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Beyond Calculations: Engineering Judgment as Epistemic Cognition in Engineering Education

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Introduction

Engineering judgment is recognized as a key competency in professional practice. Engineers routinely make complex decisions at the boundaries of established knowledge while managing significant uncertainty [1]. For all these reasons, becoming a competent engineer means developing sound judgment: a standard employed by practicing engineers as the ultimate authority in decision-making [2]. Mathematical modeling, often conflated with engineering judgment, serves only as a contributing factor or may occasionally be used to justify judgments after the fact. The engineers in Gainsburg's study identified engineering judgment with tasks like determining sufficient precision for calculations, making modeling assumptions, and sometimes overriding mathematical results. Petroski's [3] analysis of engineering failures similarly emphasizes judgment's role throughout the design process, noting that "the first and most indispensable design tool is judgment" that both initiates projects and monitors their execution.

However, engineering education typically emphasizes technical competencies over judgment-based skills, with the Grinter Report noting that "the ability to deal effectively with such broad issues comes only with experience and maturity in the years after college" [4, p. 5]. While not denying the truth of this assertion, it seems that more can be done in undergraduate education to foster the intellectual abilities needed to make sound judgments [5], [6]. Recent ABET revisions now require students to demonstrate "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions" [7]. This marks a significant shift from previous outcomes which contained no explicit references to judgment. Therefore, engineering judgment represents a core way of thinking that distinguishes engineering practice: knowing when to trust calculations versus experience, and how to navigate between theoretical knowledge and practical constraints [8]. Developing these capabilities is key to professional acculturation and embodies the standards for sound engineering decision-making.

This paper advocates for greater attention to engineering judgment in engineering education, beginning by defining engineering judgment and examining the challenges educators face in promoting its development. We then explore the cognitive aspects of engineering judgment in greater depth, highlighting differences between engineering judgment and related psychological constructs like judgment and critical thinking, highlighting important aspects of engineering judgment that other constructs fail to capture. These discrepancies present an opportunity to draw on research about epistemic cognition—how people understand and evaluate knowledge—to better understand engineering judgment. Using an undergraduate laboratory course as an example, we demonstrate how this enhanced understanding can improve how we assess and develop engineering judgment in students.

What is Engineering Judgment?

Engineering judgment has emerged as a critical focus in engineering education research [5], particularly following its formal incorporation as a required outcome for engineering graduates in the 2016-2017 ABET accreditation cycle, which promotes the use of "engineering judgment to draw conclusions" [9, p. 6]. The persistence of this outcome in ABET's current criteria underscores its continued significance in engineering education [7]. However, the development and assessment of engineering judgment presents multiple pedagogical challenges, necessitating robust conceptual frameworks, scaffolded learning approaches, valid assessment methods, and well-defined learning objectives. Francis, Paretti, and Riedner [5] note a significant gap in engineering education literature addressing these needs, leaving both researchers and educators with limited approaches for studying, teaching, or assessing engineering judgment. This gap becomes evident in hypothetical student questions such as "What constitutes good engineering judgment?" "How can engineering judgment be improved?" and "When should I hold withhold judgment?" While these questions might invite oversimplified responses like "it depends," they reveal engineering judgment's nature as a complex construct operating at the intersection of professional practice, cognitive capability, and identity formulation [6]. This conceptual complexity creates a fundamental pedagogical tension: how can educators facilitate the simultaneous development of technical engineering competencies and professional judgment? Addressing this question requires an examination of engineering judgment's conceptual evolution within engineering education research.

The foundational empirical work on engineering judgment emerged through ethnographic studies, most notably Gainsburg's [2] observations of structural engineers. This research established a taxonomy of engineering judgment practices through direct observation of professional work. These practices were specific, observable, and included behaviors such as determining calculation precision (e.g., deciding whether inch-level or foot-level accuracy is required), making mathematical modeling assumptions (e.g., simplifying complex geometries), evaluating and potentially overriding computational results, assessing technology tool appropriateness, and making qualitative assessments for formula selection. Engaging in such practices required context-dependent skills, including the ability to integrate disciplinary knowledge, professional expertise, situational constraints, and uncertainty, and dispositions, such as a "skeptical reverence" for theoretical models [2].

