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Makerspaces on the Continuum: Examining Undergraduate Student Learning in Formal and Informal Settings*

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This qualitative study focuses on sociocultural aspects of learning in makerspaces with a focus on engineering projects. The project at the center of this study, a two ton interactive metal sculpture called Unfolding Humanity, was completed simultaneously in two makerspaces: a university machine shop (embedded in a formal academic space) and a community-based arts space (an informal space). Taken together, these sites span the continuum of formal/informal learning that exists in makerspaces. Using a phenomenographic approach, we examined how students experienced these spaces and the ways in which the characteristics of both environments may complement, hinder, or support student learning. Results indicated that the presence of experienced practitioners, clear rules of engagement, and a culture fostering student creativity are key to supporting learning in makerspaces.

Keywords: engineering epistemology; STEAM; multidisciplinary design; informal learning; makerspace

1. Introduction

The increasing number of individuals interested in developing their ideas and expressing their creativity in different ways has boosted the number of spaces dedicated to the creation, design, and fabrication of artifacts for a wide variety of purposes. These creative environments, commonly known as makerspaces, give individuals an opportunity to exchange ideas, share experiences, help each other, and express their embodied knowledge through different outlets – primarily through fabricated designs. Community-organized makerspaces became one locus for individuals from different backgrounds to promote creativity in a non-rigid or rule-binding manner. The access to tools, technology, and expertise from community members made makerspaces flourish and promoted the "maker movement" to a widely-accepted status [1]. Eventually, schools, libraries, community centers and universities created their own makerspaces with their own structures, functions, programs and funding [2].

The maker movement also generated new conceptualizations for project-based educational experiences [3, 4]. The influence of these community-based creative environments, along with the increased interest in engineering education across universities and the growth of project and problem-based learning in the engineering curricula, became the catalyst for college campuses to include makerspaces in their institutions [2]. Different engineering programs adopted the maker model and integrated these units into their academic core, thus becoming a fundamental part of the engineering students' educational foundation. Academic makerspaces combined aspects of the community-organized settings while supporting the mission of the academic program by providing students with the resources to engage in engineering projects and developing engineering skills, dispositions, and habits of mind [2].

If analyzed along a continuum, makerspaces range from those that are exploratory in nature (e.g., community-organized makerspaces) to those that focus on specific outputs (e.g., academic makerspaces). On one end of the continuum is the traditional university machine shop – with formal rules, regulations, and high performing equipment [2]. At the other end of the continuum, there exists a number of community-based arts organizations that do not necessarily identify with the maker movement. Traditionally, there has been a dichotomy between what constitutes formal and informal spaces, its impact on education, and the promise of democratization of knowledge creation across space domains [1].

While academic makerspaces allow students to collaborate, share, and design, it is also important to analyze how informal spaces (e.g., community-

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based makerspaces) contribute to the learning experiences of engineering students. Although both environments are based on similar principles, an analysis of the different structures may offer insights on how learning can be complemented, supported, or hindered depending on the characteristics of such spaces. In this study, we examined student learning on a large-scale engineering project that occurred concurrently in two makerspaces. One of these spaces, referred to hereinafter as the FabLab (pseudonym), is an informal community space that brings together a broad group of artists, builders, makers, and engineers. The other space, a university machine shop, is a more formal engineering space that operates primarily as a lab unit for classes during the academic year. During breaks between classes and the summer months, however, the Machine Shop operates as a makerspace open to any student. FabLab and the Machine Shop are at near opposite ends of the continuum that are makerspaces, making this project an ideal place to examine the ways in which formal and informal spaces impact student learning.

This paper examines student learning on a large sculpture project, Unfolding Humanity (Fig. 1). The project offers a unique opportunity to study makerspaces as students worked in two very different environments. The project itself – the design and construction of a 12-foot tall, 18-foot wide, 2-ton interactive metal sculpture – brought faculty and undergraduate students from engineering, mathematics, and the arts together with local community members from a wide range of backgrounds. Featured at several large art venues, the project included components that have been described as significant to engage others in unique STEAM experiences [5, 6]. The engineering aspects of the project began during the spring semester and continued in a 10-week intensive summer research experience.

Fig. 1. The Unfolding Humanity sculpture, the engineering project at the center of this study, exhibited at Burning Man 2019. (Photo credit: B. Mule).

