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Hands-on Precalculus for Engineering: A Work in Progress

Seth Greendale, Whatcom Community College
Prof. Eric Davishahl, Whatcom Community College

Eric Davishahl serves as professor and engineering program coordinator at Whatcom Community College in northwest Washington state. His current project involves developing and piloting an integrated multidisciplinary learning community for first-year engineering. More general teaching and research interests include designing, implementing and assessing activities for first-year engineering, engineering mechanics, and scientific computing. Eric has been an active member of ASEE since 2001. He was the recipient of the 2008 Pacific Northwest Section Outstanding Teaching Award, chaired the PNW Section 2017-2019, served on the ASEE Board of Directors as Zone IV Chair 2022-2024. and currently serves as Program Chair for the Two-Year College Division.

Mr. Pat Burnett, Whatcom Community College

Pat currently teaches engineering at Whatcom Community College.

Prof. Tyler L Honeycutt, Whatcom Community College

Tyler Honeycutt teaches precalculus, statistics, and calculus at Whatcom Community College. Tyler is passionate about integrating mathematical concepts with real-world applications. As one of the math instructors in a placed-based engineering cohort, they are working collaboratively with history, english, and engineering instructors to connect precalculus principles with Pacific Northwest history and fundamental engineering concepts. They are developing pedagogical approaches that utilize math concepts within an historical and environmental research context, particularly through mapping projects and data analysis.

Work in Progress: Hands-on Precalculus for Engineering

Abstract

Students from historically marginalized backgrounds – especially low-income students, students of color, and/or first generation in college – disproportionately place below Calculus level math and are often underprepared for direct entrance to an engineering baccalaureate degree curriculum. The Engineering in Context learning community at Whatcom Community College seeks to take a holistic approach to address this challenge by welcoming students into a multidisciplinary cohort experience. This course sequence spans two academic quarters and includes six different courses including a two-quarter contextualized precalculus for engineering sequence, contextualized English composition, Pacific Northwest history, and an existing two-quarter introduction to engineering sequence.

While this approach leverages multiple high-impact educational practices, this work-in-progress paper will focus on the contextualized precalculus component, and specifically the use of hands-on math labs taught using engineering facilities and equipment. The two Precalculus for Engineering courses are taught by mathematics faculty and feature a series of inquiry-based lab activities designed by the math, engineering, and physics faculty to motivate student effort and to provide additional practice with relevant math skills and concepts. These labs use physics and/or engineering applications to introduce key math concepts and develop student buy-in before scaffolding to more abstract math problems representative of what students will encounter in future math courses.

For example, students review right triangle trigonometry and revisit more complex triangle problems in the context of analyzing the kinematics of a robotic arm. In another lab, students explore the concept of composing functions by exploring axial deformation under tension in bars of variable cross-sectional area. The paper discusses these examples and others along with the overall sequence of labs, how they intersect with the concurrent engineering courses or preview future engineering/physics courses, and how they fit together as a whole to support both the precalculus course learning outcomes and the larger goals of the learning community experience. We also share initial student feedback on the lab activities.

Introduction

Placing into an algebra or precalculus course can be a "death sentence" [1] for some students' goals to study engineering as it means they must wade through quarters, if not years, of prerequisite material for which they might see little relevance. From an educator's perspective, this challenge to retention of potential engineering students is only exacerbated by the lingering impact of the COVID-19 pandemic on college preparedness, particularly in math. Students are placing into lower math courses than before the pandemic, and even students placing into precalculus or above are often missing content or crucial study skills to be successful in those classes [2], [3], [4]. This is particularly troubling when success in a student's first math college math course– regardless of level– has been strongly correlated to retention among engineering majors [5].

Whatcom Community College offers an Introduction to Engineering course (ENGR 101) to engage incoming students with a declared interest in engineering early in their academic pathway. However, while the class connects students to peers, campus resources, and more context for what a career in engineering might look like, it does not actively incorporate large portions of the math curriculum as other first year programs have attempted [6]. Traditionally, students who place into Intermediate Algebra (MATH 099) in the fall of their first year of college must take this course as well as a two-part Precalculus sequence (MATH 141 and MATH 142) before being ready for a Calculus 1 (MATH 151) class. Students can enroll in ENGR 101 concurrent with MATH 141.

The Engineering in Context learning community changes this sequencing by offering students a multidisciplinary cohort experience over two quarters [7]. Students in the cohort take Intro to Engineering and a subsequent Introductory Design and Computing course, along with Pacific Northwest History, contextualized English composition, and a two-quarter contextualized hands-on precalculus for engineering sequence, labelled MATH 132 and MATH 133. This precalculus sequence was designed for the learning community and is taught in the engineering lab facilities by math faculty with support from the engineering faculty and lab technician.

