Collaborative idea exchange and material tinkering influence families' creative engineering practices and products during engineering programs in informal learning environments

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Soo Hyeon Kim
Department of Library and Information Science, Indiana University Purdue University at Indianapolis, Indianapolis, Indiana, USA, and

Heather Toomey Zimmerman
Department of Learning and Performance Systems, Pennsylvania State University, University Park, Pennsylvania, USA

Abstract

Purpose – This paper aims to investigate how families' sociomaterial experiences in engineering programs held in libraries and a museum influence their creative engineering practices and the creativity expressed in their products derived from their inquiry-driven engineering activities.

Design/methodology/approach – This research project takes a naturalistic inquiry using qualitative and quantitative analyses based on video records from activities of 31 parent–child pairs and on creativity assessment of products that used littleBits as prototyping tools.

Findings – Families engaged in two sociomaterial experiences related to engineering – collaborative idea exchange and ongoing generative tinkering with materials – which supported the emergence of novel ideas and feasible solutions during the informal engineering programs. Families in the high novelty score group experienced multiple instances of collaborative idea exchange and ongoing generative tinkering with materials, co-constructed through parent-child collaboration, that were expansive toward further idea and solution generation. Families in the low novelty score group experienced brief collaborative idea exchange and material tinkering with specific idea suggestions and high involvement from the parent. An in-depth case study of one family further illustrated that equal engagement by the parent and child as they tinkered with the technology supported families' creative engineering practices.

Originality/value – This analysis adds to the information sciences and learning sciences literatures with an account that integrates methodologies from sociocultural and engineering design research to understand the relationship between families' engagement in creative engineering practices and their products. Implications for practitioners include suggestions for designing spaces to support families' collaborative idea

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exchange and ongoing generative tinkering to facilitate the development of creative engineering practices during short-term engineering programs.

Keywords Creativity, Making, Sociomateriality, Interaction analysis, Family learning, Informal STEM learning, littleBits

Paper type Research paper

The significance of fostering creativity during learning is reflected through *The Next Generation Science Standards* (NGSS) (Hoeg and Bencze, 2017; National Research Council, 2012) that set aptitudes of innovation and creativity as critical educational goals. In informal learning environments such as libraries and museums, engineering and making programs that situate learners within real-world design problems support children to apply engineering knowledge and creativity. While studies have explored the nature of creativity within learning settings (Peppler *et al.*, 2011; Peppler and Kafai, 2007; Peppler and Solomou, 2011) and the creative processes in physical and computational making (Bevan *et al.*, 2015; Roque, 2016), the nature of creativity as children engage in engineering activities – particularly within engineering programs in libraries and museums – remain unanswered. Considering how children are often accompanied by their family when engaged in informal programs, educational researchers have widened their focus to include the family as an important unit of analysis (Brahms, 2014; Roque, 2016) in studies of learning. In our research on one-hour engineering programs in libraries and a museum, we examined families' engagement in engineering activities with a focus on creativity.

Public libraries actively implement Science, Technology, Engineering and Mathematics (STEM) into their existing programs (Bartolone *et al.*, 2014) by providing workshops, maker programs, makerspaces and learning labs to promote creativity (Association of Science-Technology Centers and Urban Libraries Council, 2014; Whyte, 2016). The literature on library-based makerspaces shows promising results toward community engagement and youth empowerment (Halverson *et al.*, 2017; Wang *et al.*, 2016). However, most published articles are anecdotes, best practices and how-to guides that focus on ways to successfully implement makerspaces or maker programming (Acerro, 2014; Bagley, 2014; Belbin and Newcombe, 2013) or resources to support capacity building of library professionals in Library and Information Science curriculum (Bowler, 2014; Rogowski *et al.*, 2018). While research has begun to investigate how to support learning in library makerspaces through the use of question prompts (Bowler and Champagne, 2016; Zimmerman *et al.*, 2019) and different scaffolding approaches for activities in library makerspaces (Einarsson and Hertzum, 2019), these studies do not explore the interactional processes between people, tools and the environment during the creative process (Sawyer and DeZutter, 2009). As such, we take a video-based analysis of families' engineering activities in relation to creativity in library and museum engineering programs.

The importance of fostering creativity has been discussed in multiple fields, particularly in engineering education and human-computer interaction. Scholars have pointed out that facilitating creativity includes supporting:

- divergent thinking (such as generation and exploration of ideas) and convergent thinking (Daly *et al.*, 2014); and
- an openness toward others' ideas and collaboration (Cropley, 2015; Kazerounian and Foley, 2007).

Studies have also suggested the relevance of problem framing (Atman *et al.*, 2007; Cross, 2001; Suwa *et al.*, 2006) as key to creativity. The quality of feedback in the collaborative design process has also been highlighted (Crain and Bailey, 2017; Nguyen *et al.*, 2017), suggesting to center analytical attention on supporting reflective processes. Notably, the literature on creativity in engineering education and human–computer interaction has focused predominantly on higher education settings with adult learners, limiting what we know about creativity and families with young children.

Theoretical framework

We adopt sociocultural perspectives (Cole and Engeström, 1993; Rogoff, 2003) to consider the role of cultural tools (e.g. language, STEM equipment, ways of thinking) in mediating learning within the social and cultural contexts of engineering programs in libraries and museums for families with elementary-aged children. The sociocultural perspective includes an expansive view of culture, not only ethnicity, where cultural experiences constitute and are constituted by the tools that are created for and by people to use throughout their daily lives. Or, as Rogoff (2003) suggests: "Culture is not an entity that influences individuals. Instead, people contribute to the creation of cultural processes and cultural processes contribute to the creation of people. Thus, individual and cultural processes are mutually constituting rather than defined separately from each other" (p. 51). Sociocultural perspectives highlight culture as including the routine ways of engaging, doing and performing tasks with conceptual and physical cultural tools in the multiple communities in which people are members.

Engineering practices

Researchers have explored how the science and engineering disciplines are cultural communities (Latour and Woolgar, 2013) with specific norms, cultural tools, world views and practices. The importance of the cultural nature of science and engineering has been noted in educational curricular documents such as the NGSS (National Research Council, 2012), which suggests that K-12 education includes a specific focus on scientific and engineering practices. In his argument elucidating why the NGSS adopted the term practice, Ford (2015) defined practice as "a set of regularities of behaviors and social interactions that, although it cannot be accounted for by any set of rules, can be accounted for by an accepted stabilized coherence of reasoning and activities that make sense in light of each other and in light of the practice's aim" (p. 1045). Engineering practices related to the NGSS include "specifying constraints and criteria for desired qualities of the solution, developing a design plan, producing and testing models or prototypes, selecting among alternative design features to optimize the achievement of design criteria, and refining design ideas based on the performance of a prototype or simulation" (National Research Council, 2012, p. 69). As such, in our analysis, we investigate families' engagement in cultural practices of engineering, rather than considering culture as only a variable related to families' ethnic backgrounds.

