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Understanding a Makerspace as a Community of Practice

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Understanding a Makerspace as a Community of Practice

Abstract

Lave and Wenger's framework of *situated learning* [1] provides a keen lens for understanding how a makerspace makes makers. Stemming from learning theory and cognitive anthropology, situated learning illuminates the processes by which individuals become full participants in a community of practice. In the context of makerspaces, this is to say that makers are made not just when they learn a set of knowledge or skills but when they are entrusted with privileges and responsibilities as increasingly full members of the makerspace community. Using the Stanford University Product Realization Lab (PRL) as a case study, this paper applies the situated learning lens to address the following questions: *How do students move from newcomer to more full participant in a makerspace community of practice (MCoP)? What learning resources are available to students as they participate in a MCoP, and by what processes do students access learning resources in the MCoP?* Longitudinal interviews were conducted with six students during their enrollment in ME203: "Design and Manufacturing", a core 10-week introductory course in the PRL. Findings suggest a process by which students enter the makerspace community of practice; develop an internal map of learning resources; access those resources through observing, practicing, asking questions, and being observed; and how actors in the makerspace influence how students access resources. Overall, the communities of practice framework sheds new light on learning in an academic makerspace by focusing attention on the social interactions in the MCoP; the varying levels of participation; and the different ways and conditions under which students access learning resources. The paper ends with guidance for understanding and improving the design of makerspaces and similar learning environments.

1. INTRODUCTION

Each year students arrive at the steps of engineering colleges eager to become engineers. University makerspaces have emerged as a space where engineering students appear increasingly drawn. An academic makerspace is part workshop, part classroom, and part community of practice. It is a place where real-world challenges are married with hands-on approaches; where students are encouraged to prototype and realize ideas; where design meets manufacturing; and where a student's mind, hands, and heart can be integrally intertwined. Learning in makerspaces is different than learning in typical engineering labs or classrooms not merely because of their high degree of hands-on learning. We contend that part of the magic in makerspaces is that students learn by *participating in,* and *becoming part of*, a *makerspace community of practice* (MCoP). We view a MCoP as an interacting group of people with varied expertise, interests, and identities among other characteristics who are actively engaged in designing, engineering, and/or making in the makerspace environment. Thus, participating and learning in a campus MCoP may be similar in some ways to participating and learning in a professional engineering community of practice.

Moving beyond purely knowledge and skills-based views of learning, Lave and Wenger offer *situated learning* and *legitimate peripheral participation* as an analytical framework that defines learning as increasing participation in a community of practice [1]. Learning is thus the inward trajectory of becoming a full participant in a practicing community. Using this frame, this paper addresses the following research questions:

> *RQ1: What learning resources are available to students as they participate in a campus makerspace community of practice (MCoP)?*
>
> *RQ2: By what processes do students access learning resources and become increasingly full participants in a campus MCoP?*

Addressing these research questions may shed light on our larger motivating question: *How do learners move from newcomer toward more full participant in an engineering community of practice?* The question of *access* to communities of practicing engineers matters today more than ever as engineering colleges and companies struggle to "stem the tide" of women and other underrepresented minority students leaving the engineering "pipeline" [2]. To address the above research questions, we follow six undergraduate and masters design and engineering students as case studies through their experience in a ten-week course in which they move from some level of newcomer to more full participant in the Stanford Product Realization Lab (PRL) makerspace community of practice.

2. BACKGROUND

Academic Makerspaces

In tandem with the growth of the *maker movement* and rapid prototyping tools (e.g., 3D printers) and their influence in education [3,4], the expansion of university-based makerspaces and related research have been on the rise (e.g. [5]). Consider, for example, the creation and growth of the annual International Symposium on Academic Makerspaces, now in its fifth year. Academic makerspaces vary considerably in their design, tools, materials, curricula, community make-up, leadership and culture, among other dimensions [6]. To better understand who participates and how they participate in makerspaces, Sheridan *et al.* conducted a comparative case study in three (non-academic) community makerspaces. The authors describe "learning… [in the makerspaces as] deeply embedded in the experience of making. These spaces value the process involved in making—in tinkering, in figuring things out, in playing with materials and tools" [7, p.528]. *What is the process through which students become "involved in making … tinkering… figuring things out… and playing" in a makerspace? What learning resources do students access? How and under what conditions do students gain (or not gain) access to makerspace learning resources? What are the outcomes of these processes?*

A variety of studies have found that participating in academic makerspaces is associated with positive changes in students' design, engineering task, and innovation self-efficacies; motivation; expectations of success; interdisciplinary awareness; and belonging [8-14]. A further stream of research aims to understand the barriers to equity in makerspaces, especially for women [15-17], and has uncovered "mechanisms" by which makerspaces can engender a sense of community through, for example, signals of approachability, structured help-seeking, and credentialing [18]. Several makerspace studies mention situated learning as a possible theoretical frame for understanding learning in the makerspace environment [7,18-19], however these do not describe the processes by which newcomers advance toward more full participants in the MCoP. Building upon this prior work, we examine the dynamic processes of participation in a MCoP with the lens of situated learning.

Situated Learning: Legitimate Peripheral Participation

Stemming from the learning theories of Dewey [20], Vygotsky [21] and others, Lave and Wenger offer a framework for understanding learning environments based on their study of apprentices across trades and cultures. They call this ***situated learning*** and ***legitimate peripheral participation*** which posit that learning is the social practice of becoming an increasingly legitimate and full participant in a community of practice [1]. When a learner is able to participate in activities of more and more import in a practicing community, they develop what Lave and Wenger call "knowledgably skilled identities." This view differs significantly from a purely behaviorist or cognitive view in which learning is simply the accumulation of skills, knowledge, and cognitive abilities, as detailed by Johri and Olds [22]. To clarify, let us break down each word of legitimate peripheral participation:

- *Legitimate* refers to learners being provided with sanctioned access to the learning resources of a community, e.g. the meaningful activities, tools, machines, materials, and members of the community. Legitimacy is important for learners' to develop an (e.g. engineering) identity and to be able to participate in the activities of the community and become a more learned member.
- *Peripheral* refers to the agency of a learner to make sense of a community at their own pace, to their own liking, and for their own needs. There is a spectrum of peripherality spanning partial to evermore full participation. Newcomers in a community are often relegated to highly peripheral activities while long-time community members may engage in more central activities.
- *Participation* refers to engagement with the people and in the activities of a community.