These two math classes cover the content of three traditional math courses (Intermediate Algebra, Precalculus 1, and Precalculus 2). At the end of the sequence, students are ready to enroll in Calculus 1. For students who initially placed in MATH 99, this accelerates their degree path by one quarter. For these students as well as those who would otherwise start in MATH 141, the learning community approach leverages the high support available in a cohort model class to create increased likelihood of a successful first college math course experience.

Accelerating some of the most challenging classes for incoming engineering students may not sound like a recipe for success, but the learning community draws on high impact pedagogies across the disciplines (engineering, math, English, and history) to support students. The emphasis of this paper is a sequence of inquiry-based math labs in the precalculus for engineering courses which leverage contextualized math and hands-on learning to teach challenging concepts.

It has been well documented that contextualizing math in relevant engineering applications is beneficial for student success [1], [5], [6]. Notably, Wright State University developed a successful model for a Calculus for Engineers course to increase student success [8] [9]. These models use engineering applications to motivate students to learn math concepts, preparing them for future engineering courses. Similarly, inquiry-based learning methods, such as Inquiry Based Learning Activities (IBLAs) [10] and Process Oriented Guided Inquiry Learning (POGIL) [11] have been shown to be effective forms of active learning in engineering classrooms. The math labs in precalculus for engineering draw on these two threads, as well as the use of manipulatives and hands-on learning [12] to support students working with challenging math concepts.

The Precalculus for Engineering Curriculum

Instead of simply condensing the content of the traditional MATH 099, MATH 141, and MATH 142 courses and teaching it at a "faster pace," MATH 132 and MATH 133 were designed from the ground up to focus on integrating math concepts with engineering applications. This approach included bringing forward topics traditionally taught in MATH 142 such as triangle trigonometry into the first weeks of MATH 132 to sync up with identified engineering and physics contexts.

The first step in resequencing these courses was to survey faculty who taught courses that engineering students would need to complete as part of their Associate of Science-Transfer (AS-T) degree requirements. These depend on specific engineering discipline and can include courses in the biology, chemistry, computer science, and physics disciplines, as well as additional engineering and math courses. For each of the current math courses (MATH 99, MATH 141, and MATH 142), participants were asked to rate the importance of each of the course outcomes as they pertained to preparation for success in the course the participant taught. The Likert scale on this survey ran from "Exposure" to "Autonomous Proficiency," representing the level of mastery students needed on a given outcome. The survey had 18 responses from faculty representing biology, chemistry, computer science, engineering, physics, and math. Figures 1-3 present the survey items and results for the three courses.

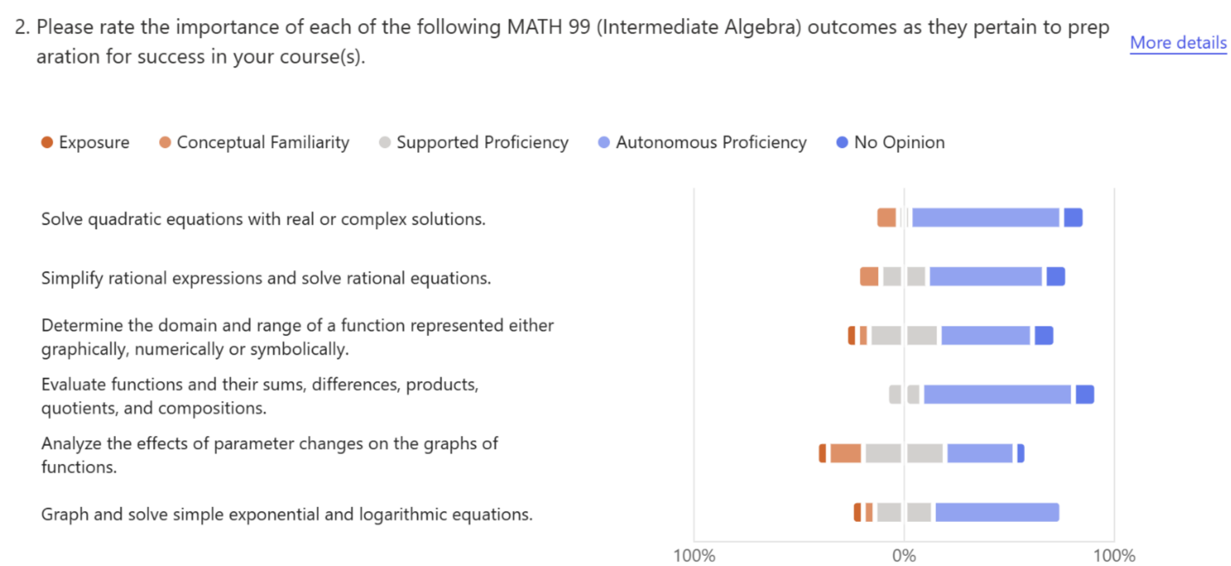

Figure 1. A summary of responses assessing the importance of outcomes for an intermediate algebra class (MATH 099).