This qualitative study analyzes the pedagogical and learning issues (e.g., how learning takes place when students are embedded in these spaces) of *engineering students* with a focus on engineering projects in makerspaces. We designed this study to deepen our understanding of the role that space plays in student learning on a large-scale engineering project. As an exploratory study, we were guided by the research question; What characteristics of formal and informal makerspaces support or hinder student learning? We describe, through a phenomenographic approach, how students experienced both formal (e.g., academic makerspace) and informal (e.g., community-organized makerspace) spaces, and the ways in which the characteristics of both environments may complement, hinder, or support student learning. Using this approach, we provide some of the characteristics that academic makerspaces may adopt to support engineering learning environments.

2. Literature Review

2.1 The Maker Movement

The quest for new spaces where individuals could create, design, and fabricate artifacts gave rise to the maker movement [1]. Maker culture has become more than just a fad – the maker movement has generated thousands of makerspaces across the world embedded in different environments including academic spaces, libraries, museums, K-12 settings, community centers, and nonprofit and for-profit organizations [1]. The movement started as a grassroots endeavor that sought to create physical items and venues for individuals to express themselves [7]. The action of "making things" provided an opportunity to "shift away from 'consuming' to 'creating'" [8, p. 80], thus allowing for the democratization of, particularly, STEAM practices and tools. Nonetheless, while promoting the democratization of STEAM, the capacity to engage students is still questionable. For instance, even with the growth of makerspaces, they are primarily occupied by white, male, middle-class, adults that have the technical skills, resources and time to engage in making activities [9].

Extensive literature on makerspaces indicates that, despite the questionable democratization of makerspaces, these spaces provide new forms of learning, knowledge construction, and systems thinking [1, 9]. Halverson and Sheridan described the constructionist nature of makerspaces and the impact of making on formal educational environments and the development of artistic practices. "Learning through making reaches across the divide between formal and informal learning, pushing us to think more expansively about where and how learning happens" [1, p. 498]. Makerspaces, in both formal and informal spaces, can provide the pedagogical environment for individuals to thinker, frame, and solve problems.

The act of building physical prototypes and artifacts can provide venues for knowledge construction while allowing individuals to explore how their embedded knowledge can be used to "make" [8]. From a heuristic perspective, individuals that engage in making can develop the skills and awareness to recognize the sociotechnical nature of designing and making artifacts. For engineering students, particularly, engaging in makerspaces could become the venue to provide meaning to the work of engineering.

2.2 Learning in Formal and Informal Contexts

Learning is typically described as taking place in either formal or informal contexts. Informal learning is situated in self-motivated and initiated learning experiences that allow the individual to build on the pre-existing skills, knowledge and practices to develop new tacit knowledge [10–12]. On the other hand, formal learning is grounded on the transfer of knowledge from the instructor to the learner, where the learner is expected to "close the gap between existing knowledge and skills, and expected performance" [10, p. 334]. It is important to clarify that formal and informal learning do not occur separately from each other. Learning, as an inherently social practice [13, 14], coexists in a continuum of both formal and informal contexts and spaces. According to Vygostkian perspectives on learning, human development and learning are based on the unlimited freedom to explore, play, and test through sociocultural practices, physical activities, games, and object manipulations [15]. It is through these informal practices that new tacit knowledge is created and can be transferred to other contexts.

Historically, however, formal spaces (e.g., schools) became more common as places of learning as many children became forced laborers with the rise of agriculture and the industrial revolution [16, 17]. As societal changes happened, schools became the prime space for learning to create better workers, to learn how to tolerate long working hours, how to be punctual, and follow directions without challenging authority [17]. Repetition and memorization became the new standard for many schools and gave rise to the banking model of education [18]. These changes resulted in the recognition and approval of formal learning spaces, and in the vilification of informal learning spaces. Nonetheless, there have been shifts in the reconceptualization of informal learning particularly because of its importance in workplace learning. These shifts have magnified the awareness and appreciation for informal learning spaces given that over 70% of all the learning throughout the course of an adult's lifetime occurs in informal spaces [10].

