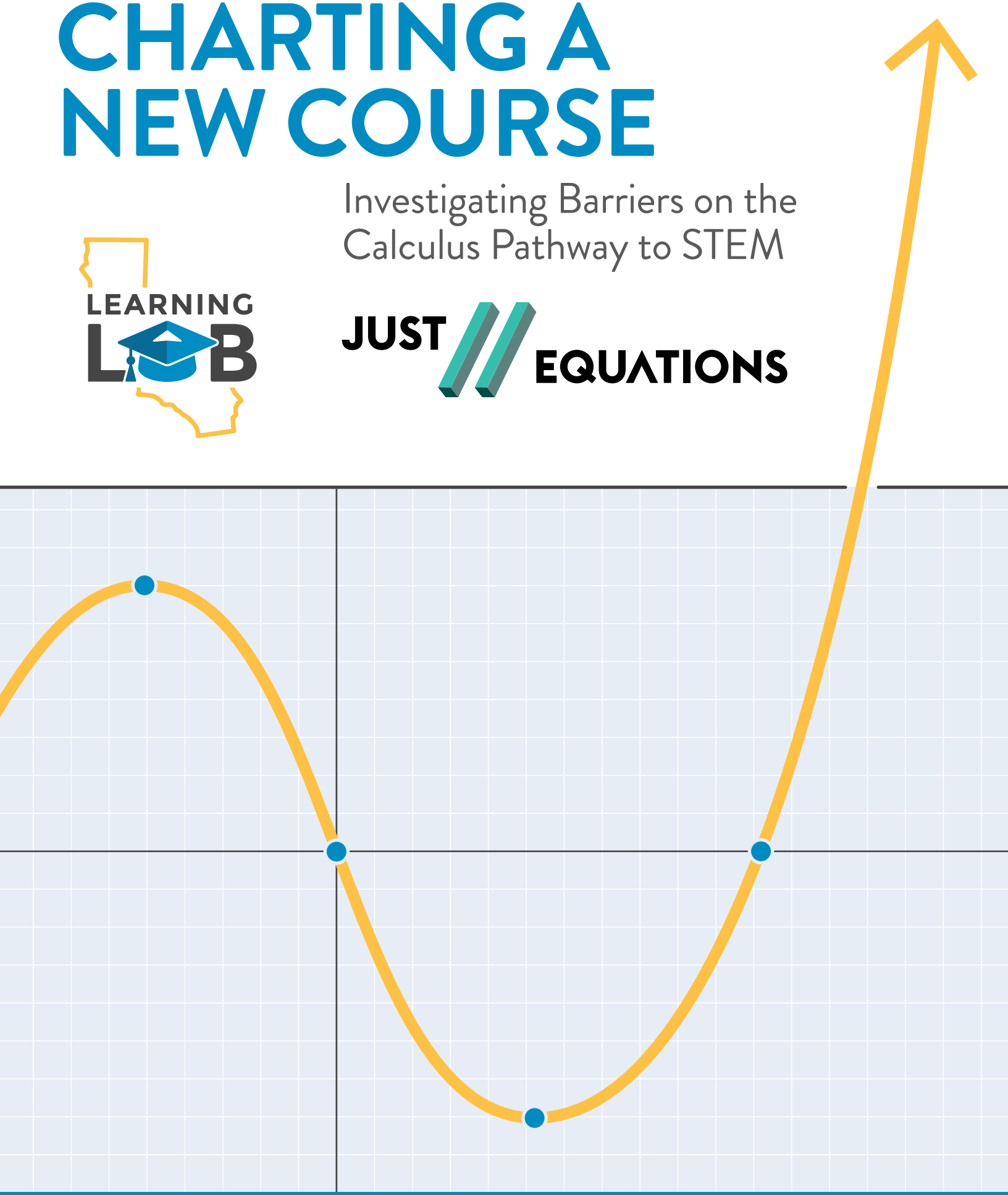
DECEMBER 2021

CHARTING A NEW COURSE

Investigating Barriers on the Calculus Pathway to STEM

LEARNING LAB

JUST EQUATIONS



Acknowledgments

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About Learning Lab

The California Education Learning Lab is a state-funded grantmaking organization charged with improving learning outcomes and closing equity gaps across California's public higher education segments. An initiative of the California Governor's Office of Planning and Research administered in partnership with the Foundation for California Community Colleges, Learning Lab supports innovation in higher education pedagogy through intersegmental grants to California's public colleges and universities. Funded projects leverage technology tools and the science of human learning to create better online and hybrid learning environments, and empower faculty to find pedagogical solutions that work best for California's diverse student population.

About Just Equations

Just Equations is a California-based policy institute whose mission is to reconceptualize the role of mathematics in ensuring educational equity. An independent resource on math-related policies in the transition from high school to and through college, Just Equations advances evidence-based strategies to ensure that all students have the quantitative foundation they need to succeed in college and beyond.

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About This Report

College Calculus serves as a cornerstone to a degree in STEM (science, technology, engineering, and mathematics). At the same time, Calculus courses and requirements can function as barriers to STEM majors and careers, with significant proportions of students leaving a STEM path after taking Calculus. This pattern is most pronounced among Black and Latinx students and others who are historically underrepresented in college.

A robust and diverse STEM pipeline is central to ensuring equitable opportunities for the next generation of Californians as well as a thriving economy. To explore the reasons students leave Calculus sequences and STEM majors, and shed light on strategies for addressing those barriers, the California Education Learning Lab commissioned Just Equations to synthesize existing knowledge from California and beyond.

Contents

This report was commissioned in conjunction with *Learning Lab's Grand Challenge: Overcoming the Calculus Barrier to STEM Success*—which is supporting multiple projects spearheaded by intersegmental faculty teams to reconceptualize the role of and approach to Calculus in students' first-year introductory STEM experiences—as well as a new funding opportunity, *Seeding Strategies to Close the Calculus Equity Gap.* The intention in disseminating this report is to inform those efforts and others around the state to strengthen undergraduate Calculus pathways and ensure that they enhance access to STEM majors and careers, particularly for populations that have traditionally been excluded from STEM. While the report highlights the influential role of students' K–12 math preparation, its focus is on how postsecondary institutions can respond to this situation. It is not drawing conclusions about how K–12 schools should prepare students for college math or STEM and should not be used to prescribe K–12 curricular or other approaches, which are beyond the scope of this report.

The report consists of two parts:

Part One

An overview of research from across the country on factors influencing Calculus outcomes at two- and four-year postsecondary institutions. Written by Just Equations, the narrative is based on a synthesis of roughly 200 sources (including books, book chapters, journal articles, research reports, and other online and print sources) and interviews with 13 experts inside and outside of California. (See p. 37 for full list of interviewees.) Part One has three subsections:

- **K–12 Preparation Shapes Postsecondary Opportunities** highlights some of the factors shaping students' math experiences before college.
- **Undergraduate Calculus: Bridge and Barrier to STEM Success** examines the reasons Calculus courses can serve as obstacles to STEM degree completion, particularly for minoritized students.
- **Promising Directions for Strengthening Undergraduate Calculus Experiences and Outcomes** highlights the range of strategies for improving Calculus as a gateway to STEM and the available evidence on those strategies.

Part Two

An analysis of data provided to Learning Lab by California's three public higher education systems. The analysis focuses on six-year outcomes of students starting at the California Community Colleges, the California State University, and the University of California systems in the 2014–15 academic year, as well as Calculus enrollment and success patterns for fall 2019 (see Technical Appendix for further details about the data and methodology). Institutional researchers with the three systems, as well as researchers at the California Policy Lab and the Foundation for California Community Colleges, performed the statistical analyses, and the Just Equations team synthesized the data.

Part One: Understanding and Responding to Calculus as a STEM Gatekeeper

"Where you stand in Calculus right now has nothing to do with who you really are. Who you really are is a mathematician. It's not your fault that you're behind. And it's not your destiny."

— Message from a teaching assistant to a first-year Calculus student (Tough, 2021, Chapter 8)[1]

The evidence is clear that Calculus functions as a critical gatekeeper for U.S. students seeking to enter STEM (science, technology, engineering, and mathematics) majors and careers. Large proportions of Calculus students don't complete their math sequences or stay in STEM (Freeman et al., 2014; Rasmussen & Ellis, 2013; Seymour et al., 2019). Indeed, Calculus' reputation as a weed-out course is well deserved (Chen, 2013; Leyva, McNeill et al., 2021), as it is a key reason that women and students from minoritized backgrounds represent 70 percent of college students but only 45 percent of students earning STEM degrees (Gates et al., 2012). With the possible exception of Introductory Chemistry, courses in Calculus bear more responsibility than any other subject for undergraduates leaving the STEM path (Weston et al., 2019).[2]

Students who switch out of STEM majors after taking Calculus may still end up graduating from college. And, on an individual basis, changing majors could even be a good choice for some students. Furthermore, though attrition exists across academic majors (Chen, 2013), the demographics of students who exit STEM pathways raise serious concerns about the role Calculus plays in winnowing out graduates in STEM. Among students entering postsecondary institutions with an interest in STEM, 42 percent finish with a STEM degree within six years. But just 29 percent of Latinx students and 22 percent of Black students do so (Eagan et al., 2014). And for some of them, experiences in Calculus may lead to their completing no degree, a more common outcome among STEM leavers than students who leave non-STEM fields (Chen, 2013; Riegle-Crumb et al., 2019).

These racial and gender disparities underscore the inequitable opportunities faced by so many college students in California and nationwide. On average, graduates in STEM jobs earn more over their lifetimes than students with degrees in other areas (Carnevale et al., 2011), so barriers to these careers constitute obstacles to social mobility. Furthermore, the gaps represent a significant loss of potential to the STEM professions themselves, given that demand for STEM skills is also growing. As algorithms and technologies play an increasingly central—and potentially biased—role in our individual, economic, and civic well-being (Benjamin, 2019), the nation needs a deeper and more diverse pool of talent entering these fields.

These challenges are not new. Initiatives to reform Calculus began in the 1990s but saw only modest achievements, in part because of their relatively narrow focus on what was taught, without addressing how it was taught (Bressoud, August 2019). The failure of existing Calculus courses to serve today's students is often visible to students: Some recent campus-level Calculus reforms have been catalyzed by controversies such as complaints in a student newspaper, negative course evaluations, and—at one university—a boycott of the math department (O'Sullivan et al., 2021; Rasmussen et al., 2021). That crises were needed to spur change highlights the need for proactive strategies to improve the role of college Calculus courses in fostering student success in mathematics and in college more generally.

To understand how the weed-out system operates and what can be done to change it requires an examination of how students experience math courses in K–12 schools and throughout their college careers. One throughline is the prominence of exclusionary attitudes that feed stereotypes about who can and cannot succeed in math. Faculty in the STEM disciplines tend to adhere to a "meritocratic narrative" in which students are "either capable or not capable of college-level STEM coursework and there [is] not much that faculty could do to change this" (Thiry, 2019b, p. 402). Rather than addressing how classroom or institutional structures may contribute to inequitable outcomes—or how the narrative itself reinforces those inequities—the notion of "individual effort and intelligence absolves faculty and institutions of any responsibility for student learning and success," according to a seminal study of why students leave math and other STEM disciplines (p. 432).

The underlying biases on the part of instructors as well as counselors and advisors can contribute to rationing access to high-quality instruction and advanced courses. They also can communicate to women and minoritized students—even those who do make it into advanced math courses—that they may not belong in STEM. In fact, research has pointed to the important role that a sense of belonging and math identity play in students' future success (Berry et al., 2014; Cheryan et al., 2015; Hyde & Mertz, 2009; Leyva, McNeill et al., 2021; Leyva, Quea et al., 2021).

On Methodology

In examining strategies for improving undergraduate Calculus courses, the report places a priority on evidence for strategies that increase student success—particularly in terms of persistence and success in the subsequent math course, or in STEM in general. Some of the literature does not include such quantitative evidence, but there are several major studies that do. These include the Mathematical Association of America (MAA) studies beginning in 2010[3] and resulting in numerous publications and journal articles, as well as the 2019 volume, *Talking About Leaving Revisited: Persistence, Relocation and Loss in Undergraduate STEM Education* (Seymour et al., 2019).

The report also pays attention to strategies that can improve outcomes for students who are underrepresented in STEM fields, particularly Black and Latinx students and, in some cases, women. Some of the research examined for this report addressed math outcomes for minoritized students, but far more of the literature on equity was about STEM fields in general. A forthcoming MAA volume to examine diversity, equity, and inclusion in college Calculus will be an important contribution to the field (Voigt, Hagman et al., in press).

Overall, there is stronger evidence documenting ways in which Calculus is not working for many students than there is evidence behind strategies to address those barriers. That said, the research on some strategies described in this report (e.g., active learning instruction) is quite robust, while the research on others (e.g., evidence for effective professional learning approaches), is less so.

When the report cites the practices of specific institutions or projects, those practices are examples to illustrate strategies that show promise. The report makes no claim that such examples are the only or best ones available, as the analysis for this report did not include any independent empirical research to validate findings or compare strategies across institutions.

Terminology

CALCULUS — The report's focus is on the first course in the Calculus sequence, typically called Calculus I. Unless specified otherwise—e.g., Calculus II—references to Calculus courses indicate this first course.

