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Building Knowledge Structures in Context: An Exploration of How Constructionism Principles Influence Engineering Student Learning Experiences in Academic Making Spaces

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Abstract: In this study, we explored how constructionism theory principles were integrated across six engineering academic making spaces to support student learning outcomes. Using a qualitative approach, we conducted a thematic analysis of semi-structured faculty and staff interviews. The data suggests that engineering academic making spaces afford students with collaborative spaces for collective discovery centered around the application of manufacturing processes and professional practices. Furthermore, data indicates that both educators and staff play an integral role in guiding student learning, autonomy-building, and lifelong learning in these spaces. However, additional considerations around learning cultures, student-centered learning, and their connections to situated cognition and collaborative learning are needed. Findings and subsequent recommendations focus on using a constructionism lens to promote engineering students' learning outcomes in academic making spaces.

Keywords: constructivism; making spaces; engineering education; faculty development

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1. Introduction & Problem Statement

Youmans, et al. [1] noted that the education of undergraduate engineering students continues to evolve as marked by notable shifts in curricular and instructional approaches that move away from passive lecture-based learning to more active innovations such as early apprenticeship opportunities and project-based learning [2,3]. The goal of the innovations is to increase opportunities for students to develop their design and professional skills [4–6]. The shift is largely a result of the Accreditation Board for Engineering and Technology's (ABET) launch of Engineering Criteria (EC) 2000, which focuses on professional considerations of student outcomes in the preparation of undergraduate students for the engineering workforce [7]. ABET outcomes reflect the skills and knowledge students need to gain to address the increasingly complex and interconnected problems that engineers face in the 21st century [6]. Recent changes to the ABET standards has catalyzed an increase in the number of first-year project courses as well as senior capstone design courses in undergraduate engineer preparation programs [7]. Commonly, the curriculum in the first-year project and capstone design courses require students to work collaboratively to address a problem that requires the application of engineering design. Thus, students can become engaged in authentic engineering activities requiring them to apply professional engineering skills such as communication, collaboration, and problem-solving.

Incorporating design-focused courses such as senior capstone and freshman project courses within engineering education involves evaluating the effectiveness of different instructional spaces for meeting the needs of students to achieve desired learning outcomes.

Instructional spaces can vary in configurations and meet different instructional goals. For example, traditional classroom instructional spaces accommodate lecture, whereas academic makerspaces with instructional spaces accommodate design and prototyping [1,8]. As a result, academic makerspaces are widely embraced as instructional spaces that bridge what students are presented through lecture to the practices, constraints, and requirements of professional engineering. A unique feature of many academic makerspaces and prototyping labs in engineering (and engineering education) is the presence of rapid prototyping equipment and tools. The tools allow for a high level of engagement in exploring new ideas and the effectiveness of new designs. The engagement between and among individuals and the constructions of solutions (or failures) to problems has been posited as integral to knowledge construction [9]. For example, Papert [9], claims that an individual's cognition can be partly explained by the way that they use technologies, objects, and media to develop solutions.

The purpose of our exploratory study is to expand our understanding of the learning experiences that occurred in existing academic makerspaces in engineering. More specifically, used Papert's learning theory of constructionism [9] to identify the learning principles that were (or not) present amongst six academic engineering education making spaces in the U.S.

2. Brief Literature Review

Constructionism is widely used term for explaining learning in maker/making spaces [9]. As Papert suggests, "traditional epistemology gives a privileged position to knowledge that is abstract, impersonal, and detached from the knower, and treats other forms of knowledge as inferior" (p. 10, [9]). Within engineering education, constructionist learning theory has been proposed as a theory to motivate and engage students in problem-based design learning [10], in model-based learning [1], and in virtual learning environments [11]. Although constructionism often confused with the developmental learning theory of constructivism from Piaget [12], there are some key differences. "Constructionism—emphasis on "N" as opposed to "V"—shares constructivism's connotation of learning as "building knowledge structures" irrespective of the circumstances of the learning (p. 1, [9]). Constructionism includes *context* and *situated learning* as fundamental to learners' consciously engaging in *constructing a public entity*, whether it's a sandcastle on the beach or a theory of the universe (p. 1, [9]). In contrast, constructivism represents the importance of individuals' cognition for a learner to tangibly translate what is being instructed and use the information to guide their learning choices [9]. Constructionism explains the deeper learning that happens through the individual or group construction of objects and is not predicated on a specific technology or process [9].

