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To Do Good, Learn Well: Engineering a Virtuous Cycle between Technical Rigor and Diverse, Equitable, and Inclusive Teaching Practice

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Abstract

In a world beset with environmental, economic, and social crises that disproportionately harm vulnerable and marginalized populations, it is clearer today than it ever has been that the engineers of tomorrow must not only be exposed to — but rather steeped in — the principles of diversity, equity, and inclusion (DEI). In recent years, incorporation of DEI principles has become a marquee focus in engineering curricula across the country. However, these efforts have also drawn considerable skepticism from pedagogical traditionalists, who perceive an intrinsically zero-sum relationship between DEI and technical rigor, the latter of which is the *sine qua non* of engineering education.

In this work, we address these (understandable and justifiable) concerns by highlighting two opportunities to engineer a virtuous cycle that simultaneously elevates technical rigor and DEI outcomes: (1) identifying mathematical concepts that are value-neutral in the abstract yet have significant DEI implications in practice; and (2) deeply integrating the history of science and mathematics to highlight technical contributions from diverse individuals. We present specific examples of the former strategy in the context of linear algebra and probability theory, and of the latter strategy in the context of numerical analysis and differential equations. We also present quantitative and qualitative results from the implementation of these virtuous-cycle strategies in a sophomore-level course on computational science. Throughout, we emphasize that technical rigor must be a front-line tool for social justice, and that technical rigor and DEI are natural and mutually enriching companions.

Introduction

Motivated in large part by landmark social and political events in recent years, numerous engineering departments around the country have begun to prioritize the incorporation of diversity, equity, and inclusion (DEI) principles in their curriculum. These efforts have taken many forms, and broadly fall into two categories: (1) Highlighting the ways in which engineering can exacerbate or mitigate social inequities, often through historical or especially contemporary case studies (see, e.g., [1]–[4]), and often with a particular focus on the potential for technology to exclude and divide (see, e.g., [5], [6]); and (2) reducing inequities within the classroom itself (see, e.g., [3], [7]). Our community should celebrate these nascent DEI efforts, which begin to address important ethical considerations that are not frequently addressed in traditional engineering curricula (including within traditional engineering ethics curricula), and which center issues of particular importance to our nation's increasingly diverse body of engineering students.

As a growing number of departments begin to undertake these attempts at curricular reform, there will be (and in fact already is) significant backlash from pedagogical traditionalists, who may perceive these efforts as "watering down" the technical rigor of a traditional engineering education with elements (e.g., "storytelling") typically reserved for the humanities or social sciences. Although the author is not aware of a specific study detailing the prevalence of backlash to the incorporation of DEI in engineering curricula, it is clear from the history of all curricular reforms that such reactionary responses are inevitable. For some departments, the resulting conflicts may undermine efforts at curricular reform, negatively impacting student learning outcomes, collegiality, and ultimately the very tenets of DEI that these reforms were meant to bolster in the first place.

In this paper, we make the case that there is a pathway to avoiding (or at least thoughtfully negotiating around) such conflicts, grounded in finding opportunities to deeply integrate technical rigor with DEI principles. Critically, these strategies must not compromise upon either competing consideration, and should ideally demonstrate that technical rigor and DEI mutually enrich each other. It is worth emphasizing that the approaches detailed herein are meant to complement (not replace) the two broad categories of DEI practices described above.

The central questions that motivate this work are: (1) "How can technical rigor and DEI principles be deeply integrated within an undergraduate computational science curriculum?"; and (2) "How does this integration affect students' sense of inclusion, beliefs about their technical mastery, and overall learning experience?"

Before continuing, it is worth briefly noting that controversy exists around the phrase "technical rigor"; in particular, this phrase has at times been used in engineering education to reinforce perverse dichotomies and justify exclusionary pedagogy [8]. While we acknowledge the (at times problematic) history of this phrase, we also see our use of this term in the work described below as fundamentally *joyful* and *reclamatory*: It is our sincere wish that a diverse body of engineering students feel equitably served, enthusiastically included, and genuinely motivated by coursework that sharpens mathematical and scientific precision and meticulousness (i.e., technical rigor).

In the section that follows, we provide brief context regarding the course in which our study is situated. We then describe several examples for deep integration of technical rigor and DEI, with a focus on broad unifying principles that are likely transferrable throughout the engineering curriculum. Finally, we provide qualitative and quantitative evidence for the effectiveness of these strategies.