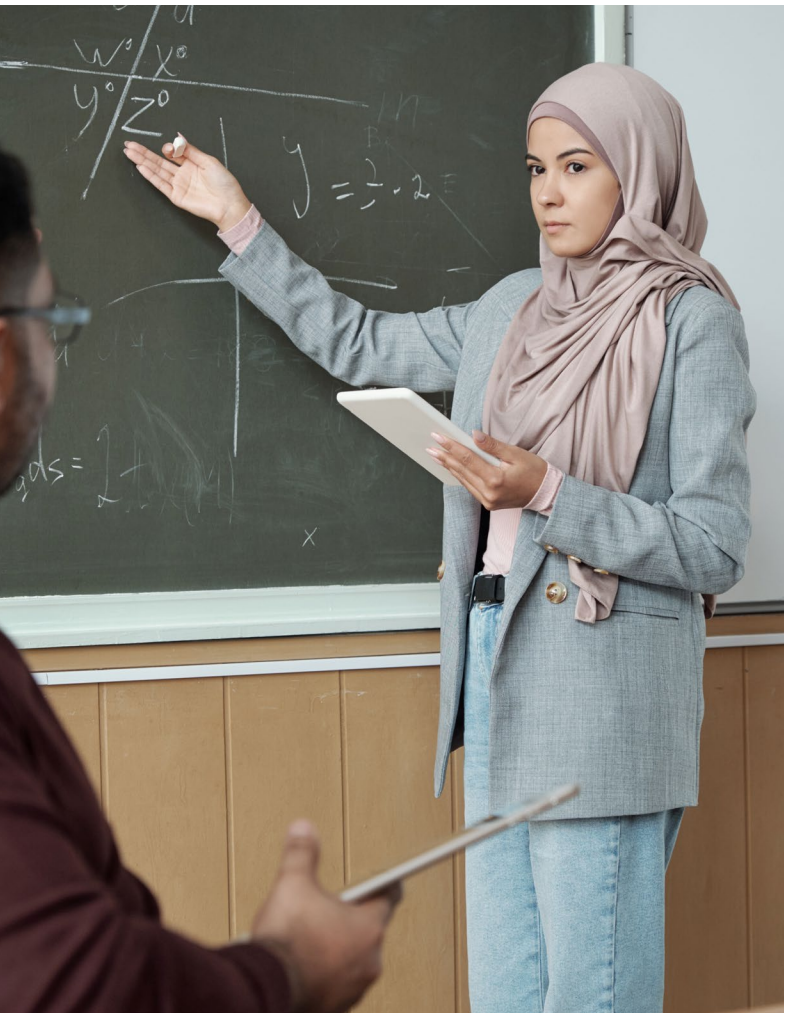
MINORITIZED — This term is sometimes used to refer to students who are underrepresented in STEM fields. The term "historically excluded," also used, reflects the literature on STEM participation. Different terms were used by different sources. Most commonly the research focuses on Black and/or Latinx students. There is less research on college STEM outcomes for other underrepresented groups, such as indigenous people, English learners, and disabled students. But there is a significant amount of literature on women's STEM outcomes, and the report generally specifies when referencing women.

PERSISTENCE — The report uses this term to describe continuation in a college course sequence or major, a common usage in the higher education literature. In other contexts, "persistence" may imply student characteristics such as perseverance, tenacity, or grit (suggesting a deficit framing of those students who do not persist). The report's focus is on how institutions can better support students to progress through their programs.

STUDENT OUTCOMES — The term "success" is used at times in a generic sense, but the term is also used in the more technical sense of receiving an A, B, or C in a course or successfully completing a sequence with a C or higher. "Course completion" has the same definition. The term "DFW" as a category refers to students who earn a D or F or withdraw from a course—i.e., don't succeed.

Stereotype threat and math anxiety are contributing factors to the pattern of lower performance in mathematics classes and tests among female and minoritized students, and both interfere with students' working memory (Beasley & Fisher, 2012; Maloney et al., 2013; Riegle-Crumb et al., 2019). However, it's important to recognize that such conditions can represent the cognitive effects of teaching practices as well as instructor attitudes and biases that inhibit students' sense of belonging in math class, rather than construe them as deficits or maladaptations of students (McCloud, 2016). Insights about stereotype threat and math anxiety can help educators modify their teaching in ways that best support students in developing math identities and capacities.

Whether in the classroom, the counselor's office, or the testing center, hierarchical assumptions can be cloaked in "seemingly neutral practices" that, in fact, serve to exclude some students based on assumptions others have about them, or on students' own level of math confidence (Ellis et al., 2016; Leyva, McNeill et al., 2021, p. 808). Feelings of isolation have been strongly linked to students' choosing to leave STEM (Thiry, 2019b). The knowledge that such feelings were most prevalent among students entering college with low math scores (Holland, 2019) demonstrates that the story about Calculus and STEM outcomes has its roots in the K–12 years.



K–12 Preparation Shapes Postsecondary Opportunities

Differences in students' K–12 experiences play a major role in who can access and succeed in college Calculus. Misalignment across educational systems as well as differential access to high-quality instruction contribute to varying levels of preparedness among college-bound students. While some K–12 students are presented with rich math learning experiences, others who may be interested in the sciences lack access to the resources necessary to prepare for Calculus or a STEM major. These opportunities can vary by school—and by demographic characteristics such as wealth, race, and gender. In California, for example, among high school seniors, Asian Americans were four times as likely as Black students and three times as likely as Latinx students to be enrolled in an AP math course between 2016 and 2018 (Asim et al., 2019).

For entry to competitive universities, taking Calculus in high school is often seen as a rite of passage, particularly for students pursuing STEM majors. Even though leading math societies caution against the "race to Calculus" (Bressoud et al., 2017), Calculus in high school is nevertheless the de facto "dominant route" to Calculus at research universities (Bressoud, 2021, p. 530). However, practices such as tracking in middle school and high school (National Council of Teachers of Mathematics, 2018; Oakes et al., 1990) place advanced high school math courses such as Calculus out of reach for some college-bound students. "Women, students of color, and first-generation college students … were most likely to report that they had been placed into a low-ability math group or experienced a general lack of encouragement in STEM in their early schooling," according to a major study exploring why students leave STEM majors (Thiry, 2019a, p. 141).

Nearly half of high schools in the U.S. do not offer Advanced Placement Calculus (Hayes, 2019, p. 17). And among AP Calculus exams earning a 3 or higher, the proportion taken by Black students has remained stagnant at 2 percent for the past 20 years, as Black students remain less likely to take the test than students of other races (Bressoud, 2021, p. 529). Because efforts to expand access to accelerated math tracks have not enhanced equity (Loveless, 2008), some experts recommend delaying math acceleration until high school, as San Francisco has done (Barnes & Torres, 2018). In addition, the California Math Placement Act of 2015 was intended to create a "fair, transparent, and objective" ninth-grade placement process to reduce misplacement—which had been experienced in particular by Black and Latinx students (Gao & Adan, 2016)—but its effects on access to advanced courses have yet to be analyzed.

A parallel dynamic plays out for students who ultimately attend community colleges or broader-access state universities: Though high school Calculus is not an entry barrier at these institutions, students of color and other

marginalized students have traditionally been more likely to be assigned to college remedial courses, in part due to the limitations of their K–12 preparation. In California, for example, before the systems began phasing out remedial classes, 85 percent of Black and Latinx students required remedial math courses at the state's community colleges (Burdman et al., 2018), while the corresponding percentages for the California State University system were 48 percent and 37 percent (Burdman, February 2017). The recent reforms have reduced (CCC) or eliminated (CSU) remedial enrollments but not fully removed equity gaps in math success (Bracco et al., 2021; Mejia et al., 2020).

Gender stereotypes in K–12 schools also limit female students' confidence as well as access to STEM opportunities. As early as kindergarten, teachers score girls lower in math proficiency than boys with similar achievement (Cimpian et al., 2016). In a related finding, strong negative math attitudes and low confidence are observed in girls as early as first grade (Cvencek et al., 2021). These gender differences in math class experiences may help explain why, for more than 50 years, males have consistently outperformed females on the mathematics portion of the SAT (College Board, 2010–2018; Rosner, 2011).

Similarly, Black and Latinx students' achievement in the classroom does not translate to aggregate performance on norm-referenced tests.[4] Among applicants to the University of California system, Black and Latinx students make up 12 percent of students in the top high school GPA decile, but only 5 percent of those in the top SAT decile (Geiser, 2017). Because SAT and ACT scores are strongly correlated with demographic factors such as race, income, and parental education (Geiser, 2015), their use may serve as another obstacle for disadvantaged students in accessing a STEM major. Equity concerns have led some institutions to reconsider their reliance on tests, and the tests' recent elimination by the UC system may present opportunities to study whether test-free admissions regimes support greater diversity in STEM disciplines.

Differing definitions of "college readiness" between and within the K–12 and postsecondary systems can also contribute to uneven preparation among entering college students. For example, some states specify which math courses are required for high school graduation, and others leave the decision up to individual districts (Achieve, 2020). For those states with specific requirements, the highest math course required can vary from Algebra I or Geometry to Algebra II or Integrated Math III.[5] In California, where the state requires only two years of math for graduation, the majority of districts require three or four (Gao, 2021). These disparities influence who can attend universities, since both of the state's public systems require a minimum of three years of math and recommend four. The discrepancies also place some students at a disadvantage in entering a STEM major, forcing those without sufficient preparation to take lower-level courses to catch up or struggle in courses alongside students with stronger K–12 preparation.

Besides course access issues, math educators also trace challenges in Calculus to the mathematical understandings students form before college (Rinaldi and Thompson interviews). "Student difficulties in Calculus are due to the meanings and ways of thinking at the root of variable, function, and rate of change students develop in elementary, middle, and early high school," note Thompson and Harel (2021, p. 509). For example, students tend to see letters as standing for unknown numbers, rather than as variables whose values change.

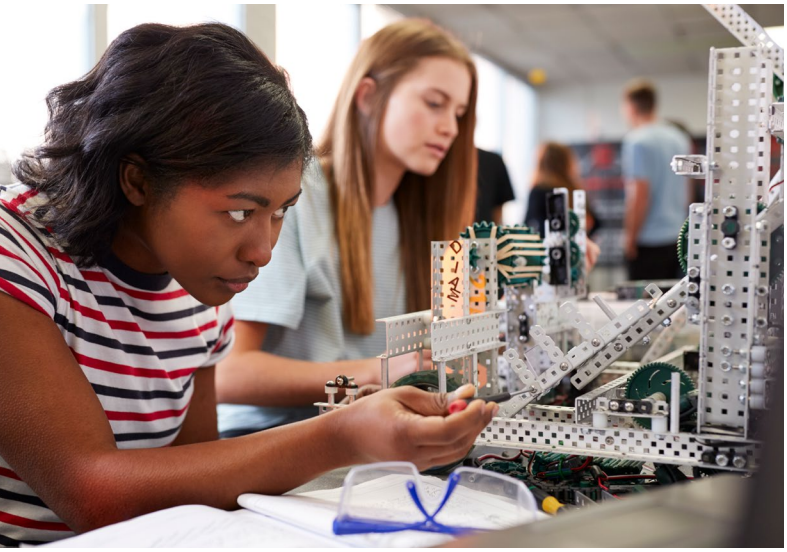
This issue is compounded by the pressure many students face to take Calculus in high school. "Too many students are moving too fast through preliminary courses so that they can get calculus onto their high school transcripts," noted leading math scholars who contributed to a statement from leading math societies[6] urging caution around high school Calculus. "The result is that, even if they are able to pass high school calculus, they have established an inadequate foundation on which to build the mathematical knowledge required for a STEM career. Nothing demonstrates this more eloquently than the fact that, from the high school class of 1992, one-third of those who took Calculus in high school then enrolled in Precalculus when they got to college, and, from the high school class of 2004, one in six of those who passed Calculus in high school then took remedial mathematics in college" (Bressoud et al., 2017, p. 77).

The Common Core math standards—adopted by 41 states, the District of Columbia, and four territories—and other recent efforts to reframe math concepts for students and teachers have sought to overcome these limitations of K–12 math instruction. These include an emphasis on modeling with functions, as well as incorporation of mathematical "practices" in addition to math topics. However, K–12 reform efforts have yet to fully address these conceptual roots of students' math learning, especially with respect to teacher professional development (Thompson interview).

Other K–12 strategies to address math preparation could include diversifying the math teacher workforce (Carver-Thomas, 2018) and adopting culturally responsive curricula (Miller-Cotto & Lewis, 2020). However, some promising solutions—such as expanding dual-enrollment opportunities—ultimately require strengthening alignment and collaboration with postsecondary institutions.

Undergraduate Calculus: Bridge and Barrier to STEM Success

Though students enter college with wide disparities in their prior preparation, that alone doesn't explain differences in their progression in math courses and STEM majors (Riegle-Crumb et al., 2019). Before examining ways of improving the Calculus experience, it is important to understand the postsecondary policies and practices that may contribute to Calculus' gatekeeping role, particularly for students traditionally excluded from STEM. The weed-out phenomenon is often more a function of how students experience undergraduate Calculus classes than a reflection of their academic ability (Tough, Chapter 8, 2021). In surveys of Calculus students across the country, both enjoyment of math and confidence in math ability dropped sharply from the beginning to the end of the term (Sonnert & Sadler, 2015).



The declines in math attitudes were greatest for women, irrespective of their actual performance in the class (Ellis et al., 2016; Sonnert & Sadler, 2015). Among institution types, students at research universities exhibited the largest drops in their attitudes toward math, while community college students reported the greatest "confidence, joy, and desire to continue" (Bressoud et al., 2013). However, it is important to remember that students enrolling in Calculus courses are a select group at community colleges, given that the vast majority of students traditionally place into sequences of prerequisite courses that often result in not completing a degree or (when remedial prerequisites are involved) even taking a college-level math course (Bailey et al., 2010).

Numerous factors within the control of postsecondary institutions appear to contribute to these experiences, including placement practices, curricular decisions, classroom instruction, and assessment and grading practices. As discussed below, many of these factors are tied to traditional assumptions and biases about how math learning is manifested.

PLACEMENT, ARTICULATION, AND THE PATHWAY TO CALCULUS

There are three main challenges with how students are placed in undergraduate Calculus. First, about two-thirds of students who take a college Calculus course at research universities have been exposed to Calculus, often AP Calculus, during high school (Bressoud, 2015a). Most students' AP Calculus experiences don't serve the initial purpose of AP (to prepare them for a more advanced math course), at least at research universities, where nearly a third of AP Calculus course takers end up repeating the course in college, and a similar number take a lower-level course in the sequence (Bressoud, 2017a, p. 5). As a result, "most college Calculus I classes in the United States contain students who are completely new to the terminology and concepts of Calculus and students who have already demonstrated proficiency in all of the topics to be covered in that course," notes Bressoud (2021, p. 521). Because of racially disparate access to Calculus in high school, minoritized students, particularly Black students, are most likely to be at a disadvantage because they are encountering Calculus for the first time (Tough, 2021), all the more so when A's and B's are rationed.

Secondly, many colleges use math tests to determine students' placement level, but the use of standardized tests for placement purposes has limited validity. Students' high school records are more predictive of their college performance, including in math, according to studies of remedial math placement (Scott-Clayton et al., 2014) and of college admissions (Geiser, 2017). Placing less-prepared students into lower-level courses may create the illusion of success, to the extent that it boosts pass rates in the higher-level course, because only more prepared students can enroll.

However, that perception obscures the attrition that occurs when students are placed in longer sequences of courses. Research on remedial sequences has shown that many students who pass a course end up not enrolling in the next course in the sequence, ultimately reducing the number of students who complete a required college-level course (Bailey et al., 2010). Furthermore, it remains unclear whether the content of Intermediate Algebra, a common remedial course similar to high school Algebra II, actually prepares students for subsequent math courses. One analysis found that Intermediate Algebra students who demonstrated mastery on tests were no more likely to pass subsequent college math classes than students who passed the course with less mastery (Quarles & Davis, 2017). Another concluded that students who skipped Algebra II in high school fared better in their math sequences, including STEM sequences, if they avoided taking the remedial version at a community college (Hayward, 2021).

