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Student Development at the Boundaries: Makerspaces as Affordances for Engineering Students' Development

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Abstract: University-based makerspaces are receiving increasing attention as promising innovations that may contribute to the development of future engineers. Using a theory of social boundary spaces, we investigated whether the diverse experiences offered at university-based makerspaces may contribute to students' learning and development of various "soft" or "21st century" skills that go beyond engineering-specific content knowledge. Through interviews with undergraduate student users at two university-based makerspaces in the United States we identified seven different types of *boundary spaces* (where multiple communities, and the individuals and activities affiliated with those communities, come together). We identified students engaging in the processes of *identification*, *reflection*, and *coordination*, which allowed them to make sense of, and navigate, the various boundary spaces they encountered in the makerspaces. These processes provided students with opportunities to engage with, and learn from, individuals and practices affiliated with various communities and disciplines. These opportunities can lead to students' development of necessary skills to creatively and collaboratively address interdisciplinary socio-scientific problems. We suggest that university-based makerspaces can offer important developmental experiences for a diverse body of students that may be challenging for a single university department, program, or course to offer. Based on these findings, we recommend university programs and faculty intentionally integrate makerspace activities into undergraduate curricula to support students' development of skills, knowledge, and practices relevant for engineering as well as 21st century skills more broadly.

Keywords: makerspaces; postsecondary education; engineering education; boundary spaces; 21st century skills

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1. Introduction

1.1. Makerspaces in Formal Education Environments

Originally conceptualized as places where community members could access tools and resources for collaborative learning and creating, makerspaces are increasingly becoming incorporated into more formal educational contexts, including in K-12 schools and postsecondary institutions [1,2]. Makerspaces are typically equipped with both "low tech" tools, such as wrenches and sewing equipment, as well as more "cutting edge" tools that provide users with advanced prototyping and manufacturing capabilities, such as 3D printers and laser cutters [3]. In community and K-12 settings, makerspaces have been found to heighten youths' interest and STEM engagement [4], including career aspirations in STEM [5]. In addition, involvement in these spaces have been found to increase youth's awareness of diversity and equity issues in STEM [6].

In the postsecondary context, university-based makerspaces also offer a wide variety of tools and technologies that enable prototyping and small-scale manufacturing capabilities, which students and faculty have been found to appreciate [3,7,8]. While access to prototyping and manufacturing tools are already available in traditional machine shops on university campuses, access is typically limited to a few students [9]. There is evidence indicating university-based makerspaces offer access to a greater number and variety of student users (across academic major and skill level) through less restrictive eligibility requirements compared to machine shops [1,10]. Barrett et al. [1] found that the most common location for makerspaces on university campuses in the United States is the campus library, suggesting they may operate as (mostly) open-access and multidisciplinary spaces, rather than spaces solely affiliated with a single discipline, such as engineering. According to these researchers, "[p]lacement of a maker space in a library may provide a central location for many campuses trying to encourage multidisciplinary activity through the maker space" [1] (p. 13).

Indeed, university-based makerspaces, at least in the United States, may exist as multi-functional and multi-faceted spaces. Beyond serving as spaces for formal coursework-related designing and prototyping projects, university-based makerspaces can serve as places for trainings or workshops for discrete skills (e.g., pertaining to the use of specific machinery or tools), student club activities, and personal or non-coursework related projects [3,10]. Faculty members teaching in a university-based makerspace have noted that makerspaces can foster the development of creativity and diverse ways of thinking through students' exposure to a variety of activities and people they may not have a chance to encounter elsewhere [8].

The growing body of research on university-based makerspaces is promising, indicating the potential for the spaces to provide opportunities for students' exposure to and interaction with a diversity of maker activities, people, and disciplines and the related development of the knowledge and skills that faculty members and programs aim to cultivate in their students. In particular, there is increasing interest by researchers, practitioners, and policy makers in fostering "soft" [11] or "21st century" skills [12,13] that go beyond "traditional" or "book-based" academic performance [14]. Examples of these soft or 21st century skills include communication, collaboration, critical thinking, and creativity [12,15]. To compete in the modern global economy, and contribute to solving pressing societal problems, many of which rely on the knowledge and skills base from multiple disciplines, students must develop into well-rounded professionals, rather than as experts of a narrow content area in their specific discipline of study [16].

Still, research regarding the potential of university-based makerspaces is limited, and the possibility that they may be well-positioned and designed to cultivate impactful student experiences is worthy of further investigation. The greater potential of university-based makerspaces in developing students' ability to communicate, collaborate, and engage in critical and creative pursuits is generally under-researched, in comparison to studies that have looked at discrete engineering-specific knowledge and skills development. The idea that exposure to and interaction with a diversity of maker activities, people, and disciplines may foster "soft" or "21st century" skills remains a hypothesis, particularly in the postsecondary context. To what extent are university-based makerspaces affording wide accessibility for a diversity of students, as well as multi-functional and multi-faceted student activity at the intersection of disciplines, and how might these things be impacting student development?

1.2. Developing Engineering Professionals via University Programming

Although often used by diverse users, makerspaces are typically affiliated with engineering departments of universities [1]. Specifically, given the characteristics, design, and goals of makerspaces, research investigating their impact on students and programming in the field of engineering is especially warranted [8,17,18]. The Accreditation Board for Engineering and Technology (ABET) accreditation criteria for baccalaureate engineering programs [19] articulate key student outcomes that graduates of accredited programs should be competent in to be successful engineers. The development of undergraduate students' competencies extends beyond traditional content knowledge and skills. Thus, the expected learning outcomes of students completing engineering preparation programs include competencies in: solving complex problems via application of appropriate knowledge and analytical processes, creating meaningful and ethical solutions, effective communication, and teamwork. Work in makerspaces may afford students' development in the field of engineering and emergent research has begun to document student learning outcomes in connection to makerspaces. One outcome that has received some attention is students' design capabilities developing in relation to their involvement in makerspaces [18,20]. Design is a versatile and crucial skill for engineering professionals [21] and it encompasses many of the aforementioned abilities emphasized by ABET. However, research concerning the cultivation of design or other related abilities that go beyond specific engineering content knowledge has largely been in relation to students' participation in discrete activities in university-based makerspaces, such as student club meetings or workshops aimed at cultivating graphic creativity (e.g., [7,22]).

As more makerspaces make their way onto university campuses and more engineering programs and faculty contemplate the incorporation of makerspaces into undergraduate engineering curricula, there is a need to know their worth and potential as multi-functional and multi-faceted spaces. Not only are makerspaces expensive to maintain and operate (in terms of the physical equipment as well as related space and staffing needs), but it can also take a significant amount of time and effort to effectively integrate makerspaces into existing engineering programs, as this can necessitate professional development of faculty and adjustment of curricula to be successful [8]. In addition, there is some research to suggest that university-based makerspaces may not be solely advantageous to students' development as engineers. Lenhart et al. [8] found that faculty members expressed concern that students may develop incomplete or inaccurate notions of engineering via makerspace activities, conceptualizing engineering practice as primarily consisting of rapid prototyping using advanced technologies. This concern is in line with some skepticism that university-based makerspaces may not be living up to the promise of being more than a "room full of tools" [23]—that is, a room full of fancy equipment that offers little in the way of students' development of skills necessary for them to succeed as well-rounded professionals.

