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Creating Public Resources to Diversifying Content in Mechanical Engineering: Fostering Awareness and Ethical Considerations

Dr. Siu Ling Leung, Pennsylvania State University

Dr. Siu Ling Leung is an Associate Teaching Professor, the Associate Head for Undergraduate Programs, and the Director of Undergraduate Laboratories in the Mechanical Engineering Department at Pennsylvania State University. Her work focuses on renovating the engineering curriculum to enhance students' cognitive skills, raise awareness of diverse problems around the world, and equip them to address real-world challenges. She employs collaborative and project-based learning to involve students and integrates storytelling as a pedagogical tool to create engaging learning experiences that enhance their understanding.

Prof. Christopher John Greer, The Pennsylvania State University

Christopher J. Greer is an Assistant Research Professor at The Pennsylvania State University's Department of Mechanical Engineering. He completed his Bachelors of Science in Aerospace Engineering at Penn State while leading a group of students in rocket engine development for a conceptual lunar lander. He gained hands-on experience while interning at SpaceX's Rocket Engine Development Facility as a Ground Support Equipment Engineer developing a new test stand for SpaceX's Falcon Heavy. His Master's work was funded by NIAC (NASA's Innovative Advanced Concepts) to advance a conceptual combustion-based power system for a Venus lander. Chris' doctoral work at Penn State was funded by NASA's STMD (Space Technology Mission Directorate) to continue his research towards a future Venus lander mission. He is currently working with Dr. Alexander Rattner in a NASA STMD subaward with Astrobotic (formerly Masten Space Systems) to develop a thermal and power solution for lunar landers to survive the lunar night.

Margaret L. Byron, Pennsylvania State University
Bladimir Alvarado Ramos
Dr. Reuben H Kraft, Pennsylvania State University
Mrs. Angela Dawn Lesko
Catherine G. P. Berdanier, The Pennsylvania State University

Catherine G.P. Berdanier is an Associate Professor of Mechanical Engineering at Pennsylvania State University. She earned her B.S. in Chemistry from The University of South Dakota, her M.S. in Aeronautical and Astronautical Engineering and her PhD in Engineering Education from Purdue University. Her research expertise lies in characterizing graduate-level attrition, persistence, and career trajectories; engineering writing and communication; and methodological development.

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Abstract

This paper explores an innovative approach to integrating social, cultural, economic, environmental, historical, and ethical considerations into engineering education. Focusing on the Mechanical Engineering curriculum, we discuss two collaborative strategies for designing course assignments that employ storytelling and a case-based approach to expand students' awareness of diverse perspectives. Instructors piloted selected assignments and shared feedback on lessons learned from these implementations. This work aims to inspire others to develop their own teaching materials, fostering a sense of community within the field of mechanical engineering and supporting future curriculum development in engineering education. It emphasizes the importance of raising awareness of diversity and providing engineering solutions that prioritize customer needs, with considerations on inclusion, justice, and belonging.

1. Introduction

It is becoming increasingly important for engineering students to develop awareness of individual differences, acknowledge human-centered values, and cultivate a belonging mindset throughout their engineering education. In this work, we define diversity broadly, encompassing awareness of human differences in social, cultural, economic, environmental, historical, and ability aspects. Engineers should recognize that equal opportunities for individuals from diverse backgrounds are essential for creating sustainable solutions. World-leading companies have highlighted the importance of the above criteria. Annie Jean-Baptiste mentioned, "Google estimates that failure to serve these untapped segments of the population will yield a lost growth opportunity in the tens of trillions of dollars [1]." Microsoft's Inclusive Design team emphasized, "Designing for inclusivity not only opens up our products and services to more people, but it also reflects how people really are. All humans grow and adapt to the world around them, and we want our designs to reflect that [2]." These statements not only highlight business prosperity but also underscore the profound relationship between engineering and humanity. Lastly, AECOM stated, "When we feel free to be ourselves, we thrive [3]." AECOM is just one of many companies that emphasize a sense of belonging, which empowers teamwork and productivity, leading to better outcomes in client experiences. If engineering education is to prepare our students for future careers, our students need to be mindful of how human-centered values are essential for real-world success. This leads to the question: how can we proactively make our designs and solutions more inclusive while upholding justice and maintaining ethical obligations? Our approach aims to parallelly equip students to apply their technical skills to address real-world problems and foster a mindset considering a broad range of human experiences in their decisions. This focus aligns with ABET accreditation requirements, which include producing solutions that account for public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors. [4]

Why is it challenging to integrate diversity, justice and belonging into the engineering curriculum? There are various forms of curriculum changes, such as content modifications, pedagogical adjustments, assessment methods, technology integration, and the incorporation of new principles. Regardless of the type, changes are always challenging, with resistance to change being the primary reason. Resistance does not typically come from individual desire and value for improvement but from time constraints, workload pressures, and concerns about losing autonomy [5]. What makes diversifying mechanical engineering beyond traditional content even more challenging is the lack of publicly available resources [6]. Therefore, there is a critical need to create and publicize shared materials addressing this gap. Developing diverse teaching materials that influence future generations is best achieved through collaborative efforts. We hope this paper can help kickstart a collaborative effort within the engineering education community, bringing together resources that help students understand how diversity in race, gender, social background, cultural perspectives, economic status, and other differences can impact engineering decisions.

In this paper, we present the collaborative method implemented by the Mechanical Engineering department at Pennsylvania State University to develop teaching material that incorporates holistic awareness into core courses, encompassing thermodynamics, heat transfer, fluid mechanics, and dynamic systems. Our goal is to provide examples that inspire others to develop their teaching materials and foster a sense of community within the mechanical engineering field. Our sample assignments utilize storytelling as a pedagogical tool, featuring thermal-fluid system problems related to critical topics such as COVID-19 vaccine refrigeration, economic and environmental trade-offs in clean energy, low-grade thermal energy recovery investments, and water access in rural villages. Additionally, we have developed dynamic system problems addressing wheelchair comfort, seatbelt safety, and prosthetic limb rotation control. These assignments leverage narratives or research on a focused topic to enhance engagement, illustrate relevance, and forge emotional connections. While technical content remains paramount in engineering education, engineers' solutions ultimately serve humanity. Thus, it is essential to maintain this balance and expose students to mindset training. We encourage our students to extend their learning beyond personal experiences, prompting them to explore broader dimensions and engage with diverse worldviews that enrich their understanding of the world.

2. Literature Review

While compiling resources from literature, universities, companies, and other publicly accessible platforms, we realized teaching resources related to human diversity, inclusivity, social justice, or belonging from universities often aimed at fostering inclusive teaching environments and supporting underrepresented groups. Resources specifically for engineering often detail the history of underrepresented groups in the field, the missions and roles of diversity, equity and inclusion committees within university engineering departments, and programs dedicated to supporting minority groups [7], [8]. Examples of teaching materials emphasizing the broadening of students' awareness of diverse human perspectives in technical courses are limited except in two fields: Engineering Design and Engineering Ethics. Given our paper aims to provide related resources for ME technical courses, we included a review of available resources on these two topics in the next section.

2.1 Current Teaching Resources for Inclusive Engineering Design

There is a wealth of resources available concerning diversity, equity and inclusion in engineering design. In this section, we summarize approaches taken by two well-known organizations, Microsoft and Google, and how their design principles can apply to classroom settings.

Three inclusive design principles highlighted by Microsoft [2] are "Recognize Exclusion," "Solve for One, Extend to Many," and "Learn from Diversity." "Recognize Exclusion" emphasizes understanding some people interact with the world differently than the majority, and engineers can design products that enhance their interactions. To teach this principle in class, instructors can facilitate discussions or assignments centered around a selected product and present case studies of how the product allows individuals facing life challenges to adapt to the world. Publicly available examples include a Google video featuring how voice recognition technology helps individuals with dysarthria [9] and an Android Accessibility video demonstrating how live transcription helps individuals with hearing barriers [10]. Instructors can then use the diversity wheel to help students identify users facing other challenges and determine how the product needs to be redesigned to meet their needs.

The second principle, "Solve for One, Extend to Many," encourages students to brainstorm ways to adapt an existing design for a specific need to achieve broader impacts. For example, designs for individuals with permanent disabilities, such as single-armed, can also benefit individuals with temporary injuries or parents with newborns. This approach significantly expands the customer base for these designs. Microsoft's final principle, "Learn from Diversity," motivates students to engage with diverse groups and gain insights from others. Successful products that illustrate this principle include various shades of foundation, diverse emoji colors, gender-neutral bathrooms, gender-diverse government forms in Canada, and more. In an engineering classroom, instructors can arrange for students to present their drafted ideas to individuals with various backgrounds, gather feedback on usability issues, and then submit an improvement plan based on the feedback received. These activities also allow students to practice active listening skills.

Google's design principle emphasizes the importance of intentional inclusivity: "To build for everyone, we must build with everyone." Their three main approaches are (1) "Prioritize historically marginalized voices—from start to finish," (2) "Build for equity, not just minimum usability," and (3) "Hold ourselves accountable through inclusive testing and best practices [11]." To incorporate Google's approaches into educational settings, instructors can encourage students to examine products they use daily and intentionally discuss usability challenges for individuals with special needs, analyzing potential issues associated with the product and brainstorming possible solutions. Sample discussions could explore usage challenges of mice, keyboards, or hotkeys for individuals with repetitive strain injuries, or early cellphone cameras, which struggled to accurately represent a range of skin tones.

