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Relationship of Undergraduate Research Mentoring and Social Legitimacy to Skill Development in Capstone Laboratory Courses

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Abstract

Undergraduate research mentoring within capstone laboratory courses represents a vital pathway for preparing STEM students for professional and academic careers. While the cognitive benefits of hands-on laboratory work are well-documented, the psychosocial and structural mechanisms that facilitate complex skill acquisition remain less clear. This paper explores how undergraduate research mentoring and social legitimacy within capstone laboratory environments drive student skill development. Drawing upon situated learning theory and the concept of legitimate peripheral participation, we present a comprehensive framework to explain how students transition from peripheral observers to competent practitioners. Using a mixed-methods research design, we evaluate student skill trajectories across multiple dimensions, including technical laboratory skills, research self-efficacy, and professional communication. Our analysis demonstrates that mentoring quality and social legitimacy are significant predictors of skill acquisition. Social legitimacy, defined as the degree to which students are recognized as authentic members of the scientific community, acts as a critical mediator between mentoring interventions and skill outcomes. The findings suggest that capstone laboratory courses must be structured not only to teach technical protocols but also to systematically foster social integration and legitimate agency. We conclude with strategic recommendations for instructional design and institutional policies aimed at optimizing undergraduate research mentoring frameworks to ensure equitable and profound skill development.

Keywords: Undergraduate Research; Capstone Laboratories; Mentoring Dynamics; Social Legitimacy; Skill Development

1. Introduction

1.1 Context and Background

Modern science education is increasingly focused on transitioning from passive, instructor-led models to active, student-centered paradigms. Historically, laboratory education at the undergraduate level relied heavily on highly structured, prescriptive experiments, often referred to as cookbook laboratories. While these structured experiences succeeded in teaching basic manual dexterity and introducing students to fundamental physical equipment, they frequently fell short of fostering genuine scientific inquiry, critical thinking, and the complex problem-solving skills required in contemporary professional environments [1]. To address this pedagogical gap, higher education institutions have increasingly integrated undergraduate research experiences directly into the curriculum through capstone laboratory courses. These courses serve as a bridge between foundational academic training and the professional workforce or graduate study, providing students with the opportunity to engage in authentic, open-ended scientific investigations.

Within these capstone environments, undergraduate research mentoring plays a central role in guiding student learning and development. Unlike traditional instructional models where the educator serves primarily as a source of information, research mentoring in a capstone laboratory involves a more collaborative, relational dynamic. Mentors, who may include faculty members, post-doctoral scholars, or advanced graduate students, act as facilitators, advisors, and role models. This mentoring relationship is crucial because scientific research is

inherently ambiguous, non-linear, and fraught with technical and conceptual challenges. Through regular interaction with mentors, students learn not only the technical mechanics of experimental design and execution but also the cognitive and metacognitive strategies necessary to navigate scientific uncertainty [2].

However, technical mentoring alone is insufficient to explain the full spectrum of student development in these intensive settings. Learning to become a scientist is not merely an individual cognitive endeavor; it is also a social process of identity transformation. To fully understand how skills are developed and internalized, educational researchers must look beyond the immediate transfer of technical knowledge and examine the social dynamics of the laboratory community. This is where the concept of social legitimacy becomes essential. Social legitimacy refers to the degree to which a novice is accepted, validated, and given agency within a professional community of practice. In a capstone laboratory, this means that students are not merely treated as transient learners or assistants, but are recognized as active, contributing members of the research community whose work has real value.

1.2 Problem Statement and Research Questions

Despite the recognized value of both mentoring and capstone laboratory courses, there remains a significant gap in the literature regarding the precise mechanisms through which these experiences translate into robust skill development. Many studies treat the capstone experience as a black box, measuring pre-course and post-course skill levels without exploring the intermediate social and relational pathways that drive these changes. Specifically, the relationship between technical mentoring behaviors, the student sense of social legitimacy within the laboratory, and the ultimate acquisition of professional skills is not well understood.