Kafai [13] expanded upon constructionism to include knowledge construction and learning culture. Described in Papert's early work as *objects to think with*, constructionism suggests that the creation of physical or virtual objects increases the opportunity for individuals to gain understanding of abstract concepts. Thus, the process of construction can enhance opportunities for learning [13]. Developing knowledge using creating and building activities is especially relevant for engineering students as they experience the benefits of constructionism when they engage in designing and testing prototypes.

The activities that take place through constructionism-based learning requires shifts in the roles of faculty members from the lecture-based didactic authoritative role, to a mentor who acts as a facilitator of student learning [14]. Thus, the emphasis on the process of learning in a constructionist learning culture is on knowledge-building and application through active engagement. Combining findings from the work of Papert [9], knowledge construction and learning culture and Kafei's descriptions of its sub-components [13], and our work [1], we synthesized the principles, sub-principles and descriptors of the most salient constructionism learning principles and translated them to engineering education making spaces and prototyping centers (see Table 1). This allowed us to develop a categorization of sorts by which to derive our analysis from.

Table 1. Salient principles and sub-principles of constructionism in engineering education making spaces and prototyping centers; adapted from [1].

Principle of Constructionism [9]	Sub-Principles of Constructionism [13]	Descriptions to Derive Categories Per Sub-Principle [1]
Knowledge Construction	Object Construction	Learners gain an understanding of the tools and equipment needed to create a physical prototype and, in the process, translates theory-to-practice via the knowledge gained in the construction of an object.
	Debugging	This process consists of the iterative cycles of problem-solving and troubleshooting when designing and constructing objects. This process requires an understanding of the design skills needed to create products. This process also requires a positive attitude towards failure where learners can learn from their mistakes.
Learning Culture	Teacher as a guide	This requires a guided inquiry process to support learners to think critically about the design project. However, in this guiding process, curricular activities are tailored to learners' prior knowledge and previous application of learned material. In order for guided inquiry to happen, learners must feel a sense of trust with their facilitators/instructors, as reflected by their approachability, interactions, and encouragement with the learners.
	Collaborative	The physical arrangement of a learning space to ensure that learners are comfortable to learn, both individually and in groups. In that process of collaboration, discovery happens with others and engenders a culture of knowledge sharing. The activities are also designed to be collaborative for knowledge-sharing to happen.
	Student-centered	The activities and projects that learners are engaged with is of their own choosing and not necessarily connected to formal schooling. Also, students directly engage in continual knowledge development through challenges that creates a learning culture of conflict resolution around continual intellectual or physical demands.

We acknowledge that context is important to constructionism [9]. There is a dearth of published empirical research focused on constructionism in the context of academic makerspaces in engineering education. The related research includes an investigation of student learning in a material science course using computer-based modeling and design tools [11]. in deepening students' conceptual understanding of causality structures in technical concepts and behaviors. Maintaining a focus on constructionism, we investigated the learning in a university engineering education prototyping center at a Midwestern institution of the United States [1]. We found the constructionism principles being leveraged in the space consisted of engaging students in iterative design skills to facilitate the translation of abstract concepts to concrete experiences. Further, the constructivism focus in the spaces effectively guided student learning, created a collaborative learning environment, and promoted student development of a range of professional skills.

The limited empirical documentation of the instructional practices and learning principles being used within engineering making spaces warrants additional exploration on this topic. Given the role that makerspaces have in knowledge constructions and learning cultures (see Table 1), we believe that documenting if and how constructionism was present in such spaces will allow scholars and educators to begin to establish assessment of educational outcomes in the future. The findings of this early can help establish the groundwork by which additional learning theories and principles in engineering education making spaces and prototyping centers can be derived from.

3. Methods and Research Design

Our qualitative study is part of a larger mixed-methods collective case study investigation of the role of engineering education academic making spaces and prototyping centers conducted pre-COVID-19 from 2017 to 2019. The larger study focused on an in-depth exploration of makerspaces used as part of core engineering education curriculum at six engineering colleges and universities [1]. To conduct the research, two or more members of the research team traveled to the university making spaces and interviewed the space leaders (directors or managers), faculty members, and staff. The research design included an approach gathering data through observations and semi-structured individual and group interviews to explore the saliency of participants' experiences.

One of the focal points of the larger research project was to explore the ways engineering education academic making spaces are integrated into the curriculum and the affordances the spaces provided to support teaching and learning [15]. Of particular interest was the learning achieved by the students when working in the spaces [16] and the influence of working in the spaces on student motivation and professional identity development [17]. We further explored the ways that the operations and activities found within these spaces influence equity of access and cultures of belonging [16]. In this work, we are interested in further exploring learning principles from the perspective of constructionism. Thus, the empirical support for our research on constructionism in the spaces is supported by analysis of the interviews of faculty members, space leadership, and staff (with instructional roles) across the six sites who strongly influenced the design and implementation of making space activities for students.

