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Beyond Making: Application of Constructionist Learning Principles in Engineering Prototyping Centers

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Beyond Making: Knowledge Construction and Learning Culture in Engineering Prototyping Centers

Abstract

The creation of student-centered spaces for making and prototyping continues to be a growing trend in higher education. These spaces are especially relevant in engineering education as they provide opportunities for engineering students to engage in authentic and collaborative problem-solving activities that can develop students' 21st-century skills [1–3]. Principles of constructionist learning theory, which promote knowledge creation through development of a physical product [4,5], may be applied to support learning within these spaces. Beyond the construction of objects, this learning theory emphasizes a learning culture where teachers serve as guides to collaborative and student-driven learning [6]. This research seeks to understand how constructionism's learning principles are integrated into an engineering prototyping center (EPC) at a large western university. Further, we explore how these principles may support engineering student development within these spaces and identify a qualitative coding scheme for future research. Thematic analysis of semi-structured interviews with faculty, staff, and students involved with the EPC suggests that the construction of physical prototypes within this space allows for the translation of abstract concepts to concrete experiences and the development of iterative design skills. Further, the data suggests that staff play an essential role in creating a learning culture aligned with constructionist learning principles. This culture supports staff in guiding student learning, fostering a collaborative environment, and promoting students' life-long learning skills. Data collected within this exploratory study suggest that constructionism's learning principles can play a central role in supporting the development of engineering students in an EPC.

Keywords: Constructionism, Prototyping Centers, Makerspaces, Engineering Education

Introduction:

Recent shifts in engineering education have called for a greater focus on developing design skills and opportunities for students to apply technical and professional knowledge to authentic problems [7,8]. The shifts reflect the growing need for an engineering workforce prepared to address the increasingly complex and interconnected problems that engineers will face in the 21st century [9,10]. The growth in the number of first-year project-based undergraduate engineering courses and senior capstone design courses [11,12] provide opportunities to prepare engineering students with progressive knowledge of engineering. In these courses, students engage in authentic project-based learning activities designed to support their professional engineering skill development and increase their capacity for effective communication and problem solving [1,11].

In conjunction with curricular shifts and the decreasing cost of rapid prototyping technologies, many engineering schools have adopted and embraced spaces for making – or "makerspaces" [13]. Wilczynski highlights this shift as follows:

> Universities have always provided elements of the now popular makerspaces, including machine shops, assembly/testing areas, CAD labs, meeting spaces, and classrooms. What universities have not always done is include all of these elements in one location and make the resulting space widely accessible to an academically diverse campus population. [8, p. 2-3]

Within engineering education, makerspaces take on many forms, yet, the spaces are commonly designed to provide opportunities for students to work collaboratively on the design and creation of physical models or prototypes. Barrett et al. report that in 2015, 40 of the top 127 engineering schools were promoting spaces for making and access to rapid prototyping technologies (RPT) on their campuses [13]. In these spaces, engineering students can access RPT such as 3D printers, laser-cutters, and electronics equipment, which can help enhance engagement in active learning and refine engineering competencies [8,13,14,15]. When students engage in authentic project-based learning activities within the spaces, they can learn and apply critical professional engineering skills such as communication and problem-solving [2,8]. For this research, we refer to makerspaces as Engineering Prototyping Centers or EPCs which we argue is a more accurate descriptor of the spaces when associated with engineering education [18].

The increased access and use of prototyping centers, makerspaces, and fabrication labs for learning in K-12 education, community centers, and universities has motivated research to document and explain how EPCs can be effectively used to support STEM education particularly engineering [5,16]. Preliminary research on EPCs focused on the infrastructure of the spaces including the tools, equipment, and staffing needed to successfully implement them [8,13]. The research expanded to explore how the spaces use could support the development of Accreditation Board for Engineering and Technology (ABET) competencies, suggesting that engaging students in "making" can help support communication and life-long learning skills [2]. More current research has focused on understanding the learning process and outcomes that occur in these spaces, including how engagement with these spaces can support creativity, self-efficacy, and other 21st century skills [1,17–20]. Work by Longo and colleagues suggests that incorporating these spaces into engineering can "increases diversity, access, and retention and to a lesser extent improves grades and classroom performance " [3, p.1]. The researchers studying learning in the spaces have determined that the integration of spaces into engineering preparation programs for making can have a positive impact on learning outcomes and student experiences in engineering education.

Constructionism is widely regarded as the theory for explaining learning in makerspaces, [21,22] particularly for framing student learning in the uses of these spaces [23–26]. Within engineering education, constructionist learning theory has been proposed as a framework for engaging students in authentic problem-based design learning [27,28]. The application of constructionist approaches in a design studio course was found to increase student learning and psychomotor skills [29]. Additional constructionist learning principles may be used to support engineering education in model-based and virtual learning environments [30,31].

