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# Opportunity Gaps for Women in Chemical Engineering: A Quantitative Critical Investigation

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## INTRODUCTION

Data collected by the National Science Foundation generally show that chemical engineering is more diverse with respect to gender than other engineering fields [1]. A more recent study shows that roughly 39% of matriculating chemical engineering students are women – the highest of any engineering discipline [2]. Yet, the discipline still falls short of gender parity, even at the undergraduate level, while other disciplines, such as biology, now see classes that may be majority women [3]. As one looks to higher levels of education in chemical engineering, gender diversity worsens [4]. Despite this, the issue of representation within chemical engineering specifically remains under-researched. Indeed, a literature search of Chemical Engineering Education (CEE) and the ASEE chemical engineering division proceedings yielded only two studies focused on gender [2, 4]; we did, however, find studies in CEE focused on student demographics more broadly [5] and one study in an international journal focused on the experiences of women in chemical engineering [6].

Most research about gender diversity in chemical engineering has focused on women's aspirations to study chemical engineering. Godwin and Potvin (2013) conducted a detailed quantitative analysis of pre-college factors related to students' reasons for choosing chemical engineering as a major, and their results align with the results of the broader STEM education literature [7]. They found that chemical engineering students were motivated by specific career-related factors, such as wanting to address issues of climate, water quality, disease, or energy. It has been suggested that this connection to societal problems is a driving force attracting women to chemical engineering over other fields of engineering [8]. Brawner et al. (2011) conducted a qualitative study of women in chemical engineering and found that the breadth of the chemical engineering field and job opportunities (including those in the medical field) were two major motivating factors [2]. They also found that role models, either in the women's families or on campus, were important in the major selection process.

To focus exclusively on which factors affect students' aspirations to study chemical engineering neglects the bulk of the process that produces chemical engineering graduates. For example, there are many points in their academic careers that women may choose to enter or exit a chemical engineering program. The problem of attrition in science, technology, engineering and mathematics (STEM) more broadly has been widely studied. The most famous study is the ethnographic study conducted by Seymour and colleagues that investigated reasons why students choose to leave STEM. One of the most cited reasons for leaving STEM in the original study was poor teaching in STEM courses; this remained true in the revisited study [9]). Other reasons included external pressures, a chilly climate for underrepresented students, and changing interests. As it pertains to attrition of women in chemical engineering specifically, one study finds no gendered patterns in attrition ([5]), while another found that, at institutions which were more successful in retaining women, providing real world experiences, the impression that faculty care about them, and forming connections with female peers were all factors that contributed to student persistence [6].

The issue of representation in STEM is usually conceptualized as a "leaky pipeline," where we lose students at certain critical junctures in their careers. This metaphor has fallen out of favor recently because it fails to account for multiple different pathways that students may take into STEM programs [10]. To address this shortcoming of the pipeline model, we instead conceptualize the issue of representation as a chemical process illustrated by a Block Flow Diagram (Fig. 1). Each critical juncture is thought of as a unit operation (a separator, to be most precise) with certain (and sometimes multiple) feed streams and certain effluents. Whatever happens inside of each unit has the potential to produce effluent streams with different compositions than the feed streams. Because we are researchers focused on undergraduate education, we focus on three critical junctures for chemical engineers: the first-year engineering program, the first chemical engineering course, and the remainder of the chemical engineering curriculum. The underrepresentation of women can be thought of as a product stream whose composition is not meeting specifications (gender parity). This could either be due to the composition of the feed stream (aspiring chemical engineers) or a malfunction with one of the units.