The primary research question that guided our investigation was: (1) To what extent do engineering education making spaces in the U.S. use (or not) principles of constructionism?

4. Study Sites

We selected six academic engineering education making spaces located in different regions of the U.S. based on the following criteria: (1) the explicit connection between the curriculum and activities taking place in the spaces to engineering course content; (2) in operation for more than a year; (3) student access to a variety of equipment and materials that support prototyping; and (4) a physical infrastructure able to support engagement of engineering education courses of 20 or more students. We classified the sites according to Wilcyznsky and Hoover's [18] attribution classification model for academic makerspaces based on accessibility, footprint, scope, management, and staff. See Table 2 for a summary of the site details. It should be noted that there were no sites in the Northeast or South. This was not intentional and was based on universities that the original research team had access to. There should be no inferences or conclusions drawn from the lack of these sites.

Table 2. Classification of the six makerspace sites, according to [16].

Site No.	Location	Accessibility	Footprint	Scope	Management and Staff
1	West	Restricted to individuals of a sponsor department	5000–20,000 sq.ft.	Grassroots and initial efforts	Faculty/Professionally managed with a hybrid (professional and students) staff
2	Midwest	Restricted to individuals of a sponsor department	>20,000 sq.ft.	Support at least one university mission	Faculty/Professionally managed with a hybrid (professional and students) staff
3	West	Restricted to individuals of a sponsor department	5000–20,000 sq.ft.	Support at least one university mission	Faculty/Professionally managed with a hybrid (professional and students) staff
4	Southwest	Restricted to individuals of a specific school/college	>20,000 sq.ft.	Support at least one university mission	Faculty/Professionally managed with a hybrid (professional and students) staff

Table 2. *Cont.*

Site No.	Location	Accessibility	Footprint	Scope	Management and Staff
5	Southwest	Restricted to individuals of a specific school/college	5000–20,000 sq.ft.	Grassroots and initial efforts	Faculty/Professionally managed with a hybrid (professional and students) staff
6	West	Restricted to individuals of a specific school/college	>20,000 sq.ft.	Support three university missions	Faculty/Professionally managed with a hybrid (professional and students) staff

5. Data Collection and Analysis

The method of choice for this project was qualitative research. We collected data by observing and interviewing faculty members, space leaders or directors, and staff of six making spaces integrated into the undergraduate engineering education curriculum. These universities were considered to have a high research activity and offered doctoral degree programs. There were at least two site visits to each making space between 2018 and 2019.

We primarily chose to focus our data collection on interviews of faculty and staff because they are the most likely to facilitate opportunities for students to engage in the principles of constructionism through making. The data collection resulted with interviews of 45 faculty members and 29 staff. We scanned the interviews for elements of constructionism learning including the process of knowledge creation and a culture of learning. Through our initial pass of the data, we reduced our sample to 31 interviewees. This reduction was solely based on the replies that included discussion about constructionism—either directly or indirectly. Some of the interview transcriptions were made by a third-party company and verified by the research team prior to analysis. Please note that the faculty and staff are discussing the learning that happens when their students are in these spaces. All of the students are considered adults since they are above the age of 18.

We took an a priori coding method for our analysis (see Table 1). We categorized our coding themes based upon Papert's principles of constructionism [9]: knowledge construction and learning culture and Kafei's descriptions of its sub-components [13]: object construction and debugging (for knowledge construction): teacher as a guide, facilitator of collaboration, and student-centered instruction: and the descriptors previously identified in engineering making spaces [1].

Following our initial coding, a second-round of emergent coding exposed additional themes. As a research team, we discussed additional sub-themes and then conducted a third and final round of coding for the sub-themes. Finally, we collectively and individually examined the coding and discussed the results to ensure that our process was trustworthy. These several rounds of coding helped minimize coding bias because each author comes from vastly different disciplines and expertise. Not all of the authors visited the sites and conducted the interviews, which helped them code in an unbiased and objective manner. Additionally, there were continual and considerable conversations that the authors used as a chance for a triangulation of the data which ensured the findings were sound and bias was minimized.

