education sciences

Commentary

Mathematics as a Gateway, Not a Barrier: Reimagining Engineering Preparation for the 21st Century

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Abstract

For more than seventy years, mathematics—particularly the calculus sequence—has defined both the rigor and the exclusivity of engineering education in the United States. While this structure was historically instrumental in professionalizing engineering, it has also produced unintended consequences: restricted access, misalignment with contemporary engineering practice, and persistent inequities in participation and degree attainment. This commentary argues that mathematics must be reimagined not as a barrier or filter, but as a gateway that enables engineering learning, persistence, and innovation. Building on The Engineering Mindset Report and decades of research in engineering education, learning sciences, and curricular reform, we examine how mathematics became a gatekeeping mechanism, assess its current impacts, and propose a framework for redesigning engineering mathematics around context, modularity, technology, and equity. We advocate for accessible, flexible, and technology-enabled pathways that emphasize modeling, data analysis, and conceptual understanding over procedural endurance. Such an approach has the potential to broaden participation, improve student success, and better align engineering education with the realities of 21st-century professional practice.

Keywords: engineering education; mathematics reform; calculus sequence; curriculum innovation; ABET; growth mindset

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1. Introduction

Engineering education is once again at a crossroads. Midway through the twentieth century, the ASEE Grinter Report (ASEE Committee on Evaluation of Engineering Education, 1955) fundamentally reshaped the profession by shifting engineering education from an applied, apprenticeship-based model to one grounded in science and mathematics. At the time, this transformation was both visionary and necessary, helping establish engineering as a rigorous, research-informed profession capable of supporting national priorities in infrastructure, defense, and technological innovation. Central to this transformation was elevating calculus as a defining prerequisite for engineering study.

Over time, however, this structure hardened into orthodoxy. Mastery of calculus became not merely a tool for engineering analysis but a proxy for engineering potential itself. For generations, calculus has served simultaneously as a symbol of rigor and a barrier to entry. Students unable to navigate extended prerequisite sequences are frequently

delayed, diverted, or excluded from engineering pathways altogether, often before they encounter any authentic engineering coursework.

Today, this system increasingly conflicts with societal needs and student realities. Engineering challenges—from climate resilience and energy systems to biomedical innovation and artificial intelligence—demand diverse perspectives, interdisciplinary collaboration, and fluency with modern computational tools. Yet, mathematics placement policies and rigid prerequisite chains prevent tens of thousands of capable students—disproportionately women, first-generation students, adult learners, and students from underserved communities—from ever accessing engineering programs. The Engineering Mindset Report (American Society for Engineering Education [ASEE], 2024) identifies this phenomenon as the "math bottleneck," arguing that it represents the most significant structural obstacle to broadening participation and strengthening the engineering workforce.

Despite efforts to reform the teaching of calculus, there has been no comprehensive effort by engineering educators to reform engineering mathematics education at the level suggested by The Engineering Mindset Report. Reimagining mathematics as a gateway rather than a barrier is therefore not a peripheral reform; it is central to the future vitality of the profession. This commentary contributes to that reimagining by tracing the historical roots of the calculus-centric paradigm, examining its contemporary misalignment with practice and learning science, and proposing a coherent framework for reform grounded in context, modularity, technology, and equity.

2. Historical Legacy: The Grinter Mindset

The Grinter Report emerged in a postwar context defined by rapid technological change and national competition. Its authors sought to professionalize engineering by aligning it more closely with scientific theory, particularly mathematics and physics. The resulting curriculum model emphasized analytical rigor, abstraction, and sequential mastery of foundational mathematics prior to engagement with advanced engineering topics.

This shift produced enduring curricular features that remain largely intact today. Most engineering programs continue to require a sequence of calculus I, II, and III, followed by differential equations and linear algebra, as prerequisites or corequisites for sophomore-level engineering courses. While the intent was to ensure analytical depth, the effect has been a rigid system that prioritizes mathematical purity over functional relevance.

Three persistent patterns characterize this legacy. First, over-specification dominates curricula, with significant instructional time devoted to analytic techniques rarely used in modern practice. Second, sequential rigidity delays meaningful engagement with engineering design and problem-solving until late in the curriculum. Third, exclusionary signaling leads students to interpret early difficulty in calculus as evidence that they do not belong in engineering.

