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Work in Progress: Launching an Equitable and Inclusive Human-Centered Pathway to Engineering

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Abstract

This work in progress paper shares our efforts to create an alternative and inclusive pathway into the engineering major at the Thayer School of Engineering at Dartmouth College, that integrates and teaches concurrently foundational mathematics and human-centered engineering.

Despite stark warnings issued over 20 years ago, a recent study revealed that engineering schools continue to “weed out” students, especially those weighed down by negative stereotypes. Rather than fostering excitement in students and engaging them in actual practices of the discipline, faculty and courses feature scope creep, passive presentations, grading on the curve, exaggerated levels of abstraction, and other practices well known to be in stark contrast with inclusive pedagogy and active learning. One of the largest drivers of attrition in engineering are so-called “gatekeeper” prerequisite courses that introduce math and science concepts in an out-of-context, high-stakes format.

Through human-centered curricular interventions interwoven with co-curricular support we will transform students' sense of belonging in college generally and in engineering more specifically. Our focus is on changing systems to promote student success rather than "fixing" or "weeding out" students. The traditional introduction to our engineering curriculum—and that of many of our peer institutions—requires that students take prerequisite courses in mathematics and physics prior to enrolling in project-based engineering courses. This pathway works well for some students but excludes many. Rather than serving as a gatekeeper, our integrated human-centered engineering pathway will serve as a gateway, thus increasing retention and attraction to engineering, among all students but particularly among those currently struggling to find a place in engineering. We will furthermore develop a sense of community and professional identity among students through a comprehensive approach that includes advising, mentoring, internships, research opportunities, outside speakers, and more.

Our work is guided by four main research questions:

1. Are we better able to retain students in engineering on a Human-Centered Engineering pathway?
2. What are student perceptions of engineering?
3. Are students better able to apply and retain key mathematical concepts on the Human-Centered Engineering pathway?
4. Which activities, support mechanisms, and programs help students to develop a sense of belonging and professional identity in engineering?

Introduction

Imagine you are 18 years old. You grew up in a big city but a recent hiking trip with friends piqued your interest in mountaineering. So you enlist the help of a coach who designs a six-month training routine consisting of weightlifting, swimming, and the treadmill. Eager to begin, you embark on the program. A month later you are fitter, but you have lost sight of your goal of mountaineering and have yet to see mountains as all your training has been in a gym. You wonder whether that coach who kindly pointed out that mountaineering isn't for everyone has a point.

Now picture a **different scenario**: On your very first day, your coach takes you on a hike. You scramble around, succeed at some challenges, see that you clearly need a lot more training for others, and are exhausted by the end of the day. That night, by the campfire, your coaches tell stories about some of the challenges they have encountered in their climbs as well as the rewards of making it to the top.

In which of these scenarios are you more likely to succeed and stick with mountaineering?

We wouldn't expect to retain students in mountaineering through conditioning exercises alone, so why do we expect to retain engineering students through theoretical math classes alone?

In the landmark publication "Talking about Leaving: Why Undergraduates Leave the Sciences", Seymour & Hewitt (1997) revealed the significant exodus of highly talented students from science and engineering programs—especially women and students from historically underserved groups. More than 20 years after their first study appeared, Seymour reported on follow-up research in "Talking about Leaving Revisited" (Seymour & Hunter, 2019). Sadly, more than 20 years later, little has changed. Rather than fostering excitement and engaging students in actual practices of the discipline, faculty and courses feature scope creep, passive presentations, grading on the curve, exaggerated levels of abstraction, and other practices well known to be in stark contrast with inclusive pedagogy and active learning. "Talking about Leaving Revisited" (Seymour & Hunter, 2019) presents damning evidence that "weeding out" works, especially for students weighed down by negative stereotypes. A recent study of 110,000 students confirms that STEM prerequisite courses drive students out of STEM majors, with disproportionately drastic implications for students from historically underserved groups (Hatfield et al., 2022). Similar to national trends, our campus data (Bonfert-Taylor et al., 2017; Bonfert-Taylor et al., 2019) shows that the majority of students who were initially interested in engineering but then declared a non-engineering major did so after poor performance in a prerequisite mathematics course in their first year, thus exiting the engineering pathway before ever taking an engineering course.

Goals, Objectives, and Research Questions

Our goal is to eliminate from our curriculum one of the largest drivers of attrition: the so-called "gatekeeper" prerequisite courses that introduce math and science concepts in an out-of-context, high-stakes format. Our focus will be on systemic changes that promote student success rather than on "fixing" or "weeding out" students.