Similar patterns can be observed in the Calculus sequence: Significant proportions of students, particularly racially minoritized students, are placed into Precalculus, which can be a detour out of STEM. According to a 2015 study, more than one-quarter of students at master's degree–granting

institutions and more than one-half at two-year colleges take Precalculus in college (Bressoud, 2015a). Students who take Precalculus are more likely to leave STEM. Three studies spanning universities in four states found that a third or more of students who were successful[7] in Precalculus nevertheless did not enroll in Calculus (Hsu & Bressoud, 2015). At Arizona State University, for example, 43 percent of students with declared STEM majors who earned an A in Precalculus opted out of Calculus, apparently forgoing a STEM path (Thompson et al., 2007, p. 4). These effects are most pronounced in the physical and life sciences: Nearly two-thirds of students in these majors did not continue to Calculus after passing Precalculus with a C or higher (p. 27).

Plus, taking college Precalculus doesn't appear to improve students' performance in Calculus and may lower it: In a 2014 quasi-experimental study based on more than 10,000 student records, students with weaker high school preparation had a slight but not statistically significant benefit from Precalculus, and better-prepared students scored six points lower in Calculus if they began the sequence in Precalculus (Sonnert & Sadler, 2014).

Students placed into remedial algebra courses intended to prepare students for Calculus are even less likely to reach Calculus, as Hsu and Bressoud note:

> The policy should be such that it would direct those students toward the sequence that will enable them to succeed when they get to Calculus I. Implicit in this process is the assumption that those who are directed toward Precalculus or other remediation find in the course effective preparation for Calculus I. Too often, this is not the case. … Restricting student enrollment in Calculus I may result in students never passing Calculus I who otherwise might have. Furthermore, there is a disproportionately frequent placement of underrepresented minorities into remedial and Precalculus courses. … The meager gains from Precalculus do not appear to offset the considerable risk that students directed to Precalculus will not persist to Calculus (Hsu & Bressoud, 2015, pp. 59-60).

The authors underscore the importance of improving the quality of Precalculus programs. While there isn't conclusive evidence to explain the limited effectiveness of Precalculus, interviewees suggested that likely reasons include (1) damage to students' self-esteem due to being placed into Precalculus, and (2) the fact that the course consists of challenging but decontextualized material that they may have confronted in high school and that, ultimately, is boring to students and faculty alike (Bressoud, Kirwan interviews). Similar critiques exist for remedial algebra courses. Self-placement is not the answer, because evidence has shown that, when offered a chance to place themselves, women and minoritized students are more likely to choose lower levels in math than white and Asian males with similar academic preparation (Fong & Melguizo, 2016; Kosiewicz & Ngo, 2019).

Lastly, there is preliminary evidence that articulation problems could subject students who transfer from community colleges to repeating the course after transferring to a four-year university. An examination, in two unnamed states, of excess credits on the transcripts of transfer students earning bachelor's degrees found that taking a 100-level math course (which corresponds to Calculus or other general education math courses such as Statistics) after transferring is associated with excess credits (Fink et al., 2018). In Washington state, nearly 30 percent of community college students who transfer with Precalculus on their transcript take the course again at a public university. Similarly, 42 percent of Calculus I completers[8] and 26 percent of Calculus II completers who transfer repeat Calculus (Davis et al., 2018, Table 10).

Researchers and practitioners in California have reported that some community college students who transfer to CSU campuses have been required to repeat Calculus courses, but more research is needed to understand the prevalence of these patterns in California and other states and how they connect to system and campus policies.[9]

CURRICULUM

The standard Calculus curriculum has changed little in the past 50 years (Teague, 2017). Calculus I and II courses primarily cover four content areas: (1) limits and continuity, (2) derivatives, (3) integrals, and (4) sequences and series. Many also begin with a review of functions (Burn & Mesa, 2015). The course was initially designed for engineering and physical sciences majors, who represent only one-third of Calculus enrollment (Bressoud et al., 2013). Calculus is less well aligned with other majors for which it is frequently required, particularly biology and computer science.

"For life science students … the quantitative and computational skills essential to modern biological research and biotechnology typically are not taught in first-year Calculus courses, and consequently students often view these classes as unpleasant and irrelevant hurdles to conquer. These challenges are particularly problematic for students from disadvantaged backgrounds or social-identity groups historically underrepresented in STEM," noted a study at UCLA. The study also found that, in surveys, life sciences students at UCLA demonstrated "low levels of satisfaction" with their calculus sequences" (O'Leary et al., 2021, pp. 1-3).

A statement by biology faculty convened by the MAA two decades ago concluded that "statistics, modeling and graphical representation should take priority" over Calculus for biology students (Ganter & Barker, 2004, p. 15). Similarly, computer science faculty who the MAA convened felt that reforms to orient Calculus toward problem-solving were beneficial but decried the "mathematics community's inattention to discrete math, [which has] forced many

computer science departments to assimilate and teach these topics themselves" (p. 42). For computer science students, discrete math—including an introduction to proof techniques—should come before Calculus, according to the MAA report, which also mentioned linear algebra as another course for computer science students that should be taught in a less theoretical fashion.

Calculus courses designed for students in disciplines such as business, social sciences, and life sciences appear to be multiplying. In a 2015 survey of math departments, "non-mainstream" courses accounted for 91,000 out of 346,000 Calculus enrollments at universities, and 26,000 of 92,000 enrollments at two-year colleges (Blair et al., 2018, p. 138, p. 164). Interestingly, those levels represent a decline at universities from five years earlier but an increase at community colleges, which might reflect the fact that such offerings may be newer at two-year colleges. However, the bulk of research on Calculus pertains to the mainstream classes that prepare students to major in mathematics, engineering, and physical sciences. The existence of the other courses is a clear indication that traditional Calculus is not meeting the needs of students in other disciplines, but more research is needed about these courses and their effectiveness.

CLASSROOM INSTRUCTION

Instruction plays a critical role in the experiences of students in Calculus courses (Ellis et al., 2014; Leyva, Quea et al., 2021; Seymour et al., 2019). Because Calculus is a common prerequisite for STEM majors, paying close attention to how Calculus instruction is enacted can support students in persisting through STEM majors (Rasmussen & Ellis, 2013). Direct instruction, also known as lecture-based instruction, is a common method of content delivery for Calculus courses (Mesa et al., 2015; Smith, Voigt et al., 2021). Students tend to experience these classes as dull and, sometimes, alienating. When instruction is "framed as 'drill and kill,'" math learning becomes a "solitary endeavor with accuracy and speed as markers of ability" (Leyva, Quea et al., 2021, p. 4). Furthermore, institutional factors such as the use of graduate students with little to no teaching experience to teach lower-level math courses present a significant challenge to delivering quality instruction to students (Hunter, 2019; Pilgrim & Gehrtz, 2018; Uhing, Webb et al., 2021), even though some students—especially women of color—find graduate students easier to approach than professors (Harper et al., 2019).

While these instructional barriers to student persistence may affect all students, there is evidence that they are felt most strongly by students from marginalized groups, including females but especially Black and Latinx students, who are also contending with racial stereotypes about math ability (McGee, 2016; McGee & Martin, 2011). Such students may be discouraged due to a belief that math in postsecondary spaces is largely abstract, void of context, colorblind and gender-neutral (Leyva, Quea et al., 2021). Instructors' beliefs are an important contributor to student attrition in STEM, and stereotypes about student abilities can affect students' opportunities to access mathematical content (Canning et al., 2019; Leyva, Quea et al., 2021).

An example in the literature is Calculus I instructors telling their class that students who are struggling with a particular assignment might want to drop down to Precalculus or leave the Calculus sequence altogether. Researchers found that instructors felt such statements would either motivate the students to work harder or help them realize they were not cut out for math, but minoritized students expressed being negatively affected by these conversations. The incident contributed to their feelings of stress, isolation, and lack of belonging (McNeill et al., in press), all of which have been connected to students' decisions to leave STEM.

Other factors, including class size and variance in instruction, have been tied to students' dissatisfaction with math and STEM classrooms (Mesa et al., 2015; Seymour et al., 2019). Large classes and lectures are common at larger universities but are less conducive to supportive instructional approaches. Because there are typically multiple sections of Calculus taught by multiple instructors, there can also be wide variance in instructional practices (Webb interview). Lower division courses such as Calculus are not routinely taught by the same instructor each year, making it difficult to sustain instructional changes such as learning objectives, exams, assignments, active learning strategies, curricular material, and grading practices (Pilgrim & Gehrtz, 2018; Smith, Voigt et al., 2021). Furthermore, high variability in instruction has been linked to students earning D's and F's or withdrawing from Calculus at higher rates (O'Sullivan et al., 2021). One of the reasons is that, unless instructors align their courses, students in different sections lack opportunities to work together on homework assignments or exam preparation (Rasmussen et al., 2021). While individual instructors play a key role in supporting students, this example underscores the fact that departmental and institutional factors can also inhibit student success and therefore need to be addressed.

Instructional challenges may also be related to the composition of mathematics faculty. At research universities, graduate students and adjunct instructors teach a high proportion of classes. Graduate students, in particular, typically have limited teaching experience. Tenure-track faculty comprise only 30 percent of Calculus instructors at these institutions nationally, and only 39 percent of Calculus instructors at research universities express "high interest" in teaching the subject. At other types of institutions, those on the tenure track make up 60 to 70 percent of Calculus faculty, and 58 to 80 percent report "high interest" in the course (Bressoud et al., 2013; p. 13).

In addition, the racial and gender composition of math instructors can play a complicated role in students' feelings about whether they belong in math or STEM. While having

same-race instructors appears to increase the likelihood of Black students persisting, the same pattern was not observed for female instructors teaching female students (Price, 2010).

ASSESSMENT AND GRADING

Calculus courses tend to use traditional approaches to measuring students' learning, such as exams that emphasize procedural fluency (Tallman et al., 2016), rather than formative approaches such as pre-assessments and short quizzes. A national survey of Calculus programs found that, though faculty in general had considerable confidence in tests and quizzes as measures of student learning, the programs that outperformed expectations for the student population they serve were more likely to use formative approaches (Burn & Mesa, 2015). At the same time, the survey documented wide variation in the complexity of problems faculty assign—with some relying more on recall of formulas and others stimulating students to use higher-order thinking, meaning that students taking similar courses may have been exposed to vastly different degrees of challenge and relevance.

Especially problematic for equity and overall student success are grading practices. In a large study examining why students leave STEM disciplines at four-year universities, introductory Calculus courses were identified (along with chemistry courses) as "severe foundational courses," or weed-out courses (Weston et al., 2019, p. 199). Such courses are characterized by "assessments misaligned with content and understanding," especially curved grading, which often includes the assumption that D and F grades will be assigned to a fixed percentage of students, regardless of their performance in an absolute sense (p. 201).

That scenario was found to lead a significant proportion of students to withdraw. "Grades may be so low, or damage to GPA so serious (especially for aspirants to medical and other professional schools) that otherwise interested and competent students feel they must leave," the study found (p. 203).

Interviewees said that, in practice, not all math departments use a strict bell curve, and allocation of D and F grades is not necessarily predetermined (Bressoud, O'Sullivan interviews). Nevertheless, letter grades are often assigned differently from what students experienced in high school, and the resulting sense of competition interferes with a collaborative learning environment (Webb interview). Even some students who ultimately receive high letter grades at the end of the term due to curving may by that time have grown demoralized from seeing lower percentage test scores than they were accustomed to receiving in high school. Plus, the inconsistency of grading standards across sections of the same course can be perceived by students as a source of unfairness (Rasmussen et al., 2021).[10]

Research suggests that some students may be particularly vulnerable to the signals sent by lower-than-expected scores or grades:

- Students who haven't taken Calculus in high school, often the minority in undergraduate Calculus classrooms (Bressoud, 2021).
- Black and Latinx students, who may experience "seemingly neutral instructional behavior … as a function of instructors' internalized racial stereotypes about mathematical ability" (Leyva, McNeill et al., 2021, p. 788).
- Women, who tend to have lower confidence in their mathematical ability, and therefore are 1.5 times more likely to leave a Calculus sequence than males with comparable achievement (Ellis et al., 2016; Bressoud, November 2014).

As Leyva et al. write, these grading practices serve as "mechanisms of academic hazing, separating those 'cut out' for STEM from those who are not" (Leyva, McNeill et al., 2021, p. 808). Students are aware—often painfully—of the phenomenon, according to interview comments such as these:

> The weed-out courses are trying to get rid of students rather than bring everyone along—it's psychologically crushing if you are in a class where you know their one objective is to get rid of you. (Weston et al., 2019, p. 229)

> Grades are like weather. Sometimes it rains; sometimes it doesn't. (Seymour et al., 2019, p. 14)

This pattern is especially problematic in light of research suggesting that good grades in Calculus don't necessarily signify understanding (Bressoud et al., 2013).

Promising Directions for Strengthening Undergraduate Calculus Experiences and Outcomes

While there has been considerable research on institutional practices to improve students' performance in math, much of this literature has not focused specifically on how to ensure equitable outcomes and thus may have primarily documented ways to improve outcomes for white or Asian male students (Brathwaite et al., 2020; Hagman, 2019). However, in recent years, there has been growing attention to students traditionally excluded from STEM disciplines, along with increasing interest in strategies for supporting their success. Rather than modest changes, many of these approaches require dislodging traditional assumptions about math learning in order to address uneven high school preparation, ensure effective placement, strengthen curriculum and assessment, and improve students' experiences in the classroom.

In other words, achieving better and more equitable outcomes will likely require mindset shifts among math faculty and others responsible for supporting students' success. Experts report that this will require new ways of engaging faculty in professional learning. It is common that faculty, especially more senior members of math departments, don't opt in to professional development opportunities and are wary of education research (Hagman, O'Sullivan, Thompson interviews). In one 2007 example, the math department at Arizona State University refused to allow a STEM improvement committee comprising fellow faculty to observe their classes (Thompson et al., 2007).

REVISING PLACEMENT PRACTICES

In an MAA survey, research university math faculty rate accurate placement as the most important feature of effective Calculus programs (Apkarian et al., 2017). An underlying reason for this would appear to be the challenges of addressing students' uneven preparation—which, at research universities, often means whether students have previously taken Calculus. However, as described above, placement into Precalculus has not generally been an effective solution.

