Graduate/Undergraduate Partnerships (GradUP): How Graduate and Undergraduate Students Learn Research Skills Together

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ABSTRACT: Research skills, such as collaborating with others and identifying and producing "good" evidence, are crucial for future engineers and are difficult to learn. Students in academic research communities must learn research skills in order to conduct everyday experimental and design work. How then do the students learn how to ask appropriate research questions, carry out methodologies, interpret evidence, and draw evidence-based conclusions? One valuable way to study how students learn research skills is to watch how graduate and undergraduate students work together to do research. Based on ethnographic observations of pairs of graduate and undergraduate engineers working in four research laboratories, we define five categories of strategies that students use to learn crucial research skills from each other: asking questions, demonstration, supervised attempts, trial and error, and imitation. Our study shows that communities of practice, such as engineering research groups, are valuable sites for graduate and undergraduate students to learn crucial research skills. In addition, these five interaction strategies are relatively stable, even across different research groups, disciplines, demographics, and levels of education. These strategies help facilitate the learning and teaching process within each undergraduate and graduate pair. We found that undergraduate and graduate students learn a great deal from these partnerships, though they tend to learn different things. This finding suggests that partnering novice and advanced researchers can help fill gaps in both partners' technical and professional knowledge and skills about research.

Research skills, such as collaborating with others and identifying and producing "good" evidence, are crucial for future engineers and are difficult to learn. These skills overlap with other categories such as professional skills, technical skills, and "soft" skills. They are necessary for conducting research, although they are rarely explicitly defined. Scholars in Science and Technology Studies (STS) have gained important insights into how *experts*, such as engineers and scientists, do research (e.g., [1][2]); however, in many academic research communities, *students*, not experts, make crucial decisions about methodological designs, techniques, and practices as part of their everyday laboratory work. How then do students learn the subtle, foundational work of asking research questions, producing and interpreting evidence, and drawing evidence-based conclusions? How can educators encourage and improve this learning?

One valuable way to study students' everyday decision-making about research is to watch how graduate and undergraduate students work together to produce and assess evidence in laboratories, in formal or informal graduate/undergraduate partnerships that we call GradUPs. We draw from the theory of situated learning in communities of practice [3] to understand students' mutual learning. Based on ethnographic observations of pairs of graduate and undergraduate engineers working in four research laboratories, we investigate how students learn crucial research skills from each other. In general, all the students learned professional skills, such as communication and collaboration, while the undergraduates also learned technical skills, such as how to conduct laboratory work. In addition, the graduate students benefitted from self-reflection about their research routines and assumptions thanks to undergraduates' questions and suggestions.

This paper investigates the interaction styles that undergraduate and graduate students use while doing research together in GradUPs. These styles are informal strategies that students develop and deploy by working together, not from instructions from textbooks, coursework, or formal training. Graduate and undergraduate students typically receive no formal training in teaching, mentoring, or collaboration before they work together; thus, they fill this gap by devising strategies for teaching and learning based on their own experiences. It is likely that students adopt strategies from their faculty advisors or other instructors; however, students typically work together on research more often than they work with faculty. Therefore, this study focuses on students only, although future research should address how faculty influence teaching and learning in GradUPs. How undergraduate and graduate students ask questions, express comprehension or confusion, and propose new ideas offers insights into how collaborators with different education levels and social statuses can exchange knowledge and achieve mutual learning. Understanding these in-situ learning processes can inform strategies for creating inclusive opportunities for students (and faculty) with different levels of expertise and research experience to collaborate and learn from each other.

