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Literature Review of Math Misconceptions Across Engineering Disciplines

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Abstract

Numerous studies have shown that students' entry into, and persistence within, engineering programs are significantly hampered by challenges they face in college level math courses and in their understanding of math concepts needed for engineering courses. We focused this literature review on the math concepts required for several core engineering courses: engineering statistics, circuit analysis, thermodynamics, fluid dynamics, signals and systems, materials science and control systems. The literature review explored approximately 40 articles from the last 20 years. Specific topics addressed in the literature included algebra, trigonometry, calculus, probability and statistics, and linear algebra. Calculus is the entry level math course in many engineering programs and is a critical foundation for engineering. While most engineering programs expect students to take calculus in their first year, engineering students often lack proficiency in a variety of fundamental prerequisite pre-calculus topics including but not limited to algebra and trigonometry. Conceptual difficulties in calculus, probability and statistics, and linear algebra have been documented throughout the literature. Some of these misconceptions have been shown to persist between high school students and university students. Improved strategies in clarifying misconceptions to students have also been reported, ranging from individualized remediation to course level strategies. The content of this review should serve as a concise starting point for content developers and instructors to help engineering students who struggle with math in their curriculum, and to provide specific misconceptions to target in efforts to remediate math understanding for these students.

Introduction

A large body of literature exists on math misconceptions (e.g.[1]) and remediation at primary and secondary levels of education, and is of great value for informing instruction, but may not always be directly applicable at a post-secondary level. This literature review focuses specifically on math misconceptions that persist at a post-secondary level, and methods of remediation at a post-secondary level. Engineering students' success in their chosen field heavily relies on their mastery of mathematics. Sithole [2] notes that basic mathematics competency (particularly algebra and trigonometry) among the majority of STEM students entering college needs improvement. Beyond algebra and trigonometry, some of the major courses/topics that Sithole [2] notes in which students usually show mathematical deficiencies include trigonometry, vector algebra, logarithms, complex numbers, calculus, graphs and equations, and statistics. Our goal with this literature review is to identify misconceptions that persist in impacting student performance in some of the most foundational engineering courses. We focused on math concepts required for engineering statistics, circuit analysis, thermodynamics, fluid dynamics, signals and systems, materials science and control systems. The math topics that are the focus of this literature review are: algebra, trigonometry, calculus, probability and statistics, and linear algebra. Common themes were found to serve as a one stop repository for educators. Articles were selected to represent a cross section of topics that are a source of students’ struggle.

Search Criteria and Methodology

To inform our methodology, we evaluated literature reviews by Reagan [3], Sambamurthy [4], and Rodrgiuez [5] related to other post-secondary education topics. Our methodology consisted of searching databases and using search engines (including ResearchGate, PEER, The Journal of Engineering Education, Wiley Online Library, Google Scholar, and Google) for specific key terms, checking reference lists for identification of additional relevant studies, and forward citation searches. Key search terms included *algebra, calculus, probability and statistics, and linear algebra* combined with *misconceptions*, *concept inventory, common errors*, *remediation*. Our search focused on literature published within the last 20 years.

Defining Misconceptions

Failures in performing mathematical calculations can arise from errors or misconceptions. We distinguish between simple mechanical mistakes in performing calculations, which we term errors, and concepts for which students have an incorrect understanding, which we call misconceptions. Both errors and misconceptions are problematic, but misconceptions will lead to systematic errors that students have no simple way to recognize or rehabilitate without external intervention.

Identifying Misconceptions

Inspired by the Force Concept Inventory in physics reported by Richardson [6], other instructors have developed concept inventories (CI) as tools to identify and assess commonly held misconceptions that hinder the success of engineering students. These include concept inventories for algebra reported by Hyland [7] and Lear [8], for calculus reported by Epstein [9], and for statistics reported by Stone [10] and Lee [11].