The Thayer School of Engineering at Dartmouth has been following a human-centered engineering approach for more than a decade and offers numerous human-centered engineering courses: both those focused on the human aspects and several that integrate the technical and human-centered aspects. Human-centered engineering is emerging as a field; for example, Boston College launched a human-centered engineering program and major in the fall of 2021 (Hayward, 2020). At most campuses, however, human-centered design and technical knowledge are taught in independent courses whereas at our school, human-centered design and technical aspects are holistically interwoven and integrated. We plan to use that same transdisciplinary approach for our new HCE pathway courses.

What is Human-Centered Engineering (HCE)? People and societal needs are at the heart of HCE, which is a collection of habits, abilities, frameworks, and processes that enable systematic consideration of human needs and societal context throughout the technical development process.

Engineering has always been carried out in service to society. HCE provides new strategies for our complex world. Human-centered engineers:

- Practice empathy and study human behavior;
- Value cultures, equity, and justice in society;
- Engage and involve stakeholders before, during, and after the technical work; and
- Analyze societal and technical risks and benefits using systematic frameworks.

Our project objectives are as follows:

1. Retain a higher percentage of students who matriculate with an interest in engineering, especially those who are placed in pre-calculus or single variable calculus;
2. Shift student perceptions of engineering from purely technical and exclusive to human-centered and inclusive;
3. Change how and when engineering students learn mathematics such that they are better able to apply and retain their learning; and
4. Help students develop a sense of belonging and a professional identity in engineering earlier in their academic career.

Our work is guided by four main research questions, which mirror our objectives:

1. Are we better able to retain students on a Human-Centered Engineering pathway?
2. What are student perceptions of engineering? Do student perceptions differ depending on the path they take? on gender identity? on background and preparation?
3. Are students better able to apply and retain key mathematical concepts on the Human-Centered Engineering (HCE) pathway?
4. Which activities, support mechanisms, and programs help students to develop a sense of belonging and professional identity in engineering?

A New Human-Centered Engineering (HCE) Curricular Pathway

The traditional introduction to our engineering curriculum—and that of many of our peer institutions—requires that students take prerequisite courses in mathematics and physics prior to enrolling in project-based engineering courses. This pathway works well for some students but excludes many. We decided to focus on math classes since our campus data indicates that over 60% of students who start in precalculus or single variable calculus never take an engineering course, despite indicating an interest in engineering at matriculation. While there is some attrition from other STEM courses, math classes show the highest rates of attrition for us.

Our new HCE pathway will be as challenging, if not more so, than the traditional pathway, but it will integrate engineering and math through inclusively designed, human-centered projects with social impact. Students will begin hands-on making in their first year. In addition, a supportive community will be created to begin cultivating students' identities as engineers and to prompt discussions of how engineering can best improve human well-being. Math will be used as a tool to elucidate practice, concepts, and ways of thinking through engineering problems, and not as a barrier to prevent participation. We hypothesize that our alternative HCE pathway, which will rely on High-Impact Practices (Kuh, 2008), will result in higher retention rates in STEM majors, especially among Black, Hispanic, and first generation students (Karlin, et al., 2022). Students on the HCE pathway will focus on projects that are tailored to their interests and are relevant to them, rather than only on theoretical math concepts without context. Students on the HCE pathway will not only be able to apply key math concepts but will also be creative problem-solvers and critical thinkers from diverse backgrounds. We hypothesize that this project-based, human-centered approach will disrupt the systemic biases inherent in the standard prerequisite pathway and make engineering retention equitable for a more diverse pool of students. We believe that engineering is for everyone, and we aim to shift the culture in engineering to one that is inclusive and welcoming to all.

By creating a new course sequence, we seek to increase retention where it is currently lowest—among students who are placed in early prerequisite math classes devoid of engineering context and without the support of engineering faculty and staff. Our core engineering curriculum, taken by sophomores through seniors, is already human-centered and project-based and has a near hundred percent retention rate. We are thus just focussing on infusing those aspects into the math prerequisite courses. Table 1 describes the new HCE course sequence that we are creating.

