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Learning in Laboratories: How Undergraduates Participate in Engineering Research

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ABSTRACT: Survey studies find benefits for undergraduate students who participate in science and engineering research, especially for students from underrepresented groups. But scholars know little about what actually happens during students' research experiences that creates these desirable outcomes. We hypothesize that a crucial factor in students' learning and development of engineering identity is how they are socialized into a research community. Our study draws on theories from the fields of education and science and technology studies, such as expertise, identity formation, and situated learning in communities of practice. To investigate learning in labs, we conducted participant observation in two engineering laboratories in a medium-sized public research university for one academic year, which included attending meetings, interviewing lab members, and shadowing undergraduates. This paper presents four emerging themes from our analyses of the ethnographic data. First, engineers and students talk about undergraduate research with regards to a few undefined concepts that we suggest may be problematic. For example, PIs expect students to demonstrate "interest" in research. We suspect that PIs' perceptions of students could unintentionally exclude students from underrepresented groups. Second, the two labs talk about failure in different ways, namely as heroic and brave vs. as tragic and deserving of sympathy, which we suggest may be gendered. Gendered discourse styles may influence women's sense of belonging in engineering. Third, we used a new methodology to investigate undergraduates' conceptions of their expertise by asking them to narrate their thoughts as they filled out a T-shaped diagram. Their ideas challenge the theory of T-shaped expertise by suggesting that it does not account for how a student's expertise changes with time and experience. Fourth, lab members believe that undergraduates primarily provide labor, but we documented a variety of additional contributions. For example, undergraduates create opportunities for other lab members to learn, such as by asking questions that challenge others' assumptions. Thus, undergraduates are active participants in the construction of both knowledge and community in engineering labs.

Survey studies find benefits for undergraduate students who participate in science and engineering research, especially for students from groups that are underrepresented in science and engineering majors and careers [1]-[6]. For example, students with research experience tend to have stronger problem-solving skills and are more likely to go to graduate school and pursue a career in science or engineering. But scholars know little about what actually happens during students' research experiences that creates these desirable outcomes. Understanding how students learn and develop a sense of belonging in engineering by joining a research community will shed light on important issues of engineering education and professionalization and inform strategies for how research communities can better support students from underrepresented groups. We hypothesize that a crucial factor in students' learning and development of engineering identity is how they are socialized into a research community. Our study (funded by NSF EEC RFE 1606868) draws on theories from the fields of education and science and technology studies, such as expertise [7], identity formation [8], and situated learning [9].

To investigate learning in labs, we collected qualitative data about students' everyday interactions with communities of graduate students, postdocs, and PIs. We conducted participant observation in two engineering laboratories in a medium-sized public university for the academic year of 2016-2017, which included attending meetings and shadowing undergraduates during lab work. The labs are about the same size and are led by tenured professors. The labs belong to different disciplines (materials science and computer engineering) and have different gender representation, in that one lab is mostly women (with a woman PI, whom I call Kate) and the other is mostly men (with a man PI, whom I call Dan). We interviewed lab members about their experiences working together, to understand how undergraduates fit into research communities. We also interviewed the undergraduates about their perceptions of the expertise they gain by working in the lab. All participants signed consent forms and are represented here by pseudonyms.

This paper presents four emerging themes from preliminary analyses of our ethnographic data. Our study is ongoing, so these themes are hypotheses rather than conclusions. First, PIs expect undergraduate lab workers to express “interest” and “excitement” about research. We worry that assessing students according to how a professor perceives their “enthusiasm” can unintentionally exclude students who differ from the professor, such as by gender, race, class, or culture. Second, members of the two labs tell stories about failure to undergraduates in different ways, which serve as powerful modes of socialization. Discourse styles as reflected in communities’ storytelling may influence undergraduates’ sense of belonging. Third, we tried a new methodology of inviting students to discuss their different kinds and levels of expertise with regards to the concept of T-shaped expertise, i.e., having shallow and deep kinds of knowledge [10]. We found that this method inspired undergraduates to assess their own expertise and also offer critiques on the T-shaped concept, such as that it does not account for learning and changes in expertise. Fourth, lab members believe that undergraduates primarily provide labor, but we documented a variety of additional contributions. For example, undergraduates create opportunities for other lab members to learn, such as by asking questions that challenge others’ assumptions. Lab members also credit undergraduates with bringing fun to research, thanks to their enthusiasm and energy. Thus, undergraduates are active participants in the construction of both knowledge and community in engineering labs. Accordingly, this study proposes several avenues for additional research.

Narratives of Required Enthusiasm

In interviews, engineering professors said that they hire student lab workers who seem enthusiastic [11]. For example, Kate explained her normal procedure for hiring an undergraduate: “Usually [undergrads] approach me, say, ‘I’m looking for some research to do,’ and I show them around the lab, and if they seem excited about it then I’m more willing to take them on.” Excitement is not sufficient for selection, because Kate also expects curiosity and acceptable grades, but it is a significant factor. This practice implies a belief that performed interest correlates with motivation, work ethic, and even ability. Likewise, undergraduates explained to me that their “interest” and “passion” inspire them to join labs, choose certain majors, and work hard. Rather than investigating the validity of this belief, we suggest problematic implications of a mental model of success as dependent on enthusiasm. In particular, we see potential for unintentional discrimination by expecting good laboratory workers to behave in ways that PIs interpret as enthusiastic. But people express interest, motivation, and ability in different ways, depending on cultural background, race, gender, and class. Engineering professors in the United States are predominantly white and/or male [12]; by expecting students to behave as they do, professors risk privileging students who are like them.