Misconceptions: Algebra

Although engineering students entering college are generally expected to have mastered math topics preceding calculus, many algebra and trigonometry misconceptions persist among engineering students. Hyland [7] developed an algebra concept inventory (ACI) to assess students' conceptual understanding of a given topic. The ACI comprised six sections, each with its own set of subtopics: Equality, Expressions, Solution, Variables, Multiple External Representations (MER), and Operations. Lear [8] used five measurable constructs of metric sense conceptual understanding to determine a student's knowledge base of algebra topics. These concept inventories and other strategies have helped inform instructors about the common student struggles with algebra we have found in the literature. For example, students often struggle with identifying like terms, as reported by Santiago [12] and Ancheta [13]. Similarly, students struggle with factoring and identifying unfactorable expressions [13]. Radical expressions also cause students problems. Students struggle to factor or combine radicals, and often confuse higher degree roots with square roots [13]. Santiago [12] suggests that working problems on a computer instead of by hand may lead students to not fully understanding the process of solving the problem. Ancheta [13] concludes that misconceptions are born of students memorizing procedures by rote, and failing to gain a fundamental understanding of the operations. Remediation recommendations in [13] include providing immediate feedback to students on their misconceptions, providing additional reinforcement activities, giving students resources to help manage their time for studying, sharing the underlying reasons causing students’ misconceptions so that other teachers and students know what to focus on, and providing students a direct and simple mathematical framework that could help students reduce errors and enhance their thinking skills.

Bigotte [14] reports that students in a calculus course were found to have shortcomings in basic skills including powers functions' product, powers of sums, sum of fractions, and distributive law from elementary algebra. Additional shortcomings in students' basic math skills of adding fractions, working with exponents, and taking square roots are reported by Weliwita [15].

An extensive set of low level math misconceptions are documented by Booth [16]. Students struggle with the meaning of symbols, including equal signs, inequality signs, and minus signs. Variables are also poorly understood, with students failing to grasp that variables represent numbers and the same variable represents the same number. Fractions present a challenge to students, as they frequently fail to perform any operation with them successfully. Students tend to solve equations left to right, instead of following order of operations rules. When dealing with functions students may misinterpret graphs as pictures of scenarios and believe that linear functions must be proportional if they increase or decrease at a constant rate. Booth [16] suggests combining self-explanation, worked examples, and cognitive dissonance by explaining correct and incorrect worked examples during problem solving practice as avenues for remediation.

Misconceptions: Trigonometry

Williams [17] reported students have good understanding of trigonometry with angles often encountered in coursework (e.g., 30°, 60°, 90°), but struggle when expected to operate with angles they encounter less frequently. A poor understanding of the unit circle and operating with radians was observed. An additional interesting observation by Williams [17] is that students struggle with approximating answers. If specific values aren't provided to work within a problem, but approximations could be made, students routinely abandoned those problems without finishing them.

In contrast, Usman [18] presents a study showing over 80% rate of transformation errors, which is figuring out what process to apply when solving trigonometry problems, even with 90° and 60° angles. The rate of errors in applying the process was also found to be over 80%. Similarly, Dewanto [19] reports students' failure to correctly apply the laws of sine and cosine, as well as struggling with problems involving 60° angles.

A specific literature review of trigonometry misconceptions is presented by Fang [20], categorizing trigonometry misconceptions into seven broad categories. The categories were reading, comprehension, transformation, process skill, encoding, language, and carelessness. Fang's conclusion [20] is that learning trigonometry with manipulative materials and digital software could eliminate misconceptions.

Misconceptions: Calculus

Calculus is a crucial math subject for engineering. Baisley [21] found that "If a student that declares engineering as their major is not ready for Calculus I upon entrance, then their likelihood to stay in engineering is greatly reduced." Thus, students' prior knowledge needed in a calculus course is critical to their success. However, Mahadewsing [22] reports that many engineering students have significant deficiencies even after they have taken a calculus course. Students particularly struggled with fractions and exponents. Factoring cubics were also shown to be problematic. Misunderstanding of trigonometric identities and functions also persisted. These struggles and several others have been identified in concept inventories, like the 22-item testing instrument developed for calculus by Epstein[9].

Limits are one of the first concepts introduced in a calculus sequence, but as Denbel [23] concludes, based on interviews, students retain many misconceptions about limits. Limits are commonly misconstrued as boundaries. Students also tend to believe that functions must be continuous through the point the limit function approaches, sometimes also believing that the limit is equal to the value the function returns at the limit. An additional worrying misconception was unveiled by Denbel [23], where students justified their other misunderstandings with the belief that $\frac{0}{0} = 0$. Students' lack of understanding of limits was also shown to be a problem for calculus students, reported by Muzangwa [24]. In addition, Muzangwa [24] showed that the lack of understanding of graphical representations of functions was undermining student success.

Cline [25] conducted a study using clickers to identify questions that students systematically answer incorrectly. Students as a group tended to lack an understanding of which Reimann sum approximations were more or less accurate. More importantly, students failed to grasp that changing the name of a variable in a function did not change the function. Student aptitude in a calculus II course was studied by Li [26] by testing their ability to use the integration techniques of completing the square, u-substitution, trigonometric substitution, and standard functions of improper integrals. Students struggled with all of these methods other than completing the square, and had particular difficulty picking which technique to use for any given problem. Students also often apply differentiation rules instead of integration for natural logs and trigonometric functions as reported by Zehra [27].