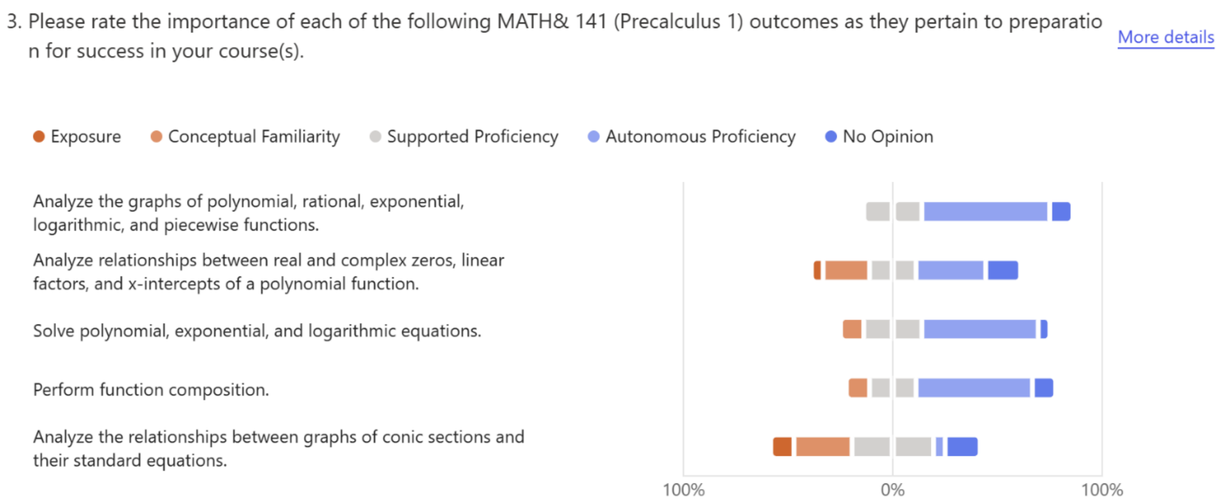

Figure 2. A summary of responses assessing the importance of outcomes for a Precalculus 1 class (MATH 141).

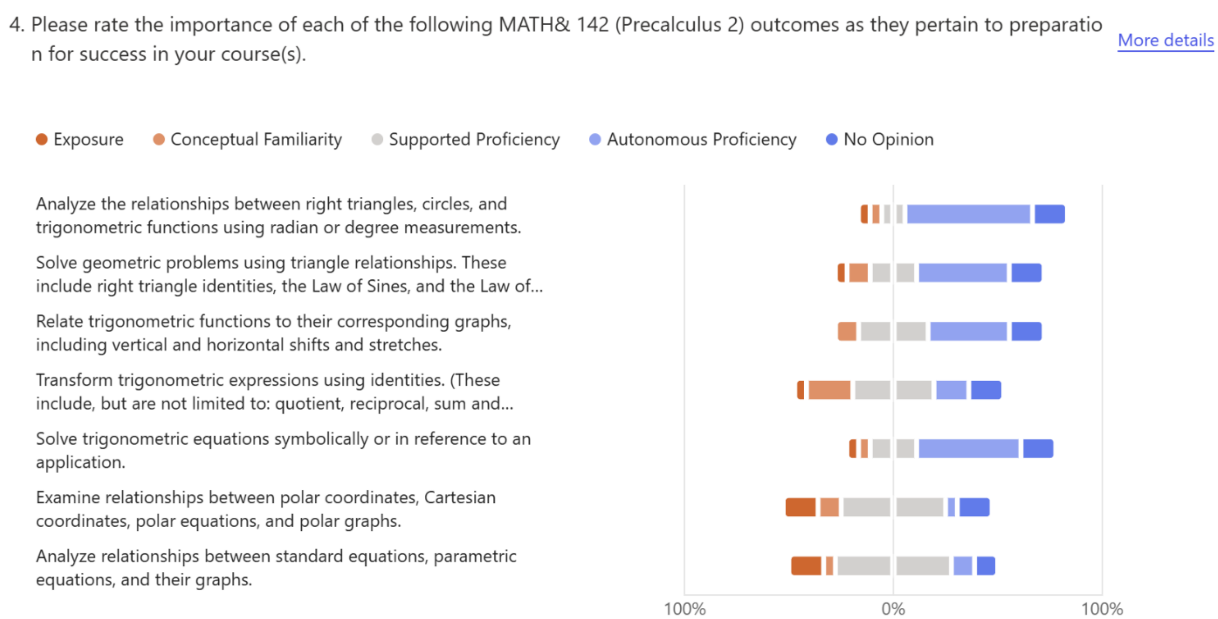

Figure 3. A summary of responses assessing the importance of outcomes for a Precalculus 2 class (MATH 142).

