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Exploring the Human Infrastructure of University Makerspaces: Undergraduate Mentors, Makers, and the Development of Adaptive Expertise

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Abstract

This empirical qualitative full paper examines the human infrastructure that sustains university makerspaces, with particular attention to the roles undergraduate mentors play in supporting learning and innovation. Drawing on interviews with current and former undergraduate makerspace mentors from a single, large engineering program's makerspace network, this qualitative study explores how mentoring practices shape experiential learning and the development of adaptive expertise in informal learning contexts beyond formal coursework. Makerspaces are now central to many engineering programs, supporting design, fabrication, and hands-on learning across the curriculum. Prior research has documented their contributions to creativity, engagement, and design learning, yet comparatively little attention has been given to the people who make these spaces function educationally. This study addresses that gap by focusing on undergraduate mentors as educators-in-practice who mediate access to tools, guide problem solving, and model ways of thinking under uncertainty. Using theories of adaptive expertise and experiential learning as interpretive lenses, this work examines how mentors foster learning environments that emphasize reflection, iteration, and judgment rather than procedural efficiency alone.

The study is grounded in adaptive expertise and experiential learning frameworks, which conceptualize learning as situated, iterative, and socially mediated. Semi-structured interviews were conducted with four current and former undergraduate makerspace mentors whose technical backgrounds included additive manufacturing, machining, electronics, and mechatronics. Interviews were transcribed and analyzed using inductive thematic analysis to identify recurring patterns in how mentors described their roles, interactions with students, and perceptions of effective mentorship.

Across interviews, mentors emphasized that interpersonal and adaptive skills were more critical to effective mentorship than prior technical mastery. While technical skills were viewed as useful, mentors described them as learnable on the job. In contrast, curiosity, communication, situational judgment, and willingness to learn alongside others were identified as essential. Mentors described supporting students by asking questions, helping them navigate uncertainty, and encouraging persistence through failure. Participants also highlighted the role of mentors in sustaining community and institutional knowledge within makerspaces, particularly in the face of faculty turnover, shifting departmental priorities, and access constraints.

These findings suggest that the educational value of makerspaces depends not only on equipment and space, but on the people who support learning within them. Within the studied context, makerspace staffing models that prioritize mentoring capacity, adaptive mindsets, and relational skills may better support experiential learning and the development of adaptive expertise. This study contributes empirically grounded insight into how undergraduate mentors shape learning in university makerspaces as informal engineering education environments.

Keywords: adaptive expertise; experiential learning; mentoring; makerspaces; engineering education

Introduction

This empirical qualitative full paper focuses on how university makerspaces have become a visible and influential component of engineering education. These spaces provide students with access to tools, materials, and environments where ideas can be tested, revised, and made tangible. Beyond supporting coursework, makerspaces foster experimentation, peer learning, and forms of engagement that are difficult to achieve in traditional classroom settings. For many students, they represent a shift from abstract problem solving to embodied engineering practice. At the same time, the nature of engineering work continues to evolve. Engineers are increasingly expected to operate in contexts defined by uncertainty, competing constraints, and incomplete information. Success in these environments requires more than procedural efficiency or technical correctness. It requires the ability to adapt, reflect, and reframe problems as conditions change. Yet much of undergraduate engineering education remains oriented toward routine expertise, emphasizing well-structured problems with predetermined solutions [2]. While this approach produces efficient problem solvers, it often leaves students underprepared for the ambiguity and complexity of real engineering practice. When thoughtfully supported, makerspaces offer a counterpoint to this dominant instructional model. They create conditions for experiential learning in which students encounter open-ended problems, learn through failure, and develop judgment about design and manufacturing trade-offs. These experiences align closely with the development of adaptive expertise, which emphasizes balancing efficiency with innovation and applying knowledge flexibly across contexts [1,2]. Prior work has shown that coaching, iteration, and structured opportunities for reflection can foster adaptive expertise in design-focused learning environments [3].

