Rethinking Engineering Mathematics Education: A Model for Increased Retention, Motivation and Success in Engineering

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Abstract

This paper describes an NSF funded initiative at Wright State University (WSU) to re-define the way in which engineering mathematics is taught, with the goal of increasing student retention, motivation and success in engineering. The approach begins with the development of a novel freshman-level engineering mathematics course (EGR 101). Taught by *engineering* faculty, the course will include lecture, laboratory and recitation components. Using an application-oriented, hands-on approach, the course will address only the salient math topics *actually used* in a variety of core engineering courses. These include the traditional physics, engineering mechanics, electric circuits and computer programming sequences. While the above core courses are traditionally reserved for the sophomore and junior years, it is proposed to move them earlier in the curriculum, with EGR 101 as the *only* math prerequisite. It is finally proposed to develop a new Engineering Calculus sequence to be taught by the Math department later in the curriculum, in concert with college and ABET requirements. By removing traditional math prerequisite requirements and moving core engineering courses earlier in the program, the WSU approach will entail a significant restructuring of the engineering curriculum. The result will shift the traditional emphasis on math prerequisite requirements to an emphasis on *engineering motivation* for math, with a just-in-time structuring of the new math sequence. While this curriculum reform initiative is still in its early stages, this paper will summarize the motivation, goals and development to date of the WSU model for engineering mathematics education.

Introduction

The traditional approach to engineering mathematics education begins with one year of freshman calculus as a prerequisite to subsequent core engineering courses. However, only about 42% of incoming freshmen who wish to pursue an engineering or computer science degree at Wright State University (WSU) ever complete the required calculus sequence. The remaining 58% either switch majors or leave the University. This problem is not unique to WSU; indeed, the inability of incoming students to successfully advance through the traditional freshman calculus sequence plagues engineering programs across the country.

A 1998 U.S. Department of Education report[1] has summarized the percent of college students who completed bachelor's degrees by age 30 in their intended fields, as indicated upon graduation from high school. In the combined fields of Engineering/Architecture, only 54% of men and 21.3% of women were ultimately successful. While more uniform among the sexes, the numbers in the combined fields of Computer Science/Mathematics are also discouraging, with success rates of only 38.5% for men and 32.7% for women. On the other hand, students wishing to pursue a bachelor's degree in business exhibited success rates of 71.8 % for men and 63.7% for women.

Clearly, there are a variety of factors influencing student retention and success in engineering, the most notable being a lack of preparation in high school. Moreover, engineering retention is of particular concern among members of traditionally underrepresented groups, as well as among transfer students and nontraditional students returning to school from the workplace. This has led engineering educators to introduce early intervention programs, aimed at increasing retention among incoming students[2,3]. The WrightSTEPP and Academic Advantage programs here at WSU are two such programs, which begin intervention with local high school students even before they begin their freshman years.

In addition to early intervention programs, there has been a strong emphasis in recent years on increasing the level of *engineering application* early in the curriculum, with the goal of increasing student motivation to study engineering. This has led to the development of problem-based freshman engineering courses[2,4-9], including the EGR 190 Fundamentals of Engineering course here at WSU. Such courses are typically designed to give students a broad, application-based introduction to the various engineering disciplines, so that they can begin to appreciate *why* they must endure the rigor of their subsequent engineering curricula. As might be expected, this can have a significant impact on early retention of incoming students. For example, researchers at Indiana University-Purdue University Fort Wayne have recently published quantitative data directly relating increased retention to enrollment in their ETCS 101 Introduction to Engineering, Technology and Computer Science course[2].

Without a doubt, the introduction of early intervention programs and application-oriented freshman engineering courses are significant steps toward increasing student retention, motivation and success in engineering. *That said, the correlation between retention rates and the inability of incoming students to progress through the required calculus sequence cannot be ignored.* This problem is not unique to WSU, and in recent years has received substantial attention in the engineering education literature[10-16]. The general consensus thus far is that the traditional approach of teaching students the required mathematical theory simply as a prerequisite to subsequent engineering application is unsatisfactory, and that a more integrated approach is required. Such integration has typically been achieved by injecting engineering application into the freshman calculus sequence, sometimes in concert with a freshman engineering course.