Both Cline [25] and Li [26] found that students often struggle with accurate notation. Cline [25] showed students did not recognize the need for constants of integration in notation. Formula errors reported by Li [26] included frequent omission of required dx notation, as well as misuse of dx, such as using dx when the variable of integration was not x.

The source of student struggle with calculus was identified by Li [26] as an overemphasis of procedural techniques over theory. Zehra [27] reports an adjusted curriculum with limits covered before derivatives and a focus on tutorials and instruction on the use of math software was reported to improve student performance in calculus.

A study of student misconceptions in multivariable calculus using clickers to identify common problems was reported by Cline [28]. The study noted that, when given multiple choice questions, students tended to hunt for a likely answer without thinking deeply about the calculus. Students failed to identify spatial orientation of surfaces described by mathematical functions. Students also struggled with variables, where the variable represented a collection of objects, such as x is thousands of cars, giving x = 1 is 1000 cars. Students were not able to change the order of integration when multiple variables were integrated in one function.
Cline [28] also noted that students would overuse calculus. When presented with a flux problem, students did not recognize that flux only needed to be integrated if it changes over the surface.

Misconceptions: Probability

Many engineering programs include a course on probability and statistics. Three common misconceptions seen among students are equiprobability bias, representativeness bias, and outcome orientation. Lee [11] validated, using a concept inventory, that students often struggle with misconceptions between independence and equiprobability. Khazanov [29] reports on an approach to remediate these misconceptions. Exercises designed to force students to confront biases helped with representativeness bias and outcome orientation; however, equiprobability bias proved to be difficult to remediate. Kaplar [30] found no correlation between high school grades or a prior probability course with the misconceptions of probability held by college students. Kaplar [30] tested misconceptions about insensitivity to sample size, base rate neglected, misconception of chance, illusory correlation, and biases in the evaluation of conjunctive and disjunctive events. Kaplar's findings in [30] showed that students were most prone to misunderstanding sensitivity to sample size, neglecting base rate, and biases in the evaluation of conjunctive and disjunctive events. Students only performed well in the test on the misconception of chance. The authors noted that using real life examples helped students overcome misconceptions, but noted the lack of impact from prior courses on students' misconceptions, stating that new ways of instruction need to be found.

Misconceptions: Vectors and Linear Algebra

A number of issues in handling vectors have been documented in the literature. Koelher [31] noted that students struggled to apply math concepts to actual problems. Koelher [31] noted that students' lack of ability to accurately assign signs or interpret quadrants for directions stood out. Although Appova [32] studied non-engineering students (the participants were were non-mathematics majors pursuing liberal arts degrees), they specifically researched what misconceptions about vector algebra were still prevalent after the students completed a freshmen-level linear algebra course, and noted students struggled with differentiating between and performing operations between scalars and vectors. Remediation efforts suggested include using applied problems [31], focusing on graphical representations [32], and using clickers to uncover when students don't understand a concept and deliver just in time corrections. Remediation on vector topics was also addressed by Fang [20], relying on clicker responses to identify weaknesses in students' understanding. Of note, Fang [20] reported that students showed significant shortcomings in vector and calculus understanding, despite previous coursework.

Junus [33] used online student discussion forums to assess inner product spaces misconceptions, noting significant struggle with understanding vector notation. Students were also unable to let go of prior concepts of vectors from physics as a directed line segment, and were unable to generalize concepts.

Montoya [34] discusses the use of geometric algebra instead of other mathematical concepts to describe electrical systems. Geometric algebra offers a way to address linear and nonlinear circuits with sinusoidal or nonsinusoidal sources with one approach. This approach avoids the need for calculations with complex conjugates and avoids student confusion in trying to apply sinusoidal signal techniques to nonsinusoidal signals.

Misconceptions: Other

Some studies have looked at math and engineering education with a wider lens. Faulkner [35] conducted interviews with 27 faculty members to gain a better understanding of students' mathematical maturity. The faculty members observed that students tended to forget concepts they learned in math courses by the time they needed to apply those concepts in engineering courses. Additionally, engineering faculty often don't know what content is taught in math courses, leading to inaccurate expectations. Students don't see math as the language of engineering, which limits their ability to fully communicate engineering concepts. Much like Williams [17], Faulkner [35] also reports that students struggle with the idea of approximations, and do not know how to cope with uncertainty in calculations.