Though there is not extensive research literature identifying the best placement practices, the MAA studies found that successful Calculus programs featured "a great deal of attention paid to those students near the [placement] cutoff, paying particular attention to programs in support of those allowed into Calculus I but most at risk and working with those who did not quite make the cut so that they were placed in programs that addressed their actual needs" (Bressoud & Rasmussen, 2015, p. 145). As for the issue of high school Calculus experiences, some schools, such as Syracuse University, address it by offering two versions of Calculus, one for students who studied Calculus in high school and one for those who didn't (Selinski & Milbourne, 2015).

A promising development is to allow students to improve their placement by reviewing the topics and reassessing, instead of using up a semester or more taking preparatory classes. To implement this approach, UC Santa Cruz used an online learning tool that helped students review material and reassess.[11] The result was reduced placements in lower-level courses—50 percent fewer enrollments in College Algebra and 36 percent fewer in Precalculus—and increases in Calculus (39 percent) and Honors Calculus (36 percent) enrollments (Lewis, 2019). This suggests the importance of shifting emphasis from course placement alone to strategies that help students reach their goals. In fact, UCSC's approach is described as "goal-oriented placement" (p. 7). Further research, showing how students perform in the sequences, could increase knowledge and awareness of this approach and confirm its effectiveness.

Absent more direct evidence on the effectiveness of specific placement approaches for Calculus, it is instructive to consider the example of remedial placement, which is more common at two-year college and broad-access universities than at research universities: When it became clear that remedial math sequences were not improving students' completion of general education math courses or progress toward a degree, colleges began redesigning the sequences themselves. These moves yielded significant improvements in outcomes in gatekeeper courses. The most common alternative to traditional remediation is the use of corequisite strategies, which involve offering concurrent courses or embedding content into a college-level course in order to support student learning. A considerable body of research has validated the effectiveness of this approach (Dadgar et al., 2021; Ran & Lin, 2019). In California's community colleges, for example, the proportion of first-time math students who successfully completed a transferable math course in one term doubled after corequisites were implemented (Mejia et al., 2020).

There are early indications that similar approaches show promise for improving Calculus outcomes. Math education leaders support expansion of Calculus corequisites (Bressoud interview), and some research supports their efficacy (Hancock et al., 2021; Vestal et al., 2015). But, partly because math departments offer supports under a variety of names—including "supplementary sessions" and "recitation sessions"—that may operate like corequisites, empirical evidence on the extent and effectiveness of Calculus corequisites is less extensive. According to a 2015 survey, about 9 percent of departments offering graduate degrees offer a form of concurrent support for students entering Calculus with less preparation. In one version, Precalculus material is infused into a Calculus course. In another, students enrolled in a Calculus course concurrently take a "co-Calculus" course that covers Precalculus and other relevant material in coordination (Voigt et al., 2020). Examples of various approaches can be found at Appalachian State University in North Carolina, Clarkson University in upstate New York, and the University of Cincinnati,

among other universities. At community colleges, work on corequisites seems to be focused on courses below Calculus. According to a 2018 survey, only 1 percent of community college math departments offered a Calculus corequisite (Burn et al., 2018).

Perhaps because of the limited amount of research, there appears to be no clear consensus in the field about designing the pathway to Calculus. Some at research universities have considered the notion of eliminating Precalculus altogether: "Integrating Precalculus with Calculus into a single course has long been discussed as an alternative to stand-alone Precalculus courses and might be a promising strategy" (Sadler & Sonnert, 2016, p. 63). A look at college websites reveals that, at Ivy League schools, Calculus typically has no prerequisite, which may reflect the preparation of students who enroll in those colleges. Institutions in California appear to be pursuing a variety of directions. Some, such as San Diego State University and UC San Diego, have a course before Precalculus. Others, including San Francisco State, have no prerequisite to Precalculus. Colleges that offer remedial courses may have more than two prerequisites. More understanding is needed about the prevalence and effects of these different approaches.

Yet another approach utilized within four-year university math departments, including many in the CSU system, is the "stretch" model, which can be similar to a corequisite, but with course content spread over two semesters, instead of one. About 9 percent of the universities in the 2015 survey reported using this approach, but, based on anecdotal reports, it appears to be gaining currency, at least in California. Research on this model is not conclusive: At California community colleges, a one-semester corequisite for statistics was associated with greater success rates than a two-semester stretch course (Rodriguez et al., 2018, Figure 5), but Calculus was not studied. A university-based study of stretch Calculus reported mixed results, because the population of students taking one- and two-semester versions differed (Wu, 2018).

REDESIGNING CALCULUS CURRICULUM

Of course, it is reasonable to ask whether improving Calculus outcomes requires changes to the course curriculum itself, as some leading researchers recommend. "Calculus has degenerated into a series of techniques for solving a finite set of problems," noted David Bressoud in an interview. "The real challenge is to help students understand. If you are good at memorizing the techniques you can make it through, but there is not much you can carry over."

In 2015, about 7 percent of math departments surveyed (which included only departments offering graduate degrees) offered a Calculus course for life sciences majors (Apkarian et al., 2017). It is quite possible that that proportion has since increased, as such courses have replaced traditional Calculus for many or all life sciences majors at some institutions, such as UC Berkeley and UCLA, which initially offered them as pilots (Flaherty, 2015). In addition, some of these courses, including UCLA's, are being taught outside of math departments, so they may not be reflected in the survey. UCLA's contextualized two-course series, Mathematics for Life Scientists, was designed to "bridge … the gap between the way math is taught and the way it is often applied in STEM fields," UCLA faculty note in a journal article (O'Leary, et al., 2021, p. 2). The sequence, they say, covers traditional Calculus topics such as the derivative and the integral with a focus on their application to dynamical systems. It also facilitates students learning computer programming in Python "so that they can numerically integrate nonlinear systems of differential equations" (p. 2). Students in the new Calculus sequence tend to have "significantly higher average chemistry and physics grades" than classmates taking traditional Calculus courses (p. 9). However, the UCLA faculty could not conclusively say whether the new curriculum contributed to more racially equitable outcomes, noting that the course could be improved by more active learning and less lecturing.

Macalaster College's Modified Calculus Approach

Macalaster's innovative Calculus course uses a modeling approach, with less attention to differentiation and integration than traditional Calculus. It was designed for students pursuing majors such as biology and economics, who need only one Calculus course, as well as those pursuing math, physics, and chemistry majors, who must take Calculus II. Most students enter with prior exposure to Calculus, and the course has no prerequisite. In addition to modeling, the course involves computer programming, using the software program R. The purpose of the course, which was developed with input from biology and chemistry faculty, is to ensure that students understand Calculus as a tool for modeling dynamical systems, including an emphasis on differential equations (Bressoud, August 1, 2018). Because of its unique curricular approach, the course offers new material for students, whether they've been exposed to Calculus or not.

Curricular redesigns involving modeling and contextualized examples are not just for disciplines such as biology, however. The National Science Foundation is supporting Florida International University in developing a modeling-oriented Calculus course (Watson interview). Macalester College offers a modified course serving all students whose majors have a Calculus prerequisite. The Macalaster course developers note that students who come to college without a prior calculus background and wish to major in math might require more experience with algebra formulations than the course provides (Bressoud, August 1, 2018). However, the

fact that the course serves students going into the physical sciences is a good indication of the potential of curricular redesign to support STEM success.

Resequencing content is another approach. Bressoud's 2019 book, *Calculus Reordered,* makes the case for a course that focuses on the big ideas of Calculus aligned with Calculus' historical development and resequencing the course. In the traditional sequence, students get the impression that integrals are about finding areas under curves and derivatives are about finding slopes, Bressoud notes (Bressoud interview). The typical ordering of the class—limits, differentiation, and integration followed by series—contributes to this problem. Bressoud recommends teaching "integration as accumulation, differentiation as rates of changes, series as limits of sequences, and limits as the algebra of inequalities," in that order (Bressoud, July 2019).

Arizona State University has adopted the concept for the Calculus I and II courses taken by math and science majors after a three-year pilot revealed positive effects on students' progress in STEM (Thompson et al., 2019). The approach was also piloted at Portland State University. However, the approach has its limits. Getting faculty across disciplines to agree on a single version of Calculus may be difficult. At ASU, for example, engineering students take a different course. Smaller campuses, including many community colleges, may be able to offer only one flavor of Calculus (Bressoud interview).

Furthermore, the fact that faculty on the same campus may not agree on a Calculus course highlights the difficulty of adopting single-institution approaches. Strategies such as Macalester's will not work well in systems with a high degree of transfer between institutions, including two-year and four-year campuses. Adoption at a regional or system level would be more practical than an individual campus approach.

Reforms Must Articulate

California's three systems of higher education—including 116 community colleges, 23 CSU campuses, and nine undergraduate UC campuses—illustrate the challenges posed by curricular reforms for course articulation. Students wishing to transfer between systems need assurances that their courses will confer credit or satisfy prerequisites at the transfer institution. Because high proportions of students in both university systems begin their college pursuits at a community college, two-year colleges in particular face challenges adopting curricular reforms without assurances that the reformed courses will be accepted by the universities to confer credit or satisfy prerequisites.

REDESIGNING ON-RAMPS TO STEM

The "math pathways" movement has revealed the potential for modifying math prerequisites to better support student success and align with students' fields of study. Discussions about math pathways have typically centered around non-STEM disciplines. Many colleges and universities that once required all students to complete an algebra-intensive course such as College Algebra instead encourage students pursuing non-STEM majors to choose options such as Statistics—especially for social science fields—or Quantitative Reasoning, also known as Liberal Arts Math (Burdman et al., 2018). Implementing such changes requires math departments to collaborate with other disciplines to understand the quantitative skills expected of students. The other departments, for their part, need to modify their requirements to ensure they represent relevant prerequisites, not arbitrary filters to screen students out of high-demand majors.

For students pursuing STEM fields, however, the Calculus pathway is often viewed as an intractable obstacle. The evolution of specialized life sciences Calculus courses is one attempt to address it, by focusing on the areas of Calculus that are most important for the life sciences and teaching them in contextualized ways. Another promising model has emerged within engineering schools. Like the life sciences, engineering programs cannot abandon all of Calculus. But some research (Faulkner et al., 2020) has shown that engineering courses may require less calculus content than typically assumed. And a model pioneered by Wright State University in Ohio has demonstrated the benefits of forgoing traditional Calculus sequencing through modifications to the engineering curriculum.

Through a "just-in-time restructuring of the required math sequence," Wright State's National Science Foundation–funded model has "shifted the traditional emphasis on math prerequisite requirements to an emphasis on engineering motivation for math," in the words of the model's founders (Klingbeil & Bourne, 2015). This allows students to experience and engage in engineering courses before tackling the Calculus sequence later in college. Studies at Wright State show that the strategy has doubled graduation rates for engineering students, with the greatest benefit to students with weaker math preparation and members of historically underrepresented groups. Such a strategy would be hard to implement at colleges where entering students may not have chosen a major, though the work on guided pathways in community colleges could support this type of approach.

From Math Prerequisites to "Engineering Motivation for Math"

After observing that the first-year Calculus sequence was a primary driver of attrition in engineering, faculty at Wright State University developed a model designed to make core engineering programs more accessible to a diverse range of high school graduates. In the model, students begin with a first-year contextualized math course taught by engineering faculty in lieu of traditional Calculus prerequisites. First offered in 2004, the course is driven by problem-based learning and covers linear equations, quadratic equations, trigonometry, 2D vectors, complex numbers, derivatives, and other topics used in core sophomore engineering courses (Klingbeil et al., 2009). In 2007, the department added a precursor course for students who were struggling with the contextualized course (Klingbeil et al., 2015). Students subsequently complete traditional Calculus requirements as they proceed through their programs, with only minimal adjustments to the engineering curriculum.

Longitudinal analyses show that this strategy has blunted much of the variance in students' high school backgrounds, allowed students with weaker math preparation to succeed in engineering, and more than doubled the average graduation rate of engineering students, with no impact on grade-point averages of graduates. Notably, the authors report that the greatest impact has been on female and minoritized students (Klingbeil & Bourne, 2015).

At least 15 other universities—including Cal State Long Beach, the University of San Diego, and California Baptist University—have replicated the model.

IMPROVING CLASSROOM INSTRUCTION AND SUPPORT

Improving students' classroom experiences begins with teaching. The literature highlights fostering positive faculty–student rapport as central to students' success in Calculus (Burn et al., 2015). In fact, the top two practices of "good" teaching, according to the MAA Calculus studies, are not even math specific. They are (1) classroom interactions that involve students, such as asking students to describe their thinking and inviting students' questions and comments and (2) faculty who are encouraging and demonstrate an interest in students' learning and a belief in their abilities (Mesa et al., 2015). In describing good teachers, STEM students highlighted "friendliness" and "caring" more than any other characteristics. In one well-known example, Uri Treisman of the University of Texas at Austin has made a habit of cramming to memorize the names and faces of all 100 students in his freshman Calculus class before the first class meeting to help them feel comfortable (Tough, 2021). One interviewee noted that it is also important for instructors to know whether their students are motivated and enjoy the class (Watson interview).

Changing instructional practices specific to mathematics is also a central part of efforts to address disparities in student engagement, access, opportunities, and, ultimately, persistence in STEM. In recent years there have been shifts toward teaching in ways designed to support students in developing conceptual understanding. "Active learning" has been well established as a more effective teaching approach than traditional lecture for supporting learning gains (Freeman et al., 2014). Active learning strategies entail less time lecturing and more time for students to work together, hold discussions, and make presentations, which compels them to grapple with mathematical ideas and discover their own conceptual understanding of mathematical topics. Active learning also helps instructors observe students' understanding.

Having students work in groups can help with articulation of mathematical ideas and engage them in higher-level thinking about concepts learned during instruction (Hagman interview; Pilgrim & Gehrtz, 2018; Rasmussen et al., 2019). Instructors and departments must also put systems in place to help facilitate group work. For example, outfitting classrooms with movable desks and multiple white boards makes it easier for students to work together (Lee interview; Webb et al., 2021). So does the use of interactive or kinesthetic activities, such as using Wikki Stix to model functions or making a train out of dominoes to represent integrals and derivatives—two strategies employed by Cal State East Bay (Oliver & Olkin, 2021).

Reducing class size can enhance implementation of active learning. Some universities can have upward of 250 students in one lecture, which inhibits the instructor's ability to create a collaborative classroom culture. Implementing smaller classes can increase collaboration as well as resources for students (Mesa et al., 2015; O'Sullivan et al., 2021; Webb et al., 2021; Webb interview). However, simply eliminating large lectures and assigning more faculty to teach Calculus can be prohibitively costly, so institutions have explored other strategies for reducing class size. These include the use of clickers and other tools so students can interact with the instructor during the lecture.