These patterns persist not because of evidence of effectiveness, but because of cultural inertia reinforced by accreditation structures, institutional tradition, and faculty identity. As a result, mathematics remains a sorting mechanism rather than an enabling tool for engineering thinking.

3. Contemporary Challenges

3.1. Misalignment Between Preparation and Practice

Many incoming U.S. engineering students place below calculus I, and post-COVID, this number appears to be growing, mirroring declines in math readiness reported across the U.S. (Carvell et al., 2024; Gray et al., 2024; Ryan et al., 2025). Thus, the average high school graduate lacks the fluency with and depth of understanding in algebra and trigonometry expected by traditional programs. Moreover, traditional mathematics and

engineering curricula focus heavily on rote repetition with little meaningful application or complex problem-solving (Pepin et al., 2021; Qi et al., 2023). In contrast, professional engineering has relied for decades on computational tools, simulation, modeling, and data analysis to solve real-world problems rather than on manual calculations (Plevris et al., 2025). The infusion of AI tools is moving professional practice even farther afield from the current focus of traditional curricula. Today's curriculum still teaches 1950s techniques while omitting 21st-century competencies.

One of many results of our current curricular structure is a mismatch between preparation and practice. Students spend significant time and effort mastering outdated symbolic procedures instead of developing transferable conceptual understanding and quantitative reasoning skills. They graduate without adequate proficiency in the tools and processes that are core to 21st-century professional practice. Graduates lack sufficient experience collaborating to solve complex real-world problems on multidisciplinary teams, employing effective communication, and spend most of their time working in isolation to solve problems that can be easily solved by ChatGPT (Cecere, 2025). Many engineering employers, and even engineering graduates themselves, have long lamented the mismatch between college and the workplace, as well as the need to spend significant time training new hires before they can be productive (Brunhaver et al., 2018).

Within higher education, awareness of this mismatch extends back decades. In fact, moving engineering education toward more active, project-based, experiential learning, with a focus on conceptual understanding and away from a sole focus on theory and rote, analytic problem-solving, was a key focus of both the seven NSF-funded engineering education coalitions and the NSF-funded calculus reform efforts in the 1990s (Froyd & Ohland, 2005; National Science Foundation, 1992, 1997; Olds & Miller, 2004; Sheppard et al., 2009). While multiple innovative models and curricula that address aspects of this mismatch have been developed since then, and some innovative programs do exist, adoption of modern curricular and instructional approaches is not widespread within the higher-education engineering landscape (American Society for Engineering Education [ASEE], 2009; Olewnik et al., 2024; Riley et al., 2023).

3.2. Institutional and Accreditation Inertia

Despite evidence that contextualized math pathways enhance retention, most programs remain tied to ABET's calculus requirements. As discussed shortly, the approach developed by Klingbeil et al. at Wright State University has demonstrated a scalable alternative that has served thousands of students since 2004, through multiple six-year accreditation cycles. Still, widespread adoption of more flexible approaches to engineering mathematics education remains rare. ABET committees, largely influenced by the "old guard," equate calculus volume with rigor, which limits experimentation at the program level. Faculty often worry that moving away from traditional mathematics sequences could jeopardize accreditation or transfer credit agreements, thus preserving the current system in an unending loop.

4. Mathematics as Context and Catalyst

4.1. From Filter to Framework

A central premise of this paper is that mathematics should function as a framework for expressing engineering ideas rather than as a filter that restricts access. When mathematics is embedded in authentic contexts—modeling physical systems, analyzing data, and informing design decisions—students are more likely to develop both conceptual understanding and professional identity (Huffmyer et al., 2022; Liquete et al., 2025; Pepin et al., 2021; Rezvanifard et al., 2023).

This perspective aligns with situated cognition and transfer-of-learning theories, which emphasize that knowledge develops through use in meaningful contexts. Early and sustained exposure to application is particularly important for students who may not initially identify as "strong in math" but are motivated by solving real-world problems (Ma, 2025; Raj et al., 2025).