This study addresses this gap by investigating the following research questions:

How does the quality of undergraduate research mentoring in capstone laboratory courses directly influence student development of technical, cognitive, and professional skills?

To what extent does student perceived social legitimacy within the laboratory environment mediate the relationship between research mentoring and skill acquisition?

What specific instructional designs and mentoring practices best promote a sense of social legitimacy and subsequent skill development in diverse student populations?

By addressing these questions, this paper seeks to provide a more nuanced, theoretically grounded explanation of skill development in undergraduate research contexts. We argue that high-quality mentoring must be coupled with structural and social validation to maximize student learning outcomes.

1.3 Significance of the Study

The significance of this study is twofold, offering both theoretical and practical contributions to the field of STEM education. Theoretically, this research extends situated learning theory and the model of legitimate peripheral participation by applying them specifically to the structured context of undergraduate capstone laboratory courses. While previous educational research has examined mentoring and social integration in extracurricular undergraduate research programs, fewer studies have systematically analyzed these dynamics when embedded directly within credit-bearing, curriculum-based capstone courses. By conceptualizing social legitimacy as a critical mediating variable, this study advances our understanding of how social structures and relational dynamics shape cognitive development.

Practically, the findings of this study offer actionable insights for university administrators, department chairs, and laboratory instructors. Developing and sustaining capstone research courses is resource-intensive, requiring substantial investments in faculty time, laboratory space, and materials. To justify these investments and ensure their effectiveness, institutions must understand how to optimize the design of these courses. This study provides empirical evidence that can guide the design of mentor training programs, the structure of laboratory group dynamics, and the development of assessment methods that prioritize both technical competence and professional identity formation. Ultimately, by highlighting the importance of social legitimacy, this research supports the creation of more inclusive, supportive, and effective learning environments that prepare all students for success in the global scientific enterprise.

2. Literature Review and Theoretical Framework

2.1 Undergraduate Research Mentoring

Undergraduate research mentoring has been widely documented as one of the most impactful high-impact educational practices in undergraduate science education [3]. The literature distinguishes between several dimensions of mentoring, primarily categorizing mentoring behaviors into instrumental or career-related support, and psychosocial support. Instrumental support includes direct technical guidance, instruction in laboratory protocols, assistance with experimental design, and help with scientific writing and presentation. Psychosocial support, on the other hand, involves active listening, encouragement, emotional support, and the cultivation of a welcoming and mutually respectful relationship.

Research indicates that both forms of support are critical for student success, but they serve different functions in the development of undergraduate researchers. Instrumental support directly correlates with the acquisition of domain-specific technical skills and the development of scientific literacy. When mentors provide structured guidance and clear feedback on research tasks, students are able to master complex laboratory techniques more rapidly and avoid costly mistakes. Conversely, psychosocial support is strongly linked to student persistence in STEM fields, the development of a strong scientific identity, and increased self-efficacy [4]. Students who feel valued and supported by their mentors are more resilient in the face of research setbacks and are more likely to pursue graduate studies or careers in research.

However, the efficacy of undergraduate research mentoring is highly dependent on the quality of the mentor-student relationship. Common challenges in capstone laboratory mentoring include mismatched expectations, poor communication, and a lack of formal training for mentors. Faculty mentors often face competing demands on their time, leading to superficial interactions with undergraduate students, while graduate student mentors, who often provide the bulk of day-to-day supervision, may lack pedagogical training. Consequently, understanding the specific mentoring behaviors that foster deep learning and skill development remains a critical area of ongoing research.