Several elements of legitimate peripheral participation can help to frame makerspaces as learning environments. First, consider the idea of *partial participation.* Newcomers in a MCoP engage in partial participation through scaffolding such as tutorials and structured labs. These initial activities or projects are typically more scaffolded, less complex, and more peripheral to the community than, for example, a full design-build project at the bleeding edge of the MCoP's capabilities. Thus, partial participation allows newcomers opportunities to not just learn how to design or make a particular object but to make sense of the activities and culture of the MCoP. As Lave and Wenger describe:

> *An extended period of legitimate peripherality provides learners with opportunities to make the culture of practice theirs. From a broadly peripheral perspective, apprentices gradually assemble a general idea of what constitutes the practice of the community. This […] might include who is involved; what they do; what everyday life is like; how masters talk, walk, work, and generally conduct their lives […] and what learners need to learn to become full practitioners.* [1, *p.95*]

A second major element of situated learning with relevance to makerspaces is the *transparency of cultural meaning.* In a makerspace, cultural messages of the MCoP might be embodied in machines, tools, materials, past projects, and the ways that experienced MCoP members interact with the objects and other members of the space. These elements of cultural meaning help to make clear to learners things like: how to operate a machine safely and adeptly; where to find a tool; how and whom to ask a given question; and the kinds of things that are deemed "well made" or "good design." The transparency of cultural meaning embedded in objects and people of a makerspace help newcomers to see what it means to participate in the MCoP and how participating may be relevant to a learner's personal goals. Lave and Wenger elaborate:

> *Legitimate peripheral participation […] places the explanatory burden for issues as "understanding" and [...] conceptualization […] on the cultural practice in which the learning is taking place, on issues of access, and on the transparency of the cultural environment with respect to the meaning of what is being learned. Insofar as the notion of transparency, taken very broadly, is a way of organizing activities that makes their meaning visible, it opens an alternative approach to the traditional dichotomy between*

> *learning experientially and learning at a distance, between learning by doing and learning by abstraction.* [1, *p.104*]

Though makerspaces are typically lauded as particularly strong at hands-on learning, much more is at play in a MCoP. Consider the hypothetical: a student is invited to design and build a project in a well-furnished makerspace, but they are the lone participant in this space. The student may be able to figure things out on their own, but the way this student "learns" is quite different from how students in typical makerspaces learn. Learning in a MCoP is often about interacting with the social community of the space; gaining access to learning resources through increasing participation; gaining new knowledge, skills, and ultimately new or revised identities as a maker, designer, and/or engineer. In a MCoP, "learning" becomes synonymous with "participating," and concepts like access and identity become intertwined with learning. In this way, the "magic" of learning in a makerspace is not only about hands-on learning but about increasingly full participation in a makerspace community of practice.

3. RESEARCH SITE: THE STANFORD PRL COMMUNITY OF PRACTICE

This study is conducted in a learning laboratory, makerspace, and associated MCoP at Stanford University: the Product Realization Lab (PRL). The PRL is both a physical space and social community. It is over 9,000ft^2 of tools and materials (e.g. woodshop, machine shop, rapid prototyping, foundry) and a community of over 1,000 practicing designers and makers (e.g. students, instructors, industry experts) who are active in the PRL each year. It is a place where ideas and designs are realized; prototyping and iteration are celebrated [23]; self-efficacy is built [13,14] and engineering-related identities may form. Professor David Beach, the Director of the PRL explains that: "learning [in the PRL] aims to engage the whole student through a process of *all-in creation*" [13, *p.4*].

Stanford students join the PRL community through research, personal projects, and roughly 35 courses that use the space each year. A primary gateway into the PRL is ME203: *"Design and Manufacturing,"* a longstanding course in which students practice designing and making through a series of hands-on labs (e.g., milling, turning, sand casting, forming, welding) and the development, design, and fabrication of an individual project. Projects are encouraged to be meaningful to each student and range widely from, for example, "Cezve," a machined Turkish coffee pot to "Toughie," a welded scooter for a student's young daughter.

The PRL is sustained by its community of four key faculty, about 20 graduate student Course Assistants (CAs), and a broad population of students from the arts, engineering, humanities, and social and physical sciences. The CAs play a special role in the community as design and making coaches [24]. Through everyday interactions in the makerspace, newcomers and long-time members of the PRL form a rich fabric of continuously evolving and renewing social relations. The aim of this study is to describe this social and cultural fabric and how it shapes student's participation in the makerspace community of practice.

4. METHODS

We take an inductive approach to understanding how students participate and make meaning in the PRL using a set of longitudinal semi-structured qualitative interviews. A theoretical sampling strategy was employed to initially select eight ME203 students who varied in gender, race, prior design and making experience, and prior connectedness to the PRL community (number of reported acquaintances among PRL CAs and ME203 classmates at the start of the course). These dimensions were chosen because we expect that they strongly influence a student's participation in the PRL community. The eight identified students were invited to participate in a total of four roughly 30-minute interviews during weeks 4, 6, 8, and 10 of the ten-week course. Three invited students declined to participate, and one new student was added yielding a total sample of six students with four interviews each over the span of six weeks. This paper focuses on only the six third-round interviews (during Week 8 of ME203) which lasted for an average of 26 minutes each. A summary of interview participants is shown in *Table 1*. To preserve the anonymity of participants, identifying information has been withheld from all PRL staff and ME203 instructors (including the second author), and pseudonyms are reported throughout this paper.