Previous Studies about Learning Research Skills

There is widespread interest in incorporating research skills into engineering education, as a crucial technical and professional component of engineering work. However, educators disagree about how best to achieve this goal. Some institutions teach courses in research skills, either as part of coursework [4], research programs [5], or teaching programs [6]. Others expect students to acquire research skills through authentic research experience (for undergraduates, see [7], ch. 4; for graduate students, see [8]) or teaching experience (see [9]; [10]). Most studies in engineering education focus on undergraduates' learning, including the importance of training graduate students as research mentors in order to improve the undergraduate mentees' learning (e.g., [11]). There are a few studies of how students learn social and technical knowledge by being socialized as members of research communities; however, these studies only investigate graduate students [12]–[15]. We strive to address this gap by studying learning interactions between graduate and undergraduate students while they do research together. There are only a few studies that follow this approach (e.g., [9], [16]–[18]), and, like our study, they find that graduate and undergraduate students learn important but different skills from working with each other. In general, undergraduates in these previous studies report learning more applied skills, such as how to operate machines or perform protocols, while graduate students report learning more professional skills, such as leadership and mentoring. Both levels of students tend to perceive improvements in their abilities to communicate and collaborate. However, we witnessed graduate students as well as undergraduates improving their comprehension of technical concepts and techniques, and undergraduates as well as graduate students learning social norms and practicing professional skills of asking questions, assessing and sharing their own knowledge, and serving as leaders and mentors. Our study investigates the complex processes that underlie graduate/undergraduate mutual learning in research communities, and proposes that research partnerships are an important and understudied way in which graduate and undergraduate students learn research skills.

Most studies only investigate how undergraduates learn to do research, perhaps based on an incorrect assumption that graduate students transfer knowledge to undergraduates and do not learn from the mentoring process or from the undergraduates. A few studies are beginning to valuably evaluate graduate students' learning in research partnerships with undergraduates (e.g., [9], [11], [19]). These studies reveal that students' collaborations are more complex than a top-down knowledge delivery. In our study, we found that students exchange knowledge when working together on research, despite their hierarchical differences as graduate and undergraduate students, while also constructing new knowledge together. Undergraduates who do research report gains in their research skills, such as problem-solving, communication, and experimental design [20], [21], and they are more likely to stay in engineering fields and careers [22], [23], especially students from underrepresented groups in STEM [24]. Undergraduates also report feeling more comfortable with graduate students than professors [17], suggesting that they might prefer the informality and lower stakes of student-to-student learning in GradUPs. Thanks to working with undergraduates on research, graduate students report gains in their communication skills, confidence, and knowledge of their field's technical knowledge [16], [25]. How then are these students learning from and teaching each other?

Methodology

We used qualitative methods and an interpretive approach for this exploratory study, to identify students' strategies in action as the basis for future studies and educational interventions. Wylie observed and interviewed pairs of graduate and undergraduate students who worked together in four engineering research laboratories at a mid-sized public research university in the United States in 2017-2018. The labs were in the disciplines of electrical engineering, materials science (two labs), and systems engineering. The overall project compares the labs across disciplines, numbers of people in a lab, and levels of representation of students from marginalized groups in engineering (Table 1).

Pseudonym	**Field**	**# of group members**	**Women**	**Underrepresented minorities**
Corrosion Lab	Materials science	14	8	1
Electronics Lab	Materials science	5	3	1
Health Systems Lab	Systems engineering	4	3	0
Sensor Systems Lab	Electrical engineering	12	1	2

Table 1: Lab demographics

This paper analyzes data from Wylie's fieldnotes about observations of the student pairs while working in the lab and having meetings. Kim, Campo, and Linville coded these qualitative fieldnotes for patterns in how students learned from and taught each other, using grounded theory and inductive analysis [26]. We identified recurring patterns in how the undergraduates, graduate students, and PIs interacted. This paper presents these patterns, categorized as five common interaction styles. We selected two examples from each lab to illustrate common ways in which lab members in general interact. These examples show that lab members usually deploy multiple interaction styles in a single situation.

<u>Results</u>

In this section, we analyze observed interactions from each lab to define the five categories of interaction styles (see Table 2) and demonstrate how students use these styles in combination with each other in pursuit of collective learning and teaching.

Interaction style	**Description**
Asking questions	This interaction style takes two forms: seeking information (e.g., a student asks another student a question to clarify something they do not understand) and evaluating knowledge (e.g., a student asks questions to solicit a brief-back from another student, to assess how well the asked student understands a technique or concept).
Demonstration	A student demonstrates to another student how to perform an action. The demonstrator explains as they physically go through the process. Physical demonstration is important for revealing the tacit knowledge (i.e., unarticulated knowledge [27]) required for the action.
Supervised attempt	This style typically follows demonstration. A student attempts to recreate another student's demonstration, while the demonstrator supervises and evaluates the attempt.
Trial and error	A student learns from mistakes, either indirectly through stories of mistakes as told by another student or directly through collaborative problem-solving with another student.
Imitation	A student learns by observing other lab members and copying their behavior, without being explicitly told to do so. This is a subtle and sometimes unconscious learning style, comparable to learning through immersion in a community of practice.