2.2 Situated Learning and Social Legitimacy

To explain how mentoring leads to skill development within the social context of a laboratory, this study draws upon situated learning theory, originally articulated by Jean Lave and Etienne Wenger. According to this perspective, learning is not merely the cognitive acquisition of abstract knowledge; rather, it is an active, situated process that occurs through participation in a community of practice [5]. A community of practice is a group of people who share a concern, a set of problems, or a passion about a topic, and who deepen their knowledge and expertise by interacting on an ongoing basis. In this framework, a research laboratory is a classic community of practice, composed of faculty, postdocs, graduate students, and undergraduate novices.

A central concept within situated learning theory is legitimate peripheral participation. This concept describes how newcomers enter a community of practice and gradually move toward full participation. Initially, a newcomer participates in peripheral, low-stakes tasks that are nonetheless authentic and necessary for the community. Over time, as the newcomer gains competence and is granted greater responsibility by established members of the community, they move toward the center, eventually adopting the identity and skills of a full practitioner [6].

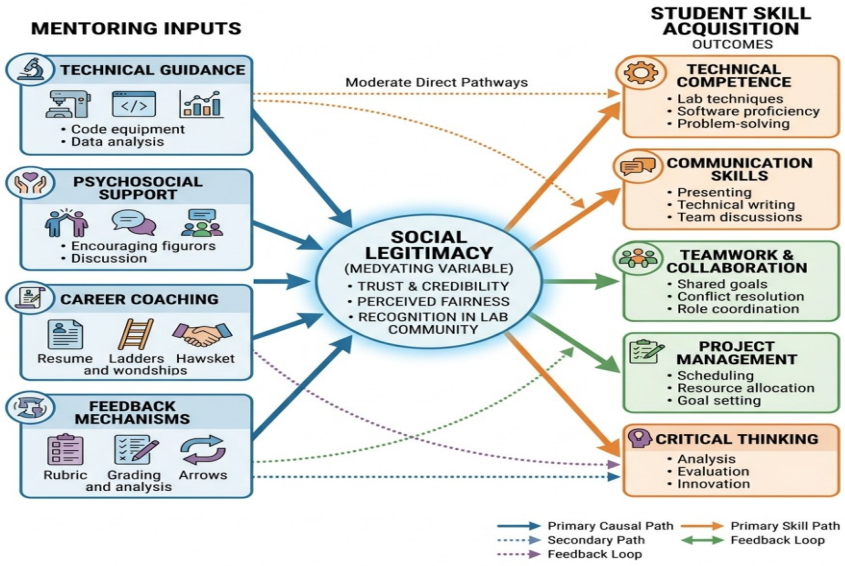

Figure 1: Conceptual Framework of Mentoring Dynamics and Social Legitimacy in Capstone Labs

Social legitimacy is the vital currency that enables legitimate peripheral participation. In the context of a capstone laboratory, social legitimacy refers to the structural and relational recognition of the undergraduate student as a valid contributor to the research group. It is the social license granted by mentors and peers that allows the student to access laboratory resources, ask questions, make mistakes, and make decisions regarding their project. Without social legitimacy, students remain structurally marginalized; they may perform routine, repetitive laboratory tasks, such as washing glassware or preparing standard solutions, without ever understanding the broader scientific context or developing advanced cognitive skills. When students are granted social legitimacy, their participation is validated, which in turn fosters a sense of ownership, responsibility, and cognitive engagement.

2.3 Skill Acquisition in Capstone Environments

Capstone laboratory courses provide a unique educational ecosystem for assessing skill acquisition because they integrate multiple learning domains simultaneously. Unlike introductory courses that focus on isolated skills, capstone courses require students to synthesize and apply knowledge across technical, cognitive, and professional domains.

Technical skill development in capstone laboratories involves the mastery of advanced instrumentation, experimental protocols, and data analysis software. These are the concrete, hands-on capabilities that are directly transferable to professional scientific roles. However, technical proficiency alone is insufficient. Students must also develop cognitive skills, such as scientific reasoning, problem-solving, and experimental design [7]. Cognitive skill development is demonstrated when a student can troubleshoot a failing experiment, modify an existing protocol to suit a new research question, or critically evaluate conflicting data.