With these limited findings in mind, we explored the impact of university-based makerspaces on the development of undergraduate engineering students. Specifically, we investigated undergraduate engineering students' notions of these spaces in supporting their abilities to work with a diversity of others in creative and collaborative ways to address some of society's most complex and pressing problems. Based on our findings, we discuss makerspaces as offering interstitial or "in-between" spaces bringing together diverse individuals, disciplines, and activities that, ultimately, seem to allow learning important for the development of emerging engineers. We situate our findings in recommendations for makerspace staff and engineering faculty towards designing, motivating, and delivering meaningful makerspace experiences that can enhance students' development in engineering and beyond.

1.3. Conceptual Framework

Our exploratory work relies on the concept of *social boundary spaces*, where multiple communities, and the individuals and activities affiliated with those communities, come together, giving rise to potential opportunities for learning and developing new knowledge or skills [24]. The term boundary space, in this context, does not necessarily denote an edge, periphery, or even something obviously physical [25]. Rather, a boundary space denotes the interactions of entities with some unique characteristics or practices [24]. The notions of social boundary spaces and *boundary crossings* (movement across social boundary spaces) has gained traction in the education science literature since the mid-1990s [24], particularly with their incorporation within the well-known sociocultural learning theories of cultural historical activity theory [26] and communities of practice theory [27]. Both of these theories emphasized the potential for learning that social boundary spaces afford, noting boundaries as learning resources rather than barriers [24].

Contexts that call for "a high degree of specialization and a need for interdisciplinary and cross-sectional work" [24] (p. 138) have often been the subject of studies that make use of the social boundary framework. This is due to the framework's potential to illuminate whether and how disparate communities and their members make sense of, and learn from, interactions at the boundaries. Star and Griesemer [28], who first introduced the concept of social boundary spaces, documented the boundary crossings required of the communities and individuals (i.e., scientists, university administrators, amateur collectors, private sponsors) that were involved in developing a university-affiliated natural history museum. Each brought specific expertise and interests, informed by the norms and practices of their own communities; together, they found ways to work within and across various social boundary spaces, resulting in the successful establishment of the museum.

Boundary spaces allow for potential opportunities for learning as members of the multiple communities in these spaces come to understand unfamiliar knowledge and practices. In particular, Akkerman and Bakker [24], who synthesized and reconceptualized some of the earlier work on social boundary spaces, such as that of Star and Griesemer [28], to an education science context, discuss four processes that may give rise to learning in boundary spaces: identification, coordination, reflection, and transformation. Briefly summarized, boundary spaces can present opportunities for community members to develop new or enhanced understandings about their own identities and their community in relation to other communities (via the processes of *identification* and *reflection*), devise ways to navigate multiple communities (via *coordination*), and even create completely new or hybrid sets of knowledge, skills, and practices (via *transformation*), especially if the members of the different communities are aiming to work towards a common goal. A boundary space is somewhat flexible, where contributions from distinct communities or bodies of knowledge may emerge into something else, leading to a "sense of here and there [being] confounded" [25] (p. 603). New knowledge and practices can emerge via co-creation by those interacting in a boundary space.

We contend that university-based makerspaces offer a context that is ripe for investigating how members of different communities may come together to arrive at new understandings through their interactions at social boundary spaces. In the context of this study about students at university-based makerspaces, we are less interested in the creation of physical entities, such as a museum, and more interested in the development of new understandings about oneself and others, about one's own and others' communities, and how to navigate and make sense of these understandings—or what may be summarized as *learning.* University-based makerspaces are oftentimes designed to bring together diverse users, activities, and communities. They are also oftentimes explicitly described as places that enable and encourage interdisciplinary and cross-sectional work. However, questions remain as to whether these intended outcomes of university-based makerspaces bear out in practice and whether users of makerspaces perceive the potential learning opportunities offered in university-based makerspace—places that are notably complex and messy per the diverse activities and actors involved in them. Through an application of the notion of social boundary spaces, we explored the potential of university-based makerspaces to offer the types of experiences that can lead to undergraduate students' development as well-rounded 21st century professionals, particularly from the perspectives of students themselves.

2. Materials and Methods

2.1. Research Question

We hypothesized that university-based makerspaces may allow for multiple boundary spaces, where multiple communities and the knowledge, practices, and commitments they bring with them, co-exist and intermingle. Additionally, for most university students, makerspaces may be novel in these respects, including for engineering students. We explored these hypotheses, specifically the different types of boundary spaces engineering students may encounter and recognize in these spaces, and the degree to which these spaces serve as affordances for learning, via students' exposure to a diversity of communities, individuals, and related knowledge and skills that can contribute to their development as engineers. Thus, the research question guiding our study was: How can university-based makerspaces serve as affordances for students' exposure to a diversity of communities and individuals, knowledge and skills bases, and professionally related activities that can contribute to students' development as engineers?

2.2. Setting

This exploratory study was part of a larger National Science Foundation-funded project that investigated the experiences of faculty, staff, and students at six university-based makerspaces across the United States. The larger study's goal was to determine potential connections between university-based makerspaces and undergraduate students' access, success, and persistence in engineering. All six U.S. university-based makerspaces in our larger study were selected per their affiliation with a college of engineering or engineering department at their respective institution. As well, we selected those functioning both as teaching facilities in which courses or course-related components took place, and as open spaces for drop-in student use (e.g., for student organization meetings, as study areas, as places to just "hang out" and socialize). Attempting to limit potential confounding factors, all makerspaces of our study were designated as *Doctoral Universities: Very High Research Activity* by the Carnegie Classification of Institutions of Higher Education [29].

The findings presented in this paper draw from student interview data at two university-based makerspaces. The two sites were chosen from our larger study based on their similar location (Western United States), age (3 years), size (around 2200 m^2), and student demographics. The two universities housing these makerspaces shared some similarities in terms of student demographics. According to data from the Integrated Postsecondary Education Data System (IPEDS) from the National Center for Education Statistics [30] the total undergraduate student enrollment was a little over 30,000 at each of these institutions during the 2019–20 school year, with roughly 60~75% of the students identifying as non-white. The annual number of engineering bachelor's degrees conferred at these two universities was around 900 to 1000. Additionally, relevant for our specific focus regarding the potential of university-based makerspaces offering exposure to, and interactions at, social boundary spaces, each of our two sites were characterized by their offering of multi-disciplinary, multi-functional, and multi-faceted experiences for engineering students; significant use of the makerspace by undergraduate engineering programs, faculty, and students; and prevalence of course offerings not affiliated with engineering. In the reporting of our findings, we do not separate our findings according to these two sites, given that no relevant differences were found and noted per the focus of our study. However, brief descriptions of the two sites are provided for added context.