6. Results and Discussion

6.1. Constructionism Principle: Knowledge Construction

Our findings indicated that the constructionism principle of knowledge construction helped support students translate theory to practice in engineering making spaces. The translation consisted of having students apply a comprehensive understanding of the manufacturing process while additionally being supported during debugging and iterations, both essential in engineering education. Our findings suggested the spaces were effective at promoting student development of collaborative and life-long learning. However, the strategies to accomplish the student engagement in skills happened in multiple ways including teachers serving as guides, assignments designed for collective discovery, student-choice of projects, and the open exploration of personal projects beyond class meetings. Single-student learning is synonymous with independent play by which individuals play by themselves and isolated from others. What we're referring to as collective discovery is more similar to parallel play in which people are working on their own individual projects but physically together so that they can be inspired by others. By being in the same space as others but working on individual projects, students can see and reach for things/ideas that they would not have considered if they worked in isolation. In Table 3, we present the themes and representative responses for each of the subsections, and the frequency of each theme.

Table 3. Coding for constructionism principles in the making spaces.

Constructionism Principle: Knowledge Construction [6]			
Sub-Principle of Constructionism [13]	**Sub-Code [1]**	**Description**	**Code Count**
Object Construction	Learning and Applying Manufacturing Process	Students gained an understanding of the tools and equipment needed to create a physical prototype (3D Printing, Machining, Laser cutting)	80
	Translating Theory to Practice	Students apply the theoretical knowledge gained in class to the construction of a physical object	24
		Total	104
Constructionist Principle	Sub Code	Description	Code Count
Debugging	Iterative Nature of Design	Refers to the iterative nature of problem-solving and troubleshooting that occurs in designing and constructing objects	34
	Design for Manufacture	Students understood the design skills needed to create a product that is manufacturable (tolerancing, drawing skills, selection of fasteners)	13
	Fail-Forward	Refers to a culture created in these spaces that take into consideration safety but also encourage a student to try something and learn for themselves	8
		Total	45

6.2. Object Construction

Our analysis exposed the practice of creating objects as being central to and for students' knowledge construction. By producing tangible objects, students were able to familiarize themselves with the needed tools and equipment for manufacturing. Object creation required the students to visualize a product, from creative inception to the sharing of the final product. The process is pivotal for engineering student development and understanding, which requires knowledge application and transfer resulting in enhanced learning engagement. Thus, the leaders in the spaces (faculty and staff) were creating and facilitating learning opportunities that required the students to apply manufacturing processes and translate theory to practice. The leaders achieved their goal of engaging students in constructionism learning opportunities to understand more readily *what* it takes to create a product and *how* to create products applying equations and theoretical concepts. For example, the following two quotes provide insight into how constructionism was used for problem solving and theory to practice (it is important to note that the bolded sections are to show direct alignment with the theme):

> *(interviewee): so in this class it is kind of like you know more about like kind of* ***going into depth you know in the calculations, but then actually building something.*** *(Interviewer)****: so it is both theoretical and applied****, in a very kind of unique way. (Interviewee): yeah where you know there* ***a lot of skills in translating theory into a device into an object*** *so that is kind of more of what I focus on.* (Area Manager)

> *Yeah. So I think the motivation I guess is that they can create something.* ***We're trying to get them to build something and to sort of feel some ownership*** *over okay, what is the problem and identifying their own problem which I think is maybe the hardest part for freshmen, so we're really working hard on trying to get that right*. (Instructor)

Our findings reflect object construction as a culminating experience for student users, rather than as opportunities for early exploration, brainstorming, design ideation, or iteration. Additionally, these makerspaces are tailoring the use of the space to how the curriculum is designed. With that, the artifact that is created is as much, if not more, an artifact of the curriculum rather than of the user and space. The learning (and subsequently, the evidence of the curriculum) is in the processes, not simply the final product. This is an important distinction when considering the academic engineering culture, which should focus on helping society and/or people rather than producing products simply for production's sake. This type of (over)emphasis on prototyping in a vacuum as the end goal does a disservice to novice engineers *and* society.