Table 2: Interaction styles used between students in GradUPs. Note that graduate or undergraduate students can play the roles of learner and instructor, depending on the situation.

Corrosion Lab (Materials Science)

Undergraduates in Corrosion Lab are primarily taught to operate equipment to collect data for the graduate students' research projects. For example, graduate student Joe taught undergraduate Liam how to operate the scanning electron microscope (SEM) so that Liam could collect micrographs of Joe's material samples. First, Joe defined the machine's parameters for Liam, such as that "higher magnitude means higher spot size, lower magnitude and depth of field means lower spot size." During this explanation, Liam asked Joe a question: "How does the SEM deal with temperature changes?" Liam is seeking information that will influence how he operates the machine. Not only does the process of asking questions reduce uncertainty for the learner, it also establishes a relationship and work environment in which asking questions is allowed and even encouraged. Joe answered Liam's question, confirming his own role as a supportive instructor. Joe then demonstrated how to use the SEM, narrating his actions as he set up the imaging process. For example, as he focused the SEM on one area of a sample, the screen blurred. Joe explained, "If it's smearing like that while we're focusing, it means stigmation is off." Joe thereby identified a kind of feedback from the machine, what it means, and how to respond to it (i.e., by correcting the stigmation). By going through his actions step by step, Joe has the opportunity to explain them to Liam, so that Liam can understand the normal steps as well as when to adapt those steps based on feedback from the machine.

We noticed that demonstration can be instructive to the graduate student as well as the undergraduate. Specifically, narrating and explaining one's steps provides an unusual opportunity for the graduate student to review and polish their research skills. For example, Joe taught Liam how to cut samples in cross-section to prepare them for the SEM. As he demonstrated and narrated how to place a sample in a vise to hold it against the saw, Joe warned,

> 50% of the time I end up cutting the side with the holes, which doesn't work. [laughs] It's the opposite side! Now that I'm showing you, I'm thinking more about what I'm doing, so I'm not going to screw it up this time.

Joe noticed that he was thinking more deeply about his actions in order to explain them to Liam, which helped him avoid making mistakes. Crucially, by admitting a mistake he commonly makes, Joe is inviting Liam to learn from Joe's own trial and error. One moral of Joe's story about cutting the wrong side of the sample is "don't do what I did," a generous and humble invitation to Liam to learn from Joe's mistake and be spared the trouble of learning by making that time-wasting mistake himself. For more on storytelling as an instructional strategy, see [28]. Another moral is that teaching an undergraduate makes Joe think about what he is doing; he becomes aware of his own problem-solving processes and can imagine ways to improve them. This important skill is a form of metacognition.

After an instructor demonstrates an action, they typically invite the learner to try to imitate it, to learn by doing and to receive immediate feedback and advice from the demonstrator. We call this strategy a supervised attempt. For example, Joe taught Liam how to hang samples from a clip and then coat them in epoxy to prepare them for the SEM. Joe narrated as he worked, "I hold the cup [of epoxy] beneath as I drip epoxy over the sample from just below the clip … That's it. Go ahead." Joe handed Liam the dropper of epoxy. Liam replied confidently, "Okay, seems straightforward," and began dripping epoxy over the sample as Joe had. Joe watched and then commented, "Sometimes I guide the epoxy along, closer to the bottom. As long as you get the whole surface, it's fine." Joe was not criticizing Liam's technique, but rather offering advice and defining the overall goal of the task, i.e., to coat the sample's surface. He is letting Liam know which aspects of the task are flexible, i.e., how he covers the surface, and which are not, i.e., that the surface must be covered. Liam coated a few samples as Joe watched. As Liam hung up one sample, the clip broke off in his hand. Joe said reassuringly, "No worries, it happens. Put the pin in the next clip." Liam apologized, "My bad." This scenario exemplifies the value of a supervised attempt: it creates an opportunity for the learner to experience both normal and abnormal actions (e.g., a broken clip) through trial and error, while also receiving immediate reassurance and advice from a more experienced practitioner. It also provides an opportunity for the instructor to assess the learner's progress and decide whether to trust them to do the task alone. In this example, the graduate student told the undergraduate that the problem he just experienced happens often and can be solved by using another clip. Joe let Liam continue trying, possibly indicating that one can only learn by practicing. In addition, it is likely that Liam is gaining a better understanding of how to handle the equipment, which will help him avoid making the same mistake, such as perhaps by handling the clips more gently. Liam continued to coat the samples for a few minutes as Joe watched. Then Joe nodded approvingly, commented, "Make sure to get the back [of the samples]," and walked away, signaling that Liam had proven himself capable of epoxying samples without supervision.