Table 1: Summary of Interview Participants (ME203 Students)

Brittany	**Cindy**	**Jennifer**
- Major: Biomechanical Engineering - B.S. 3rd year; Born: 1997 - Prior Experience: **None** - Prior PRL Connectedness: **Medium** - Select Identities: Woman	- Major: Product and Arch. Design - B.S. 3rd year; Born: 1998 - Prior Experience: **None** - Prior PRL Connectedness: **None** - Select Identities: Woman, FLI	- Major: Mechanical Engineering - M.S. 1st year; Born: 1996 - Prior Experience: **High** - Prior PRL Connectedness: **High** - Select Identities: Woman
Victor	**Darren**	**Max**
- Major: Mechanical Engineering - B.S. 4th year; Born: 1997 - Prior Experience: **None** - Prior PRL Connectedness: **Medium** - Select Identities: Man, URM, FLI	- Major: Product Design - B.S. 4th year; Born: 1997 - Prior Experience: **Low** - Prior PRL Connectedness: **None** - Select Identities: Man, URM, FLI	- Major: Mechanical Engineering - B.S./M.S. 5th year; Born: 1996 - Prior Experience: **High** - Prior PRL Connectedness: **High** - Select Identities: Man

URM (under-represented minority): students who report identifying as Latinx, African American, Native American and/or Pacific Islander.
FLI (first-generation low-income): students who report identifying as first-generation college or low-income.

Interviewers adhered to IRB-approved semi-structured interview protocols focused on stories of critical incidents in the PRL and students' expectations and interpretations of these events [25,26]. In particular, interviews aimed to elicit students' activities and interactions in the PRL, their evolving sense of their available learning resources, their confidence in designing and making, and their sense of belonging in the community. All interviews but one (per interviewer request) were audio recorded and transcribed. Hand-written notes were taken during the unrecorded interview and subsequently coded. A team of two authors collaboratively and iteratively built a codebook starting with line-by-line open coding of a subsample of transcripts [27,28]. After building the codebook, the remaining transcripts were coded with a subsample of data independently coded by both coders with an intercoder reliability score of 0.71. Thematic analysis was performed in two rounds, starting with a review of the content in each code followed by a second reorganization into emergent themes, as presented below.

We conclude this section by acknowledging our positionality as authors and active members, former students, and a former CA of the PRL. As authors, we come from different backgrounds and career paths and have pursued this study in an attempt to better understand and thereby improve participation and access to the learning resources in makerspaces (e.g. the PRL).

5. FINDINGS

Our emergent themes are organized into four categories that characterize processes by which students move from newcomer to more full participant in a makerspace community of practice (MCoP): (1) *Initial Participation in the MCoP*; (2) *Internal Mapping of MCoP Learning Resources*; (3) *Accessing MCoP Learning Resources*; and (4) *How MCoP Actors Influence Access to Learning Resources*. These themes are detailed in the following subsections using illustrative quotes from the six case study students. The themes are further examined in the Discussion section from the theoretical frame of situated learning. In closing, implications are discussed for how and when students access learning resources as they more toward more full participation in makerspaces and other engineering communities of practice.

5.1 Initial Participation in the MCoP

In many cases, a student's first experience in the PRL are safety training and ME203 Structured Labs. Structured Labs are formal, dedicated sessions located in the makerspace during the first four weeks of ME203. In each lab, roughly seven ME203 students spend four hours with one CA engaged in (1) rapid prototyping and woodworking, (2) milling, (3) turning, (4) sand casting, (5) welding and sheet metal forming, or (6) sanding and polishing. By observing a CA make parts and then making parts while being observed by a CA, students practice using machines and tools, preparing material, reading engineering drawings, following operations sequences, developing technique, and ultimately making parts to specification. When all Structured Labs are complete, each student assembles their finished parts into a magnifying glass (machined brass, Delrin, and acrylic), plaque (cast bronze), and plaque stand (formed and welded sheet steel). Students are given unlimited access to stock material to make Structured Labs parts so they may start over as many times as desired, and they are permitted to work in the PRL anytime during open hours (roughly 8:30AM to 11PM M-F and 8:30AM to 5:30PM Sat). ME203 students report spending an average of 31 total hours on Structured Labs, including 24 hours (6 labs x 4-hours ea.) of formal Structured Lab time.

The Structured Labs are meaningful in both providing a window into the culture and practices of the PRL and providing newcomers with valuable scaffolding for their initial participation in the MCoP. Four of the six students had no prior experience in the manufacturing processes they used for their final projects, and Structured Labs served as a first introduction into the craft of these processes. As Brittany explains, Structured Labs helped to extend her understanding of making processes in a low pressure environment:

> ***Brittany:*** *Yeah, no I thought [Structured Labs were] fun. I was definitely nervous, but I had fun and like I picked sand casting [for my project] because I really like that Structured Lab and I liked doing that. [...] I really liked the structure of labs, honestly, because they [...] were so low stakes and so I could just have fun. Like welding; so there's no grade for it. I thought that was really fun 'cause I'd never done that before and I feel like it's cool to say like: "Oh I can weld now."*

Structured labs are opportunities for students to engage in partial participation. In being highly scaffolded and focused on just making (not yet on designing *plus* making), these activities allow newcomers to begin practicing while also beginning to make sense of the culture of the MCoP and its many learning resources.

5.2 Internal Mapping of MCoP Learning Resources

Once a student registers and undergoes safety training in the PRL, they are told they have access to nearly all the resources that the PRL has to offer. Indeed, access is critical for participation and learning, but espoused access to learning resources does not necessarily mean a student feels that they can access those resources in their everyday use. Each student's perception of the PRL's learning resources influences how they participate and learn in the makerspace. Through a combination of these resources, students make their way toward completing their projects and, more fundamentally, toward becoming who they want to be as designers, makers, and/or engineers. Table 2 lists the physical, virtual, and people-related MCoP learning resources potentially available to ME203 students. This is followed by examples illustrating ways that students come to understand the learning resources that are available to them.