Both formal and informal learning are on a continuum, influenced by both formal and informal learning environments, activities, and levels of mastery of prior knowledge, skills, and practices [10, 19]. Within the learning spectrum, formal learning involves a selection of predetermined courses, curriculum, assessment, and schools, among others. Informal learning is not constrained by limitations imposed by curriculum, time, assessment, or even attendance. Informal learning is characterized by the learners' decision to establish their own timeframe and organizing their own activities that will eventually facilitate the transfer of knowledge to other contexts [10]. Informal learning is facilitated by an environment that allows individuals to learn in community, share common experiences, and frame problems based on prior knowledge and skills. In informal spaces, the learner seeks to identify and close the knowledge and skills gap necessary to solve a problem [10]. On the other hand, formal learning is characterized by a series of learning objectives that are dictated not by the learner but someone else (e.g., the instructor). The predetermined curriculum requires that the learners demonstrate a significant level of achievement and performance while addressing the learning objectives. "Formal learning or 'book learning' is what most people in Western culture think of when they envision learning in terms of schools, classrooms, and instructors who decide what, when, and how learning is to take place" [10, p. 340].

Although there is no consensus on what constitutes formal and informal learning [20], there exists a series of characteristics or activities that help highlight the importance of both formal and informal learning spaces. Both coexist in the same continuum and hybrid or blended learning experiences may be beneficial for students, particularly when centered around makerspaces. The non-linear experiences from informal spaces may contribute to the more organized formal experiences. Community-based programs, books, hobbies, and out-of-school activities may complement the more structured activities in a classroom setting to meet a specific set of objectives.

3. Study Context

3.1 The Project: Unfolding Humanity

The sculpture Unfolding Humanity was inspired by famous unsolved questions in both mathematics and cosmology [21, 22]. The piece was also designed to illuminate the complex relationship between humanity and technology. Twelve feet tall, thirty feet wide, and made from two tons of steel adorned with 16,000 LEDs, Unfolding Humanity is a STEAM collaboration – bringing together mathematicians, scientists, artists, and engineers. The sculpture was conceived, designed, and built by a group of five faculty and dozens of students at a small, private, predominantly undergraduate institution working in collaboration with over 50 community volunteers.

The sculpture was a metal, wood, and acrylic dodecahedron, whose faces unfold interactively using chain hoists. The 16,000 LEDs were individually programmed and illuminated the edges and external faces with a variety of animations. Its conception and fabrication involved a significant collaboration among the fields of mathematics, art, and engineering – the mathematical and cosmological open questions initiating the project and overseeing its realization, artistic inspiration providing intrigue and boosting creative expression, and the engineering developing a solid and functional structure to support it all [21, 22].

Students engaged with the project from the very beginning – the idea for the sculpture emerged from a math class where students were asked to pitch ideas for math-inspired sculptures [22]. Several of those students then invited the participation of the engineering faculty on the project [21]. The student team met weekly with faculty during the spring semester and worked on the conceptual design of the sculpture. This included prototyping early versions of the sculpture, both at FabLab and the Machine Shop.

During the summer months, four engineering students were hired as undergraduate research assistants. Two students successfully won university funded summer research scholarships, while the other two were paid using departmental funds. Many other students, most but not all from engineering, volunteered their time in a range of capacities. For example, two students were consistent participants at build days at FabLab, while others brought in particular technical expertise such as welding or graphic design. Several students even came to the event to help install the sculpture.

Students met daily with faculty and completed most of their work at either the Machine Shop or FabLab. A major focus for the students was the design and construction of the structural elements of the sculpture. This work focused on two subsystems – the pentagonal panels and the skeletal structure of the dodecahedron. Once they fabricated these components, their role shifted to assembly and testing. These activities included applying an 8,000-pound proof load to validate welds at the dodecahedron's vertices and measuring the force required to move the steel faces. Students used this information to correlate and validate finite element and kinematic models of the sculpture. The summer experience for students culminated with a launch party where students, faculty, and community members came together to celebrate their accomplishments.

3.2 The Informal Space: FabLab

Funded by a local non-profit organization, FabLab (pseudonym) was created to build community by offering space and tools needed to build art projects and providing space for meetings and event organization (Fig. 2). FabLab provides both space for building and a range of tools including a large format 4′ × 8′ computer numerical control (CNC) router, a 3′ × 4′ laser cutter for plastic and wood, and a wide range of hand and power tools for woodworking. In addition to these freely available resources, FabLab also offers training for community members on how to use these tools. This training, together with the knowledge and good suggestions from the extensive community of makers associated with FabLab, makes it a unique space for the creation of art and artifacts.