Furthermore, capstone laboratories are crucial sites for the development of professional or transferable skills. These include scientific communication, both written and oral, teamwork, time management, and ethical decision-making. In a typical capstone course, students must document their research in a formal scientific report, present their findings to their peers and mentors, and collaborate with team members to share laboratory equipment and resources. The development of these professional skills is highly dependent on the social interactions within the laboratory [8]. For instance, a student who is fully integrated into the laboratory community and possesses high social legitimacy is likely to receive more constructive feedback on their scientific writing and presentations, leading to greater improvement over time.

3. Methodology and Research Design

3.1 Participant Selection and Context

To empirically investigate the relationship between research mentoring, social legitimacy, and skill development, this study utilized a mixed-methods research design within the context of upper-level chemistry and biochemistry capstone laboratory courses at a major research university. These capstone courses are structured as semester-long, project-based laboratory experiences where students work in small groups on novel research projects aligned with the ongoing research programs of the department faculty.

The study cohort consisted of undergraduate students enrolled in these capstone courses over four consecutive semesters. Participation in the study was entirely voluntary, and informed consent was obtained from all participants. The total sample size included 124 undergraduate students, 12 faculty mentors, and 18 graduate student mentors who assisted in the laboratory instruction. The demographics of the student cohort represented a diverse range of academic backgrounds, prior research experience, and career aspirations, providing a robust dataset for analysis.

Table 1: Demographics and Laboratory Cohort Characteristics

Demographic Category	Metric Evaluated	Value or Percentage
Total Student Participants	Count	124
Prior Research Experience	No Prior Experience	41.9 Percent
Prior Research Experience	Less than One Year	35.5 Percent
Prior Research Experience	More than One Year	22.6 Percent
Intended Career Path	Graduate School	48.4 Percent
Intended Career Path	Industry Employment	32.3 Percent
Intended Career Path	Professional Health	19.3 Percent

The pedagogical structure of the capstone laboratory was deliberately designed to facilitate collaborative research. Students were organized into research teams of three to four individuals, each assigned to a specific faculty-led research project. Graduate student mentors provided daily, hands-on supervision in the laboratory, while faculty mentors met with the teams weekly to review progress, discuss experimental design, and provide strategic feedback. This dual-mentor structure allowed us to examine how different levels and styles of mentoring affected the students' educational experiences.

3.2 Data Collection and Instrumentation

Data collection utilized a multi-method approach designed to capture both quantitative trends and qualitative depth. Quantitative data were gathered through pre-course and post-course student surveys, as well as objective performance evaluations conducted by the mentors and independent course instructors. Qualitative data were collected through semi-structured interviews with a subset of students and mentors, as well as student reflective journals submitted throughout the semester.

The student surveys utilized validated instruments adapted from the literature to measure mentoring quality, social legitimacy, and self-reported skill development. Mentoring quality was assessed using a modified version of the Mentor Behavior Scale, which measures instrumental support, psychological support, and communication. Social legitimacy was measured using a newly developed scale based on the principles of legitimate peripheral participation, evaluating aspects such as student sense of belonging, perceived agency, and recognition by the lab group. Skill development was measured through both student self-efficacy ratings and objective laboratory performance rubrics.

Table 2: Summary of Pre and Post Intervention Skill Assessments

Skill Domain Measured	Pre Course Mean Scale	Post Course Mean Scale	Standard Deviation
Technical Laboratory Proficiency	2.45	4.12	0.52
Experimental Design and Troubleshooting	1.88	3.65	0.61
Scientific Communication Skills	2.10	3.90	0.58
Professional Team Collaboration	2.95	4.30	0.44
Research Self Efficacy	2.20	4.05	0.49

The objective performance rubrics were completed by course instructors and mentors at three distinct points during the semester: the start of the course, the midterm point, and the final project presentation. These rubrics

assessed specific behaviors, such as the ability to independently operate analytical instruments, the quality of lab notebook documentation, the clarity of scientific arguments during oral presentations, and the ability to work collaboratively in a team setting. Qualitative interviews with twenty selected students and ten mentors were conducted at the end of each semester to gain deeper insights into the specific interpersonal interactions and structural barriers that influenced the students' sense of social legitimacy and scientific agency.