However, within the engineering education community, limited work has been done to explore makerspaces through the lenses of learning sciences concepts [32]. Implementation of EPCs within engineering programs has created an opportunity for educators to expand teaching methods and learning opportunities used in the field. This research explores the constructionist learning principles that can be identified within makerspaces and EPCs. Further, the research provides a qualitative coding framework that will support future investigation of constructionist learning principles within engineering education spaces for making. With a growing number of these spaces being incorporated into university-based engineering programs, it is important to consider how these spaces support engineering curriculum and how constructionist learning principles can further support learning in these spaces. Understanding the presence of constructionist principles can provide evaluative support for the benefits of constructionism, a void that would support arguments for more evidence-based, experiential, and hands-on experiences in engineering.

Theoretical Framework: Constructionism

Constructionist learning theory was popularized by Seymour Papert in the late 1980s. Building on Piaget's theory of constructivism, Papert sought to illuminate the type of learning that occurs, specifically, when individuals engage in the construction of an object to be shared with the community. Papert and Harel compare constructionism and constructivism in the following way:

> Constructionism—[…] --shares constructivism's connotation of learning as "building knowledge structures" irrespective of the circumstances of the learning. It then adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sandcastle on the beach or a theory of the universe. [33 p. 1]

While both constructivism and constructionism both conceptualize learning through knowledge building, there are a few key elements that differentiate them. Piaget's theory of constructivism is a developmental model in which students construct their knowledge through interactions with the world, people, and things [34]. Papert's model of constructionism is more situational and involves obvious physical representations of individuals' cognition, suggesting tangible elements of an instructional model to be applied in an educational setting [35]. Papert's model focuses more on the ways in which technology and media may be used to facilitate student learning choices and promote life-long learning [34]. Two essential components of the constructionist learning theory are further explored below.

These two essential principles of the learning theory are identified by Kafi [6] as : (a) knowledge construction and (b) learning culture. Elements of these components are highlighted in Figure 1.

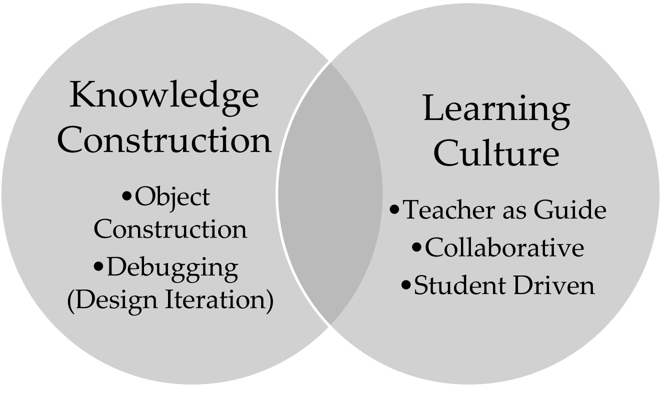

Figure 1: Elements of the Constructionist Learning Theory

2.1 Knowledge Construction

Knowledge construction happens as individuals create an object or artifact. Papert describes these as “objects to think with,” connoting that the creation of physical (or virtual) objects allows for the abstract to become more concrete [6,29]. As the use of computer technologies increased in classroom settings, Papert sought to engage students in learning through the development of computer programs whose goal was to move an object (in this case a turtle) around the screen. In constructing these programs, students developed their programming skills and applied mathematical concepts in the form of angles and geometric shapes, which deepened students’ learning through the iterative process of debugging the program [6].

Developing knowledge through doing and creating is especially relevant for engineering students as they translate theoretical principles to concrete experiences by designing and building prototypes. Further, the construction of prototypes involves an iterative process of troubleshooting and debugging, both problem-solving strategies that can lead to deeper learning [6,29,30]. Research on design practices within engineering education suggests that troubleshooting and debugging as problem-solving strategies in design iteration are essential to learning engineering processes [36,37].

It is important to note that while the constructionist learning model may be frequently associated with computer applications or programming languages, Papert maintains constructionism should not be technocentric [33]. Thus, constructionism is not predicated on a specific technology, but rather that learning can occur through the construction of artifacts using technology [34]. This can be especially important as we explore constructionism in prototyping centers, which do not always share the same technologies or equipment, but always afford students the opportunity to engage in the construction of an object or artifact.

2.1 Learning Culture

Kafi highlights learning culture as a second essential component of constructionism arguing that the environment for learning is as important as the mode for learning [6]. We claim there are three elements of the constructionist learning culture that are relevant to learning in EPCs. First, there is the shift from the traditional “instructionist” model, where the teacher delivers knowledge in a didactic lecture style. Instead, the teacher serves as a guide or mentor for student learning, providing resources, guidance, and support as needed by the student [33]. Central to instructors acting as learning guides is the process of facilitating student learning without providing direct instruction, which is reflective of constructionist learning [8,27].