This survey allowed us to identify outcomes such as those relating to conic sections (in MATH 141), Trigonometric Identities, Polar Graphs, and Parametric Equations (in MATH 142) for which future instructors did not expect autonomous proficiency in their students. While MATH 132 and 133 cover all the content from the traditional math classes, less time and depth is spent on these topics. This creates the flexibility to spend more time implementing hands-on and inquiry-based activities for those outcomes participants identified as more important.

Another key consideration in developing the new course outcomes for MATH 132 and MATH 133 was the distinction between teaching for coverage and teaching for understanding, from the book *Understanding by Design* [13]. Course outcomes such as "Perform Function Composition" from MATH 141 indicate a mathematical topic that will be covered in the course but are narrowly defined. In changing this outcome to, "Use toolkit functions as mathematical building-blocks to develop models (e.g., function addition, multiplication, division, and composition)" we aim to connect the specific task (in this case, the composition of functions) to a broader context in which it will be used. This can help give students some of the "why," as well as refocusing teachers on the larger patterns of thought and skills we are developing in students.

These broader outcomes also opened space for us to touch on topics not traditionally included in our precalculus sequence. For instance, MATH 132 shifted some of the work on triangle geometry, triangle trigonometry, and polar coordinates (previously MATH 142 outcomes) to include applications of 2D vector operations, which is not included in the existing precalculus sequence at Whatcom Community College. Similarly, a new outcome focusing on solving mathematical questions presented solely as functions incorporated concepts such as concavity, invertibility, and end behavior (previously MATH 141 outcomes) but also created space to build a lab around kinematics which is also not included in our standard precalculus sequence.

Table 1. Course outcomes for MATH 132 and MATH 133

MATH 132 Outcomes	**MATH 133 Outcomes**
Explain the social role of mathematics and its relation to the goals and values of individuals and societies.	Analyze instances in which mathematics influence power dynamics in our society.
Communicate chains of mathematical reasoning using symbolic notation.	Develop problem solving algorithms from a variety of inputs including graphs, narrative, social values, and empirical observation.
Use function notation in operations and evaluations of functions and graphs.	Analyze the relationships between right triangles, circles, and trigonometric functions using radian and degree measurements.
Simplify and solve mathematical equations such as exponential, logarithmic, and triangle trigonometric equations.	Analyze how linear transformations affect equations and graphs of functions.
Solve systems of equations using matrix notation for linear systems.	Describe relationships within algebraic expressions, using the concept of mathematical identity, and apply it to solve equations (e.g. exponent rules, logarithmic rules, and basic trigonometric identities).
Solve mathematical questions by interpreting graphs of functions and approximating slopes or rates of change from a graph (without accompanying equations and/or data tables).	
Define trigonometric relationships and apply them to triangle geometry problems (e.g. sin, cos, tan, law of sines, law of cosines).	Solve mathematical questions presented solely as functions, using the relationship between functions, equations, graphs, tables, and narratives (eg. the properties of functions such as increasing/decreasing behavior, concavity, invertibility, and end behavior)
Perform 2D vector operations, including conversions between polar and Cartesian component representations as appropriate for engineering applications.	Use toolkit functions as mathematical building-blocks to develop models (e.g. function addition, multiplication, division, and composition).

Our new sequencing places a majority of algebraic computation in MATH 132 while shifting some of the more abstract topics such as composition of functions into MATH 133. Placing topics like basic triangle trigonometry and 2D vector operations at the start of the sequence opened the possibility for using engineering mechanics applications as early labs. This shift also allows students to revisit topics at a greater depth in their second quarter.

Lab Implementation

During the first year of teaching MATH 132 and MATH 133, each course met for 5 credits per week, which is standard for MATH 099, MATH 141, and MATH 142. Course meetings were typically 70-100 minutes in length, spread over three contact days with students. For the second year of implementation, these classes were re-envisioned as lab courses with additional contact hours analogous to their counterparts in engineering and the sciences, increasing the meeting time to 7 hours per week for 5 credits (3 hours lecture plus 4 hours lab) without changing the cost to students. This time was added to account for the increased time that hands-on and exploration-based learning takes, as well as for the extra time overhead for students to learn to use unfamiliar engineering equipment.

Implementation Context

To date, MATH 132 and 133 have only been taught as part of the Engineering in Context learning community at Whatcom Community College. The college has approximately 4000 students (2900 full time equivalent enrollments), about 150 of whom have declared intent to major in engineering. The learning community has an enrollment cap of 24 students per year, which represents approximately 20% annual ENGR 101 enrollment. All math contact hours are taught by math faculty in the engineering lab, using engineering equipment and lab tech support. In particular, the math labs have relied on these facilities, equipment, and support.