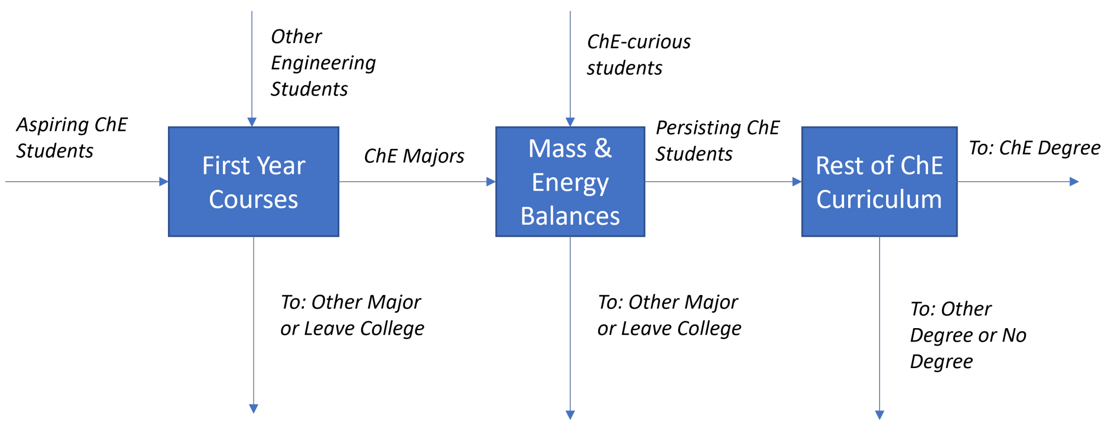


**Figure 1:** Block flow diagram metaphor for representation in chemical engineering (ChE). Each box represents a unit operation, arrows pointing into the boxes represent feed streams and arrows pointing away from boxes are effluent streams.

Our research questions for this study were as follows:

1. Are there gender disparities in aspiration to study chemical engineering at the beginning of college?

2. For students who do intend to major in ChE, are there gender disparities in degree attainment in ChE?

3. Given the gender disparities in degree attainment in ChE, where does the system fail women? In high school? During the first year of college? During the first chemical engineering course? Or during the remaining ChE curriculum?

## CONCEPTUAL FRAMEWORK

We draw heavily on the conceptual framework employed in Costello et al. (2023), which frames gender disparities in STEM degree attainment as ‘opportunity gaps’ [11]. Moving from ‘attainment’ or ‘achievement gaps’ to opportunity gaps focuses on deficits in the broader systems in which students learn, rather than the students themselves. Classrooms, institutions, and disciplines all have certain norms of operation that have been structurally excluding women from thriving in higher STEM education. For example, women and gender minorities who enter higher education face discrimination amid chilly classroom and campus climates [12, 13] and lack relatable role models among faculty and in curricular materials [14]. These obstacles frequently lead to disparities in educational achievement at the university level [9, 15, 16] and underrepresentation in the engineering workforce.

Many studies have investigated factors affecting the retention of marginalized students in STEM [17, 18, 19, 20, 21, 22, 23, 24] and have identified several factors that might improve STEM diversity such as undergraduate research opportunities and peer mentoring (reviewed in [25]). However, higher education is part of a broader inequitable system. If inequities that occur before college divert students from pursuing STEM degrees, changes to university programs will have little impact.

The current work is a quantitative study focused on studying the systemic factors that impact the representation of women among chemical engineering graduates. We note that the granularity of our analysis is limited by the use of institutional data. For example, we have ACT scores as a crude proxy for opportunity gaps in high school (the hypothesis being that opportunity gaps would be reflected in this metric).Following the framework of Costello et al. (2023), we hypothesize that the lack of representation of women in chemical engineering could be due to (1) disparities in aspirations to study chemical engineering at the beginning of college or (2) disparities in rates of attrition at various points during the chemical engineering curriculum [26]. As illustrated in Figure 1, we focus on two main junctures in a chemical engineering education: (1) the first-year engineering experience (which is largely devoid of chemical engineering-specific content, instructors, and social interactions) and the first chemical engineering course (which would be a student’s first introduction to the norms of the chemical engineering department and discipline more broadly). We focus on these two junctures as most attrition is typically the highest within the first three semesterss of the college experience [27].

## POSITIONALITY

The authors’ life experiences and identities influence the design and analysis of all studies, including quantitative ones [28]. The authors of the paper are researchers in both engineering and physics education with formal training in chemical engineering (rheology, to be specific). The authors were born in the United States, are cisgendered, white, male, and members of the LGBTQIAP+ community. We believe in the potential of any person to be successful in chemical engineering given that they are provided with the proper resources, motivation, and environment in which to learn.

## METHODS

We used regression and structural equation modeling (SEM) to quantitatively analyze institutional enrollment and demographic data to identify where structural inequities created demographic disparities in chemical engineering degree attainment. When not considered carefully, quantitative analyses of demographic disparities can encourage deficit thinking and downplay the role of systemic inequities [29, 30]. By exploring the mediating relationships between gender and degree attainment, we are critically identifying structural barriers to chemical engineering degree attainment for women and thereby identifying places where structural change is required to achieve equity.