Second, Kafi highlights that the constructionist learning culture is collaborative, allowing community members to introduce each other to new activities and share their expertise [6]. Students are encouraged to learn with other students as well as with other groups or staff [36]. Collaborative learning is strongly reflected in the maker-movement, which promotes a culture in which peer-to-peer learning is encouraged, and all members of the community are expected to contribute [15].

Finally, the constructionist learning culture shifts focus from knowledge to knowing, emphasizing the process of learning, rather than the specific knowledge.

> "[It] reminds us that learning, especially today, is much less about acquiring information or submitting to other people's ideas or values, than it is about putting one's own words to the world, or finding one's own voice, and exchanging our ideas with others."[34, p 2]

The shift in perspective to constructionist principles allows for student-centered learning and provides greater flexibility in the curriculum for increased motivation through student choice [32]. Papert suggests that the constructionist learning model allows students to drive their own learning [38]. Further, the learning model emphasizes the importance of learning how to learn, a meta-skill that is increasingly important with the rapid change of technology and the need for engineers to be prepared for life-long learning [39]. However, how these constructionist principles are evidence in different learning context within engineering is unknow. This exploratory study sought to assess how constructionist principles are evidenced in an EPC. Identifying its presences may further ignite future conversation and studies to understand how these principles can support the development of engineering students.

Research Design

This qualitative exploratory study is part of a larger mixed-methods collective case study design intended to understand the role of university-based makerspaces and prototyping centers as they are integrated into the engineering curriculum and their impact. This study is supported by NSF Grant # EEC- 1664272 and includes a total of six spaces. These spaces were selected for their diverse representation of spaces that support collaboration, project-based learning, and prototype construction within undergraduate engineering programs. To select these spaces several databases of makerspaces in higher education and within colleges of engineering were consulted including two websites (http://make.xsead.cmu.edu/ & https://hemi.mit.edu/higher-education-makerspaces-initiative-hemi) and a 2015 review of makerspaces in engineering programs [13]. Through this process, seventeen academic makerspaces or prototyping centers were identified. These spaces were specifically identified based on the following criteria:

1. Space must be used in support of academic curriculum in a college of engineering and have been in operation longer than a year
2. Space must include a variety of equipment (beyond 3D printers) and materials to support prototyping
3. Space must be large enough to support a project-based engineering course or 20 or more students at a time

These spaces were further evaluated and narrowed down to six sites based on their use by engineering faculty (integrated into the curriculum), their length of establishment (more than one year), their equipment (rapid prototyping, woodworking, and electronics), and student accessibility (open to engineering students). After potential sites were identified, the research team reached out to each site's director to arrange on-site visits to collect interview data from students, faculty, and staff. Once the group of sites were selected members of the research team were assigned to specific locations based on travel feasibility and willingness of the center to allow a visit from the research team. Visits to these sites took place between 2018 and 2020.

Site Description

This study will focus on one of these cases, a site at a mountain West institution in the United States. This particular case was selected because, its supports senior capstone projects along with a junior level component manufacturing course, in addition to several sections of the introductory engineering design course. We opted to define this particular site as an engineering prototyping center (EPC) based upon interactions with the staff and directors of the space who preferred the omission of the term “makerspace” due to their intentional culture of engineering professionalism and focus on preparing students to be workplace ready.

As a resource within the engineering curriculum this EPC is critical in supporting the project-based nature of the school’s senior capstone design course, junior manufacturing design, and first-year project courses. Each of these courses were designed around involving students in collaborative project-based learning that requires them to define the problem and construct a physical prototype to be shared with their peers, faculty, and in some cases, clients. For example, as part of the senior design course, students were working on projects such as a prototype airlock system to be used for testing or a balance board developed to prevent injuries in the NBA. Each of the senior design teams has a dedicated space within the senior design lab and the course utilizes the common areas of the prototyping center as a classroom meeting and lecture space.

The EPC also provided the tools and equipment needed for component fabrication and assembly within the junior component design course. This course is intended to familiarize students with the materials and equipment they may need to use to complete their senior design projects. The EPC also houses two sections of the introductory engineering projects course. This course utilizes the workshops and projects to introduce students to prototyping. At the beginning of the course, these projects are designed as building-blocks to support the development of critical skills, while at the end of the semester they shift to open-ended projects which center around each group’s interests.