Associated with our finding was little evidence of using constructionism for debugging, particularly the failure positive sub-code. Together, the findings suggest that the six-engineering education making spaces are being supported to attend to the primary motivations of the students as they engage as budding engineering trainees new to the design process [19]. Objects-to-think-with, as Papert suggests [20], are not necessarily fixated but evolving as knowledge is "formed and transformed within specific contexts, shaped and expressed through different media, and processed in different people's minds" (p. 8, [12]). One aspect that was unclear from our findings was if students demonstrated preferences over one representation or medium during their object construction process (e.g., 3-D printing, solid modeling, algorithms, and codes, etc.). We can infer from the following quotes, that most likely students perceived 3-D printing as a preferred approach to object construction although additional investigation of these mediums are warranted:

> *They* ***[the students] become very discouraged when they're not given the opportunity to make things****. In the past, we didn't have them making stuff until close to their time for graduation. That becomes a frustration to them at times. But, once we offered the opportunity to actually start to make something and be able to hold something physical in their hands, then they become excited again. So,* ***they can kind of understand that perhaps they really are learning to do certain things, and they're having fun as opposed to trying to figure out why they have to do this mathematical modeling for this digital model or something like that****. They can actually see the physical models that produce and find out whether or not the modeling that they've done to try to* ***predict and respond to what they create actually matches what they've created.*** (Instructor)

> *I think that students get lulled into* ***the perception that they can 3D print just about anything*** *without realizing that the tolerances that are involved, the volumes that are involved, and even the strength of the material that's involved is not catered to many types of products. It's really good to see what a particular part might look like, how it might function, how it might fit into other parts. But,* ***overall, the 3D printed parts have still fairly low fidelity as opposed to using machine metal parts.*** *They have relatively low strength. In certain circumstances, they're slower to produce than anything, just machining a part.* (Instructor)

For those students that engaged in a fail-forward approach, it appears that knowledge construction was strengthened by leaders assisting them to situate their learning, an important component of constructionism [9]. Fail-forward cultures ensures that all students can safely share their perspectives and participate without the fear of failure; also, infrastructure and supports are afforded so that students can safely make mistakes and learn from them [21,22]. Thus, space leaders can enhance student learning opportunities by creating a fail-forward culture, focused on the process rather than product—a condition that is fundamental to constructionism for learning. As is noted in the following quotes, some leaders recognize the importance of a fail-forward culture to enhance opportunities for student learning:

> *They only appear when you start to form actual physical models. The experience actually becomes ingrained in the engineer, it's almost, Ah Ha,* ***this has become a problem before in the past when I built this model, this happened, it was unexpected****. Now, when I build my next model,* ***when I go to my next product, or something like that, okay, this is something I do have to consider because I knew this was a problem before in the past****. It's likely to become a problem again in the future.* (Instructor)

> *And so these kinds of activities, and coming in here and going through the process of,* ***"I built it as designed and it doesn't work, so scrap it, start over." I think that's really important for them to get used to, just because everybody's got to fail and I'd rather they fail in here where they can throw away their cardboard and start over****.* (Instructional tech)

7. Constructionism Principle: Learning Culture

Our findings suggest the constructionism principle of learning culture, while in engineering education making spaces, can afford guided experiences for learning about engineering. However, there are areas that require more intentionality to ensure students fully benefit from constructionism. Centering the premise, constructionism learning cultures prioritize students' choice and need by shifting teachers to facilitators of learning [23]. Considering our data from a perspective of constructionism-based learning cultures, we examined the data to determine how space leaders were using the facilities to create intentional opportunities for student learning. Specifically, the research team sought evidence of how the leaders supported student learning of the theoretical, practical, and interpersonal skills of engineers through constructivist methods. A summary of our findings is found in Table 4.

If space leaders are not effective, making spaces can be intimidating to engineering students, particularly those with nondominant identities. However, if space leaders provide opportunities for students to express their knowledge and experiences to their process of learning, students can deepen their learning [9,12]. Student-centered instructional approaches in the spaces increase student motivation to explore new ideas, increase opportunities for students to develop new knowledge, and ignite a journey by which making becomes an epistemology [9,12]. Papert's learning theory of constructionism [9] states that learning leaders should create opportunities for students to experience alternative epistemologies encouraged by constructionism because object construction via "concrete thinking is no less important than figuring out things 'in the head'" (p. 9, [12]). The following quotes reflect efforts by leaders to offer making as a way of learning and developing knowledge for their students:

> *And I* ***had mentors, other professors that were teaching me their ways****. And so I'm trying to bring in a little bit more of... I don't know what the technical term is but just* ***basically creating an environment by which you're guided****...* (Instructor)

> *I think that* ***the good thing is that when students are struggling and they are in a Makerspace, there's always like a community around them that can support them****. Whether that is staff or other students working on their assignment or whether it's me the instructor or my teaching assistant* (Instructor)

> *I would say their excitement and learning the material. How they approach it for me,* ***I like seeing that different students approach a problem differently****. So,* ***I try not to***

> ***force them to go down one certain path, to think the same way I think because maybe I don't think the best way****...* (Instructor)
>
> *Even if the student doesn't look like they're struggling,* ***just to walk up and say, "Hey, how are you? What are you working on?" To show that we're involved and that we care about what they're doing****...* (ResEdSpecialist)

Table 4. Constructionism supporting principle of learning engineering knowledge.