Recent research has advanced our understanding of engineering judgment by examining its cognitive, social, and contextual dimensions. For example, Weedon [10] describes engineering judgment as an inherently rhetorical-technical capacity, demonstrating how engineering teams integrate technical knowledge and rhetorical practices to understand and tackle novel problems. Weedon's ethnomethodological study reveals that engineering judgment operates through the fusion of technical understanding and rhetorical action, making it fundamentally interactive in nature and inseparable from its context. Building on this understanding, Edmondson and Sherratt [11] propose a framework that identifies three interrelated types of judgment: diagnostic judgment for defining problems, inductive judgment for synthesizing evidence across parameters, and interpretive judgment for understanding contextual implications. Their research shows how these judgment types build upon each other hierarchically as engineers develop expertise. Similarly, Francis et al. [5] examined how engineering judgment develops through the interplay between cognitive decision-making processes, professional identity formation, and contextual influences within engineering practice. Taken together, these frameworks highlight the multifaceted nature of engineering judgment while pointing to common developmental mechanisms like failure analysis, authentic contexts, and reflective practice.

Despite growing theoretical understanding of engineering judgment, significant challenges remain in teaching and evaluating it effectively in engineering education [5], [8], [12]. While project-based courses often incorporate complex scenarios meant to develop engineering judgment, several key difficulties persist. First, the range of acceptable solutions in open-ended problems makes it challenging for faculty and students to identify and assess good judgment

[13], [14]. For example, should a student earn points for recognizing multiple interconnected aspects of an engineering system? Or must they also express opinions and justifications as to how those aspects function and/or could be modified? Second, when engineering judgment development isn't made explicit in course and lesson objectives, students may fail to recognize when they are exercising judgment versus following procedures, limiting their ability to transfer these skills to new contexts [15], [16]. Without explicit discussion and practice, students may continue to view engineering problems as purely technical and analytical challenges rather than opportunities for exercising judgment [17]. Assessment poses additional challenges. Traditional methods of evaluating engineering judgment through workplace observation (i.e., Gainsburg) are impractical in engineering settings, while post-hoc analysis of engineering decisions may miss critical aspects of judgment processes; particularly individual cognitive elements that leave no paper trail [18], [19]. Although frameworks like the Productive Beginning of Engineering Judgment (PBJ) offer diagnostic tools [6], implementing them may require time-intensive coding and may miss opportunities to advance students' metacognitive abilities if quality feedback is not provided. Other rubric-based assessments, though helpful for reflection, often fail to advance students' conceptual understanding of engineering judgment or promote its development [20], [21]. These limitations highlight the need for comprehensive approaches that explicitly direct students' attention to judgment processes while providing scaffolding for long-term development and transfer [22], [23].

The centrality of engineering judgment to engineering practice makes it critical for educators to develop students' abilities to address uncertainty, evaluate tradeoffs, and make reasoned decisions in complex problems. While recent research has advanced our theoretical understanding of engineering judgment, challenges remain in teaching and assessing these capabilities. We argue that these challenges stem partly from how previous literature conceptualizes the cognitive aspects of engineering judgment; specifically, the tendency to oversimplify the complex mental processes involved in engineering problem-solving. A more nuanced understanding of these cognitive processes, particularly through the lens of related psychological constructs, can provide valuable insights for engineering education. For these reasons, we conceptualize engineering judgment as both a cognitive and social competency. As opposed to the binary notion of "soft skills" or "technical competencies" alone, engineering judgment emerges from interactions between an engineer and others. Although a simplistic distinction, this helps clarify the cognitive emphasis following section that examine how theories of judgment, critical thinking, and epistemic cognition can enhance our understanding of engineering judgment and inform more effective approaches to developing students' judgment capabilities.

The Role of Cognition in Engineering Judgment

While multiple frameworks acknowledge the cognitive dimensions of engineering judgment, their treatment of these psychological processes remains underdeveloped. Complex cognitive capabilities like evidence synthesis, data interpretation, and knowledge integration are described by broad "cognitive" descriptions without deeply examining their underlying psychological mechanisms and developmental trajectories. This simplified conceptualization of cognitive processes in engineering judgment poses significant challenges for educators attempting to scaffold and assess these sophisticated judgment capabilities. Scaffolding here referencing theories of learning and development in which students are provided progressively withdrawn supports as they become more aware and capable of a requested task [24]. We argue that more explicit scaffolding for engineering judgment in both individual and group assignments can better foster its development among students, though this is not to say that students should exhibit engineering judgment on par with practicing engineers. Development takes time, and rather than presuppose it is taking place through activities and assignments that do not draw students' attention to engineering judgment, we argue for it to be placed as a central theme that students must consider and articulate when completing their work.