While integrating engineering application into the freshman calculus sequence is a step in the right direction, it is proposed herein that a more radical approach is required, involving a large-scale restructuring of the engineering curriculum.

The WSU model begins with the development of a freshman-level engineering mathematics course (EGR 101). Taught by *engineering* faculty, the course will include lecture, laboratory and recitation components. Using an application-oriented, hands-on approach, the proposed course will address only the salient math topics *actually used* in a variety of core engineering courses. These include the traditional physics, engineering mechanics, electric circuits and computer programming sequences. *While the above core courses are traditionally* *reserved for the sophomore and junior years, the WSU model proposes to move them earlier in the curriculum, with EGR 101 as the only math prerequisite.* It is finally proposed to develop a new Engineering Calculus sequence to be taught by the math department later in the curriculum, in concert with College and ABET requirements.

Development of EGR 101

The WSU model begins with the development of EGR 101, a novel freshman-level engineering mathematics course. *The goal of EGR 101 is to address only the salient mathematics topics actually used in the primary core engineering courses, thereby fulfilling math prerequisite requirements within the context of a single course.* This will open the door for students to advance in the engineering curriculum without first completing the traditional calculus sequence.

The EGR 101 concept has been under investigation at Wright State University for several years. In early 2001, the College of Engineering & Computer Science (CECS) formed a committee to come up with a plan to address the math-related retention issues at WSU. The committee proposed the idea of developing an engineering course which would teach the students only the math they really needed to know in order to progress into their sophomore and junior years. The committee surveyed the various departments to determine exactly what mathematics material was critical for their core engineering courses, and developed a pilot program to test the feasibility of the concept.

The proposed content of EGR 101 consists of the mathematical prerequisites for the following core engineering courses: PHY 240-244 (General Physics I, II and III), ME 212 (Statics), ME 213 (Dynamics), ME 313 (Strength of Materials), EE 301 (Circuit Analysis I), CEG 220 (C Programming), and EGR 153 (Fortran Programming). Currently, all of these courses require a minimum of Calculus I, while some require Calculus I-III and Differential Equations. Clearly, it would be impossible to cover all topics in Calculus I-III and Differential Equations within a single course, let alone a freshman course. However, only a handful of these topics are actually applied in the above core engineering courses. Moreover, the above core courses also include engineering mathematics concepts not found in the traditional calculus sequence, including basic operations in vectors, complex numbers and matrix algebra.

After consultation with faculty from around the College, the following topics have been slated for inclusion in EGR 101: Basic Algebraic Manipulations; Trigonometry; 2-D Vectors; Complex Numbers; 3-D Vectors and Matrices; Sinusoids (Amplitude, Frequency, Phase, etc.); Basics of Differentiation; Basics of Integration; Linear Differential Equations with Constant Coefficients. The structure of EGR 101 is to be 5 credit hours (4 hours lecture, 1hour lab), plus mandatory recitation sections. The course is to be taught by *engineering* faculty, with all topics to be motivated by direct engineering application. *In particular, course material will be emphasized by physical experiments in the classroom and laboratory, and will be thoroughly integrated with the engineering analysis software Matlab.*

While the development of EGR 101 is still underway, the course is already scheduled to run beginning Fall, 2004. The following is the tentative course outline over a period of one 10 week quarter (4 hours lecture per week). *Note that all mathematical topics are presented within* *the context of their engineering application, as reinforced by hands-on laboratory experience and a thorough integration with Matlab:*

Week 1
Lecture:
Course Introduction (1/2 hour)
Manipulation of Algebraic Engineering Formulas (1/2 hour)
Kinematic and Trigonometric Relationships in 1 and 2-link Rotating Planar Robots (3 hours)
Lab:
Overview of Matlab for Solution of Engineering Systems

Week 2
Lecture:
Kinematic and Trigonometric Relationships in Rotating Planar Robots, Cont. (3 hours)
Representation of Rotating Planar Robot in Complex Plane (1 hour)
Lab:
Observation and Measurement of Kinematic Relationships in Rotating Planar Robots
Analysis of Observed Kinematic Relationships using Matlab