Table 2: Learning Resources in the MCoP (according to ME203 students)

Physical Resources	**Virtual Resources**	**People Resources**
- Materials - Machines - Tools - Signage, documents - Prototypes - Previous projects	- Internet (e.g. YouTube) - Documentation (e.g. PRL "Tech. Notes")	- Peers (e.g. ME203 classmates) - Near-Peers (e.g. PRL CAs) - Masters (e.g. PRL faculty) - Suppliers

Perceptions of People Resources in the MCoP

Victor is a mechanical engineering student with no prior making experience but with some prior connection to the people of the PRL (through personal projects). In Victor's experience, sharing and helping is a natural part of what occurs in the MCoP:

> ***Victor:*** *Every time I've reached out for help, people have just been so willing, or people have asked me for help, I've been so willing to give it. It's just like a very natural, I dunno, very calmly characteristic there. And it's just like with the CAs who sometimes they go out [of] their way, in making sure [...you have] what you need.*

Jennifer, who has a lot of prior making experience and prior connection to the community, has a similar perception of the MCoP as Victor:

> ***Jennifer:*** *Overall [the PRL is] a pretty good work environment. There's lots of knowledgeable people, TAs and students included. Everyone's working on their parts and everyone's pretty curious about what you're doing and people ask what are you making, what class is that for.*

Victor and Jennifer's perceptions of the MCoP are marked by stories of their relationships with the people of the community and their asking for, receiving, and giving help. Their view is that of an open and collaborative environment.

Victor and Jennifer's perceptions of the MCoP and its people-related learning resources stand in contrast to Cindy's. Cindy is a student in a self-designed major with no prior connections to the PRL community, no prior making experience, and is not familiar with her peers in ME203. When asked to describe the PRL to someone who has never been there before, Cindy describes it as "a place where people just go in to get work done," so "you don't want to bother people because they are working on their own projects." She describes her experience in the PRL as being lonely and explains that at one point in the course she dreaded going to the PRL and had to have a friend who was not in the course "drag her there."

This begs the question: under what conditions do students view a MCoP as a relatively closed and lonely place like Cindy versus a relatively open and collaborative space like Jennifer and Victor? This question is partially addressed in section 5.4.

Expanding Internal Maps of Learning Resources through Familiarity
Brittany's experience in ME103D, a companion course of ME203, illustrates how her internal map of MCoP learning resources expands by interacting with the PRL faculty member who teaches the course. She is glad that ME103D gave her the opportunity to get to know him:

> ***Interviewer:*** *And … why do you think having a relationship with [this PRL faculty member] is important?*
> ***Brittany:*** *Just 'cause like he runs the PRL and his office is right there every time you walk in. And I feel like it's just nice for him to at least recognize your face and like I feel like if I really had an issue and or couldn't go to any other CA, I could definitely go to [him]. And I for sure feel more comfortable doing that just because I've had a couple of conversations with him.*
> ***Interviewer:*** *And have you ever gone to [him] about help for a part or any challenges?*
> ***Brittany:*** *No, but it's nice to know that I could.*

Similarly, many students discuss the importance of familiarity when describing which CAs they go to for help. As illustrated by Brittany, even a relatively low level of familiarity can make a big difference in how students construct their internal map of learning resources and elucidate which resources are available to them.

How Internal Maps of Learning Resources Influence Action
Darren is another student who is new to the PRL and has little prior experience designing and making things. A key factor that shapes Darren's understanding of the CAs as learning resources is his interactions with his assigned CA coach early in the course:

> ***Darren:*** *… Maybe that started with my [coach] … because I'd asked [my coach] tons of stuff early on, and I just realized, 'Yeah, you know, a lot more than me. You're really helpful.' Then I mean there's tons of TAs like her so I'm going to ask them too.*

Further, Darren's understanding of various machines as learning resources influences how he engages in problem-solving with his project. When using an unfamiliar manufacturing process, Darren makes a critical error. He explains his response to this event:

> ***Interviewer:*** *When you first had this moment of being like, "Oh [...], these are not fitting the way they're supposed to be..." What were your initial feelings and did you seek out help in any way?*
> ***Darren:*** *Oh yeah. So much help. I probably asked every TA at some point for their opinion. […] Just because I know they know more than me about this, so they'd actually give me different answers. […]A bunch of TAs told me like, "Hey, won't be that big a deal." But then a bunch told me, "Hey, finish it […] What if water gets in there?" Concerns that were kind of valid. […] Specifically one TA told me, "Yeah, go ahead and use the die grinder and sand off the top half of the tube." Another was like, "Just fixture it and machine off the top." And so just getting multiple sources of feedback was good*

> *because I decided I'm just going to use my hand because I can stop. It's a lot more personal. It might be slower but that's fine. It might not be as clean initially, but I'd rather do more work on the backend than go in there trying to mill it and mangle my part or something.*

In addition to highlighting how Darren understands the CAs as learning resources, this incident highlights how Darren understands the mill and die grinder as resources. Though the option to practice and use the mill so "late in the game" was an option, Darren's time constraints and lower familiarity with the mill moved him away from this resource. The next section builds a bridge between the concept of an internal map of learning resources and the various ways that students access these resources.

5.3 Accessing MCoP Learning Resources

Provided an ever-evolving internal map of learning resources, students may assess and access these resources. This is often spurred by 'it worked' and, more often, 'it didn't work' moments. To illustrate, Darren recounts:

> ***Darren:*** *Yeah, I would say [it] did not go well when I initially welded my tubes on, and then I was like, "All right, let's see if they're strong." And I snapped it right off.*

ME203 students respond to such moments by referencing their internal map and accessing one or more learning resources through: (1) observing, (2) asking, (3) practicing, or (4) being observed. Consider how Darren responds to the above 'it didn't work' moment:

> ***Darren****: [...My parts] weren't assembled because I couldn't weld them together, so I was showing [one of the PRL faculty] my welds and he's like, "Yeah, you should probably just do brazing." Because given my application, it was just a better process to use. [...] So I just took his advice [...] There's tons of ways to do things, but there's also easier ways to do things. And if you don't ask, you don't know what those ways are. [...] I didn't even know I could braze. Had I not gone to [PRL faculty member], I'd still be working on this.*

Darren experiences a challenge with his welds and accesses a resource from his internal map. He asks a question to one of the veterans in the MCoP, and this person provides unexpected knowledge that leads Darren to change his manufacturing process and finish his project more quickly and effectively than he would have otherwise. In this way, accessing MCoP learning resources facilitates the revision of one's design, manufacturing process, knowledge, and/or technique and further amends one's internal map of learning resources. Ideally, such revisions eventually result in 'it worked' moments. In the following subsections we detail key activities through which ME203 students access learning resources in the PRL MCoP.