Instructors at this site expressed the importance of this space in supporting integration of project-based learning into the curriculum:

> *Without this space, what we do in the class and the type of projects that the students can achieve is absolutely not possible. They have access to a machine shop for metalworking, and for plastics, for welding. For the Makerspace, they can also do plastics, they can do wood, the Electronic Shop, without these resources, they would not be able to do these things. April-18-7-Instructor 2*

In addition to providing support for the courses, the EPC also provides workshops on specific equipment or skills such as 3D Printing, CAD modeling, or wood working. A student may decide to get involved with these workshops individually, allowing them access to the space and equipment, or faculty may choose to integrate these workshops within their coursework. Currently, the majority of projects within the space are related to coursework, however, there is the opportunity for the student to use the space and associated resources to develop personal projects.

In summary, this case focuses on the space that includes a prototyping center with woodworking and machine shops, rapid prototyping equipment, an electronics lab, and open collaborative spaces to support design projects. This space represents the components associated with academic makerspaces and engineering prototyping centers including access to rapid prototyping technologies and the space to work collaboratively on teams.

Research Questions

In investigating the data collected with this particular case, the research team sought to explore the following research questions:

1. RQ 1: How do engineering students, staff, and faculty describe knowledge construction in an engineering prototyping center?
2. RQ 2: How do engineering students, staff, and faculty describe the learning culture in an engineering prototyping center?

Participants

A team of three researchers visited the EPC during the spring semester of 2018. During the day and a half site visit, four observations of the space were conducted along with 15 semi-structured interviews. Participants in this study consisted of the engineering undergraduate students, staff, and engineering faculty affiliated with the EPC. These participants were purposefully selected due to their role or status within the College of Engineering at this institution and their active involvement in the EPC. A summary of the demographic information of participants and their pseudonyms is summarized in Table 1. All participants have been given a generic participant ID to highlight our commitment to the privacy and confidentiality of participants to implement safeguards against unwanted exposures [40].

Table 1. Case Study Participant Demographics

Participant ID	**Role**	**Discipline**	**Gender**	**Race**
Faculty 1	Tenured Faculty	Mechanical	Female	N/A
Faculty 2	Non-Tenured Faculty	Electrical	Female	White
Faculty 3	Non-Tenured Faculty	Mechanical	Female	Asian
Staff 1	Staff	Mechanical	Female	Asian
Staff 2	Staff	Mechanical	Male	White
Staff 3	Staff	Mechanical	Male	White
Staff 4	Staff	Mechanical	Male	N/A
Student 1	Ph.D. Student	Mechanical	Male	White
Student 2	Undergraduate	Mechanical	Male	N/A
Student 3	Undergraduate	Aerospace	Male	N/A
Student 4	Undergraduate	Mechanical	Male	Asian
Student 5	Undergraduate	Civil	Female	White
Student Staff 1	Undergrad Student Staff	Business	Male	N/A
Student Staff 2	Undergrad Student Staff	N/A	Male	N/A
Student Staff 3	Undergrad Student Staff	Technology Arts & Media	Female	Asian

Data Collection and Analysis

Qualitative data was collected in the form of semi-structured interviews, observational protocols, researcher memos, and member-checking sessions. For the purpose of this paper, primary emphasis was be on the interviews and researcher memos. Interview with faculty and staff explored how they supported or interacted with students in the EPC and their perception of how these spaces helped students develop competencies in engineering. Interviews with undergraduate students consisted of asking the students to describe their use of the space and the value they attributed to these spaces in supporting their undergraduate engineering education. A total of 410 minutes of interviews were collected and analyzed.

Interview data from de-identified audio recordings were transcribed using a third-party group (Speechpad). The first author then verified the transcripts for accuracy and made pertinent corrections to include non-verbal cues (e.g., pauses) in the transcription. Coding and memoing occurred primarily amongst the first two authors of the manuscript and a process of intercoder agreement was conducted between the two until a full consensus was achieved. The rest of the authors assisted in the refinement of interview protocols and interpretations and writing of the findings, as needed.

A multistage coding strategy was used to analyze the transcriptions for all fifteen interviews collected during the site visit. The first cycle of coding involved thematic and emergent coding to identify ideas common across the interviews [41]. Categories, sub-categories, and representative quotes for these codes were used to develop a codebook. After reviewing the emergent codes and associated literature on makerspaces, constructionist learning principles were identified as an appropriate theoretical framework for further evaluation of qualitative data.

Subsequently, a theoretical coding approach was used during a transitional cycle to integrate thematic and emergent codes from the first cycle with the constructionist theoretical framework. To do so, the first two authors conducted a review of the literature to identify principles of constructionist learning theory and establish a group of *a priori* codes. These codes are identified in Table 2. After identifying *a priori* codes associated with constructionist learning principles the emergent codes from the first cycle of coding were then refined and aligned with the *a priori* principles of constructionism. During the transitional cycle, the codebook was updated and reorganized, and the second cycle of coding was conducted by the first author and confirmed by the second author using MAXQDA 2018 software.