Electronics Lab (Materials Science)

In Electronics Lab, graduate student Lucien was helping undergraduate Jessie collect data for Jessie's capstone research. This unusual setup is the opposite of Corrosion Lab's undergraduates' role as assistants on the graduate students' research. Furthermore, Jessie had significant research experience in materials science (though not in electronic materials), unlike Liam in Corrosion Lab, who had no prior experience in materials science research. As a result, Lucien and Jessie worked more as collaborators than as an instructor and a learner. Despite these differences in experience levels and divisions of labor, all the students in this study's four labs relied on the strategies of asking questions to seek information and assess each other's knowledge, demonstration to share practical skills and explain normal and abnormal outcomes, and trial and error.

Electronics Lab members Lucien and Jessie worked together to figure out how to operate a complex experimental setup that included components that only one or the other of them knew how to operate. Thus, they divided the labor and took turns explaining the components to each other. For example, Lucien demonstrated how to prepare and mount a sample for an experiment, which Jessie had not done before. While Jessie watched, he narrated some of his actions and worked in silence during other actions. He explained that the sample was "flexible" because it's so thin, as he used Scotch tape to remove a contaminated layer of the sample. He carefully moved the cleaned sample to a container, then rinsed the mounting plate it had been on because, he explained, the tape had touched it and perhaps contaminated it. But Lucien did not narrate other aspects of this action, nor did he invite Jessie to do a supervised attempt, perhaps because Lucien did not expect Jessie to prepare future samples herself. Lucien asked if she had questions, and Jessie said no. She was watching his actions closely, and when Lucien finished she retrieved a notebook from her backpack to write down what he had done, so that she could later write about the research methods in her capstone paper. She was reporting his work, as a collaborator, rather than learning how to do that work herself.

After Lucien prepared the sample and performed the experiment as Jessie watched, then Jessie performed an imaging technique on the sample, because she had experience using that technique and Lucien did not. She pointed at parts of the imaging machine and told Lucien what they were, such as the detector, the arm, and the stage. She started to set up the machine and then stopped, saying, "I thought it'd be straightforward. I know what I need to do, but I'm not sure how to do it. It's easy to change the angle, but I don't know how to change the path [of the imaging detector]." She checked the machine's manual to look for the answer to her question. Lucien watched her without saying anything for a few minutes, then suggested following the protocol in a published paper that Jessie had been working with. She showed him how she was trying to do just that, but that it wasn't working. She explained that she had only done "student" things on this machine before – "I haven't played around with it" to learn all of its settings, such as how to change the path. Lucien asked, "Is there someone we can ask? A technician?" Together, they were brainstorming ways to solve this problem. Following Lucien's suggestion, Jessie emailed the person in charge of the machine to ask for help. She explained to Lucien, "I set the takeoff angle to 6 degrees and that might work." Lucien asked, "Can you set the initial and final angles to be the same?" Jessie said, "No, I thought I could but I can't control that. It's an old [machine], so maybe it just doesn't let me control that." They both stared at the machine, unsure of what to do. Jessie invited Lucien to try it, which he did with some trepidation: "It'll just be a maze [of settings]," he worried. Jessie affirmed his concern, saying, "I don't want to change things too much" on the machine's settings in case they inadvertently broke something. Lucien agreed, saying, "I'm worried I'm going to double-click something and ruin it." Jessie commiserated, "Yeah, like crash the detector into something. I've come this far without breaking anything!" Both the undergraduate and graduate student were working together as equals, bouncing knowledge and ideas off each other to try to problem-solve when neither of them knew exactly what to do.