However, the educational impact of a makerspace is not determined by equipment alone. Tools do not teach students how to think. Learning in these spaces is shaped by the people who staff them, guide interactions, and model approaches to problem solving. Undergraduate makerspace mentors play a central role in mediating access to tools, supporting students in moments of uncertainty, and establishing norms around safety, collaboration, and experimentation. Despite their importance, mentors are often discussed primarily in terms of staffing models or operational cost rather than as contributors to learning and pedagogy [5,6]. As a result, the educational role of undergraduate mentors is often implicit rather than explicitly examined in engineering education research.

This study focuses on the human infrastructure of engineering makerspaces, specifically the undergraduate mentors who support day-to-day learning and making. Through interviews with current and former makerspace mentors, this research examines what mentors do in practice, how they understand their roles, and which skills and dispositions matter most for effective mentorship. Rather than positioning mentors as technicians or safety monitors, this work frames them as educators-in-practice who shape learning through interaction, guidance, and example. The study is exploratory in nature and is intended to provide in-depth insight rather than broad generalization. By examining makerspace mentorship through the lenses of adaptive expertise and experiential learning [1–4], this study contributes to engineering education research by foregrounding the pedagogical role of undergraduate mentors in informal learning environments. The findings offer insight into how staffing decisions, mentoring practices, and organizational structures influence not only what students make, but how they learn to think, adapt, and persist as engineers.

Background

This study approaches university makerspaces as learning environments where expertise is developed through experience, interaction, and reflection rather than through direct instruction alone. To examine how learning is supported in these spaces, this work draws on theories of adaptive expertise and experiential learning as complementary lenses. Together, these frameworks provide a way to understand how undergraduate makerspace mentors shape learning by guiding students through uncertainty, iteration, and sensemaking in informal engineering education contexts. Adaptive expertise distinguishes between routine and flexible forms of problem solving. Routine expertise emphasizes efficiency and accuracy within familiar contexts, whereas adaptive expertise involves the ability to reframe problems, innovate, and respond productively when conditions change or solutions fail [1,2]. Engineering education has traditionally emphasized routine expertise through structured problems and standardized methods. While this approach builds technical competence, it often underrepresents the judgment and adaptability required in authentic engineering practice.

Research has extended adaptive expertise into engineering and design contexts by emphasizing reflection, problem framing, and strategic decision making. Neeley's theory of adaptive design expertise characterizes design as a dynamic process in which engineers shift between action and reflection as constraints evolve [1]. Similarly, McKenna and colleagues describe adaptive experts as those who balance efficiency with innovation while navigating ambiguity [2,9]. These perspectives frame expertise not only as what engineers know, but as how they respond when familiar approaches no longer suffice in complex, ill-structured situations. Experiential learning theory further clarifies how adaptive expertise develops in practice. Kolb's experiential learning cycle emphasizes learning as an iterative process involving concrete experience, reflection, conceptualization, and experimentation [4]. Makerspaces naturally support this cycle through hands-on fabrication, failure, and revision. However, experience alone does not guarantee learning. Without guidance and opportunities for reflection, students may focus on task completion rather than deeper understanding. Mentoring plays a critical role in mediating experiential learning by helping students interpret outcomes and connect experience to broader design principles and engineering ways of thinking.

Prior research on makerspaces has documented their educational potential and institutional motivations for adoption [6,7]. Studies have also examined staffing structures, noting that personnel costs represent a substantial portion of makerspace investment [6], and have highlighted leadership development and peer learning among undergraduate staff [5]. While this work establishes the importance of staffing, mentors are often treated descriptively or operationally rather than as contributors to learning and pedagogy. As a result, the pedagogical dimensions of undergraduate mentorship remain underexamined. This study addresses that gap by focusing on undergraduate makerspace mentors as educators-in-practice who enact adaptive expertise through everyday interactions. Mentors operate at the boundary between students, tools, and institutional structures, translating abstract design principles into situated guidance and supporting reflection in the moment. Prior work has shown that coaching and structured guidance can foster adaptive expertise in formal design contexts [3]. This study extends that work into informal learning environments, examining how similar pedagogical practices emerge within makerspaces through day-to-day mentoring interactions.

By using adaptive expertise and experiential learning as interpretive lenses, this work frames undergraduate mentorship as a key component of makerspace learning withing the studied context. This perspective shifts attention away from equipment and infrastructure alone and toward the human relationships and mentoring practices that shape how students learn to navigate uncertainty, failure, and design complexity in engineering education.