5.3.1 Observing

One way to access the physical, virtual, or people resources of a MCoP is to simply observe them (e.g., watch a video on YouTube, observe others operating a machine). For example, Victor explains how he observes virtual resources:

> ***Victor****: If I know, like, I'm going to be using this machine the next day, and I haven't ever used it before, I definitely try my best [to] watch a YouTube video or do some quick wiki-how research on, like, that process.*

Beyond online resources, students directly observe and are inspired by the work of their peers or others in the makerspace, as Brittany illustrates:

> ***Brittany**: I've made friends in the class and they all talk about how they're doing, and, like, I am curious to see their different techniques and processes that they have to use to make their different pieces and, like, how they're doing. It's cool to see other people's projects, and I think I just would've never thought to do something like that.*

Darren also observes his peers in the MCoP, and he feels that some areas of the makerspace are more conducive for observation than others:

> ***Darren**: [In the welding room] people are sanding or bending things or filing and you can look at what other people are doing […] You're sitting at a metal table and everyone's facing each other, so if you're filing or something you can look up and take a glance [... but in the machine shop,] if you try looking at someone's milled part, [...] it's fixtured; it's x feet away; it's probably blocked by the actual mill; [...] their body's probably in the way. [...] You're looking away from the machine; you kind of have to stop what you're doing [in order to watch others].*

Observing others in a MCoP can contribute to students' know-how of materials and manufacturing processes; inspiration for projects; knowledge of who to go to for help; and awareness of what a designer, maker, and engineer can be and do. In these ways, observation shapes students' understanding of mature practice in the MCoP.

5.3.2 Practicing

Practicing is another key activity through which students access learning resources in a MCoP. Here, we define *practicing* as any act of realizing a design with the intention of learning (not just executing a design or process that one knows well). Students engage in both physical practice (e.g., developing or testing a physical prototype) and/or virtual practice (e.g., developing a CAD model or drawing). Students in the PRL MCoP often engage in physical and virtual practice; experience 'it worked' and 'it didn't work' moments; and revise their knowledge, technique, designs, and manufacturing processes accordingly. For example, consider how Brittany manages the end of her casting project. With her project due in about two weeks, she has successfully cast her major part but realizes a concern. Although she has conferred with CAs and has a plan for fixturing and machining her casting, this will be her first time post-machining, and she is unsure how it will go. She explains that she normally prefers to ask CAs many questions before trying something, but in this case she feels that she just needs to try it:

> ***Brittany:** I did create a practice piece basically to practice end milling just because I knew that all the CA could tell me is, like, which tool I should probably use or whatever, but I had to kind of feel it out, like, how much I should take off at a time and how much it will go outside the boundaries that I want it to; so, like, I just kind of knew I had to try it for myself, and I'm glad that I had that time to just do it once and figure out all of my mistakes and everything and then be able to do it again.*

Taking advantage of how castings are relatively easy to duplicate, Brittany casts an extra part to practice post-machining. (It helps that she has allotted time for this.) While practicing on the mill, several things go wrong and she works with CAs to improve her machining process for her next casting. Ultimately, this practice leads to a near-perfect second iteration of her post-machined cast part.

Brittany's experience also highlights the roles of severity of risk and cruciality of parts. Because sand casting allows quick and cost-effective multiples of cast parts, the severity of destroying a casting through poor post-machining is relatively low. This frees Brittany to take advantage of practicing as a learning resource. Max echoes how the cruciality of a part (the time or money involved in its creation) and the riskiness of a machine or procedure influences whether he chooses to engage in practicing or asking:

> ***Max:*** *There definitely has been a balance. […] I'm trying to do research ahead of time if I know it's gonna be expensive or time intensive, so then I'll try and ask more questions. But if […] I can prototype without spending a whole lot of time or money, then I'm probably more likely to just jump in and start doing because asking questions only gets you so far. At the end of the day you need to get your hands dirty and actually start building something.*

Familiarity and comfort with a given process, machine, material, or tool similarly influences how and when students engage in practicing, as described by Jennifer, Victor, and Brittany:

> ***Jennifer:*** *I think I'm pretty comfortable with that [experimenting on my own]. I kind of know the limits of what can be done with each of the processes and what kinds of things that I can change in order to improve my pattern or something like that.*
>
> ***Victor:*** *I was a little bit anxious because I was like, "Oh, I actually don't know what I'm doing." Because I haven't done it before. I'm just hoping I've thought through the details -- hopefully it will work. So let's just "send it," and it actually worked out pretty well.*
>
> ***Brittany:*** *But I definitely am a person that likes to ask a lot of questions because I like to do things right the first time. I probably ask too many questions but the CAs are good about answering them, so I'll usually ask the CAs if I'm unsure about something.*

Depending on a student's prior experience, comfort level, and perceived risk of "just trying" or "sending it" (i.e., making a part), they may be more or less inclined to practice on their own versus asking questions. *Table 3* details students' emergent considerations for engaging MCoP learning resources through practicing versus asking.

5.3.3 Asking

Asking questions is another prominent way by which ME203 students engage MCoP learning resources. Victor describes question asking as an "act of courage." As a newcomer to making and the PRL community, Victor engages many different kinds of MCoP learning resources in designing and making his ME203 project. He observes CAs and YouTube videos on wood turning, engages in both virtual and physical practice through CAD models and physical prototypes, and he frequently asks CAs for help. For example, while working on his casting pattern in the woodshop, Victor needs to cut a piece of wood. He knows very little about saws, and on top of that, he is not sure how to ask for the help he needs:

> ***Victor:*** *At one point when I was just trying to cut a quarter inch piece of wood off, and I literally had no idea like how… Should I use the band saw? Do I use a miter saw? Do I use the table saw? There [are] just many different options. [...] I was like pretty unsure […]how to, like, form an actual plan. So I just went up to a TA at the time [in] the wood shop and just asked questions. I told them this is what I was trying to do, this is like what I considered. How should I go about it? And, like, they just went above and beyond by actually showing me what ways the machines could, like, do what and in what capacity.*

[...] They gave some great advice for me personally - ways I could go about it. I eventually [...] used a bandsaw, and it was actually like a whole process in itself, like, learning how to, like, position the bandsaw and all of that. So yeah. And that was a great positive experience.