In short, both Google and Microsoft advocate for reflecting on marginalized perspectives, listening to diverse voices, and maintaining accountability at every stage of development. In the era of artificial intelligence (AI), diversity and accountability are particularly crucial as AI technology increasingly influences engineering designs. AI algorithms are built by people and trained on data. Without intentionally including marginalized populations, these algorithms generate results from data primarily made available by the majority, leading to AI-powered biases. Notably, biases related to AI algorithms have been widely documented[12], [13]. For instance, studies show higher face-recognition error rates for individuals with darker skin tones. These biases raise significant safety and security concerns as facial recognition technology often unlocks private data. The risk of wrongful detentions based on surveillance camera data can lead to increased scrutiny, exacerbating inequalities. These prompted ethical questions about equitable access and usability.

2. Current Teaching Resources in Engineering Ethics for Social Justice

Engineering ethics is another area with a wealth of public resources, covering a broad spectrum of topics. Ethics case studies often address conflicts between personal values, professional responsibilities, economic, environmental, public health, safety, welfare, social, and cultural considerations. Professional societies that provide valuable resources include the National Society of Professional Engineers (NSPE), which has documented study guides, procedural instructions to make ethical engineering decisions, key concepts, and case studies developed by their Board of Ethical Review [14]. The Ethics Committee of the Institute of Electrical and Electronics Engineers (IEEE) documented actual cases reported to the institute during the 1990s [15]. The Association for Computing Machinery (ACM) offers case studies related to technology and the Internet [16]. The American Society of Mechanical Engineers (ASME) provides an engineering ethics teaching guide for instructors [17]and other resources [18]. Additionally, the National Institute for Engineering Ethics (NIEE), housed at Purdue University, has compiled numerous case studies on engineering ethics [19].

One approach to connecting engineering ethics to technical content is to dedicate a small section of selected assignments featuring related ethical scenarios related to help students practice making ethical judgments. For example, questions about flow rate, pressure losses, pumping power, or pipe size can relate to an ethical dilemma involving water main upgrades, considering cost, policy, and the benefit to locals, as discussed in one of the NIEE case study examples [20]. Similarly, an assignment related to vehicle kinematics, control, or design can connect to IEEE Ethics Cases, in which an inexperienced engineer was pressured by his manager to sign off on an airbag design, creating a conflict between his career and adherence to the professional code of conduct [21]. Instructors can design assignments that link to the NSPE Code of Ethics [22], use NSPE Ethical Engineering Decision Steps [23], teach ethical thinking methods like Utilitarianism or Deontology [24], or facilitate peer discussions through anonymous boards. While technical courses often emphasize technical skills but ABET student outcome four highlights the importance of recognizing ethical and professional responsibilities in engineering. To balance these priorities, students should practice ethical decision-making throughout the curriculum.

2.3 Storytelling in Pedagogy

Storytelling has been a fundamental tool for transferring human knowledge since early human societies and is used to pass down cultural traditions, survival skills, and education to younger generations. The power of storytelling as a pedagogical method has gained recognition for its ability to foster personal connections and increase engagement [25]. In social justice education, storytelling has been successfully applied in middle and high schools to address topics such as racism, ethnicity, ethical justice, and social responsibility, with literature reporting positive outcomes [26], [27]. This suggests that storytelling could be an effective approach to discussing diversity, justice and inclusion content in engineering education.

Story types have many definitions. In this paper, we will follow the four types of stories detailed by social justice educator Dr. Bell, L.A.in her book *Storytelling for Social Justice: Connecting Narrative and the Arts in Antiracist Teaching* [28]: stock stories, concealed stories, resistance stories, and transforming stories. Stock stories are narratives that reflect broadly accepted social norms or structures. These stories often omit underrepresented groups and can perpetuate stereotypes. Concealed stories, on the other hand, are hidden narratives that represent marginalized groups, providing alternative viewpoints to the dominant beliefs. Resistance stories provide examples, methods, or tools that people have used to fight for equality, challenging the dominant beliefs established by stock stories. Transforming stories are narratives that evolve over time, reflecting changes in societal values. These stories guide and inspire students to consider how dominant beliefs can be transformed.

These four types of stories can be naturally integrated into engineering education. **Stock stories** illustrate how engineering design, analysis, and development have often prioritized the needs of the majority. For example, common tools and equipment, such as kitchen utensils, safety features on power tools, and musical instruments, are primarily designed for right-handed individuals. Similarly, as of 2018, only 24% of subway stations in New York City were accessible to individuals with mobility impairments [29]. **Concealed stories**, on the other hand, inspire engineers to recognize shortcomings in their designs and decision-making processes. In engineering education, these stories can be shared with students to encourage advocacy for underrepresented groups and overlooked conditions, ultimately leading to positive change for all. For instance, infrastructure design worldwide has often prioritized higher socioeconomic populations. Inadequate pedestrian infrastructure in lower-income neighborhoods is linked to higher accident rates in major cities in Canada and the United States [30]. Additionally, dams constructed by the United States Army Corps of Engineers along the Columbia River have disrupted traditional fishing practices for Native American tribes, including the Yakama, Umatilla, and Nez Perce [31]. Engineers have the power to redesign systems and craft **resistance stories** that promote equality. Finally, **transforming stories** can strengthen students' belief in engineers' ability to drive meaningful change. For example, in the early 1800s, communication was limited to letters and face-to-face interactions until the telephone revolutionized how people connected. Today, smartphones have reshaped communication norms. Sharing these stories can inspire students to believe in the future possibilities they can help create.

3. Methodology: Collaborative Curriculum Design

The Pennsylvania State University Mechanical Engineering Department has applied a collaborative approach to integrating diverse forms of awareness into core courses, such as thermodynamics, heat transfer, fluid mechanics, and dynamic systems. We believe that creating inclusive teaching materials to influence future generations is best achieved through joint efforts with individuals from varied backgrounds, each contributing unique perspectives and stories. As a result, we have developed a resource pool, summarized in this paper, that aims to benefit educators.

To facilitate collaboration, we have explored several methods, including hiring undergraduate student helpers, graduate teaching assistants, and instructors, as well as forming faculty learning communities. Based on our experience, we recommend that other institutions prioritize the latter two approaches, hiring an instructor (a project lead) and forming learning communities, for greater impact.

3.1 Designated Project Lead Model

Hiring undergraduate or graduate assistants can be challenging in typical mechanical engineering programs due to their limited breadth of knowledge and experience. On the other hand, we found hiring a designated instructor, either as a part-time or project-based external instructor or through temporary supplemental support provided to a faculty member, effective in creating teaching examples.

Our project lead met weekly with a small team consisting of the Associate Head for Undergraduate Programs and the Academic Program Specialist responsible for the program's ABET assessment. Together, they identified a list of core courses within the curriculum that would benefit from diversity content, prioritized and ranked the course implementation sequence, brainstormed ideas based on the personal experiences and knowledge within the group about possible concealed stories related to the nature of the selected courses, and identified faculty expertise for each core course or related area. Consultation with our external project consultant was conducted as needed. Starting with the highest-priority topic, the project lead initiated conversations with the identified faculty to understand the core topics within the courses, discuss the types of awareness that could be integrated, and listen to personal stories from the instructors. The lead then gathered feedback, drafted assignments tailored to each course and sought additional input from the project team and individual instructors to refine the assignment. Using this approach, we compiled sample assignments for six core curriculum courses: thermodynamics, fluid mechanics, heat transfer, vibration, circuits and measurements, and dynamics control in one semester.

This approach offers several advantages, including capturing input from faculty who may hesitate to make changes due to time constraints, reducing faculty workload, and encouraging personalized conversations with those who believe engineering courses should focus solely on technical content. These discussions provide an opportunity to explore how technical knowledge can address real-world challenges faced by underrepresented populations. However, it also has limitations, such as a lack of ownership over the material by course instructors and limited opportunities for implementation due to the absence of incentives or commitment to ensure the material is used.

3.2 Faculty Learning Communities Model

The learning community approach actively involves faculty in designing materials and implementing them in their courses. This method emphasizes ownership, which can lead to more sustainable implementations. Once faculty successfully implement these strategies, they gain confidence, increasing the likelihood of repeating and expanding these efforts in the future. Their successes also serve as examples to colleagues, demonstrating that these changes are feasible.

The main benefit we observed from this model is the support network the community creates, where faculty can share challenges, collaborate on solutions, and learn from one another. Furthermore, this approach facilitates the cohesive integration of diverse content across multiple courses, enhancing the overall student learning experience throughout the curriculum. Recruiting faculty volunteers for such programs can be challenging, but we strongly believe that every institution has faculty who recognize the importance of educating students to be holistic thinkers, capable of solving engineering problems with consideration for the diversity of all forms of life.

At Penn State, our first learning community cohort consisted of faculty members who taught thermodynamics, fluid mechanics, heat transfer, dynamic modeling, and computational courses. A small stipend, funded by the Leonhard Center for Enhancement of Engineering Education at Penn State, was provided in exchange for faculty commitments to:

1. Pilot and evaluate new materials and assess their impact on students.
2. Share developed materials as publicly available resources.
3. Share assessment results.
4. Attend four learning community meetings in a semester.