2.2.1. Makerspace A

Makerspace A is located in a standalone building on the campus of a large public university located in the Western United States. This standalone building is among a cluster of buildings affiliated with the university's College of Engineering and the makerspace's top two administrators hold faculty positions within engineering departments. Despite this connection to the university's engineering program, Makerspace A purposely brands itself as a hub of "design and innovation" that is open to users of all disciplines beyond engineering. In fact, a wide variety of courses are offered in the makerspace, including those from the multiple sub-disciplines of engineering (mechanical, electrical, industrial, biological), as well as courses from departments such as architecture and those within the fine arts. The makerspace also offers a series of courses designated as "design" courses, which are intended as interdisciplinary courses open to students from all majors. This includes an introductory design course, meant to foster students' design mindsets and skill sets across majors. From our conversations with faculty who teach these design classes, we were made aware of the wide variety of academic majors represented in these classes, including, but not limited to biology, business, cognitive science, economics, geography, media studies, as well as engineering. After taking a series of design classes at Makerspace A, students across majors are able to obtain a design certificate. According to available data from fall 2019 (the time of the study team's data collection at Makerspace A), 40% of the makerspace users were women, 11% of users were Chicanx/Latinx, and 2% of users were African American. Figures 1 and 2 depict some of the tools and equipment available in Makerspace A.

Figure 1. Makerspace A was equipped with rapid prototyping technologies, such as 3D printers (pictured above).

2.2.2. Makerspace B

Makerspace B is located on the ground floor of a newly constructed building on the campus of a large public university located in the Pacific Northwest of the United States. Makerspace B is jointly funded and operated by the university's Housing office as well as the College of Engineering. The makerspace came to fruition due to the vision and initiative from the associate dean of the College of Engineering and offers mostly introductory-level engineering classes that provide vastly expanded access to advanced machinery for lower division engineering students, which was not previously possible without the makerspace. Due to the connection to the Housing office, Makerspace B operates with an ethos of being a part of campus services affiliated with student affairs. As such, Makerspace B frequently hosts workshops intended to be "fun" and "low key," such as a series of workshops focused on making holiday gifts for friends and family (e.g., screen printing t-shirts, laser engraving mugs). Interviewees at Makerspace B also mentioned that the makerspace is frequently used by student groups that print stickers or posters for their student organization or by individual students who would sew Halloween costumes using the sewing machines in the makerspace. Makerspace B emphasized making the space accessible to all students regardless of skill level or interest area. According to available data from fall 2019 (the time of the study team's data collection at Makerspace B), 40% of the makerspace users were women. Administrators of Makerspace B stated that they do not collect information on the race/ethnicity of makerspace users. Figures 3 and 4 depict some of the tools and equipment available in Makerspace B.

Figure 2. Makerspace A was also equipped with "low tech" tools and materials, such as tape and pipe cleaners (pictured above). The sign above the cart reads: "Prototyping Materials (Design Lounge) These materials are provided for student use, as are the sticky flipchart pads hanging on the wall".

Figure 3. Offerings at Makerspace B included equipment such as the desktop CNC mills (pictured in the foreground) as well as large tables and chairs with wheels (pictured in the background) that were conducive to group work.

Figure 4. Makerspace B also featured several sewing machines (pictured above) and materials conducive for textile work.

2.3. Data Collection

The larger six-site study utilized a collective case study approach [31], comprising data collected from interviews with faculty, staff, and students affiliated with university-based makerspaces as well as observations at the six study sites. A case study approach was chosen for the larger study as this method is commonly used when researchers are interested in understanding generally underexamined or new phenomena in an in-depth manner and assumed complexified by real-world contexts [31,32]. This paper presents results from the collection and analysis of student interviews at two makerspaces, Makerspace A and Makerspace B. The interview portion of our study was guided by a phenomenological approach [33,34], often rooting case study research, that can uncover the lived (and potentially diverse) experiences of participants regarding a phenomenon (e.g., students' engagement with and perception of university-based makerspaces) as described by the participants [32]. Thus, our methodological choices were informed by our aim of gaining an understanding of the relatively under-researched phenomenon of university-based makerspaces from the perspective of participants in a naturalistic and exploratory, rather than in an experimental, manner.

For the student interview portion of our case study, three study team members visited Makerspace A in the fall of 2019 and conducted in-person semi-structured interviews with 24 students (17 engineering majors, 7 non-engineering majors). Two study team members (both of whom also visited Makerspace A) visited Makerspace B in the fall of 2019 and conducted in-person semi-structured interviews with 22 students (15 engineering majors, 4 non-engineering majors, 3 undeclared). Non-engineering majors included one student each from the disciplines of business, chemistry, computer science, economics, English, geography, math, and public health, and three students from cognitive science. Study team members had already established contact and had visited each of the study sites once prior to the visit during which student interviews were conducted. As noted above, one of the goals of our research was to provide a naturalistic study where individuals were interviewed in their regular learning environments. Thus, rather than pre-arrange interviews or conduct them in settings removed from students' "normal" engagement in makerspace activities, we conducted impromptu interviews with students while we encountered them in the makerspaces. We conducted these impromptu student interviews until we reached saturation, or to the point of study team members no longer gleaning new information from additional interviews [35]. The interviews took place in fairly public places, and in our efforts to make these interviews as unobtrusive, unintimidating, and as comfortable as possible for the student interviewees, we did not ask about, nor can we assume, interviewees' social identities (e.g., race, gender).

Student interview questions were designed to elicit how the students engaged with their campus makerspace and what they learned in their use of the makerspace. The interview protocol was developed by the research team during the conceptualization of the larger study around undergraduate students' access, success, and persistence in the engineering fields, connected to their sense of belonging [36,37], motivation [38,39], and professional identity [40–42]. Borrowing from extant bodies of research, we formulated the interview questions to suit the context of university-based makerspaces and students' activities in, and perceptions of, these spaces. See Appendix A for the interview protocol. Informed consent was obtained from each interview participant. We audio-recorded and transcribed the interviews verbatim.

2.4. Data Analysis

We largely followed the recommendations of Auerbach and Silverstein [43] in coding and analyzing our interview data. The first two steps of analysis according to Auerbach and Silverstein [43] entail identifying relevant text and noticing repeating ideas (which may eventually become inductive codes). Informed by our conceptual framework of social boundary spaces [24], the first and third authors independently went through these initial steps by each reading and coding a random sample of three interviews each from each of the two study sites (for a total of 12 interviews). We looked for instances in which student interviewees talked about more than one community (and the individuals and practices associated with the communities) co-existing or coming together at the makerspace and categorized these instances as "boundary space types." The two researchers then met to compare the inductive codes we each came up with, and discussed and resolved any discrepancies. This process resulted in us agreeing on five different social boundary types. Afterwards, each of the two researchers coded one half of the remaining interviews independently according to our coding scheme consisting of five boundary space types. During this phase of coding, we applied a second layer of deductive codes, which consisted of the four processes that may give rise to learning in boundary spaces according to Akkerman and Bakker [24]: identification, coordination, reflection, and transformation. Throughout the coding process, the two researchers communicated frequently to clarify any questions or discuss the creation of additional boundary space types, two of which were created this way. When all coding was complete, the first author spot-checked 12 of the 23 interviews coded by the third author (52%) and found general alignment in coding. When there were any discrepancies, the first and third authors discussed these discrepancies and came to an agreement.