To support the validity of the analysis an intercoder agreement session was conducted between the first and second author on three of the interviews (1 student, 1 staff, 1 faculty) during the second cycle of coding. While the agreement in the initial iteration was low (less than 40 %) this led to further clarification and refinement of the code definitions. After discussion and clarification of the code definitions, the sample of three interviews was reviewed a second time and the first and second author reached full agreement on the assignment of codes. Following this refinement and reorganization, the codebook was updated, and the first author conducted the third cycle of coding.

Positionality

Authors in this publication consist of a group of engineers, engineering education researchers, science and math educational researchers, and educational psychologists. All are collectively committed to improving the representation in STEM education as well as educational outcomes, both in formal and informal learning environments. The first author of the manuscript has experience with designing, teaching, and working in a makerspace environment in a K-12 educational setting. All authors adhere to the aforementioned theoretical framework and aim to better inform scholars and educators on how constructionism can be used to support learning in EPCs. Recognizing our positionalities also implies that we recognize that our individual lives and professional positions may color the lens that are provided on these findings.

Interpretive Paradigm

This exploratory study is centered in a subjectivist epistemological paradigm. This means that researchers make meaning through their own "cognitive processing of data-informed by their interactions with participants" [41 p. 33]. As a result, knowledge will be socially constructed as a result of the personal experiences and positionalities within the natural settings explored [41].

Results

Analysis of interviews with faculty, staff, and students suggests that EPCs can support the development of engineering students through the knowledge construction and learning culture associated with constructionist learning principles. Participants suggest that access to this space can support the construction of knowledge by providing access to facilities and RPT for students to construct objects. In constructing these objects, students can translate theory to practice, gain a better understanding of prototyping and manufacturing processes, and develop debugging skills through design iteration. Additionally, participants suggest that the learning culture where the staff and faculty serve as guides fosters collaborative learning and supports the development of students' life-long learning skills. In the sections below, we explore how the principles of knowledge construction and learning culture associated with constructionist learning are supported within the EPC and how these principles can support the development of engineering students.

Knoweldge Construction

In our analysis of interviews from faculty, staff, and students, two central themes emerged, which related to the construction of knowledge in the EPC. The theme first suggests that by having access to prototyping equipment, students are able to construct physical objects that facilitate the translation of abstract engineering concepts to concrete experiences and an understanding of manufacturing processes. The second theme suggests that through this object construction, students gain a deeper understanding of the iterative nature of design which requires troubleshooting and debugging. These themes are discussed in further detail in subsequent sections and an overview of occurrences of the parent codes and subcodes is provided in Table 2.

Table 2: Summary of Code Counts for Knowledge Construction

Knowledge Construction			
Constructionist Principle	Sub Code	Description	Code Count
Object Construction	Learning and Applying Manufacturing Process	Students gain an understanding of the tools and equipment needed to create a physical prototype (3D Printing, Machining, Laser cutting)	23
	Translating Theory to Practice	Students apply the theoretical knowledge gained in class to the construction of a physical object	27
	Total		50
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	14
	Design for Manufacture	Students understand the design skills needed to create a product that is manufacturable (tolerancing, drawing skills, selection of fasteners)	12
	Failure Positive	Refers to the failure positive culture created in these spaces that take into consideration safety but also encourage a student to try something and learn for themselves	8
	Total		34

Object Construction

The EPC contained tools and equipment that one would expect to find in a prototyping center including 3D printers, laser-cutters, and woodworking tools. In addition, there was a full machine shop and electronics lab, both of which are supported by professional staff. By having access to these tools, students, faculty, and staff felt that students were able to better understand and apply manufacturing and fabrication processes. The examples below highlight how faculty and staff felt that having access to tools and equipment in the EPC can support student learning and applying manufacturing process.

> *It doesn't matter if they ever touched a tool and run a machine again in their life. The fact that they do so now gets them the exposure so they can actually see the things in action and really become better engineers through understanding how things are made. April-18-6- Staff-4*

In addition to better understanding manufacturing processes, these experiences with prototyping equipment and the creation of objects allows for the translation of abstract concepts to a more concrete understanding of design. In the examples below staff and students highlight how access to the EPC and the construction of physical objects allows for the translation of abstract engineering concepts into concrete understanding.

> *The value of a makerspace for students is that they can practice the concepts of actual engineering. At the university, we focus a lot on the theoretical standpoint of it, but in many*

> *real-world applications, like a job, that is probably not the primary focus. April-18-2-Student-1*
>
> *But just also the technical knowledge that you get [...], the application of the skills that you've been learning in all of your classes. It's the culmination of, "Yes, I learned this in static. Yes, I learned this in dynamics. I'm gonna put those two together plus my physics, plus this, and put everything together in practice," because technical problems are great for practicing a single skill, but very rarely is a real-world situation gonna be the same.. April-18-6- Staff 4*

Through these experiences of object construction, students gained hands-on experience with manufacturing processes and were able to translate their theoretical knowledge from coursework into a physical application. These results are aligned with the promotion of construction of physical objects within constructionist model. Further this suggest that that faculty, students, and staff recognize the value in the knowledge construction through the construction of objects as it allows students to gain an understanding of manufacturing processes and translate abstract concepts into concrete experiences.