In alignment with sociocultural theories, our work examines the creative engineering practices in which the *social* and the *material* are neither independent nor interdependent entities, but inseparable as the social and the material co-constitute each other (Johri, 2011; Orlikowski, 2007). We use the sociomaterial perspective that considers how learners' experiences with people and resources influence their engineering practices and products. Specifically, we draw upon distributed (Sawyer and DeZutter, 2009) and material views of creativity (Glaûçveanu, 2012) to conceptualize creativity as a distributed and materially grounded activity. Furthermore, to examine the nature of creativity in families' engineering practices in libraries and museums, we adopt the definition of engineering creativity that includes the novelty and the appropriateness of ideas and solutions (Howard *et al.*, 2008). In this view, creative engineering practices are operationalized in our study as sociomaterial activities that give rise to externalized forms of novel and appropriate ideas and solutions when families address the design problem in engineering programs (Howard *et al.*, 2008; Vygotsky, 2004).

Distributed creativity across everyday expertise

We developed *Distributed Creativity across Everyday Expertise Framework* as a theoretical lens by bringing together distributed views of creativity and everyday expertise framework (Zimmerman and Bell, 2012) to explore families' creative engineering practices situated within engineering programs in informal learning environments. The everyday expertise framework considers the individual, social and cultural aspects of learning and has been used by multiple studies (Bell *et al.*, 2006; Zimmerman *et al.*, 2010) to understand learning in informal learning institutions or across settings (i.e. home and school). In our work, we focused on the families' sociomaterial experiences in informal engineering programs that gave rise to engaging in creative engineering practices and how these sociomaterial interactions influenced their products of making (Figure 1). We specifically build our theoretical framework on two areas of research – dialogic inquiry and sociomaterial interaction – that influence creative engineering practices.

Dialogic inquiry to facilitate creative engineering practices. Our analytical focus is on dialogic inquiry that facilitates families to act creatively during engineering practices. Dialogic inquiry – co-constructed by participating members – is a reciprocal conversation, which supports the social group's collaborative sense-making and inquiry (Ash, 2003; Wells, 2000). The literature on family science learning and making suggests that children's learning is highly dependent on the quality of dialogic inquiry (Brahms and Crowley, 2016; National Research Council, 2009). Dialogic inquiry provides opportunities for youths and families to sustain understanding, articulate observations, engage in collaborative argumentation, make interpretations and engage in science practices (Allen and Gutwill, 2009; Ash, 2003; Kim and Zimmerman, 2017; Zimmerman *et al.*, 2010). Dialogic inquiry is an effective facilitation move in museum-based makerspaces (Brahms, 2014; Brahms and Crowley, 2016) in which adults spark, sustain, and deepen youths' interests during making (Gutwill *et al.*, 2015). In engineering education, research suggested that collaborative problem-solving discourse (similar to dialogic inquiry) predicted the product novelty of students' engineering artifacts (Deitrick *et al.*, 2014).

Sociomaterial interaction that supports creativity. We seek to understand how families' sociomaterial interaction facilitates their engagement in creative engineering practices. Scholars concerned with constructionist practices (Kafai, 2006; Papert and Harel, 1991) have

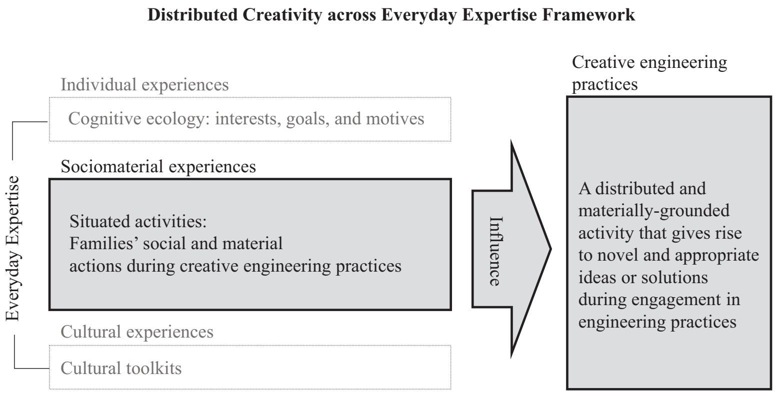


Figure 1.
Distributed creativity across everyday expertise framework. The focal area of analytical attention is highlighted in gray in the theoretical framework

underscored the interconnected relationship between the materials and the actor – calling for investigating practice-based activities along with disciplinary-relevant tools. Relatedly, in the learning sciences, scholars (Litts, 2015b; Resnick and Rosenbaum, 2013; Wardrip and Brahms, 2015) have emphasized providing a space in which learners can freely tinker, experiment and improvise with the materials during making. Specifically, within public libraries, scholars have suggested considering ways to make the making and tinkering processes visible to the patrons to promote creativity and learning (Halverson *et al.*, 2017). Our analysis, then, attends to families' verbal (dialogical inquiry) and non-verbal communications (e.g. gestures, tool handling, pointing) from video-based records of families' sociomaterial interaction in engineering practices.

Research questions

Given that engineering is "one of the most material-saturated disciplines" (Johri and Olds, 2011), researchers need to consider how families' interactions unfold around the STEM materials by bringing theoretical sociocultural perspectives from the learning sciences. As such, our work used the *Distributed Creativity across Everyday Expertise Framework* to investigate the dialogic inquiry and sociomaterial interaction during families' creative engineering practices as they collaboratively engaged in engineering programs. In addition, we adopted a creativity assessment metric to explore how creative practices shape the novelty of the families' products. We answer two questions in our study:

Q1. How do families with different novelty scores (a proxy for creativity) interact with sociomaterial resources during novel idea generation and feasible solution generation?

Q2. How do families' engineering practices interconnect, accumulate, and shape the creativity of the final products in engineering programs held in libraries and a museum?

Research design

Participants and sites

This analysis was part of a three-year design-based research (DBR) (Barab and Squire, 2014) project called the STEM Pillars (Zimmerman *et al.*, 2018), which is funded by the Institute of Museum and Library Services (IMLS). Partners included Homebrooke Library, Mayfield Library, Waterview Library, Clinton Library, Lexington Library, Landmark Science Center (pseudonyms) in the northeastern USA, and two engineers (Max and Aimee; pseudonyms) from a biomedical company. This analysis includes data from hour-long engineering programs held in five libraries and one museum during the second DBR iteration in 2017 and builds from our prior study (Kim and Zimmerman, 2019). Our study sample was library-and museum-going families that participated in regularly scheduled public programs. Families were recruited on-site immediately before programs began. As such, during consent, the research team did not collect any demographic information, except for names and ages. We also did not collect information about families' prior experiences with STEM learning or their motivation for attending the program. Of 87 people who attended programs, 75 consented to participate in our research (42 children, 33 adults). Only consented participants were filmed during the programs (approximately 21 h of video and 18 h of audio).

The researchers consented and assent participants, ran data collection equipment, handed out surveys and took fieldnotes. The biomedical engineers facilitated the program.

Max facilitated programs at three libraries and one museum; Aimee facilitated programs at two libraries.