An influential example of this belief is Max Weber's reflections on "Science as a Vocation", published in 1919. Weber claimed that being a scientist requires passion, inspiration, and hard work:

> Without this strange intoxication, ridiculed by every outsider; without this passion … you have no calling for science and you should do something else. For nothing is worthy of man as man unless he can pursue it with passionate devotion. [13, p. 135]

This "passionate devotion" is presented as characteristic of a scientific "calling" and therefore as a prerequisite for scientists. It does not necessarily refer to happiness, but rather a willingness to work hard to pursue a scientific career: "Both, enthusiasm and work, and above all both of them jointly, can entice the idea" [13, p. 136]. For Weber, a researcher needs enthusiasm alongside hard work to achieve a novel and important scientific idea. Employers can use the belief that workers should love their work to justify unpaid internships, employee surveillance, and dangerous overwork [14]. This expectation also implies Marxist false consciousness, in that workers' passion can obscure their awareness of their exploitation. Employers in care occupations assume that caregivers' "intrinsic reward" and "love" for their work motivate them strongly enough to accept low pay [15-16]. Expecting workers to be passionate also demands unpaid emotional labor [17], which may conflict with the expectation that scientists approach their work with objective, emotionally-detached rationality [18-19].

In the 21st century, psychologists and education scholars further perpetuate the idea of enthusiasm and interest as linked to motivation and inspiration. For example, undergraduates' "passion" for a subject correlates positively with their motivation and effort in that subject's courses [20] and undergraduates feel happier while doing something that they are passionate about [21]. I, and I imagine many other professors, hear a common refrain from students that they are working hard because they're interested in a topic (or the unfortunate opposite). However, we all pursue skills and knowledge that do not interest us, for reasons of necessity and external pressures, and we can achieve them without feeling or expressing enthusiasm. Undergraduate lab workers will be trusted with valuable equipment, data, and training time, so of course it is important for professors to choose the most capable candidates. However, assuming that students cannot succeed without expressing passion narrows the definition of a good researcher, and thereby has the potential to limit the kinds of people who are given the opportunity to become one.

The characteristics that researchers value for future researchers shed light on whom they invite into research careers and on the skills and social norms students learn by participating in research communities. Specifically, these two engineering professors expect undergraduates to express enthusiasm. PIs must select undergraduates somehow, to maximize the return on their investment of training and trust in students to handle expensive equipment and priceless data. We do not claim to know how to choose fairly; however, we suggest that all professors pay attention to how we select students for professional and educational opportunities. It is a ripe occasion for unintentional discrimination, through mechanisms such as implicit bias (i.e., unconscious beliefs we have about groups of people) and homophily (i.e., a human preference to interact with people who resemble us physically or culturally).

Socialization Through Storytelling

The process of initiating novices into research communities relies on the communication of tacit knowledge, behavioral norms, and moral values. Much of this instruction happens informally, as messages subtly embedded in everyday interactions. We observed that a key method of conveying knowledge about social behavior and technical practices is when a principal investigator or a graduate student tells an undergraduate about his or her experiences of mistakes and failures. As a powerful tool of socialization, these "disaster stories" contain messages of self-deprecation, humility, teamwork, and mutual learning. They generously offer novices the opportunity to learn vicariously through more experienced engineers' errors. I argue that disaster stories can reduce hierarchy, normalize learning through mistakes, and build relationships among workers through the sharing of humbling personal struggles. Thus these stories have the potential to promote collaboration, a sense of belonging, and the value of continuous learning for all lab members.

In Kate's materials science lab, graduate students tell disaster stories to help guide undergraduates' learning and performance of lab techniques. In one example, grad student Kenny was helping undergraduate Gretchen set up an experiment, which included cutting a thin glass tube to a certain length. Because Gretchen had not cut tubes before, Kenny narrated how to place the tube in a vice while Gretchen carried out his instructions. Kenny watched her actions and occasionally corrected them, either orally or by physically demonstrating what he wanted Gretchen to do. He was calm and friendly rather than demanding or critical, and egalitarian rather than dictatorial. When it was time to orient the glass-cutting apparatus, Kenny said, "I always mess up doing this." He then demonstrated the *wrong* way—the trap he apparently falls into—and then a better way, as Gretchen watched. He thereby showed Gretchen a pitfall so that she could avoid it. He shared his hard-learned lesson to save her the trouble of learning it from experience. Crucially, he said that he can and does "mess up," thereby admitting his own humanity and ongoing learning and lessening the power differential between Gretchen and him. A few minutes later, he similarly warned Gretchen, "Never hand-cut, it'll break it [the tube]. I've done that many times." He shook his head and rolled his eyes at this misdeed. He could have pulled rank by simply ordering her to "never" do it this way, but instead he offered his own experience of failure as evidence to convince her to follow his advice. Kenny is striving to prevent Gretchen's potential failures (at least the ones that he has already experienced), while also implicitly teaching her that failure happens, even to grad students.

Learning through others' experiences requires community. Therein lies the general power of storytelling, in that sharing stories encourages social interaction and helps unify how community members think. For example, in one meeting PI Dan explained to a new undergraduate worker that the finishing touch of the group's latest design for a computing system was "finding the last bug." To me, and I assume to the new undergrad, this sounded like a straightforward description of fixing the remaining errors in the system. But everyone else in the room laughed. Dan leaned over to the new undergraduate to clue him in, saying, "That's one of our jokes. You never find the last bug." This was a moment of simultaneous implicit/explicit and behavioral/technical socialization for the novice. He didn't understand the intended irony of Dan's statement, so Dan made it explicit. Dan thereby included the newcomer in the lab's shared knowledge of "our jokes" as a social lesson that humor is encouraged, which contributes to the new student's ability to practice interactional expertise in that lab, i.e., to understand and communicate [22]. Dan's joke also conveyed that there is no end to problems in research, as a technical lesson about the reality of lab work. This view of failure denies the possibility of perfect research, which perhaps lessens the pressure on lab members to achieve flawless work. It implies therefore that failure should not be a barrier to research or researchers' motivation, because it is always present. Joking about it also subtly forgives the unfortunate act of "finding bugs" and builds group unity by being a joke that outsiders don't understand. While not a disaster story, this humorous motto about failure conveys the community's beliefs about how to do good research and how to talk about it.