Methods

Research Design

This study employed a qualitative research design using semi-structured, one-on-one interviews to examine how undergraduate makerspace mentors understand and enact their roles in supporting learning. A qualitative approach was selected to capture the situated nature of mentoring practices and how mentors make judgments while supporting students in makerspaces [5]. This approach was well suited to the exploratory aims of the study and to examining mentoring as it is enacted in practice rather than prescribed in policy or training materials. The interview protocol was designed to elicit reflective accounts of mentoring practice rather than task-level descriptions. Questions prompted participants to describe typical interactions, challenging situations, and decision-making related to safety, design guidance, and student support. While a shared protocol guided each interview, follow-up questions were adapted to probe participant experiences and clarify emerging ideas as interviews progressed.

Participants and Context

Participants included four current and former undergraduate engineering students who served as mentors within a university makerspace network at a large undergraduate engineering program. Mentors represented a range of technical domains, including additive manufacturing, machining, electronics, and mechatronics, providing insight into mentoring across spaces with varying levels of risk, equipment complexity, and access constraints. Participants varied in length of service and mentoring responsibilities, allowing for perspectives across different stages of mentorship experience. The first author brought over four years of experience working within the same makerspace ecosystem, including responsibilities related to staff training, equipment oversight, and student support. This positionality informed the study design and interpretation and was addressed through reflexive practices throughout the research process, including memoing and ongoing attention to how prior experience shaped analytic decisions.

Data Collection

Interviews were conducted remotely using Zoom and audio recorded with participant consent. Each interview followed a semi-structured format to ensure consistency while allowing mentors to describe their experiences in their own terms. Interview questions addressed mentoring roles, interactions with students and faculty, perceived barriers to effective mentorship, and skills required to support learning in makerspaces (see Appendix). Audio recordings were transcribed verbatim and served as the primary data source for analysis.

Data Analysis

Data were analyzed using inductive thematic analysis. Transcripts were read multiple times to identify recurring ideas and patterns across participant accounts. Initial codes were generated directly from the data rather than from predefined categories. The first author conducted the coding, iteratively refining codes and grouping them into higher-level themes through repeated engagement with the data. Codes were iteratively refined and grouped into higher-level themes related to mentoring practices, skill development, community building, and organizational constraints. Reflexive memos were maintained throughout the analysis to document analytic decisions and emerging interpretations, and points of alignment with adaptive expertise and experiential learning frameworks.

Research Questions

The analysis was guided by the following research questions:

1. What staffing characteristics support effective undergraduate mentorship in engineering makerspaces?
2. What skills and dispositions are necessary for undergraduate makerspace mentors?
3. How do mentors describe their interactions with students in practice?
4. How do organizational structures influence mentoring and learning in makerspaces?

Scope and Limitations

This study provides an in-depth qualitative examination within a specific institutional context. The intent is not to generalize findings across all engineering makerspaces, but to offer empirically grounded insight into mentoring practices and organizational conditions that shape learning. Given the exploratory nature of the study and the small sample size, findings should be interpreted as illustrative rather than representative. Findings are situated within existing literature on adaptive expertise and experiential learning [1–4] and are intended to inform future research and practice related to makerspace mentorship.

Results

This section presents patterns observed across interview data from undergraduate makerspace mentors. The results focus on what participants described about their experiences, roles, skills, and interactions within makerspaces. Interpretation and theoretical synthesis are addressed in the subsequent Findings section.

Mentorship Experiences and Mentor–Student Interactions

Participants consistently described their experiences as undergraduate makerspace mentors as positive and formative. Mentors emphasized learning through hands-on practice, enjoyment in supporting others, and sustained engagement with making and engineering:

"Mike: I got a lot of experience on how to build things and how not to build things because you really learn by doing things incorrectly. So, when you have a couple hundred people a year trying to build things, stuff goes wrong a lot."

"Paige: I can say that being a mentor has by far been one of my favorite things that I've gotten to do in college. I love learning about engineering education. I love seeing people learn new things and absorb new things… it's one of my favorite things and it's definitely an honor and a privilege."