Engineering curriculum and materials provided
We adopted Engineering is Elementary process (ask-imagine-plan-create-improve) to describe the engineering practices to families (Cunningham, 2009). littleBits™ were distributed as prototyping tools. The research team configured our program kit that included a battery, cord, power, bright LED, DC motor, servo, button, fork, screwdriver, motor mate and two wires (Plate 1). Families with siblings sometimes had two kits. We also provided craft materials (e.g. scissors, tape, felt, pipe cleaners, construction paper, cardboard, cups, cupcake liners) to support their engineering solution generation.

With a goal of open-ended exploration (i.e. limited instruction was provided), at the start of the program, families explored the littleBits and shared what they observed. Then, families engaged in the simple design challenge that had four design examples (i.e. lantern, flashlight, tickler, waver). The images in this handout were from the *littleBits projects lesson* from the littleBits website. We configured our design challenge handout by bringing four design example images (but without step-by-step instructions) to align with project-based learning (Kim and Zimmerman, 2019). Lastly, the engineer introduced the complex design challenge in which families design an interactive toy for a sick neighbor in the hospital. There were three different neighbors (i.e. elder, child, person with a disability) that the families could select.

Data analysis
We undertook a naturalistic inquiry (Guba and Lincoln, 1982), including both qualitative and quantitative analysis (Figure 2). We explored families' creative engineering practices by considering one parent–child pair as the unit of analysis. The parent-child pair was the smallest group of individuals who directly interacted with one another during making at the engineering programs. The approach to focus on parent-child pairs as the unit of analysis has been used by previous literature that investigated families' science practices in informal

Plate 1.
littleBits kit used in the study

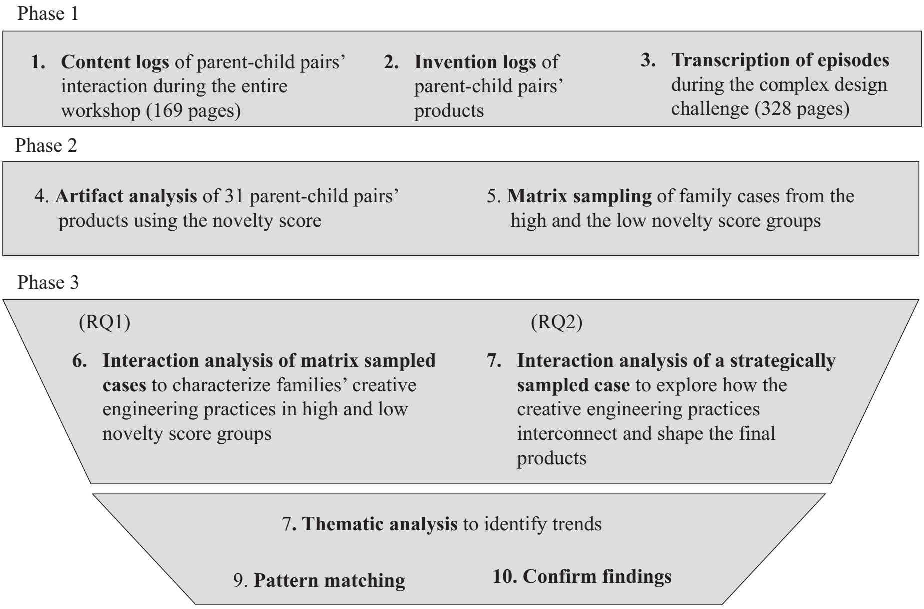


Figure 2. Data analytical procedures

learning settings (Ash, 2003; Eberbach and Crowley, 2017; Sanford *et al.*, 2007), as this unit of analysis "represents the fact that each individual is crucial to the final product but that the product itself is greater than the effort of any one individual"(Ash, 2003, p. 144). Given the informal nature of our engineering program, determining the unit of analysis was complicated. If one parent equally collaborated with two children, we identified two parent-child pairs (i.e. parent-child1; parent-child2). If both parents collaborated equally with each child in the family, each parent–child pair had two parents (i.e. parent1/parent2-child1; parent1/parent2-child2). Families engaged in conversations with other families as well as the engineer and the research team. While the unit of analysis was parent–child pair, we included other family members, the engineer and the research team in our analysis, if they had interaction with the focal parent–child pair that contributed to their engagement in the program. Given that this study explored both the families' creative engineering practices and the creativity of the families' products from making, family cases were excluded if final products were not completed or if families communicated in a language that could not be translated by a native speaker on the research team (i.e. only English, Korean and Chinese language speaking families were included). Children outside the age range of 5–11 years old were excluded. Consequently, 31 parent–child pairs were analyzed (average child's age: 8 years old).

Our protocol included three stages of analysis.

Phase 1. First, we created content logs (Jordan and Henderson, 1995) of parent–child pair's interactions during the entire program (approximately 169 pages). We also developed product logs (a graphic overview of the products created with littleBits by each parent–child pair). Then, we identified the episodes of the complex design challenge when each parent–child pair designed the final product in our logs. Participating families were encouraged to engage in ways that were comfortable to them. If families wanted to work longer on the simple design challenge rather than moving onto the complex design challenge, the engineer leading the program encouraged them to do so. To account for families whose final products were the modification of the products created during the simple design challenge, we included the entire episodes during the simple and complex design challenges. These making episodes were transcribed line-by-line with verbal and non-verbal communications using the transcription software, Inqscribe (approximately 328 pages) prior to data analysis.

Phase 2. We categorically aggregated the 31 parent–child pairs by assessing the novelty of their final products using the novelty score in SVS metrics (Shah *et al.*, 2003). Among the two outcome-based creativity assessment tools (i.e. CAT, SVS), we chose Shah, Vargas-Hernandez, and Smith's metrics (SVS) that acknowledge every idea and solution as meaningful to assess relative creativity in a local context – rather than using the subjectivity of the experts. We used the novelty metric in SVS that measures the infrequency of an idea compared to other ideas using the feature tree approach developed by Shah *et al.* (2003). The feature tree had four levels: purpose, electronics, craft materials and embodiment. A feature tree was created for this set of products. It used the novelty of an individual feature to compute the feature's overall novelty in the program, f_i. If a feature is frequently incorporated in other families' products, the feature's novelty score was lower. We used the equation below to calculate the feature's novelty (T is the total number of products in this data set and C_i is the total number of products that incorporated the feature i):

$$f_i = \frac{T - C_i}{T}$$

The novelty of the j th product in this dataset, D_j, was calculated as the ratio between the sum of the feature novelty (f_i) and the sum of f_i in a product. Two raters individually rated 31 products using the feature tree. The Cohen's Kappa (inter-rater reliability) was 0.867. The full detail of using the SVS novelty metric to assess families' final products have been outlined in our prior study (Kim and Zimmerman, 2019).