Of course, not all engagements between students and people resources in the MCoP are so positive, as will be discussed in the section 5.4.

Table 3: Students' Considerations for Asking vs Practicing in a Makerspace Community of Practice

Asking	Practicing
When the time or financial cost of "just trying" is *high*	When the time or financial cost of "just trying" is *low*
When a student perceives significant risk in their operation of a machine or "feels intimidated to try and hop on a machine"	When a student perceives little risk in their operation of a machine and that they "know the limits of the process and machine"
When a student believes that the person they're asking for help "knows more than me," is likely to provide helpful advice, and "builds cool stuff too"	When a student believes that more advice would only complicate their design decisions or produce more alternatives than they have time to investigate
When a student believes that their design or manufacturing process has room for productive intervention	When a student believes that their design or manufacturing process is so constrained that more advice is unlikely to be helpful
When a student perceives that MCoP people resources are currently available and accessible to them	When a student perceives that MCoP people resources are currently busy, inaccessible, or that they would be "hogging" them from other students
When a student perceives little time pressure or that asking for help is their only option	When a student perceives too much time pressure to permit question-asking and sees available options that they can try
When a student has someone available who is familiar with them and/or their project history	When a student does *not* have someone available who is familiar with them and/or their project history
When a student feels that those they could ask for help will offer patience, non-judgement, a consistent willingness to help, and genuine care	When a student feels that those they could ask for help will make them "feel dumb," intimidated, or otherwise uncomfortable
When a student feels the need to affirm their approach	When a student feels *no* need to affirm of their approach
"Asking" may not involve an explicit question but merely the presentation of a failed part; in this way "asking" can be a collaborative problem-solving activity	A student may believe that practicing or "just trying" something first is necessary to facilitate the formation and asking of "good" questions

A closer look at Jennifer and Darren suggests that question-asking may vary by a student's level of experience or connectedness in the MCoP. While many students ask questions to gain direct knowledge about their making process or design, Jennifer—who entered the course with prior casting experience—tended to engage CAs not as question-answerers but as problem-solving partners—people to brainstorm with and solicit ideas from. While she clearly respects CAs' opinions, she does not feel obligated to incorporate their ideas unless she really likes them. In contrast to Jennifer, Darren entered the course with little MCoP experience. However, he observes a change over the ten weeks in the way he asks questions:

Darren: *The way I feel about asking the questions, I would say initially, I would think maybe if you have a question, ask it. But then after you start getting answers that are* *along the lines of what you were thinking anyway, maybe it's building confidence. You just know when you really don't know the answer versus when you're looking for reassurance. It's like being comfortable taking that leap and believing that you know a good way to do it; you always find out there's not just one way.*

In this case, as Darren becomes more comfortable welding, he begins to ask less knowledge-seeking questions and more reassurance and affirmation-seeking questions.

A final set of cases illustrates how practicing can lead to question-asking in a mutually reinforcing loop. Consider Brittany's quote near the top of the Practicing section (5.3.2). She articulates that the most she could learn from a CA is perhaps what tool to use to make her part, but after making a practice piece she re-engages in question-asking: "*I kind of messed up the milling but it was okay and I talked to a couple of people about how to fix it and [now the] magnets fit […] so it was good."* Further, consider Jennifer while she is working on her casting project. Early on, when testing her sand casting pattern, her part had poor surface finish. Puzzled, she presents her part to her CA coach, someone she says she particularly trusts because he is taking a sand casting class. Her coach shares that pour temperature can affect the porosity of sand casted parts, something she did not know. She requests that her next pour be at a lower temperature, and her next part turns out well. On another occasion, she has a sand cast part turn out poorly, and this time she turns to a CA present in the foundry to talk about what went wrong. That CA, on checking out Jennifer's sand casting mold, suspects that the horizontal air vents she is using are not the best way to vent her parts and teaches her how to make vertical vents.

5.3.4 Being Observed

It is possible to gain access to people-related learning resources in a MCoP without directly asking a question. Take for instance Max who is working on drilling a hole in his part:

> ***Max:*** *"[One] of the CAs, I didn't even ask him, he just came over and asked what I was doing, and I was getting ready to tap and stuff, and he was like, 'Do we have taps that are that long?' And so then we went and looked, and sure enough, there weren't; my piece was too long for the tap, I wasn't gonna be able to tap all the way through. And it wasn't critical for my design, for it did not have to be that long, so I was able to just chop a section off, and then do that. But yeah, so it wasn't [that they] just actively were looking for errors, and it wasn't like they were like, 'Oh, you're doing this wrong.' They came up and approached it in a really good way and were like, 'Have you thought about this?' And it was like, oh, no I didn't actually."*

Cindy also learns through being observed by a CA who watches her and recommends that she make a loose pattern for sand casting mold. This observation saves Cindy stress, time, and helps her to achieve a better outcome. Similarly, Jennifer speaks of the benefits of being observed:

> ***Jennifer:*** *"I think there was quite a bit of learning from whoever was on duty when I was doing the first casting or so just because I would have them come over or they would just be walking around and look at it as well. They would be like, 'Oh that looks good.', and I would be like, 'Oh this little bit fell in. Do you think it's okay?' Usually they're like, "Yeah, it's fine.'"*