Our dataset consisted of institutional enrollment records from a single public research institution in the southeastern United States. Enrollment records included enrollment data for all students and described students' incoming academic preparation (ACT score), incoming declared major (which is declared at the time of matriculation), undergraduate academic performance (first-year GPA), grades in Materials and Energy Balances (MEB), and postsecondary degree completion. The institutional data about student identity is limited to binary gender, which does not adequately capture the full spectrum of both gender identity and expression. Both gender identity and expression may be distinct from biological sex. This particular institution is predominantly white ( 80%) and somewhat selective (interquartile range of ACT scores is 25-31). We had access to all student records dating back to 2011. To ensure that we had complete records for all students included in our analysis, we only included records for students who enrolled between the Fall of 2011 and the Fall of 2015. This ensured that we had records from students' first term at the university and that we could investigate a 6-year graduation window. We examined outcomes only for first-time freshman and domestic students, as the transfer and international student populations at this university are small and face different sets of challenges from "traditional" students. When cleaning the data, we created binary variables that indicated whether a students' major was Chemical Engineering or some other discipline at (1) the time of matriculation and (2) graduation. The total number of students in the whole sample was approximately 15,600.

We used multivariate logistic regression to compute the probabilities of male and women students enrolling in chemical engineering and graduating with a chemical engineering degree. For example, the regression used to model gender disparities in chemical engineering major aspirations was:

$$\ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 Gender \tag{1}$$

where $P$ is the probability of enrolling in chemical engineering at the time of application to the university, and $Gender$ is a binary measure of gender (1 = women, 0 = male). Following this, the regression used to predict degree attainment was:

$$\ln\left(\frac{P}{1-P}\right) = \gamma_0 + \gamma_1 CheMajor + \gamma_2 Gender \tag{2}$$

where $P$ is the probability of graduating with a chemical engineering degree within six years of entering the university and " Major" is a binary variable representing whether or not a student was a declared chemical engineering major when they enrolled at the university. This was included to see if gender disparities in degree attainment were explained by the disparities in chemical engineering majors at the beginning of college. Said more plainly, a statistically significant $\beta_1$ indicates a gender gap in aspirations to study chemical engineering, and a statistically significant $\gamma_2$ indicates that this gender gap widens between matriculation and graduation.

To explore the underlying opportunity gaps that create observed demographic disparities in chemical engineering degree attainment, we used structural equation modeling (SEM) with the lavaan package in R [31]. SEM explores systems of relationships among variables [32] and can be thought of as computing a system of regression models simultaneously. In our model, the base variable is Gender. We explored whether there were gender differences in measures of high school academic preparation (ACT score). We also considered gender differences in college academic performance (first-year GPA, MEB grade), measuring whether the system fails women during the first-year engineering experience or within the first chemical engineering course specifically. If there remained a link between Gender and degree attainment after controlling for all these other junctures, it would indicate an attrition of women from chemical engineering late in the curriculum. There are a number of fit measures associated with SEM that tell whether the model is an acceptable fit to the data. Good measures of fit are Tucker-Lewis Index (TLI) ¿ 0.95, Comparative Fit Index (CFI) ¿ 0.95, Root Mean Square Error of Approximation (RMSEA) ¡ 0.05, Standardized Root Mean Square Residual (SRMR) ¡ 0.05, and a non-significant Chi-squared test [32].

Our SEM analysis included only students who started out as chemical engineering majors (N = 605). All measures of achievement were converted to z-scores so that the model coefficients could be interpreted in units of standard deviations from the mean. We explored the role of high school educational opportunities (ACT score) in shaping disparities in aspiration for and/or attrition from chemical engineering. Because this is a quantitative study using institutional data, we use measurements of academic performance as proxies for systemic challenges faced by women in chemical engineering. For example, if we were to find that women received lower first-year GPAs than men, we would ask whether this result is explained by disparities in high school achievement, highlighting that women face a systemic disadvantage because of opportunity gaps at the high school level.

## RESULTS

We found that male students were 2.3 times more likely to major in chemical engineering than women students ($p < 0.001$). This odds ratio is calculated relative to the whole student population: to the nearest percentage point, male students have a 6% chance of majoring in chemical engineering, while women students have a 3% chance. A male chemical engineering student is 2.6 times more likely to receive a chemical engineering degree than a women chemical engineering student ($p < 0.001$). This gap in graduation rates is statistically larger than the gap in initial major rates (significant $\gamma_2, p = 0.005$).