T-Shaped Expertise

We showed the five undergraduate students who work in the two laboratories a T-shaped diagram and engaged them in dialogue as they listed areas in which they were experts on the diagram. Because they work in laboratories, we hypothesized that these students would have a nuanced sense of their own and others' expertises in several engineering fields. This interactive protocol was recorded and transcribed. The prompt was, "Please put disciplines, practices and/or systems in which you feel you are an expert in the vertical bar. In the horizontal bar, please put disciplines, practices and/or systems you could talk about with an expert, using enough of their language and concepts so they would understand your questions and concerns." The horizontal bar indicates interactional expertise, which is the ability to speak the language of an expert community without being able to do what they do. The canonical example is how sociologist Harry Collins embedded himself in the gravitational wave physics community to the point where he could hold serious and deep conversations with experts about why and what they were doing although he had neither the mathematical nor practical skills to be an expert [23]. T-shaped expertise can incorporate Collins' interactional expertise, but also includes experience with different disciplinary systems.

We invited the students to modify the T diagram as they tried to identify and place their levels of expertise, and we asked them to explain their thinking as they worked. Their responses show a range of ways to interpret their own expertise, such as relative to others in their peer group or in the field. Consider one student's diagram:

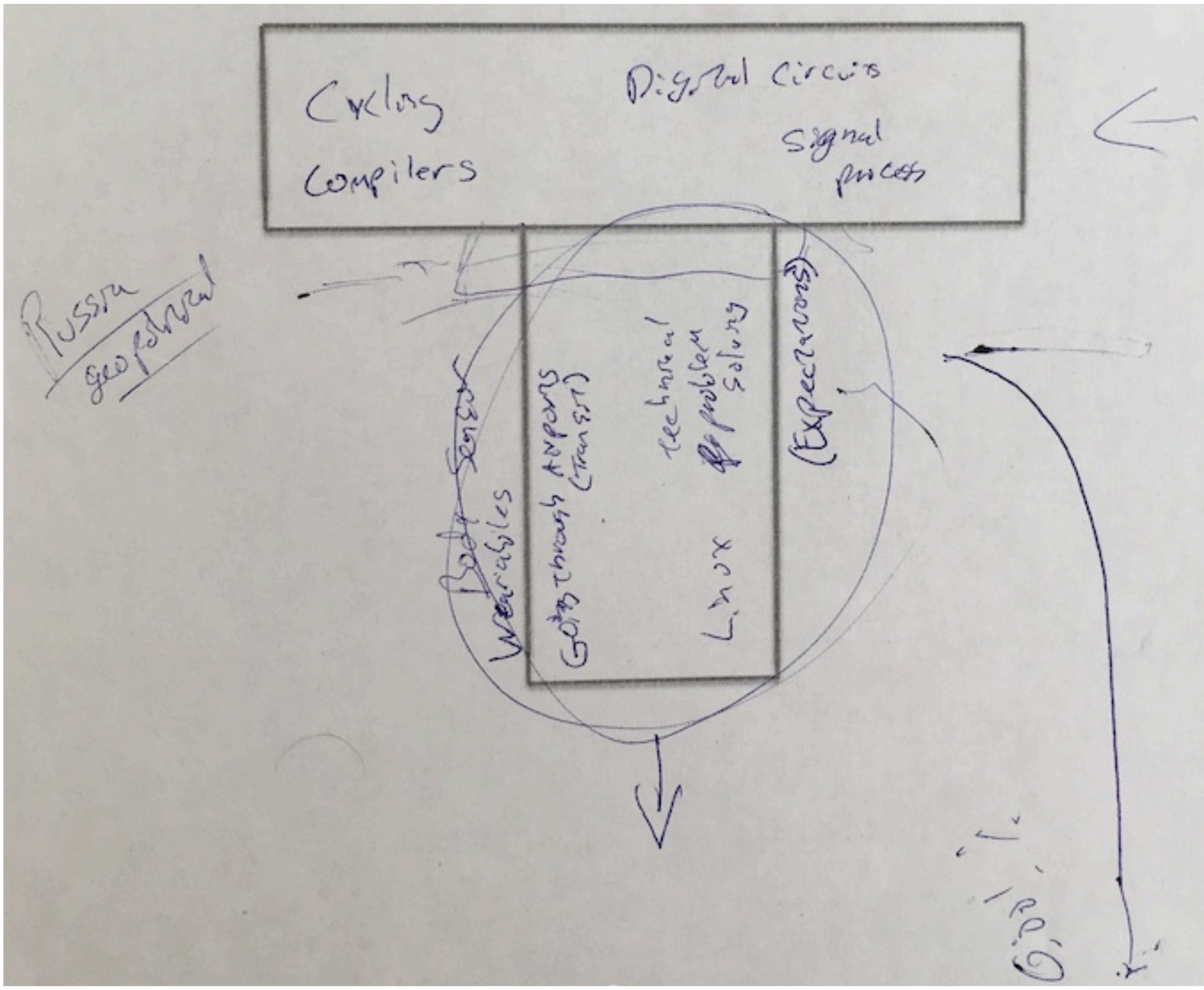

Figure 1: This student's deep expertises included Linux, technical problem-solving, and "going through airports (transport)." The shallow expertises included cycling, compilers, digital circuits, and signal processing.