3.3 Analytical Framework

Quantitative survey data were analyzed using statistical software to perform descriptive statistics, paired-samples t-tests, and hierarchical linear regression. Paired-samples t-tests were used to compare pre-course and post-course scores for all measured skill domains, validating the overall effectiveness of the capstone laboratory model. Hierarchical linear regression analysis was conducted to test the primary hypothesis: that social legitimacy acts as a mediator between mentoring quality and student skill development.

In the regression model, demographic variables and prior research experience were entered in the first block as control variables. Mentoring quality, split into instrumental and psychosocial dimensions, was entered in the second block. Perceived social legitimacy was entered in the third block. This allowed us to determine whether social legitimacy explained additional variance in skill development beyond what was accounted for by mentoring quality alone. Mediation was formally tested using the process macro, which estimates direct and indirect effects with bias-corrected bootstrap confidence intervals.

Qualitative data from the interviews and reflective journals were analyzed using thematic analysis, guided by situated learning theory. The transcripts were coded independently by two researchers using a codebook developed through an iterative process of reading and discussing the data. Initial codes focused on specific mentoring actions, student feelings of inclusion or marginalization, moments of scientific insight, and barriers to participation. These codes were then grouped into broader themes, such as transitioning from novice to peer, the impact of technical failure on confidence, and the role of peer validation in fostering a professional identity. The integration of these qualitative findings with the quantitative results provided a comprehensive, multi-dimensional explanation of how mentoring and social legitimacy drive skill development.

4. Results and Discussion

4.1 Quantifying Skill Trajectories and Mentorship Effects

The quantitative analysis revealed a significant positive shift in all evaluated student skill domains over the course of the semester. As shown in the comparison of pre-course and post-course means, student self-reported self-efficacy and objective performance ratings improved dramatically. This general upward trajectory confirms that the project-based, mentored capstone laboratory is an effective pedagogical environment for skill acquisition [9]. However, a closer examination of the data shows that this improvement was not uniform across all students, and the variation can be largely explained by differences in the quality of mentoring received.

Regression analysis showed that both instrumental and psychosocial mentoring support were positive predictors of skill development. Interestingly, the relative impact of these mentoring dimensions varied depending on the specific skill domain being evaluated. Instrumental mentoring, characterized by clear technical instruction, modeling of scientific techniques, and structural feedback, had the strongest direct impact on technical laboratory proficiency and scientific writing skills. When mentors provided high-quality, task-oriented feedback, students demonstrated more rapid technical progress and higher performance on laboratory assessments.

Psychosocial mentoring, on the other hand, was the strongest predictor of research self-efficacy and experimental troubleshooting skills. When students felt supported, encouraged, and safe to make mistakes without fear of harsh judgment, they developed the resilience necessary to navigate the inevitable failures associated with original research [10]. Qualitative reflections revealed that students with supportive mentors were far more likely to persist through scientific obstacles. Rather than viewing a failed experiment as a personal failure or a sign of incompetence, these students, guided by their mentors, re-framed the setback as an opportunity to troubleshoot and learn. This cognitive reframing is a crucial step in developing the scientific mindset.

4.2 Social Legitimacy as a Mediator of Learning Outcomes

A central focus of this study was testing whether the relationship between research mentoring and skill development is mediated by student perceptions of social legitimacy. In other words, does mentoring work simply because of the direct information transferred, or does it work because high-quality mentoring helps the student feel like a legitimate, valued member of the scientific community?