4.2. Principles for Reform

4.2.1. A Framework for Modernizing Mathematics in Engineering Education

Mathematics has long served as a gatekeeping mechanism in engineering education, disproportionately restricting access, contributing significantly to attrition from our programs and remaining misaligned with contemporary engineering practice. Modernization (Faulkner et al., 2025; Peck et al., 2016) requires reframing mathematics as an enabling infrastructure—supporting modeling, decision-making, and design—rather than as a prerequisite filter. Five principles guide this transformation.

4.2.2. Contextual Integration

Mathematics should be introduced through authentic engineering contexts from the first semester, so students encounter concepts such as functions, rates of change, linear systems, and probability as tools for modeling real systems rather than as abstract formalisms. Grounded in theories of situated cognition and transfer of learning, contextualized instruction improves motivation, coherence, and application by anchoring mathematical meaning in use (Buckingham, 2025; Choi & Hannafin, 1995). Early relevance is particularly critical for persistence among students historically marginalized by traditional mathematics sequences.

4.2.3. Modular Flexibility

Linear, one-size-fits-all mathematics sequences assume uniform preparation and progression, an assumption incompatible with diverse educational pathways. Competency-based modular structures—organized around modeling, statistics, trigonometry, linear algebra, and optimization—allow students to progress based on demonstrated mastery rather than seat time. This approach aligns with mastery learning and learning progression frameworks, supporting acceleration, remediation, and discipline-specific alignment while preserving rigor (Duschl, 2019; Malhotra et al., 2023; Perez & Verdín, 2022).

4.2.4. Technology-Enabled Learning

Contemporary engineering practice relies on computational tools; mathematics education must reflect this reality. Computer algebra systems, numerical solvers, simulations, and AI-assisted tools reduce extraneous cognitive load associated with routine computation and shift instructional emphasis toward conceptual understanding, interpretation, and judgment. Consistent with cognitive load theory and instrumental genesis, technology serves as a cognitive amplifier when integrated intentionally, enabling deeper exploration of assumptions, sensitivity, and model validity (Ritella & Hakkarainen, 2012; Sweller, 2020).

4.2.5. Equitable Access

Equity-oriented design (Wood et al., 2022) recognizes that variation in mathematical preparation often reflects unequal opportunity rather than unequal ability. Lack of access to excellence in pre-college mathematics preparation is a nationwide problem in the U.S., ranging from small rural schools with limited capacity for course offerings to under-resourced urban areas. Further, in many cases, a "wrong" choice in middle school mathematics may prevent a student from enrolling in the "right" kind of mathematics course in high school, limiting access to engineering programs. Multiple on-ramps, diagnostic assessment,

and just-in-time mathematical instruction embedded in engineering courses will reduce attrition and time-to-degree while maintaining standards. This principle draws on funds of knowledge and asset-based perspectives, shifting the burden of adaptation from students to institutions (Denton & Borrego, 2021; Verdín & Smith, 2021).

4.2.6. Interdisciplinary Collaboration

Sustainable reform requires sustained collaboration between mathematics and engineering faculty to co-design learning outcomes, instructional materials, and assessments (Faulkner et al., 2025; Goos et al., 2023; Pepin et al., 2021). Historically siloed curricula create misalignment between what is taught and what is needed. Interdisciplinary design supports curricular coherence, authentic assessment, and shared responsibility for student success, consistent with systems-level change models in STEM education.

Together, these principles reposition mathematics as a bridge rather than a barrier—expanding access, strengthening conceptual understanding, and aligning education with modern engineering practice. By integrating theory, technology, and equity-centered design, this framework supports the development of a robust, adaptive, and diverse engineering workforce capable of addressing complex societal challenges.

5. Reimagining Curriculum Structures

Following the framework established by the Grinter Report, the traditional engineering curriculum is perhaps the least flexible undergraduate curriculum in all of higher education, particularly regarding its mathematics requirements. In the typical engineering degree program, students are required to complete a full sequence of traditional math courses as pre- or co-requisites for core sophomore-level engineering courses. The introductory mathematics sequence typically includes three semesters of calculus, as well as at least one semester of differential equations and linear algebra.