Institutions can also support active learning in large lectures by requiring students to attend smaller "recitation" sessions, or labs, in addition to the lecture (Bressoud & Rasmussen, 2015; Burn & Mesa, 2017). These are commonly taught

by graduate students, but some universities have hired undergraduates as learning assistants and trained them to lead recitations. In these sections, students can ask questions, review problems, and relearn material from the lecture as needed, all while in a smaller class of approximately 15 to 30 students (Smith, Voigt, et al., 2021; Watson interview).

Though active learning has been linked to conceptual understanding, it does not on its own lead to improvements in persistence rates for students in STEM. While providing opportunities for students to discuss math concepts with one another, group work has the propensity to perpetuate inequities in the classroom. For example, some students have reported feeling uncomfortable during group work if they viewed their group mates as more knowledgeable. They described increased anxiety and other emotions that inhibited their ability to participate authentically in group discussions (Tough, 2021; Uhing, Haas et al., 2021).

Additionally, Esmonde and Langer-Osuna (2013, p. 2) note that, "In diverse classrooms in which students from historically dominant groups learn alongside students from historically excluded groups, issues of power and privilege arise that are distinct from the issues that arise in more culturally homogeneous contexts." Thus, when instructors are utilizing active learning techniques, it is important for them to understand and try to mitigate possible hindrances to students' ability to access group work. Moreover, it is imperative to include positive rapport-building between instructors and students and among students in order to help create an environment conducive to authentic engagement and participation.

Given this understanding, some institutions have found success with blended strategies: The Memphis Mathematics Method program consists of an interactive lecture followed by problem-solving using digital tools and technology. A large-scale study showed that working with this hybrid method yielded statistically significant increases in grades and test scores for students (Bargagliotti et al., 2012). Similarly, at some community colleges with successful Calculus programs and typically small class sizes (up to 35 students), interactive lectures have some of the features and benefits of active learning (Burn & Mesa, 2017).

In addition to these methods, scholars have highlighted the importance of incorporating diverse social and cultural contexts into instruction (Tromba interview). These include engaging students in participating in mathematics in ways that affirm their thinking and have relevance to their lives (Miller-Cotto & Lewis, 2020), though the research on these approaches is more robust at the K–12 level. Writing exercises that explore the role of mathematics in students' academic goals is one example (Priniski & Thoman, 2020). Postsecondary examples showing the potential of these strategies include a preliminary study at the University of Arizona of students' participation in a Calculus workshop involving critical conversations about race and gender. The workshop was correlated with higher GPAs and STEM persistence (Anhalt, 2018), though more rigorous analysis would be required to determine whether this was a causal relationship.

Other approaches to support college students' math identity and sense of belonging include the use of student networks and peer collaboration, a strategy that was popularized by Uri Treisman's Emerging Scholars workshops at UC Berkeley. Treisman discovered that Black students with poor math success commonly studied alone, but when they were placed in peer learning networks, their success rates increased sharply (Adiredja & Andrews-Larson, 2017; Fullilove & Treisman, 1990; Hsu et al., 2008; Treisman, 1992). In addition to providing academic and social support, such approaches can help students "reduce perceptions of racism and feel more comfortable in their STEM courses" (Henfield & Byrd, 2014, p. 217). Treisman's Emerging Scholars Program—considered an honors program into which students are recruited, the opposite of a remedial course—has since been replicated at dozens of universities around the country (Gomez interview; Hsu et al., 2008). At the University of Illinois in Chicago, for example, a quasi-experimental study found that the 400-some students in the Emerging Scholars Program outperformed nonprogram students in grades earned in Calculus I and II (Brugueras et al., n.d.).

Community colleges in California and several other states have traditionally used programs such as MESA (Mathematics, Engineering, Science Achievement) to foster STEM engagement and success among traditionally underrepresented students. Students have spoken positively about their experiences in interviews (Purnell & Burdman, 2020), and one state has linked enrollment growth in Precalculus and Calculus to MESA programs (Washington State Board for Community and Technical Colleges, 2016).

More recently, some community colleges have been using their corequisite courses to foster community and strengthen students' math identity in Precalculus, often the first course in the STEM math sequence. "The sense of belonging happens in the classroom," noted Sophia Lee, math instructor at Citrus College, where more than two-thirds of students are from historically excluded groups.[12] "If they're feeling math anxiety, imposter syndrome in their Calculus classes, they're out of there. Building that support in the classroom is what we're all about."

Lastly, efforts to support inclusive classrooms and foster students' sense of belonging should also attend to instructor diversity. Research has found that exposure to Black instructors has a positive effect on persistence rates of Black students. In fact, having at least one STEM course taught by a Black instructor has been linked to an 8.1 percentage point increase in Black students' likelihood of persisting, a difference that eliminates the persistence gap between Black and white students (Price, 2010). Likely explanations include the important role of faculty as role models and mentors (Beasley & Fischer, 2012).

RETHINKING GRADING AND ASSESSMENT PRACTICES

Grading and assessment practices are a central aspect of students' classroom experiences and ultimate learning. In fact, fair assessment is considered one of the three primary components of good teaching in the MAA's 2013 study of undergraduate Calculus. One of the most important ways highlighted by the study to ensure fairness and equity in assessments is for faculty to collaborate on developing assessments—with professional development related to item construction—as well as on grading them (Mesa et al., 2015).

The research on curved grading in STEM notes that students who persist generally manage to adjust their expectations and put their grades in context. This suggests that support strategies to help students understand how "norm-referenced" approaches such as curved grading differ from the "criterion-referenced" grading approaches often used in non-STEM courses might be a useful strategy (Thiry, 2019b). However, the very need to help students adjust also raises the question of whether the grading practices—especially those with a built-in assumption that a certain percentage of students should fail—themselves should be changed.

Some of the most selective institutions do take a different approach to grading, focused on ensuring that students succeed and providing opportunities for students to revise their work, notes Ebony McGee of Vanderbilt University (2021), but McGee points out that many state universities and historically black institutions don't use this strategy.

Though there is research on standards-based grading approaches, it focuses on K–12 education, and there is little evidence on the existence and effectiveness of alternative grading approaches in Calculus courses (Brilleslyper et al., 2011). Conversations are emerging about using mastery-based grading in undergraduate mathematics as an alternative to traditional assessments based on percentages, points, and letter grades (Campbell et al., 2020; Krinsky, 2021). Mastery-based grading, similar to standards-based grading, allows students to show their mastery through repeated opportunities to solve problems on the same concept (Campbell et al., 2020).

A similar approach is used in UCLA's life sciences math sequence, which eschews the use of norm-referenced approaches in favor of criterion-referenced grading, which UCLA faculty argue "cultivates a collaborative, rather than competitive, learning environment" (O'Leary et al., 2021, p. 6). Interestingly, this decision was motivated, in part, by a 2015 report to UCLA's provost in partial response to then–Attorney General Kamala Harris' request that the campus "address the climate for diversity and disparities in completion rates for underrepresented groups," according to an early draft.

PRIORITIZING OTHER STUDENT SUPPORTS

Efforts like the Emerging Scholars Program have shown that students' experiences of participating in a community can address feelings of isolation. Institutions can also support strategies outside of math classrooms to help students integrate or transition to college and increase their sense of belonging. UC San Diego, for example, runs a program called Summer Bridge that serves first-generation and under-resourced students. The credit-bearing program is designed to fill gaps in students' prior math knowledge that may interfere with learning Calculus. It also addresses the "hidden curriculum" of college, so students acquire learning strategies that will help them succeed (Rinaldi interview). Other student supports some institutions emphasize are extracurricular activities in the math department and math learning centers (Bressoud & Rasmussen, 2015).

Experiences with counselors and academic advisors questioning their readiness for Calculus can have an effect on racially minoritized students in pursuit of STEM degrees, either dissuading or encouraging them (Watson interview). One strategy to address the discouraging signals some students receive from advisors is to race-match advisors and students (Battey et al., 2018; Leyva interview; McCoy et al., 2015). In general, more research is needed on the role of counseling and advising in students' STEM progression.

Institutions also need to be cognizant that students have disparate financial situations. Even effective strategies, such as corequisite courses, can be problematic for student success if they add time and costs to students' academic journeys (Leyva interview). Furthermore, students with less financial security are at a disadvantage when other students are hiring tutors to help them learn math (Hagman interview). Providing student supports such as tutoring and other resources without cost to students can help equalize access.

DEEPENING PROFESSIONAL LEARNING

Though the strategies highlighted above are associated with improvements in students' STEM outcomes, they don't occur on their own. Generally, faculty implement them and require support to do so. "For Calculus I, the teacher may be the student's most important resource. As such, investing in faculty development and in hiring high-quality instructors would be of paramount importance," note Vilma Mesa and colleagues (2015, p. 89). While hiring faculty who are equity-minded and open to new instructional methods was highlighted in the research and interviews (O'Sullivan interview; Webb et al., 2021), that alone cannot lead to departmentwide instructional improvements, given the slow pace of faculty turnover.

Professional development, therefore, is a necessary component of institutional change efforts. One emphasis in the literature has been universities' common use of graduate students to teach lower-division math courses such as Precalculus or recitation sections connected to Calculus lectures. Strategies for developing graduate students' efficacy in teaching include maintaining a well-organized archive of course materials that is available to instructors (Pilgrim & Gehrtz, 2018) and offering multiday workshops and yearlong apprenticeships (Rasmussen et al., 2019).

However, faculty themselves can also benefit from professional development, particularly to address misconceptions about students. Since stand-alone workshops rarely show results, professional learning needs to be well integrated into faculty work. One effective means of improving practices is shared ownership of courses, which entails faculty meeting regularly to align their practices (Bressoud & Rasmussen, 2015; Burn et al., 2015). Also known as course coordination, this is a growing approach in math departments to help address variation in course content, grading, and assessments and ensure greater instructor interaction about the course. Some departments also align syllabi, providing templates for faculty to ensure that communication with students is transparent and consistent. A course coordinator is often appointed to facilitate these efforts to build communities of practice (Curtis interview; Rasmussen et al., 2021; Watson interview).

Such approaches can be key to successful implemention of curricular and instructional innovations. For example, the math department at Cal State East Bay, considered one of the most diverse regional universities in the country, used a course coordination strategy to implement a redesigned Calculus course that emphasized "big ideas" and conceptual understanding. To nudge faculty toward more active learning, course coordination included a pacing guide, suggested group tasks, and guided handouts—all of which are linked via a dynamic calendar. A community of practice meets monthly. Project directors report that the strategy has led to a sharp reduction in the DFW rate, from 36 percent to 17 percent over a two-year period from 2015–16 to 2017–18. Notably, the entire decline in the DFW rate in the project's second year reflected better success for underrepresented students, who ultimately had a lower DFW rate than non-underrepresented students (Oliver & Olkin, 2021).

A related practice of successful Calculus programs that may be part of a course coordination system or community of practice is analyzing student outcomes data to inform improvement efforts (Bressoud & Rasmussen, 2015; Zazkis & Nuñez, 2015). Such efforts can help build buy-in for changes as well as strengthen adoption of specific practices. It can also contribute to enhancing equity, as long as the data is disaggregated by student characteristics to explore ways of better serving students, a practice that is still not commonly utilized, even among programs considered successful (Voigt, Smith et al., 2021). Student evaluations can also be an important resource if used effectively: Sharing evaluations solely with individual instructors can limit their value. Distributing them to course instructors or to all instructors of a given course can help provide instructors with a baseline for understanding their ratings and motivate them to improve their teaching (Zazkis & Nuñez, 2015). Lastly, a full picture of student persistence requires looking not only at success rates in a given course, but also at students' progression and success in subsequent courses (Hagman interview; Zazkis & Nunez, 2015;).

Professional development should also specifically address how faculty implicit bias can play out in the classroom and influence students' sense of belonging. Given the predominance of meritocratic narratives in math and STEM, it is important that faculty have the opportunity to examine their own racial bias and listen to student needs and concerns. One public university math department started an advisory council made up of students from marginalized backgrounds in order to channel consistent feedback to faculty about the needs of the students (Hagman interview). Changes implemented as a result included creation of a mentorship program to support STEM students of color, because some students on the advisory council described their experiences in math as isolating. An added benefit of the group's feedback was an opportunity for the faculty to reflect on their classroom practices (Hagman interview; Voigt, Gehrtz et al., in press).

Professional development practices such as reflective teaching have been shown to reduce instructor bias (Boysen et al., 2009; Brathwaite et al., 2020; Joseph et al., 2016). To support student interactions effectively in the classroom, faculty may also need to become aware of racial dynamics and learn ways of supporting inclusive environments (Esmonde & Langer-Osuna, 2013). For example, understanding racial dynamics and individual students' interactional styles can help an instructor facilitate culturally heterogeneous groups in ways that minimize power imbalances in the classroom.

Directions for Future Research

This report, being of an exploratory nature, raises a number of opportunities for future research. While it has identified potential strategies for mitigating barriers students experience prior to and while taking Calculus I, further study is necessary to elaborate on these findings. Also, more quantitative analysis can extend this research and provide generalizable evidence of the effectiveness of these strategies.

First, this study revealed the need to better understand the influence of course placement and intersegmental articulation—as well as how those policies are communicated—on students' Calculus opportunities and success. Misalignments between educational systems can delay or deter students in completing their programs.

Second, emerging literature on the development and redesign of Calculus I presents opportunities to examine the effectiveness of alternatives to traditional course models, such as Calculus for majors such as Business and Biology. Also, to address students' preparation requirements, more understanding is needed about the effectiveness of different prerequisite pathways to Calculus, as well as Calculus corequisite and stretch models.

There is consensus from the field that aligning grading practices is helpful in terms of supporting learning and improving persistence, but more knowledge is needed about the most effective grading strategies. Counseling and advising can also influence students' choices to pursue or remain in STEM, and further research could help identify promising models.

Finally, the research team worked diligently to recruit interviewees and uncover literature that would reflect diverse perspectives, including scholars from historically excluded groups. However, the limited amount of research by scholars of color suggests that the field can still benefit from additional perspectives. Knowledge about student success in Calculus and STEM majors—as well as future reform efforts—will be substantially strengthened through increased contributions from individuals who experienced the disadvantages underscored in this research.

Toward a New Role for Calculus

The research surveyed in this report presents Calculus I as the primary gatekeeper to STEM programs. While opening the door for some, the course serves as a major stumbling block for many students interested in STEM careers. The disproportionate rates of women and minoritized students leaving a STEM major following experiences in Calculus classrooms underscore the need for departments and institutions to work together to cultivate students' STEM interests and talents.