The trajectories of students who at any point in their careers where chemical engineering majors

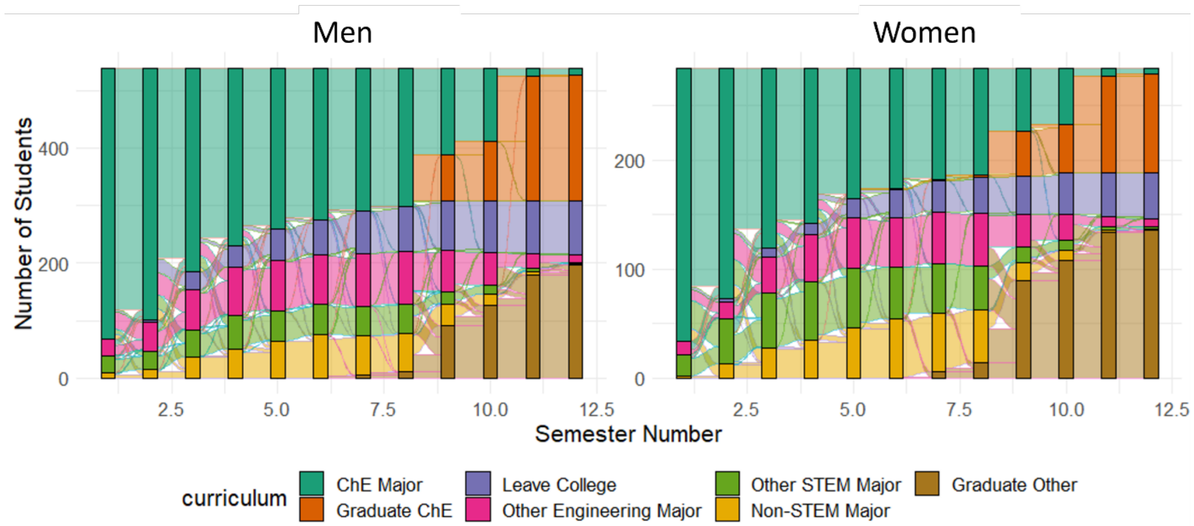


**Figure 2:** Sankey plots illustrating the flow of chemical engineering students between different curricular pathways over the course of 12 semesters. The graph on the left represents men students, and the graph on the right represents women students.

is shown in Figure 2. The chance of a student receiving a chemical engineering degree if they did not initially declare a chemical engineering major was statistically indistinguishable from zero. The chance of a student who declared chemical engineering as a major in their first semester receiving a degree was 0.46 ($95\% CI = [0.42, 0.50]$), which was calculated using the emmeans package in R [33]. Figure 2 showed that there is a large attrition of male students into other engineering majors or out of the university entirely after the first year. Women students were much more likely to switch to a non-STEM major or a non-engineering STEM major, and there was a large outflow after the first and second semesters. Ultimately, women chemical engineering majors had a 42% chance of receiving a chemical engineering degree, whereas male majors had a 48% chance.

We used a mediation analysis to explore potential explanations for the gender differences in chemical engineering graduation rates among chemical engineering majors and determine at which point within the university system women were leaving chemical engineering at higher rates than men (see Figure 3). We tested several partial and full mediation models exploring the relationship between gender and first-year GPA, ACT scores, and graduation rates. Ultimately, the best fitting model was the one illustrated in Figure 3 below. We found that the only two factors in our data set that predicted the probability of receiving a chemical engineering degree were first-year GPA and grade in MEB. Each standard deviation increase (0.76 grade points) in first-year GPA made a student 1.4 times more likely to receive a chemical engineering degree, while each standard deviation increase in MEB grade (1.3 grade points) made a student 2.4 times more likely receive a chemical engineering degree.