Given our research interest to explore families' sociomaterial interactions with different novelty scores, we explored four different ways of grouping the 31 parent–child pairs: low – high; low – medium – high; low – medium low – medium high – high; and low – low medium – medium – medium high – high (Figure 3). Based on the content logs and transcriptions of 31 parent–child pairs, we analyzed how many groupings would provide the most similar cases (Seawright *et al.*, 2008). The analysis showed that categorizing the family cases into two, three, or five groups would not account for the subtle differences between different product features and families' engineering practices. Thus, we categorized the 31 parent–child pairs into four groups based on their novelty scores ranging from 0 to 1 ($0 \leq$ low group < 0.25; $0.25 \leq$ medium-low group < 0.5; $0.5 \leq$ medium-high group < 0.75; $0.75 \leq$ high group ≤ 1). We used matrix sampling to select all the cases in high and low novelty score groups for further analysis (low: n = 17, medium-low: n = 10, medium-high: n = 2, high: n = 2).

Phase 3. We next used interaction analysis (Jordan and Henderson, 1995) of the 19 matrix sampled cases to explore the families' creative engineering practices in high and low novelty score groups. Envisioning multiple solutions and constructing models and prototypes were the two engineering practices that were commonly observable based on fieldnotes, content logs and transcriptions. To establish an analytical focus, we examined the parent–child pairs' engineering practices around generating ideas and solutions during the complex design challenge.

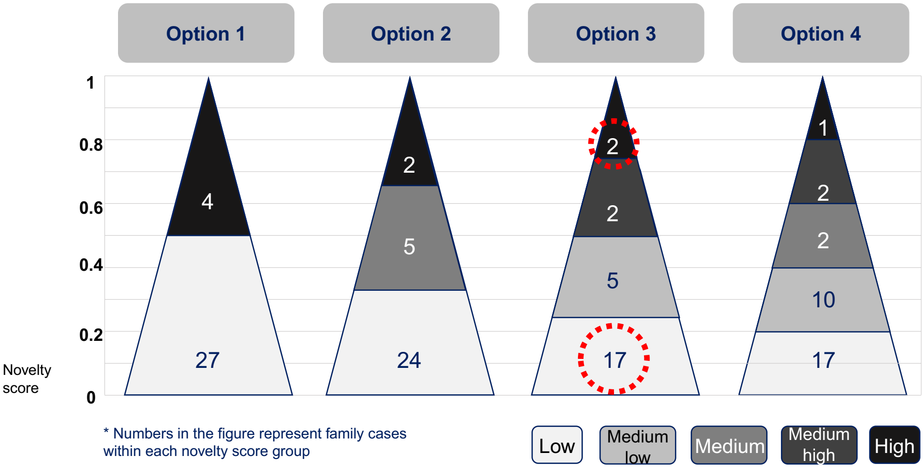


Figure 3.
Four ways of categorizing 31 parent-child pairs

To examine families' engineering practices of idea and solution generation, we identified moments, on the transcripts using ATLAS.ti, when a family experienced an idea spark on what to design and a solution spark on how to feasibly translate the idea into a solution. Given the short duration and low frequency of idea and solution sparks in the 17 pairs in the low novelty score group, we compared and contrasted all the episodes of idea and solution sparks in Microsoft Excel. Furthermore, we strategically sampled the two high novelty group families with multiple episodes of idea and solution sparks to examine the micro-development of creative engineering practices. (Given there are only two cases of the high-novelty group, we acknowledge the limitation of such a small sample, even in a qualitative study). We created timelines of the two families' design trajectories with texts and screenshots from the video-records to describe their discourse, gestures and use of tools around each moment of idea and solution sparks. We used rich and thick descriptions to illustrate how the focal families' creative engineering practices shaped the final products.

For each analytical phase, we held multiple video-viewing sessions to discuss, question and review emergent trends. We looked for both typical cases and for extreme and unique cases to increase the validity of our findings. To confirm findings, key patterns with transcripts and video were shared multiple times in research meetings that involved two other researchers. With our naturalistic aim, the settings varied – five libraries and a museum that involved different numbers of participants, physical configurations and engineers leading the programs. While it may be meaningful to account for families' prior experience, interest and disposition, as well as any differences between the two engineers' facilitation techniques, these factors are beyond the scope of this paper.

Findings

Our study findings illustrate that collaborative idea exchange and ongoing generative tinkering with materials supported the emergence of novel ideas and feasible solutions when families engaged in library or museum engineering programs. While the two families in the high novelty score group both shared common sociomaterial interactional patterns, the sociomaterial interactions of 17 families in the low novelty score group showed nuanced differences. To illustrate the spectrum of collaborative idea exchange in the low novelty score group, we strategically sampled two families from that group. Lastly, an in-depth analysis of one family with a high novelty score is presented to demonstrate how creative engineering practices connected, accumulated and shaped the final products.

Low novelty score group: limited collaborative idea exchange

The 17 low novelty score parent–child pairs did not engage in improvisatory tinkering with materials – with different variations in their collaborative idea exchange. We present the Alexis–Hudson pair to highlight the brief collaborative idea exchange with specific ideas suggested by the parent that was typical in low novelty score groups and the Walden–Cindy pair to demonstrate longer-duration, but limited, collaborative idea exchange with high involvement from the parent.

Brief collaborative idea exchange with ideas suggested by the parent in typical low novelty score cases. Alexis (parent) and Hudson (child, 6 years) came to the engineering program at Landmark Science Center with another sibling, Brooklyn (8 years). Alexis worked with both children to support them as they created two different engineering solutions. When the complex challenge was introduced, Alexis asked questions to engage Hudson, as illustrated below.

Excerpt 1:

1	Alexis:	What's your project going to be, Hudson? ***[prompt idea]***
2	Hudson:	((silent))
3	Alexis:	What if we made a helicopter? Do you want to make a helicopter?
4		***[idea suggestion] [idea spark]***
5	Hudson:	I will try and do it.***[idea agreement]***

Alexis prompted Hudson to generate ideas through questioning to guide their inquiry during engineering design (Line 1). When Hudson did not share any ideas (Line 2), Alexis's questioning shifted from an open-ended question to a specific suggestion of making a helicopter (Line 3), which was immediately taken up by Hudson (Line 5). As a result of the specific idea suggested by the parent, the duration of their collaborative idea generation was short – without an opportunity to inquire in-depth on how they can frame the design problem. Instead, Hudson agreed to the idea of a helicopter and used a littleBits servo and added a green pipe cleaner on the servo blade to create a "ninja helicopter." The helicopter used the same mechanism as their previous product, a tickle machine that incorporated a motor to turn the pipe cleaner. As such, Hudson and Alexis did not experience any challenges in regards to creating a feasible solution. This episode highlights the brief collaborative idea exchanges with specific idea suggestions from the parents that were visible in typical pairs from the low novelty score groups.

Longer-duration, but limited, idea exchange with high involvement from the parent. We present Walden and Cindy's interactions to illustrate the other end of the spectrum of parent–child pairs in the low novelty score group that had longer-duration (yet limited) idea exchange in which the parent influenced the evolvement of the idea. Cindy was a 9-year-old who came to the engineering program with her father, Walden, at Waterview Library. For the final product, Walden and Cindy created an interactive cat, which used the same littleBits arrangement of the auto-greeter that they had previously built. To provide an overview, we first describe Cindy and Walden's design trajectory.