Debugging

Further investigation of the qualitative data suggests that students engage in an iterative process of debugging as they work through the physical construction of an object. As students engage in the construction of physical objects, they encounter challenges or issues which must be addressed in order to progress with their design. This process introduces students to the iterative nature of design and the skills needed for troubleshooting or debugging, recognized as an essential principle of constructionism. Staff and student participants in this study suggested that practicing design iteration is necessary in the development of engineering students' design skills.

> *So the students [...] that I feel are most prepared to be successful engineers have had a chance to iterate. They've gone through the design process multiple times. They've struggled through various fabrication problems. I mean, if they're gonna be a mechanical engineer ... they need to design and build stuff. Build things and realize their drawings aren't very good and realize their tolerances don't make sense. That whole process is really enlightening. April-18-3-Staff-2*
>
> *I think they're learning a lot of problem-solving. So, you have to iterate a lot. And students learn how to design up an idea, ask for help, fix their design multiple times, and then finally get to a final product, and I think that's just how the engineering world is. April-18-5-Student-5*

Additionally, the process of object construction helped students understand the intricacies of designing objects for manufacturing as highlighted by faculty below:

> *You need to understand how parts are made by industry so that you can design good parts [...]. They sit down with the machinist, walk through the steps and he teaches them exactly what to do. April-18- Faculty -1*

Furthermore, the faculty and staff emphasized the importance of trial and error in creating a failure-positive environment. This failure positive environment described by faculty below can encourage students to try something and learn for themselves

> *Just generally, I found students who were afraid to do something wrong. You know, that's always the thing, is like people are like, "I'm gonna do it wrong,"? And so trying to get them to not worry about that as much, or to say, "Okay, if you do it wrong, like no big deal. Then we'll just fix it. Or if you break it, it's okay, it's not that expensive,"? April-18-15-Faculty 3*

Responses from students and faculty suggest that the translation of theoretical knowledge into concrete experiences, afforded by the construction of an object, helps prepare engineering students for industry. Along with understanding manufacturing processes, the construction of a physical object allows students to engage in the iterative nature of design and fosters troubleshooting and debugging skills. By integrating principles of constructionist learning including the construction of a physical object and the iterative process of debugging EPCs support engineering student development.

Learning Culture

While the infrastructure of prototyping centers and academic makerspaces has been explored, we are only beginning to understand how the underlying culture in these spaces supports learning[32]. To explore this within the context of constructionism, we explored the principles associated with constructionism's learning culture including the role of the teacher as a guide and collaborative and student-driven learning. In exploring these elements, we found that participants identified the importance of faculty and staff as guides for student learning along with the value of collaborative spaces and a student-centered environment. These themes are summarized in the following sections and the codes and sub-codes are summarized in Table 3 below.

Table 3: Summary of Code Counts for Learning Culture

Learning Culture			
Principle	Sub Code	Description	Code Count
Teacher as Guide	Teacher as Guide	Guided inquiry used to help students think critically about the design project they are seeking to complete	28
	Differentiation	Information is tailored to a students' prior knowledge and previous application of learned material	26
	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	26
	Mentoring	Staff provides feedback, support, or encouragement to students in an informal context	10
	Total		**90**

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	22
	Collective Discovery	Students learn by being in a space where others (faculty, students, & staff) are doing interesting things. The culture of this space encourages asking what people are working on.	9
	Total		**31**
Principle	Sub Code	Description	Code Count
Student-Centered	Student Choice	Students are allowed to explore projects of their own choosing	6
	Personal Projects	Personal projects are non-school related projects done by students in their free time	4
	Life-Long Learning	Students are encouraged to engage in continuous knowledge development.	7
	Growth mindset	The success that comes from the way students confront challenges they come across during the different iterations in projects. It can be a physical or an intellectual challenge.	6
	Total		**23**

Teacher as Guide

Within the prototyping center, each of the lab spaces has at least one dedicated professional staff who has an engineering degree as well as some experience in an industry setting. These individuals share a passion for tinkering and making and seek to develop this passion within students. Additionally, there are several faculty who have integrated the space into their courses and therefore spend time hosting class or office hours there. In reviewing the responses, it is evident that the faculty and staff who support the prototyping center play a central role in creating the culture of the space.