Constructionism Principle: Learning Culture [13]			
Principle	**Sub Code**	**Description**	**Code Count**
Learning Culture	Teacher as a Guide	Guided inquiry used to help students think critically about the design project they are seeking to complete.	25
	Differentiation	Information is tailored to a students' prior knowledge and previous application of learned material.	10
	Staff Approachability	Refers to the approachable nature of faculty and staff, which support students within the space and the nature of interactions between students and staff.	9
	Mentoring	Staff provides feedback, support, or encouragement to students in an informal context.	32
		Total	**76**
Principle	Sub Code	Description	Code Count
Collaborative	Collaborative Spaces	The space is arranged so that students are comfortable being in, both individually and in groups.	65
	Collective Discovery	Students learn by being in a space where others (faculty, students, & staff) are doing interesting things rather than working in isolation. The culture of this space encourages asking what people are working on.	56
		Total	**121**
Principle	Sub Code	Description	Code Count
Student-Centered	Student Choice	Students are allowed to explore projects of their own choosing.	32
	Personal Projects	Personal projects are non-school related projects done by students in their free time.	30
	Life-Long Learning	Students are encouraged to engage in continuous knowledge development.	23
	Self-directed mindset	The way students view challenges, not as obstacles, but rather as processes that take time, effort, responsibility, and persistence to meet said learning goal. The challenge can be of intellectual nature but is not limited to just the cognitive side of the challenge (e.g., emotional, physical, etc.)	19
	Total		**75**

Our findings highlight the importance that space leaders place on a culture and environment of mentoring within engineering education making spaces—one where staff and faculty are ready to support students through formal and informal communication. These forms of communication were facilitated through collaborating in the creation of products, which can act as a point of reference for said communication [9] and have the potential in improving student outcomes [24,25]. Knowledge development via student object construction transcends the individual through idea exchanges in which norms and professional practices are shared and facilitated by mentoring. The creation of objects has the potential to (although not consequential) to support learners in connecting experience with knowledge [12].

We found that the space leaders tended to focus on making spaces to support a culture of belonging [8] and accommodate physical infrastructures for students so that they can create new knowledge. We recognize each person has a different journey to their knowledge formation and different starting points in this journey [9]. Thus, a constructionism approach may allow space leaders to engage at a level in which students are prepared to learn. Furthermore, allowing students to genuinely form their knowledge in ways that are authentic to them and others [26,27], allows them to form knowledge as with constructionism. To truly consider everyone's forms of knowledge [27], boundaries of these affordances must be leveraged by space leaders [15] so that "convictions break down... alternative views sink in... adjusting, stretching, and expanding... [a] current view of the world" (p. 9, [12]).

8. Constructionism Principle: Collaboration

Space leaders fostering collaboration in making spaces was highlighted several times in the data. Making spaces can be used to teach engineering communication skills. Engineering students need to develop an understanding of the importance that effective communication has with clients, managers, machinists, and society at large. Leaders who leverage making spaces to promote collaboration, foster student development to think as a team, process information, and produce prototypes for collective discovery and problem-solving allow space for these skills. Furthermore, leaders are responsible for considering the connectedness that is created through collaborative exploration in which individuals can witness that thinking processes often lead to creating novel products. When considering the use of making spaces for the education of future engineers, leaders should consider opportunities for collaboration. The following quotes reflect space leaders' consideration of the use of making space activities as opportunities for developing students' understanding of the importance of collaboration and using the spaces to support students' development of collaboration skills:

> *Well I think the* ***very nature of the class really is why it was created, in order to support and generate and create an atmosphere of collaborative learning and thinking, and experiencing together****. I think the thesis of the class, it is that. All the components of it, without overstating it, are for that.* (Instructor)

> *It's always a team sport. It's like playing soccer, it's like playing basketball, or all sorts of team-based sports.* ***You need to know how to pass the ball and trust your teammates as much as you trust your own gut****. So ideally this is the goal, is they have their own depth, but they're also able to connect with other players as well, so that they would form a team to tackle some really wicked problems, like climate change or inequality in the world, or hunger and starvation, and all sorts of weird things in the world.* (Instructor)

> *So, it's just not the one on one either, the individual student and machine producing what the student wants,* ***it's the opportunity to actually participate in a community to be exposed to an environment to see what other people are doing, what other ideas are being generated, what other types of structures or products are being produced****. And that, I think, is a really helps the creative side.* (Instructor)