When the engineer introduced the complex design challenge, Cindy and Walden had finished two of the simple design challenges (a flashlight and a tickle machine) and had started working on the auto-greeter. Walden explained the challenge to Cindy and asked her what she would want to design for a sick neighbor in a hospital, at which point Cindy first generated the idea of a tickler. However, Walden disagreed: *"How would you have a tickle machine? They tend not to want you to be tickling people in the hospital."* Cindy then expressed that she wanted to finish all the simple design challenges rather than developing her initial idea of a tickle machine. She resumed back to completing the auto-greeter. When Cindy had completed it, Walden asked again whether she wanted to build a product for a sick neighbor. Cindy expressed that instead of engaging in the complex design challenge, she wanted to create the fourth simple design challenge. Walden prompted Cindy to engage in the complex design challenge. Walden asked a series of questions to guide Cindy to come up with some design requirements for the product, such as "fun, interactive, safe." We present an episode that illustrates their interaction after this moment to show how Walden and Cindy decided to make a teddy bear that waves, which later evolved into an interactive cat, for a sick child.

Excerpt 2:

Walden: Right. Okay, so fun, interactive, safe. What kind of toy might you make? ***[prompt idea]***
Cindy: A teddy bear! ***[idea suggestion][idea spark]***
Walden: Out of these parts?***[idea questioning][uncertainty]***
Cindy: No.***[idea rejection]***
Walden: Maybe if you had a hand-waving teddy bear that shoots lasers out of its eyes. Ah! ((laughs)) ***[idea modification]***
Cindy: Maybe I can make a teddy bear that waves. ***[idea suggestion] [idea spark]***
Walden: There you go. ***[idea confirmation]***
Cindy: Is that—
Walden: How do you think you would do that? ***[prompt idea]***
Cindy: Would that be a good toy? ***[checking for approval]***
Walden: You tell me. This is your product.***[assurance]***
Cindy: Okay ((nods)). ***[idea agreement]***

Walden asked Cindy what she would make, considering three design requirements they decided (Lines 1-2). Cindy shared her idea of a teddy bear (Line 3), but Walden questioned whether it was appropriate, considering the materials they had at the program (Line 4). Cindy agreed that the teddy bear idea would not be appropriate (Line 5). In this way, Cindy's initial idea was rejected following Walden's feedback that signaled uncertainty about the idea during their problem framing. Walden repaired this moment by suggesting a slightly modified idea of a teddy bear (Lines 6–7). Consequently, instead of completely dismissing the idea of a teddy bear, Cindy took the first half of her father's idea – the hand-waving teddy bear – to modify her idea (Line 8). However, instead of embarking on solution generation, Cindy was still hesitant in developing this idea into a product (Lines 11, 13). When Walden encouraged her to take ownership of her design, Cindy finally proceeded with developing her idea into a product (Line 15). After cutting the paper into the shape of a teddy bear, Cindy changed her mind and decided to call their product a "kitty" and created an interactive cat for a sick child.

In comparison to Alexis and Hudson, Walden supported Cindy's inquiry on what to design through different dialogical approaches such as prompting, questioning, modifying and confirming an idea; however, ideas suggested by the parent still dominated their collaborative idea exchange. When Walden noticed that his questioning move (Line 4) brought a brief stop in their idea generation, he responded with a modified idea to continue their collaborative idea exchange. However, the overall collaborative idea exchange was still limited in expanding the ideational scope beyond their initial idea, which was influenced by the parent. Walden and Cindy's family case highlights the limited collaborative idea exchange that was visible in several parent–child pairs in the low novelty score group in which the parent influenced the idea evolvement during collaborative idea exchange.

High novelty score group: expansive collaborative idea exchange

Our analysis suggested that families in the high novelty score group experienced multiple instances of collaborative idea exchange and ongoing generative tinkering with materials – co-constructed through parent–child collaboration – that were expansive toward further idea and solution generation in engineering programs. We illustrate this finding through the Jimmy–Shelley pair. Jimmy was a nine-year-old who came to the engineering program at Lexington Library with his mother, Shelley. We provide an overview of all the artifacts that they created. We considered an artifact when new features were added to enable new functionality or aesthetic feature. Given this view, Shelley and Jimmy's created 11 artifacts (Plate 2).

During the simple design challenge, Jimmy's family started with a tickle machine [Plate 2(a)]. However, when Jimmy noticed a waving machine that another family had created, he decided to make a spinning device using a littleBits servo and felt [Plate 2 (b)]. After another moment of idea spark, Jimmy added a button and drew a face on the felt fabric to create "a little girl shaking its head saying no" [Plate 2(d)], which we will refer to as *frowny*. Jimmy then made a similar artifact of "a boy laughing" [Plate 2(f)], which we will refer to as *smiley*. The *smiley* and the *frowny* were later incorporated into the final product, a communication device for a child who cannot say either "yes" or "no" [Plate 2(i)]. Meanwhile, Shelley had tinkered with a littleBits purple screwdriver, which could be used to change the input level of some littleBits components. She used the purple screwdriver to adjust the RGB light to change its color to red, green, or blue [Plate 2(c)]. Shelley had also used a motor to create a spinning flower [Plate 2(e)]. During the complex design challenge, the collaborative idea exchange inspired Jimmy's family to create a communication device that can say "yes" or "no" and an RGB light that changes color to communicate different feelings [Plate 2(j)]. Jimmy created feasible solutions for stabilizing *smiley* and *frowny* by using two cups and masking tape [Plate 2(h)]. However, the early prototype incorporated one button that would enable two faces to turn simultaneously [Plate 2(i)]. Jimmy and Shelley were able to fix this problem by incorporating one more button for the second face. Later, Jimmy made a small adjustment to their final product by incorporating Shelley's spinning flower as an interactive component [Plate 2(k)]. In sum, Shelley and Jimmy continuously evolved their artifacts, which led to the development of their final product.

Jimmy and Shelley's final product – a communication device for a child who cannot speak – had the highest novelty score in our data set because it incorporated the greatest number of novel features. The analysis findings illustrated that the communication device emerged through multiple instances of collaborative idea exchange and ongoing generative tinkering with materials that were expansive toward further idea and solution generation. Jimmy and Shelley did not start the design process with a clear design goal. Instead, the final idea evolved multiple times as they interacted with social others and material resources around them within the engineering programs. When the complex design challenge was introduced, Jimmy approached the engineer to show the *smiley,* and the engineer Max briefly shared a comment and moved away. Jimmy then approached Max for the second time by bringing both the *smiley* and a spinning flower that Shelley had made. The excerpt starts as Jimmy shares the two artifacts with Max.