The Unfolding Humanity team made heavy use of this facility over an eight month time span. Initially, the space was used for experimentation in the design, specifically in the creation of LED rain animations that mimicked the computer code from The Matrix [22]. Each of the 7′ tall wood panels skinning the ten visible external faces of the project were precision cut into half-pentagons, with 112 rectangular windows, on a CNC router at FabLab. More than 2,200 individual acrylic characters were etched and cut on FabLab's laser cutter for each of the panel windows, and these characters were glued into the windows in FabLab's outdoor space. All of the electronic work was also completed at FabLab – this included hundreds of person-hours spent cutting LED strips to custom lengths, solder-

Fig. 2. FabLab, the informal makerspace discussed in this paper, is a community-based space that provides artists with dedicated space for creating art. (Photo credit: Danksa)

ing on data and power connectors, and testing the assembled system.

From early Spring through mid-Summer, "community build" meetings were held on Saturday days and Monday evenings at FabLab for about 12 hours per week. A variety of community volunteers showed up on those days and were assigned to tasks based on their interests and skills as well as the needs of the research team at the time. Students often participated in these events and commingled with the community volunteers. During some of that time, there were only 1 or 2 volunteers working, but at other times there were 15 or more people working at once on various tasks. In addition, at least 60 volunteer hours were spent laser cutting the acrylic characters. In all, more than 55 volunteers from the community came to help with the project at FabLab.

3.3 The Formal (Academic) Space: Machine Shop

The machine shop in this study is part of an engineering school at a small, private, primarily undergraduate institution. The shop is a "traditional" educational space [1, 9] – the primary mission is to provide undergraduate engineering students a place to develop their machining skills. Most of the learning occurs in a structured and scaffolded manner, with the Machine Shop providing a venue for classes such as "Machine Shop Practices" and "Manufacturing Processes Lab."

When classes are not scheduled, including during the summer months, the shop functions like a makerspace where any student is welcome to use the facilities – always under supervision. The shop has two full time staff members who are there to support students. The facility is quite large: there is a 1,600 ft^2 metal shop with multiple CNC machines, lathes, mills, and laser ablation systems and a 1,000 ft^2 wood shop with a CNC router, table saw, sliding mitre saw, and band saw. There is also a separate 1,000 ft^2 fabrication lab containing six 3D printers and electronics testing equipment.

Fig. 3. The Machine Shop, the formal makerspace featured in this paper. (Photo Credit: G. Hoople).

During the summer, the Unfolding Humanity team spent 40–50 hours a week in the Machine Shop. This was the period when the bulk of the structural elements of the sculpture were built. The team at the university consisted primarily of students and faculty, though toward the end of the summer many community members also came to campus to assist in the project. Over the course of the summer students in the Machine Shop focused on a wide range of manufacturing skills, including how to make drawings, cut material, CNC custom fixtures, and weld.

4. Methodology

This study took on a phenomenographic approach to qualitative research [23]. The goal was to investigate how the participants in this study experienced the formal/informal space phenomenon, and how they would respond to the particular situations presented at both FabLab and the Machine Shop. The project (e.g., fabrication of the Unfolding Humanity Sculpture) involved an ill-structured problem that was "not constrained by the content domains being studied in classrooms" [24]. This study relied primarily on data collected from interviews conducted with six engineering students that participated in the Unfolding Humanity project. Out of the six students interviewed (three male, three female), one was a rising junior, three were rising seniors, and two had recently completed their degrees. Some of the students had previous experience working in machine shops, particularly those further along in their degree program that had taken the Machine Shop classes. All six participants in the project were engineering undergraduate students. These six students made up the core team of engineering students that contributed to the project, though there were many other students who were also involved.

The semi-structured interviews were conducted after the students completed the sculpture. Each interview lasted from 45 to 60 minutes on average and their responses to the questions were audio recorded and transcribed. To facilitate the interviews we prepared a semi-structured interview protocol. We framed questions around the experiences of the participants in both makerspaces, and, to help them reflect on the perceived culture in both spaces, the ways in which both spaces supported their learning, the obstacles experienced through the process, the skills gained, the exchange of lived experiences, and how the makerspaces facilitated knowledge production. In addition to the interviews, field notes and observations were used to support a more holistic view of the phenomenon taking place at both makerspaces. Particular attention was paid to the layout of the space, relations between persons and objects, discursive practices, and overall interactions between participants.