The student commented that s/he was keeping the order of deep expertises increasing down the vertical axis, to represent expertise as a distribution with more general knowledge up towards the top of the vertical bar and more esoteric knowledge down at the bottom, where "you're like 0.001%" of the experts at this level (see bottom right of Figure 1). S/he placed "Russia" outside the T diagram because s/he had taken one course about US-Russian relations and found it very interesting but didn't want to claim shallow or deep expertise in the topic. Instead, it's a topic "I've had a lot of exposure to." For this student, exposure alone does not indicate expertise but still belongs somewhere on the diagram.

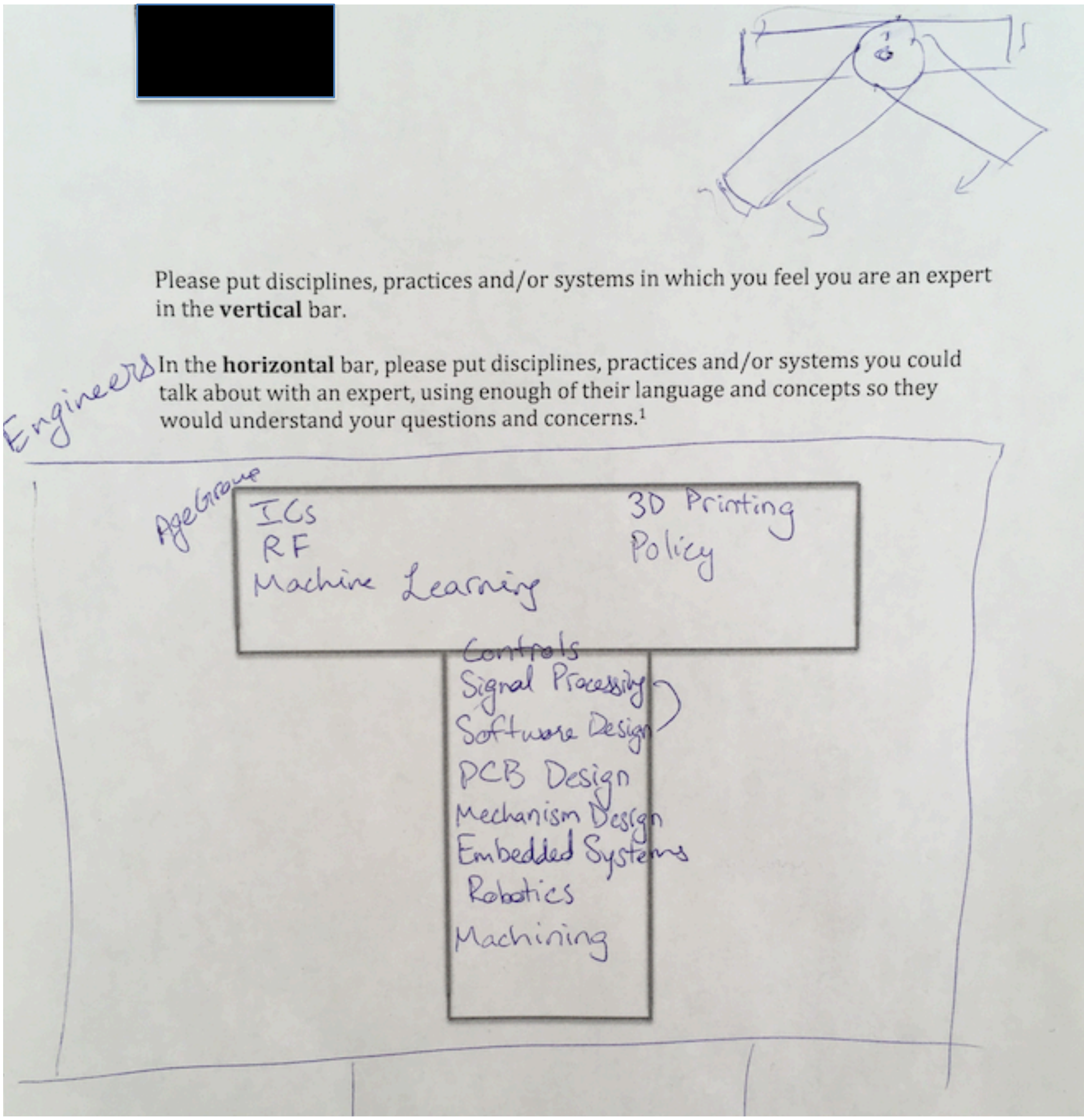

Figure 2: This student's deep expertises include controls, signal processing, and machining. The shallow expertises include 3D printing, radio frequency, and science policy.

This student created a version of the T that included the possibility of the horizontal arm rotating towards the vertical one to represent expertise as a dynamic category that changes as you learn (see top right of Figure 2). The student said that s/he "came in with zero signal processing background [but] now I think I can say that prong of signal processing has rotated down to the point where it's past the breadth but also not where I can say that it's vertical, like I'm a great expert in that area." The student also suggested that s/he "would draw a larger box around this first T. [The smaller T] would be [my expertise relative] to my age group and the larger would be the relative to all other engineers" (see Figure 2).