Though the demographics of Calculus students and their reasons for taking the course have changed dramatically in the past 50-plus years, the course itself has seen little change (Teague, 2017). Likewise, the meritocratic narrative common to STEM and Calculus has been decades in the making. Updating it for a more equitable future will require dedicated resources and leadership to redesign practices that leave far too many capable students behind.

While more research is always valuable, the report highlights some strategies for improving the Calculus experience that have shown promise for advancing persistence in STEM majors for students from diverse backgrounds. An underlying theme is that institutional accountability for student success is needed in order to ensure the adoption of evidence-based practices and promote better outcomes at scale. Without institutional buy-in, the success of any reforms may be short-lived or too anemic to have a broad impact. Institutions must proactively support the work of math departments to improve instruction, invest in solutions such as those mentioned in this report, and ensure that math faculty work with one another and with colleagues in other disciplines whose students they prepare.

What successful efforts also have in common is that they center changes around supporting students and understanding their contexts, to ensure that their prior math preparation doesn't dictate their destinies. This entails shifting the focus from measuring students' readiness to designing Calculus experiences that serve students—particularly those traditionally excluded from STEM fields—as effectively as possible. It means transforming Calculus class from a weed-out mechanism to fertile terrain for cultivating the next generation of STEM researchers and professionals.

Part Two: The California Landscape of Calculus Enrollment and Success

With the nation's largest and most diverse systems of higher education, California will be central to efforts to ensure that Calculus serves as an on-ramp to STEM success for a broader population. The state produces nearly one-eighth of the nation's STEM degrees.[13] An analysis of data on Calculus enrollment and success patterns provided to the California Education Learning Lab by California's three public higher education systems reveals that the state is no exception to the inequitable patterns of undergraduate Calculus enrollment and success described in national studies[14] (see Technical Appendix, p. 39). While the data do not suggest the reasons for the patterns, the research in Part One points to a range of structural conditions and barriers that California higher education leaders can investigate as they seek to address the disparities.

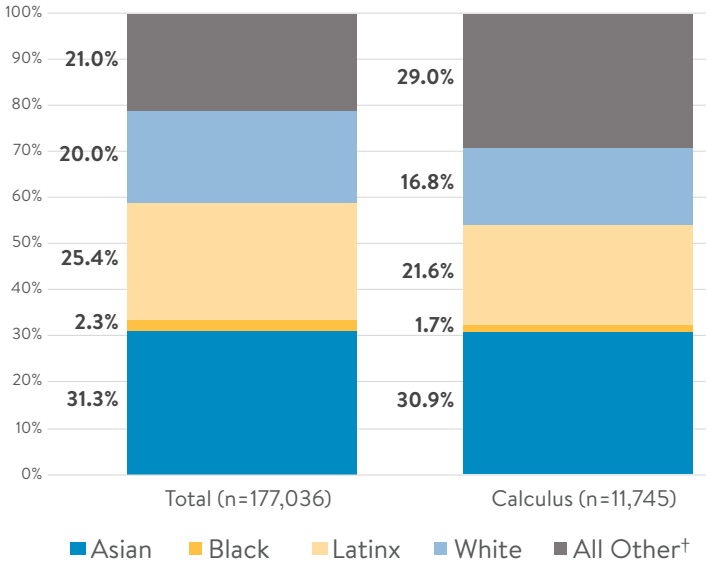
Calculus Enrollment

In terms of access to Calculus, University of California students were almost three times as likely to enroll in Calculus in Fall 2019 as were California State University students, a probable reflection of the UC system's more selective admissions requirements and emphasis on STEM disciplines. UC admits predominantly come from the top one-eighth of high school graduates statewide, with nearly two-thirds of them having taken at least one AP math course (i.e., AP Calculus AB, AP Calculus BC, and/or AP Statistics) in high school, as compared with just over 40 percent of CSU admits (Asim et al., 2019, p.14, Figure 10). Furthermore, UC campuses confer more STEM bachelor's degrees than their CSU counterparts in both proportional and absolute terms: Despite its smaller enrollment, UC confers 48 percent of the state's STEM bachelor's degrees vs. 37 percent for CSU (Johnson & Sanchez, 2018).

Community college students were proportionally less likely to enroll in Calculus than undergraduates in the university systems, a likely reflection of the community colleges' multiple missions: While some students enter community college seeking to transfer to four-year universities and earn bachelor's degrees, others are more focused on preparing to enter the workforce (Baime & Baum, 2016). Still, by virtue of the CCC's large enrollment (more than 1.5 million students), more of their students (21,934) took Calculus in Fall 2019 than at the other two systems combined (18,231).

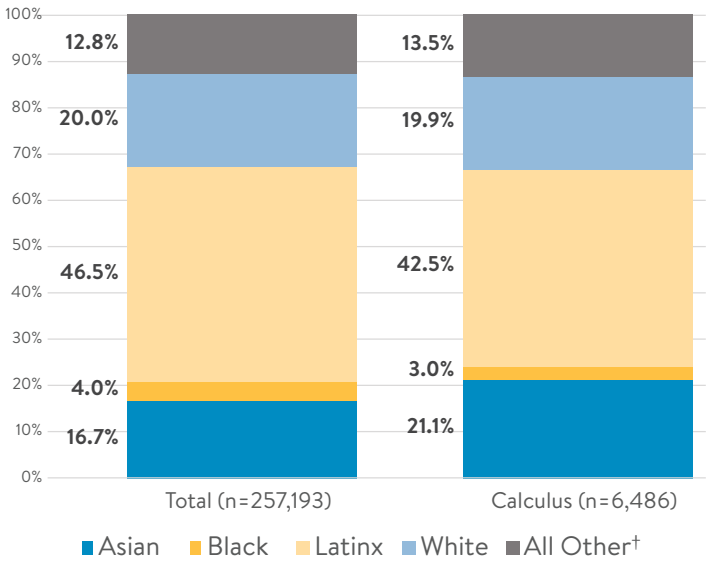
Across all three systems, the differences in Calculus enrollment were also pronounced by race. Whereas Asian American students' enrollment in Calculus at UC was somewhat higher than their proportion of the student body in Fall 2019, Latinx, white, and Black students were proportionately less likely to take Calculus courses (in that order, with Black students having the lowest representation). Among CSU and community college students, Asian American students' Calculus enrollment was disproportionately high relative to their share of enrollment, with white, Latinx, and Black students (in that order) less likely to enroll (see Figures 1–3).

FIGURE 1: UC Fall 2019 Non-Transfer* Enrollment vs. Calculus Enrollment



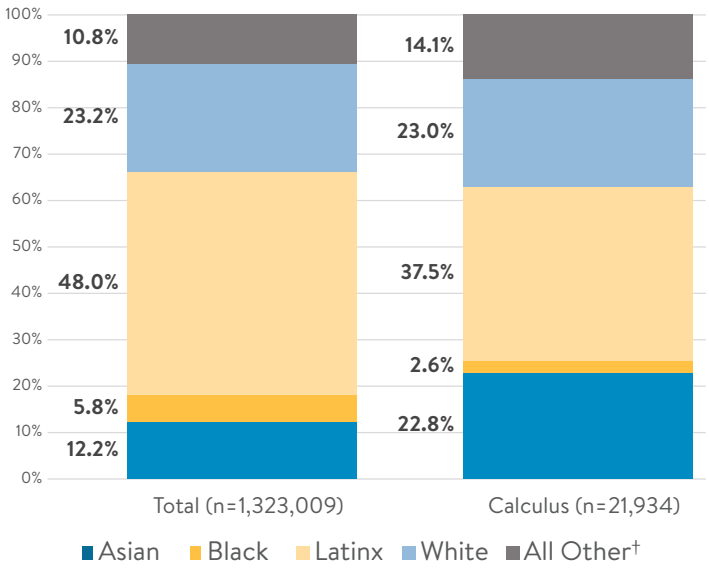
Non-transfer enrollment includes all students who began at UC as freshmen

FIGURE 2: CSU Fall 2019 Non-Transfer** Enrollment vs. Calculus Enrollment



**Non-transfer enrollment includes all students who began at CSU as freshmen*

FIGURE 3: CCC Fall 2019 Total Enrollment vs. Calculus Enrollment



†"All Other" includes international students (who enroll in Calculus at disproportionately high rates), American Indians, Pacific Islanders, two or more races, and domestic unknown

The racial disparities carry over to the timing of students' Calculus enrollment. Students enter the Calculus sequence in different ways, and where and when they enter is often dictated by the interplay between their prior experiences and institutional policies and practices. Students who go further in a high school math sequence are better prepared for the college Calculus pathway than their peers, but the mechanism used to determine students' actual placement (often a placement test or an AP test score) varies by campus. It is altogether possible that a student admitted into Calculus at one campus would have been required to take Precalculus or another prerequisite had they enrolled elsewhere (Academic Senate of the CSU, 2016; Burdman, 2015; Melguizo et al., 2015).

What is consistent across both university systems is that fewer of the Black and Latinx students who took Calculus did so in their first year than did white and Asian students, again an indication that prior math preparation affects students' momentum. As discussed on page 8, delayed enrollment in Calculus can reduce students' persistence and progress into a STEM degree.

Among STEM-majoring students who entered CSU in 2014, for example, 41 percent of Black Calculus takers and 36 percent of Latinx Calculus takers took the course as sophomores or later (vs. 19.7 percent of whites and 22.5 percent of Asians who took the course). Other than students belatedly opting in to a STEM major, the likely reason a student would take Calculus after the first year would be the need to take prerequisites such as Precalculus, College Algebra, or even remedial math courses (prior to 2018, when CSU stopped offering remedial prerequisites). Indeed, CSU data showing that Black and Latinx students were more likely than other students to take Calculus after first enrolling in Precalculus is consistent with this explanation. At the CCC, delayed enrollment in Calculus was the norm for all students. In Fall 2014, only 24 percent of Latinx and 27 percent of Black students took the course in their first year, along with 35 percent and 41 percent of white and Asian students respectively.

The system data also revealed gender disparities in Calculus enrollment, particularly at the CSU, where the Calculus course–taking rate of males was 2.5 times that of females: only 10 out of every 1,000 females enrolled in Fall 2019 took Calculus that term, compared with 25 out of every 1,000 males. As a result, despite making up 56 percent of the student body, females accounted for just 35 percent of CSU students enrolled in Calculus in Fall 2019 (which is, however, close to the 38 percent of that fall's STEM majors who were female). Community colleges displayed a similar pattern: Females constituted 53 percent of students and 36 percent of Calculus takers. The gender gap was smallest at UC, where females made up 54 percent of the student body and 44 percent of Calculus enrollees.

Success

Successful completion of Calculus (defined as passing the course with a C or better) presents a greater challenge within the CSU system than at UC. Among UC non-transfer students enrolled in Calculus in Fall 2019, about 84 percent earned a C or better, with 16 percent in the DFW category—earning a D or an F, or withdrawing from the course. However, more than 30 percent of fall 2019 CSU (non-transfer) Calculus takers earned a DFW. In other words, fewer than 70 percent of CSU students who took the course passed with a C or better.[15] Differences in the preparation levels of incoming students is one contributing factor. Data provided by the systems showed that, among students enrolled in 2019,[16] 88 percent of UC students and 49 percent of CSU students had earned a high school GPA of 3.5 or higher.

CCC Calculus course success rates are lower, with nearly half (46 percent) of the Fall 2019 Calculus takers receiving a DFW.[17] Unlike the universities, which admit a more select group of high school graduates, the CCC are open-enrollment institutions that serve a much broader population of students.[18]

Across all three systems, success rates were disproportionately low among historically underrepresented populations. Within the CCC, Black and Latinx students were more likely to earn a DFW than complete successfully: 59 percent of Black students and 56 percent of Latinx students who took Calculus earned DFWs during Fall 2019 compared with 39 percent of Asian and 42 percent of white students. At the CSU, 40 percent of Black students and 37 percent of Latinx students earned DFWs in Calculus in Fall 2019 compared to 31 percent of all students taking Calculus. At the UC system, 36 percent of Black students and 27 percent of Latinx students who took Calculus earned DFWs vs. an average rate of 16 percent for all students who enrolled in the course (see Figures 4–6).

Disparities in completion by income at the universities were even more pronounced, with lower-income students less likely to succeed in Calculus: At both systems, the DFW rates of students with Pell Grants were double or nearly double that of non-Pell students. In Fall 2019, UC students who received a Pell Grant had a DFW rate of 24 percent, while non-Pell students were at 14 percent. At the CSU, Pell students had a DFW rate of 31 percent, double the 15-percent rate of non-Pell students that Fall. At the CCC, though DFW rates were higher, they were notably less varied by income: 44 percent of students who received fee waivers earned DFWs, as compared to 49 percent of students who did not.[19] Questions for further examination include the reasons for greater disparities by income level at the two university systems, as well as the intersection between racial and income disparities.

Intersectionality is also a concern with respect to gender. The California systems are performing somewhat better than suggested by the literature with female students in Calculus, to the extent that the overall success rates by gender are proportional to enrollment rates. However, this trend does not apply at CSU when race is considered: Black female students are overrepresented in the DFW column among Fall 2019 CSU non-transfer students.