In the introductory meeting, we highlighted the benefits of emphasizing individual differences and integrating human-centered values into engineering education, and shared examples of storytelling-based course assignments created by the project lead mentioned above. These examples were intended to inspire community members and help them generate ideas for their own courses. The second meeting focused on developing an actionable integration plan, and community members spent the following month drafting at least one new assignment in preparation for the third meeting. Below is a four-step framework we used to guide faculty in developing their new materials for enhancing student awareness.

Step 1: Identify the ME Knowledge Domain. Before delving into the specific details of your course, take a step back and begin by determining how your course aligns with the core knowledge areas, as defined below:

- Mechanical Systems
- Thermal Fluid Systems
- Design Concentrations
- Embedded Labs (Hands-on components)

Step 2: Select Awareness Areas. Based on the identified knowledge domains, choose a few related areas of awareness from the list below that you would like to introduce to students. Faculty are encouraged to consider their own experiences and areas of interest when making these selections.

- Cultural Understanding
- Social Justices
- Global Perspective
- Public Health and Safety Concerns
- Environmental Responsibility

- Economic Disparities
- Historical Perspectives
- Ethical Considerations

Step 3 (a): Choose a Delivery Method. Choose a delivery method that can be adapted to your course such as:

- Case Study Analysis
- Embedded Questions in Traditional Homework Assignments
- Project-Based Assignments
- Literature Review
- Problem-Based Analysis
- Design Action Plans
- Presentations
- Reflections

Step 3 (b): Identify Relevant Course Topics. Review your course topics and determine how and where the selected areas of awareness can be integrated. Instructors may need to refine their chosen areas of awareness after identifying relevant course topics. Therefore, it is recommended to select more than one area in Step 2. Revisions to the chosen delivery methods may also be modified to ensure effective alignment with the course content, which is why topics and delivery methods are assigned within the same step.

In the third meeting, community members sought peer feedback on their drafted assignments and worked on designing a grading rubric to assess both technical knowledge and students' awareness of selected areas. We recommended using Bloom's Taxonomy's cognitive domain to evaluate technical skills and the affective domain to assess awareness. The final meeting served as a showcase for all faculty in the college, offering an opportunity to address questions and gather feedback from a broader audience on the developed work. The outcomes achieved by our learning community are summarized in Section 5.

4. Storytelling as a Pedagogical Tool

The storytelling pedagogy applied in our work is based on either comparing dominant and minority perspectives, using both stock and concealed stories, or describing the experiences and challenges faced by underrepresented groups, often through concealed stories alone. Our sample assignments are designed to encourage students to understand, research, and analyze situations, apply their knowledge, and propose improvements.

We define diversity as raising students' awareness of cultural and socioeconomic differences, global issues, environmental impacts, historical perspectives, and ethical considerations. Inclusion and equity are framed by a proactive approach that involves including all stakeholders in our designs and decisions, thereby creating equal opportunities for all forms of life.

Below, we summarize four elements applied in our storytelling assignment design. Examples in the following sections demonstrate the use of one or more of these elements.

1. **Connecting the Familiar with the Unfamiliar:** When individuals encounter unfamiliar situations, they may feel disconnected, less engaged, and struggle to see their relevance. One way to address this disconnection is by drawing comparisons and highlighting contrasts between the unfamiliar situation and a familiar one. In one example below, students were guided to analyze a water pump system based on the average living conditions in their current location. They then evaluated the effectiveness of a gravity-fed system in a hidden village in Nepal, highlighting that safe drinking water is a fundamental need and human right, yet not equally accessible everywhere.

2. **Build an emotional connection:** Care is inherently emotional and plays a vital role in raising awareness. To help students care about the topics explored in their assignments, it is important to connect with their interests, emotions, and personal experiences. Effective strategies for fostering emotional connections include presenting compelling facts, incorporating universal themes, and leveraging personal stories to engage the audience. For instance, UNICEF effectively uses striking facts to capture attention: "Worldwide, women and girls spend an estimated 200 million hours — daily — collecting water." Another impactful statement highlights a personal story: "In Afar, Ethiopia, 13-year-old Aysha trudges eight hours, round trip, every day to collect water for herself and her family [32]." Beyond facts, assignments related to profound events, such as COVID-19, create immediate connections through shared universal experiences. Finally, stories of our personal experience create heartfelt and lasting connections with students because of their authenticity.

3. **Conduct purposeful research:** Encouraging students to conduct research and apply their own knowledge promotes ownership of their learning. Additionally, students should practice obtaining relevant resources to solve problems, preparing them for future challenges they may not have encountered before. Instead of simply providing numbers and equations, we can purposefully ask students to search for references, explore relevant tools, and learn how to use new technologies. These exercises promote lifelong learning skills and foster student engagement. Moreover, this approach helps students recognize the real-world relevance of their class assignments. Research can range from looking up parameters to using unfamiliar tools, such as a loan calculator, to evaluate the economic benefits of their engineering decisions.

4. **Call to action:** After evaluating a given case, encourage students to create solutions by asking questions such as, "How can improvements be made?", "What are the risks and benefits of this solution?", and "What would you do differently if you were in charge?" These questions empower students to understand the responsibility and power of being an engineer, promote critical thinking, and reinforce their technical knowledge.

Lastly, we realized that visual elements in assignments often help the audience better remember and understand the stories. This can be explained by the Picture Superiority Effect [33], a cognitive phenomenon in which humans recall images better than text due to the faster processing speed of visual information compared to words. Additionally, images evoke emotional responses, triggering deeper semantic processing of associated items, making it easier for individuals to remember the information [34].

4.1 Sample Assignments – Outcomes of the Project-Lead Model:

In this section, we present sample assignments created using the Project-Lead Model, described in Section 3. The learning objectives, core ME principles, technical topics, and areas of awareness are introduced at the beginning of each example, followed by the selected story and sample questions. The five examples included in this section are:

Thermal-Fluid Systems:

- Vaccine Refrigeration
- Water Filtration Systems
- Sustainable Construction Materials

Dynamic Systems:

- Wheelchair Vibration Comfort Analysis
- Modeling of Prosthetic Limb Rotation

The examples of thermal fluid and dynamic systems assignments presented in this section were created as templates for course instructors to adapt and have not yet been piloted with students. In Section 5, we present examples of assignments designed by our learning community, some of which have already been implemented.

4.1.1 Vaccine Refrigeration

Learning Objective: This homework assignment has students calculating the refrigeration load needed to store COVID-19 vaccines in cities with significantly different climates. Students compare two ideal vapor-compression refrigeration cycles and determine the most suitable cycle and vaccine for each location.

Core ME principles	Topics	Type of awareness
Thermodynamics	• Refrigeration cycles and performance	• Environmental Difference • Global Accessibility • Public Health • Cost-conscious

The Story: COVID-19 vaccine refrigeration presents significant challenges in some parts of the world, particularly in regions with extreme climates or limited infrastructure. The Pfizer vaccine requires ultra-low temperatures of -70°C, demanding energy-intensive refrigeration units. In contrast, vaccines like Oxford–AstraZeneca and Janssen can be stored at 2–8°C, while the Moderna vaccine requires freezer storage at -25°C to -15°C. The energy efficiency of refrigeration systems varies based on vaccine storage requirements and environmental conditions. In high-temperature regions, maintaining the required temperature range can be especially challenging. Depending on the vaccine type and geographical location, energy consumption for refrigeration can differ by up to 9.34 times, resulting in up to 35 times less environmental impact for certain vaccines [35].

The Assignment: In this assignment, students were asked to calculate the Coefficient of Performance (COP) and sketch the TS-diagram of the refrigeration cycles using two different refrigerants at two distinct geographical locations with significant temperature variations during the summer. The type of refrigerant, evaporation temperature, ambient temperature, and high-side temperature requirements were provided. It was assumed that steady operating conditions existed, and changes in kinetic and potential energy were negligible. Students were directed to look up the refrigerant properties using an online toolbox to find the enthalpy at the four stages of the cycle. This enabled them to calculate the amount of heat removed by the system in the cooling cycle and the work input, from which they could then determine the COP.

$$COP = \frac{Q}{W} = \frac{h_1 - h_4}{h_2 - h_1} \tag{1}$$

(Q) is the amount of heat removed by the system, (W) is the work or energy input to the system, (h_1, h_2, h_4) are the enthalpies of the refrigerant at the temperatures it enters the compressor, exits the compressor, and during isenthalpic expansion.

Students were then asked to understand how COP relates to operational costs and to recommend the most cost-efficient vaccine for each location based on storage costs. This question could be further expanded to encourage students to explore the environmental impact of different refrigerants and balance other considerations the public may have in vaccine selection, prompting them to conduct a literature review.

4.1.2 Water Filtration Systems

Learning Objective: The objective of this homework assignment is to apply the concepts of head pressure and pressure loss to understand the power required for filtering and delivering safe drinking water to both an average American household and a rural gravity-fed system. Students calculate the power required to meet the daily water needs of an average American family, analyze a gravity-fed system to evaluate if it can provide sufficient water with limited power access, understand the challenges posed by filters that increase pressure loss in the system, and suggest modifications to improve its efficiency.