Health Systems Lab

In Health Systems Lab, undergraduate Zoe was tasked with building an online dashboard to organize large datasets that the other lab members would later analyze. The datasets were for a study comparing participants' activity levels, as measured by wearable sensors, with their health outcomes. Zoe worked closely with postdoctoral researcher Darius to design and program the dashboard. Although Darius is no longer a graduate student, he played the same mentoring role that graduate students often play for undergraduate researchers. Throughout their year-long learning/teaching process, Zoe asked Darius numerous questions about the practical aspects of dashboard-building as well as the epistemic meanings of the data they were working with. For example, she asked Darius, "Fat is 0.00. What does that mean?" Darius replied, "Good question. It's not calculated from other data ... Let's see. We have always zero. That's weird. We need to check." Zoe didn't necessarily need to know the meaning of the data to organize it in the dashboard, but she asked Darius about it to get a broader understanding of what was important about the data. She also wanted to make sure that it wasn't a problem that all the values for the "fat" measurements were zero. When Darius didn't know why the values were zero, he and Zoe problem-solved together:

> Zoe: I can check the files you sent me against the ones I sent you. [She compares the files.] It's always zero. Does it mean people have to input fat values?
> Darius: I think so.
> Zoe: And they're not doing that?
> Darius: Yeah. [The sensor] can estimate it but it needs some initial values.
> Zoe: Okay, like weight or something?
> Darius: Let's check whether [the sensor] can do that.

This example illustrates two collaborators trying to learn where the data come from, such as measurements or calculations based on participants' self-reported inputs. They were indirectly also learning about the challenge of getting participants to input their own data. This information is arguably crucial for Zoe to design a functional dashboard and also to learn about how to study human subjects. However, Darius did not volunteer this information; he only thought to share it in response to Zoe's question. Thus, the undergraduate's question played an important role in guiding the information that she learned from the postdoc as well as what the postdoc knew about the sources of the data.

Darius expected Zoe to code the dashboard by herself, as the only way to learn how to program. Every week he gave her a task and then expected her to figure out how to achieve it before their next meeting. This trial-and-error strategy required Zoe to assess her own knowledge and then find out the answers to her own questions, from Darius as well as from other sources. For example, Zoe told Wylie as they walked together to a meeting with Darius, "I figured out [how to code] triggers over the break. I read the first whole page of Google results, every result, like 12 of them. Didn't get it. Then I watched a video today that explained each line as the guy coded a trigger. I think I got it now." By learning on her own through trial and error (e.g., by Googling and watching online tutorial videos), Zoe is practicing critical problem-solving skills that are essential to research as well as independent learning. After trying to work out how to do her tasks on her own, Zoe would bring her attempts to Darius, who would then correct her mistakes, offer advice, direct her to more sources of information, and answer her remaining questions, as in the conversation above. Seeking out knowledge and trying to accomplish tasks on her own meant that Zoe developed specific questions for Darius that were very productive for both of them, by getting the information Zoe needed and by informing Darius what Zoe did and did not understand. Zoe was also subtly learning how to be an independent learner and how to behave as a member of this research community.

Sensor Systems Lab

Unlike the other labs, Sensor Systems Lab lacks a formal, structured mentor-mentee relationship. Instead of assigning a specific graduate student to mentor each undergraduate, the PI invites the undergraduates to create their own niche within the lab. The undergraduates typically bring specialized skill sets that make them an integral part of whatever project they join. For example, all lab members, including graduate students, defer to undergraduate Rick when it comes to 3D-printing components for the sensors that the group designs and builds. As the group's expert on 3D printing, Rick is responsible for most of that work and only occasionally teaches it to other lab members. The group tends to divide their labor based on who already knows how to do which tasks, rather than training others to do multiple tasks. As a result, the students rarely demonstrate techniques for each other or supervise each other's attempts.