Week 3
Lecture:
Analysis of Rotating Planar Robot in Complex Plane (3 hours)
2-D Vector Representation of Rotating Planar Robot (1 hour)
Lab:
Manipulation of 2-D Vectors and Complex Numbers in Matlab

Week 4
Lecture:
3-D Vector Representation of Forces in Engineering Systems (1 hour)
Vector Operations for Calculation of Force Components and Moments (2 hours)
Systems of Equations for Force and Moment Equilibrium (1 hour)
Lab:
3-D Vector and Matrix Analysis in Matlab

Week 5
Lecture:
Systems of Engineering Equations in Matrix Form (1 hour)
Application of Cramer's Rule to Systems of Equations (1 hour)
Introduction to Harmonic Motion (2 hours)
Lab:
Measurement of Harmonic Signals Using Oscilloscope and Analysis in Matlab

Week 6
Lecture:
Introduction to Derivative as a Rate of Change (1 hour)
Application of the Derivative to Instantaneous Velocity and Acceleration (1 hour)
Differentiation of Simple Engineering Functions (2 hours)
Lab:
Measurement and Matlab Analysis of Projectile Motion

Week 7
Lecture:
Graphical Interpretation of Derivative as Slope of a Curve (1 hour)
Application of the Derivative to Optimization of Engineering Systems (3 hours)
Lab:
Transient Response of a Leaking Water Bucket and Analysis with Matlab

Week 8
Lecture:
Differential Equations for Transient Response of Engineering Systems (2 hours)
Application to Leaking Water Bucket and Spring Mass Systems (2 hours)
Lab:
Measurement of Oscillating Spring Mass Systems and Analysis with Matlab

Week 9
Lecture:
Concept of Integration as Area Under a Curve (2 hours)
Concept of Integration as an Antiderivative (2 hours)
Lab:
Numerical Integration Using Matlab

Week 10
Lecture:
Application of Integration to Centroids and Centers of Mass (3 hours)
Course Summary and Review (1 hour)
Lab:
Make-up lab session

In order to address the feasibility of EGR 101, lecture notes and supporting laboratory material have been developed for what is arguably the most ambitious topic: Differential Equations for Transient Response of Engineering Systems (Week 8 in the tentative course outline). Note that the proposed lecture material is pre-empted by a laboratory project in Week 7 (Transient Response of a Leaking Water Bucket), and is reinforced by an additional laboratory project in Week 8 (Oscillating Spring Mass Systems). The mathematical content is restricted to the specific topic of linear differential equations with constant coefficients, which accounts for only a fraction of a traditional course in Differential Equations. However, this topic appears repeatedly throughout the engineering curriculum, and is the only topic from Differential Equations which is critical to the core engineering courses previously mentioned.

The pilot material was presented to the entire freshman class as part of the college-wide Fundamentals of Engineering course during each of the past two years, with encouraging results. Specifically, student performance on homework and exams suggested that even students with little to no calculus background could digest and apply material from differential equations within the context of its relevant engineering application. It is proposed that these encouraging results are due to the hands-on, application oriented approach employed.

In particular, pre-empting the lecture material with laboratory measurement of the physical system provides a level of motivation which is difficult to achieve in a traditional mathematics course.

Excerpts from the laboratory project entitled, "Transient Response of a Leaking Water Bucket" (week 7 in the tentative course outline) are shown in Figure 1. Prior to any classroom theory on differential equations, the students measure the water level in a leaking container as a function of time, and observe the exponential decay shown in the figure. As part of the laboratory assignment, the students are presented with a description of the physical principle, the governing first order differential equation, and the solution to that equation. Having observed the character of the solution in the laboratory, the students are left to ponder how in the world one comes up with such a solution. And then they attend lecture, where the systematic procedure for solving linear differential equations with constant coefficients is presented, and illustrated step-by-step for the very physical system observed in the laboratory.