5.4 How MCoP Actors Influence Access to Learning Resources

Across all six students, the influence of other actors (e.g., peers, near-peers, and veterans) is central to their experience of participating in the makerspace community. Of particular salience is whether and how MCoP actors build rapport and take interest in one another. Take Max for example. Silicone casting is a central process in Max's project, however it is not one of the most common processes used in the PRL. So, when a CA holds a silicone molding workshop, Max is the only attendee. He gets a one-on-one tutorial that marks the start of an on-going relationship with this CA who demonstrates sustained interest in Max and his project, as he explains:

> ***Max:*** *The CA who, she did my silicone molding training session, and I was the only one that showed up, so it was like a one-on-one session, which was really cool. And then since then she's been like, "Oh, how's the project going?" And stuff. And I showed her the prototypes of my handles as they've gone along, and she's given me some more tips and stuff, and like, oh, you should go talk to this person, and stuff like that. So that's been cool […that] they've stayed in touch and have been showing active interest in the project throughout.*

Other students' stories highlight the influence that active interest, rapport, and familiarity have on whom they ask questions:

> ***Brittany:*** *Okay. I really trust [a PRL CA] cause she's been really nice throughout the whole quarter and I met her at my first Structured Lab, and then she ended up teaching two of my Structured Labs, so she kinda knew my face and I had seen her a couple of times throughout random parts of my process and I just tried to ask her questions or at least tell her what I was doing so she knew what was going on and we just get along pretty well […] So I knew that I could ask her really any questions and she would probably know them and then she helped me give good ideas or she gave me good ideas for my pattern, and then she helped me wax fillet the inside and she knew how to do that, so we just kind of went through different processes together and she was really nice about helping me and answering my questions. And now I haven't seen her in awhile. I saw her a couple of days ago, but she was like, "How's your project going? It's almost done, right?" And so it's just nice that she cares and like I know I can ask her for help and she will probably know the answer and be really willing to help me with it too.*

> ***Darren****: Yeah, and I think sometimes when you ask a TA that you're not used to, you feel like they don't understand what you really mean. And I feel like when you're familiar with the TA you can tell that the answer […] is answering what you meant when you asked the question because they know where you're going, which is helpful. Sometimes they'll even give you the answer you weren't looking for but answers your question better.*

All six students describe their preference for accessing their CA coaches as learning resources, with whom they have longstanding rapport and relationships:

> ***Victor:*** *I actually haven't seen a reason not to trust any [CAs], but in particular I'll say … It's always helpful for me … whenever I see [my coach] on shift, so he's supported me with 203 and I'm always asking him like it makes you feel like, oh yeah, I can definitely ask them a question in […] those moments that seem very seamless because he and I ended up discussing my project a lot more together. So just then him seeing him on shift and me being like in the machine shop. It just […] makes him more, I guess, fluid in a way.*

> ***Cindy:*** *Thank God when I see [my coach].*

MCoP actors can also serve to connect students to other learning resources. This is evident in Darren's comment on how his relationship with his coach helped him to see other CAs as useful (see section 5.2). Similarly, Max got in contact with one of the veteran members of the community to help him when he experienced difficulties in silicone molding:

> ***Max:*** *[It] was difficult initially to get that plastic insert centered inside the silicone, and then I was having some issues with material leakage, I was getting these big air bubble spots. But reached out to [one of the PRL faculty], she's in charge of the silicone molding stuff and she's the expert in the PRL, and she gave me some tips, and made some adjustments.*

The relationships students have with PRL MCoP actors also influences who students do not talk to. During Brittany's project, she asks a CA for some help in working on her sandcasting mold. His response makes her unwilling to ask questions from him going forward – *"[he was] not very forgiving and kind of angry and frustrated and didn't really want to help me. So I just don't really want to ask for help".* Cindy similarly voices aversion to CAs who made her feel "dumb" by the way they respond to her questions and gravitates toward "non-judgmental" CAs. However, Cindy's experience is also notable in that she entered the makerspace with few peer relationships. This makes her experience in the MCoP lonely, as mentioned in section 5.2. Ultimately, while she expressed enjoyment in the course, she emphasizes that "the experience of the course is elevated if you've both learned and developed at least one friendship."

In line with Cindy's assessment of the value of peer relationships, other students describe the variety of ways that peer relationships influence motivation and participation in the MCoP:

> ***Darren****: You start to get to know the same people in there who were there the same times as you. You just check in on each other's projects or you'll ask them like, "Hey, do you know where this is?" Or "Hey, how do you think the best way to do this is? [...] For instance, I had a TA actually in one of my other product design classes who I hadn't seen for quarters, but we recognized each other, and she was working on [a project], and I was working on my [project] and I would just be like, "Hey, do you think this is a good way to do this?" And she would tell me no or she'd tell me yeah. So it was cool.*
>
> ***Max:*** *I think I spent a lot of time at the beginning thinking through how [my parts] would work before just jumping in and building something. So I like, especially, I spent a lot of time on McMaster, and looking at my different options, different materials, how those materials would interact, and coming up with the best combination. And in addition to doing that myself, I actually sat down with a friend, and we both had stuff that we needed to work through for both of our projects, so we helped each other out. And that was a really cool ... We spent a few hours for each of the design choice we were making for our project, bounced ideas off each other, and kind of worked through the best solution, which was really, I think, critical.*

MCoP actors constitute a primary learning resource in the PRL. While activities such as checking-in may appear non-essential, through a lens of access these interactions (or the absence of them) serve to alter the perceived learning resources that students feel are available to them while participating in a makerspace community.

6. DISCUSSION

The concept of an "internal map of learning resources" is a metaphor that describes the personalized understanding of available resources that a learner gains while participating in a community of practice. It is through building this ever-evolving map and making use of its resources that learners increasingly participate in and become more full members of a MCoP. Becoming part of a MCoP involves newcomers learning how to observe, ask, advise, and generally practice designing and making like a mature member of the community. As Lave and Wenger describe, it is important to consider the "deeper sense of value [... that] lies in becoming part of a community" [1, *p*.111] and how learning is motivated by the learner's ideas of who they want to become. Overall, if our goal is to facilitate makerspace learning environments in which more students can increasingly participate and become who they wish to be, this study offers four key considerations:

1. **Facilitate Students' Internal Map of Learning Resources:** Students are not always aware of the makerspace learning resources (e.g. persons, materials, machines) most relevant to their work. Also, depending on a student's familiarity with or perception of a learning resource, they may or may not feel that the resource is actually accessible to them. Faculty, staff, and student makerspace leaders may consider ways to build and expand students' internal maps of available learning resources including efforts to: clarify and reiterate for students the available physical, virtual, and people resources; actively build students' familiarity through interactions with resources; and demonstrate ways in which the resources can be useful to students' goals. By doing so, makerspace leaders can better support students as they expand and evolve their internal maps of learning resources and thereby understand how to participate in a MCoP.