Educational Context

The activities described and data collected in this work were in the context of a course entitled, "Intro to Computation and Data Science in Civil and Environmental Engineering," offered in Spring 2021. It is a required course in the Civil and Environmental Engineering (CEE) undergraduate program at Carnegie Mellon University. This course is generally taken by students in their sophomore year, with a typical enrollment between 30 and 45 students. This course presumes prior knowledge of computer programming fundamentals and (single-variable) calculus, but does not assume prior exposure to more advanced college-level mathematics. This course has been taught in the department by CEE faculty ever since it was first created in the late

1990s (when it was first created, it was entitled, "Intro to Computer Applications in Civil and Environmental Engineering").

Computing and data science play critical roles in the CEE undergraduate (and graduate) curriculum at Carnegie Mellon University. The undergraduate curriculum in this department provides students with a grounding in traditional CEE material, but has a particular emphasis on empowering students to play an active role in reimagining the field of CEE in the future. This course establishes the foundation for further computing (and sensing) skill development in required junior- and senior-level lab and project courses, including our senior capstone design course. Before graduation, a significant number of undergraduates also elect to take at least one graduate-level course with a strong computational focus.

Opportunities for Deep Integration of Technical Rigor and DEI

In this section, we provide two broad approaches for deeply integrating technical rigor with DEI principles; in each case, we also provide several examples explaining how this deep integration was carried out.

1. Identifying the DEI significance of mathematical principles that are value-neutral in the abstract. Here, we provide three examples out of several provided in the course.
    a. Eigendecomposition, diversity, and inclusion in image processing: Numerical linear algebra sits at the heart of computational science and engineering, and no introductory unit on linear algebra would be complete without a discussion of eigendecomposition. In brief, for any square matrix A (having a full set of linearly independent eigenvectors), there exists a factorization of A as

    $$A = U\Lambda U^{-1}$$

    where U is a matrix containing the eigenvectors of A and Λ is a diagonal matrix containing the eigenvalues of A. It is possible to reconstruct an approximation of A using only a subset of its largest eigenvalues, a common approach to compressing the size of an image (if, for example, A is a matrix of pixel intensities). As part of a hands-on activity to numerically evaluate the eigendecomposition of various matrices representing images, students were asked to evaluate the effect of varying the percentage of the total number of eigenvalues used in image reconstruction. Critically, students were provided with images showing a diversity of skin tones, hair colors, and background colorations. In class-wide reflections after this activity, several students expressed surprise and amazement that the choice of where to terminate the spectrum of eigenvalues in the image reconstruction (a decision that seems entirely value-neutral, in mathematical principle) can have a dramatic effect on the quality of the reconstructed image; this effect was particularly pronounced for several images featuring individuals with darker skin tones. This is a noteworthy example of technical material enriching students' understanding of an important DEI issue (one that is, in fact, growing in importance as an increasing number of public and private entities develop and deploy face-recognition software). It is worth noting that due to pandemic-related compression of the academic calendar, these ideas were introduced exclusively in the context of square matrices in Spring 2021, and singular value decomposition was left as optional learning for students interested in more advanced material.

b. Jensen's inequality and the conscientious inclusion of marginalized perspectives: One of the most important inequalities in basic probability theory compares the value of a (convex) function evaluated on an expected value against the expected value of that function itself. In particular, this inequality gives

$$f(E[X]) \leq \mathbf{E}[f(X)],$$

which holds for any convex function f and random variable X having expected value E[X]. As part of a lesson on Jensen's inequality, students were asked to compare two approaches for assessing food poverty: Estimating the average supplemental nutritional assistance needed in a neighborhood based upon household-level income data vs. estimating this same quantity using only the neighborhood-averaged household income. The instructor found that students almost immediately grasped the idea that the latter approach would produce a lower estimate of the degree of food poverty as compared to the former approach, since higher-income households can "screen out" the need of lower-income households, if the average is computed before need is assessed. In this example, a seemingly value-neutral mathematical principle (the order in which function evaluation and expected value are computed) can have profound consequences for the equitability of a social welfare policy. Based upon the instructor's substantial body of prior experience teaching probability theory (at both the undergraduate and graduate levels), this experience was particularly remarkable: In fact, the instructor cannot recall any prior example of so many students so quickly and intuitively grasping the core idea behind Jensen's inequality. This is a noteworthy example of DEI considerations improving learning outcomes for a strictly technical topic.

c. Graph theory, gratitude, and inclusion and belonging: We direct the interested reader to a more detailed account [9] of yet another opportunity for deep integration of rigor DEI, carried out in the context of this same course.