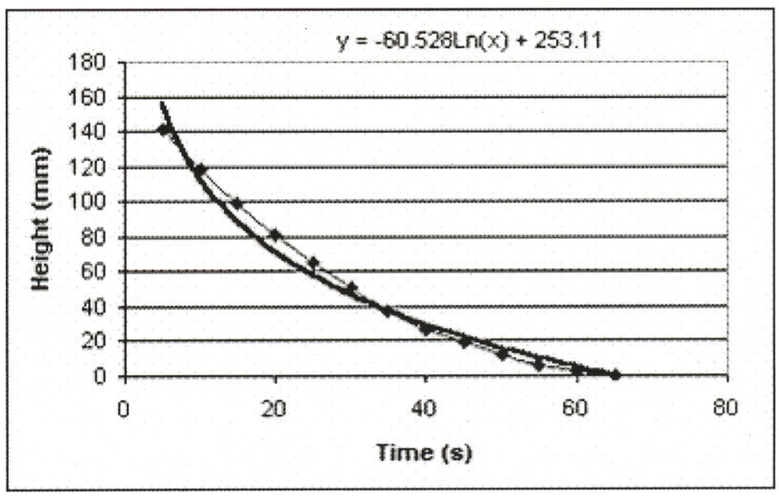

Figure 1. Excerpts from Pilot Laboratory, "Transient Response of a Leaking Water Bucket"

The proposed prerequisite requirement for incoming students to register for EGR 101 is a minimum mathematics background in Trigonometry, as indicated by a combination of math placement scores and high school transcripts, or by the completion of MTH 131 (Trigonometry) at WSU. Of the 300 incoming freshmen typically arriving each year, it is estimated that roughly one-third will satisfy the prerequisite requirements immediately in the Fall quarter. However, it is anticipated that EGR 101 will run every quarter, so that the remaining students can register immediately upon completion of the necessary prerequisite mathematics background.

Restructuring of the Engineering Curriculum

The primary goal of EGR 101 is to facilitate a large-scale restructuring of the engineering curriculum. *Without the traditional calculus sequence as a prerequisite, core engineering courses can be moved earlier in the program, and a new Engineering Calculus sequence can be integrated in a more just-in-time fashion..*

In order to emphasize the need for the proposed curriculum changes, the current freshman year curriculum for Mechanical Engineering is shown in Table 1. In order to advance into their sophomore years, students are expected to complete MTH 229 Calc I, MTH 230 Calc II and MTH 231 Calc III during their first three quarters at the University. This is the case for the remainder of engineering majors in the College, and is standard practice in engineering programs across the country. No wonder students who struggle in calculus end up switching majors!

It is proposed herein that by structuring the curriculum in the traditional fashion, we are effectively telling those students who struggle in calculus that they are not cut out to be engineers, and should find another major!

The proposed alternative to the traditional freshman year curriculum is shown in Table 2. The EGR 101 course appears immediately in the Fall quarter. However, as previously noted, the course is expected to run every quarter, so that those students who do not immediately qualify for EGR 101 can register as soon as they complete the necessary math background (Trigonometry).

Table 1. Traditional Freshman Year (Mechanical Engineering)

Fall Quarter		Winter Quarter		Spring Quarter	
ENG 101	4	ENG 102	4	ME 199	3
EGR 190	4	EGR 153/CEG 220	4	PHY 240	5
CHM 121	5	GE	4	GE	4
MTH 229*	5	MTH 230*	5	MTH 231*	5
	18		17		17

* Traditional calculus sequence, Calc I, Calc II and Calc III

Table 2. Restructured Freshman Year (Mechanical Engineering)

Fall Quarter		Winter Quarter		Spring Quarter	
ENG 101	4	ENG 102	4	ME 199	3
EGR 190	4	EGR 153/CEG 220	4	PHY 240	5
CHM 121	5	Engineering Calc I**	5	GE	4
EGR 101*	5	ME 220	3	ME 202	4
	18		16		16

* Proposed freshman engineering mathematics course
** First course in the proposed Engineering Calculus sequence

