Ingenuity Lab: Making and Engineering through Design Challenges at a Science Center

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Abstract

Many engineers attribute their careers to early interest in STEM. Interest, not performance, has been shown to be a greater predictor of choosing to concentrate in STEM. However, schools often neglect the engineering component of STEM. Consequently, extracurriculars such as science centers must play key roles in influencing children by fostering interest in engineering. Taking advantage of the popular tinkering and Do-It-Yourself Maker movement, increasingly more science centers are offering engineering and maker programs. But are they empowering visitors to engineer?

This paper details the study of the Ingenuity Lab, an engineering maker space at the Lawrence Hall of Science. The space is open to drop-in visitors on weekends, serving mostly family groups with ages ranging from infant to elderly. The majority of children are between the ages of four and ten. A monthly open-ended engineering design challenge and theme is presented to visitors, along with materials consisting of low-cost consumables and/or reusable electronics. Visitors design, build, and test solutions to the challenges. In particular, this study aims to assess the program’s impact on its visitors with regards to visitors’ perceptions of engineering and identity with engineering, as well as visitors’ confidence in and agency to do engineering. Three challenges over three months were studied via visitor number and time tracking and post-surveys.

Across the challenges, families engaged in and recognized their own engineering behaviors through the refinement of their design solutions, perceiving engineering as accessible. Many parents hoped to pursue such activities at home and return to the engineering space. Design guidelines resulting from the findings are allowing for multiple paths and solutions; utilizing a variety of everyday accessible materials; offering challenges that are achievable within the timeframe; fostering multiple iterations of refinement; and supporting collaboration through varying levels of open-endedness.

Introduction

The Ingenuity Lab is a novel learning space for families of all ages to tinker and engineer solutions to design challenges. 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.

Because engineering is not required in most schools, the public perception of engineering must be changed elsewhere. Programs at science centers traditionally focus on science and mathematics concepts, while relatively few focus on engineering. However, 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, the often-neglected subfield of STEM (science, technology, engineering,
math) education, has potential to integrate science, math, humanities, and arts for effective education. 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 when and how to create accessible opportunities for learning engineering. Opportunities should be presented to children early on; many engineers attribute their careers to early interest in STEM. Interest, not performance, has been shown to be a greater predictor of choosing to concentrate in STEM. A popular activity for STEM learning is tinkering, and following the recent Maker and Do-It-Yourself Movement (see the Making and Tinkering section below in the Theoretical Framework), science centers are now increasingly offering tinkering programs. Tinkering, in contrast to the typical hands-on interactive exhibit, 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 learning.

Despite the increase in tinkering programs at science centers, these programs have yet to be rigorously established as educationally productive with respect to engineering. Centers can therefore benefit from guidelines for developing and improving these activities. My aim is to draw guidelines from case studies on three engineering design challenges implemented over three months at the Lawrence Hall of Science’s drop-in engineering lab.

Theoretical Framework

Making and Tinkering: Engineering Design

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. The Maker Faire Report describes making as “tinkering, hacking, creating and reusing materials and technology.” Making is not only personally motivating and socially engaging, it is also accessible to a diverse audience. The report notes that making encourages experimentation safely; learners make mistakes but still retain their confidence and identity to pursue their interests.

Over the past few decades, the renewed interest in DIY projects has brought about questions of how these projects can be educationally productive. One perspective is to view these projects as design. Resnick and Silverman 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. claim that “design is both a mechanism for learning and in itself a learning process.” Beckman & Barry also liken the design process to the learning process. Lewin 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 and is accessible to many types of learners. Open-ended design activities give students responsibility for structuring their own activities and creating their own artifacts through various possible paths.
Consequently, design can foster experiences that are much more meaningful than other types of activities.

Resnick 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 also states 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 assert that play can be meaningful, and meanings are created by the player’s actions. Meaningful play, they explain, emerges through the relationship between player actions and system outcomes, in which the player and system influence each other. Salen and Zimmerman 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. Thus, design offers an opportunity for meaningful play.

In this type of play, what is learned? STEM content serves as a guide, as the context, and as the means for designing. The Maker Faire Report focuses on STEM as the process, pushing that STEM is not the end goal. 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.

In theory, design seems to work as an educational pedagogy. In practice, there is a dearth in the literature, but the few papers focusing on design in K-12 engineering seem to show its effectiveness. Cunningham and Lachapelle 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 both students and teachers. Sadler et al. show that after engaging in design challenges, middle school students’ science skills increased, though they evaluated solely the ability to design science experiments. Kolodner 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. demonstrate that students who designed physical models better understood science models, though their instruments seemed biased towards these students. Further studies are needed to evaluate the learning of engineering. However, with respect to some engineering habits of mind, researchers have shown that design provides an opportunity for students to test their preconceptions, creatively develop unique solutions through multiple paths, engage in systems thinking, iteratively refine their design and thinking, learn from failure, collaborate and communicate, manipulate and reflect with materials, and ethically and civically design for people. Therefore, though the results are still slim, it seems that design activities are educational.