Student-Centered

Our findings suggest that among engineering education making spaces, students were afforded the opportunity to select and participate in personal projects as well as choose the topics of their projects. These experiences allowed students to connect with their projects, ideas, and objects more meaningfully; in that connectedness, knowledge was formed *and* transformed within specific contexts and processed in different people's minds [9]. At the same time, these personalized topics allowed students to situate their learning within the real world and position the context of their topics to the society they live in. It is at that intersection of the personal and the academic, that students may become "situated, connected, and sensitive to variations in the environment" (p. 8, [12]). Other avenues to explore for future research include the ways that real-world applications are principles of project-based learning.

> *One of the reasons* ***I leave that final project open ended for them is because I found that the freedom for them to just design something, to incorporate the design that most of them want to do is really empowering****. They get to not just have to do a series of exercises, but they learn some stuff and then say, "Oh, how can I apply this to a real world?"* (Instructor)

> *And then* ***in terms of projects, I've also seen a lot of hobby projects****. And again, this is something that's still working out in my mind, but I've feel this disconnect between hobby and academics. And so as I'm interviewing students, as I'm observing, it's either, this is just a hobby, this is just for fun and this is for academics. And I think maybe that's a good thing, right? Like maybe* ***it's a good thing that students are creating like this identity around what they do for fun and what they do for school****. But now that, especially with this location where it's meshed into student life, how does that incorporate,* ***where does the line become drawn between your personal life and your academics****, but then also in terms of first year experience and in terms of senior capstone and thinking about engineers,* ***ideally you're blending the two in some way that feels productive and synergistic.*** (Instructor)

The sub-code for self-directed mindset was the least coded in the category of collaboration and may suggest an area to focus on for leaders of engineering education making spaces. Self-directed mindsets involve the way that students view challenges, not as obstacles but rather as processes that take time, commitment, effort, and attention. These challenges can be both intellectual and emotional in that individuals can simultaneously express ideas that shape and sharpen how they communicate with others about problems and how they persist the challenges. Thus, self-directed mindsets involve an iterative process where learners create for themselves "the tools and mediations that best support the exploration of what they care about the most" (p. 4, [12]). Evidence of learning leaders' creation of opportunities to develop and express self-directed mindsets within making spaces is evident in the following quote:

> *I think that they do not know when they are picking the projects that this is good, you know that this is going to be successful. Part of the process that they go through once they pick the project is doing really extensive background research and I* ***think a lot of times they become disillusioned because they realize the weaknesses and the things that the sponsor missed, and so I think that you know then they become a little disappointed and jaded, but I think it is also real-world experience****.* (Area Manager)

We recognized life-long learning as a subcode in the domain of collaboration realizing the effort needed to achieve learning and application for knowledge to create products through constructivism requires multiple supports. Iterations in designs and experiences with product failure support the development of students thinking as engineers. Life-long learning is a critical skill in engineering (and other professional disciplines) and requires students preparing to be engineers to be aware of, and exposed to, the skills required to be professionally successful as an engineer. Using the context of making spaces to support engineering education, leaders should create opportunities to connect student learning to professional of engineering. Additional efforts are needed by space leaders to leverage the constructionism focused engineering education opportunities that can take place in making spaces to attend to the need to foster student life-long learning development.

9. Implications

Within the consideration of our findings in the context of Papert's constructionism principles [9], there is little to no evidence that engineering education leaders are using the academic making spaces to provide students with opportunities based on principles of constructionism. The education leaders are leveraging engineering education curriculum and making activities to provide students with opportunities to collaborate, to choose, to discover, gain understanding of the profession of engineering, but all these are based on anecdotal experiences with little connection to evidenced-based pedagogical or learning practices. Our findings revealed the need to delve deeper into the use of engineering making spaces to support curriculum integration. These areas of need include focusing on the use of the spaces to support differentiated learning opportunities, staff and student collaboration, and self-directed learning mindsets. Furthermore, learning leaders need to provide students with opportunities to use making spaces to situate their prior learning and apply their engineering related content from their classes. However, these situated learning experiences cannot occur unless students are given the opportunity to authentically connect the knowledge they are learning in class with their personal experiences or experiences connected to situations outside of school. Thus, there would likely be great learning benefits for undergraduate engineering education students if their faculty members leveraged making spaces to engage the students in constructionist aligned learning and making opportunities.