Core ME principles	Topics	Type of awareness
Fluid Mechanics	• Pressure Loss • Internal Flow	• Environmental Differences • Global Awareness • Public Health • Social Justice • Gender Equity • Sustainability

The Story: Millions of people still lack access to safe drinking water, and gravity-fed water systems offer a hopeful solution to the current situation, where village children, mostly girls, spend hours each day collecting water, which limits their educational opportunities[32]. UNICEF believes that gravity-fed systems, which are electricity-free and low-cost, are essential to achieving the United Nations' Sustainable Development Goal of ensuring clean water for all. However, the story doesn't end with installing gravity-fed systems. Water filters also play a critical role, especially in areas where contamination threatens public health. Even in places like the United States, where the water supply is considered one of the safest globally, clean water cannot always be guaranteed due to aging infrastructure and occasional contamination. Filters are effective in purifying water and making it safe for consumption, but they can increase pressure loss in a fluid system. This raises important questions: Can a gravity-fed system provide enough pump power to support filtration for a single household? How does a decrease in water level affect pump power? How can the system be improved to support multiple households or other situations with higher daily water consumption? Two assignments were created for this story, with the second one further examining how the water flow rate changes when one or multiple taps are opened in a gravity-fed system.

The Assignment: This sample assignment is split into two parts: (A) Pump Power Calculation, and (B) Internal Flow Analysis.

<u>(A) Pump Power Calculation</u>

Students were asked to calculate the pump power for two situations: a U.S. single-family house with a submersible pump and a single filter, and a gravity-fed water system with a single filter design for rural villages. The given parameters included fluid density (ρ), dynamic viscosity (μ), gravitational constant (g), volumetric flow rates (Q_v), pump efficiency (η), pipe diameter (D), and length (L), suction head (H_s), discharge head (H_d), filter head loss $\left(H_f^{filter}\right)$, and pipe roughness ($\epsilon$). We expected students recall,

$$\text{Pump power} = \frac{\rho g H Q_v}{\eta} \tag{2}$$

$$\text{Flow velocity } (v) = \frac{Q_v}{2\pi (D/2)^2} \tag{3}$$

$$H = H_s + H_d + H_f + H_v + H_f^{filter} \tag{4}$$

$$H_f = \frac{fLv^2}{2gD} \tag{5}$$

The Reynolds number dictates the equation used to calculate the friction factor (*f*). If the flow is laminar, Equation 7 is used. The Colebrook-White equation (Equation 8) is applied if the flow is turbulent.

$$Re = \frac{\rho v D}{\mu} \tag{6}$$

$$f = \frac{64}{Re} \tag{7}$$

$$\frac{1}{\sqrt{f}} = -2log\left(\frac{\epsilon/_D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \tag{8}$$

We anticipated that students would obtain a negative pump power for the gravity-fed system, indicating that the given design is insufficient to provide filtered water to the household. We then instructed the students to redesign the system so that their improved design would meet the application's requirements. Lastly, students were asked to study the impact of adding an additional filter and the increased water demand due to supporting multiple households, and to recommend further improvements to the system. Through solving the problem, we hope students realize that while the required pump power may be easily accessible in their region, it can be a significant challenge to obtain in other parts of the world.

(B) Internal Flow Analysis

This part was designed as a standalone assignment or as a second assignment following Part (A). In this part, students were asked to calculate the flow rate through a series of water taps, where the water is provided from an elevated gravity-fed water source. Students were provided with fluid density (ρ), dynamic viscosity (μ), gravitational constant (g), the reservoir pressure ($P_{reservoir}$), the elevation of reservoir ($z_{reservoir}$) , the elevation of each tap ($z_{tap_{1,2,3\,..}}$), the pipe roughness (ϵ), the pipe diameter (D), the pipe length from the reservoir to the taps ($L_{tap_{1,2,3\,..}}$), and the loss coefficients for each filter ($K_{filter_{1,2,3\,..}}$), inline tee ($K_{tee_{1,2,3\,..}}$) and spout ($K_{spout_{1,2,3\,..}}$) for each taps. It was assumed that the flow is steady, incompressible, turbulent, and fully developed. Additionally, velocity heads were considered negligible. We expected students to recall and apply Bernoulli's and the Darcy-Weisbach equations to solve for the flow rate.

The Bernoulli's Equation:

$$P_{reservoir} + \rho g z_{reservoir} = P_{tap} + \rho g z_{tap_n} + H_{Total} \ , n = 1,2,3 \ .... \tag{9}$$

where the total heat loss (H_{Total}) is equal to the sum of friction losses in the pipe ($H_{friction}$) and minor losses (H_{minor}).

$$H_{Total} = H_{friction} + H_{minor} \tag{10}$$

The friction loss can be calculated using the Darcy-Weisbach equation:

$$H_{friction} = f\left(\frac{L_{tap_n}}{D}\right)\left(\frac{V^2}{2g}\right) \tag{11}$$

where V is the fluid velocity to be determined and f is the friction factor obtained using Equation (7) or (8).

Minor losses are related to the given loss coefficients as follows:

$$H_{minor} = \left(K_{filter_{n.}} + K_{tee_{n.}} + K_{spout_n}\right)\left(\frac{V^2}{2g}\right) \tag{12}$$

Using the equations above, students calculated the fluid velocity with software such as Engineering Equation Solver (EES) and then determined the flow rate using Equation (3)

4.1.3 Sustainable Construction Materials

Learning Objective: This homework assignment aims to introduce students to sustainable construction materials and understand the environmental consequences, public health concerns, and socio-economic implications of traditional construction materials. Students apply the concept of thermal resistance to compare the performance of a composite wall made from traditional materials to one that incorporates agro-waste materials. Additionally, students conduct a literature review to thoroughly evaluate the advantages and limitations of alternative materials, fostering a deeper understanding of their effectiveness and potential for sustainable development.

Core ME principles	Topics	Type of awareness
Heat Transfer	• Thermal Resistance	• Environmental Pollution • Biodiversity • Public Health • Sustainability • Socio-economic Implications

The Story: Atmospheric scientist Andrew Schwartz, in a *National Geographic* article, warned that "a large portion of the world will have snow-free winters by 2100" [36] unless decisive action is taken to reduce human-produced carbon footprints. Construction materials, such as cement, contribute significantly to this issue, with cement production releasing 600–900 kg of CO_2 per ton [37]. Additionally, extracting raw materials, like gypsum, involves clearing large land areas, resulting in habitat destruction and biodiversity loss. The mining process also generates dust, posing severe health risks to workers. To mitigate these environmental and health impacts, scientists have identified agro-waste, such as rice hulls, as a promising alternative for sustainable construction materials. Using rice hulls can reduce CO_2 emissions by 25% and improve the cost efficiency of concrete by 65% [37], [38], [39]. Given that rice is one of the most widely cultivated crops globally, it holds immense potential for integrating food, energy, and materials, advancing a circular economy, and promoting sustainable resource use.

The Assignment: This assignment required students to research material thermal conductivities (k_n) using online resources and cite the references appropriately. Students calculated the heat flow per unit area of a traditional composite wall composed of stainless steel, glass wool insulation, and gypsum board under specified exterior and interior temperatures, along with given convection heat transfer coefficients. We anticipated that students recall the total thermal resistance of a composite wall is the sum of the thermal resistances of each layer. When convection is present, the convective resistances on the surfaces must be included in the total resistance calculation:

$$R_{total} = \frac{1}{h_{external}} + \sum \frac{T_n}{k_n A} + \frac{1}{h_{internal}} \tag{13}$$

The convection heat transfer coefficients for the external and internal surfaces are $h_{external}$ *and* $h_{internal}$. T_n is the given thickness of each layer in the composite wall, and A is the cross-sectional area through which heat is transferred. The heat transfer rate ($\dot{Q}$) was calculated using Equation 14 where ΔT is the temperature difference across the composite wall.

$$\dot{Q} = \frac{\Delta T}{R_{total}} \tag{14}$$

Students then compared the thermal resistance of a composite wall in which gypsum was replaced with an agro-waste material. Finally, they performed a literature review to evaluate the limitations of agro-waste materials, helping them understand why traditional construction materials had not been fully replaced.

4.1.4 Wheelchair Comfort

Two homework assignment options are provided below: one focused on Simulink modeling for a statistics, circuits, and measurement course, and the other on analytical methods for a vibrations course.

Learning Objective: The objective of this homework assignment is to analyze a spring-mass-damper system subjected to harmonic base motion, simulating the experience of a manual wheelchair user on uneven ground. Students evaluate the relationship between system frequency and user comfort. Additionally, they study the impact of incorporating a damper into the design and its effect on user comfort, followed by proposed improvements. Students apply data analysis, visualization techniques, and engineering judgment to inform biomechanical design decisions.