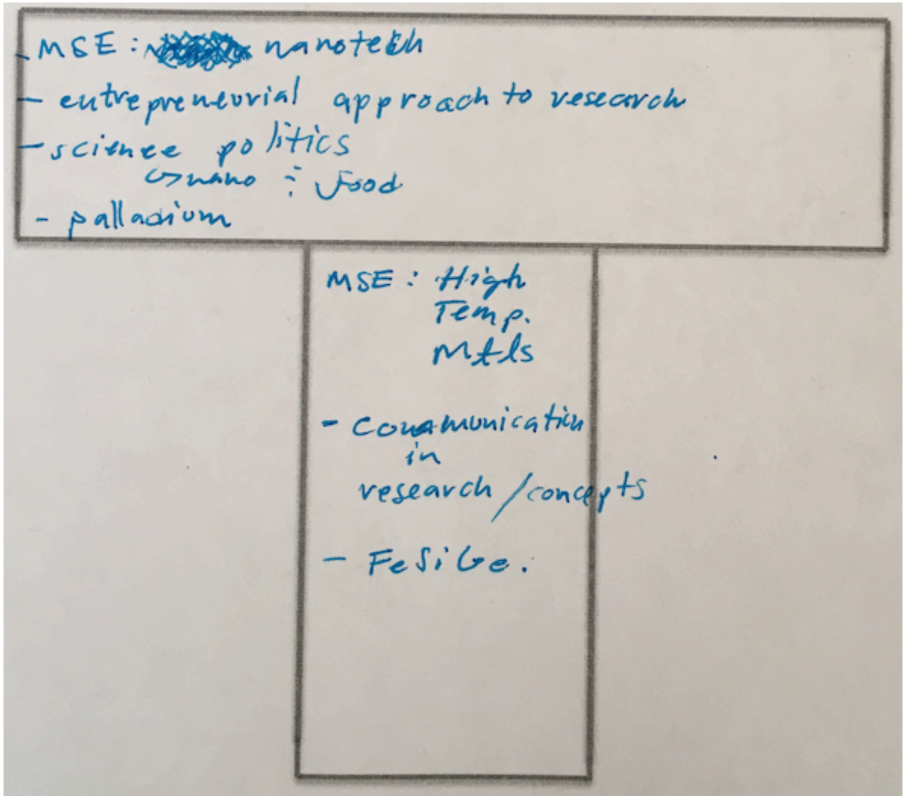

Figure 3: This student's deep expertises included high-temperature materials science, communication, and FeSiGe (a material s/he studies). The shallow expertises included nanotechnology, entrepreneurship, nanoscience, the politics of food, and palladium.

One student distinguished between the ability to talk about a topic and being an expert on that topic (Figure 3). This student works extensively with palladium as part of her/his contributions to the laboratory. Despite this experience, s/he said, "my expertise is on the lower end for palladium. I can talk about it but I wouldn't say I was an expert on it." Perhaps this assessment is a result of her/his exposure to published studies and hands-on realities of working with palladium, thus recognizing the broader field and his/her own place in it. Interactional expertise is the ability to talk about an expertise without being able to perform like an expert. So these diagrams show the validity of interactional expertise as a category that is worth teaching and assessing for undergraduates as novice researchers. The students did not know this term or concept when creating their diagrams—they arrived at it on their own.

These diagrams show that students who work in the labs we studied understand the T-shaped concept and can diagram it, making useful modifications to the diagram that reflect their understanding of expertise. Therefore, this method could be used to study the expertise students think they gain by working in laboratories.

How Undergraduates Contribute to Research Communities

Learners enable certain epistemic interactions in the lab thanks to their identities as *non*-experts. For example, PIs and grad students perceive undergraduates as low-stakes learners and broadly-educated, interdisciplinary scholars. Undergraduates take more diverse courses than grad students do and they have less experience in the lab's field, making them less indoctrinated. These attributes are why Kuhn credited most paradigm shifts to fields' relative newcomers [24, p. 90]. Likewise, undergraduates lack grad students' deep knowledge, but their flexibility and open-mindedness make them capable learners and thinkers. Dan's postdoc James explained this difference in terms of identity: "Entering graduate school, [students] may have a self-definition about 'I'm an electrical engineer,' 'I'm an engineer,' 'I'm a doctor.' The undergraduates don't have any definition about themselves. They are open for any kind of things." As a result, "sometimes I prefer more undergraduates instead of grads" in a lab, thanks to undergraduates' broad interests that are not yet restricted by a field-specific identity. Also, other members assume (often correctly) that undergraduates know little about the lab's work. As a result, they freely offer explanations, invite questions, and are relatively open to undergraduates' unorthodox ideas. In comparison, PIs and undergraduates expect grad students to have significant field-specific knowledge. This role arguably grants undergraduates more freedom to learn than graduate students, who have more invested in their reputation in the community as knowledgeable and professional.

Undergraduates bring ideas to the lab from their courses, previous experiences, and hobbies. They can be catalysts for trading zones [25] because they carry knowledge from various fields into the lab community, perhaps more than other members due to their ongoing broad education. Dan's grad student Edward credits this ability to undergraduates' use of social media to follow new trends in technology. He explained,

> Will and Rick know stuff that are more on the tech news, not on the textbooks … So they have better ideas … For example, me, I start thinking from, like, textbook style, "Is it possible to do?" But they say, "Yeah, it has been done, maybe not feasible in some cases," based on a [specific] project's perspective. It's nice to have those ideas.

Edward rejects Kuhn's [24] and Fleck's [26] portrayals of students as reservoirs of textbook knowledge (except for himself); instead, he admires undergraduates' ability to suggest cutting-edge approaches for the lab's research. For example, Edward credits Rick for improving how the group builds their sensor system by contributing cutting-edge skills drawn from experience instead of textbooks: "We would just protect [the sensors] somehow, using some casing. We never thought really about 3D printing. But then Rick said, 'Yeah, we can 3D-print' and the professor said, 'Yeah, that's a good idea.'" The undergraduate brought the grad students a novel idea (as well as his ability to achieve that idea), which they implemented. Dan's approval no doubt contributed to the decision to 3D-print casings, but everyone credits Rick for the idea. It seems that not knowing how sensors are typically protected enabled Rick to suggest an unconventional way to solve that problem based on his experience, which the community then adopted.