Given the state of modern computational tools, including the rapid evolution of generative AI technologies, we should question whether four or more semesters of traditional math requirements are really necessary to train the next generation of engineers. However, the bigger issue in this outdated curricular structure is its impact of such requirements on our collective ability to produce engineering graduates. In particular, the average American high school graduate is woefully underprepared in math, a reality that has only worsened since the pandemic. As a result, the median incoming engineering student at many institutions is placed at the college algebra level or below, at least two semesters behind the first required calculus course in our current curricula. Instead of four or more required math courses on paper, a typical incoming engineering student faces a sequence of six or more math courses before making any real progress in their intended engineering degree program, with the first two or three math courses not even counting toward their engineering degree. Practically speaking, this makes the traditional engineering curriculum effectively inaccessible to the average American high school graduate. Further, this bottleneck makes engineering programs unattractive to a large proportion of our population.

The issues highlighted in the previous sections raise the question of whether alternative curricular pathways might exist—pathways that may ultimately be necessary to produce the engineering workforce required for our nation's continued global competitiveness. As detailed subsequently, a number of alternative approaches have been developed for engineering mathematics instruction over the past two decades, aiming to increase student retention and success in engineering. For the long-term viability of the engineering profession, we believe the time is now to consider these changes.

5.1. Math-in-Context Courses

Perhaps the earliest and sustained approach to addressing the "calculus bottleneck" in the traditional engineering curriculum was proposed by N. W. Klingbeil et al. (2004) at Wright State University. The Wright State approach includes the development of EGR 101 Introductory Mathematics for Engineering Applications, a first-year engineering course that replaces traditional calculus prerequisites for core sophomore-level engineering courses. This allows students to advance in the engineering curriculum without first completing any part of the traditional calculus sequence.

The EGR 101 course is not intended to replace the required calculus sequence, which remains fully required. Instead, EGR 101 provides a comprehensive introduction to the math topics most frequently used in core engineering courses, with all topics set in the context of an engineering application. Rather than contrived physical contexts for math, the content of EGR 101 is drawn directly from the engineering courses for which it serves as an alternative math prerequisite. These include General Physics I, Statics, Dynamics, Mechanics of Materials, and Electric Circuits, with occasional applications from upper-division courses. The math topics include algebra and trigonometry, vectors and complex numbers, derivatives and integrals, differential equations and matrix algebra, offering a window into the entire required math sequence. The course structure includes problem-based lectures, hands-on laboratories, and mandatory recitations, designed to engage students across the full range of learning styles. The course is staffed by engineering faculty members and engineering student TAs, whose presence in the first-year classroom reinforces the importance of mathematics in the engineering curriculum. Perhaps more importantly, the course helps reinforce how math is actually used in the engineering degree program, straight from the mouths of the faculty members who teach it. Finally, the required math placement for EGR 101 is at the pre-calculus level, making the engineering degree program immediately accessible even to students who are not yet calculus-ready.

Following more than a decade of continuous funding from the National Science Foundation, the longitudinal impacts of the Wright State model have been widely reported. For students enrolled in the EGR 101 course, these impacts included an overall increase in engineering degree attainment by more than a factor of two, with the greatest impact on students from underrepresented groups (women and minorities) (N. Klingbeil & Bourne, 2013). The introduction of EGR 199 as a precursor to EGR 101 for initially underprepared students further strengthened the approach, making the core engineering curriculum almost immediately accessible to incoming students who placed as many as 3 math classes below the first required calculus course (N. Klingbeil & Bourne, 2015).

The reasons for the success of the Wright State model are multifaceted and vary across the student population. That said, work by N. Klingbeil and Bourne (2014) and Bourne et al. (2015) has shown increases in both student motivation and self-efficacy among students enrolled in the EGR 101 course, which has undoubtedly played a significant role in the observed increases in engineering degree attainment. However, more recent work by Finfrock and Klingbeil (2023) has also examined the impact of the associated restructuring of the engineering curriculum (i.e., the removal of the calculus bottleneck). Building on the pioneering work of Heileman et al. (2017, 2018) and the development of the Curricular Analytics platform, Finfrock and Klingbeil showed that the Wright State model has substantially reduced both the curricular complexity and the curricular centrality of the required calculus sequence, which was likely a significant contributor to its longitudinal impact on student success and degree attainment.

Following the publication of a nationally marketed textbook (Rattan & Klingbeil, 2015) and the completion of a national dissemination grant (N. Klingbeil et al., 2008), aspects of the Wright State model have now been implemented by dozens of institutions nationwide.