Core ME principles	Topics	Type of awareness
Vibrations	• Statistics • Spring-Mass-Damper Systems • Simulink	• Mobility limitations • User Safety and Comfort • Public Health

The Story: People who use mobility chairs such as wheelchairs or scooters can face several challenges when navigating uneven terrain, with comfort being a primary concern. User comfort is greatly driven by the vibration frequency and acceleration experienced and its connection to the resonant frequencies of the human body[40], [41]. Some research has found that rear suspensions reduce shock and vibration exposure by shifting the vibration transmitted to the wheelchair from a lower (7.81–9.84 Hz) to a higher (12.40–15.63 Hz) octave [42]. Shifting vibrations away from the natural frequency range of humans (4–12 Hz) and reducing the amplitude or power potentially reduce the risk of injury [43]. Additionally, it was reported that an acceleration induced by vibration with amplitude greater than 0.63 m/s^2 was uncomfortable for most users. Several companies have developed suspension systems for wheelchairs to enhance user comfort. However, the effectiveness of rear suspension systems has been debated, and their advantages over traditional frame designs have yet to be determined. In part of this assignment, students analytically evaluate the impact of different suspension designs and predict the potential benefits of incorporating a suspension system on user comfort.

4.1.4.1 Statistics and Simulink analysis for statistics, circuits, and measurement course

The Assignment: The statistical portion of this assignment tasked students with comparing the weight of spinal cord injury (SCI) paraplegics and able-bodied individuals, raising awareness of the fact that SCI patients generally experienced initial weight loss [44]. While some continued to lose weight and consequently become underweight, others may have gained extreme amounts of weight, highlighting the need for appropriate nutrition and rehabilitation follow-up. Students were tasked with computing statistical measures (mean, standard deviation, variance, and median) for given data sets using Excel or MATLAB, creating histograms with an appropriate number of bins, and identifying outliers using the Interquartile Range (IQR) method, analyzing the impact of weight changes caused by the injury. This part could elaborate to study the effects of factors such as age, sex, ethnicity, marital status, education, and neurological level to post-injury weight change, as reported in the literature [44].

The Simulink portion of the assignment tasked students with comparing the dynamic response of a spring-mass system and a spring-mass-damper system and evaluating the impact of spring constant and damper selection in wheelchair design for users with different weights. Students were provided with a Simulink model to analyze a wheelchair user's response to rolling over a bump modeled as a step function, as shown in Figure 1.

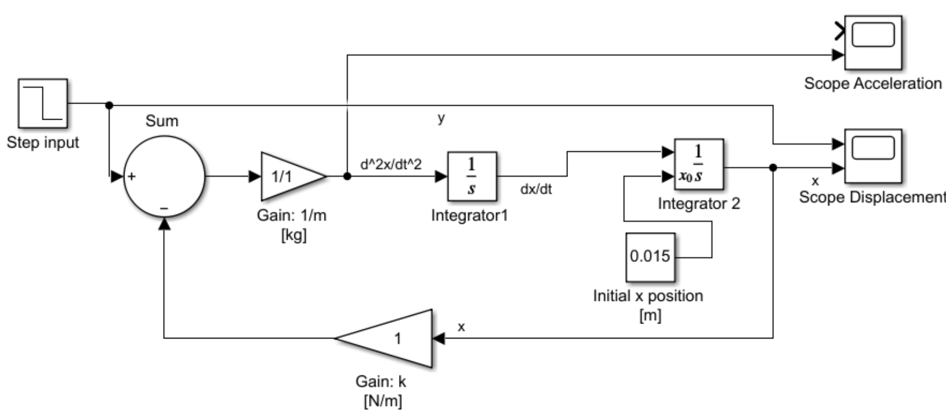

Fig 1. Model of Spring-mass system provided in Simulink

Students' analysis began by selecting and justifying a mass value for an SCI user based on their statistical analysis. Next, they studied how varying the spring constants (k) affected system behavior, documenting Simulink output and explaining the observation. They then modified the model to include a suspension and analyzed the effects of varying damper constants (c).

Next, students were instructed to calculate the peak acceleration experienced by the user under two specific spring and damper conditions and were asked to compare their results with accelerations and vibration data reported in the literature, analyzing the impact on user comfort levels. Lastly, the assignment concluded with students recommending optimal values for k and c to maximize user comfort, justifying their choices. They also studied how variations in user weight, ranging from underweight to obese, influenced their recommendations for the optimal values of k and c in wheelchair design. This assignment can be expanded to explore the trade-offs in students' designs, considering factors such as economics, portability, and other relevant considerations

4.1.4.2 Analytical analysis for vibration course

The Assignment: In this assignment, students were tasked with calculating the spring stiffness of the wheelchair system as it passes over uneven ground, modeled as a sinusoidal surface. Students evaluated the peak acceleration experienced by the user to estimate the potential user comfort range and suggested modifications to the wheelchair design. The combined mass of the wheelchair and user (m), force transmissibility (T), wheelchair forward moving velocity (V_f), input base amplitude (Y) and surface wavelength (L_s) were provided. In this example, students were told damping was negligible (ξ) and that when frequency (f) increased, the force transmissibility decreased. Lastly students were reminded the force transmissibility is equal to a ratio of the steady-state amplitude of the system (X) to the input base amplitude (Y).

Students calculated the system's spring stiffness based on the force transmissibility and surface characteristics.

$$T = \sqrt{\left(\frac{1 + (2\xi r)^2}{(1 - r^2)^2 + (2\xi r)^2}\right)} \tag{15}$$

Knowing the damping ratio $\xi = 0$ and the frequency was increased while the force transmissibility decreased, the ratio (r) of the system's excitation frequency (ω) to the natural frequency (ω_n) could be solved by,

$$r = \frac{\omega}{\omega_n} = \sqrt{\left(1 \pm \frac{1}{T}\right)} \tag{16}$$

The provided information allowed students to determine which of the calculated r values in Equation 16 to use for the given condition. Students then resolved the spring stiffness (k) of the system using Equations 16-18.

$$f = \frac{V_f}{L_s} = \frac{\omega}{2\pi}, \quad \omega_n = \sqrt{\left(\frac{k}{m}\right)} \tag{17-18}$$

Next, students were given a list of resonance frequencies for different body parts and asked to analyze whether the system's frequency (*f*) matched any of these resonance frequencies. They discussed the importance of avoiding resonance to ensure safety and comfort. Additionally, students calculated the peak acceleration experienced by the user to further evaluate comfort levels and proposed design modifications to enhance user comfort. Students were given Equation 19 and were expected to derive the maximum acceleration magnitude ($X\omega^2$) by taking the second derivative of the system steady state response ($\ddot{x}$) as shown in Equation 20. With these values they compared their results to comfort levels reported in the literature for various peak accelerations.

$$T = \frac{X}{Y}, \quad \ddot{x} = -X\omega^2 \sin(\omega t - \varphi) \tag{19-20}$$

where φ is the phase angle.

4.1.5 Prosthetic Limb Rotation

Learning Objective: The objective of this homework assignment is to understand the constraints of supination and pronation motions in amputees, derive the equation of motion to model a user rotating a doorknob with a prosthetic limb, and analyze the system dynamics to evaluate its damping behavior. Through this process, students gain insight into the challenges amputees face with prosthetic devices and develop the skills necessary to model and assess the dynamic performance of prosthetic systems.

Core ME principles	Topics	Type of awareness
Dynamics	• Vibration Analysis • Control Systems • Mechanical Design	• Accessibility & Inclusion • Biomedical • User Safety and Comfort • Physical Diversity

The Story: Arm rotation is essential for performing daily activities like opening doors, eating, writing, or even basic self-care. Without the ability to rotate our arms, simple actions like adjusting posture, using utensils, or manipulating objects become challenging and require additional effort. For amputees, the lack of arm rotation presents significant challenges to their daily life. Most commercially available upper-limb prostheses only allow passive rotation, meaning that for individuals with one intact arm, adjustments must be made using their healthy hand. For bilateral amputees, the prosthesis must be rotated against a fixed object in the environment, such as a table edge or nearby surface. Current control of these rotators is cumbersome, slow, and unintuitive.

Additionally, like other prosthetic components, prosthetic rotators lack proprioceptive feedback. Amputees cannot feel the orientation of their prostheses and must rely on visual feedback to determine the position of their artificial limb in space. This lack of proprioceptive feedback impedes control of the prosthesis, increases the cognitive burden of use, and impairs function.

Current research has developed an alternative approach to improve the user experience by using a magnetostatic field. A small permanent magnet is inserted into the distal end of the residual bone in subjects with an upper-limb amputation [45] When the amputee rotates their residual arm, the magnet rotates with the residual bone, causing a change in the magnetic field distribution. This change can be detected by magnetic sensors fixed in the prosthetic socket. The information on the residual arm's rotation is then used as an input signal to control a powered rotator in the prosthesis.