The mediation analysis supported the hypothesis that social legitimacy plays a crucial mediating role. While mentoring quality had a direct, positive effect on skill development, this relationship was significantly mediated by student ratings of social legitimacy. Specifically, the indirect effect of instrumental and psychosocial mentoring on student research self-efficacy and complex problem-solving skills through social legitimacy was statistically significant. This finding suggests that mentoring is most effective when it is translated into concrete social validation within the laboratory.

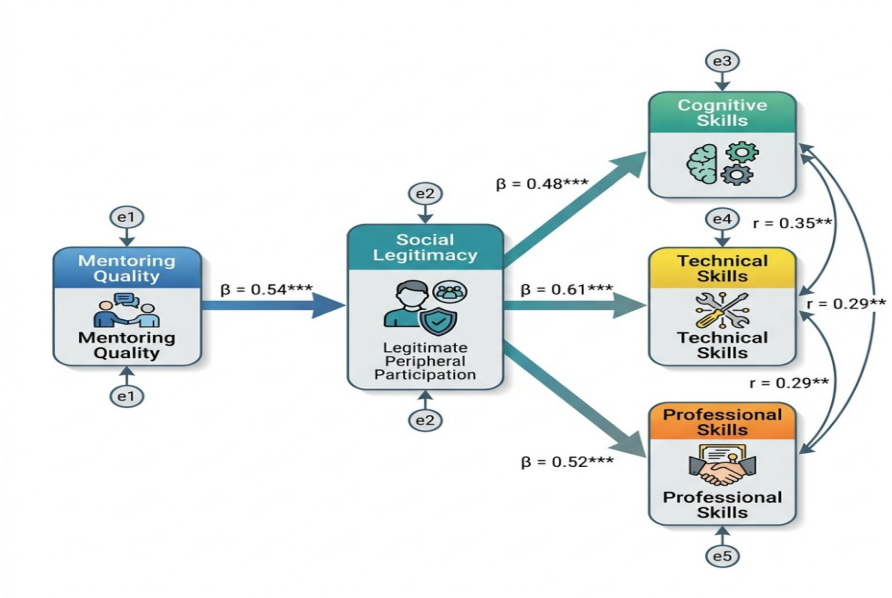

Figure 2: Path Analysis Model of Skill Development via Mentoring and Legitimate Peripheral Participation

The importance of this mediating effect is illustrated by the contrast between students who experienced high mentoring quality with high social legitimacy and those who experienced high mentoring quality with low social legitimacy. In some instances, mentors provided extensive technical instructions (high instrumental mentoring) but maintained a strict hierarchy that kept the students in a subservient, peripheral role (low social legitimacy). In these cases, despite receiving high-quality instructions, students did not develop the same level of independent problem-solving skills or research self-efficacy as their peers who were granted greater agency and recognition.

Qualitative interview data provided a deeper understanding of what social legitimacy feels like from the student perspective. Students who felt highly legitimized described moments where their mentors actively sought their opinions, included them in research group meetings, and gave them authentic responsibility for managing their portion of the project. As one student shared, the turning point was when my mentor asked me what I thought we should do next after the gel electrophoresis failed, rather than just telling me what to do. That simple act transformed the student from an assistant executing a protocol into a partner in scientific inquiry [11]. This validation motivated the student to read literature outside of class, spend more time in the lab, and take cognitive ownership of the project, ultimately leading to superior skill development.

4.3 Synthesized Discussion of Laboratory Dynamics

When we synthesize these findings within the framework of situated learning theory, it becomes clear that the capstone laboratory is a complex social ecosystem where relational dynamics and structural design are inextricably linked to cognitive growth. The transition from legitimate peripheral participation to full participation requires that the student be recognized as a valid member of the community. In a traditional class,

the instructor is the sole authority, and student progress is measured through individual assessments. In a capstone laboratory, however, progress is social; it is measured by how well the student participates in and contributes to the collective work of the research group.