After the data was collected, authors Hoople and Mejia coded and analyzed the data following a deductive coding approach [25]. An open coding approach was used to identify meaningful units (codes) that would describe the phenomenon experienced by the participants. Pre-defined codes were established from a literature analysis, and served as the basis for data analysis and the development of new codes. The codes were then grouped to develop themes and given tentative definitions that would be descriptive of all the grouped units [25]. Finally, the data was systematically analyzed to ensure congruency and refine the theme scheme. This final step required dual criteria [26] to distinguish themes from each other (e.g., external homogeneity) while ensuring data coherence (e.g., internal homogeneity). Theoretical validation and methodological soundness was achieved through peer debriefing and interrater agreement throughout the analysis [27].

5. Results

While each student had a unique experience on this project, several consistent themes emerged about the ways student learning is supported by completing engineering projects in makerspaces. The emergent codes obtained from data analysis were grouped into two themes that describe the ways in which each of the spaces either hindered or supported learning. While we analyzed several meaningful units in depth, we have chosen to present the information here in aggregate form (e.g., themes) to highlight the favorable and unfavorable practices observed in these spaces. This analysis was done with an eye towards our ultimate goal of suggesting points of departure for makerspaces in higher education that can potentially and positively contribute to engineering learning. A summary of our emergent codes is presented in Table 1.

5.1 Favorable Factors and Practices for Learning in Makerspaces

One of the most important ways student learning was supported in both these spaces was by the presence of experienced practitioners. At the Machine Shop, the experienced practitioners were two dedicated staff. These staff members have a combined 50 years of manufacturing and machining experience of which most was spent in industry. At FabLab a rotating cast of community members filled the role of experienced practitioners. While there was no one person there consistently, the group was made up of a wide range of individuals including practicing engineers, furniture makers, graphic designers, artists, welders, teachers, and construction workers in various trades, among others. These two groups of experienced individuals had a wealth of knowledge and skills, and were always willing and eager to engage with students.

As one student described during an interview, *you do have people who are there to help in both [FabLab and the Machine Shop] if you need it . . . I think that's really cool. You have that support and you have the people to ask*. Students acknowledged that the presence of experienced practitioners was central to their learning. Not only did the practitioners provide their expertise to the students, they also engaged in knowledge construction with them. As indicated by Halverson and Sheridan [1], learning in makerspaces happens when participants who are peripheral to the environment become full participants and ensure the distribution of expertise in the learning process. Students valued the input from these experts as this community gave them a support network to turn to when they got stuck on a problem.

In addition, having the hands-on experience provided by the makerspaces made it possible for students to discover what they did and did not

Table 1. Emergent codes obtained from data analysis organized according to the factors and practices that support or hinder learning in both formal and informal makerspaces

	Formal Space (Machine Shop)	**Informal Space (FabLab)**
Favorable factors and practices for learning in makerspaces	• Presence of experienced staff • Clear expectations through formally defined safety guidelines • Opportunities for applying engineering concepts to hands on projects • Structure and organization	• Presence of experienced community members • Participants required to take charge of their own safety • Unique opportunities for creative engagement
Unfavorable factors and practices for learning in makerspaces	• Intimidating oversight • Hegemonic practices in formal spaces • Reinforcement of male-dominated culture	• Ambiguity around some expectations • Perceptions related to safety

know, which is the foundation for building on prior knowledge and creating new tacit knowledge [10]. There is no substitute for simply getting stuck on a problem and asking for help. Students found the one-on-one attention they received in makerspaces to be some of their most valuable learning. This aligns well with Boileau's assertion that communities are an integral part of informal learning [10], and Vygotsky's emphasis on the sociocultural nature of learning processes [13, 14]. One of the great benefits of makerspaces is the ability to learn from experienced practitioners; however, as will be discussed in the next section, the oversight of practitioners can also create tension in the makerspaces where students work.