The Assignment: In this dynamic modeling assignment, students were tasked with deriving the equations of motion (EOMs) for a prosthetic limb system in a daily living activity scenario involving the rotation of a doorknob, as shown in the FBD in Figure 2. The system parameters included a residual humerus (inertia J_1), a servomotor (inertia J_2), a gear (inertia J_3, with radius R), and a doorknob connected to a latch. The latch had a given mass (m), spring constant (k), and viscous damping coefficient (b). In Figure 2 the humerus was shown with an initial torque (T_i) and angular velocity (ω) that lead to the rotation of the doorknob. The students were expected to perform an analysis to derive the EOM in the form presented in Equation 21, where $a_0, a_1,$ a_2 *and* A were expressed in terms of $J_1, J_2, J_3,$ R, m, b and x. This was performed by using the sum of the torques and rearranging to get all variables in the form of Equation 21.

$$a_2\ddot{x} + a_1\dot{x} + a_0 x = \mathrm{Ti} \tag{21}$$

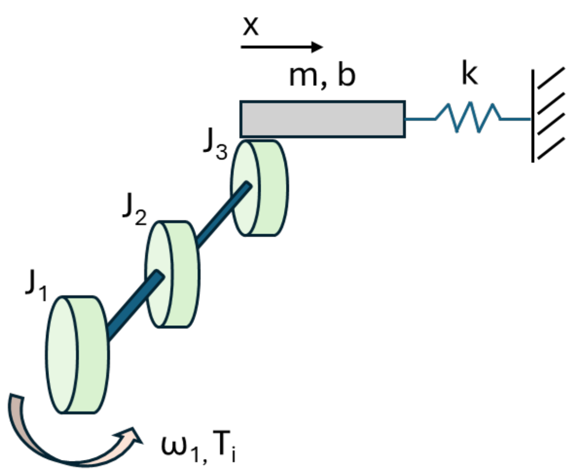

Fig 2. A schematic sketch of prosthetic limb with control system to turn doorknob

Next, students calculated the natural angular frequency (ω_n) and damping ratio (ξ) using Equations 22 and 23 and sketched the system's step response on an amplitude vs. time plot. The plot was required to include labels for rise time, peak time, maximum overshoot, and settling time, reflecting the system's dynamic behavior. Lastly, students determined whether the system was underdamped, overdamped, or critically damped, and then plotted the system's dynamic behavior.

$$\omega_n = \sqrt{\left(\frac{a_0}{a_2}\right)} \tag{22}$$

$$\xi = \frac{a_1}{2\sqrt{(a_0 \cdot a_2)}} \tag{23}$$

4.1.6 Laboratory course development ideas

In addition to lecture-based courses, discussions with embedded laboratory instructors led to innovative course development ideas. The development of this assignment is a work in progress. Here, we share the design concept for others to refer to. The first idea involved developing computational fluid dynamics (CFD) assignments to evaluate the cooling needs of battery packs for electric vehicles (EVs), enabling the analysis of safety and environmental impacts in computational analysis courses. Our second idea was to incorporate frequency analysis of natural environments to identify animal species incorporated into circuits and measurement courses. This approach aimed to raise awareness about critically endangered and extinct species [46]. Our last idea was sound wave analysis for EVs in acoustics and vibration laboratories. This analysis addressed safety concerns related to EV detectability and incorporated inclusive design principles for extreme users, such as individuals with visual impairments [47], [48]. These designs could extend benefits to broader populations, including older people, children, and unassisted individuals with vision correction needs.

5. Pilot Program, Implementation and Student Feedback – Outcomes of the Faculty Learning Communities Model

Our first Faculty Learning Community cohort, titled the Belonging Excellence & Transformational Research (BETR) Learning Community, devoted the Spring 2024 semester to creating assignments for four technical courses, including Thermodynamics, Computational Tools, Heat Transfer, and Fluid Mechanic, with the aim of broadening students' awareness of individual differences and developing an inclusive decision-making mindset. Each assignment was designed to engage students with topics, experiences, or challenges inspired by the instructors' interests, expertise and life experiences. Table 1 summarizes the connection between core knowledge areas and awareness types, along with an outline of the design concept for each assignment. These assignments were delivered in various formats, such as homework tasks, mini-research projects, and comprehensive design proposals. The following sections provide an overview of the learning objectives, presented the assignment layout, and present instructors' observations, offering insights into the assignments' implementation and impact.

Table 1. Mapping ME Core Knowledge, Design Concepts, and Awareness Types in Course Assignments

Core Knowledge	**Awareness**	**Concept**	**Related Section**

Thermodynamics	Social/ Economic/ Global/ Environmental Awareness	Assignment 1 - As an engineering consultant, conduct a thermodynamic and economic analysis to determine whether your client should invest in alternative energy systems, taking into account government tax incentives and potential cost savings. Assignment 2 - Develop a concise educational video aimed at the public, explaining the thermodynamic cycle and its applications in gas turbines or water heat recovery systems. Additionally, analyze the diverse impacts of these technologies, including their environmental, economic, and societal implications, for the audience.	5.1
Heat Transfer	Socioeconomic Awareness	Owners of a small fried chicken restaurant in rural Georgia could potentially reduce operational costs through waste heat recovery. Compare the electricity costs of the existing system and an upgraded system with a crossflow heat exchanger, based on the systems' waste heat recovery potential, while considering the family's financial situation, including a personal loan for financing this engineering project, down payment to an engineering firm, and loan amortization. Provide recommendations regarding their investment.	5.2
Solid Mechanics Simulations	Social Awareness/ Historical Perspective	The world's first female crash test dummy was introduced in 2022, 136 years after the invention of the car [49]. Research the diversity gaps, considering factors such as gender, age, physical ability, and more, and propose a plan to improve the current safety testing standards for crash tests.	5.3
Fluid Mechanics	Social/Global/ Environmental Awareness	The assignment aimed to educate students on methane's impact on global warming and mitigation strategies through short-answer questions, a landfill case study, and real-world research on methane measurement, featuring an interactive virtual tour of a wind tunnel.	5.4

Overall, both students feedback and instructors observations found the assignments beneficial but identified areas for improvement, including better structure, scaffolding, and a clearer understanding of students' prior knowledge. Some students appreciated working with real data and recognized the assignments' connection to engineering principles, though this sentiment was not universal. Others struggled to see a clear link between the projects and course learning objectives, particularly those focused solely on technical knowledge, which impacted their engagement. For example, the inclusion of financial aspects of engineering was unexpected for many students. However, it is essential for engineering students to understand that their solutions must be both technically viable and suitable for the customers' background. Therefore, suggestions for improvement included providing supporting tutorials, offering more structured guidance throughout the assignments, explicitly explaining why diversity, justice and inclusion are related to the course material, and incorporating reflective components that clearly link project outcomes to engineering principles and professional skills.

Instructors considered the learning community to be an invaluable resource for refining these assignments. The collaborative environment enabled them to develop innovative teaching methods, such as micro-projects, to foster greater student engagement. This effort was further supported by the learning community's incentive structure, which encouraged instructors to dedicate time to refining and enhancing their assignments. Additionally, the community had a positive ripple effect, with one teaching assistant gaining insights into the integration of applied, socially relevant projects into content-heavy courses.

5.1 Thermodynamics

Two assignments were introduced in the thermodynamics course that enrolled 115 students as part of their mini-research projects. The first assignment was given early in the semester when students started to learn the fundamental concepts of thermodynamics. The second assignment was introduced near the end of the course, by which time students had developed a more comprehensive understanding of the subject. Both assignments were designed to encourage students to think beyond the textbook, conduct independent research, and explore the real-world implications of thermodynamics in practical applications.

<u>Assignment 1 - Engineering and Financial Analysis of Alternative Energy Installation</u>

Learning objective: Students develop the ability to identify and evaluate household alternative energy options by analyzing and critiquing data from multiple online sources. They assess the feasibility of these systems from both energy efficiency and financial perspectives, supported by data-driven justifications. Additionally, students explore the sociological and economic barriers that prevent average families from adopting alternative energy solutions and present their findings in a professional report tailored for an educated client.

Assignment Layout: This project tasked students with acting as consultants to provide a thorough analysis and recommendation on whether a homeowner (the instructor) should invest in installing a residential solar panel system or a geothermal heat system. Students were given an estimate of local electricity costs and insights into the client's energy usage habits pulled from the instructors' authentic annual energy usage data collected each day of the previous calendar year. They were informed about current government tax incentives for alternative energy systems and the possibility of selling excess electricity back to the grid. Working individually or in pairs, students conducted online research on alternative energy options, pricing, analyzed local solar radiation patterns, and estimated the maximum feasible system size and energy output. They evaluated the system's ability to meet average home energy demands, calculated the payback period, and assessed potential long-term financial gains. The findings were synthesized into an engineering and economic analysis, culminating in a well-supported recommendation for the client.

Assignment 2 - Modern Frontiers of Thermodynamic Cycle Applications

Learning objective: Students develop the ability to describe the motivation behind applying thermodynamic cycles to address significant engineering challenges. They gain skills in explaining a specific cycle and its real-world applications to targeted audiences, high school graduated adults with non-STEM backgrounds, by refining their language to ensure clarity and accessibility. Students articulate how these technologies impact everyday lives, emphasizing the importance of scholarly efforts in advancing them. The final deliverable, a synthesized video presentation, demonstrate their mastery of the content and effectively communicate their findings.

Assignment Layout: In this assignment, students were tasked with creating a two-minute educational video on one of two topics: next-generation gas turbine engine technologies using the Cheng cycle or the application of the Rankine or Organic Rankine Cycle for landfill waste heat recycling. The videos required students to explain how the chosen technology works, its engineering objectives, and its underlying thermodynamic cycle in a way comprehensible to a general audience. Students also identified key challenges associated with the technology, highlighted the benefits of potential advancements, and justified the value of engineering efforts dedicated to these improvements. Finally, they explored the broader societal impacts, such as environmental, economic, and public considerations, emphasizing how technology affects everyday life and national competitiveness.