Several mentors noted that mentoring reinforced their own learning and provided opportunities to develop leadership and communication skills.

Mentors described interactions with students as guided rather than directive. Participants emphasized asking questions, helping students clarify goals, and supporting decision making throughout design and manufacturing processes:
"Carter: …being able to guide the teams from the start of the project throughout the design process and into the manufacturing process definitely seems to have a better outcome…"

Mentors also described redirecting students who fixated on early solutions:
"James: A lot of times, people will find themselves… pigeonholing themselves into a solution instead of looking at the actual problem."

Roles, Responsibilities, and Skills of Undergraduate Makerspace Mentors
Participants described their roles as multifaceted, including safety oversight, technical support, and knowledge sharing. Mentors emphasized that they were not expected to know everything, but rather to help students access information and resources:
"Mike: You don't necessarily need to be the best at what you do; you just need to know how to get there."
"Carter: …a student coach to basically promote safety within the shop…"

Mentors also described serving as intermediaries between students and faculty and maintaining continuity across student cohorts.

Across interviews, mentors emphasized interpersonal and adaptive skills as central to effective mentorship. Participants frequently cited curiosity, communication, leadership, and willingness to learn:
"Mike: Problem solving, curiosity, good people skills."

Leadership and authority were described as particularly important in safety-related situations.
"Carter: Definitely very strong leadership skills and the ability to say no…"

While technical skills were discussed, mentors consistently described them as learnable within the role:
"James: Honestly, I'd say no… you can still be an effective mentor purely with the drive to learn."

Organizational Context, Constraints, and Community
Participants described organizational factors that shaped their ability to mentor effectively. Mentors noted that faculty turnover, inconsistent departmental support, and changes in access policies influenced mentorship continuity.

“Paige: …it feels like every single year, it’s about to fall apart, and we’re constantly trying to not get it to fall apart.”

Changes to physical access and visibility were described as limiting informal interaction:
“James: …the door was propped open. ‘Hey. Come in here. Make stuff.’”

Mentors emphasized the importance of community within the makerspace environment. Participants described relying on one another for support, sharing expertise, and maintaining institutional knowledge.
“Mike: I would never be where I’m at right now without the community…”
“Carter: …having the community of mentors to look up to… definitely fairly important.”

Across interviews, undergraduate makerspace mentors described a role that involved guiding learning, supporting safety, sharing knowledge, and sustaining community. These results illustrate how mentors experience their work and articulate the skills, interactions, and organizational conditions that shape mentorship in engineering makerspaces.

Findings

Building on the interview results, this section synthesizes the data into four findings that explain how undergraduate makerspace mentors support learning and how organizational conditions shape the educational function of makerspaces. These findings represent analytic interpretations grounded in participant accounts and informed by the theoretical lenses described above.

Finding 1: Undergraduate makerspace mentors function as educators who scaffold learning through interaction
Across interviews, mentors described practices that align with teaching rather than technical troubleshooting alone. Mentors guided students through questioning, reframing, and iteration, helping them articulate goals and recognize misalignments between problems and proposed solutions. These practices mirror coaching approaches associated with the development of adaptive expertise in engineering design contexts [1–3].

Rather than prioritizing efficiency or correctness, mentors emphasized supporting reflection during moments of uncertainty. This approach aligns with experiential learning processes in which concrete experience is paired with reflection and conceptual adjustment [4]. Through repeated exposure to this mentoring style, students encounter opportunities to develop judgment, persistence, and flexibility in problem solving.

Finding 2: Adaptive and interpersonal skills are prioritized over prior technical mastery
Mentors consistently valued adaptive and interpersonal skills more highly than incoming technical expertise. While technical skills were described as useful, they were viewed as learnable within the role. In contrast, curiosity, communication, leadership, and willingness to learn alongside others were identified as foundational to effective mentorship.

This emphasis reflects key characteristics of adaptive expertise, particularly the ability to navigate uncertainty and adjust strategies in unfamiliar situations [1,2]. Mentors who openly acknowledged gaps in their own knowledge modeled learning behaviors that reinforced exploration and inquiry as acceptable and expected.