Undergraduates' ideas vary in practicality. Edward recounted Will's innovative solution to a problem with the group's sensor system: "We had this issue with the wifi routers … Will was saying, 'Why not use powerline data communication [instead]?'" Edward was impressed that Will knew about this emerging technology, about which Edward then read several research papers. He was less impressed with the technology's limitations: "It is the trend, but it's not really established and there is a lot of noise in the powerline data." He didn't adopt Will's suggestion; nonetheless, an undergraduate's open-mindedness and broad knowledge influenced a grad student's learning and decisions.

Undergraduates can serve as labs' windows on the world beyond the lab, as Rick and Will did above. Similarly, at a lab meeting Rick presented his idea for a new purpose for the lab's sensor systems: monitoring environmental factors that affect public health. His ability to understand the lab's systems and situate them in new uses is impressive, reflecting undergraduates' strong connection to fields outside the lab's and perhaps also to the "real world" of users because they have not yet become specialized researchers. Rick summarized a paper about a method of monitoring air quality as "It's [our] system on top of a stoplight," thereby using his personal interest in public health to broaden his coworkers' thinking and potentially the impact of their research. Likewise, undergraduate Gretchen's interest in mechanical engineering inspired Kate to think more broadly about her research. Kate told Gretchen about a grant proposal she was writing about alloys. She detailed, in technical terms, the experiments she wanted to include, then added, "I'm trying to make it relevant to the navy" to improve the proposal's chances of being funded. Gretchen asked whether the navy could use these alloys to build engine turbines. Kate answered thoughtfully, "Yes. Oh, maybe I'll put a picture of a ship turbine blade in there." While the PI was thinking about lab-based specifics, the undergraduate asked about general applications, thus creating an opportunity for the PI to consider a new perspective. The PI appreciated this angle and incorporated it in her research proposal. Perhaps non-experts can more comfortably play roles of innovators and outsiders than experts can. Without deep knowledge in the field, non-experts draw instead on wide-ranging experiences and knowledge.

Undergraduates' identity as lab novices means that they are encouraged to ask questions. PIs also invite questions from grad students but expect them to know more than undergraduates; therefore grads' questions are more risky for their reputations than are undergraduates.' Grads might be admonished for asking a "dumb" question, for example, while undergraduates would be forgiven. This grants undergraduates a privileged position as question-askers, which simultaneously provides opportunities for grads to hear answers to questions they may share but don't ask for fear of looking ignorant. In addition, undergraduates' questions and lack of deep knowledge create a demand for PIs and grads to explain ideas and instructions well, including contextualizing them in terms of what the undergraduates already know. This combination of expertise about a topic and about an audience, known as pedagogical content knowledge, is crucial for effective teaching and communication [27]. Answering novices' questions can improve the answerers' own understanding of concepts and inspire them to think about their knowledge from different perspectives.

Undergraduates often invite PIs' and graduate students to make their assumptions explicit by asking seemingly basic questions. Kate's grad student Laurie, for example, was showing undergraduate Jessie how to use a machine that measures chemical bonds. A graph of measurements popped up on a computer screen, and Laurie rejected it as lacking any "peaks." She adjusted a parameter on the machine, explaining to Jessie: "I know from experience there's a lot of noise [i.e., meaningless results]. You want the [graph] lines to be smoother, so upping the power can smooth it out." She ran the analysis with higher power. The new results showed one tall, thin peak which Laurie dismissed, saying, "That's cosmic." She raised the machine's power and ran the test again. Jessie asked, “What was wrong with that one?” Laurie said absently as she worked on the computer, “It’s called a cosmic ray. It’s not data.” She contrasted the cosmic “spikey” peak with a desirable “smoother,” “broad” peak. This is a typical example of undergraduates’ frequent requests for justification. Explaining tasks requires researchers to reflect on how and why they do that work and how to communicate those reasons to non-experts (e.g., undergraduates). Schön argues that such “reflection-in-action,” i.e., questioning one’s assumptions and routines while enacting them, enables professionals to better identify problems and adapt their practices accordingly [28]. Undergraduates’ in-the-moment demands for explanations can thereby illuminate the assumptions that underlie “normal science” [24] by asking grad students and PIs to explain. For example, which results are data and not data is obvious to Laurie but not to Jessie. Articulating the difference means that Laurie thinks through her actions and choices, creating an opportunity for error-spotting and new ideas. When not teaching an undergrad, Laurie probably does not think about why she dismisses cosmic rays. Thus this common interaction around undergraduates’ questions has the potential to inspire graduate students to revise their assumptions or routines.

Some labs value undergraduates as knowledgeable enough to understand the field yet not specialized enough to be mired in isolated conversations with experts. Kate relies on undergraduates to judge the accessibility of grad students’ presentations in lab meetings, precisely for their lack of deep knowledge. For example, after grad student Sam finished a practice conference talk, he commented that it is targeted at the conference’s audience so “it’s tough to understand this talk” if you’re not an expert. Kate asked Jessie, “How’d it go for you?”, making Jessie a test case for whether non-experts could understand Sam’s talk. Jessie rarely speaks in meetings, but she did not hesitate to respond to Kate’s question. She told Sam that she understood his results but the experimental setup “went over my head.” She also asked why he used the oxygen isotope O_{18} instead of the more common O_{16}. Kate, impressed, said, “That’s a really valuable question. Thank you.” The grad students then discussed where to add the answer to Jessie’s isotope question into Sam’s presentation. It’s possible an undergraduate could have been scolded for questioning a methodological choice. Instead, the non-expert’s confusion served as a guide to improve the expert’s communication skills. This situation resembles interactional expertise, in that Jessie can talk competently about a field without necessarily contributing to it (i.e., contributory expertise [7]). Grad students benefit from knowing when their presentations are too specialized and “go over [the] head” of educated generalists such as undergraduates. In response, grad students acquire widely-applicable communication skills in the form of pedagogical content knowledge, i.e., they learn to recognize concepts that only experts know and to explain them effectively to non-experts.