Class time in MATH 132 and MATH 133 outside of math labs is used for other student-centered teaching strategies. These include flipped classroom methods, small group work, peer instruction, inquiry-based handouts, pair problem solving, and limited didactic lectures. Outside of class time, students are assigned graded online practice supplemented with additional video lectures three to four nights per week, alongside the extension problem assigned with each math lab. While assessment strategies have varied among math professors, they have included traditional exams, mastery-based assessments, and rigorous group assessments. One of the primary goals of the Engineering in Context project is to prepare students for a traditional Calculus 1 course. Pairing math labs with a more traditional array of teaching, assessment, and homework strategies is intentional, aiming to use contextualized examples to motivate student understanding without losing out on traditional math content they will need for their future math courses.

Overview of Labs

By the end of the second year of implementation, in March of 2025, we developed and implemented twelve math labs over the course of two quarters. Many of the labs were only developed in the second year (2024-2025), but some of the labs in MATH 133 were used in both years. These are the labs on Robotic Arms, Axial Deformation of Tapered Bars, Pulse Width Modulation, Damped Harmonic Oscillation, and Kinematics (indicated with an asterisk in the table below).

Table 2 breaks down each of the labs into its engineering applications (used to motivate student inquiry), the math concepts it contains (which are the primary outcome of the lab), and its status (finalized, needs minor revision, or needs major revision). As a work in progress paper, we anticipate continuing to tweak each of these labs based on student and peer feedback over the coming years; however, "finalized" is used to refer to labs we would be comfortable giving to another instructor to implement in their own class as is. We plan to make all of the labs and associate curriculum publicly available online once they are finalized.

Table 2. Summary of Math Labs for fall 2024 and winter 2025. Labs marked with an asterisk were also implemented during winter 2024.

Quarter	Engineering Application	Math Concepts	Status
1	Components of Force	Vectors and vector arithmetic, modelling on Desmos	Needs minor revisions
1	Circuits, Kirchoff's Voltage and Current Laws	Linear systems of equations, Error	Needs minor revisions
1	Projectile Motion, Ballistic Pendulum	Quadratic equations, vector modelling on Desmos	Needs minor revisions
1	Beam Deflection	Cubic polynomials, modelling in Excel, Curve fitting	Needs minor revisions
1	Radioactive Decay	Exponential Decay, Experimental vs. theoretical models	Needs minor revisions
2*	Kinematics of a robotic arm	Right triangle trigonometry, Solving literal equations, Developing mathematical models	Finalized
2	Gear ratios	Radians and degrees, Arclength, Angular Speed	Needs minor revisions
2*	Axial deformation under tension in bars of variable cross-sectional area	Composition of functions, modelling in Desmos	Finalized
2	Triangulation as used in surveying	Law of Sines, Law of Cosines	Needs minor revisions
2*	Pulse width modulation	Periodic functions, modelling in Desmos, Linear transformations	Finalized
2*	Damped harmonic oscillation	Trigonometric functions, function algebra, linear transformations, modelling in Desmos	Finalized
2*	Kinematics	Properties of functions (e.g. concavity, increasing/decreasing behavior)	Needs Minor Revisions

The layout of this table also conveys the primary trajectory of the labs: using engineering applications to motivate student inquiry, but then shifting the focus to more abstract mathematical concepts. This is different from models like the Wright State Engineering Calculus, which focuses on the engineering applications and the math specifically related to them. Since MATH 132 and 133 are intended to prepare students for a traditional calculus course, these labs are designed to convey all the same math concepts that students would encounter in a traditional precalculus sequence.

Lab Examples

Axial Deformation Lab

The lab on axial deformation of tapered bars under tension begins by introducing students to tapered bars of varying cross sections (square and circular) and varying tapers (linear and reciprocal). Students are given 6-inch manipulatives of these bars that have been 3D printed, which they can take apart to examine the cross section at different intervals. Engineering faculty then introduce students to the ideas of tapered bars and their cross sections, focusing on structural engineering applications.