Structured rules for engagement, particularly in the academic setting, were perceived by some of the participants as a positive attribute of makerspaces. The sense of security that a space with guidelines, rules, and clear hierarchical structures provides was a clear example of how makerspaces can manifest the connections between intentionality and initiative. The rules for engagement were established intentionally by the Machine Shop to ensure safety for the students, which resulted in students having the initiative to work in the makerspace because it was perceived as "safe." The Machine Shop took a very strategic approach to guarantee that students would come "prepared" to the makerspace before they were allowed to use any of the tools or machines. A series of "safety badges" were required and had to be obtained by passing quizzes provided through an online learning management system. For example, there was a general lab safety badge, a welding badge, a woodworking badge, and a laser cutter badge. These badges clearly communicated the expectations of the shop staff about how various tools and spaces were to be used. While these created a higher barrier for entry than FabLab, when students accessed the Machine Shop they expressed they had a better understanding of the rules than after entering FabLab.

It is important to note that the two makerspaces took very different approaches when establishing their rules for engagement. FabLab, in comparison to the Machine Shop, had a very "informal" set of guidelines. Students were asked to sign a waiver releasing FabLab of liability upon entering the space and participants were charged with being stewards of their own safety. At the time of the project, there were official trainings offered for only two tools: the laser cutter and CNC router. However, after the project was completed classes were added in arduino programming and silkscreening. As one student said, *It was nice to work, I think, in a place where you're sort of trusted a little bit not to hurt yourself.* For the most part, members were expected to monitor themselves. While access to tools was limited to several trusted community members, they relied on community members self-reported competency when deciding who could check out a particular tool. In general, if someone did not know how to use a tool they were expected to be honest about that fact and ask for help.

Regardless of the mechanism used, creating clear expectations supports student learning. As one student reported about the Machine Shop after spending a week working in the space, *I walked in and I knew where everything was, like I knew who to ask for help and I knew where certain things were.* This confidence makes it possible for students to engage in self-motivated and self-directed learning while helping each other [28]. With a clear set of guidelines about how to use the space, students can develop a new skill base, or build on a pre-existing one, thereby allowing them to cultivate new tacit knowledge. Students can direct their own learning, they are interested in the immediate application of new knowledge while engaging in making, and stay motivated through the process due to the clear, independent, and self-directed learning [28].

The last major unit of analysis that emerged from the data was the importance of fostering an environment where students were able to explore their own creativity and have a better understanding of engineering practices. As one student described:

> "When you have to actually take this project and take all these materials and make it into something and use not only engineering tools and machining tools, but also creativity and adaptability . . . It makes it tangible and it takes engineering out of the textbook and into real life . . . . I think that really helped me grow as an engineer and as a person."

The two makerspaces described in this paper offered an opportunity for students to fabricate artifacts of their own design limited only by their own creativity. In addition, working in these spaces facilitated a change in the students' perception of engineering, their self-efficacy, and their cognizance of engineering dispositions and habits of mind. As one student observed,

> "I think this [project] really helps me see what engineering means in the real world and I think that's something that a lot of people constantly wonder because if you take these classes and there's all these theoretical problems. It's like is this box pushing on a spring really going to relate to the real world somehow? I think that something everybody wonders, but this really taught me how the things that we learn in class really do matter and do make a difference. It also taught me how engineering is so interdisciplinary, it's not just – everybody says it's not just a science and math."

Makerspaces are uniquely poised to help students connect learning from the engineering classroom to "real life." Creating a space that supports creativity is a key element for supporting student motivation. This motivation, in turn, enables self-directed learning and supports students in building a set of skills and abilities to achieve their goals. Each of the students we interviewed spoke about the ways in which they enjoyed developing creative solutions to the parts of this project about which they were most motivated.

5.2 Unfavorable Factors and Practices for Learning in Makerspaces

While these spaces have many excellent qualities, there were elements that detracted from student learning. The primary factor that inhibited student learning was feeling intimidation or discomfort. Even with relatively well defined rules of engagement, the nature of the large, expensive, and dangerous equipment in these spaces sometimes put students "on edge." This sentiment was particularly true in the Machine Shop, where oversight from staff could make students feel uncomfortable even if they were doing everything correctly. As one student mentioned during an interview,

> "Sometimes at the Machine Shop I'll be working on something and [staff member] will come look over my shoulder and I'm like, "Am I doing something wrong?" and I'm not. He's just checking what you are doing like what are you working on. He's just curious, but I get nervous."