We found no gender disparities in ACT score or first-year GPA among chemical engineering majors. This suggests that high school academic preparation or challenges in the first-year engineering experience do not explain the gender disparities seen in degree attainment. Controlling for ACT score and first-year GPA, we found that women students score 0.21 standard

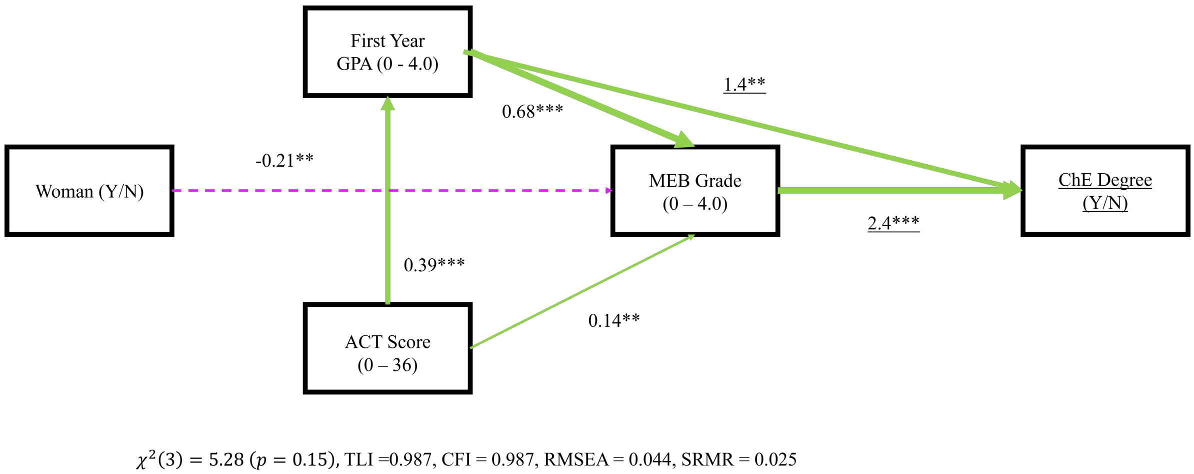


**Figure 3:** SEM model indicating how academic achievement mediates gender gaps in chemical engineering degree attainment (N = 605). Links in green represent positive associations and links in magenta (which are also dashed) represent negative associations. All coefficients to the left of MEB grade are correlation coefficients, and the coefficients going from first year GPA and MEB grade to chemical engineering degree are odds ratios (and are underlined). This figure only visualizes statistically significant relationships. ** p ¡ 0.01, *** p ¡ 0.001. The thickness of the line represents the relative size of the effect.

deviations lower in MEB than male students. The average grade on a 4.0 scale for male students was 2.55, while for women students it was 2.24. As this university does not assign partial letter grades, we converted this to probability of getting a C or below. We found that male students had a 44% chance of getting a grade of C or lower, while for women students it was a 57% chance—this again controlled for equivalent high school preparation and first-year college success. As there was no gender disparity in degree attainment after controlling for MEB grade, this indicates that the gender disparity in degree attainment among students initially majoring in chemical engineering is entirely explained by performance in MEB.

## DISCUSSION

We found that men were much more likely than women to receive chemical engineering degrees at this university. While the gap in graduation rates is mostly due to a gap in initial intent to pursue in studying chemical engineering, we find that there is a statistically significant gender gap even when controlling for initial interest in chemical engineering. Women are more likely to depart chemical engineering for non-engineering STEM majors or non-STEM majors rather than select a different engineering major or leave the university without a degree. Our mediation analysis explored this gender gap in chemical engineering degree attainment further. We found that the primary factors predicting chemical engineering degree attainment were first-year GPA and grade in MEB. We found that MEB grades were the primary mediator of the gender gap in chemical engineering degree attainment among students who initially intended to major in chemical engineering.

The analysis suggests that the gender disparity in chemical engineering degree attainment is both a problem of aspiration and attrition, but 90% of the disparity is explained by the gender gap in chemical engineering aspirations. Women's pre-college experiences are discouraging them from pursuing chemical engineering. The literature from STEM education more broadly suggests many possible explanations for this. Early family influences [34, 35], positive experiences in STEM courses and/or STEM outreach programs [35, 36], and prior achievements in STEM [37, 38] are all factors that contribute to the decision to pursue a STEM degree, and women are less likely than men to receive encouragement to pursue STEM degrees [39, 40, 41]. Additionally, there is a documented lack of women role models in many STEM disciplines [14, 42], which may contribute to a difficulty for women to see themselves as scientists and engineers [43, 44]. Outreach programs focused on encouraging women in their secondary education to study chemical engineering (perhaps led by women chemical engineers) could provide both role models and greater encouragement to pursue chemical engineering.