Learning in Informal Environments

Design challenges in classrooms and afterschool programs can be effective in promoting understanding of science and engineering (see, for example, Cunningham & Lachapelle);
Kolodner et al.\textsuperscript{22}; and Sadler et al.\textsuperscript{21}). 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 paper intends to provide a study of this type of environment.

Informal environments are unique because they offer free-choice learning\textsuperscript{29}. Science center visitors choose which activities to participate in and can choose to leave at any time. Furthermore, visitors tend to visit in diverse groups with varying backgrounds\textsuperscript{29}. Parents come to science centers with children to spend time together, have fun, and learn\textsuperscript{2}. 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\textsuperscript{30,31,32,33}. Parents can act as educators, co-learners, or passive observers\textsuperscript{34}. 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\textsuperscript{35,36}. Therefore, parents can help sustain children’s efforts, increase their competence\textsuperscript{37}, and positively reinforce their identities\textsuperscript{2,38}.

Science Center Context

The context of this study is the Ingenuity Lab, an engineering design program at the Lawrence Hall of Science in Berkeley, California. The program is currently open to the public on a drop-in basis during weekends, providing open-ended and 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 program 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. Science center staff, college engineering students, and community volunteers facilitate and guide visitors as they develop solutions to the challenge. Past challenges have included 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.

Research Questions

This paper focuses on two goals of science center engineering programs: (1) to engage families together such that both parents and children experience and recognize their own agency in
engineering and (2) to help visitors understand engineering and its relationship to the activities. To develop guidelines for achieving these goals, I seek to understand:

1. What are visitors’ perceptions of the program activities related to engineering?
2. What are successful characteristics of the program?

Methods

The three engineering design challenges studied were each implemented for one month. See Table 1 for descriptions and examples.

Table 1: Descriptions and examples of each challenge. Descriptions modified from the science center website.

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marble Machines</td>
<td>Using a pegboard and simple materials like rubber, PVC pipes, funnels, and tubes, design a marble rollercoaster.</td>
<td></td>
</tr>
<tr>
<td>Spinning Tops</td>
<td>Design the longest spinning top by selecting the size of plates, number of plates, and its height. Spin the top with an electronic hand mixer. See how your design compares to others on the data graph.</td>
<td></td>
</tr>
<tr>
<td>Cars</td>
<td>Design, build, and test a robotic LEGO car by putting together the right gears and wheels and learning how to connect the microcomputer to the appropriate sensors and actuators. Time your car on the racetrack.</td>
<td></td>
</tr>
</tbody>
</table>
While other museum studies have taken place in an isolated lab environment or tracked visitors with recording equipment, this study aims to collect data in a naturalistic manner to prevent visitor actions from being influenced by the study. This study was conducted in a public environment at a science center in which visitors paid for their admission and careful consideration was taken to not disturb their experience. I collected numbers of visitors and implemented a survey with visitors after their experience. To track the number and duration of visitors with minimal disturbance, a simple one-box model is 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 (every five minutes), noting 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. The total number of visitors along with their estimated stay time per challenge and across all challenges are listed in Table 2.

Table 2: Total number of visitors to the challenges, their estimated stay time, and number of groups that were surveyed.

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Visitors</th>
<th>Stay time (min.)</th>
<th>Surveyed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marble Machines</td>
<td>1073</td>
<td>28.6 (± 9.5)</td>
<td>35</td>
</tr>
<tr>
<td>Spinning Tops</td>
<td>891</td>
<td>25.7 (± 10.2)</td>
<td>23</td>
</tr>
<tr>
<td>Cars</td>
<td>951</td>
<td>53.1 (± 13.1)</td>
<td>38</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2915</td>
<td>44.0 (± 10.7)</td>
<td>96</td>
</tr>
</tbody>
</table>

While other museum studies have taken place in an isolated lab environment or tracked visitors with recording equipment, this study aims to collect data in a naturalistic manner to prevent visitor actions from being influenced by the study. This study was conducted in a public environment at a science center in which visitors paid for their admission and careful consideration was taken to not disturb their experience. I collected numbers of visitors and implemented a survey with visitors after their experience. To track the number and duration of visitors with minimal disturbance, a simple one-box model is 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 (every five minutes), noting 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. The total number of visitors along with their estimated stay time per challenge and across all challenges are listed in Table 2.