This argument stems from empirical work and personal experience suggesting that engineering judgment is difficult to scaffold as it has been commonly conceptualized. For example, if students should learn to process uncertain and potentially unreliable information, they should understand that confusion and frustration are to be expected and that corroborating sources may be a viable approach [25]. Yet Faber and Benson [26] explored students' real-time problem-solving on an open-ended biomechanics assignment, asking them to talk through and justify their approaches. Although students were told there was not a single correct answer to the problem, many were frustrated during problem-solving and later expressed annoyance when told their answers were incorrect or that they used improper methods. Students' perceptions of the instructor, the assignment's utility value and purpose, and their interest in the subject guided their problem-solving approaches, which Faber and Benson recommend considering when designing course content. Nevertheless, in our teaching experiences, learning how to handle the confusion, frustration, and anxiety that arises from judgment-based problems is an active task when trying to foster engineering judgment. This aligns with research suggesting it is possible for students to engage in collaboration while failing to develop advanced collaboration skills [27]. Effective collaboration skill development requires deliberate pedagogical frameworks that direct students' learning rather than assuming skills will naturally emerge through existing educational experiences.

If engineering judgment is indeed "almost always an individual and cognitive capacity" [10, p. 165], then it is essential to investigate how these cognitive capacities develop. Currently, research on engineering judgment offers limited insight into how students navigate complex social environments or form sophisticated beliefs about engineering knowledge and ways of knowing. In their work which draws from the legacy of Perry [28], Faber and Benson [26] identified students who could be termed "multiplists," as they had moved beyond absolute, binary notions of right and wrong and acknowledged multiple perspectives. Nevertheless, these students struggled to evaluate validity and justifications thoroughly, often relying on superficial or insufficient evidence. Alarming in this regard is Wise et al.'s [29] finding that most engineering students only reach such a stage of epistemic development by their fourth year, rather than advancing to the more nuanced "evaluatist" stages (that is, adopting a more sophisticated view of knowledge and knowing processes; see [30]). When applied to engineering judgment, if educators aim to cultivate students' cognitive abilities related to engineering judgment, more research is needed to understand how these competencies develop, manifest in educational contexts, and intersect with identity formation and professional practice. This would involve helping students grasp sets of dispositions and skills necessary for competent engineering practice [31]. Yet, such an endeavor extends beyond merely learning sets of dispositions and skills; it calls for students to conceptualize, assess, apply, and reflect on the choices embedded in those sets. As Petroski astutely notes, "Although examples of good engineering practice can certainly serve as paradigms of good judgment, great people do not become so merely by reading biographies of great men and women" [3, p. 524]. Consequently, while many have advocated for practical experience and interdisciplinary opportunities as means of fostering engineering judgment, these approaches may inadvertently undermine or not affect students' development unless grounded in concrete, actionable learning objectives.

To this end, engineering judgment can be understood psychologically as a complex evaluative process involving multiple cognitive and metacognitive components. This psychological perspective differs from pervious conceptualizations of engineering judgment by treating it as involving cognitive processes that can be empirically investigated and developed through education and experience. Adopting this perspective requires we first differentiate engineering judgment from related psychological constructs, namely judgment writ large and critical thinking. Both general judgment and critical thinking are involved in engineering judgment but analyzing their alignment reveals the important role of epistemic cognition (epistemic cognition)—how individuals develop and use beliefs about knowledge and knowing. Understanding engineering judgment through the lens of epistemic cognition offers new insights into how we can better develop engineering judgment in students.

Defining Engineering Judgment

To define engineering judgment psychologically, we must differentiate it from "judgment" more broadly. In contemporary psychology, "judgment" is a vague term but commonly refers to the evaluative or inferential process about a specific stimulus, event, or proposition that results in an opinion, conclusion, or estimation [32], [33]. This process involves integrating multiple sources of information (e.g., prior knowledge, contextual cues, affective states, expectations) to reach an appraisal. To draw contrast, cognition generally refers to the full range of mental operations, such as perception, attention, memory, problem-solving, and reasoning, which do not inherently require a value-laden conclusion [34]. Judgments are particularly sensitive to affective and social factors and susceptible to cognitive heuristics and biases, such as representativeness, availability, anchoring, and adjustment [35].