After this coding process, we moved onto generating themes and theoretical constructs, then creating a theoretical narrative in connection to our larger research concerns [43]. The first three authors were involved in this phase of the analysis. After reading representative coded excerpts from each of the seven boundary space types selected by the first author, the three researchers discussed how these boundary space types may be connected to potential opportunities for students' development as engineers. We collectively explored connections between boundary space types and potential learning processes. We met to discuss these issues and connected our reflections on the data to our conceptual framework.

3. Results

We identified seven different types of boundary spaces that students perceived in their university-based makerspaces as they engaged in various activities within and outside the scope of their formal coursework in these makerspaces. While it is possible for more than two different communities, and their affiliated individuals and practices, to come together at a boundary space (for example, multiple disciplines come together at the boundary space referred to as "STEM"), student interviewees tended to talk about two communities at a time. Students did talk about multiple disciplines or sub-disciplines within engineering (e.g., mechanical engineering, electric engineering, civil engineering) in some cases, but they usually talked about one community as being the reference point while the other communities were in juxtaposition to the reference point. For instance, students often described the makerspace as "not just for engineering students" but for students in other disciplines such as art and architecture as well. We deemed such statements effectively referring to the two communities of "engineering" and "non-engineering."

The seven boundary space types found in university-based makerspaces according to the students at our two study sites are summarized in Table 1. These boundary space types were: (1) engineering and non-engineering disciplines, (2) novice and expert users, (3) academic/professional and personal activities, (4) theoretical and hands-on activities, (5) students and staff, (6) one sub-discipline or specialization of engineering and another sub-discipline or specialization of engineering, and (7) school-related and entrepreneurship/industry-related activities. We provide brief explanations and illustrative quotes for each of the boundary space types below.

Table 1. Seven boundary space types identified by student interviewees.

Boundary Space Type	Code Occurrences	Interviewees
Engineering and Non-Engineering Disciplines	32	26
Novice and Expert Users	30	25
Academic/Professional and Personal Activities	31	19
Theoretical and Hands-On Activities	30	18
Students and Staff	12	12
Sub-Disciplines/Specializations of Engineering	6	6
School-Related and Entrepreneurial/Industry-Related Activities	5	5

3.1. Boundary Space 1: Engineering and Non-Engineering Disciplines

Even though both makerspaces included in our study had strong ties to their respective College of Engineering, students observed their campus makerspace as being open to and used by diverse students outside of engineering. In many cases, they saw the applicability of the makerspace equipment to disciplines other than engineering as the below student noted:

> *[The makerspace] gets really popular, especially when finals [final exam period] comes around and everyone has their final projects, especially not just engineering [students]. We've had architecture students come in here and laser cut stuff for their buildings and things like that. So, I have to say, I've seen a very diverse amount of people from different backgrounds and different majors.*
>
> (Makerspace B, Student 22)

In the above excerpt, the student implicitly acknowledged that makerspaces may typically be perceived as places reserved for engineering students by stating, "especially not just engineering [students]" when the makerspace gets busy near final exams. The interviewee proceeded to provide an example of a non-engineering student using a specific equipment in the makerspace for a specific purpose, demonstrating that the interviewee perceived the makerspace to be a place where both engineering and non-engineering communities can come together.

Students also commented on being able to "tap into" different sides of engineering, such as creativity, by virtue of being in a space that encourages interactions with, and reflects the practices of, disciplines other than engineering, such as art. One student interviewee expressed this sentiment when asked what skills or knowledge they are taking away from being in the makerspace: "you can do lots of projects . . . not just engineering, but like art or other things besides that. So, it [being in the makerspace] is more [about] tapping into the creative side and really utilizing the technology that allows you to show that" (Makerspace B, Student 1).

3.2. Boundary Space 2: Novice and Expert Users

Another frequently mentioned boundary space found at makerspaces according to student users was one in which users of various skill-levels came together. As one student interviewee mentioned, the makerspace was perceived to be a place where "there's a lot of knowledge base, whether that's from someone [student user] who's just here a lot . . . to the design specialist [professional staff] who you can talk to." This particular student who self-identified as a novice in the makerspace also stated that they appreciated being able to work independently when desired, but also being able to interact with more expert users if needed:

> *[T]he fact that you can work on it [projects] independently, and when you need help, you can go reach out, helps you build up your own confidence . . . it [makerspace environment] is really accessible when you're willing to ask for that help and realize it's a learning experience, not just a shop to build things.*
>
> (Makerspace A, Student 6)

In addition to the overall environment that made the makerspaces conducive for novice and expert users to co-exist in ways that met each user's needs, student staff played a major role in bridging the gap between novice users and expert users at both of our study sites. One of the interviewees, who was a student staff member, acknowledged how the makerspace might be intimidating to new users with little experience at first, but noted both the efforts of the staff as well as the characteristics of the other users that allow for the co-existence of both novice and expert users in the makerspace:

> *When you come in here [makerspace] at first it can seem intimidating, but the way I think that the space is structured, in the way we have [student] staff like us . . . the way they've trained us, is that we're able to come in and say [to the new users], "Don't be afraid to ask. No question is stupid" . . . we're here to walk you through every single process and during tours when students are doing admission previews or things like that, every time I give a tour I always emphasize, "I'm not an engineering student . . . I was not familiar with this equipment. A lot of kids who come in here are not like specialists at anything. A lot of people just come to like mend their clothes or solder something small that they need fixed."*
>
> (Makerspace B, Student 7)

In addition to this student staff member emphasizing that novice and expert users are welcome in the space, this example also shows that it is possible for novice users (like the student interviewee who was not an expert to begin with) to become a more experienced user who is able to work as a staff member and help others.

3.3. Boundary Space 3: Academic/Professional and Personal Activities

Students frequently perceived their university-based makerspaces as places where activities they considered to be "school-related" or "professional" came together with activities they considered more "personal" or "casual." The makerspaces were places where students either did not have to draw the distinction between these two types of activities or could seamlessly transition between these two types of activities, as explained by one student, who was using their campus makerspace to create a mold for a concrete canoe as a part of a student club:

> *I think it [the makerspace] creates a really cool space for people to be able to work on whatever projects they need to. Because our club does not have the budget to just buy a 3D printer, we don't have the money or resources to be able to do that. But then, having resources like this on campus allow students from whatever club, or for whatever project,*

> *or school, or personal, or whatever they want to do, that gives them an opportunity to be able to express what they want to do.*
>
> (Makerspace B, Student 16)

As this student observed, it was common for students to use their campus makerspace for whatever project they wanted, whether it was related to school or personal interests. At both university-based makerspaces, there were no restrictions on the types of projects students could work on and this facilitated a wide variety of students with a wide variety of interests and purposes making use of the makerspace.