Another way in which undergraduates create learning opportunities for lab members is by serving as mentees, thereby enabling grad students to learn how to mentor. Most studies assume that mentors are faculty; however, most undergraduate lab workers interact more often with grad students than with PIs and they describe grads as more approachable than PIs [29]. Good and coauthors found that undergraduates from underrepresented racial and ethnic groups who served as peer mentors reported benefits to their own learning and professional skills [30]; it’s logical to assume that grad student mentors from underrepresented groups, and perhaps all grads, earn similar benefits. Serving as a mentor may also build grad students’ confidence by reminding them how much they have learned since they were undergraduates. Undergraduates give grads opportunities to learn how to communicate with and manage others, a valuable professional skill. Dan's postdoc James argued that this is the most important reason to include undergraduates in a research group: "I think [teaching undergraduates] is not very helpful for the project, but it's very helpful for grad students to learn how to teach the junior students." He believes that undergraduates' presence benefits grad students' development more than the lab's research. Thus even by doing simple tasks, novices can instigate important learning mechanisms for other community members.

Few labs or institutions formally teach experts how to work with non-experts. Likewise, grad students learn to work with undergraduates primarily through experience and by observing the PI's approach [29]. We observed senior grad students performing more effective mentoring and teaching than newer grad students, suggesting that students acquire or at least improve these skills during grad school. For example, as senior grad student Alison helped undergraduate Frank set up an apparatus in Kate's lab, she gently quizzed him about the procedure and accepted or corrected his answers. She created opportunities for him to practice, reinforce, and show off his understanding and for her to assess how well he knows the procedure. In one instance, I asked both of them what results the apparatus produces, and Alison said to Frank, "You can answer that." Frank answered, then asked Alison if he was right. She agreed, and elaborated by explaining what can be learned from those results. Alison artfully boosted Frank's confidence by inviting him to demonstrate knowledge she knew he had, and then she added to his knowledge by sharing her own. She probably acquired these skills by observing Kate's mentorship methods and by working with undergraduates in the lab for several years. In comparison, Kate's grad student Kenny is about halfway through graduate school and is still learning to work with undergraduates. For example, when undergraduate Gretchen was explaining a tool to me, Kenny interrupted her to provide the explanation himself. He preferred the role of information-provider to standing back to let the undergraduate demonstrate her knowledge. Gretchen allowed herself to be interrupted, probably in deference to Kenny's higher status as a grad student and his presumed greater expertise. There could also be a gendered component to this exchange, in that men tend to interrupt more often than women and women tend to acquiesce to being cut off more often than men [31]. A grad's eagerness to showcase his knowledge over an undergraduate's suggests that he hasn't yet learned how to create space for mentees to practice and take credit for what they know.

Undergraduates clearly provide labor, ideas, and learning opportunities for lab communities. Other contributions, such as conveying enthusiasm and strengthening relationships among lab workers, are subtle though powerful influences on lab culture and knowledge production. Both PIs describe undergraduates as "fun", based on the enthusiasm and energy they express about lab work. Similarly, Gary Fine found that amateur naturalists express excitement about their work in ways that scientists don't [32]. In addition, amateur mushroom collectors' enthusiastic interest in mycologists' research and expertise made the scientists feel encouraged and valued [32]. Undergraduates can play this role in laboratories, by expressing wonder and interest in work that more experienced researchers might find mundane. Undergraduate Jessie, for example, was weighing and photographing material samples before they were experimented on, a task Kate considers "grunt work". But after an hour of this work, Jessie held up a sample to show me its unusual surface appearance. She examined it closely and explained what looked unusual. Her sense of wonder and attention to detail do not match Kate's perception of sample preparation as monotonous. Kate appreciates this undergraduate trait. She told me, "I forget sometimes [that] I've been immersed in this [research] so long. [Undergrads] have helped me because … it's fun seeing them so excited about stuff and so that excites me too." Undergraduates' enthusiasm can therefore remind lab members of their own interest in their research, which they may otherwise take for granted.

Undergraduates can bring humor and informality to a lab. For example, undergraduate Gretchen often imitates TV presenter Bill Nye by crying, "Science!" with great excitement. Once, Gretchen was quietly leaving a lab meeting early, and Kate interrupted the meeting to say goodbye to her. Gretchen waved and said, "Off to do *more* science!", meaning to go to class. Kate responded by yelling, "Science!" and pumping her fist. Everyone laughed. The PI instigated this moment of levity in an otherwise business-like meeting in response to an undergraduate's enthusiasm and charming naiveté. Kate's action was funny because everyone knew she was imitating Gretchen. Without that backstory, Kate shouting "Science!" would have seemed strange. PIs and grad students who express strong emotions through somewhat silly actions like Gretchen's might be chastised as unprofessional or not serious about their research.

Undergrads, however, are excused from these expectations, perhaps for their youth and inexperience. The PIs and grad students tend to see occasional undergraduate antics as funny and harmless, rather than disruptive or childish (assuming none of it affects lab work or safety). Undergraduate Will often teases grad students, such as about individuals' night-owl or slacker work schedules, reliance on caffeine, and past mistakes. They either tease him back or ignore him. Will proudly told me stories about lab shenanigans, such as jousting in the lab's rolling chairs with the grad students. No one seems offended or frustrated with this somewhat juvenile behavior. The undergraduates' behavior also creates space for the PIs and grads to play along and share the joke, as Kate did. Dan is quick to joke around with undergrads, but tends to be more businesslike with grad students. After all, Dan has more at stake in grad students' success than in undergrads'. Likewise, grad students have invested significant effort and career aspirations in their lab work and therefore take it seriously. Undergraduates have little to lose in lab work, and their lightheartedness is often rewarded with others' laughter and participation. These factors might encourage undergraduates to goof off. Grads and PIs of course can be humorous in their own right; however, undergraduates have a striking power to lighten the mood.