We argue that engineering judgment shares essential characteristics with psychological judgment but greater scrutinizes aspects of the stimulus. This contextual scrutiny qualifies judgment as "engineering judgment" so long as it fulfills at least four conditions: domain specific, involves quantitative rigor and standardized knowledge, entails high-stakes consequences, and occurs within a professional framework of methodological analyses. First, engineering judgment is embedded in the technical domain of engineering, requiring specialized knowledge, disciplinary standards, and professional norms. While general judgment applies across various contexts, engineering judgment involves reasoning about problems that often demand advanced quantitative and scientific expertise. Second, engineers rely on mathematical models, technical data, and established procedures to guide their decisions. engineering judgment often involves systematically analyzing complex variables, running simulations, or referencing codes and standards; practices that are often more structured and organized than general judgments. Third, the outcomes of engineering decisions often involve safety, environmental impact, or substantial financial investment with wide-ranging societal impacts. Incorrect engineering judgments can cause critical failures and societal dilemmas, reinforcing the need for rigorous validation and peer review. Fourth, engineering judgment operates within a professional framework where engineers must systematically analyze trade-offs between competing factors like cost, safety, efficiency, and environmental impact, often while working within established professional codes and standards. This structured approach to weighing alternatives distinguishes engineering judgment from more informal judgments made in everyday life and positions engineering judgment as depending on, but with a slightly different focus than, judgment. This different focus originates in the function of engineering judgment within a framework of professional standards, technical expertise, and trade-off analyses. Yet, we can see their similarity with regard to bias because, like all judgments, engineering judgment is vulnerable to unfairness, prejudice, favoritism, and the like [5]; hence why engineers benefit from the structured methods of analysis, validation, and reflection that are integral to engineering practice. Thus, engineering judgment appears to focus more on the social conditions and consequences for its happening than on the processes involved in the engineer's own thinking.

Critical Thinking and Engineering Judgment

While defining how judgments function in engineering decisions is crucial, it raises questions about what dispositions, skills, and beliefs reflected in "expert-like" engineering judgment. Put another way, what happens when the focus "shifts" toward instead focusing on the engineer's thinking when making engineering judgments? Pedagogically, such a shift presents challenges because, for instance, a practicing engineer's deference to subject matter experts is an insufficient guide for helping students understand why that deference is important. Obviously, the engineer does not adopt such deference in all situations, but this difference is something students may not recognize unless it is made explicit. The desire to bring attention to judgments' dispositions and context relates to another psychological concept, critical thinking. Critical thinking concerns how individuals evaluate information through specific dispositions and skills [36], which makes it like judgment in that both are ingredients in engineering judgment. critical thinking dispositions are relatively stable attitudes that impact reasoning, such as intellectual curiosity, diverse perspective seeking, and tolerance for complexity [37]. These dispositions support critical thinking skills used to interpret, evaluate, and relate information and meanings; particularly when connections are not immediately apparent [38], [39]. Since engineering judgment requires competent evaluation of technical information, these critical thinking skills and dispositions are necessary components of engineering judgment. For example, when engineers evaluate the adequacy of calculations and mathematical models, they employ critical thinking skills to analyze assumptions and assess evidence.

However, engineering judgment extends beyond critical thinking in several ways. First, while critical thinking may terminate in analysis or understanding, engineering judgment must result in actionable decisions within real-world constraints. Engineers must move beyond pure analysis to make choices that enable progress, even with incomplete information or competing demands from cost, safety, and efficiency. Second, engineering judgment is inherently value-laden and social, taking place in environments where multiple stakeholders negotiate solutions based on different expertise, values, and priorities. This social dimension of engineering judgment—where judgments emerge through collective sense-making, distributed expertise, and trust relationships—is not well captured by traditional critical thinking frameworks that focus on individual cognitive skills (ergo the focus on judgment stimulus features). Third, engineering judgment requires integrating multiple modes of thinking beyond traditional analytical reasoning, including visual-spatial reasoning, experiential knowledge, theoretical understanding, and intuitive "feel" [2]. This integration creates challenges for developing engineering judgment in students, as they may excel at one mode while struggling with others [40], particularly when these modes are often separated in traditional engineering curricula. Given these differences, it is understandable why simply encouraging students to "think more critically" is insufficient for developing engineering judgment capabilities. Such directives can misleadingly imply that critical thinking exists on a simple linear scale where more is always better, similar to nascent views on fixed intelligence [41]. Instead, Gainsburg's research reveals that engineering judgment involves conscious choices about when and how to apply different modes of thinking based on specific engineering situations.