Table 1. Proposed Human-Centered Engineering (HCE) course sequence

<table>
<tr><th>Course
Term</th><th>Sample Math Concepts</th><th>Sample Engineering Concepts</th><th>Cross-cutting
concepts and support</th></tr>
<tr><td>HCEP
summer</td><td>Precalculus, algebra, trigonometry, intro to calculus: differentiation and integration.</td><td>Statics, kinematics, momentum, energy, work, principles of analysis, experimentation.</td><td rowspan="4">Algebra and trigonometry, error analysis, units and dimensional analysis, logical reasoning, spatial reasoning, advising, mentoring, guest speakers, study groups, computer programming & visualization, design thinking, empathizing, prototyping (e.g., laser-cutting, 3D printing), computer-aided design, entrepreneurship, & social impact.</td></tr>
<tr><td>HCE1
Fall
Year 1</td><td>Single variable calculus: differentiation and integration.</td><td>Mechanics of materials, dynamics, waves, stress and strain, introduction to circuits.</td></tr>
<tr><td>HCE2
Spring
Year 1</td><td>Vectors and coordinate systems, lines and planes, series, complex numbers, multivariable calculus, intro to differential equations.</td><td>Kinematics and dynamics in three dimensions, electricity and magnetism, energy, harmonic motion, resonance.</td></tr>
<tr><td>HCE3
Fall
Year 2</td><td>Vector calculus, Matrix algebra, eigenvalues, ODEs, finite differences.</td><td>Thermodynamics, lumped systems, fluids, biological and chemical engineering.</td></tr>
</table>

The new three-course sequence (HCE 1, 2, 3, with an optional pre-college HCEP class) will be offered as an alternative to the more traditional mathematics-only pathway that consists of proof-based courses in Single Variable Calculus, Multivariable Calculus, and Vector Calculus. A Precalculus course, Mathematical Foundations for Engineering, has already been developed and proven very successful. It is adapted from a very successful course at Wright State University (Finfrock and Klingbeil, 2023). An online version of that course and a slightly adjusted in-person version that may be taken by participants of our in-person summer bridge program will be created.

By incorporating HCE in math courses, we will reduce the centrality of mathematics in engineering, thus reducing the perception among students that they must perform exceptionally well in theoretical mathematics to succeed in engineering. To further reduce the centrality of prerequisite mathematics in the engineering curriculum, first-year students will be placed into our project-based Introduction to Engineering Design course before completing the math sequence. Curricular complexity research (Finfrock and Klingbeil, 2023) suggests that such a reduction in centrality, or focus, will have additional positive effects on retention.

Our proposed HCE pathway will be competency-based, interdisciplinary, student-centered, and project-based, all High-Impact Practices (Kuh, 2008), which have been shown to result in increased learning and retention (Freeman et al., 2014). Traditional pedagogies are often too passive and provide insufficient opportunities for application. And traditional grading schemes focused on performance, rather than growth and learning, often drive competition and erode student confidence and persistence, especially among students who feel marginalized. We will instead use teaching and grading approaches that foster a growth mindset and engage students actively in the learning process. A growth mindset has been shown to mitigate the effects of stereotype threat and enhance the learning of African American students (Aronson et al., 2002) and of girls and marginalized students (Good et al., 2003). And, developing a growth mindset is associated with higher levels of achievement, more persistence in math classes, and a greater likelihood of taking advanced math classes (Boaler, 2014a; Boaler, 2014b; and Boaler, 2015). We'll employ additional research-based teaching practices that have been shown to lead to better student outcomes such as instructor transparency about course assignments (Ferrari et al., 2015), proactive student support (Cox, 2009; Dadgar, Venezia & Nodine, 2013) and creating a safe and supportive learning environment (Bonham & Boylan, 2011).

The pilot of the HCE pathway will be open to all students by application but we will work with our admissions office to specifically invite those students who are placed into Precalculus or Single Variable Calculus. We expect to select 30 to 40 students for the HCE pathway initially and anticipate admitting more students in future years as they ‘vote with their feet.’

Rather than being discouraged and dropping out of the traditional prerequisite pathway (as depicted in the top half of Figure 1) students following the HCE Pathway (depicted in the bottom half of Figure 1) will thrive and be involved in HCE projects, as well as enhanced advising, mentoring, and support from the start.