Bringing wonder and fun to labs, which notoriously harbor stressed grad students and PIs under pressure, is just one of many ways in which undergraduates can help connect lab workers. Another way is that Will and Rick often do homework in the lab, and grads wander over to see what they're studying. Often the grads discuss the problem sets and offer help, occasionally gloating that they no longer take classes. Undergraduate homework therefore can unite a group of grads with disparate projects and expertise, because they all understand the foundations of their field as captured in problem sets. Undergraduates can also shape researchers' interactions outside the lab. One undergraduate visiting Dan's lab for the summer complained that she'd been told that "paid lunches were a thing in this lab, but they're not." Dan laughed and said, "I guess you're volunteering," implying that she should organize one. The undergraduate looked uncomfortable, but grad students eagerly picked up the idea and started planning a catered lunch. The undergraduate's time-limited visit to the lab created an occasion for a special event, an idea that had not occurred to the PI and grad students who work in the lab long-term. The presence of undergraduates who are younger than the legal drinking age also shapes how groups interact outside the lab. Kate's group wanted to visit a bar to celebrate the start of the academic year, but they didn't want to exclude Jessie and Gretchen, who were underage. So they chose a restaurant that served alcohol instead of a bar. People behave differently in bars than in restaurants; this decision most likely affected how the group practiced informal relationship-building.

Undergraduates' lab work also helps build relationships. Will and Rick, as mentioned, create websites and 3D-print parts for multiple projects, which means everyone in the lab works with them. Grad student Edward explained that the undergraduates "participate in all the projects but according to their expertise … The grad students orient in a different manner. For example, I'm in charge of these two projects. The other projects … use techniques that we use, but I don't participate in those." Undergraduates apply their specific skills for all project groups, while grad students tend to apply theirs only for their own group. As a result of this unwritten norm, Edward credits undergraduates for improving communication in the lab: "Will and Rick participate in multiple projects with multiple subgroups, so we interact more with everyone else … Whereas before, I mean, if I was doing something, I didn't really care what he was doing or someone else was doing. But now it's more dynamic." Grad students tend to focus on one project, making them potentially isolated. But undergraduates integrate seamlessly into project cliques and travel frequently among groups, creating opportunities for everyone to talk. David Kaiser argues that postdocs, a newly created position in mid-20th-century physics, played this circulating role by traveling between institutions every few years, thereby transporting ideas and methods between somewhat isolated research groups [33]. John Law observed that technicians also circulate freely among research groups, causing an unintentional and often unrecognized cross-pollination of ideas [34].

Edward likened undergraduates' travel between project groups to "Brownian motion", in which particles collide at random and thereby change each other's paths. He described undergraduates' movements as altering groups' plans, because undergraduates share ideas they learn from other groups, coursework, and hobbies. Undergraduates can thereby influence grads' plans, ways of thinking, and behavior as well as their own, as Brownian particles exchange energy and shape new trajectories. These exchanges between lab members, though, happen more intentionally than the pure randomness of Brownian motion. Kate's undergraduate Jessie similarly described herself as bouncing between people in the lab, typically in search of help: "If I don't know what to do, then I refer to either the grad students or Kate, whoever I see first [laughs]. Sometimes the grad students will tell me to ask Kate, [then] Kate will tell me to ask someone else." Her view of herself, like Edward's view of undergrads, is as a dynamic force freely interacting with everyone in the lab. These interactions enable the undergraduates' successful work, such as by achieving answers to questions, and also shape how grads and PIs think about and do research.

Lab members talk about working with undergraduates in similar ways to working with collaborators from other labs. Dan's grad student Larry explained that he relies on Rick for advice about 3D printing and designing circuits, continuing,

> That's one of the things I like about the lab. Dan always says that we don't like to pretend that we know things, so most of the projects involve people from the medical area or psychology or different [fields]. Then when we don't know, we just go and ask them.

Today's knowledge is specialized and divided, meaning that research often requires collaboration between various kinds of experts. Larry counts undergraduates as potential collaborators with knowledge that he needs. Larry may have learned this perspective from postdoc James, who told me that he had encouraged Larry to learn to work with undergraduates by assigning him a summer student as a mentee. James told me, "Teaching the junior students … and building a team, it takes a longer time but once you finish and once you really build a very good team, it will save you so much time. It will save your life." This perspective places undergraduates as a valuable part of a research team, despite their required training time.

Conclusion

These preliminary results from our ongoing study show the power of ethnographic methods for investigating undergraduate research experience. Our participant observation and interviews capture the subtle nuances of laboratory workers' beliefs about good researchers, storytelling, notions of expertise, and undergraduates' epistemic and social contributions to research communities. These trends raise questions about how socialization in engineering laboratories may inadvertently create barriers to participation in undergraduate research and therefore in engineering careers. Further studies on how PIs choose undergraduate workers and how lab storytelling styles affect students' sense of belonging would offer insights into the development of engineering identity. These studies could inspire strategies to make research communities more inclusive by altering recruitment strategies and discourse styles. The study also raises questions about the effects of mentoring undergraduates on graduate students and PIs. For example, do non-experts' questions inspire reflection-in-action, novel perspectives, improved communication skills, and/or a stronger sense of engineering expertise and identity for graduate students and PIs? In addition to raising important future research questions about engineering education, this study demonstrates that undergraduates play diverse and multidimensional roles in research communities. Thus, studies of collaboration and laboratory culture should include undergraduates as relevant actors.

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