Taken together, while engineering judgment relies on general judgment abilities and critical thinking dispositions and skills, it is unlikely that simply asking students to "judge better" or "think more critically" will lead to its development. Neither is it guaranteed that students develop engineering judgment in team-based experiences; particularly those without sufficient scaffolding around the types of judgment educators seek to instill. Although other psychological constructs are also relevant to understanding engineering judgment beyond critical thinking and general judgment, such as metacognition [42], team cognition [43], and self-efficacy [44], we argue these constructs can be differentiated from engineering judgment in similar ways to general judgment and critical thinking because they all naturally overlap and interdepend. However, understanding these overlaps and interdependencies is crucial for developing effective pedagogical strategies that promote engineering judgment in engineering education. For example, when engineering students confront an ambiguous design constraint, what influences whether they recognize the need to seek additional information versus prematurely committing to a solution? Similarly, how do differences in students' self-efficacy in mathematical modeling affect engineering judgment development? In team settings, distributed cognition across members with varying expertise necessitates negotiated judgments [45]; how do students learn when to trust others' expertise versus when to question their underlying assumptions? These examples illustrate why a deeper psychological understanding of engineering judgment is necessary for effective pedagogy. In an effort not to assume that technical competence automatically develops good judgment, approaches to teaching engineering judgment must account for its cognitive and social epistemic dimensions shaped by how engineers evaluate and apply knowledge in practice [2]. Students may excel at solving well-defined problems while struggling to make sound judgments in authentic engineering scenarios that involve ambiguity, competing values, and the need to integrate multiple knowledge sources [26], [46].

Among the psychological constructs that inform engineering judgment, we argue that epistemic cognition offers particularly promising insights for engineering education [47], [48], [49]. How students conceptualize the nature of engineering knowledge—its certainty, complexity, source, and justification—fundamentally shapes their approach to engineering problems and their development of judgment. When students view engineering knowledge as fixed and absolute, they may fail to recognize situations requiring engineering judgment rather than algorithmic application of formulas. Conversely, students who appreciate the contextual and evolving nature of engineering knowledge may be better positioned to develop nuanced judgment skills that integrate theoretical principles with practical constraints. The next section explores epistemic cognition in greater detail, examining how this framework can illuminate the development of engineering judgment and inform pedagogical approaches.

Epistemic Cognition

Epistemic cognition is a process where individuals determine what information they know, believe, and value, versus what they do not [50]. Engineers tacitly enact epistemic cognition in the form of dispositions, beliefs, and skills about engineering knowledge and knowing processes [36], [48]. For example, when an engineer pushes code to a remote server, they are confident the code can be retrieved at a later date. Similarly, an engineer may trust and use standardized codes when deciding between bolt sizes because of regulatory requirements. Research suggests that epistemic cognition relates to learning outcomes, such as critical thinking and judgment, by facilitating students' relationships and approaches to knowledge and knowing processes [12], [36]. In engineering education, Faber and Benson [26] showed that engineering students who believed that knowledge is constructed and subject to change were more likely to spend more time completing an open-ended assignment and say they gained knowledge and understanding in the process. Such beliefs reflect students' environment because the environment provides the setting for belief construction [51]. For instance, Tenenberg and Chinn's [52] investigation of a computer science course connected classroom epistemic practices (e.g., using computers to verify code success) to students' understanding of the discipline as prioritizing certain forms of knowing (i.e., mathematical proofs) over others (e.g., incorporating community knowledge in design; see [53]). Classroom features help constitute both classroom-specific and disciplinary epistemic cultures [54], which also manifest as dominant epistemic dispositions, skills, and beliefs [55]. Such dominant epistemologies may marginalize students when they experience tension between their identities and engineering programs for epistemological reasons, not just social, cultural, or personality-based ones [54], [56]. Thus, when engineers exercise engineering judgment, they draw upon their epistemic cognition: evaluating what they believe to be true, why they believe it, and how they know it [57]. Further, these are processes that are and can be informed by educators through the techniques they employ [58]. We argue that epistemic cognition directed toward specific epistemic tasks provides the conditions for engineers to integrate their technical knowledge, practical experiences, and professional identity to reach decisions in specific contexts. This is a tremendous responsibility and, applied to the classroom, mean that students should encounter tasks that provoke their epistemic cognition in such ways as to recognize that responsibility.