> *All of the above, I think. I think it's important not only, architecturally, the interior design of this place, the use of it, how the tables are laid out, what materials are here, but it also matters what people are here. I think you can very easily have maybe an artificial intelligence or robot here telling you to do things, but if you have somebody else who maybe has done it before and is really pumped and excited about it, you feel that. And you can't help but feel excited. April-18-7-Faculty 2*
>
> *So we have an incredible staff because we're all working together awesome and make it a place where people want to be. Like my student workers, for example, they come in for their shift, and then they'll just stay there the whole day. And they're not even working some days. And they're just hanging out and just want to be in the place. Yeah, it's hard to describe how that, like, came about, but I think it's just the energy here. April-18-4-Staff-3*

Rather than provide direct instruction or specific answers, the faculty and staff serve as guides to direct students towards the necessary resources or ask questions to further engage students. This strategy helps support students to go beyond just absorbing knowledge through direct instruction and instead to seek out the resources they need to be successful on a project. This aligns with the principle of the teacher serving as a guide in constructionist learning.

> *Let's say a student will come to .... the Electronics Shop, "Can I use this part to do this thing?" And he'll say, "I don't know. You figure it out." We also provide them with pointers like, "Oh, you should take a look at the datasheet for this part and make sure that it's compatible with this other part that you're using." But it's the accountability of, they're the engineer, they're the one who is making that final decision. We're not holding their hands the entire time because nobody will do that not only in their education, but in the real world. And so the expectation is that they can do this. So if we expect they can do it, that means that they can expect that they can do it. April-18-7-Instructor 2*

> *So I'm not gonna hold your hand. This is your project. I may give you some advice on where you need to go to look for things, but you need to go find them. You need to Google it. You need to figure it out. I will introduce you to the resources you have available, but you need to figure out how to use them. Not so much…we just call it handhold in here and a lot of our students want their hand to be held until we get them to this, this stage in their career. And all that is how we kind of push them from, "This is your design. You're gonna be out there and you're gonna be the one people are asking questions to in the future." April-18-6- Staff- 4*

In order to support a positive environment while challenging students, it is necessary for the staff to implement differentiated instruction and to be approachable. Differentiated instruction refers to the practice of personalized learning based on a students' skill level, while approachability refers to the openness and willingness of the staff to provide help [4,21] One staff highlights the importance having a positive interaction with students in the quote below:

> *I think there's a lot more opportunity for personalized attention because it's not part of a large class. So I, you know, interact with students individually, for the most part. So there's more of a chance to talk through what they're not getting, and reach a kind of resolution, just because of the nature of the one-on-one aspect. If they're struggling with, [..], engineering identity, like, "I don't feel like I belong here. I'm," you know, imposter syndrome, like just seeing some success in making something and getting to the end can help. April-18-3-Staff -2*

The staff within the EPC are able to create personalized learning at varying levels of difficulty based on an individual's experiences and knowledge level. Additionally, they strive to be approachable so that students have a feeling that they belong within the space. The data suggest that creating differentiated learning and being approachable as a guide to learning is critical to the success of the EPC. This approach reflects the role of a teacher serving as a guide within the constructionist learning principles.

Collaborative Spaces

While the labs and shops house the tools and equipment that are critical for the construction of prototypes, another essential component of the space is the open collaborative areas. In an academic setting, we see this in the collaborative nature of project groups as well the collective discovery which occurs in EPCs. This space is designed for students to gather and collaborate with peers or staff and has an open concept layout that includes large-tables, whiteboards, and the essential outlets handing from the ceiling. These spaces help to foster a sense of cooperation across groups.

> *Well, I think...one thing is, I think it's important for students to work on teams, and this space...there's enough space where students can do that. I think space is a huge thing when it comes to being able to work together as a team, and having conference rooms and, you know, just places to meet, places to gather. Places to bump into people and to, you know, "Oh, hey, what are you working on?" You know? Is big. April-18-3-Staff-1*
>
> *I think it really facilitates working with each other. The proximity of everybody else as well as like the design of like how close the tables are, as well as how they're structured really facilitates teams plus when working with each other to overcome certain obstacles. April-18- Faculty -1*

The open collaborative spaces not only support the collaboration of groups, but also create a feeling of belonging and welcoming within the space. These spaces also serve as a central location for meeting with faculty and for TA's to hold office hours. The collaborative environment of the EPC supports the collaborative learning culture described as part of the constructionist learning principles.

Student-Driven Learning

Finally, faculty and staff emphasized the importance of the space being student-centered and fostering a sense of excitement. This is supported by integrating student choice in the curriculum and through the support of personal projects within the EPC. Engaging in these projects and feeling a sense of success may foster the motivation of students and subsequent success in other areas of their engineering education. the quotes from faculty and staff below highlight the importance of student ownership and excitement around projects as students engage in the EPC.