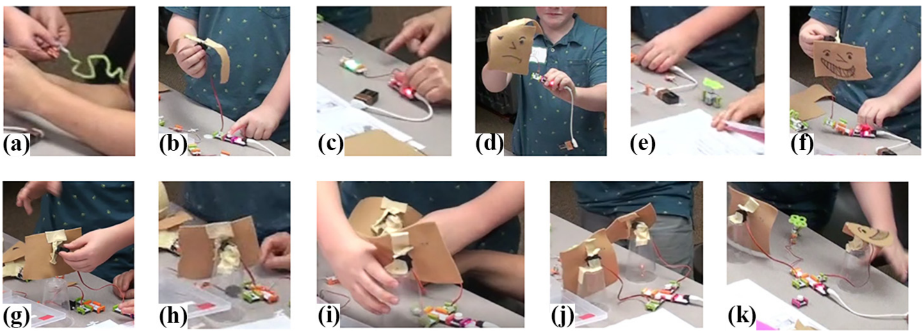


Plate 2.
11 artifacts created by Shelley (parent) and Jimmy (child): a) tickle machine, b) spinning device, c) changing RGB light, d) *frowny*, e) spinning flower, f) *smiley*, g) device to communicate yes with the use of cup, h) device to communicate yes with the use of cup and masking tape, i) communication device to express yes or no with one button (has errors), j) communication device with two buttons, k) communication device with a RGB light to express different emotions and a spinning flower

Excerpt 3:

Max: Oh, I love it! It's like a beautiful spinning flower! ((touches the branch))I wonder if you could actually hook up like if you wanted to, your two different faces ((points at *smiley* and *frowny*)) to two different things using the two branches ((grabs branch)).***[idea suggestion]***

Shelley: Oh!!! You can do that!***[idea agreement] [idea spark]***

Max: And I don't know how—I don't have the idea of the circuits-

Shelley: Let's see!***[idea encouragement]***

Max: …but then you could actually…

Jimmy: Three things. ***[understanding the suggestion]***

Max: …switch between smiling and frowning.***[idea suggestion]***

Shelley: Then this child ((points at challenge handout)) could play a game and say, "Yes" or "No."***[idea suggestion]***

Jimmy: I don't know. ***[idea questioning] [uncertainty]***

Shelley: Maybe the person has a disability and can't talk, so they could use ((points at *smiley*)) your "yes" ((nods)) and "no" ((shakes head sideways)) to talk to the nurse.***[idea explanation]***

Jimmy: Yeah! Because maybe we could combine those, a child, a child with a disability.***[idea confirmation/ ideamodification]***

When Jimmy shared the artifacts, Max noticed that Jimmy was using a branch (Lines 1–2) that can connect the output of a single Bit to other Bits. Then, Max suggested using the branch to connect two different face puppets (Lines 2–4). Shelley reacted with excitement (Line 5). Max provided a suggestion to allow Jimmy to create a product that could switch between smiling and frowning (Lines 7, 9, 11). Shelley directed Jimmy's attention to the final challenge by pointing at the handout (Line 12) and shared her idea of creating a game for a child to communicate "yes" or "no" (Lines 12–13). When Jimmy reacted with uncertainty (Line 14), Shelley repaired the moment by re-describing her idea (Lines 15–17) to align more closely with what they had previously decided to make (i.e. an interactive toy for a person who cannot speak). Jimmy reacted positively and added that the product will now be for a child with a disability (Lines 18–19). This excerpt illustrates how families' collaborative idea exchange in the high novelty score group was shaped by ideas suggested by both the parent and the child, and the parent's responding the child's dialogic turns with idea encouragement and idea explanation.

Overall, the engineers encouraged families to take ownership of their engineering design. However, given the informal nature of the engineering program, the engineers often walked around and casually shared comments or ideas on families' artifacts. The engineers also prompted families to use the purple screwdriver to find out how it might change the functionality of some littleBits components. However, we highlight that the Shelley–Jimmy pair was the only family whose creative engineering practices were directly influenced by the engineer's comment. We also emphasize that the above excerpt was the only instance in which the engineer suggested an idea during a family's collaborative idea exchange. In this regard, despite the presence of the engineer, families' creative engineering practices in our data set were predominantly driven by the family members themselves. In Jimmy's family, the initial idea suggested by the engineer emerged after noticing the abundance of artifacts that Jimmy and Shelley had previously created. Prior to sharing the spinning flower in Excerpt 3, Jimmy had shared *smiley,* to which Max had responded by briefly sharing a comment and moving away. However, Jimmy attracted Max's attention by sharing a spinning flower. When Max came closer to look at Jimmy's product for the second time, he noticed the abundance of littleBits artifacts, as well as the branch Bit, and suggested connecting the already-available resources to create something new.

Our further analysis illustrated that the creative engineering practices in Jimmy and Cindy's families evolved in contrasting ways in regards to the idea holder, questioner, modifier, and confirmer. In Jimmy's family, the idea for combining the *smiley* and the *frown* was suggested by Max. However, the parent encouraged, modified, and explained the idea until the child agreed to take up the idea. Jimmy was positioned as the idea confirmer and took the lead in the engineering design process to create the communication device through the parent's encouragement and explanation when he questioned and expressed uncertainty toward the idea. We also note that this interaction pattern was continuously noticeable throughout Jimmy and Shelley's engineering design process. However, in Cindy's family, the parent influenced the evolvement of the idea by questioning the idea's appropriateness, suggesting a modified idea, and confirming the idea as appropriate. The two cases highlight how the outcomes of families' creative engineering practices were influenced by the parent's feedback and openness toward considering ideas as improvable. It further suggests that the parent and the child's collaboration during their dialogic inquiry supported two families in the high novelty score group to engage in more instances of collaborative idea exchange.

High novelty score group: ongoing generative tinkering with materials

Our analysis of creative engineering practices around the solution sparks of two cases in the high novelty score group illustrated that ongoing generative tinkering with materials supported them to discover new affordances of materials and create a prototype during feasible solution generation. We present an excerpt from Jimmy's family that is representative of ongoing generative tinkering that was visible in two cases in the high novelty score group. When Jimmy decided to incorporate the *smiley* and the *frowny* in the communication device, he then had to find a way to attach them to something. The excerpt shows that Jimmy appropriated the plastic cup and masking tape in ways that were beyond their traditional usages to serve new functions in their product. Jimmy first tried putting *smiley* directly on the plastic cup but noticed that it would collide with the cup when it moved. The following excerpt presents Jimmy's tinkering with available materials to overcome this challenge. We included the written transcript and two figures (Plates 3 and 4) to illustrate Jimmy's object manipulation.