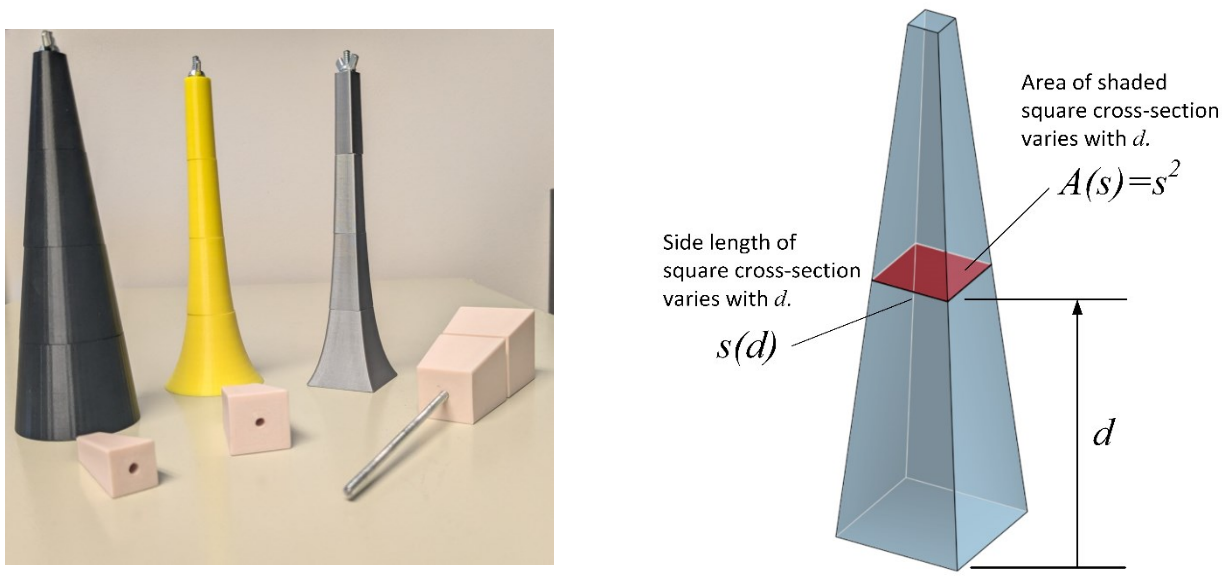

Figure 4. (Left) The manipulatives given to students during the lab. (Right) An image of the cross-section labeled using function notation given to students in the lab handout.

From here, student groups are given the problem of finding the cross section of a tapered bar at an arbitrary height. They use Desmos to develop an equation for the taper, and present both the taper and the cross section as equations in function notation. Once developed, students are asked to use these functions to find the area of a cross section at specific heights (not measurable on the manipulative) and then at an arbitrary height. Finally, a third equation is added, relating cross sectional area to deformation. This introduces the idea of function composition and of using functions as building blocks in mathematical models.

After completing the lab portion of the assignment, students are given a more conceptual extension problem to complete at home. This extension problem asks students to use Desmos to create a regression for the reciprocal taper and construct a similar mathematical function relating height from the base to the deformation on the tapered bar. Students also complete traditional math homework exploring function composition algebraically, graphically, and in the context of non-engineering word problems.

This lab is typical of our goal of using engineering applications to motivate math concepts. Students are introduced to function composition entirely through the process of developing a deformation function. Once they have completed the task, they are asked to identify the steps they took so that they can repeat the process on their own. After completing the lab, they are then given homework to connect this process to the more general notion of function composition that they will need to successfully implement processes like the chain rule in a traditional differential calculus course.

Kinematics of a Robot Arm

In this lab, students play a game using a Dobot Magician robotic arm, competing with their peers to pick up wooden disks from a table. The primary math outcome for this lab is to review the algebra of right triangle trigonometry that students learned in MATH 132 to prepare them for deeper trigonometric concepts in MATH 133. However, it is also used to reinforce understandings and practices used by successful mathematicians and engineers such as building algorithms to solve multi step problems.

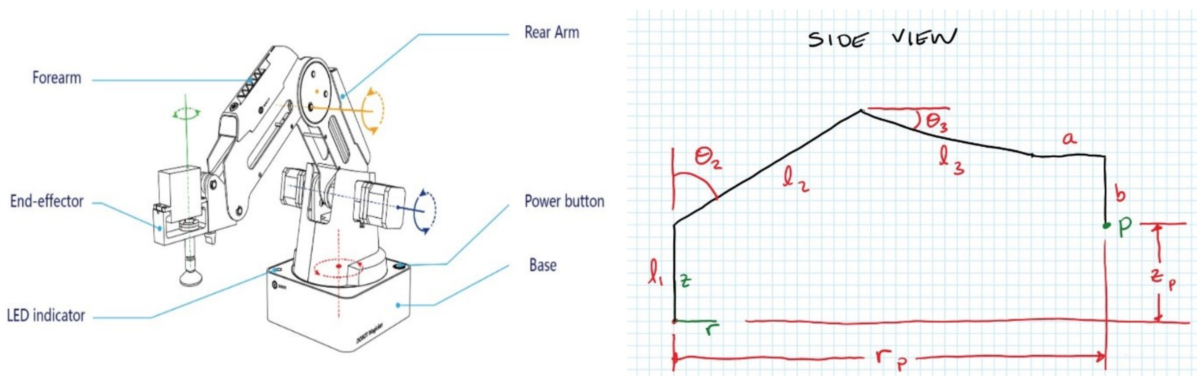

Figure 5. (Left) A diagram of the Dobot Magician from the user manual, provided to students in the lab handout. (Right) A two-dimensional simplification of the Dobot Magician provided to students in the first handout.