Concerns about criticism or self-awareness of being a novice in makerspaces lead students to disengage. The reasons students felt more "on edge" at the Machine Shop as compared to FabLab were primarily due to the fact that the safety cultures were very different between the two spaces. The Machine Shop, through the safety badging process and oversight from the staff, consistently reinforced the ways in which students could hurt themselves or the tools. In this case the rules of engagement somewhat stifled self-efficacy. While students perceived the rules of engagement as important for safety, it was not without a downside. Students expressed concerns that they would draw the ire of the staff for making a mistake or breaking the machines. This perception, while at times unfounded, lead to them feeling more restrained about how they approached problem solving. For instance, one student indicated that,

> "I didn't always have a good time in the Machine Shop. I didn't feel as like compelled to trying to suggest something new or try different method of doing something even it might be faster. It's just I basically don't feel as open to self-expression."

As the student mentioned, at times they felt apprehensive while working in this space. Some of these feelings were likely due to the power dynamics taking place in the Machine Shop. This sentiment was shared by others in this study. Most students indicated they were aware they were working in someone else's space. They knew of examples of people having their shop privileges revoked and feared that if they made a serious judgment error they, too, would be asked to leave. This fear lead students, in some instances, to self-censor and restrain their activities. One of the characteristics of formal academic spaces is the hierarchical nature of the faculty/student relationship, which is based on predetermined behaviors of following directions according to power dynamics [17]. While makerspaces are primarily sites for more informal learning, they are not immune to recreating these same issues with regard to access.

While too much organization and structure caused students to feel more restrained, too much chaos also detracted from students' learning. For instance, students uniformly agreed that FabLab was a less organized space – both in terms of management and tools. FabLab is a collaborative space. While there were official managers of the space, they were not always present. The community was by and large in charge of organizing itself. A few students felt that this disorganization was a safety issue, expressing concerns over the ways in which the space would sometimes become too crowded. Although learning was not dictated by an individual, the ambiguity of interpreting the unwritten rules of the space sometimes prevented students from fully engaging. While safety for both students and equipment is of paramount concern in any makerspace, achieving the optimal environment to support student learning is a delicate balance that must be addressed carefully and intentionally.

These feelings of discomfort and intimidation were further compounded along gender lines. While several of the male students reported excitement about getting to work in the Machine Shop for the first time (often citing prior experience with similar tools), the female students interviewed uniformly expressed trepidation about their first time walking into the Machine Shop. One of the female students said, *I also built up the machines a lot more in my head like these are killing machines. They're scary. They're really big and they are really powerful.* This hesitation reflects barriers not only for women to enter makerspaces, but is also indicative of broader challenges within engineering culture. Later on she added,

> "There are men working in an environment and knowing that I'm a woman stepping in to this space . . . I need to make my presence known here otherwise, I'm going to get pushed to the side. The guys going to say, "Let me do it. Let me just finish it." That has happened to me.

> That definitely happened to me during Machine Shop class."

Female students were particularly aware of their gender and how it impacted their work not only in makerspaces, but more broadly in engineering spaces. Historically, engineering has been characterized by practices that have created gendered boundaries that perpetuate systemic male-dominated structures [29, 30]. As Calabrese Barton and colleagues observed, makerspaces are still primarily occupied by white, male, middle-class, adults that have the technical skills, resources and time to engage in making activities [9]. The fact that these spaces reinforce this male-dominated culture leads to the persistence of boundaries around what counts as making and who can be a maker. While there are examples of feminist maker spaces that run counter to this narrative [31–33], makerspaces are not a silver bullet for resolving the historical challenges engineering has faced around diversity and inclusion. To promote student learning in these spaces it is important to recognize the existing obstacles within engineering culture and to seek to actively deconstruct them rather than perpetuating them in new contexts.

6. Discussion

This study explored the ways in which two different makerspaces impacted student learning on a large sculpture project. The two spaces where students completed their work were at opposite ends of the makerspace continuum - one space was embedded in an academic setting with the other was community-organized. It is well known that STEAM experiences can have strong benefits for students [5, 6], and research into makerspaces is emerging as an important theme for engineering educators [1–3, 32–35]. Here we focused on how students experience learning when navigating two dissimilar makerspaces. Important commonalities between these seemingly disparate spaces emerged suggesting how makerspaces could be designed to complement formal learning. We also observed the ways in which makerspaces are not a panacea, just as with formal academic settings there are elements that detract from student learning. On balance, the results indicate that more informal learning sites like makerspaces are key tools for supporting student learning. When students are allowed to explore engineering through sociocultural making practices they are able draw connections between their engineering coursework to their lived experience. Based on the results obtained from this study, we have developed the following recommendations for those seeking to support student learning in makerspaces and to more productively engage students.