In addition to the presence of EGR 101, the proposed freshman year curriculum has a number of features which distinguish it from the traditional curriculum of Table 1. Most notably, the only Math department course in the freshman year is Engineering Calc I, which is the first course in the proposed Engineering Calculus sequence. *It should also be noted that because EGR 101 will be the only math prerequisite for core sophomore year engineering courses, students who are not immediately successful in Engineering Calc I can still advance in the program.*

Another key feature of the proposed curriculum is the presence of formerly sophomore-level courses in the freshman year. In place of MTH 230 and 231 (the traditional Calc II and Calc III courses), both ME 220 Introduction to Manufacturing Processes and ME 202 Engineering Graphics have been moved to the freshman year. These are hand-on, application-oriented engineering courses which will go a long way toward making incoming students feel like they are actually *doing* engineering. This is in contrast to the traditional freshman calculus sequence, which effectively precludes all too many students from exposure to sophomore-level engineering courses.

While Table 2 is specific to Mechanical Engineering, similar changes have been proposed for degree programs across the College. To date, restructured program guides have been developed for Mechanical Engineering, Materials Science and Engineering, Electrical Engineering, Engineering Physics, Biomedical Engineering, and Industrial and Systems Engineering. Each of these follows the freshman year model of Table 2, including the introduction of EGR 101, the removal of the second and third calculus courses from the freshman year, and the introduction of formerly sophomore-level engineering courses within the freshman year (as appropriate). While not shown in Table 2, the restructuring of the engineering curriculum and just-in-time placement of the new Engineering Calculus sequence affects program guides for most majors in the College all the way through the first quarter of junior year.

Finally, the necessary paperwork for changing math prerequisite requirements for the core engineering and physics courses previously summarized has been submitted for approval. In all cases, the words "or EGR 101" have been appended to the traditional math prerequisite requirements. This automatically accounts for transfer and continuing students, who can advance in the program with either the traditional math sequence or the completion of EGR 101.

Development of the Engineering Calculus Sequence

While EGR 101 will provide an introduction to the salient math topics required to progress in the engineering curriculum, it is not intended to be a replacement for the calculus sequence and other subsequent mathematics courses. The existing calculus sequence at WSU consists of four quarters of calculus: MTH 229 Calc I, MTH 230 Calc II, MTH 231 Calc III, and MTH 232 Calc IV. Each of these courses is 5 credit hours, including 4 hours lecture and 1 hour lab. In addition to this four quarter calculus sequence, the majority of majors in the College of Engineering and Computer Science also require a 5 credit hour course in Differential Equations, as well as a 3 credit hour course in Matrix Algebra.

In order to accommodate EGR 101, the various engineering and computer science departments will be forced to free up 5 additional credit hours in their respective degree programs. Towards this goal, it was initially proposed to streamline the existing calculus sequence into three quarters, with greater emphasis on engineering application. This idea was strongly supported by the industry members of the College's External Advisory Board. In fact, there is a growing climate in industry that engineers are forced to spend too much time learning mathematical details that are readily handled by software packages like Matlab, Maple, MathCAD, and Mathematica.

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That said, there was significant concern among members of the Department of Mathematics and Statistics that streamlining the calculus sequence cannot be done without jeopardizing student learning, including the development of problem solving skills so critical to engineering. In light of these concerns, it is anticipated that the Engineering Calculus sequence will remain four quarters long, but with enrollment restricted to engineering students, and with a greater emphasis on engineering application.

The proposed four course sequence will be Engineering Calc I-IV, with each course to be 5 credit hours (4 hours lecture, 1 hour lab/recitation). As previously described, Engineering Calc I will be part of the freshman curriculum, with the remaining courses delayed until the sophomore and junior years. The exact locations of the remaining courses are specific to each major in the College, as determined at the Department level. In Mechanical Engineering, the Engineering Calc II and III courses will occur in the sophomore year, while Engineering Calc IV will be reserved for the first quarter of junior year. In addition, it is proposed that the existing Differential Equations and Matrix Algebra courses be combined into a single course, offered in the Spring quarter of sophomore year.