Instructor Observations, feedback from Dr. Berdanier:

After implementing these assignments in a large, 100-person class, I noticed that students seemed to either fully lean in to the applied nature of the assignments or reject the premise that these assignments were reflective of values in the real world. Some examples of particularly well-done projects included one student who requested actual quotes from several local solar panel companies to help him perform his cost analysis. Another student became a disciple of geothermal energy and it became a class joke about how many times he would volunteer information about geothermal systems to support in-class examples of thermodynamic topics even through the rest of the semester! Importantly, many students were able to identify that even effective technologies require upfront financial investments, being potentially unfeasible for many American families, and also that the implementation of solar panels or geothermal heating requires home or land ownership, which is increasingly out of reach for American families, and is potentially fully impractical in some urban areas. From a data skills perspective, this project was intended to be able to be done in Excel with basic calculations, but many students made the inaccurate assumption that solar intensities would be equal all months of the year, which in our region is untrue. Some students also struggled with the idea that they needed to find their own data sources and evaluate the efficacy of those data: They had to date not been in any situations that required them to source their own data. These students also were uncomfortable with the idea that different people, based on what their inputs were, may have different “answers” to the calculations and to the recommendation to the “homeowner” on whether they should install solar panels.

In the video project, students generally did not struggle to explain the cycles, but overwhelmingly struggled to remember who the intended audience was to be for the video: A general audience doesn’t know or care about the variables Q and W, but can understand what efficiency is. Because of the two-minute time constraint (essential for grading in a large 100 person class), some students felt they “couldn’t address the ethical/social implications” because of time constraints, while others understood that in order to address all the parts of the project, they would need to weave the conversation on motivation and context for waste heat recovery in with the societal, environmental, and ethical consequences.

While I think both assignments were successful overall, I think if I were to do this again, I would expand the first project to be more scaffolded, spread out across the entirety of the course (rather than having two mini-projects)--or potentially having a “Part 1" and “Part 2” of the class to be able to teach some of the peripheral skills in a targeted way. For example, I had assumed that more students were able to make graphs in excel, or be able to pull data from one excel file into another, but there were some barriers even on this type of data skill. There were also issues in writing the technical report that (though I provided resources) continued to be issues that may need to be better scaffolded as well. While in this offering, I as the instructor discussed how the project connected to thermodynamic principles and skills needed for the real world (and many students loved the ability to work with real data, from the teaching evals), other students missed that entirely and complained that the projects were not at all connected. In a future implementation, I would also ask students as part of the project to make the connections from the applied project to their course learning and the skills they will need in the future.

From my point of view as a participant in the learning community, it was nice to have a platform to be able to manifest some of my ideas for micro-project implementation that had been knocking around in my head. I feel like I’m always full of good ideas but never have the time to work through the assignment write-up—and there’s always some inertia that prevents changing an already very successful course (I’m sure I’m not alone!) But being part of an incentivized community with like-minded peers helped distribute the task for me over time, and knowing that I was teaching this class made it “real” to think through all the parts of the assignment, from framing to introducing the assignment to rubric development/grading. Having summer salary resulting from this also made me know that this effort is not invisible and is valued. A last reflection that I have as an instructor is that through this process, my TA from this semester was excited by these assignments, having herself taken a very traditional and boring thermodynamics class as an undergraduate. As a future professor, she enjoyed seeing how even very large classes with lots of material to cover can have micro-infusions of social, ethical, and applied projects to help students make connections between course materials and the real world—so, our learning community had some downstream impact as well, as she may apply similar assignments in her own future courses as an instructor!

5.2 Heat Transfer

Learning objective: This assignment focuses on energy analysis and cost optimization, emphasizing understanding the client's social and economic background to provide customized recommendations. In this assignment, students calculate energy balances to assess a kitchen's thermal operation, estimate operational costs based on energy usage and operational data, and select an appropriate heat exchanger for waste heat recovery. Additionally, students evaluate the overall thermal engineering project cost, create visual data representations, and determine the optimal solution based on financial and operational factors. Finally, they use amortization loan tables to assess the feasibility of pursuing this energy optimization project based on the client's financial limitations.

Assignment Layout: This assignment is structured around a story of the Petersons, a couple in their 50s, operated a small fried chicken restaurant, El Fried Pollo, in Dalton, Georgia. The restaurant's primary source of income relied on a large fryer, heated by an electric heater, which operates day and night. Noticing an oven that exhausts hot air, a mechanical engineering student suggested recovering the thermal energy from the oven's exhaust to help heat the fryer oil, using a crossflow heat exchanger where the hot air and oil flow separately through pipes and around finned surfaces. Provided parameters included the total hours of fryer operation per week, oil flow rate ($\dot{V_{oil}}$), initial (T_i) and final (T_f) temperatures in the fryer, oven exhaust hot air temperature ($T_{hot\ air}$), properties of the oil ($specific\ heat\ capcity, c_{p,oil}; density, \rho_{oil}$), and the cost of electricity per kilowatt-hour. Students were directed to assess the viability of the suggested upgrade.

Students were first asked to draw a schematic of the system and calculate the fryer's heat transfer rate coming from an electrical heater and the annual operational cost of the heater, assuming a perfect electrical-to-thermal energy conversion. We expected that students would recall the energy balance equation for calculating the heat transfer rate and obtaining the annual operational cost by multiplying the heat transfer rate (electrical heater power) by the total operational hours and the cost of electricity per hour.

$$\dot{Q}_{heater} = \rho_{oil}\dot{V_{oil}}c_{p,oil}\left(T_f - T_i\right) \tag{24}$$

Next, students were tasked with providing a schematic of the upgraded design using a crossflow heat exchanger and use EES to calculate the heat exchanger's heat transfer rate while the exhaust hot air flow rate ($\dot{V_{hot\ air}}$) and conductance of the heat exchanger (UA) were given. Students were expected to identify the relevant values of air properties ($c_{p,hot\ air}, \rho_{hot\ air}$) using EES or online resources and recall that the heat exchanger's heat transfer rate ($\dot{Q}_{HX}$) could be calculated using the NTU method:

$$\dot{Q}_{HX} = \epsilon C_{min}\Delta T_{max} \tag{25}$$

where ϵ is the effectiveness of the heat exchanger, calculated by the NTU-ϵ expression:

$$\epsilon = 1 - exp\left\{-\frac{1}{C_r}[1 - \exp(-C_r NTU)]\right\}, NTU = \frac{UA}{C_{min}} \tag{26}$$

and $C_r = \frac{C_{min}}{C_{max}}$, the heat capacity rates C_{min} *and* C_{max} can be calculated by multiplying the mass flow rate by the specific heat capacity, with the mass flow rate ($\dot{m}$) equal to the density (ρ) multiplied by the fluid flow rate ($\dot{V}$).

$$\dot{m} = \rho\dot{V} \tag{27}$$

After obtaining the heat transfer rate of the heat exchanger, students calculated the operational cost of the electrical heater in the upgraded system. The heat transfer rate of the upgraded system was equal to the difference between the heat transfer rate of the heater and the heat exchanger, as heat was added to the oil by the heat exchanger. The annual operational cost could again be calculated by multiplying the heat transfer rate by the total operational hours and the cost of electricity per hour.

The second part of the assignment focused on analyzing the financial viability for the owner. Students were provided with the cost of the heat exchanger per UA and instructed to plot the monetary savings from the heater's operation as a function of UA. Additionally, the total cost, which included both the heater operation and the cost of acquiring the heat exchanger, was plotted as a function of UA. The findings provided insights into the optimal UA for the heat exchanger, the cost of the optimal heat exchanger, the minimum cost of operation over the years, and the annual energy savings. Students were then provided with the cost of installation, the client's available cash, and an amortization calculator to evaluate whether a 5-year personal loan or home equity loan, with or without a down payment at the current interest rate, would be a viable investment for the family.

Instructor Observations, feedback from Dr. Ramos-Alvarado:

The conventional undergraduate heat transfer task of heat exchanger sizing was carried out in this assignment, and for the sake of simplicity, the heat exchanger's conductance, UA, (U is the overall heat transfer coefficient, and A is a reference heat transfer area) was used as a known parameter; where, a high UA value signifies a highly efficient and expensive equipment and a low UA value indicates an inefficient and likely cheaper device. As presented, the technical aspects of this assignment are rather standard for an undergraduate heat transfer course. However, what allowed for the inclusion of aspects of diversity in economic income levels and the provision of customized solutions that are feasible and tailored to the client's background was a simple motivating story. Placing this technical problem in a setting as relatable as a commercial kitchen and invoking the financial limitations of running a small business by a low- to middle-income family in the United States, made this whole exercise as feasible as could be. Additionally, the BETR learning community facilitated the pedagogical structuring of these assignments by creating a monthly meeting plan where guidance and collegial feedback was given to all participating faculty, which concluded with a mini seminar where all projects were presented for further feedback from a larger college community.