Staff approachability influences students' comfort level in sharing ideas and knowledge, thus, staff need to convey a welcoming and supportive environment to encourage student engagement and belonging [8], which is particularly critical in a constructionism culture. New environments can be intimidating to students and early exposure without proper scaffolding experiences may hinder users from participating fully in the making spaces. Positive interactions between students and making space staff, leaders, and faculty members may minimize student hesitations with entering and working within the spaces. We argue that for instructors who ask students to make use of these making spaces, to be more intentional in facilitating exposure to, and interactions within making spaces throughout a semester. Furthermore, instructors could consider bringing space-staff to the classrooms so that when students use the making space, they can see a familiar face and have a greater sense of what to expect when working in the spaces.

10. Concluding Thoughts and Recommendations

Space leaders can benefit students by fostering their development of self-directed and process-oriented mindsets to support their willingness to interact with tools and equipment to explore interests and develop passions for learning and engineering. One way to guide students toward a more self-directed mindset is by creating a culture where students are encouraged to chase and explore things they are curious about with available low cost and safe rapid prototyping technology, and the freedom to explore. Thus, making space leaders can further support student engagement in constructionism-based learning by finding ways for students to explore possibilities and solutions and looking for ways to provide more access for community buildings which shifts the common focus away from the individual or isolated learning [28].

Our research team has provided several evidence-based possibilities for space leaders to build upon to support student engagement in constructionism focused learning (see Table 5). Our ideas are aligned with the constructionism principles, which have been documented to support student knowledge acquisition and transformational learning [9,12]. However, we also provide words of caution to readers that the ideas presented in Table 5 are not exhaustive and should be catalysts for tailored initiative and not be interpreted prescriptively. We embrace the position that constructionism centers on *context*, *situated learning*, and *connectedness* to the objects created [9]. We finally acknowledge the constructionism principles we have explored may not be transferrable to other engineering education making spaces as resources, classifications, and approaches may vary depending on resources and leader experiences.

Table 5. Baseline suggestions for using engineering education making spaces to support constructionism.

Principle	Sub Code	Suggestions for Potential Activities
Learning Culture	Differentiation	• ***3-tiered peer-to-peer learning approach (beginner/intermediate/expert).*** This approach could serve as a way to provide differentiation to students. A system like this could be achieved by, in essence, each student having a tutoring "buddy" in which they discuss the current sticky points of their learning. The peer-to-peer system has mutual benefit: the student in need of help gains knowledge and becomes unstuck with whatever complex issue might be at hand, and the tutor-student begins to better understand and articulate particular issues within their discipline. This continues the practice of humanizing pedagogy [14] where teachers are students and students are teachers. For this, you create activities with varying levels of difficulty to allow students to self-select which tier they feel most comfortable with. Tap your experienced students to be the lead and incentivize their efforts with extra credit.
	Staff Approachability	• ***Diversify.*** Diversify your staff. Not simply on identity, but also discipline. Allow those entering the space to identify that they are not the only ones who might be new. This promotes buy-in from your students and permits them the ability to mess up. • ***Professional development.*** Regular professional development for the staff centered around effective communication, which benefits the spaces they currently operate along with provide them invaluable skills for the world beyond college. • ***Regular staff introductions.*** Consider bringing a staff or worker to your classroom and have them share a bit about their experiences and why they work in making spaces. Coordinate a follow-up tour of the making space with these staff members. • ***Familiar faces.*** Source out student-workers to participate in the classroom as potential TAs. This allows students that potentially enter these spaces to become more familiar with the staff. An example of this would be student-workers being called into a classroom to give a 30 min tutorial. Then, these same students visit the makerspace said student-workers are working and they automatically have a rapport, which could ultimately allow the student to feel more comfortable in their discomfort of being in a new space.
Student-Centered	Self-directed mindset	• ***Repurposing/refurbishing Jamboree.*** By taking old equipment that is soon-to-be discarded, or already broken equipment, create a contest to refurbish and/or repurpose said equipment. By doing this, students can flex their ability to take old and make new. • ***Jigsaw puzzle problem-solving contest.*** Propose a problem to be solved to a few sets of student teams. Allow them to identify solutions. Then, have them implement their solutions. However, they must switch their workstations and pick up where a different team left off. Both ideas allow students to work on several different kinds of equipment that they might not have picked themselves. With this kind of exposure, students might find a knack they did not know they had. • ***Choose your own adventure.*** Students have the option of choosing three of six makerspace trainings that are most interesting to them. These are then used to fulfill a graded assignment. This allows for more student-centered, student-directed learning that allows the students to have ownership of their education and learning.

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