FIGURE 4: UC Fall 2019 Calculus I Outcomes by Race for Non-Transfer Students

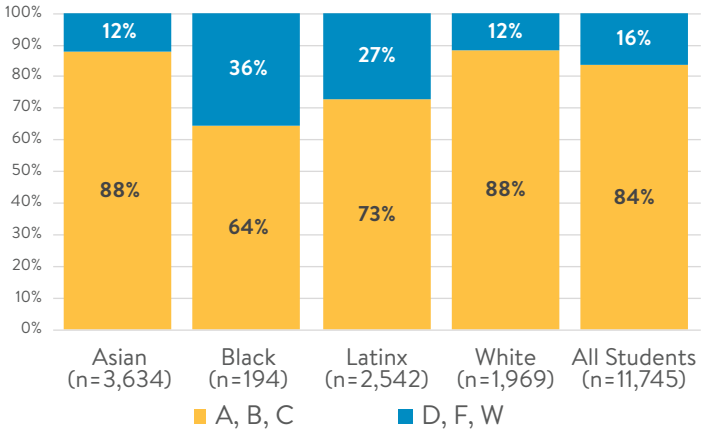


FIGURE 5: CSU Fall 2019 Calculus I Outcomes by Race for Non-Transfer Students

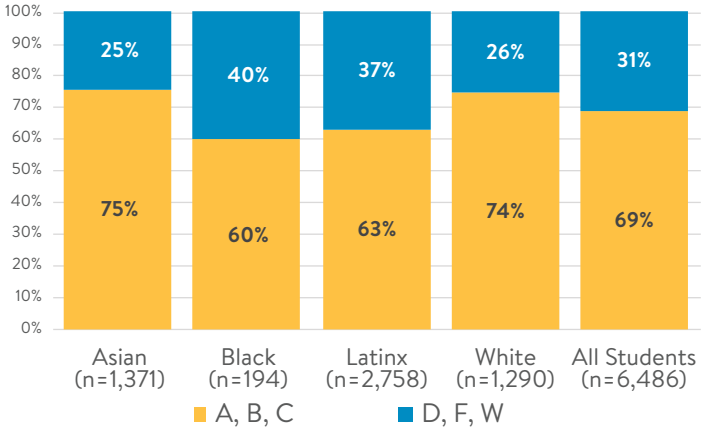
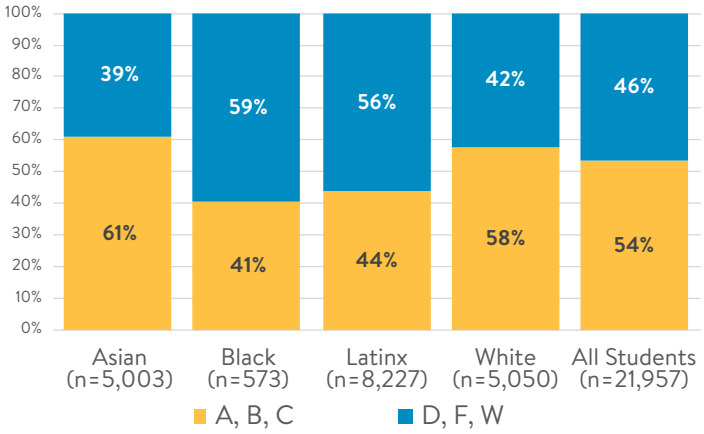


FIGURE 6: CCC Fall 2019 Calculus I Outcomes by Race



STEM Outcomes

Six-year completion of STEM degrees among students taking Calculus was provided by the university systems for a 2014-15 first-year cohort. The CSU cohort consisted of students who had declared a STEM major, whereas the UC analysis focused on all students who took Calculus (because UC does not require all entering students to declare a major), so the cohorts are not directly comparable. Within six years, 55 percent of CSU STEM first-year Calculus takers had earned a degree in a STEM field, as had 51 percent of Latinx and 49 percent of Black students. At UC, 47 percent of first-year Calculus takers had completed a STEM degree during the six-year period, including 40 percent of Latinx Calculus takers and 36 percent of Black Calculus takers (see Figures 7-8). It is likely that more UC students take Calculus without planning to major in STEM, especially because some non-STEM majors, including psychology (Burdman, 2021) and economics, require Calculus. Still, since far more UC first-year students enrolled in Calculus than CSU first-year students (16,239 vs. 3,771), the absolute number of STEM graduates for UC (7,638) was far higher than at CSU (2,080).

Data from the CCC system doesn't directly compare to that from the four-year universities, in that it illustrates transfer patterns as well as STEM and non-STEM degree completion. Though the system has expanded offerings of transfer degrees (the Associate in Art for Transfer and the Associate in Science for Transfer), many students choose to transfer to four-year universities without earning degrees. In all, 61 percent of CCC students who took Calculus in Fall 2014 had earned a STEM degree and/or transferred to a four-year institution within three years (see Figure 9). However, it is unknown whether students who transferred entered a STEM or non-STEM program, so precise STEM outcomes cannot be inferred from the data.

FIGURE 7: UC Six-Year STEM Degree Completion by Race* Among Fall 2014 First-Time First-Year Calculus I Takers

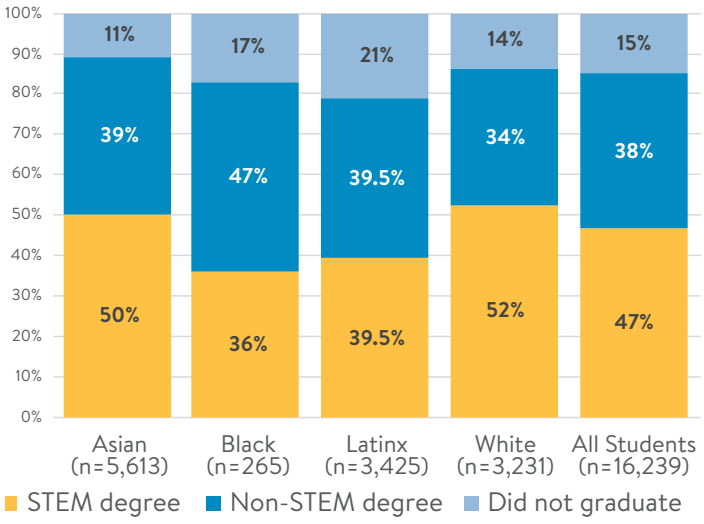
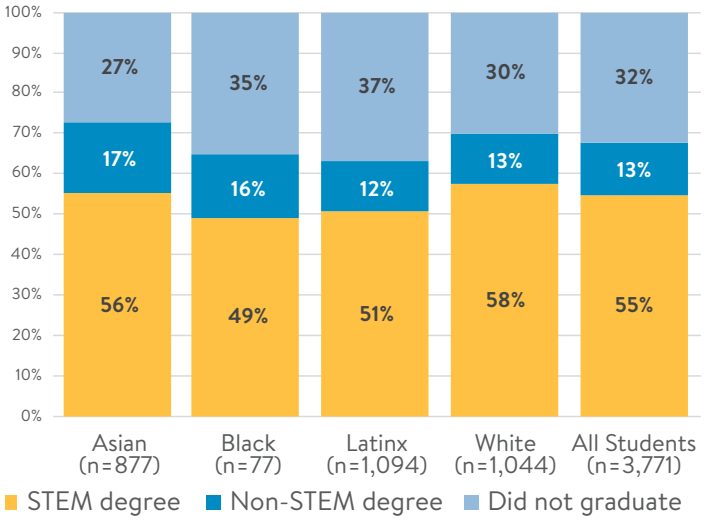
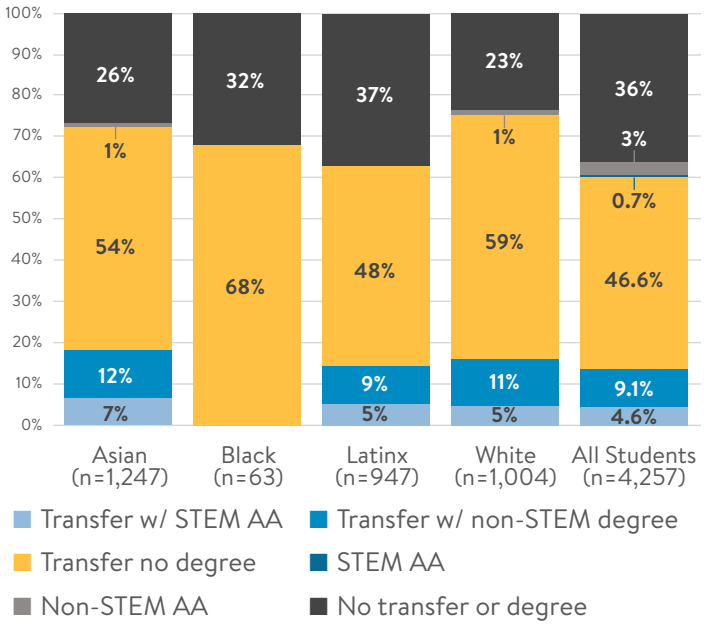


FIGURE 8: CSU Six-Year STEM Degree Completion by Race* Among Fall 2014 First-Time First-Year Calculus I Takers



*Some columns do not add up to 100% due to rounding

FIGURE 9: CCC Three-Year Completion by Race* Among Fall 2014 Calculus I Takers



*Some data may be missing, particularly for Black students, due to cell suppression for privacy reasons

Among university students who took Precalculus before enrolling in Calculus, completion outcomes were lower than for those students who began the sequence with Calculus. The pattern was more pronounced at UC than at CSU, perhaps because the UC cohort included Calculus takers who had not yet declared a STEM major. Only 23 percent of the Fall 2014 UC Precalculus students who later enrolled in Calculus completed a STEM degree, compared with 47 percent of the Calculus-only students. At CSU, among students with declared STEM majors, 43 percent of the Fall 2014 Precalculus-to-Calculus takers completed a degree in

STEM, lower than the 55 percent of the Calculus-only cohort who earned STEM degrees.

Repeating Calculus reduced the chances a student would earn a STEM degree at all three systems. For UC students who did not pass on their first attempt and took Calculus again one or more times, only 28 percent earned a STEM degree within six years vs. 48 percent of those who took the course just once. The impact on STEM outcomes was most pronounced for Latinx students: Those with a single attempt earned STEM degrees at the rate of 40 percent, whereas multiple attempts were associated with 22 percent STEM completion. By contrast, Black students (whose STEM completion rate for one attempt was just 36 percent) were comparatively less affected by multiple attempts. The STEM completion rate for Black students with multiple attempts was 29 percent, the same rate as that for Asian students (whose completion rate for one attempt was a much higher 51 percent). The reasons for these varying patterns could not be discerned from the data.

Similar patterns were observed at the other two systems. At the CSU, 31 percent of Fall 2014 first-year STEM students with multiple Calculus attempts completed a STEM degree within six years, as compared with 55 percent of those with a single attempt. At the CCC, students who attempted Calculus multiple times were also less successful overall. Within the three-year period examined, 14 percent of first-time students with multiple attempts transferred to a four-year institution (with or without a degree), compared with 46 percent of those with a single attempt.[20]

Opportunities for Expanding STEM Access and Equity

California's higher education systems have exhibited their commitment to education equity in multiple ways. The CCC's implementation of Assembly Bill 705 to provide all students access to college-level math and English courses, the CSU's Graduation Initiative, and UC's revised admissions and transfer policies are all designed to expand equitable postsecondary access and success for California students, and all have demonstrated early momentum to improve outcomes for minoritized students.

The data highlighted in this report reveal a need for the systems to continue these efforts with a particular focus on access and success in STEM programs for historically minoritized students. The findings point to stark disparities by income and race. They also suggest a need for particular attention to the participation of females in STEM, as well as the intersection of race and gender with regard to Calculus outcomes.

But demographics are not destiny. The range of strategies highlighted in Part One have shown promise for supporting Calculus and STEM success for historically excluded populations. Taking responsibility for improving outcomes for these students is essential to ultimately diversifying the STEM professoriate and the STEM workforce to better reflect California's population and the needs of the 21st century. Making sure that undergraduate Calculus serves as a gateway, rather than a gatekeeper, to STEM will be a central element of this work.

Endnotes

1. Tough is quoting University of Texas at Austin teaching assistant Erica Winter, speaking to Ivonne Martinez, a student who was struggling in Professor Uri Treisman's freshman Calculus class.
2. The claim refers to Calculus I and Calculus II courses.
3. For the MAA studies, see https://www.maa.org/programs-and-communities/curriculum%20resources/progress-through-calculus/cspcc-publications and https://www.maa.org/programs-and-communities/curriculum%20resources/progress-through-calculus.
4. As explained by Geiser (2017) and Atkinson & Geiser (2009), norm-referenced tests such as the SAT and ACT are designed to differentiate among students (i.e., college applicants) by ranking each test-taker against the national pool of test-takers. As such, these tests are considered more likely to produce racially disparate outcomes than criterion-referenced tests, which evaluate students against a predetermined standard. See also Kurlaender & Cohen (2019).
5. The traditional high school math sequence in the U.S. includes algebra, geometry, and Algebra II, but the integrated sequence weaves these topics into the curriculum each year.
6. The statement was from the National Council of Teachers of Mathematics and the MAA.
7. The studies used various measures of success, which included earning an A, earning a B or higher, and earning a C or higher.
8. Completers here refers to students who pass the course, but the source did not provide a definition of passing.
9. Researchers have heard this concern about Calculus courses transferring while conducting research on other topics. To date, it has not been a primary focus of research in California.
10. For an example of the variation in grading practices in STEM classes at one university (UC Berkeley), see https://liorpachter.wordpress.com/2013/12/23/time-to-end-letter-grades/.
11. It should be noted that not all universities and faculty employing tools such as ALEKS, MyMathLab, and EdReady use them in this way. Many use them strictly as placement tools; others use them primarily as forms of supplemental instruction. This is an area that merits further research.
12. The California Community Colleges' definition of underrepresented includes students who are African-American, American Indian/Alaskan Native, Filipino, Hispanic, Multi-Ethnicity, and Pacific Islander.
13. Estimate of undergraduate and graduate STEM degrees is based on the authors' analysis of 2019-20 provisional completion data from the U.S. Department of Education, National Center for Education Statistics, Integrated Postsecondary Education Data System.
14. The UC and CSU systems provided data for all enrolled fall 2019 students, as well six-year data on a fall 2014 cohort of first-time first-year students. The CCC provided data that was subsequently analyzed by the California Policy Lab as well as the Foundation for California Community Colleges. For fall 2019, the CCC data included students who took classes for credit, excluding high school students in dual enrollment courses. The fall 2014 cohort includes all first-time college students (excluding high school students) who at any point between 2014-15 and 2019-20 had established an initial or informed educational goal of obtaining an associate degree and/or transferring to a four-year institution.
15. In addition, 59 percent of UC students earned a B or better in Fall 2019, as did 44 percent of CSU students.
16. This includes all students who initially enrolled as freshmen, i.e., non-transfer students.
17. At the CCC, 38 percent of students taking Calculus in Fall 2019 earned a B or better.
18. High school GPAs were not available for the CCC students.
19. The Board of Governors Fee Waiver (now called the California College Promise Grant) was used for this analysis because the proportion of students receiving a waiver is higher than the proportion receiving Pell Grants.
20. The proportion earning STEM degrees without transferring was not discernible with accuracy because small totals for some racial groups led to cells being suppressed.
21. The California Community College data request was fulfilled in partnership with California Policy Lab and the Foundation for California Community Colleges.

