). • 9 y.o.: "[What made me feel like an engineer was I] made it my self" • 7 y.o.: "[What makes me feel like an engineer is to] build something that actually

works”
- 6, 7 y.o.: “The college age docents that assisted the kids with the experiments were awesome. they treated the children with genuine respect, as though challenging the little scientists within.”; “I enjoyed watching my children make multiple attempts and not give up.”; “This is the first time my children have been challenged in this way!” “I just wish science was incorporated into school - it seems like there is nothing left but reading, writing, and math.”
- 7 y.o.: “[What makes me feel like an engineer is to] Use my brains and hands.”
- 6, 8 y.o.: “it was great for us to recognize the importance of the height. we have a lot of spins toy at home. but we have never been curious of the secret for spinning. Thanks!”
- 7 y.o.: “Building the top. Looking at past data on the chart and adapting our design accordingly.”

Interviews
- 10M: “I wanted to add, [an engineer] makes stuff to make life easier, [while] enjoying what he does and building. Yes, [this was engineering] because I felt I was building stuff that was using electricity and math
- 8F: “Engineers Help people and the planet. Yes, [this was engineering because] I was making something that could be used instead of playing on the computer or watching TV.”

Cars

Surveys
- 5, 8, 10 y.o.: “[I was surprised] that the cars were simpler to make than i expected.”; “[What made me feel like an engineer is] I made my car better.”
- 7 y.o.: “[I was surprised at] How innovative kids can be on their own without adult help.”
- 7, 9 y.o.: “[Our favorite part was] seeing our vehicles fail.”
- 8, 10 y.o.: “our girls were able to stick with it with just a little help”
- 5, 8 y.o.: “[What made me feel like an engineer was] finding the right parts and calculating how many parts”

Interviews
- 9M: “just trying to create my own design nothing like anybody else.”
- 9F: (pre) “[Engineers] build products to help in everyday life.” 14M: (pre) “[Engineers] build a wide range of machinery and structures.” 14M: (post) “Engineers design machinery and structures to perform a task in the most efficient and cost-effective way. [This was engineering, through] not very professional, but to some extent – [trying to get it to] run as efficiently as possible.”
- 8M: “[How I chose what to make was I was] having problems, and this was the only successful one. [Other projects I looked at were] someone else left this car and [I added my car to it] to make Megacar. [Also, my] gear system wasn't working and I saw another train, [which gave me the] chain drive idea.”
- 8M: “[I felt like what I did was engineering] in a way. I had to make sure all the gears fit, chain was the right length, make sure it was the right size.”
- 7M: “I thought to choose what to make. Yeah, l Iooked at other [designs], and was inspired [by them].”

Engineer the World

Surveys
- 3 y.o.: “[My favorite part was the] structure - free to interpretation”; “[I was surprised about the] connection to real world”
- 8, 8 y.o.: “the kids did it by themselves”
- 4, 2 y.o.: “Friendly and open people; loved the 'girl power'”; “[I was surprised at] how accessible it was to my 4 year old”; “engaged my little girl in coding”
- 5 y.o.: “opportunity for my kid to get creative and excited about turning his ideas on paper into something real”
- 9 y.o.: “allowing youngsters to make programs”
- 8 y.o.: “What made me feel like an engineer was] Designing before building”
- 8, 11 y.o.: “Seeing kids comfortable with computers.”
- 5, 6 y.o.: “It allows kids to think about how to organize the information.”; “think the

	way to help users navigate information” Interviews • 12M: “Yes, [I would do this kind of activity again] a lot [such as] posting videos daily, […] recording software.” • 12M: "with newfound information, we can do whatever we want." S: "recording software. […] I feel more like an engineer now because we're making new things and new designs. […] This is probably the awesomest class ever." • 12M: (in discussing ads on websites) “I don't want money. I just want to be popular.” • 7M: “My website was not really like a real website - mine wasn't as long, more like a ‘mini’ website.” • 8F: “[This activity is] related to what I do and like - not like websites I've seen before with videos.”
Sound Engineering	Surveys • 12F, 8F: “learn how to cause vibration to make music”; “yes [I hope to continue these activities], kept the kids entertained for an hour” • 9F: “Create my own instrument with only four materials [made me feel like an engineer]” • 11F: “[I was surprised] that there are infinity options of sounds”; “I changed, revised, and edited the stuff I was making just like an engineer” • 10F, 10F: “[their] way of looking and using the materials is different than mine” • 7F: “[I was surprised] That it actually worked with recycled materials” Interviews • 13F: [This was related to things I’ve seen like a] speaker - music, radio, headphones. The cup was so small, like a larger version of headphones. […] [Engineers] work with sound and anything. […] Yeah, I felt like this was engineering because I] experimented with how different things work.” • 8F: “If you were an engineer, you would have to do same thing. […] [Engineers] make new machines. […] Yeah, [I felt like this was engineering because I was] working with certain materials to have a result.” • 8F: "[My goal was to] make it work" • 13F: “I picked not the 100 coil since [my sister] had it. [I wanted it to] vary and not be the same.” • 13F: “At some point in our lives, we build things and we're all kind of engineers - some stay on, some branch off.” • 7M: “Yes, [this was like engineering because] some engineering stuff doesn't work. [Engineers have to] test it before they do real work.”