Table 3: 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?

The survey was developed in collaboration with science center staff (see Table 3). In order to minimize disturbance to the experience, visitors were only asked to take a post-survey. Staff asked groups as they were leaving to take an online anonymous survey. Survey responses were analyzed for age, number of children per group, and whether visitors had been to previous challenges. Qualitative responses to “What surprised you about this challenge?” and “What did you do today that made you feel like an engineer?” were coded. These items were studied for
three challenges to understand how visitors’ expectations, experiences, and perceptions of the relation to engineering vary across challenges. The total number of visitor groups surveyed is shown in Table 2.

Participants

Visitors on weekends are mostly families with children and adults. No criteria were used to select visitors; only visitors who wished not to be surveyed were excluded. Children in this study mostly ranged from infant to age 12 (see Figure 1). The average age for all challenges was 6.8 years. Groups had anywhere from one to six children, with an average of 1.6 children per group. Figure 2 shows the ages of children by challenge.

**Figure 1**: The age of children surveyed across all three Ingenuity Lab challenges.

**Figure 2**: Age of children, by challenge.
Results

Returning Visitors

Survey responses show that 72.7% 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 3). Others stated that they were not local, but would “definitely” become members if they were.

![Number of challenges visitors previously attended (n = 19)](image)

**Figure 3**: The number of challenges returning visitors previously attended, according to survey responses.

Visitors 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. The majority by far (37 responses; 38.6%) indicated that building or making made them feel like engineers (see Figure 4). 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 4). 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.

By challenge (Figure 4), visitors to the Marble Machines challenge most frequently mentioned iterating, refining, and problem-solving as engineering. Visitors encountered many mini-problems that they needed to solve or fix as they tested their marble tracks. Furthermore, this group also discussed being creative and inventing as engineering. Only one group mentioned engaging in science concepts. 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. 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 creating a working design, understanding the science concepts of gears and drive trains, and selecting appropriate materials.

What did you do today that made you feel like an engineer? (n = 96)

Figure 4: Coded survey responses to “What did you do today that made you feel like an engineer?” by challenge.

Table 4: Comments highlighting iteration and refinement of designs.

<table>
<thead>
<tr>
<th>Representative comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>“How well a 3.5 year old could do with trial and error”</td>
</tr>
<tr>
<td>“construct, run a trial, then adjust according to results of the trial.”</td>
</tr>
<tr>
<td>“fixing the machine to make it work”</td>
</tr>
<tr>
<td>“I enjoyed watching my children make multiple attempts and not give up.”</td>
</tr>
</tbody>
</table>
Visitor comments indicated several characteristics of the program that they appreciated and enjoyed (see Figure 5). By far the most frequently discussed was the hands-on component that involved building, making, designing, and creating something that works as intended. Other appreciated components were seeing how the design works through testing, experimenting, and competing; challenging or difficult parts of the activity that visitors persisted in overcoming; and how much fun they had. An important characteristic mentioned across all three challenges is the facilitation aspect. Because the program is so open-ended, the facilitator interaction is 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. they treated the children with genuine respect, as though challenging the little scientists within.”

**Successful characteristics of the program**

![Bar chart showing successful characteristics of the program]

- share experience
- interactive
- sharing
- iteration/refining
- outside connection (home, real world, personal)
- color
- problem-solving
- failure
- surprising / intriguing / not as expected
- technical content
- tracking data
- decorating
- variables
- all ages / accessible
- collaboration
- engaging / persistent
- recognition
- variety of materials/simple materials/surprising materials
- goal
- simple / easy
- creativity
- facilitation
- fun
- open-ended/exploring/self-discovery/multiple paths/
  challenging
- test / experiment / competition
- working design / designing / making / building / hands-on

**Figure 5**: Successful characteristics of the program that visitors mentioned in the survey responses.
Furthermore, other characteristics mentioned were how creative the visitors could be, 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 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