Finding 3: Mentorship sustains community and institutional knowledge
Participants described mentorship as central to sustaining community within makerspaces and maintaining continuity across student cohorts. Mentors acted as repositories of experiential knowledge, passing along lessons related to tools, processes, and design decisions that were not formally documented.

The presence of visible and accessible mentors supported peer learning and contributed to a sense of belonging within the makerspace. These findings align with prior research highlighting the importance of mentoring and social interaction in informal engineering learning environments [5] and extend that work by highlighting the role of undergraduate mentors in maintaining continuity over time.

Finding 4: Organizational structures enable or constrain mentoring practice
Organizational conditions strongly influenced mentorship effectiveness. Faculty turnover, inconsistent departmental support, and restricted access policies disrupted mentorship continuity and limited informal interaction. Even when mentors were motivated and capable, institutional constraints shaped what forms of support were possible.

This finding reinforces prior work identifying staffing and organizational support as critical to makerspace sustainability [6,7]. Mentoring effectiveness depended not only on individual capability but also on institutional recognition of mentoring as educational work, within makerspace systems.

Taken together, these findings position undergraduate makerspace mentorship as a pedagogical practice that supports adaptive expertise through interaction, reflection, and community in informal engineering education settings. The educational impact of makerspaces depends on the human infrastructure that enables students to learn how to navigate uncertainty, failure, and design complexity alongside others.

Discussion

This study reframes undergraduate makerspace mentorship as a pedagogical practice rather than a logistical or technical role. While prior work has documented makerspace infrastructure, staffing models, and student outcomes [5–7], this study foregrounds how learning is enacted through everyday mentor–student interactions within makerspace contexts. Examining mentorship through the lenses of adaptive expertise and experiential learning clarifies how makerspaces support forms of engineering learning that extend beyond formal coursework in informal learning environments.

Mentorship as a mechanism for developing adaptive expertise
The findings indicate that undergraduate makerspace mentors consistently support behaviors associated with adaptive expertise. Mentors described guiding students through uncertainty, encouraging reflection, and helping them reconsider assumptions when initial solution paths

failed. These practices align with distinctions between routine and adaptive expertise, where adaptive expertise emphasizes flexibility, innovation, and judgment in unfamiliar contexts [1,2,9]. Mentors modeled adaptive behavior by acknowledging limits in their own knowledge, seeking resources, and connecting students to others with relevant expertise. In doing so, they made adaptive problem solving visible and accessible. This extends prior work on adaptive design expertise by demonstrating how adaptive practices emerge through mentoring interactions in informal, student-driven learning environments rather than structured classroom settings [1].

Experiential learning requires mediation, not just access

Although makerspaces provide rich opportunities for hands-on learning, this study reinforces that experience alone does not guarantee learning. Kolb's experiential learning theory emphasizes reflection and conceptualization alongside action [4]. Mentors played a central role in mediating this process by prompting students to pause, interpret outcomes, and adjust approaches. Without such mediation, experiential environments risk becoming task-oriented rather than learning-oriented. These findings align with prior research demonstrating that coaching and guided reflection are central to fostering adaptive expertise in design education [3] and suggest that mentorship is a key mechanism through which experiential learning becomes educationally meaningful.

Human infrastructure as a determinant of makerspace effectiveness

A key contribution of this study is its emphasis on human infrastructure as a determinant of makerspace effectiveness. Participants identified mentorship continuity, community, and access as shaping learning in ways that tools alone could not. These findings complement survey-based studies that identify staffing as a major operational concern [6] by demonstrating how and why staffing matters educationally. Organizational instability, including faculty turnover and restricted access policies, limited mentors' ability to engage students proactively and reduced opportunities for informal learning. Even when mentors were motivated and capable, institutional conditions constrained mentoring practice. These findings suggest that investments in makerspace facilities must be matched by sustained support for mentoring structures if makerspaces are to function as learning environments rather than solely as fabrication resources.