Additionally, several students mentioned that their initial perception that one has to be working on something "super professional" when in the makerspace was quickly dispelled. These students talked about starting to use the makerspace for a variety of school and non-school related purposes, and also noticing other users doing the same. The following student interview excerpt demonstrates this fluid switch between school and non-school projects, and the variety of activities possible in university-based makerspaces:

> *I thought … you had to come in with a project, you had to, you know, be working on something super professional. But now people come in here and they don't even use the machines. They just study and that's totally normal … I made stickers for my friend and they were really silly and it was just, you know, a random project. There was nothing really structured or super important, you could say, about it. Nothing schoolwork-wise … a lot of people would just come and meet in here. They'll use the whiteboards, they'll use just the tables and they'll do homework, they'll work on stuff.*
>
> (Makerspace B, Student 9)

3.4. Boundary Space 4: Theoretical and Hands-on Activities

Given that makerspaces are usually noted for their availability of various high- and low-tech equipment and tools, students talking about the ability to get hands-on experiences in the makerspaces was somewhat expected. However, particularly notable was students' talk about the coming together of theoretical ideas and tangible products at makerspaces. When asked about the value of their campus makerspace, one student replied,

> *I think being able to actually make what you're designing is super helpful. Because you can design whatever you want in a computer, but … I think it's easier to tweak stuff off a physical model than having to rotate it and seeing it on [a] flat [platform] … actually seeing it in 3D is really helpful.*
>
> (Makerspace B, Student 14)

This notion of being able to connect the theoretical (or ideational) to tangible (or physical) in the makerspace was mentioned by many students. Other students specifically talked about coming to better understand specific concepts learned in class through their makerspace activities as did the following interviewee: "Some of the [concepts from the] CAD [Computer Aided Design] classes I've taken, I can actually put that to use [at the makerspace] and be like, 'Oh, this is why we've learned this'" (Makerspace B, Student 22). Others connected this ability to bridge the theoretical and tangible aspects of engineering, which they learned to hone in the makerspace, as a valuable skill for their future career:

> *[T]here's a difference between knowing how the book tells you to design it or how a professor tells you to do it and then actually getting in there and playing with it, figuring out how it works yourself. Getting that hands-on interaction with it is really what makes a difference in your career.*
>
> (Makerspace A, Student 16)

3.5. Boundary Space 5: Students and Staff

In the two university-based makerspaces under study, students talked about how friendly and helpful the makerspace staff were and how this helped to facilitate an easy and comfortable relationship between students and staff. Part of this ease and comfort may have come from the fact that some of the makerspace staff at both study sites were either current or former students at the institutions hosting these makerspaces. Even in the case of professional staff members who were not current or former students, they were fairly diverse in terms of their professional backgrounds and interests (e.g., architecture, construction); through these staff members, students had the chance to interact with non-engineering professionals who were passionate about making in general. Students noted that unlike the relationships they had with staff in machine shops (who are typically engineers with industry background) or with faculty members in classrooms, students described a less hierarchical and more collaborative relationship with staff at makerspaces:

> *[T]he people here [in the makerspace] are so helpful. Even if I can't really talk to a teacher [faculty member] about something . . . I can come here and the staff are really knowledgeable. They'll bring up things that I would have never thought of. I really like having that community of people here.*
>
> (Makerspace A, Student 12)

As explained in the above excerpt, the student saw the makerspace staff offering a sense of community that they did not necessarily get from classroom faculty. Another student talked about how much they appreciated the fact that the staff of the makerspace were themselves users of, and passionate about, the machines:

> *Everyone who works here wants to be here and really enjoys something about the machines, or you can even talk to them and they have like one machine they really enjoy using, so I think that's great. Instead of you know, coming in somewhere else and they're [the staff are] just working to work. They don't really know that much about the machines [and] they're not as invested . . . A lot of the staff members, like I said before, actually use the machines . . . .if you don't have a project or a class [assignment] that you're working on, you [can] come in here . . . you can even talk to staff members and they'll be like, "Oh let me tell you about something I made." Or, "Oh my gosh, I was working with someone and here's what they did. Here is how they, you know, use the space."*
>
> (Makerspace B, Student 9)

As expressed in the above excerpt, the availability and knowledgeability of the makerspace staff allowed the student to feel as if they were among a community of passionate and caring makers, rather than among a group of uninterested employees. Therefore, the makerspace served as a place where the community of students and the community of staff could come together in a novel relationship not commonly seen on other parts of campus.

3.6. Boundary Space 6: Sub-Disciplines or Specializations within Engineering

Although relatively infrequently, in comparison to instances of students talking about the boundary space of engineering and non-engineering disciplines coming together at makerspaces, several students acknowledged different sub-disciplines or specializations of engineering co-existing at and making use of the makerspace. For instance, one student commented that "it's cool to see" two different types of engineering classes taking place at the makerspace "because they use the space a bit differently." The student elaborated by stating that, "Engineering 105 [general engineering class typically for first-year students] is doing more of 3D printing and laser cutting. And then the HCDE [Human Centered Design and Engineering—a more specialized course for upper-class students], obviously doing more interactive things [and] more complex design stuff" (Makerspace B, Student 9). As stated by this student, the makerspace was conducive for various types of engineering classes and associated activities to take place.

Additionally, students commented on the ability to interact with students outside of one's own sub-discipline or specialization of engineering being a benefit of engaging in makerspace activities. In response to the interviewer's question about whether the student's experience in the makerspace would be helpful for their intended future career in engineering, the student provided the following response:

> *I think as me being an electrical engineer, I think being able to have an understanding of another team's perspective if I'm working with like two mechanical engineers, being able to know what they're talking about and have some insight on what they're doing can help on the EE [electrical engineering] side of things and I get that a lot in my robotics club as well, where you have to be able to work with multiple different disciplines, which I think is really useful to have that.*
>
> (Makerspace B, Student 12)

Earlier on in the interview, this particular student talked about their robotics club (referenced in the above excerpt), which meets and creates robots in the makerspace. The student's response to the interviewer's question directly addresses the fact that the student gets experience working across the different sub-disciplines of engineering in their campus makerspace, which they believe will be helpful for their future career because they anticipate having to work across multiple sub-disciplines of engineering in a professional setting.