Misconceptions: Remediation

The post-secondary education literature about math misconceptions and remediation does not typically identify methodologies that are specific to particular misconceptions. Rather, recommendations for remediation in the literature often focus on instructor and student awareness/identification of misconceptions when they occur within a course, then applying general teaching and learning methodologies to address misconceptions as they arise. Examples include the use of concept inventories as pre and post tests, and using clicker questions as a forum to both identify and discuss misconceptions within a class of students. Expanding students' awareness of the math course's use in their field of study through more exposure to applications is discussed by Klingbeil [36] as a way to engage and motivate students to persist with the level of work required to overcome their misconceptions.
Recommendations for remediation from Sithole [2] are:

- Mathematics review sessions: Implementing review sessions to help students strengthen their foundational math skills, particularly in algebra and trigonometry.
- Creation of student learning communities: the learning community approach restructures the curriculum, and the time and space of students to intentionally link together courses or coursework to provide greater curricular coherence, more opportunities for active teaming, and interaction between students and faculty. Baisley [21] also discusses the idea of providing a better social experience in calculus to increase student persistence in engineering.
- Bridging high school and college curricula: Developing a more cohesive transition between high school and college math curricula to ensure students are better prepared for college-level STEM courses.
- Professional development for teachers: Providing ongoing professional development for STEM teachers to enhance their teaching methods and better support students' learning needs.
- Ground in applications: In STEM, there is more emphasis on academic mastery of concepts, rather than career applications and relevancy. Cited sources indicate that mathematics studied independently of applications remains abstract, dull, and difficult. They also show that instructional practices need to be adjusted to meet these challenges.

Discussion

Certain common themes emerge from the studies found despite the variety of math topics addressed. Students' tendency to carry misconceptions through multiple courses speaks to the persistence of misconceptions. For example, trigonometry misconceptions appear in earlier math courses, and persist through calculus courses, making successful acquisition of new skills more difficult, as they rely on misunderstood concepts.

Misunderstandings in some fundamental math concepts, for example division by zero, are a troubling discovery. Students struggling with concepts like radians in college level courses is also worrisome. These findings suggest that fundamental changes in math education might be necessary.

Another theme that arose across several papers was students' general lack of comfort with uncertainty. On the surface this is not a misconception, but students' inability to approximate or operate without explicit values reveals their lack of understanding of concepts and theory. This finding suggests that less emphasis should be placed on mathematical processes and precision and more on fundamental understanding.

As cited in Kaplar [30], the lack of correlation between students' performance and prior success or education suggests new methods of instruction might be needed. Some approaches to remediation are discussed in the studies reviewed. For example, the flipped classroom for linear algebra was the subject of study by Klingbeil [36]. The results showed that while the flipped classroom was not superior overall to traditional lecture, the flipped classroom did narrow the gap between male and female students, and between students of different educational backgrounds. Several studies cite use of real world examples and specific applications to make math more accessible to engineering students. This approach also helps reinforce the idea that math is the language of engineering as noted by Faulkner [35]. As such, reviewing sources like Hardebolle [37] may provide additional real world examples and applications that instructors could reference within their courses. Another approach shown to have some success in finding and correcting misunderstandings within the student body is to do so live in class. Questions can be used to prompt students to identify errors in their own thinking, and help confront their own biases.

New approaches to instruction may also need to be considered to focus on required math skills and to eliminate persistent misconceptions detailed above. The Wright State Model [36] has been shown to improve student outcomes. The approach focuses on math instruction specific to engineering students' needs for underprepared students. Sazhin [38] also reports successful approaches to the instruction of math in his courses. Sazhin's approach focuses on breaking math down into smaller clearer steps, and insisting on absolute clarity in communication to avoid misunderstandings. Chariker [39] reports on using a summer course to remediate the poor math skills of students entering their first year. All of these approaches have shown substantial improvements in student persistence and success in engineering programs, suggesting that addressing math deficiencies early in students careers are key. The papers [36] [38] and [39] all underline the need for addressing algebra weaknesses, which aligns with the findings of papers reviewed here. Given the high impact of math misconceptions on drop out rates of engineering students, any efforts that address this issue would provide a positive change in student success in engineering programs.

Conclusion

A review of literature on engineering students' misconceptions in math has revealed many weaknesses in engineering students' understanding of math. The fact that the misconceptions are often not corrected over multiple courses suggests new approaches to instruction are required. Addressing these misconceptions proactively in the courses where they are introduced and used would go a long way towards ensuring student persistence in engineering programs.

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