Implications for engineering education research and practice

For engineering educators and administrators, these findings highlight the importance of recognizing undergraduate makerspace mentors as educators who shape learning through interaction and modeling. Staffing models that prioritize interpersonal skill, adaptability, and willingness to learn may be more effective than those focused narrowly on technical specialization. Training that supports reflective practice, peer mentoring, and knowledge transfer may further strengthen the educational role of makerspaces. Mentor training that emphasizes reflective practice, questioning strategies, peer mentoring, and knowledge transfer may further strengthen the educational role of makerspaces. For researchers, this study demonstrates the value of examining informal learning environments through theories of expertise and learning rather than treating makerspaces as neutral contexts. Future research might explore how mentoring practices vary across institutional settings, how students experience learning differently in spaces with varying levels of mentor support, or how mentorship influences longer-term development of adaptive expertise.

Overall, this study positions undergraduate makerspace mentorship as a critical site of engineering learning within informal education settings. Through interaction, guidance, and modeling, mentors support experiential learning and the development of adaptive expertise. The educational value of makerspaces depends not only on access to tools, but on the human infrastructure that enables students to learn how to use them thoughtfully and adaptively.

Conclusions and Future Work

This study examined undergraduate makerspace mentorship as a key component of the human infrastructure that enables learning in university makerspaces. By focusing on the experiences and perspectives of undergraduate makerspace mentors, this work highlights how learning is supported through interaction, guidance, and community rather than through equipment and space alone. The findings position mentorship as an educational practice that shapes how students navigate uncertainty, learn from failure, and develop adaptive ways of thinking within makerspace contexts. Using adaptive expertise and experiential learning as interpretive lenses, this study provides empirical insight into how learning unfolds in informal engineering education environments. Undergraduate makerspace mentors supported learning by prompting reflection, encouraging problem reframing, and modeling adaptive behaviors in real time. These practices align with broader efforts in engineering education to prepare students for complex, ill-structured problems that extend beyond routine expertise while remaining grounded in everyday mentoring interactions. The study also underscores the role of organizational context in shaping the educational potential of makerspaces. Mentorship effectiveness depended on institutional conditions such as staffing continuity, faculty engagement, and access policies. Even motivated and capable mentors faced constraints when organizational structures limited visibility, authority, or continuity. These findings suggest that investments in makerspaces must attend not only to physical infrastructure but also to systems that support mentoring as educational work if makerspaces are to function as sustained learning environments.

Future work could extend this study in several directions. Multi-institutional research could clarify how mentoring practices vary across makerspace models and organizational contexts. Longitudinal studies could examine how participation in mentorship influences students' development of adaptive expertise over time. Additional research incorporating student perspectives could further illuminate how mentoring shapes learning, identity, and belonging in engineering across diverse institutional settings.

Overall, this study emphasizes that the educational value of makerspaces lies not only in the tools they house, but in the people who help students learn how to use them thoughtfully. Recognizing and supporting undergraduate makerspace mentors as educators is essential to realizing the full potential of makerspaces as sites for experiential learning and adaptive expertise development in engineering education.

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Appendix A: Interview Protocol

1. Tell me about your experience as a mentor.
2. Tell me about a typical experience for you in working with student teams.
3. What does a student mentor do?
4. How has your experience been helped or hindered by faculty, staff, or students?
5. How do you interact with the students and faculty that enter your makerspace?
6. What do you help them with?
7. Can you describe a basic interaction between yourself and someone asking for help?
8. How do you approach problems that a student brings to your attention?
9. How do you prefer to help students?
10. What skills do you need to be an effective mentor?
11. Do you want to have a professional staff member in your space to help with more difficult problems, or can you handle all situations that arise?
12. Are there certain things in the makerspace that need to have staff accountable for their correct function?
13. Are there certain things in the makerspace that need to have students accountable for their correct function?
14. Tell me about an experience you had with students where they learned a lot or gained deeper knowledge.
15. What role does community play in your experience as a maker?
16. Describe some of the people you regularly interact with in your making.
    (a) What are your relationships like with them?
17. Do you think there is enough staff in the makerspace?
18. Is the equipment in your space in good working order?
    (a) If not, what steps need to be taken to fix or replace the non-functional equipment?
    (b) Who is responsible for fixing or replacing broken equipment?
19. What question should I have asked you that I didn't?
20. Is there anything else you would like to tell me?