It is anticipated that the Engineering Calculus sequence will run under the traditional course numbers MTH 229, 230, 231 and 232 for the first two years of the program, with sections of MTH 229 and MTH 230 restricted to engineering students (there are not enough non-engineering students in MTH 231 and MTH 232 to justify such a restriction). This will provide the Department of Mathematics and Statistics an opportunity to evaluate the success of EGR 101 and the associated large-scale curriculum reforms before making significant, permanent changes to its own MTH course descriptions.

Coupled with the restructured program guides previously described, the result of the proposed Engineering Calculus sequence will be a more just-in-time, application oriented approach to engineering mathematics. Compared to the traditional freshman calculus sequence, the benefits of such an approach are many. In the proposed Engineering Calculus sequence, advanced math concepts will be presented much closer to the time they are needed in the engineering curriculum. For example, while advanced concepts in calculus (e.g., the Divergence Theorem) are traditionally presented in the late freshman or early sophomore years, the application of such concepts in the engineering curriculum is typically not encountered until the junior or senior years. As a result, students can lose the connection between the mathematical theory and its relevant engineering application, which can result in a decreased motivation to study math. In contrast, the just-in-time structure of the new Engineering Calculus sequence will reinforce the students' motivation to study both math and engineering. Moreover, with the new Engineering Calculus sequence offered later in the curriculum, the students enrolled in calculus will be more mature, and will benefit from the problem solving skills already developed in their entry-level core engineering courses.

Development of Assessment Methodologies

As previously outlined, the goal of this work is to increase student retention, motivation and success in engineering. *Hence, the development and implementation of appropriate assessment methodologies will play a key role in determining the ultimate effectiveness of the WSU model for engineering mathematics education.*

In particular, the assessment component of this work will be used to address a number of fundamental pedagogical questions associated with WSU model for engineering mathematics education. Among the key questions to be investigated are the following:

- Have the introduction of EGR 101 and the restructuring of the engineering curriculum increased retention and ultimate graduation rates of engineering students?

- How are retention and graduation rates related to student performance in high school, initial math preparation, student race/gender, and other factors?

- How has the introduction of EGR 101 and the restructuring of the engineering curriculum affected student performance in the introductory core engineering courses (PHY 240-244, ME 212- 213, CEG 220, EGR 153, ME 313, EE 301)?

- How has the introduction of EGR 101 and the just-in-time structuring of the new math sequence affected student proficiency in mathematics?

- Has the introduction of EGR 101 and the just-in-time structuring of the new math sequence enhanced student appreciation of mathematics in engineering (i.e., are they more excited about math)?

With the above questions in mind, the authors are currently working with WSU's Center for Teaching and Learning, Statistical Consulting Center and Institutional Research Office to develop and implement both quantitative and qualitative assessment strategies which are tailored to the goals of this program.

Fortunately, data will be readily available on student retention, success in core courses and ultimate graduation rates, and will provide clear quantitative feedback on the effectiveness of the program. However, in order to draw conclusions regarding long-term effectiveness, such data will need to be recorded over a period of several years. The collection and analysis of this data is expected to begin in Fall of 2004. Since the current freshman class has already begun the traditional engineering mathematics sequence, their progression through the program will provide a datum for comparison with next year's incoming students, who will begin with EGR 101 and progress through the restructured engineering curriculum.

The data will be sorted and analyzed to provide statistically meaningful answers to several of the above research questions. In addition to raw data on student retention and success in core courses, this will provide the *relationship* of such data to past performance in high school, initial math preparation (ACT and standard math placement scores), and race and gender. It is also expected that standardized tests will be developed to quantitatively compare the mathematics proficiency of students following their completion of either the traditional or the restructured engineering curriculum.

In addition to the above quantitative measures, the authors will develop student and faculty surveys to provide qualitative feedback on the success of the WSU model. Of particular importance will be the students' *perceived* mathematics proficiency at each level of the program, which is anticipated to correlate with their motivation and success in both math and engineering courses. In addition, faculty in both Math and Engineering will be surveyed to assess their perception of student preparedness, as well as the overall effectiveness of the WSU model for engineering mathematics education.

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