2. Directly incorporating the history of science and mathematics into the technical arc of a course, in order to highlight contributions from diverse individuals. Here, we provide three examples out of eight provided in the course.

    a. Gertrude Blanch: Incorporated into the course's module on numerical interpolation, and introduced as an example of a female computational scientist with a non-traditional educational trajectory owing to her disadvantaged socioeconomic background, as well as a person who faced unjust political persecution later in her career. Students were introduced to Blanch's work as lead of the Mathematical Tables Project, and shown schemes that her team developed to tabulate values of special functions that play an important role in homework assignments and assessments later in the course, including hyperbolic trigonometric functions, functions of significant use in probability theory, and special functions that occur in the solution of differential equations.

b. Katherine Johnson: Incorporated into the course's module on numerical solution of differential equations, and introduced as an example of a female African-American computational scientist who faced enormous amounts of discriminatory prejudice during a (now highly celebrated and memorialized) career at NASA. Students were provided technical reports that Johnson authored, and invited to reproduce some of her most elaborate hand calculations, many of which were performed with little to no support from what we would consider modern computing machinery.
c. Phyllis Nicolson: Incorporated into the course's module on numerical solution of differential equations, and introduced as an example of a female computational scientist denied numerous career opportunities due to her gender. Students were invited to reproduce one of Nicolson's critical contributions to the field, namely, the existence of a numerical instability in a technique for solving the heat equation developed by Lewis Fry Richardson. Students were then taught the Crank-Nicolson scheme, which is not affected by this instability.

Methodology

To collect data on the efficacy of these practices, we performed a pre- and post-survey of students in the course, with both surveys containing identical questions. Completion of the surveys was optional and was rewarded with a small amount of extra credit (on the order of a tenth of a percent of the total number of points available in the course); approximately three-quarters ($N = 23$) of the course completed both pre- and post-surveys. These questions were designed with the goal of assessing several critical facets of DEI, ranging from awareness about diverse contributors to the field of computational science to beliefs about personal belonging within this field. The specific survey prompts are detailed in Table 1.

Topic Assessed	Specific Prompt(s)
Awareness of important members of field	Jot down the first few (< 5) names that come to mind when you think of a "computational scientist or engineer."
Sense of self-efficacy	(1) I find that I am good with computers for everyday tasks. (2) I find that I am good with computing. (3) I find that I am good with mathematics.
Beliefs about career relevance	(1) Computational science and engineering will play a major role in the career that I wish to pursue. (2) Data science and analytics will play a major role in the career I wish to pursue.
Growth mindset	It is possible to meaningfully improve comfort with computing skills over the course of a semester.
Anxiety	I experience feelings of anxiety when I think about having to code.

Beliefs about innate talent	(1) There are people who just "have a knack" for coding. (2) I "have a knack" for coding.
Beliefs about collaboration	I think of computing as a collaborative activity.

Table 1: Prompts for pre- and post-surveys. The first prompt permitted as much textual response as desired by the student; all subsequent prompts allowed a response on a 10-point Likert scale (with "1" indicating "strongly disagree" and "10" indicating "strongly agree").

Results

In Figure 1, we show changes in student beliefs following a semester in which the above practices were implemented. These results show across-the-board improvements in all categories measured. Although the design of this study cannot, of course, attribute these changes exclusively to the activities described herein, this data is nevertheless consistent with a significant body of qualitative feedback from students indicating that these activities were useful, engaging, and beneficial to their learning outcomes. In particular, we find increased perceptions of self-efficacy, increased belief that the subject matter of the course is related to future career aspirations, increased belief that it is possible to improve computing skills within the timespan of one semester, a sharp reduction in feelings of anxiety associated with coding, and an increased belief that computing is a collaborative activity. Perhaps most intriguingly, the data also show that students have a decreased belief that computing skill is an innate talent possessed by *other* people (in other words, investment of effort can yield improvements even if one does not start out strong in this area) with a *simultaneously* increased belief that they themselves possess innate talent!

Beyond these measures of changed student beliefs, we also observed an enormous increase in awareness of the contributions of diverse individuals to the subject matter. When asked to name computational scientists or engineers on the pre-survey, only three students out of 23 identified individuals who were either female or members of a racial minority. The number of students who identified at least one female or racial minority on the same question on the post-survey changed by *over seven-fold* (22 out of 23). Remarkably, seven students named diverse computational scientists or engineers who were not introduced through course lectures, suggesting that this DEI activity can have "knock-on effects" that spur further out-of-the-classroom interest. Although formal data was not collected on the effect of these activities on office-hours attendance and other out-of-the-classroom engagement, the instructional staff found that over three-quarters of all students attended at least one instance of office hours, demonstrating strong levels of student engagement and interest in the course material. The instructor noted that at least a quarter of all students attended office hours on at least one occasion to discuss material related to one of the instances of deep rigor-DEI integration discussed above.