3.7. Boundary Space 7: School-Related and Entrepreneurship/Industry-Related Activities

Another boundary type mentioned by student interviewees was activities related to school and activities related to entrepreneurship or industry coming together at the makerspace. Although this was one of the least frequently mentioned boundaries in our data, several students talked about the makerspace affording students the opportunity to connect school-related activities and entrepreneurship or industry-related activities. In the following excerpt, a student talked about their and their friend's experience in a class that was designed to guide students through starting a business and how they were using the makerspace equipment to achieve their goals:

> *So, we're both in a creating-a-company class, so it spans two [academic] quarters. The first quarter is prototyping and really ideating and research–market research. And then the second quarter is about selling our product and getting it out there. So, for now we're putting the designs on clear AirPod boxes and our company is called Clear Pods for that reason ... we're using the ... UV printer to print the designs onto the cases.*
>
> (Makerspace B, Student 4)

The availability of a specific equipment in the makerspace aided students in engaging in an activity that was simultaneously for school and for their intended business. The makerspace provided a physical space and equipment for this boundary space, which was encompassing school- and entrepreneurship-related activities.

In another example, students talked about a "student-run design consultancy" or a "student-run organization in which we get industry people to be our clients" (Makerspace A, Student 17). Similar to the coursework with connection to entrepreneurship opportunities, the student club with connections to industry was made possible by the infrastructure and available resources of the makerspace. Not only was the overall ethos of the particular makerspace encouraging of students making industry connections, one student interviewee noted that the student design consultancy club meets in the makerspace and "[i]t's helpful because we have all the tools ... readily available to us" (Makerspace A, Student 17).

4. Discussion

University-based makerspaces are receiving attention as affordances in the development of university students training to be future engineers [1,3]. An emerging body of research shows their promise as places where engineering-related activities are available (e.g., prototyping, designing). However, this research is limited by typically focusing on a specific student club or a discrete workshop taking place in a university-based makerspace (e.g., [7,22]). Additionally, there is still some concern that such spaces may be distracting for student development of skills deemed most important by postsecondary programs and faculty [8], especially given the complexity of activities and individuals within them. We sought to examine university-based makerspaces holistically, to ascertain their potential as affordances for the development of undergraduate engineering students via their engagement in these spaces, both through formal coursework and otherwise. Specifically, we sought to investigate undergraduate engineering students' notions of makerspaces in supporting their development as engineers, including abilities to work with a diversity of others in creative and collaborative ways to address complex problems. Such 21st century skills are relevant and important to consider for engineering students per the reality of (and ABET criteria emphasizing) professional engineering work as encompassing much more than content expertise. 21st century skills, in fact, are vital across disciplines and professionals, including those represented by the other university students engaging with campus-based makerspaces.

We examined whether student users of university-based makerspaces perceive makerspaces as boundary spaces [24], or the "in-between" spaces that bring together diverse individuals, disciplines, and activities that, ultimately, may allow learning. A main premise of the social boundary framework is that boundary spaces are resources for learning, as opposed to barriers that could also arise per their complexity. Learning can happen as individuals navigate boundary spaces, by making sense of, and overcoming or better appreciating, the differences and diversity within them. Our exploratory study was premised on Akkerman and Bakker's [24] conceptualization of four learning processes that may occur at boundary spaces (identification, reflection, coordination, transformation). We were interested in the nature of the boundary spaces students perceived that could act as precursors to potential learning around engineering, as well as 21st century skills more broadly.

4.1. Types of Boundary Spaces Available in University-Based Makerspaces

We start with an accounting of the different boundary space types identified, as well as a discussion of the relevant characteristics of university-based makerspaces that may have facilitated the existence of boundary spaces and students' recognition of these boundary spaces as potential resources for learning. In examining student interviewees' descriptions of their experiences, we identified seven different types of boundary spaces in which students may engage in makerspaces. These included boundaries consisting of: (1) engineering and non-engineering disciplines, (2) academic/professional and personal activities, (3) novice and expert users, (4) theoretical and hands-on activities, (5) students and staff, (6) one sub-discipline or specialization of engineering and another sub-discipline or specialization of engineering, and (7) school-related and entrepreneurship/industry-related activities.

There were several characteristics of our two study sites which likely facilitated the existence of boundary spaces and students' recognition of these boundary spaces. Most notably, both makerspaces in our study were open and available for use by all members of the campus community (faculty, staff, students) and without regards to academic major, skill-level, and interest area. This open access policy likely played a significant role in diverse individuals, disciplines, and activities being present in these makerspaces in the first place. Relatedly, makerspaces were described as not only allowing for the co-existence of diverse people, disciplines, and activities, but as actively welcoming and encouraging the co-mingling and interaction among the diverse groups. Interviewees who described themselves as non-engineering majors or those who were not working on projects that require a high level of technical skills stated feeling accepted in the space and being able to interact with others comfortably. These characteristics likely gave rise to boundary spaces and potential learning opportunities in these boundary spaces. Aside from this wide accessibility and welcoming environment, makerspaces also potentially facilitated the existence of boundary spaces via the availability of machinery, such as laser cutters or UV printers, that had diverse applicability for multiple disciplines and multiple purposes, ranging from engineering to architecture, and from school-assignments to entrepreneurial activities. Professional as well as student staff were also an important aspect of the university-based makerspaces that facilitated the existence of, and learning potential at, boundary spaces that typically might not exist elsewhere, consisting of novices and experts, and staff and students.

Ultimately, we recognize the scope of this study does not allow us to comment on whether some of these characteristics contributed to the creation of boundary spaces or whether boundary spaces encouraged these characteristics of university-based makerspaces to flourish. At the same time, we note these characteristics are an important part of better understanding university-based makerspaces and their potential to function as affordances for students' development as engineers. As we argue in the ensuing sections, boundaries have the potential to give rise to several learning processes, which in turn may lead to students' cultivation of skills required to be well-rounded engineering professionals.

4.2. Interactions and Activities Occurring at Boundary Spaces

Utilizing Akkerman and Bakker's [24] notion of four learning processes occurring in boundary spaces, we saw evidence of makerspaces providing students with potential opportunities to engage in interactions and activities conducive for their development as engineers. We saw evidence for three of these processes: identification, reflection, and coordination, that we contend point to the different ways that university-based makerspaces may serve as affordances for students' development as engineers.

It was fairly common for students to indicate that they *identified* their own communities and practices in relation to those of others, as they *reflected* on how knowledge about individuals or practices of other communities may benefit their own identity development and future practice as aspiring engineers. For instance, a mechanical engineering student identified the distinction between mechanical and electrical engineering (boundary space type 6), stating that gaining a better understanding of electric engineering is helpful for future possibilities of having to work across diverse disciplines and sub-disciplines of engineering. In some cases, machinery such as a laser cutter afforded opportunities for identification and reflection, as in the case of an engineering student who remarked on how they witnessed architecture students making use of a laser cutter, and another engineering student who took full advantage of the machinery to explore and express the artistic side of engineering (boundary space type 1). These types of interactions available in boundary spaces—and by extension, the opportunity to engage in identification and reflection—may contribute to students' development as engineering professionals. ABET criteria emphasize students being able to collaborate and communicate with diverse others to solve complex and multifaceted problems [19]. Such activities require students becoming aware of their own identities and practices in relation to the identities and practices of others, in order to collaborate and solve problems in diverse teams. Additionally, scholars have called for the need for engineering education to better reflect the work of professional engineers, which is more open-ended (rather than solving formulaic problems with known answers) and people-oriented (rather than technical and objects-oriented) than is typically thought [44,45]. By providing opportunities for students to interact with diverse others, and experience and experiment with objects in open-ended ways, university-based makerspaces, via boundary spaces, offer opportunities for students to consider and reflect their identities and activities in relation to those of others. In turn, these experiences at boundary spaces may serve as affordances that contribute to students' development as engineers.