It is noteworthy that many students were initially challenged and confused about the expectations from this exercise, particularly on the financial aspect of this assignment. Students had, probably for the first time, realized that engineering is a service that they will eventually provide, and as such, it must be remunerated. From the pilot implementation of this assignment, a small number of students realized this on their own, but for many more, an email explaining that a project as small as a waste heat recovery system for a kitchen, even if it is technically and ecologically viable, requires a financial investment that could be out of the reach of a large portion of the population. For future implementations, I would recommend either discussing the economic aspects of engineering projects or adding a brief paragraph related to this at the end of the problem statement. A brief reflection and concluding remarks were asked at the end of the assignment, yet a few students only focused on the technical aspects of this exercise. One could also explicitly ask for making the technical-socioeconomic connection in the last section of the assignment.

5.3 Solid Mechanics Simulations

Learning objective: The learning objectives for this assignment focus on understanding the evolution and limitations of crash test dummies in vehicle safety testing. Students explore the historical development of crash test dummies and their limitations, analyzing the impact of non-diverse crash test dummies on car safety features. They apply their knowledge to propose designs for more inclusive crash test dummies, while also evaluating the ethical implications of the historical approach to the dummy design. Finally, students create a plan to integrate diverse crash test dummies into current safety testing standards, promoting inclusivity in vehicle safety.

Assignment Layout: In this assignment, students were tasked with creating a design proposal for a crash test dummy that addressed the diversity gaps present in historical approaches. They analyzed the importance of incorporating diverse body types into crash test dummy models and explored the broader implications for safety standards and ethical engineering practices.

Their task began with reviewing articles and podcasts from 2018 on the development of the first crash test dummy modeled after the average woman's body. Students summarized the article, highlighting the significant differences between male and female crash test dummies. They identified historical limitations in crash test standards and their impact on car safety for diverse populations. They critically analyzed how the lack of diversity in crash test dummies affects safety features, design, testing protocols, and regulatory standards, while reflecting on the automotive industry's ethical responsibility to all users.

After a comprehensive evaluation, students suggested design modifications or a new crash test dummy concept to address these diversity gaps, considering factors such as gender, age, and physical ability. Their design proposal aimed to improve safety testing outcomes and support more inclusive safety standards. Finally, students reflected on the role of engineers in ensuring equity and inclusion in product design and testing. The assignment concluded with a written report summarizing their responses, design proposals, and reflections.

Instructor Observations, feedback from Dr. Kraft:

The concept of the female crash test dummy assignment was explored with a group of teaching assistants and top-performing students to evaluate its feasibility and impact. While the CAD files for the project were accessible, a significant technical challenge emerged in that the SolidWorks simulation models did not include boundary conditions or mechanical material properties. This limitation proved to be a major obstacle, as creating these models from scratch required concepts beyond the prerequisite knowledge of students in this introductory course in computational tools for engineering. For successful implementation, these models would need to be pre-populated with the necessary data, enabling students to focus on analyzing and interpreting results rather than building the simulations themselves. Once this preparation is in place, it would significantly streamline the process, making the assignment more approachable and effective for introductory-level students.

The teaching assistants and small collection of top students polled reacted positively to the assignment concept, finding it both engaging and relevant to real-world diversity and safety issues. Some felt overwhelmed by the technical complexity of the problem and that the proposed assignment deviates too much from the current curriculum in that it is supposed to focus on introductory curriculum from other core classes (i.e., heat transfer, mechanical design, fluid mechanics). Suggestions for refinement include pre-populating these models with boundary conditions and material properties and providing additional resources or tutorials to guide students in analyzing simulation results. The BETR Learning Community provided valuable insights and a collaborative environment that facilitated the development of this assignment. The brainstorming sessions were particularly helpful in refining the concept and anticipating challenges.

5.4 Fluid Mechanics

Undergraduate mechanical engineering students consistently list issues related to sustainability and energy as a motivating factor for pursuing careers in STEM. To better connect these motivations to the core curriculum, an integrative assignment was introduced in an introductory fluid mechanics course of 83 students. This assignment served as a pilot for a planned series of assignments themed around the United Nations' Sustainable Development Goals (SDGs). The assignment combined traditional problem-solving with open-ended questions designed to help students explore modern technology related to sustainability, specifically focusing on methane emissions from landfills as well as related capture/containment systems. A secondary goal was to introduce students to contemporary scientists doing cutting-edge research in fluid dynamics, particularly those from underrepresented demographics. This is particularly relevant to the core area of fluid flow, since the course introduces a large number of equations and expressions that are exclusively named for men of European descent. We additionally ask students to critically reflect on the skills and training to pursue a career in research on this topic, helping them to potentially envision themselves in the role.

Learning objectives: Learning objectives for this assignment included the following: 1) calculate the total amount of methane being emitted from a landfill given realistic inputs and conditions; 2) contrast this amount with emissions using various mitigation techniques; 3) compare methane emissions from landfills, natural gas extraction, and various other sources; 4) recommend methane-capturing technologies for developing nations without access to advanced mitigation strategies; 5) summarize various technology/instrumentation approaches used to study the problem, and 6) evaluate the skills and training required to study the fluid dynamics of methane transport and related problems.

Assignment Layout: The assignment consisted of three parts. Part I consisted of four short-answer questions designed to introduce the students to methane (a greenhouse gas), the concept of warming potential, the contribution of methane to global warming, and available mitigation strategies and their efficacy. Part II was a series of problem-solving exercises, written as a case study of a relatively nearby landfill (the Wayne Township landfill in Clinton County, PA); numbers/value were taken directly from available data for this landfill. Part II also asked students to reflect on the role of fracking in global methane emissions—a relevant topic for new engineers entering the workforce in Pennsylvania. Part III focused on the real-world research of Dr. Theresa Oehmke, a professor at the University of New Hampshire who studies methane transport and dispersion. Dr. Oehmke shared a freely available interactive virtual tour of the very large-scale wind tunnel used in her work; students were asked to go through the tour and complete a set of questions related to modern techniques to measure and mitigate methane emissions.

Instructor Observations, feedback from Dr. Byron:

Students were invited to give feedback as an optional Part IV of the assignment. They were asked to respond to any of the following four questions: 1) Was this assignment format helpful for your understanding? 2) Did this assignment change your self-conception of your identity as an engineer and/or your professional goals? If so, how? 3) Would you like to see more of this type of assignment in your engineering classes? 4) What suggestions do you have for improving this assignment, or for future assignments in the same format?

In general, students seemed cautiously positive about the assignment format, though some expressed concern that it was too long/involved. They enjoyed the real-world application of the landfill (Part II) but had trouble seeing the connection to the modern research project (Part III). Some students were also frustrated with the amount of time required to find answers to the more open-ended questions, and did not think their time was spent efficiently—they were particularly focused on relevance to course exams. Students were also unsure how helpful the format was for their understanding compared to a traditional "problem set" format. Several students reported that it caused them to think differently about "what engineers do".

Student feedback was reasonable and helpful, with many implementable suggestions that will improve future offerings. In the future, it may be more helpful to assign a self-contained reading and then ask students to answer a series of questions, rather than expecting students to search broadly. However, finding answers to relevant questions without knowing exactly where to look is part of the skillset we must instill in undergraduate engineering students! When refining the assignment, we will seek an intermediate approach which still requires some self-driven research but is not quite as open-ended as the pilot assignment. The assignment should also be more tightly integrated with course material and core topics from the syllabus.

7. Conclusion and Future Work

Our experience at Penn State demonstrates that collaboration, whether facilitated through a designated project lead model or faculty learning communities, is an effective strategy for encouraging the integration of diversity, justice and inclusion content into engineering courses. Developing diverse teaching materials that influence future generations is most successful when individuals from varied backgrounds collaborate, each contributing unique perspectives and stories. We have intentionally defined diversity broadly, fostering broader acceptance of the concept and providing greater flexibility for implementation. Our process involved encouraging participants to reflect on personal experiences and apply a storytelling approach to enhance student awareness of inequality, inequity, and injustice worldwide. This approach resulted in the development of course content that not only reinforces technical knowledge but also equips students to become holistic thinkers. Students are prepared to consider cultural understanding, social justice, global perspectives, public health and safety concerns, environmental responsibility, economic disparities, historical contexts, and ethical considerations, traits essential for responsible engineers.

While resistance to change and faculty commitment to broadening course content beyond traditional examples in all engineering courses remain challenges, we believe that integrating diverse forms of awareness across the curriculum, particularly in core courses, will foster well-rounded student development. This multiple-touchpoint approach engages students continuously, enhancing their decision-making skills with consideration of a wider range of perspectives. This collective approach allows connection points to be spread across the curriculum, leveraging each faculty member's unique expertise. We also recognize that a collective approach is essential to overcoming challenges such as limited course time. By distributing the workload among multiple faculty members, each can contribute in a manageable way, reducing the burden on courses like engineering design or teamwork-based classes, where most ABET curriculum requirements are often naturally incorporated.

Moving forward, we will focus on expanding and refining our approach by assessing the effectiveness of storytelling in enhancing student awareness of real-world factors. Our immediate goal is to encourage more faculty to adopt, adapt, and implement these resources into their courses. Next, we plan to conduct longitudinal studies to evaluate the project's impact on increasing student awareness of human diversity and the ability to make human-centered decisions. We also aim to build a more comprehensive public library of adaptable teaching materials, including case studies and project-based assignments, through cross-institutional collaboration, fostering a stronger sense of community within the mechanical engineering field.

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