While the bulk of the gap in degree attainment is due to gaps in aspiration, it would be unethical and unwise to ignore the disproportionate attrition of women from chemical engineering early in their college careers. This problem has two pieces: women's experiences in the first-year engineering program and their experiences in MEB. Women perform just as well as men in their first-year engineering coursework, yet they are more likely to leave engineering during this first year (Figure 2). Their reasons for departure could be due to either performance challenges or climate in the classroom. There is prior literature to suggest that, while women overall tend to have similar GPAs to men, they may receive lower grades in STEM courses like physics 1 [15]. The literature suggests that these gaps are primarily due to differences in high school STEM preparation, with women less likely to take more advanced STEM courses prior to entering the university [45]. Because first-year GPA is a crude measure, we cannot tell whether there are gender gaps in first-year STEM GPA that might mediate the gender gap in degree attainment. However, other analyses conducted at this university do not provide any evidence to suggest women receive lower grades in introductory STEM courses [26]. This would suggest that performance challenges in the first-year STEM courses are not driving women out of chemical engineering, pointing to other factors like chilly classroom climate.

There are numerous reports in the educational literature detailing how women in STEM experience microaggressions, lack of recognition of their abilities, and instances of sexual harassment and assault [12]. Indeed, in our own conversations with women in other STEM departments, discrimination from their male peers and professors is a highly cited concern.

Even for women who persist through the first-year engineering program, equity issues exist once they get to MEB. Even though women perform just as well as men academically in the first year, they receive lower grades in MEB. One of the strongest predictors of future academic performance is prior academic performance. Thus, it seems unlikely that women suddenly encountered material in MEB for which they were less prepared than their male counterparts, given that their first-year GPAs were similar. One potential explanation for the gender gap in MEB grades could be an overreliance on high stakes exams. [46] showed that courses with high-stakes exams systematically disadvantaged women in biology. Other explanations could include classroom culture such as men dominating classroom conversations or discounting the contributions of women in study groups [47]. Li & Singh (2022) showed that, in physics, whether women feel that their instructors perceive them as physics people has a significant impact on self-efficacy and sense of belonging, both of which are hypothesized to affect persistence [48].

Qualitative studies investigating women's reasons for deciding to leave chemical engineering would provide greater detail as to the issues that they face in this discipline specifically. Talking About Leaving Revisited [9] investigates reasons for attrition from STEM more broadly but doesn't account for potential transitions between STEM disciplines like we observe in this data set. There are also further quantitative studies that could be conducted. For example, the standard first-year engineering curriculum consists of chemistry, calculus, and physics courses. We can perform similar analyses on these individual courses to determine if there are specific courses that are contributing more to women's decision to leave engineering. We defer this to a future investigation due to the limitations of space in conference proceedings.

We wish to also provide potential guidance to instructors as to potential methods to improve women's grades in MEB, and thereby improve degree attainment. Research has shown that women are more negatively impacted by test anxiety on high-stakes summative exams [49]. Thus, a refocus of assessment practices on lower-stakes exams (e.g., by allowing test corrections) or projects is one way that could potentially benefit women while still providing meaningful learning for all students.

## LIMITATIONS

One limitation of this study is that we only analyzed data from a single institution. We hope that this analysis will encourage other chemical engineering departments to examine demographic patterns in student recruitment and attrition. A more substantial limitation is the reliance on binary measures of gender kept in institutional records. These data keeping practices erase transgender and nonbinary students, who face harassment and increased attrition from STEM professions [50, 51]. We are currently collecting continuous measures of gender identity and expression in introductory courses to better understand the role of gender in STEM persistence.

## CONCLUSIONS

In this quantitative study of chemical engineering persistence, we found that women were less likely to major in chemical engineering than men but also that they were less likely to receive chemical engineering degrees even after accounting for initial intent. We found that women primarily left chemical engineering for non-engineering STEM majors or non-STEM majors. The primary mediator of the gender gap in chemical engineering degree attainment was performance in MEB. This study indicates that chemical engineering departments should be aware of issues of both recruitment and retention of women in the discipline. It is essential that this work is done in tandem, as it would be unethical to recruit women into an environment that is known to systemically disadvantage them. Though chemical engineering has made great strides in gender parity compared to other engineering disciplines, the results of this study reinforce the idea that diversity is not the same as equity.

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