Making should be learner centered: Following Vygostkian perspectives on learning [14], makerspaces in academic environments must consider how sociocultural practices impact the learning of engineering. Although structured rules of engagement are prioritized in academic spaces, these should be designed so that they do not diminish student engagement. One way to make learning student centered is to incorporate community-based projects that complement the formal classroom experience. Acknowledging that most of the learning of an adult's lifetime takes place in informal spaces [10], it is important to complement classroom-based instruction with self-directed and self-motivated learning that draws from and builds on students' lived experiences and embodied knowledge. Another way to center learners is to involve them in the decision-making process for governing these spaces. For example, learners could help set the goals for how they want to create a culture of responsibility and safety. Makerspaces, as foundational units for practicing adult learning, provide an ideal site for students to develop the necessary skills to become lifelong learners [28].

Build a community of experienced practitioners: In the classroom, students are often hesitant to ask for help, some may be intimidated by their professors, and others may fear being perceived as novices by their peers. Makerspaces provide an ideal opportunity for students to learn from others. Building a community of experienced practitioners willing to teach others is critical for supporting student learning. These practitioners bring with them a wealth of tacit knowledge that they can share with students, and can help ease students' transition into the space. To support engineering projects in particular it is critical to have practitioners with an engineering or technical background. We have seen two examples for creating this type of community in this paper: hiring dedicated staff (the Machine Shop) or by bringing together community partners (FabLab). Another approach that can be successful is to have experienced students serve as peer mentors for students new to the space [35]. Regardless of the mechanism taken, the presence of individuals with experience in makerspaces is critical for student learning.

Create a culture of trust and responsibility: Students perform best when they are in supportive environments. One of the great challenges for engineering projects in makerspaces is striking an appropriate balance between safety and autonomy. A culture of safety is paramount as engineering tools are both dangerous and expensive. However, for those unfamiliar with the tools or the hidden curriculum [36] these spaces can become very intimidating. As one student recalled about their first time in the Machine Shop, *everything is big and scary and [the machines] can all hurt you.* The hesitation to operate the tools and machines came from the uncertainty that comes with unfamiliar territory, especially when the individual has never had access to those tools [9]. Moreover, these "unwritten" rules of engagement legitimize only certain kinds of behaviors, values and attitudes that may perpetuate inequity and access to engineering learning [9]. One of the objectives for makerspaces should be to foster a culture where students are trusted to be responsible stewards of both the space and their own learning. The best makerspaces are welcoming places that invite students to pick up tools and start making.

Encourage creativity: We heard time and again in our interviews how much students enjoyed having the opportunity to be creative when working on this Unfolding Humanity engineering project. Formal engineering education is often devoid of this creativity – too many engineering science courses consist of complicated lectures paired with long homework sets of abstracted problems. Makerspaces are well situated to provide students with a creative outlet where they can apply engineering concepts when coupled with project-based learning. These projects can occur within the context of co-curricular activities like the large sculpture design project described in this paper, but it can also be achieved by encouraging students to work on projects of their own design. When asked about creativity students described a wide range of projects they had completed on their own in these spaces such as designing and manufacturing a custom scrabble board or making Christmas ornaments.

7. Conclusions

As more makerspaces emerge worldwide, cementing better practices for these spaces is of extreme importance. Makerspaces can provide a venue for the democratization of learning in engineering by providing more access to students who are traditionally peripheral to these environments. Allowing students to bring forth their own selves to making can create empowering experiences that transcend the traditional engineering classroom. Many students go into engineering because they enjoy making things. Successful makerspaces can help students sustain that passion as they move through challenging courses. Thus, makerspaces should be designed to be accessible and inclusive while fostering a climate where students can learn in community. If this vision is realized, makerspaces will emerge as ideal sites for supporting student learning of engineering concepts across multiple contexts.

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