Students also perceived *coordination* occurring in various boundary spaces. Staff—both professional and student workers in the makerspaces—encouraged and modeled interaction and communication between novices and experts, serving as coordinators that span these two communities (boundary space type 2). As was the case with identification and reflection, machinery available in the makerspace sometimes afforded opportunities for coordination. A student explained their use of the UV printer was allowing them to engage in activities that straddled course-related work and entrepreneurship (boundary space type 7). Students also engaged in hobbies or clubs that afforded them with opportunities to coordinate activities that were academic/professional in nature with those that were personal in nature (boundary space type 3). Through coordination, students gained the necessary skills and knowledge relevant for engineering practice (by moving from novice to expert) and they were also able to incorporate non-engineering specific activities (such as entrepreneurship or hobbies) into their engineering repertoire. Coordinating also likely allowed students to practice being a part of, and navigating across, multiple communities and their associated activities by translating the practices of one community to another and vice versa. Such affordances available via coordination at boundary spaces are highly aligned with several ABET criteria. For instance, according to ABET [19], students are expected to develop the ability to function effectively on diverse teams that produce solutions that take into consideration "public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors" (p. 5). In other words, it is crucial that engineering professionals are skilled at working across and taking into account the needs of diverse communities, via coordination. In fact, Trevelyan [46], who conducted an ethnographic study of professional engineers to better understand the nature of their work, concluded that one of the major tasks of professional engineers is "working with and influencing other people so they conscientiously perform some necessary work" (p. 191), or what Trevelyan called "technical coordination." Other engineering education scholars have concurred with this perspective that much of engineering work consists of coordinating and communicating across diverse groups of individuals and communities [45,47], which students in university-based makerspaces were gaining the opportunity to practice.

Student interviewees did not indicate participating in or noticing instances of *transformation*, or a profound change in the knowledge bases or practices of the different groups that come together at a boundary space, resulting in a new or "in-between" practice. This finding was not surprising given what Akkerman and Bakker [24] noted regarding the process of transformation; it is oftentimes a lengthy and multi-step process that requires concerted and sustained effort on the part of the multiple communities and their members. Transformation occurs on a community or group—rather than on an individual—scale and involves members of different communities first encountering a "confrontation" or "some lack or problem that forces the intersecting worlds to seriously reconsider their current practices and the interrelations" [24] (p. 146). In our study, student users of makerspaces were usually focused on their individual use of the university-based makerspace, rather than seeing themselves as representing or shouldering the responsibility of transforming or improving the communities they represent. Additionally, students may not have had the adequate level of expertise regarding their discipline or other communities they were a part of, which would have allowed them to detect a "confrontation," then devise potential solutions to enact profound change for the discipline/community at large. In cases where students did notice a temporary disconnect between their personal understanding or use of the makerspace (e.g., engineering students use the space in different ways compared to architecture students), these dissonances were resolved via some combination of the three previously mentioned processes of identification, reflection, and coordination. The scope of this study did not capture whether and how decision-makers, such as makerspace administrators or engineering faculty may have been noticing and addressing possible sources of "confrontations" between the multiple communities coming together via boundary spaces, resulting in instances of transformation.

4.3. Cultivation of 21st Century Professionals

Beyond being conducive to providing the opportunities necessary for the cultivation of well-rounded future engineers, university-based makerspaces may help cultivate 21st century professionals in general. Although makerspaces are typically affiliated with engineering departments of universities [1] and thus equipped with tools and machinery typically expected to be of use to engineers, the types of experiences that undergraduate students were exposed to, as they engaged with diverse boundary spaces and relevant learning processes in makerspaces, were those pertinent for students developing a general set of "soft" [11] or "21st century" skills [12,13]. For instance, we saw evidence of students solving problems creatively and communicating effectively with diverse others as they identified, reflected upon, and coordinated across various lines of difference such as, skill level, interest, and major. These skills are not uniquely valuable in the discipline of engineering and are in fact becoming increasingly relevant and important for all professionals, especially with the rapid ongoing economic, social, and technological changes that necessitate learners be well-versed in skills beyond those that make them content experts with technical know-hows [12,15]. Thus, just as engineering students must know more than engineering content knowledge [19], society needs graduates of postsecondary programs who can innovate and translate basic and applied research to tackle complex global societal challenges. To be effective and translate innovations into practical use, graduates must possess more than just deep foundational knowledge and skills in one area (i.e., *I-shaped professionals*); they must also possess teamwork, leadership, and communication skills that allow them to effectively coordinate efforts within a broader ecosystem of education, government and private sectors (i.e., *T-shaped professionals*) [16,48]. Student interviewees revealed that in most cases, they perceived makerspaces as not restricted to gaining exposure to, and developing expertise in, one particular discipline or sub-disciplines of engineering. Instead, makerspaces acted as boundary spaces that afforded students with opportunities for interacting with diverse communities and individuals. These opportunities in turn gave rise to their engagement in processes such as identification, reflection, and coordination, which were called for in order to navigate and make meaning of the diversity and differences encountered at boundary spaces. These processes then allowed for students' learning of knowledge, skills bases, and professionally related activities that encompass, and have the potential to go beyond, development as well-rounded 21st century engineers.

4.4. Considerations for Practice

As we have demonstrated in our work, along with others that have documented the increasing number of makerspaces making their way onto university campuses [1,3,8], university-based makerspaces offer exposure to people and practices that engineering students may not otherwise be able to easily experience in other settings. Whether the availability of these diverse experiences is a source of distraction and barrier to learning, or whether it is a resource that should be leveraged for students' learning and development, is a valid concern. This is an especially important question to consider given that an intentional integration of makerspaces into postsecondary engineering curricula can require concerted time, effort, and monetary resources. Prior research suggests that faculty who teach in university-based makerspaces may perceive certain features of makerspaces (e.g., open floor plan, availability of rapid prototyping equipment) as distractions or hinderances to students' development as engineers, including their understanding of engineering [8,49]. These possibilities are necessary for faculty to understand in order for them to develop teaching practices (e.g., discussion of all that engineering entails) that help students combat any inaccurate notions that may be fostered via engagement in these spaces.