Despite these differences, as in the other labs Sensor Systems Lab students rely on asking questions, both to seek information and to evaluate their own and others' knowledge. Because these undergraduates are expected to seek out graduate students to find out how to contribute to a project, they ask questions as an active way to learn about the group's projects and about how to do tasks for those projects. They also practice brief-back, in which a learner repeats information back to an instructor to check or prove their understanding. Because of the distributed expertise among graduate and undergraduate students, as for Lucien and Jessie in Electronics Lab, both groups play the roles of learner and instructor based on the situation. For example, graduate student Robert asked undergraduate Steve to introduce him to a program that Steve had helped code, so that Robert could begin working with that program. For example, they discussed the purposes of several lines of the code while they both stared at Robert's desktop computer screen:

> Steve: [Line] 125. Initially this receives three bytes, so it's checking something or receiving metadata. So it's receiving initial stuff to see if it's okay, and then it tries to get the real data.
>
> Robert: So it's checking to see if it's good data, and then getting the data?
>
> Steve: Hold on, it sets the length of the message to itself, so this should equal three here, I think. Because after it's received the data, this should be three bytes. So the message isn't the message anymore, it's the length of what it used to be, itself, so it's three bytes.
>
> Robert: So [line] 122 sets the message length to three.
>
> Steve: That's what I'm assuming.

In this excerpt, Robert uses brief-back twice, first to repeat Steve's explanation that the program is checking the incoming data and then downloading it, and again later to repeat Steve's explanation of line 122. In the first instance, Steve doesn't respond to Robert's interpretation because he is distracted by trying to interpret the previous lines of code. In the second instance, he agrees, confirming Robert's attempt to understand the code. Robert's questions in this excerpt are not seeking new information, but rather stating his understanding in a way that invites Steve's approval or correction. Thus, brief-back is a valuable way for a learner to ask the instructor to evaluate their knowledge in real time, which can invite feedback or show the instructor that the learner understands.

The students in Sensor Systems Lab are aware of their own learning through imitation, in which they observe others and, consciously or unconsciously, try to imitate their actions. In this interaction style, students pick up knowledge that is not explicitly taught. This is a widely used learning strategy, but it can be difficult for learners to realize when they are using it. Nonetheless, undergraduate Regina told Wylie in an interview, "I learned a lot about professionalism in this lab, like just from, you know, the lab meetings everyone brings their notebook and their pen, so now I know to do that. I know how to behave a bit more, like during a lab meeting." No one specifically instructed Regina to bring a notebook to meetings; rather, she saw other students doing it and copied them, in an attempt to fit in and learn to belong in the group. Regina is right that what she calls "professionalism," i.e., social norms in certain situations, is rarely defined or explained. Newcomers learn these behavioral norms by imitating others in the community of practice, and sometimes by being corrected if they break an implicit social norm. Everyone learns through imitation and immersion, but few of the students we studied mentioned or seemed aware of this interaction style. Perhaps Regina and other Sensor Systems Lab students were aware of their learning through imitation because of the relative rarity of explicit teaching and learning. We suspect that the students who did not mention this learning style are unaware that they learn social norms through observation and imitation, or perhaps they considered it such an obvious way of learning that it wasn't worth mentioning in interviews as a learning strategy. This lack of metacognitive awareness (i.e., awareness of their own learning processes) about imitation deserves further research and perhaps interventions to help students recognize how they learn social and technical research skills.

Discussion: Implications for engineering education

Our study shows that communities of practice, such as engineering research groups, are valuable sites for students to learn crucial research skills, such as how to learn, collaborate, and collect and analyze data. Students apply certain behavioral strategies to try to make their interactions with each other educational, respectful, and productive. Some of these strategies may seem obvious, such as asking questions and demonstrating. However, our observations reveal the nuances of applying these strategies in action, such as asking questions to seek information *or* to assess one's own or others' knowledge. In addition, not all teaching or learning strategies are active. For example, one purpose of demonstrating an action for a learner is to allow them to watch the tacit knowledge embedded in that task. If the instructor doesn't think to articulate that knowledge or it cannot be articulated (i.e., it is tacit knowledge [27]), then the learner can still witness how the instructor applies that knowledge during the demonstration. Also, learning by immersion, or what we call imitation, is a crucial mechanism of socialization but can be difficult to capture in studies because learners may lack awareness (i.e., metacognition) that they are imitating their community members. Regina's comment about bringing a notebook to meetings demonstrates this subtle but widespread form of learning. Also, this strategy is usually studied in young children, not in adults. Our results show that imitation continues to be an important learning strategy for adults. This strategy deserves more research, including how it overlaps with other strategies.