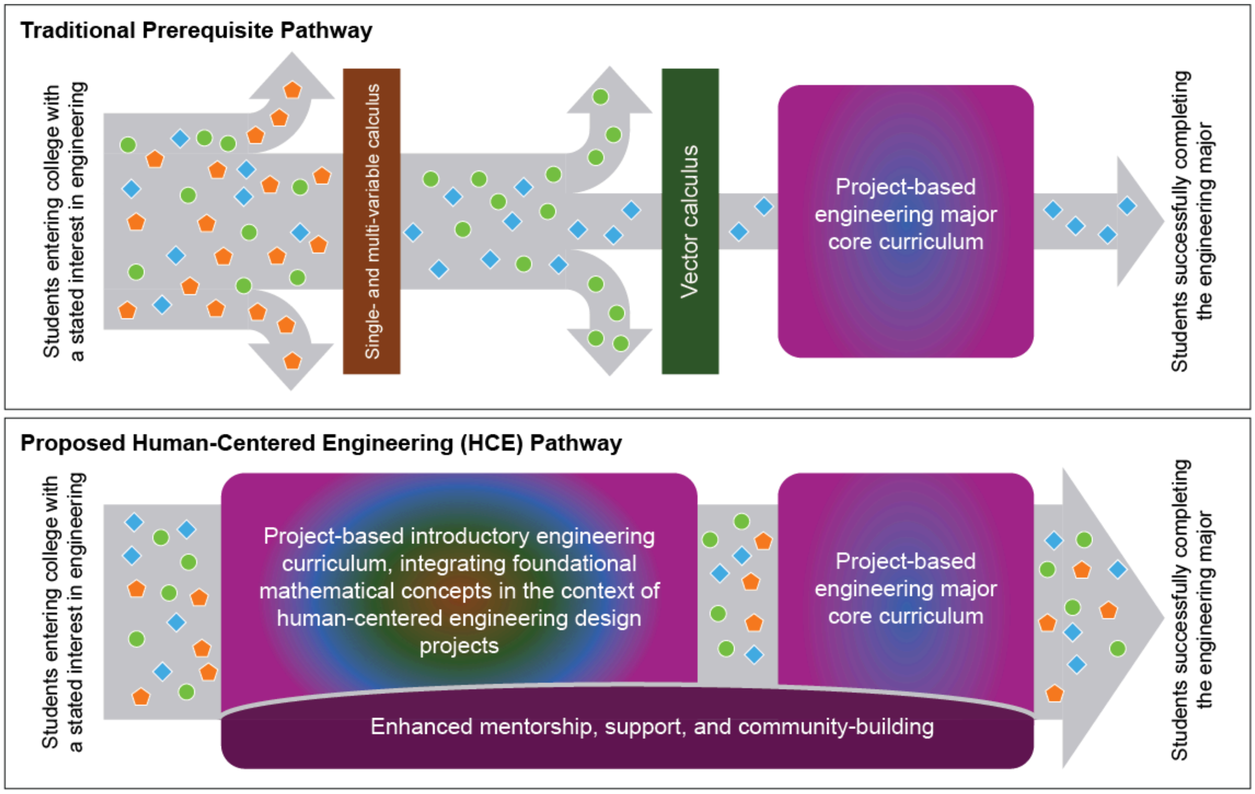

Figure 1. Traditional prerequisite pathway (top) vs. proposed HCE pathway (bottom)

The problem of prerequisite, acontextual math and science courses serving as gatekeepers to engineering is not unique to our institution and others have tried to tackle this problem (Burdman, et al., 2021; Hughes, 2021). Integrated math/engineering/physics pathways have been created successfully at the Olin College of Engineering (Somerville et al., 2005) and at Princeton (personal conversation with A. Houck, 2022), but such pathways have yet to become widespread in less-experimental settings and none exist that focus on human-centered engineering.

Of key importance is the fact that core mathematical concepts will be introduced to students in the context of engineering. Contextualized courses have been found to improve student confidence and learning (Govindasamy et al., 2018) and tackling engineering design problems has been shown to increase engineering identity and persistence (Gray et al., 2021; Morelock, 2017). Both shorter-term activities and longer-term projects centered around topics that resonate with and are engaging for our student population will be developed. We will work closely with student groups, such as the Society of Hispanic Professional Engineers, the National Society of Black Engineers, the American Indian Science and Engineering Society, and oSTEM (a group for LGBTQ students in STEM) to develop and vet projects that resonate with students. Research has found that students from historically underserved groups are often more interested in projects focused on social justice and equity (McGee & Bentley, 2017). We will structure projects such that students have choices and can apply engineering concepts to design solutions for real-world challenges, including climate resilience, energy security, and healthcare equity. By focusing on social justice considerations in these projects (a core tenet of HCE), our students will be motivated to learn foundational mathematical concepts because they will see their immediate relevance to creating positive social impact.