Excerpt 4:

1	Jimmy:	I want to tape that [the servo] to there [the cup]. Oh, wait! I need
2		something out there because… ***[identify a problem]***
3		((observes *smiley* turning; when it touches the cup, gently rotates
4		the angle until it does not touch the cup)) Okay, off. Turn off
5		switch. ***[plan; object manipulation]***
6	Shelley:	((turns off))
7	Jimmy:	Okay, so hold it at an angle just like that ((checks the angle)). This
8		((points at the servo)), hold that at an angle right there. ***[create]***
9	Shelley:	((holds the servo))
10	Jimmy:	((takes a piece of masking tape and crumbles it)) [solution spark] I
11		meant to do this. I need something to hold it up in the air. ((puts
12		roll of tape on the cup)) ***[create]***

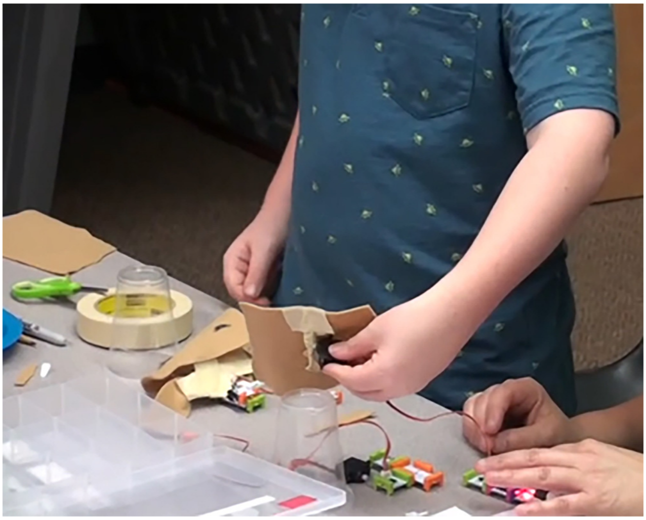


Plate 3.
Jimmy's solution generation after problem identification by planning through object manipulation (corresponding to transcript line 3-5)

Jimmy identified a problem because he could not tape the servo directly on the cup. With the vague solution of putting "something out there" in between the servo and the cup (Line 2), Jimmy's solution included object manipulation by modifying the angle and the position of the *smiley* (Lines 3–5). Jimmy optimized the position of the artifact and directed Shelley to hold it (Line 7). Jimmy looked around to see whether there was anything that he could put in between the cup and the artifact. When he noticed a roll of tape, he crumbled a piece of tape and used it as a hinge to hold the artifact "in the air" to prevent it from colliding with the cup (Lines 10–12). In this regard, Jimmy was able to resolve a problem by looking for appropriate materials and engaging in ongoing tinkering with materials to create a feasible solution for their final product. A similar pattern was noticeable in the other family with a high novelty score. As such, our finding demonstrates how families' collaborative idea exchange and generative tinkering with materials contributed to the emergence of creative ideas and solutions when engaged in engineering programs in informal learning environments.

Accumulation of creative engineering practices that shape the product

An in-depth case study of how Jimmy and Shelley's creative engineering practices accumulated to shape the final product illustrated that equal engagement by the parent to tinker with the littleBits technology provided opportunities to discover new features of the littleBits, which were used as resources for iterative idea generation. We describe two episodes of how independent tinkering by the parent developed new physical resources for future idea generation.

The first episode occurred while Jimmy worked on completing the *frowny*. Shelley independently engaged in learning how to change the color of the RGB light. The screwdriver allowed people to change the color of the RGB light or the speed of the motor. Later, when Shelley shared that she had figured out a way to change the RGB light, it elicited interest from Jimmy and provided an opportunity for him to learn the role of the screwdriver.

The second episode occurred when Jimmy decided to work on the *smiley* instead of a tickle machine that he had previously worked on using a pipe cleaner and a feather. As Jimmy began to work on something else, Shelley silently picked up the pipe cleaner and made it into the shape of a flower. She grabbed the littleBits motor and attached it to the pipe cleaner flower to create a spinning flower. Shelley's tinkering with the materials reflect her engagement in the engineering practices of investigating the use of materials and envisioning solutions, as Shelley thought that this spinning flower could be used as a solution for the sick child: "Do you think the child would like my flower?" However, Jimmy responded: "Well, that's not really interactive. It's a nice thing to watch, though". However, when Jimmy noticed another family improving their product, Jimmy decided to connect the spinning flower to the communication device as an entertainment piece to watch. As such, this episode highlights that equal engagement by the parent to tinker with the littleBits technology provided an artifact that the parent–child pair could later incorporate into their final product.

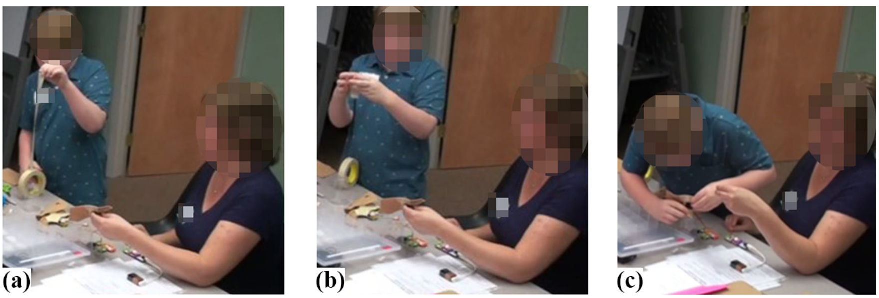
Looking at these two episodes separately only highlights the parent's engagement in envisioning solutions and investigating the use of materials, which may seem unrelated to their final product. However, when these two episodes were analyzed in relation to their final product and other episodes of collaborative idea exchange and ongoing generative tinkering, findings suggest that these two episodes later became new sources of inspiration during idea generation, as demonstrated in the next episode.

Excerpt 5:

1 Jimmy: Then, hang on, let’s put them on these, ((connects *smiley* and
2 *frowny* to branch Bit)) and then we could have a light. And then,
3 maybe, then, if, for feelings, we could add the light in ((grabs
4 ascrewdriver andanRGB light)), so then the nurse could explain
5 what it does ((changes color of the light)). ***[idea suggestion]***And if
6 they’re angry or something they could have that ((changes light to
7 red)), or upset. ***[idea suggestion]***
8 Shelley: Red is for angry? ***[ask questions to sustain understanding]***
9 Jimmy: Uh-huh. And if they’re blue, they’re—oh, yeah—sad. ***[idea suggestion]***
10 Shelley: Okay.
11 Jimmy: And green, they’re like, happy. ***[idea suggestion]***

While arranging the littleBits components to create the communication device, Jimmy noticed the RGB light that he had used before and suggested using different colors to communicate with the nurse (Lines 3–4). Jimmy then expanded this idea by elaborating that each color of the RGB light could represent a different feeling (Lines 6–7). Using the changing lights to communicate different feelings was a unique idea that only a few families had across all programs. In this regard, Jimmy was able to discover a new affordance of the RGB light by combining different potentials that each color could communicate. Later, Jimmy and Shelley also added the spinning flower as an interactive component to their communication device. This episode illuminates how equal engagement by Shelley to tinker with the littleBits technology provided

Plate 4.
Jimmy’s solution generation by creating a prototype (corresponding to transcript line 10-11): a) Jimmy takes a piece of tape, b) Jimmy crumbles the piece of tape, and c) Jimmy puts the roll of tape in between the cup and the servo



opportunities for new idea generation. As Jimmy and Shelley allowed new inspirations to guide their design process when they discovered new affordances of materials and tools, Jimmy and Shelley collaboratively created multiple intermediate artifacts that provided the space for spontaneous, yet novel, idea generation.