Furthermore, we observed all of these strategies in use in all four labs, suggesting that the strategies are relatively stable, even across different research groups, disciplines, and levels of education (i.e., undergraduate vs graduate students). Crucially, students use these strategies in various combinations to both teach and learn, a useful flexibility that allows adaptation to different situations. Students also exchanged roles of instructor and learner, depending on who had more expertise about a specific task. We suggest that combining strategies and exchanging roles can produce outcomes that are greater than the sum of the parts.

It is interesting to note that knowledge and skills do not travel in one direction, such as solely from graduate students to undergraduates as one might assume based on graduate students' longer time spent in higher education and research. Instead, both categories of students learn from working with each other, sometimes consciously alternating between the roles of teacher and learner and sometimes unconsciously creating opportunities for their partner to teach or learn, such as by asking questions and sharing ideas. This finding suggests that creating more opportunities for students of different levels to work together is a valuable way for all the students to improve their research skills.

Our study raises important questions about the effects of these strategies on students' sense of identity as an engineer and their sense of belonging in engineering, particularly for students from underrepresented groups. For example, asking questions requires a student to be assertive and to admit what they don't understand, which can be intimidating for all students and particularly so for students who experience discrimination or feel marginalized in engineering research communities [29]. In comparison, perhaps practicing mutual trial and error with a graduate student mentor could help undergraduates feel appreciated for their knowledge and problem-solving skills. Which of these strategies empower and disempower students based on their identities and backgrounds, and in which situations and combinations of strategies, deserves further study.

This study doesn't focus on *what* students learn, but rather *how*. However, our hypothesis based on these findings is that graduate students and undergraduates tend to learn different things from working together, as previous studies have found [9][11][16][19][25], but that these learned skills overlap more than students and education scholars realize. For example, the undergraduates in our study certainly gained technical skills in the practical work of doing research, such as conducting protocols, operating machines, and managing experiments. But, perhaps without realizing it, they also learned professional skills, such as how to problem-solve, ask questions, assess their own knowledge, and behave in meetings. Similarly, the graduate students certainly gained professional skills, such as communication, project management, and leadership, but they also acquired a deeper understanding of the techniques and concepts that they were explaining to the undergraduates. Further study can test this comparison between which kinds of skills each group tends to acquire by working together. Clearly, these skills are all important for future engineers to master, and learning them relies on collaboration and relationship-building.

Conclusion

This study examines how students learn from and with each other while working on research in graduate/undergraduate partnerships (GradUPs). We observed that students use five distinct interaction styles, in various context-dependent combinations, to teach and learn from each other: asking questions, demonstration, supervised attempt, trial and error, and imitation (see Table 2). These strategies help students seek information, assess their own and others' knowledge, improve their technical skills, and build relationships with each other. We found that both undergraduate and graduate students learn a great deal from these partnerships. This finding suggests that partnering novice and advanced researchers can help fill gaps in both partners' technical and professional knowledge and skills.

Future studies might build on these preliminary findings by investigating when and where students first develop these strategies, whether they change over time (such as if a GradUP continues beyond one academic year), and whether students adopt the practices they witness other students or faculty advisors deploying. Another crucial question raised by this study is whether and how students adapt these strategies or develop different strategies to facilitate the inclusion of underrepresented groups. For example, which strategies do students find more empowering or more disempowering? Future studies might also assess learning in quantitative ways to build on the findings from our qualitative interviews and observations, such as a pre/post questionnaire or rubric-based observations of task performance. Also, it would be useful to compare the efficacy of different strategies in various situations, to identify whether certain interaction styles better serve specific purposes. These insights are valuable for defining and practicing research skills for undergraduate and graduate students. Our findings could also inform training programs for graduate and undergraduate students as well as for faculty and others who work with multilevel research teams.

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