Building Community and Professional Identity

Adjusting course content and teaching strategies is great but not sufficient for creating inclusive learning environments. To retain students from all backgrounds, we need to develop a comprehensive approach to supporting students, building community, and helping them to develop a professional engineering identity. A comprehensive approach to supporting students has been shown to increase retention and a sense of identity (Kezar & Holcombe, 2018; Stolle-McAllister, 2011). Using existing community-building efforts as a foundation, we will create a suite of interconnected initiatives designed to meet students from historically underserved communities where they are along their development arc. We aim to increase students' sense of belonging and shared identities as human-centered engineers through advising, mentoring, and career exploration.

Course planning and advising for prospective engineering students is complex at a liberal arts institution and often favors those students who are already at ease and comfortable with advocating for themselves. While each first-year student at our institution is assigned an academic faculty advisor, meetings with advisors are currently not mandatory. Thus, advising is highly dependent on the random student-advisor pairings and a student's initiative to seek out their assigned advisor's help. In order to provide more equitable advising solutions for all students, advising will be built directly into our HCE course sequence, making it a mandatory (and thereby more equitable) component of the program. An advising study and pilot done at our institution in 2012 revealed that students are most comfortable seeking academic and course-planning advice from the faculty who teach their courses (Zhang et al., 2015). Thus, the faculty teaching the HCE courses will regularly incorporate advising into the courses and encourage students to meet with them individually outside of class.

Further we will establish an advising office. Advising is often cited by students as a weakness at our institution (Zhang et al., 2015) and elsewhere (Chan et al., 2019). Much of the issue is that students don't know who to ask or where to go for help. Faculty who teach the HCE courses will hold regular office hours and the advising office will be open to all prospective and declared engineering students. Rather than requiring students to email a professor for an appointment (a step that is often intimidating, especially for students from underserved populations), students may drop in for advice. In addition to faculty, advanced engineering students, who may be viewed as more approachable, will hold advising sessions and office hours in the advising office to offer a near-peer perspective. Peer advisors will be trained and paid.

Study groups for our HCE courses will be encouraged and space will be available for students to meet and study in small groups. Study groups have been shown to increase a sense of belonging among students in science and engineering (TEAM-UP, 2020). Faculty and teaching assistants will also run study and problem sessions in the evenings.

Opportunities for career exploration will be incorporated directly into the HCE courses but will also be provided outside of courses. Within the HCE courses, guest speakers will be invited to share relevant projects and experiences. We will focus on inviting guest speakers from underserved groups. Our Career Services Office will also host career-building seminars to teach students strategies for navigating job and internship searches, building a network, and connecting with mentors. Furthermore, Career Services counselors will meet one-on-one with students to discuss their personal career goals.

Assessment

Our project is guided by four main **research questions**, which are listed in our Goals section and mirror our objectives. Table 2 describes goals and approaches associated with each research question.

Table 2. Approaches and Metrics to answer research questions

Research Question	Approach	Goal
1. Retain students	Track students who matriculate with an interest in engineering and all students who take our HCEP and HCE courses; disaggregate by gender, race/ethnicity, and math preparation and placement.	>75% of students retained in engineering on our HCE pathway
2. Student perceptions	Administer an adapted version of the Longitudinal Assessment of Engineering Self-Efficacy survey (AWE, 2009) before students take HCEP and again after they complete HCE courses. As a control, students will also be surveyed before and after taking the standard mathematics prerequisite courses.	Self-efficacy and perceptions of engineering are higher in students taking HCE than Math courses and significant gains are seen from pre to post.
3. Apply and retain key math concepts	Longitudinally track student performance in later math, science, and engineering courses. Evaluate students' ability to apply key math concepts in their capstone project. Compare students who took HCE courses with those on the standard prerequisite pathway.	Students on the HCE pathway are better able to apply and retain key math concepts than students on the standard prerequisite pathway.
4. Sense of belonging	Correlate self-efficacy and perceptions as measured by the adapted version of the Longitudinal Assessment of Engineering Self-Efficacy survey (AWE, 2009) to activities, support mechanisms, and programs that students participated in (self-report and tracking of certain programs such as First-Year Summer Enrichment and Emerging Engineers).. Interview students in HCE courses.	Key activities, support mechanisms, and programs identified.

Conclusions and Next Steps

The first two courses of our HCE pathway will be offered in the 2024-25 academic year. Approvals are in place and curricular planning is in progress, including the development of an open-source, interactive textbook that will be made freely available through Creative Commons. Our next step will be to pilot the courses, share our experiences, and revise the courses and projects as needed.