This perspective highlights several key dynamics that are often overlooked in curriculum design. First, it emphasizes that learning to be a scientist is a process of identity development [12]. Students do not simply acquire skills in a vacuum; they develop skills as they build a professional identity. When a student is granted social legitimacy, they begin to see themselves as a chemist or a biochemist, rather than just a student taking a required chemistry course. This shift in identity changes how they engage with the material; they become more proactive, more willing to tolerate ambiguity, and more committed to rigorous scientific practices.

Second, our findings highlight the social barriers that can impede this transition, particularly for students from underrepresented backgrounds in STEM. In the interviews, several students noted that they initially felt like imposters in the research space, believing that they did not possess the necessary background or intuition to succeed. For these students, explicit acts of validation from mentors were critical. When mentors proactively granted them social legitimacy, by assigning them authentic tasks, introducing them to other researchers, and valuing their contributions, these initial feelings of isolation and self-doubt were mitigated. Conversely, when mentoring was distant or purely instructional, imposter feelings persisted, hindering the students' ability to fully engage and develop their skills.

Finally, the study demonstrates that the structure of the capstone course itself can either facilitate or hinder social legitimacy. Courses that incorporate peer review, collaborative group projects, and public presentations of research findings provide natural platforms for students to claim and receive validation [13]. When a student must defend their research findings to a room of peers and faculty, they are performing the authentic work of a scientist. This performance, and the recognition that follows, cements their status as a legitimate contributor to the field, driving the final stages of advanced skill development.

5. Conclusion and Recommendations

5.1 Summary of Key Findings

This study has explored the complex pathways of skill development within undergraduate capstone laboratory courses, focusing specifically on the critical roles of research mentoring and social legitimacy. Our analysis confirms that project-based capstone courses are highly effective environments for fostering technical, cognitive, and professional skills. However, the key contribution of this research is the demonstration that skill acquisition is not a purely individual cognitive process, but a deeply social and relational transition.

The findings establish that while high-quality mentoring is essential, its impact is significantly mediated by the student's sense of social legitimacy within the laboratory community. Mentoring behaviors that provide instrumental and psychosocial support are most effective when they empower students to transition from peripheral observers to active, recognized contributors. When students are granted social legitimacy, they experience a boost in research self-efficacy, take greater cognitive ownership of their projects, and develop more sophisticated problem-solving and troubleshooting capabilities. Conversely, when students are denied this legitimacy and kept in a rigid, hierarchical, and peripheral role, their learning outcomes are constrained, even in the presence of technical guidance.

5.2 Implications for Curriculum Design

These conclusions suggest several concrete recommendations for universities and instructional designers seeking to optimize the impact of undergraduate research capstone courses:

Formally Train Mentors in Inclusive and Validating Practices: Institutions should not assume that because faculty members and graduate students are excellent researchers, they are naturally effective mentors. Mentor training programs must be established, with a specific focus on teaching mentors how to cultivate social legitimacy. Mentors should be trained to provide constructive, growth-oriented feedback, actively involve students in decision-making, and intentionally foster an inclusive laboratory environment that supports students from diverse backgrounds.

Design Curricula that Promote Scientific Agency: Capstone laboratory courses should be designed to move away from highly structured protocols as quickly as possible. Course structures should incorporate open-ended research questions where students must design their own experiments, troubleshoot failures, and defend their scientific choices. This design naturally creates opportunities for students to exercise scientific agency and claim social legitimacy.

Incorporate Structured Platforms for Peer and Public Validation: To reinforce the social legitimacy of undergraduate researchers, courses should include formal milestones where students present their work to the broader department or scientific community. Poster sessions, research symposia, and peer-review writing exercises are excellent mechanisms for providing students with the external validation that solidifies their professional scientific identity and drives advanced skill development.

By integrating these strategies into capstone laboratory designs, higher education institutions can ensure that all students have the opportunity to develop the advanced skills and professional confidence required to succeed in the modern scientific workforce.

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