In preparation for this lab, students are shown a Dobot Magician, and given two handouts to familiarize themselves with the tool. The first handout gives them two-dimensional schematics of a Dobot Magician and asks students to calculate the horizontal position of the end effector based on the angular position of the joints. These forward kinematics problems ask students to develop a mental model of the arm using right triangle trigonometry to solve for the position, sequencing together multiple right-triangle problems. The second handout builds on the answers to the previous handouts, asking students to create a formula to calculate the angle of one joint based on the horizontal position of the end effector. This handout engages students' discomfort with literal equations, asking them to solve a problem without knowing the specific values to prepare them for a game in which they won't know where they need the end-effector.

With this prep work done, students then play the game in teams of two, competing to pick up disks of various sizes with limited time to complete their calculations. Using the tool only after completing the prep work means that this lab is sequenced a little differently than the axial deformation lab. However, students are still given an engineering application (positioning of a robotic arm, as used in manufacturing) to motivate the math. The game itself is meant to reinforce the skills of right triangle trigonometry, and to create an environment in which students can better identify the benefits of solving literal equations. In the extension to this lab, students to solve a literal equation for the vertical position of the end-effector (which was not necessary for the game). They also complete a metacognitive reflection about their strategy during the game and how they could have better prepared for it.

Results and Discussion

Initial student feedback results are promising. For each lab piloted in 2024-25, we administered an anonymous survey to collect student impressions of the activity. The survey uses a standard Likert scale with 1 = Strongly Disagree, 2 = Somewhat Disagree, 3= Neutral, 4 = Somewhat Agree, and 5 = Strongly Agree. Students were given the following five prompts:

- **Item 1:** I found this activity engaging and interesting.
- **Item 2:** The difficulty level of this activity was appropriate for my current knowledge and skills.
- **Item 3:** The engineering application in this activity helped me better understand the mathematical concepts.
- **Item 4:** I can see how the math skills used in this activity are relevant to my future engineering career.
- **Item 5:** After completing this activity, I feel more confident in applying mathematical concepts to real-world engineering problems.

Figure 7 shows the aggregate responses to these questions for all twelve labs taught in MATH 132 in Fall 2024 and MATH 133 in Winter 2025. Responses suggest a generally positive student experience, with means falling between 3.5 and 4.5.

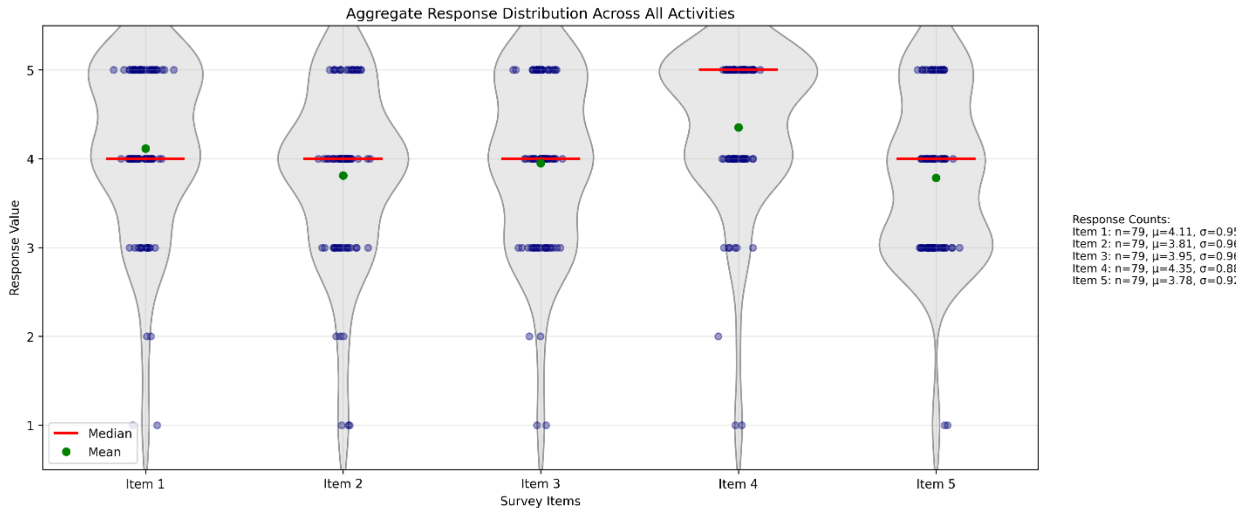

Figure 7. The aggregate responses to each survey statement, including the mean and sample size.