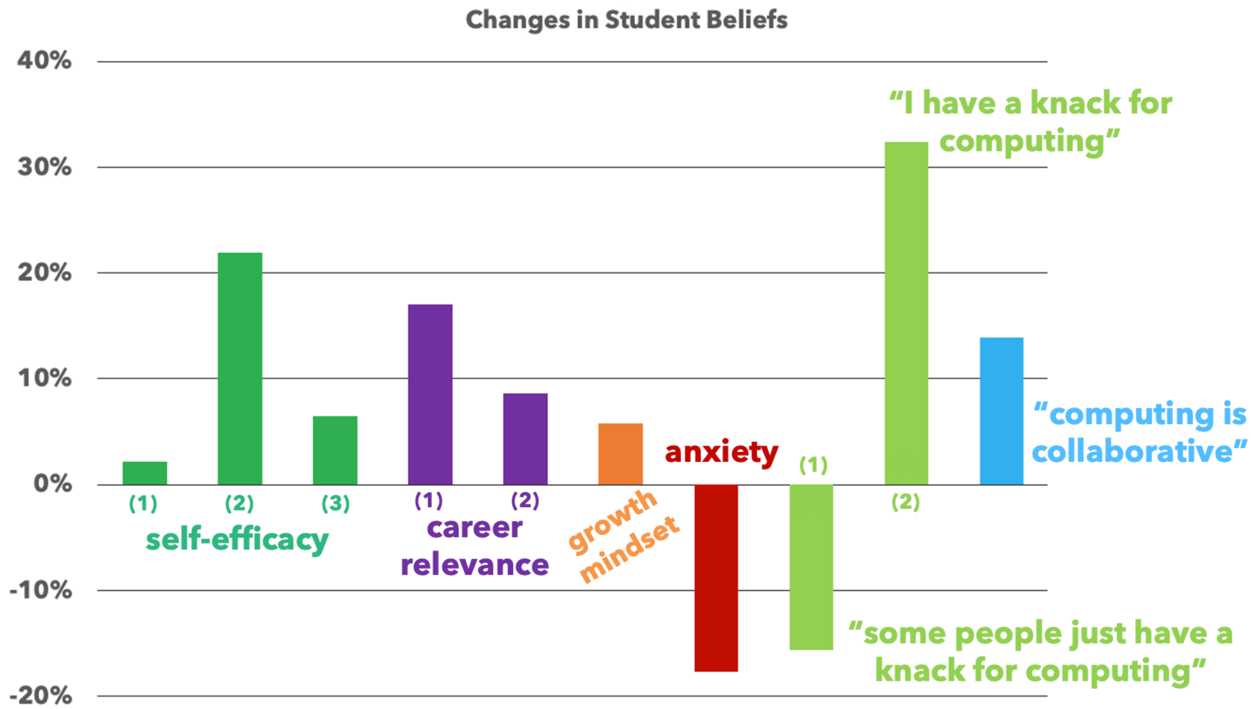

Figure 1: Changes in student beliefs from pre- to post-survey, as assessed by the questions detailed in Table 1.

The present instructor has offered this course twice; the activities described in this work were implemented in the second offering. After the implementation of these activities, overall ratings of the course increased from an average of 4.81/5.00 to 4.84/5.00 and ratings of the instructor increased from an average of 4.90/5.00 to 4.92/5.00. Although neither of these increases are, of course, statistically significant, both data points are consistent with numerous pieces of qualitative feedback from students that these interventions were positively received.

Conclusions and Future Directions

In this work, we have described two broad strategies for deeply integrating technical rigor with the principles of diversity, equity, and inclusion (DEI): (1) Identifying the DEI implications of nominally value-neutral mathematical principles, and (2) Incorporating historical information about diverse computational scientists and engineers directly into the technical arc of a course. We have found that both practices illuminate the synergistic relationship between technical rigor and the principles of DEI, and help students better understand both ideas from both domains. Qualitative and quantitative data collected over the course of a semester substantiate the claim that these practices improve students' learning outcomes and their sense of belonging in a computational science and engineering environment.

In the future, we plan to continue to investigate further opportunities for deep integration of technical rigor with DEI, including in graduate-level computational science coursework. We plan to survey alumni from this course several years after completion of this course, to collect data on whether such deep integration promotes retention of both technical concepts and DEI principles. Having seen the substantial positive benefits of these practices, the instructor for this course has no plans to roll back any of these changes. Nevertheless, by conducting pre- and post-surveys in other undergraduate computation and data science courses in the College of Engineering at Carnegie Mellon University, we hope to establish a baseline for changes in student beliefs in courses that do not pursue deep integration of technical rigor with DEI, which would be valuable for comparison with the data collected in the present study. Although it would be an exceptionally challenging hypothesis to quantitatively assess, we believe that the strategies detailed above would allow for greater penetration of DEI principles into engineering curricula, including and especially in more pedagogically conservative environments. Finally, the instructor is currently preparing a full collection of the profiles of diverse computational scientists and engineers introduced in this course, which will eventually be released as a freely available educational resource.

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