However, despite the number of institutions currently implementing their own adaptations of the EGR 101 course, only a handful have implemented the associated restructuring of the engineering curriculum (i.e., the removal of traditional math prerequisites for core sophomore-level engineering courses). Ultimately, the collective resistance of engineering faculty to increasing the flexibility of their own curriculum has preserved the traditional calculus bottleneck in most engineering degree programs nationwide.

5.2. Modularized Pathways

Conventional calculus-first prerequisite structures assume uniform preparation and treat deviations as deficiencies, delaying or excluding capable students whose prior experiences differ from the assumed norm. Modularized pathways replace this rigidity with design-by-choice ecosystems that recognize diverse entry points while maintaining rigor.

In this model, mathematics is organized around engineering-relevant competencies rather than fixed course sequences. Students entering at the algebra level may begin with an engineering mathematics-in-context module that integrates algebra, trigonometry, vectors, data analysis, and computational modeling through authentic engineering problems. These modules emphasize quantitative reasoning and sense-making rather than formal symbolic completeness.

Completing such modules serves as a gateway, granting access to core engineering courses without requiring the full calculus sequence upfront. Calculus is repositioned as a tool introduced when it becomes functionally necessary rather than as a universal filter. This alignment shortens time-to-degree, reduces attrition, and preserves curricular coherence while allowing pathways to adapt as disciplinary needs evolve.

5.3. Competency-Based Assessment

Assessment strongly influences whether mathematics supports learning or is used for sorting students. High-stakes, time-constrained exams often privilege speed and memorization over understanding, reinforcing failure cycles that disproportionately affect students from nontraditional backgrounds. Competency-based assessment reframes evaluation around demonstrated mastery rather than comparative ranking.

In competency-based frameworks, learning outcomes are explicit and assessed through multiple demonstrations of proficiency. Students advance by demonstrating conceptual understanding, interpretive ability, and effective use of tools through applied problems, projects, or iterative assessments. Conceptual understanding—supported by technology—should replace elaborate hand calculations as the benchmark of proficiency in engineering mathematics.

A competency-based approach preserves rigor through clearly articulated standards and reduces barriers unrelated to mathematical understanding. When paired with modularized pathways, competency-based assessment transforms mathematics from a gatekeeping mechanism into an enabling structure that supports access, persistence, and success in engineering education.

6. Technology and AI as Partners in Learning Mathematics

Modern computational environments (e.g., MATLAB, Python, symbolic AI) redefine mathematical practice in engineering. Engineers rarely perform extended manual calculations; instead, they formulate problems, interpret computational outputs, and assess model validity. Mathematics learning at the university must therefore shift from procedural execution to model reasoning.

Technology-enabled learning emphasizes the formulation, interpretation, and validation of mathematical models. As AI increasingly generates mathematical and engineering

solutions, students must learn to interrogate assumptions, analyze errors, and assess trustworthiness. Instruction should prioritize uncertainty analysis, model interpretation, and the ethical use of AI. Offloading routine computation frees time for creativity, collaboration, and reflective problem solving—core competencies in human-centered engineering.

7. Equity, Access, and Student Success

Calculus-first rigid pathways with competitive grading act as structural bottlenecks to engineering degree attainment (B. D. Bowen et al., 2017), disproportionately affecting nontraditional and underserved students, particularly adults returning to college (B. Bowen et al., 2019). Pandemic-era learning losses have further widened readiness gaps (Lewis & Kuhfeld, 2023; Morton et al., 2026). Flexible, application-driven mathematics pathways directly address these inequities.

When mathematics is taught through real-world engineering challenges—such as sustainability, energy, or biomedical systems—student engagement and motivation increase (López-Díaz & Peña, 2021). Modular curricula enable recognition of prior learning, reduce redundancy, and shorten time to degree, aligning engineering education with the diverse trajectories of contemporary learners.

8. Redefining Rigor: From Survival to Mastery

Rigor must move from a mindset of "survival of the fittest" to one of "growth through mastery." Traditional definitions equate rigor with speed and procedural endurance, often at the expense of understanding and equity. The Engineering Mindset Report advocates replacing punitive grading with environments that foster persistence, confidence, and intellectual risk-taking.