With these realities in mind, we have found evidence in this study (at least from student perspectives) that makerspaces do have the potential to cultivate future (engineering) professionals, rather than providing students with access to just a "room full of tools." While further research is surely warranted (e.g., those that incorporate faculty or administrator perspectives), we posit that university-based makerspaces can add value to postsecondary engineering programs, as well as other programs on campuses, in terms of students' learning and development. Specifically, we found students perceiving and making use of the diverse offerings available in makerspaces to advance their understanding of themselves as well as others, and devising ways to work across lines of differences. These types of activities and the skills they gain along the way in navigating diverse people, practices, and communities prepare students to be collaborative, creative, and ultimately ready for interdisciplinary and dynamic professional work. Thus, we assert that university-based makerspaces have the potential to offer valuable developmental experiences that individual programs or departments and faculty alone may not be able to easily offer. Makerspaces exist at the crossroads of multiple individuals, activities, and disciplines coming together, offering opportunities for students from diverse backgrounds to easily and efficiently access experiences that are beneficial for their learning and development.

Additionally, through their largely open-access policies and welcoming environment, university-based makerspaces may help diversify the field of engineering, which continues to be one of the least diverse disciplines of STEM in terms of gender, race/ethnicity, (dis)ability, and other lines of difference [50]. University-based makerspaces may be providing more equitable access to more cutting-edge equipment (when compared to machine shops, for instance), as well as the necessary ABET-aligned experiences, that a diverse group of potential future engineers may not have access to elsewhere. As well, the spaces may be solidifying a more diverse student body interested in engineering.

Given that postsecondary engineering coursework is still largely criticized as too "book-based" or focusing on students solving problems with known answers [45,51], makerspaces may be providing students with experiences that more accurately reflect the complex, open-ended, and enjoyable work of practicing engineers. In fact, these experiences are at the core of many *high-impact practices* (e.g., undergraduate research projects), that foster success and persistence of diverse students across postsecondary STEM, and that postsecondary institutions are strategizing how to further support in light of the heavy financial resources needed to offer them [52].

University-makerspaces may also play a role in students' (both majors' and nonmajors') development of more authentic [51,53] understandings of key engineering practices (e.g., design) that have wide applicability for problem solving in diverse contexts, including beyond engineering [54]. Socio-scientific problems most pressing to society (e.g., global warming) are best addressed through reliance on theories, data, and practices across STEM and the social sciences [55]. Students' engagement with socio-scientific problems in their university courses has been shown to be correlated with their motivation in STEM courses [56]. Makerspace activities, which offer opportunities for students' exposure to, and engagement in, multi-disciplinary and cross-sectional problems, may contribute to students' greater commitment and ability to address socio-scientific problems and persist in the STEM fields. As a result, students may be better prepared for professional work, simultaneously benefitting future employers and the professional field as a whole, since they will be able to welcome graduates who are well-versed in solving dynamic, complex problems while working across diverse disciplines.

Given this, we recommend that engineering faculty currently engaged with makerspaces, as well as makerspace administrators and staff, leverage the affordances of university-based makerspaces by making them known and available to faculty within and beyond engineering departments. With this surely requires helping faculty to also recognize the worth of makerspaces across diverse discipline- and teaching-based realities and goals that can sometimes make implementation of teaching innovations feel daunting [57,58]. Faculty, themselves, may need help navigating the boundary spaces consisting of the diverse individuals, disciplines, and activities intersecting in makerspaces [59,60]. We also recommend that faculty, staff, and administrators support students in their development of skills, knowledge, and practices relevant for engineering (and, indeed, 21st century skills relevant across professions) by helping students become more aware of the various affordances of makerspaces and encouraging them to be metacognitive about their development.

4.5. Limitations and Directions for Future Research

Our study focused on the perceptions of student users of university-based makerspaces to center the lived experiences of these critical stakeholders. Yet we believe additional insights about student users' engagement with university-based makerspaces can be gained via methods such as discourse analysis [61] or interaction analysis [62], allowing capturing of students' activities and interactions in makerspaces in real-time. Such approaches could be supplemented by tracing specific aspects or characteristics of makerspaces to more concrete learning outcomes for students. Future research might build upon the current study concerning affordances to document actual outcomes for students, both in the short and long-terms, concerning acquisition of specific knowledge, skills, and dispositions, and persistence in their engineering degrees and in the field. Our study was limited in that we interviewed students once and while they were engaging in some type of activity in the makerspace during the time of our site visits. Thus, our methods captured student activities at one particular moment in students' involvement with the makerspace, which may have skewed our findings.

Additionally, due to the impromptu nature of the interviews we conducted with study participants, we did not collect demographic information of these students (e.g., race, gender) unless interviewees voluntarily disclosed this information without prompts from the interviewers. As our study was exploratory in nature, it presents a limited view of university-based makerspaces and students' experiences with them. Given that engineering disciplines tend to be some of least diverse of the STEM disciplines in the United States [50], and given the close connection that university-based makerspaces have with the disciplines of engineering, we see a need for future studies to more carefully document and draw the connection between various dimensions of student diversity and their experiences in makerspaces.

Specifically, there is a need to document the perspectives of students who perhaps found their makerspace experiences unaccommodating or unfulfilling for their purposes, and thus did not return. Additionally, given that our two study sites were relatively similar on several dimensions (e.g., student demographics, types of courses or activities offered in the makerspace, affiliation with College of Engineering), we see promise in testing the relevance of our findings at a greater diversity of makerspaces and university campuses. Locating and focusing on some of these untold stories would enhance the research base around university-based makerspaces and help enhance their impact for a diversity of students and institutions.

5. Conclusions

University-based makerspaces are relatively novel additions to U.S. university campuses with much promise for providing opportunities for students' exposure to, and interaction with, a diversity of activities, people, and disciplines that may be relevant for students' development as professional engineers. Through an application of social boundary spaces, we identified seven different types of boundary spaces that students perceived in their university-based makerspaces as they engaged in various activities within and outside the scope of their formal coursework in these makerspaces. We have added to a growing body of research that posits that university-based makerspaces act as affordances for developing students' abilities to communicate, collaborate, and engage in critical and creative pursuits, for engineering students and beyond. We see potential for more university programs and departments integrating into existing curricula and taking advantage of the affordances of university-based makerspaces.

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Appendix A. Student Interview Protocol

1. Tell me about your experiences working in makerspaces. [Probe for formal education (course affiliated) experiences AND any informal (participant-initiated) experiences]
2. What's the value of being in a makerspace?
3. What do you think your instructor(s) want you to gain from being in the makerspace?
4. How are the makerspace assignments helping you learn about what engineers do?
5. Through participation in makerspace activities, what practices are you learning that you think are essential to engineering and how valuable do you think the skills are?
6. Do you feel you belong in a makerspace, why or why not? What does belonging look like to you?
7. How do you form and work in teams in the makerspace as compared to classroom or study groups?
8. Do you feel there are norms or unwritten rules for participating in the makerspace? If so, what are they?
9. Are there people you feel you relate better to in the makerspace? If so, how, and if not, why?
10. Share a time when you got stuck when working on a makerspace project. What did you do? Is this the same approach with other engineering assignments?
11. [If applicable, any questions that occur to interviewer per what witnessed during observed makerspace activity]

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