Epistemic cognition can be differentiated into three categories: epistemic dispositions, beliefs, and skills, each of which presents unique implications for conceptualizing engineering judgment [59]. Epistemic dispositions, like critical thinking dispositions, describe the combination of attitudes, affects, and habits that affect how engineers approach and evaluate engineering knowledge [60], such as intellectual humility [61] and the need for closure [62]. For example, the "skeptical reverence" that structural engineers display toward mathematics [2] reflects a sophisticated understanding that mathematical knowledge is both essential and inherently limited; leading engineers to trust calculations while remaining open to overriding their results when other evidence suggests otherwise. Epistemic dispositions implicate epistemic beliefs, or engineers' personal theories about the nature of knowledge and knowing processes [63]. Such beliefs hold large sway over how individuals perceive information and make judgments [13], [36], and are generally described as developing along a four-stage continuum from "realist" to "evaluativist" [13], [63], [64], [65], [66]. This research suggests that individuals with more sophisticated evaluativist beliefs—who understand the impossibility of perfect knowledge, making some solutions are better than others based on evidence and argument—may be better equipped to handle complex engineering tasks that require weighing multiple perspectives and evidence types. Epistemic beliefs may relate to whether engineers see their judgments as finding single "right" answers or as constructing defensible solutions among various possibilities. Finally, epistemic skills determine how engineers justify their judgments through different types of evidence: testimony from reliable sources, accepted analytical practices and procedures, or combinations of both. Applied to the earlier example, when deciding between bolt sizes, engineers must evaluate manufacturer specifications (testimony), conduct theoretical calculations (normative practices), and often integrate multiple forms of evidence to reach and defend their conclusions. Further, their decision also involves epistemic beliefs (certainty about "right," trust in the manufacturer's specifications, theoretical calculations vs. field experience) and epistemic dispositions (openness to questioning specifications, willingness to seek multiple perspectives, skeptical reverence toward standards), which are collectively shaped by their personal experiences, background, disciplinary knowledge, and context [51], [67]. Epistemic dispositions, beliefs, and skills help explain why engineering judgment goes beyond technical knowledge and critical thinking skills. It requires sophisticated epistemic cognition—the ability to thoughtfully evaluate different types of engineering knowledge, understand their limitations, and integrate them appropriately for specific contexts.

An ongoing and active area of research regarding epistemic cognition concerns its domain specificity, as epistemic dispositions, beliefs, and skills can vary between situations and environments [68]. For example, an engineer may not employ rigorous source verification when trusting their dentist's advice, though models of epistemic cognition differ with respect to how much they (de)emphasize these differences. Nevertheless, the dispositions, beliefs, and skills comprising epistemic cognition are inherently social because they are learned and function in social interactions. This social perspective on epistemic cognition is relevant to engineering judgment as engineers rarely make decisions in isolation [69]. When evaluating knowledge claims, engineers operate within a "division of cognitive labor" [70, p. 225], relying on testimony from vendors, specifications from manufacturers, codes from regulatory bodies, and expertise from colleagues. This distributed expertise means that engineers must develop sophisticated epistemic skills to evaluate the credibility of different sources and justify their use of others' knowledge. For example, Gainsburg [2] describes how one engineer came to trust a vendor's specifications through previous interactions that demonstrated the vendor's deep knowledge of wood properties. Such social validation of knowledge extends beyond individual trust relationships—engineering judgments are frequently negotiated through team discussions, peer reviews, and professional networks where collective expertise helps validate or challenge individual judgments. In short, examining the social dimensions of epistemic cognition is particularly important for understanding how engineering judgment develops, as students must learn not just what knowledge to trust, but how to participate in the social practices through which engineering knowledge is constructed, validated, and applied.

Teaching for Epistemic Cognition

Modern problems require engineers who can not only make challenging and uncertain engineering decisions but understand the justifications and processes used to make them. Studying epistemic cognition may help to address these concerns by providing educators with concrete ways to ground their teaching and curricular practices according to students' epistemic dispositions, beliefs, and skills about engineering knowledge. Several successful interventions have been developed that illustrate the effects of classroom instruction and teacher preparation on students' epistemic cognition [71]. For example, Muis and Duffy [72] adjusted the teaching style, curricular materials, and supports for a graduate-level course, which impacted students' epistemic beliefs and learning approaches, leading to improved class performance compared to a control. However, fewer such investigations have been conducted in engineering despite concerns about overly simplistic engineering material and teaching that does not reflect the complexities present in actual engineering practice [73], [74]. Educators may already be coping with these ramifications, such as Frye et al.'s [75] observation of sophomore civil engineering students who tended to view statics knowledge as simple, certain, and objective. Similarly, students' epistemic beliefs can clash with their experiences or outcome expectations, resulting in difficulties for both instructors and other students, particularly in innovative educational settings [76]. These examples highlight the important role of epistemic cognition in students' learning and success, development of critical thinking skills, and transition to real-world engineering practice. Consequently, educators should consider students' evolving epistemic cognition and work to integrate pedagogical strategies, evaluation practices, support systems, and curricular materials to support its development.