2. **Reduce Barriers to Accessing Learning Resources:** Even after a student has constructed a preliminary, ever-evolving map of learning resources, they might perceive barriers to accessing these resources. While makerspace leaders may not be able to affect all barriers that students perceive, they can take steps to adjust the social norms and situational dynamics that obscure access for students. A dominant theme across our data is that the behavior of other actors in a makerspace influences students' participation and learning in the MCoP. This occurs through situation-specific interactions including: whether and how a student is observed or engaged by others; the engagements between others that a student observes; and whether or how a student observes or engages others (asking questions vs. practicing on one's own). By being in a makerspace and building a personal catalog of observations and engagements with others, students uncover the interactional dynamics and norms of the MCoP. Depending on what a student catalogs, they may come to feel that the makerspace is a relatively closed and lonely place where people come to do their own work versus a relatively open and collaborative place where people get to know one another and invest in each other's efforts (e.g. Cindy versus Jennifer and Victor in section 5.2). We recommend that makerspace leaders intentionally catalog the international dynamics and norms of their makerspace, including how these differ for different students, and work to reinforce norms that encourage an open and collaborative environment and discourage norms that obscure students' perceived access to learning resources.

3. **Curate Exemplar People:** Exemplars are important because they show what is possible in a makerspace; what is considered quality and worthwhile work; and who a newcomer might

become through participating in the community. We find exemplars take two forms. First, exemplars are people who exhibit mature practice and knowledgeably skilled identities such as makerspace faculty, CAs, and exceptional students who are viewed by MCoP members as "good" designers, makers, engineers, coaches, etc. MCoP newcomers observe exemplars' design and making practices, how they interact, who they interact with, and the legitimacy they confer upon others. Students also consider whether exemplars are "like me" and whether they are the kind of designer, maker, engineer, or person they might like to become. In this way, the cultural markers of a mature practitioner are intertwined with elements of identity such as race, gender, socioeconomic class, and professional identities. When considering who to elevate as staff, sanctioned volunteers, and celebrated students, makerspace leaders may consider whether and how exemplars' identities and interactional norms embody the intended values of the MCoP. This is important because exemplar people will convey to the community things like: "this is how good design and making is done," "this is how good guidance is given," and "this is what a good engineer looks like."

4. **Curate Exemplar Objects:** The second form of exemplars are objects that showcase quality design and craftsmanship. These include past projects, example tooling, drawings, operations sequences, models, portfolios, and other documentation. These may be displayed prominently throughout the makerspace, showcased in presentations, or stored away and revealed only when needed to provide guidance. In the PRL, exemplar objects (e.g. a curated selection of decades of sand casting patterns) are displayed on the walls in the place where students design and build such objects (e.g. the woodshop). Such objects are embodiments of cultural messages that communicate things like: "this is what a mature operation sequence looks like," "this is what a quality weld looks like," and "this is the kind of work that is celebrated here." Exemplar objects and the transparency of their cultural messages influence how learners understand the outputs of mature practice and how to emulate them.

Taken together, by facilitating the development of students' internal maps of learning resources, lowering barriers to accessing these resources, and intentionally developing and curating culturally transparent exemplar people and objects, makerspace leaders can help students to more clearly understand how to participate in a makerspace and who this may allow them to become.

The findings and considerations discussed above have implications for diversity and inclusion in makerspaces. Academic makerspaces may be viewed as microcosms of larger engineering and manufacturing practice, which have been described as historically "pale male" professions by William Wulf, former president of the U.S. National Academy of Engineering [29]. Building upon studies like Vossoughi et al. [30], this study aims to recognize the lived experiences of non-dominant identity students who engage in academic makerspaces, including the barriers they face in accessing learning resources, and the pathways they take to become more full participants in a makerspace community. Future work may further elucidate barriers to accessing learning resources in MCoPs or other engineering communities.

A limitation of our findings is that we have put great analytical focus on the resources that students access in relation to their learning. As indicated by other codes and emergent themes from our interviews (not presented here), factors such as emotions and even the physical layout of a space can have implications for how participation occurs. Though the findings presented here are intertwined with these factors, there is room for improving understanding of participation in makerspace by more directly considering such factors. Further, by taking an inductive theory-building approach, this study does not test the extent to which the described phenomena occur, how much they affect participation or learning outcomes, nor how much the findings generalize to contexts beyond the PRL. Using the framework of situated learning, this study provides an expanded view of learning in makerspaces and related environments. We invite future work that further elaborates or tests the findings through deductive study (e.g. quantitative associations, experiments, etc.).

7. CONCLUSION

This study uses the frame of situated learning to describe how students move from newcomer to more full participant in a makerspace community of practice. Upon entering a MCoP, students develop an ever-evolving internal map of the learning resources available to them. A student's perception of their available learning resources influences how they participate in and ultimately identify with the makerspace and associated community. We present a set of learning resources that students use in an academic makerspace, including physical, virtual, and people resources—machines, tools, materials, the internet, documents, peers, near-peers (CAs), and veterans of the community (faculty). Further, this work shows how students access MCoP learning resources (observing, practicing, asking, being observed) and how MCoP actors influence students' access to these resources. These later findings have implications for how and under what conditions different students make use of available learning resources and ultimately become more full participants in a MCoP. We close with four considerations for constructing makerspace learning environments that allow students of varied skill levels and backgrounds to more effectively participate in a makerspace community and thereby develop in their knowledge, skills, and identities as designers, makers, and/or engineers.

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