<table>
<thead>
<tr>
<th>Table 5: Quotes of visitors’ surprise about the activities.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Representative comments</strong></td>
</tr>
<tr>
<td>Agency and persistence to make something “work”</td>
</tr>
<tr>
<td>“kids stayed very focused”</td>
</tr>
<tr>
<td>“my six year old is better at it than i am”</td>
</tr>
<tr>
<td>“That the kids could be creative, curious and problem solve”</td>
</tr>
<tr>
<td>“kids kept working they were extremely engaged”</td>
</tr>
<tr>
<td>“Entering data was great -- really captured the 7 year old, who kept trying to improve his time.”</td>
</tr>
<tr>
<td>“… you could actually make a working top.”</td>
</tr>
<tr>
<td>“… the cars were simpler to make than i expected.”</td>
</tr>
<tr>
<td>“How innovative kids can be on their own without adult help.”</td>
</tr>
<tr>
<td>“seeing our vehicles fail.”</td>
</tr>
<tr>
<td>“our girls were able to stick with it with just a little help”</td>
</tr>
<tr>
<td>Simplicity of materials and challenge</td>
</tr>
<tr>
<td>“even though it was simple but it still took a little bit of effort”</td>
</tr>
<tr>
<td>“Variety of materials”</td>
</tr>
<tr>
<td>“materials that i would not expect to be used for the challenge were available”</td>
</tr>
<tr>
<td>“lots of fun materials. “</td>
</tr>
<tr>
<td>“The creativity of objects to design the marble maze”</td>
</tr>
<tr>
<td>“The mixer!”</td>
</tr>
<tr>
<td>Accessible, multiple paths and solutions</td>
</tr>
<tr>
<td>“the open-ended structure”</td>
</tr>
<tr>
<td>“The marble tracks are fun and there are so many ways to build them”</td>
</tr>
<tr>
<td>“interactive, self pace, self discovery - then photo at the end.”</td>
</tr>
<tr>
<td>“there were so many different ways of doing things”</td>
</tr>
<tr>
<td>“Total freedom to use anything.”</td>
</tr>
<tr>
<td>“easy for all ages.”</td>
</tr>
<tr>
<td>“free discovery/exploration”</td>
</tr>
<tr>
<td>Teamwork</td>
</tr>
<tr>
<td>“interaction with the kids and getting them to think it through”</td>
</tr>
<tr>
<td>“forcing my child to share”</td>
</tr>
<tr>
<td>“working all together”</td>
</tr>
<tr>
<td>“work together to make somethin”</td>
</tr>
</tbody>
</table>
the height. we have a lot of spins toy at home. but we have never been curious of the secret for spinning. Thanks!"

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.

On the whole, 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. See Table 5 for quotes.

Continuing the Experience

Most visitors had never done any activities like the design challenge prior to their experience at the museum. Twenty-two out of 62, or 35.4%, said they had done something like this before while 40, or 64.5%, said they had not done anything like this before. On the other hand, almost all visitors (51 out of 54) said that they would continue doing similar activities, with fifteen saying that they would come back to the program, 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 program, some of which mentioned that they are not local.

Discussion

Each challenge had several unique and successful characteristics, and the Ingenuity Lab 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[40,41]). All challenges had similar 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. Visitors were very persistent in getting their design to work. Because the challenge was so open, 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. 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. They also understood failure as a method of learning rather than as a result of their inability. Visitors in the Cars challenge further mentioned science of the car’s mechanisms they learned in order to design and build a working car.

Overall, families were very satisfied with the program. They found that all ages and backgrounds, including adults, actively participate. Parents were very surprised that anyone can engineer; their children were able to learn technical concepts and design and build things “that work.” The variety of paths of accessibility was appreciated. Parents were surprised at the simplicity of the materials and indicated their desire to continue similar activities with their own materials. Many parents hoped to pursue such activities by collecting similar materials for home and returning to the engineering space. 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, perceiving engineering as accessible. 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. 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, they persisted without giving up. However, visitors still had difficulty connecting their actions to their personal lives and to engineering in the real world.

Conclusion

The significance of this study is the analysis of these activities in terms of engineering and family engagement. Even though most survey responses were from parents, their influence is strong and their positive involvement is likely to lead them to extend these activities and continue these conversations at home. 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. Many chose to become members because of the program and others indicated their desire to continue similar activities at home. 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. In conclusion, the popular tinkering engineering activities do have educational merit, and can teach aspects of the nature of engineering and influence parents to further these experiences.
Design guidelines resulting from this research include:

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.

2. **Utilize a variety of everyday accessible materials.** Visitors 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.

3. **Offer challenges that are achievable within the timeframe.** In science center settings, visitors often expect to stay in an area for several minutes at the most. This program engages visitors for an average of 30-50 minutes, so successful designs should be achievable at the lower end of about 20 minutes.

4. **Foster multiple iterations of refinement.** Visitors were extremely engaged in getting small problems fixed—going through engineering design in testing, experimenting, improving, and problem-solving. By creating opportunity for small successes, visitors can persist and achieve success, thus gaining confidence in their ability to engineer.

5. **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.

Following these guidelines, this type of space may be replicated to inspire the next generation of engineers.

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