Given the parallels between epistemic cognition and engineering judgment, we argue that epistemic cognition interventions also present opportunities to develop students' engineering judgment. Mirroring epistemic cognition, interventions aimed to develop students' engineering judgment could be directed toward both the classroom environment and teacher preparation. Regarding the classroom environment, research shows that constructivist classrooms are most successful for developing students' epistemic cognition [36]. Environments that allow students to co-construct knowledge, work together, and receive meaningful feedback promote engagement and critical analysis, helping to challenge students' epistemic cognition and advance their understanding of disciplinary knowledge and knowing processes. Other strategies, such as directing students' attention toward arguments and justifications [77] and allowing students to take the lead exploring problems [78], also positively contribute to students' epistemic cognition. Applied to engineering judgment, interventions to evaluate and develop students' epistemic cognition may also promote the cognitive capabilities required for sophisticated engineering judgment. For example, classroom activities can incorporate epistemic elements into design work rubrics, such as evaluating how students negotiate different epistemic skills or justify their design choices. Even complex epistemic skills can be developed early; research suggests that with proper support, middle school students can learn to evaluate and choose between different scientific models [79].

Teachers' epistemic cognition also influences their students' epistemic cognition development, impacting students' success [36]. In the context of teacher preparation, epistemic cognition frameworks can help instructors provide more targeted feedback. Rather than simply stating "I disagree with your judgment," instructors can connect feedback to specific epistemic elements, giving students concrete areas for improvement. For example, an instructor might design prompts to elicit students' epistemic beliefs, allowing them to comment about a student's assumptions and values. Additionally, instructors can deliberately incorporate epistemic considerations into course narratives; for instance, introducing scenarios that require students to weigh different types of evidence or consider competing stakeholder needs. Such scenarios can directly call out disciplinary norms and practices, helping students learn to evaluate their application and efficacy. While these interventions show promise, educators need structured ways to assess and develop students' epistemic cognition. The AIR model of epistemic thinking, emerging from epistemic cognition research, offers one such framework [57]. This model provides educators with specific tools to evaluate students' epistemic development and design targeted interventions, which we describe in the next section. Ultimately, epistemic cognition provides a valuable lens for understanding the cognitive processes underlying engineering judgment. Through its three components—dispositions, beliefs, and skills—epistemic cognition helps explain how engineers approach, evaluate, and justify knowledge claims in their decision-making. Understanding how these components of epistemic cognition manifest in engineering practice can help educators better support the development of students' engineering judgment through targeted interventions in both classroom instruction and teacher preparation.

The AIR Model of Epistemic Cognition

Chinn and Rinehart [57] proposed the AIR model of epistemic cognition to help educators more holistically conceptualize, develop, and assess students' epistemic cognition. Drawing on extensive previous work on epistemic cognition and philosophy literature, the AIR model consists of three interrelated constructs: epistemic Aims and values, epistemic Ideals, and Reliable processes. Epistemic aims are goals related to developing representations of how the world works, including pursuing knowledge, understanding, models, theories, and evidence. Values refer to what kinds of knowledge are considered axiomatic and important. For example, a structural engineer's aims might include understanding the precise behavior of a new composite material under various stress conditions (aim) or prioritizing practical, implementable solutions over elegant but impractical ones (value). Epistemic ideals are the standards or criteria used to evaluate epistemic products (knowledge claims, theories, models, etc.). They guide both the creation and evaluation of knowledge. In engineering design, design performance is frequently reproduced (i.e., results must be reproducible) and may need support from multiple lines of evidence (e.g., simulations, prototypes, and testing). Lastly, reliable processes are the methods and procedures that dependably accomplish epistemic aims and produce knowledge claims. They are reliable only under certain conditions and can operate at individual, group, or institutional levels. Examples include following standardized testing protocols, peer review of designs, conducting failure mode and effects analysis, and using calibrated instruments. The AIR model highlights several aspects of epistemic cognition discussed previously, such as epistemic skills, though referred to as reliable processes. It allows educators to assess and evaluate students' epistemic cognition along the three dimensions of epistemic dispositions, skills, and beliefs by focusing on their epistemic aims, ideals used to evaluate aims, and processes employed to achieve aims.