> *So the idea with the makerspace and idea with some of this hands-on curriculum is you get them that experience early on. And it's self-directed and it's autonomous, [...]. And then hopefully, they have that memory of a satisfactory, mastery experience, right? So like, "Oh, I made this ping pong paddle and now I have it forever," you know? And so maybe that helps them stay motivated to say, "That's why I'm taking Calc 3, right? That's why I'm struggling through Diff Eq, so then I can actually get to the next class where I'm gonna learn how to do this or learn how to make other stuff," right? And I think that that's really the appeal. -April-18-15-faculty 3 (0)*
>
> *So I think that's also the spirit of this place. It's like, "Let's do something crazy and totally out of our realm and figure out how to do it." And I think students are jumping on that too because students are always in the sense of like, "Anything is possible." So I think that feeds into why this place is so exciting -April-18-4-Staff-3*

Each of the above elements described by faculty, staff, and students contributes to creating a positive learning culture in the EPC reflective of the constructionist learning model. The culture of the EPC is reflective of constructionist learning principles as teachers serve as guides for learning, collaboration is encouraged, and a student-centered focus supports motivation and life-long learning.

Discussion

Analysis of interviews with students, faculty, and staff connected with an engineering prototyping center at a large western university suggested that many elements of constructionist learning theory including learning through knowledge construction and collaborative learning culture are reflected in these spaces and can be leveraged by engineering faculty in the development of their curriculum. This paper highlights these elements and proposes a coding framework to serve as a foundation for future exploration of constructionism in engineering prototyping centers or makerspaces.

Knowledge Construction Through the Development of Physical Prototypes

First and foremost, these spaces allow for the construction of physical objects by providing students with access to prototyping equipment and manufacturing tools. Interacting with these tools allows students to engage in the iterative process of constructing a physical object while also learning the tools and equipment relevant to engineering professions [3]. Additionally, the construction of these physical prototypes provides an opportunity for engineering students to engage in the iterative nature of design by tackling issues and challenges that come up in the production of their prototype. Referred to as "debugging" in constructionism, this mindset promotes a hands-on trial and error approach that encourages students to learn from failure and foster a deeper level of understanding [25, 36]. Implementation of these spaces allows engineering students to translate abstract concepts to concrete experiences through the construction and debugging of a physical artifact. The codes found in Table 2 highlight these experiences and the application of the constructionist principle of knowledge construction within the EPC. These codes include physical object construction which allows for (1) learning and apply manufacturing processes and (2) translating theory to practices. In addition, students practiced debugging that can support (1) the iterative nature of design, (2) design for manufacturing and a (3) failure positive environment.

Creation of a Positive Learning Culture

Beyond providing access to the equipment and tools needed to construct physical prototypes, we found that the learning culture of the EPC reflects the constructionist learning model. This culture supports the role of a teacher as a guide, creates opportunities for collaboration, and is student-centered. Within the spaces, staff and instructors provided guidance and mentoring without providing direction or instruction. Further, students are encouraged to learn collaboratively within their own groups as well as with other groups or staff in the space. Finally, these spaces strive to be student-centered and foster a growth mindset. Dweck's growth mindset, which supports taking risks so that students may continue to grow their own capabilities [43]. In addition, a growth orientation fosters student agency and the development of life-long learning skills in line with the learning culture of the constructionist learning model [14]. AS highlighted in Table 3, codes related to the learning culture of constructionism included, teachers serving as guides, as well as collaborative and student driven learning spaces. Creating this environment in the EPCs where peer-to-peer learning can occur, and instructors and staff serve as guides, supports the implementation of constructionist learning theory.

5.3 Future Work

Within the analysis, several additional observations were made, including the fact that while staff and faculty were aware of the intentional practices used to engaged students in learning within the space, students themselves were less aware of the strategies used in the EPC. Bringing greater awareness to the learning theory and pedagogy, which are being intentionally implemented by educators, may elevate students' engagement in these practices. Additionally, we found that there were several barriers that limited the full use of constructionist learning principles in the EPC including a need for detailed engineering drawings and training certifications. While EPC promotes a positive learning culture, it will be important to explore the barriers which limit the use of the space by engineering students in future work.

5. Conclusions

Engineering prototyping centers and academic makerspaces provide an exciting opportunity to implement constructionist learning theory into engineering education. Qualitative data collected from faculty, staff, and students suggest that EPCs can support the construction of physical objects, deepen students' understanding of manufacturing processes, and develop students' design iteration and collaboration skills. Opportunities for growth within these spaces may also foster student's motivation and life-long learning skills. By providing opportunities for knowledge construction within a positive learning culture, EPCs can support the development of engineering students' skills through the application of a constructionist learning model. Investigation of the constructionist learning principles found withing the EPC supported the development of a coding framework that may be used to further explore how this educational philosophy may be conscientiously applied to support education of engineering students in EPCs and makerspaces.

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