Discussion

Our study advances the field of information and learning sciences' understanding of the relationship between creativity, families' engineering practices and sociomaterial interaction in library and museum engineering programs. This study provides an example of how the creativity of families' products is related to two specific activities – collaborative idea exchange and ongoing generative tinkering with materials – that are pervasive and pertinent to our everyday life. These empirical accounts of family creativity suggest that engagement in creative engineering practices may be open to more families if appropriate guidance for collaborative idea exchange and ongoing generative tinkering are provided during library and museum engineering programs. We discuss practical implications related to the design of family engineering curricula at libraries and museums that focus on fostering creative engineering practices around two areas: collaborative idea exchange and ongoing generative tinkering with materials.

Our study adds to the research that illustrates how dialogic inquiry can support family science learning (Ash, 2003; Gutwill and Allen, 2010; Gutwill *et al.*, 2015; National Research Council, 2009) and making practices (Brahms, 2014; Brahms and Crowley, 2016) in informal learning environments. This study provides two cases of high novelty score groups in which parents and children collaboratively engaged in multiple iterations of idea exchange to produce creative products through parent–child collaboration and 17 cases in which families produced creative products with lower novelty scores when their collaborative idea exchange was compromised by specific idea suggestion or high involvement from the parent. Contrasting the ways of collaborative idea exchange between Jimmy's and Cindy's families further emphasizes the importance of quality of collaborative idea exchange, which suggests the relevance of considering the type of feedback that shifts and influences each family members' openness toward considering ideas as improvable. As such, our findings suggest that collaborative idea exchanges were a form of engaging in dialogic inquiry during the engineering design process in library and museum engineering programs, as family members' utterances co-constructed and shaped the trajectory of idea and solution development.

While the importance of openness toward ideas and collaboration has been highlighted by engineering educators (Cropley, 2015; Kazerounian and Foley, 2007), our findings from the in-depth analysis of Shelley and Jimmy's family expands the role of collaboration by illustrating how equal engagement between the child and parent can be crucial for the family's creative engineering practices in informal engineering programs. As Jimmy tinkered on his own, Shelley curiously explored and learned about the littleBits technology instead of just observing her child. We noted that Shelley's equal engagement to notice, observe and point out sociomaterial interactions that caught her attention supported this pair to engage in multiple instances of collaborative idea exchange and ongoing generative tinkering with materials. Jimmy and Shelly's case, despite being the only instance, brings insights about the parental engagement in the engineering making process that can broaden the family's design space by connecting and evolving an idea into the unknown in ways that are unexpected and novel. This family case also points toward future research on the role of the parent's use of questions, gaze and gestures to elicit a child's attention to the peripheral interaction and sustain an understanding of the design process. Building from our study, we invite educators in libraries and museums to encourage dialogical inquiry between parents and children in engineering programs to facilitate meaningful moments of collaborative idea exchange.

Furthermore, our findings suggested that families' creative engineering practices are supported through ongoing generative tinkering with materials in library and museum engineering programs. Jimmy and Shelley tinkered with available materials to generate new ideas and tinkering with new materials facilitated them to generate more ideas. As such, collaborative idea exchange and ongoing generative tinkering with materials reciprocally influenced one another in supporting their creative engineering practices to generate novel and feasible ideas and solutions. In this regard, people and the materials used during the creative engineering design process are closely linked and mutually influencing one another, which is in resonance with making as having a reflective conversation with the materials (Kafai and Resnick, 1996). The littleBits prototyping tool, when used in a personalized engineering design process with craft materials, created representations of the families' knowledge as external artifacts that served as objects-to-think-with (Kafai, 2006). As such, our study findings support the learning processes of constructionism as a pedagogical approach to use in engineering education.

Implications

Our findings have practical, theoretical and methodological implications for researchers and educators. First, the way in which families iteratively tinkered with materials during creative engineering design has direct implications for how the structuring of sociomaterial arrangements within makerspace-related environments in libraries and museums. One suggestion to library professionals and informal educators is to provide ample tools for iterative design, which will allow for a deeper dialogical inquiry by families – resulting in novel products. This implication related to the importance of access to making tools expands the previous studies' findings on the role of the arrangement of material resources for visitors in makerspaces (Litts, 2015b; Wardrip and Brahms, 2015). Litts (2015b) showed that arranging the tools and materials directly in the workspace supported a ready-to-make spirit: "The visibility – not availability – of tools was what mediated the making process in the design experiment." (p. 186). Similarly, other scholars (Halverson *et al.*, 2017; Resnick and Rosenbaum, 2013; Wardrip and Brahms, 2015) have suggested providing tools and materials visibly, accessibly and abundantly to support learners' collaboration and creativity. In accordance with the importance of tools, our study suggests that library professionals and informal educators make tools easily visible (i.e. open storage, clear plastic storage bins) rather than stored away in cupboards or opaque containers for learners to engage in iterative, generative tinkering with materials that supports learners to engage in creative practices.

Relatedly, a second practical implication is how our programs were designed to be implemented in libraries and museums. Our program was designed in concert with an advisory board of children's and youths' librarians, a museum educator and a nature center educator to ensure the applicability of our engineering curriculum to small informal institutions serving rural families. Feedback from the advisory board was that they did not feel comfortable teaching certain content areas, although they often lead programs for their organization. When our advisory board did not feel comfortable teaching content, they relied on community volunteers. Based on advisory board feedback then, our tactic was to develop an engineering curriculum (STEM Pillars Team, 2019) that could be used for drop-in or scheduled programs to be taught by community volunteers with an engineering background. Our curriculum, with embedded advice on how to teach in an informal, open-ended manner (which may be unfamiliar to non-educators) is now available for other libraries and museums to download.

Third, our study has a theoretical implication, which suggests researchers develop better understandings of families' everyday expertise that manifests in library and museum engineering programs. By understanding families' everyday practices of dialoguing, questioning, and exchanging ideas, researchers can develop stronger analytical accounts of families' engagement in creative engineering practices of designing solutions while making. While previous studies that highlight how learners' everyday activities acted as channels for engaging in science learning (Bell *et al.*, 2006; Zimmerman, *et al.*, 2010), our work creates a similar argument for using theories that focus on learners' assets to study engineering learning.

Finally, our research has a methodological implication. Our findings suggest that to holistically understand how to support learners' creativity more deeply in informal learning environments, research approaches need to draw data collection and analytic tools from multiple fields. Our study demonstrated the insights that can be gained by integrating methodology from sociocultural learning sciences studies (i.e. data from video-recordings, interaction analysis, presentation of vignettes that combine verbal and gestural evidence) and engineering design research (i.e. SVS metrics) to understand the relationship between creative engineering practices and products. Integration of methodological approaches from two fields allowed our study to investigate how sociomaterial interactions in different novelty score groups elicit different creative practices and products, and provide detailed accounts of how they look like in informal learning environments. With integrated research methods, a blended methodological approach can inform a deeper understanding of how and when to support creative practices of learners in multiple learning environments.

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Further reading

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Corresponding author

Soo Hyeon Kim can be contacted at: skim541@iu.edu