Accordingly, the AIR model is particularly relevant to engineering because engineers routinely navigate multiple epistemic aims, ideals, and reliable processes. Engineers must balance competing aims, such as safety, efficiency, cost, and sustainability, where success in one dimension often requires trade-offs in others. These aims are evaluated using both well-defined criteria (building codes, material specifications) and evolving standards (sustainability metrics, novel performance requirements). Similarly, the processes engineers use to generate and validate knowledge span from highly standardized procedures (laboratory testing, computational analysis) to more contextual methods (professional consultation, experiential knowledge). For example, when designing a bridge, an engineer might need to balance the aim of structural safety (evaluated through established load calculations) with environmental impact (assessed through evolving sustainability metrics), while integrating knowledge from both standardized material testing and local construction expertise. This complex interplay of aims, ideals, and reliable processes makes the AIR model especially useful for understanding and developing engineering judgment. In support of this perspective, it has been used in engineering education to analyze students' problem-solving approaches [26], providing additional credence for its applicability in both scaffolding and evaluating students' engineering judgment.

We are currently building off this work in an in-progress publication to understand how students recognize and employ engineering judgment in an undergraduate engineering laboratory setting. Students completed several open-ended design experiments throughout the semester that integrate progressive AIR-based scaffolding in the instruction and curricular materials. Our intent was for them to identify an aim (e.g., "measure the voltage of the battery using the multimeter under a given load"), an ideal to assess the aim (e.g., "measure the voltage under several loads to confirm the trend and verify with other groups"), and a process to achieve the aim (e.g., "measure the voltage every X seconds under Y load conditions"). Lessons and materials frequently mentioned that no one solution was correct and that many different aims, ideals, and reliable processes could work for each design. Early results suggest that while epistemic frameworks like AIR offer valuable structure for thinking about engineering judgment, their effectiveness depends heavily on how and when they are introduced. Simply providing the framework late in students' engineering education may not be sufficient to overcome established patterns of approaching engineering problems [29]. Earlier and more consistent exposure to epistemic frameworks, combined with regular opportunities to practice engineering judgment in scaffolded settings, may be necessary for students to develop these sophisticated cognitive capabilities [30].

Conclusion

While previous frameworks acknowledge situational dimensions of engineering judgment, they often deemphasize the complex mental processes involved in judging. Understanding engineering judgment through psychological lenses provides alternative perspectives for engineering educators seeking to complement existing efforts by positioning students' learning about engineering judgment as preceding its development. This theoretical reframing shifts pedagogical attention from assuming judgment naturally emerges through technical coursework toward deliberately cultivating the cognitive foundations that support sophisticated judgment capabilities. To support these efforts, epistemic cognition provides a particularly valuable framework for conceptualizing the cognitive underpinnings of engineering judgment. By examining how students acquire, evaluate, and apply knowledge—processes central to engineering practice—epistemic cognition illuminates why technically competent students may struggle with judgment-based problems that involve ambiguity, competing values, and integration of multiple knowledge sources. The AIR model, with its tripartite focus on epistemic aims, ideals, and reliable processes, offers a structured methodological approach for conceptualizing and evaluating students' epistemic cognition, thereby providing a systematic lens for assessing engineering judgment development.

This reconceptualization of engineering judgment through epistemic cognition yields significant implications for engineering education. Engineering judgment requires explicit pedagogical attention rather than implicit development through technical coursework alone. Students need structured opportunities to recognize when they are exercising judgment versus following procedures, with deliberate scaffolding that makes judgment processes visible and accessible. Integrating frameworks like AIR across the curriculum may facilitate progressive development of not only technical competencies but also the sophisticated epistemic dispositions, beliefs, and skills that underlie sound engineering judgment. Future investigations may look to examine varied pedagogical approaches that incorporate epistemic frameworks, particularly in early engineering coursework, where students begin forming disciplinary epistemologies. Longitudinal studies examining the co-evolution of students' epistemic cognition and engineering judgment capabilities could further illuminate developmental trajectories and inform targeted interventions. By systematically addressing the cognitive foundations of engineering judgment, educators can better prepare students for the complex decision-making demands of contemporary engineering practice.

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