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Interviewees

David Bressoud, Ph.D. — Director, Conference Board of the Mathematical Sciences; DeWitt Wallace Professor of Mathematics Emeritus, Macalester College (May 10, 2021)

Christopher W. Curtis, Ph.D. — Associate Professor, Department of Mathematics and Statistics, San Diego State University (May 11, 2021, with Michael O'Sullivan)

Concha Gomez Ph.D. — Professor of Mathematics, Mathematics Department, Diablo Valley College (May 20, 2021)

Jess Ellis Hagman, Ph.D. — Associate Professor, Mathematics Department, Colorado State University, Fort Collins (May 12, 2021)

Brit Kirwan, Ph.D. — Chancellor Emeritus, University System of Maryland; Professor Emeritus of Mathematics, University of Maryland, College Park; Executive Director, Transforming Post-Secondary Education in Mathematics (May 12, 2021)

Sophia Lee, Ed.D. — Professor of Mathematics, Citrus College (May 12, 2021)

Luis Antonio Leyva, Ph.D. — Assistant Professor of Mathematics, Education Department of Teaching & Learning, Peabody College of Education & Human Development & Faculty Affiliate, Department for Gender and Sexuality Studies, Vanderbilt University; Postdoctoral Fellow, National Academy of Education and Spencer Foundation (May 14, 2021)

Michael E. O'Sullivan, Ph.D. — Professor, Department of Mathematics and Statistics, San Diego State University (May 11, 2021, with Christopher Curtis)

Susan Rinaldi, M.A. — Director, Academic Achievement Hub, Teaching and Learning Commons, UC San Diego (May 24, 2021)

Pat Thompson, Ed.D. — Professor Emeritus, Mathematics Education, School of Mathematical & Statistical Sciences, Arizona State University (May 18, 2021)

Anthony Tromba, Ph.D. — Professor of Mathematics, UC Santa Cruz (May 14, 2021)

Charity Watson, Ph.D. — Visiting Assistant Professor, Florida International University, STEM Transformation Institute (May 28, 2021)

David Webb, Ph.D. — Executive Director, Freudenthal Institute US; Associate Professor of Mathematics Education, School of Education, University of Colorado Boulder; Co-Principal Investigator, SEMINAL Project (May 17, 2021)

Expert Reviewers

Kendrick Davis, Ph.D. — Chief Research Officer and Associate Professor of Research, Rossier School of Education, University of Southern California

John Eggers, Ph.D. — Teaching Professor in Mathematics, UC San Diego

Jess Ellis Hagman, Ph.D. — Associate Professor of Mathematics, Colorado State University

Michael Kirst, Ph.D. — Professor Emeritus of Education and Business Administraion, Stanford University

Saburo Matsumoto, Ph.D. — Professor, Department of Mathematics, College of the Canyons

Chris Rasmussen, Ph.D. — Professor of Mathematics Education, Associate Chair, Department of Mathematics and Statistics, San Diego State University

Authors

Pamela Burdman, a policy analyst and strategist on equitable college access, readiness, and success, is the founder and Executive Director of Just Equations, a policy institute focused on reconceptualizing the role of mathematics in education equity. She began her career as a reporter for the San Francisco Chronicle and first focused on math equity issues as a program officer at the William and Flora Hewlett Foundation, working with the early developers of new college statistics pathways. She is the author of numerous reports and articles on math opportunity that have influenced policy changes in K–12 and postsecondary math education in California and beyond. She earned a bachelor's degree in philosophy and East Asian studies from Princeton University and a master's in business administration and master's in Asian studies from UC Berkeley.

Melodie Baker is the National Policy Director at Just Equations, where she works to advance the role of math education in promoting equity through national partnerships and policy initiatives. A nationally recognized education leader and advocate, Baker has devoted her career to expanding opportunities for students. She has chaired various national and statewide initiatives, including the Coalition for Community Schools and Raising New York, and was recently tapped to serve on New York's Reimagining Education Advisory Council to devise strategies for reopening schools amid the COVID-19 pandemic. Prior to joining Just Equations in 2020, she was director of education for the United Way in Buffalo, New York. Baker earned her bachelor's degree in public relations from Buffalo State College, a master's in executive leadership and change from Daemen College, and is finishing a doctorate in educational psychology and quantitative methods at SUNY Buffalo.

Francesca Henderson, Just Equations' Math Educator in Residence, serves as in-house math education expert as well as liaison to the larger mathematical community. She is a career educator with a range of experiences and a passion for social justice and equity. She has worked as a researcher, high school math teacher, vice principal, curriculum designer, and education consultant. Her current research focuses on the transition from high school to college, and the role of mathematics in supporting or hindering the college-going process. Henderson received a bachelor's degree in mathematics from San Diego State University and a master's in education from High Tech High Graduate School of Education, where she also teaches graduate students about positive school cultures and equitable discipline practices. She is pursuing a doctorate in mathematics education at the University of Maryland.

Technical Appendix

Data

Learning Lab requested system-level data from each of the public higher education segments in California: the University of California, California State University, and California Community Colleges.[21] The overall goals of the data request were to:

1. Establish state of racial and gender equity gaps in introductory calculus course access and success in the CCC, CSU, and UC in the fall semester of 2019; and
2. Understand the correlation of Calculus I and Precalculus-to-Calculus enrollment with six-year degree outcomes (for UC/CSU) and three-year degree and transfer outcomes (for CCC) by race/ethnicity, income, and gender for a single Fall 2014 cohort. (2014-15 to 2019-20).

Learning Lab submitted data tables that were populated by the segments to provide the following data:

FALL 2019 CALCULUS I COURSE OUTCOMES ANALYSIS

A. Total undergraduate student enrollment by race/ethnicity and student level
B. Total undergraduate student enrollment by race/ethnicity and Pell status
C. Total undergraduate student enrollment by race/ethnicity and gender
D. Enrollment in Calculus I by race/ethnicity, Pell status, and student level
E. Enrollment in Calculus I by race/ethnicity and gender
F. Grades received by students taking Calculus I by race/ethnicity and Pell status
G. Grades received by students taking Calculus I by race/ethnicity and gender

2014 COHORT CALCULUS I COURSE AND DEGREE OUTCOMES ANALYSIS

A. Total undergraduate student enrollment by race/ethnicity and student level
B. Total undergraduate student enrollment by race/ethnicity and Pell status
C. Total undergraduate student enrollment by race/ethnicity and gender
D. Students enrolled in Calculus I by race/ethnicity and Pell status (unduplicated, only first attempt)
E. Year of first attempt of Calculus I by race/ethnicity
F. Number of attempts of Calculus I by race/ethnicity
G. Precalculus coursetaking among students who took Calculus I (unduplicated, only first attempt) by race/ethnicity
H. Average Calculus I grades and average Precalculus grades by race/ethnicity and Pell status
I. Grades received in Calculus I by race/ethnicity and Pell status
J. Grades received in Calculus I by race/ethnicity and gender
K. STEM degree completion for students who took Precalculus by race/ethnicity
L. STEM degree completion for students who did not take Precalculus by race/ethnicity
M. STEM degree completion for students who made multiple attempts at Calculus by race/ethnicity
N. STEM degree completion for students who made only one attempt at Calculus by race/ethnicity
O. Grade received in Calculus I for students who complete at STEM degree by race/ethnicity
P. Degree completion for all undergraduate students by race/ethnicity and Pell status
Q. STEM degree completion for all undergraduate students by race/ethnicity and Pell status
R. Degree completion for all undergraduate students by race/ethnicity and gender
S. STEM degree completion for all undergraduate students by race/ethnicity and gender

- For CCC-specific tables, financial aid information was also disaggregated to include Board of Governors Fee Waiver recipient status.
- For the outcomes tables (items K through S), CCC-specific data requests included associate degree completion only, transfer only, and transfer with an associate degree outcomes.
- STEM degrees for CCC students were determined by TOP Codes: 01 (0101-0199), 04 (0401-0499), 07 (0701-0799), 09 (0901-0999), 17 (1701-1799), 19 (1901-1999), and 490200.
- CCC precalculus data was not used in this report.

STUDENTS INCLUDED IN THE ANALYSIS

UC

Fall 2019

- Total enrollment — Any undergraduate student enrolled in the fall of 2019.
- Calculus I enrollment — Any undergraduate student who enrolled in Calculus I in the fall of 2019.

Fall 2014 Cohort

- Total cohort enrollment — All undergraduate students who were first-time students (disaggregated by first-time freshmen and transfer students) in the fall of 2014.
- Calculus I enrollment — Any undergraduate student from the fall 2014 cohort who at any point took Calculus I between the 2014-15 and 2019-20 academic years.

CSU

Fall 2019

- Total enrollment — Any undergraduate student enrolled in the fall of 2019.
- Calculus I enrollment — Any undergraduate student who enrolled in Calculus I in the fall 0f 2019.

Fall 2014 Cohort

- Total cohort enrollment — All undergraduate students who were first-time students (disaggregated by first-time freshmen and transfer students) in the fall of 2014.
- Total STEM major enrollment — All undergraduate students from the fall of 2014 cohort who declared a STEM major.
- Calculus I enrollment — Any undergraduate student from the fall 2014 cohort who declared a STEM major and at any point took Calculus I between the 2014-15 and 2019-20 academic years.

CCC

Fall 2019

- Total enrollment — Any student who was enrolled in credit-bearing courses in the fall of 2019 semester, excluding high school/dual enrollment students.
- Calculus I enrollment — Any student enrolled in Calculus I in the fall of 2019, excluding high school/dual enrollment students.

Fall 2014 Cohort

- Total cohort enrollment — Any student that was a first-time college student in the fall of 2014, who had at any point between 2014-15 and 2019-20 established an informed or initial educational goal of obtaining an associate degree, transferring to a four-year university, or obtaining an associate degree and transferring to a four-year university (excluding high school/dual enrollment students).
- Calculus I enrollment — Any student from the fall 2014 cohort, as defined in total cohort enrollment above, who took Calculus I between the 2014-15 and 2019-20 academic years.

DATA DEFINITIONS

STEM — Using the NCES definition of STEM for the purposes of this report, a STEM major was any major in the following disciplines: Mathematics, natural sciences (including physical sciences and biological/agricultural sciences); engineering/engineering technology; and computer/information sciences.

Race/ethnicity — The race/ethnicity categories used for the data analyses are the race/ethnicity categories used by institutions to report to the U.S. Department of Education's Integrated Postsecondary Education Data System (IPEDS).

Calculus I — Calculus I or introductory calculus was defined in alignment with the Mathematical Association of America's definition of "Mainstream Calculus I," which is "any first course in calculus that can be used as a part of the calculus prerequisite for higher level mathematics courses" (Bressoud, et al., 2015).

CCC Calculus I Course List

The primary source for developing the CCC Calculus I course list was the California Community Colleges Chancellor's Office Course Identification Numbering System (C-ID) website. If Calculus I courses were not present in the C-ID course search, Calculus I courses were manually identified for the missing colleges through the CCCCO Data Mart list for all courses and colleges. Using the Data Mart list, we added each Course ID and Control Number to the list of Calculus I courses identified in the C-ID search. Guided by the MAA definition of mainstream Calculus I described above, this report was only focused on the first Calculus course a student would encounter in the sequence. Therefore, if there was a sequence of Calculus I courses, only the first course in that sequence was included in the list. Additionally, honors courses were not included.

Methodological Note

The California Community Colleges Chancellor's Office suggested this report include a disproportionate impact analysis for the CCC data, but this suggestion could not be accommodated before publication.

Data for Figures 1-9

FIGURE 1

UC Fall 2019 Non-Transfer Enrollment vs. Calculus Enrollment	Total (n=177,036)	Calculus (n=11,745)
Asian	31.3%	30.9%
Black	2.3%	1.7%
Latinx	25.4%	21.6%
White	20.0%	16.8%
All Other	21.0%	29.0%

FIGURE 2

CSU Fall 2019 Non-Transfer Enrollment vs. Calculus Enrollment	Total (n=257,193)	Calculus (n=6,486)
Asian	16.7%	21.1%
Black	4.0%	3.0%
Latinx	46.5%	42.5%
White	20.0%	19.9%
All Other	12.8%	13.5%

FIGURE 3

CCC Fall 2019 Total Enrollment vs. Calculus Enrollment	Total (n=1,323,009)	Calculus Enrollment (n=21,934)
Asian	12.2%	22.8%
Black	5.8%	2.6%
Latinx	48.0%	37.5%
White	23.2%	23.0%
All Other	10.8%	14.1%

FIGURE 4

UC Fall 2019 Calculus I Outcomes by Race for Non-Transfer Students	A, B, C	D, F, W
Asian (n=3,634)	88%	12%
Black (n=194)	64%	36%
Latinx (n=2,542)	73%	27%
White (n=1,969)	88%	12%
All Students (n=11,745)	84%	16%

FIGURE 5

CSU Fall 2019 Calculus I Outcomes by Race for Non-Transfer Students	A, B, C	D, F, W
Asian (n=1,371)	75%	25%
Black (n=194)	60%	40%
Latinx (n=2,758)	63%	37%
White (n=1,290)	74%	26%
All Students (n=6,486)	69%	31%

FIGURE 6

CCC Fall 2019 Calculus I Outcomes by Race	A, B, C	D, F, W
Asian (n=5,003)	61%	39%
Black (n=573)	41%	59%
Latinx (n=8,227)	44%	56%
White (n=5,050)	58%	42%
All Students (n=21,957)	54%	46%

FIGURE 7

UC Six-Year STEM Degree Completion by Race Among Fall 2014 First-Time First-Year Calculus I Takers	STEM Degree	Non-STEM Degree	Did Not Graduate
Asian (n=5,613)	50%	39%	11%
Black (n=265)	36%	47%	17%
Latinx (n=3,425)	39.5%	39.50%	21%
White (n=3,231)	52%	34%	14%
All Students (n=16,239)	47%	38%	15%

FIGURE 8

CSU Six-Year STEM Degree Completion by Race Among Fall 2014 First-Time First-Year Calculus I Takers	STEM Degree	Non-STEM Degree	Did not Graduate
Asian (n=877)	56%	17%	27%
Black (n=77)	49%	16%	35%
Latinx (n=1,094)	51%	12%	37%
White (n=1,044)	58%	13%	30%
All Students (n=3,771)	55%	13%	32%

FIGURE 9*

CCC Three-Year Completion by Race Among Fall 2014 Calculus I Takers	No Transfer or Degree	Non-STEM AA	STEM AA	Transfer No Degree	Transfer w/ Non-STEM Degree	Transfer w/ STEM AA
Asian (n=1,247)	26%	1%	0%	54%	12%	7%
Black (n=63)	32%	0%	0%	68%	0%	0%
Latinx (n=947)	37%	0%	0%	48%	9%	5%
White (n=1,004)	23%	1%	0%	59%	11%	5%
All Students (n=4,257)	36%	3%	0.7%	46.6%	9.1%	4.6%

**AA in these data is used generically and is inclusive of all different categories of associate degrees.*