True rigor is demonstrated when students can apply mathematical principles flexibly, adapt models, and justify decisions across contexts (Campbell & Dortch, 2018). This reframing aligns with growth-mindset theory and evidence from learning science showing that challenge paired with support—not exclusion—produces durable learning and excellence.

9. Institutional Change and Policy Implications

Scalable reform requires institutional alignment across policy, accreditation, and faculty incentives.

Accreditation bodies such as ABET should recognize multiple mathematics pathways—including algebra, statistics, modeling, and computation—when outcomes are met.
Faculty development should support sustained collaboration between mathematics and engineering educators.
Transfer and articulation policies must accommodate modular, competency-based curricula.
Research and assessment should document long-term impacts on access, retention, and conceptual mastery.

Without institutional courage, mathematics reform will remain localized rather than transformative across our nation.

10. Conclusions: Rewriting the Equation

Engineering education stands at a pivotal moment (Sorby et al., 2021). The profession can continue to refine a mid-20th-century system that equates mathematical endurance with engineering potential, or it can embrace a 21st-century model that prioritizes relevance, flexibility, and inclusion. The evidence reviewed in this paper makes clear that the traditional calculus-first paradigm—while historically important—no longer aligns with contemporary engineering practice, workforce needs, or the realities of today's learners.

Rewriting the equation requires a fundamental shift in how mathematics is positioned within engineering education. Mathematics should no longer serve as a filter that determines who is "worthy" of becoming an engineer. Instead, it must serve as enabling infrastructure—a language and toolset that empowers students to model systems, analyze data, and make informed design decisions. When mathematics is embedded in context, supported by modern computational tools, and assessed through demonstrated mastery rather than speed and memorization, it becomes a gateway rather than a barrier.

This paper has shown that alternative pathways are not hypothetical. Models such as math-in-context courses, modularized pathways, and competency-based assessment have already demonstrated substantial gains in retention, degree completion, and student confidence—particularly for women, first-generation students, and other groups historically excluded by traditional structures. Importantly, these approaches do not dilute rigor; they redefine it. Rigor emerges not from procedural survival but from the ability to apply mathematical reasoning flexibly, critically, and ethically in authentic engineering contexts.

The rapid evolution of computational tools and generative AI further underscores the urgency of reform. As professional engineers increasingly rely on modeling, simulation, and data-driven decision-making, mathematics education must prepare students to interpret, validate, and critique computational results rather than reproduce hand calculations disconnected from practice. This shift elevates the human dimensions of engineering—judgment, creativity, collaboration, and responsibility—while preserving the discipline's analytical foundations.

Achieving this transformation, however, requires more than isolated curricular innovation. Institutional policies, accreditation frameworks, transfer agreements, and faculty reward systems must evolve to support flexible, competency-based mathematics pathways. Without such alignment, reform efforts will remain as localized pilots rather than systemic change. The engineering education community must demonstrate the institutional courage to question long-standing assumptions and align educational structures with evidence, equity, and contemporary practice.

Ultimately, the future of engineering depends on who is allowed to participate and how they are prepared. By reimagining mathematics as a gateway to engineering success, the profession can broaden access, deepen conceptual understanding, and cultivate a more diverse and adaptive engineering workforce. Rewriting the equation is not merely a curricular adjustment—it is a strategic imperative for the vitality, relevance, and societal impact of engineering in the decades ahead.

Call to Action

The responsibility for rewriting the equation does not rest with students—it rests with the profession. Engineering educators, institutions, and professional organizations must move beyond incremental reform and commit to structural change grounded in evidence, equity, and contemporary practice. The National Science Foundation can accelerate this transformation by prioritizing research, implementation, and scaling of modular, context-driven mathematics pathways. Accreditation bodies such as ABET must modernize standards to recognize multiple legitimate mathematics foundations aligned with learning outcomes rather than course sequences. Professional societies—including ASEE and disciplinary engineering organizations—should lead national dialogue, faculty development, and the dissemination of best practices that normalize innovation rather than treat it as an exception. Together, these stakeholders can align incentives, policies, and culture to ensure that mathematics serves its intended purpose: empowering diverse learners to become engineers prepared, confident, and equipped to address society's complex challenges. The time for alignment is now; the cost of inaction is a profession that falls short of its potential.

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