The survey includes two open-ended questions prompting students to (1) explain in their own words one math concept the activity helped them understand and (2) provide any additional feedback on the activity. As a work in progress paper with a small sample size, we primarily engaged with this qualitative feedback on an individual basis. For instance, responses to the first question about the lab on Triangulation used in Surveying generally expressed students developing a deeper understanding of the concept. One student wrote, "*I finally understand what triangulation is!! I hear that word all the time (and have even used it myself) but never really understood in a direct way how it works. I'm sure there's much more nuance to it but I feel like this is something I could actually use in real life.*" Similarly, responses to the second question about the lab on Components of Force demonstrated a theme of confusion, as expressed in the comment, "*I think the instructions were a little unclear - I wasn't sure what the purpose of the newton-to-inch scale was for, or what exactly we were trying to achieve.*"

However, as our sample size grows (through subsequent years and hopefully larger cohorts), we also intend to use word clouds to draw out such themes in student responses. Sample word clouds for the second prompt are shown in Figures 8 and 9 below, corresponding to the first (Components of Force) and last (Radioactive Decay) math lab given during Fall 2024. Figure 8 illustrates points of improvement opportunities for the lab, specifically around clarity of instructions. Figure 9 gives a qualitative counterpart to the survey responses in Figure 7, emphasizing students sense of engagement and enjoyment in the activity.

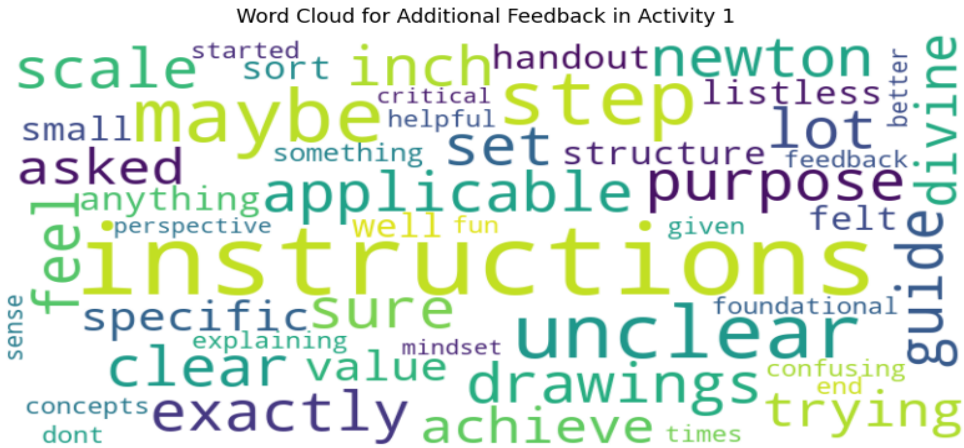

Figure 8. A word cloud of common student responses providing feedback on the first lab of Fall 2024 on Components of Force.

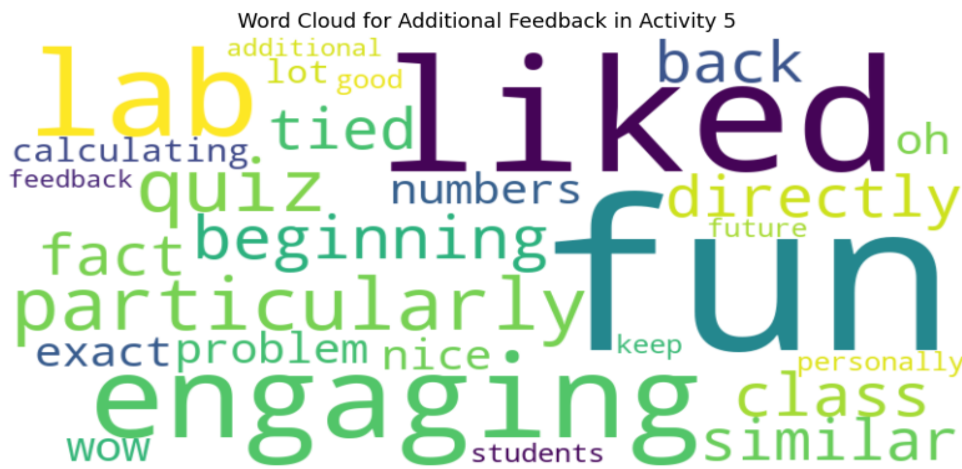

Figure 9. A word cloud of common student responses providing feedback on the last lab of Fall 2024 on radioactive decay.

Conclusion and Future Work

While our sample size is limited, the above results suggest that students are seeing the benefit of this approach to math instruction. We plan to continue revising the labs for clarity of instruction and alignment with available class time. Our primary work moving forward will be to continue to collect student feedback and measure the impact on student learning by comparing the follow-on math course outcomes of learning community students to those in our control population. We are also administering the Physics Inventory of Quantitative Literacy (PIQL) in the first week of

MATH 132 and then again in the last week of MATH 133 to measure student growth in quantitative literacy that results from their precalculus for engineering experience and anticipate reporting on those results in the future.

Another goal of this project is to create a model that can be replicable outside of the full cohort model of the learning community. While these math labs rely heavily on the equipment and technical support of our engineering department, we plan to develop versions that can be more readily implemented in other educational contexts.

Acknowledgment

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