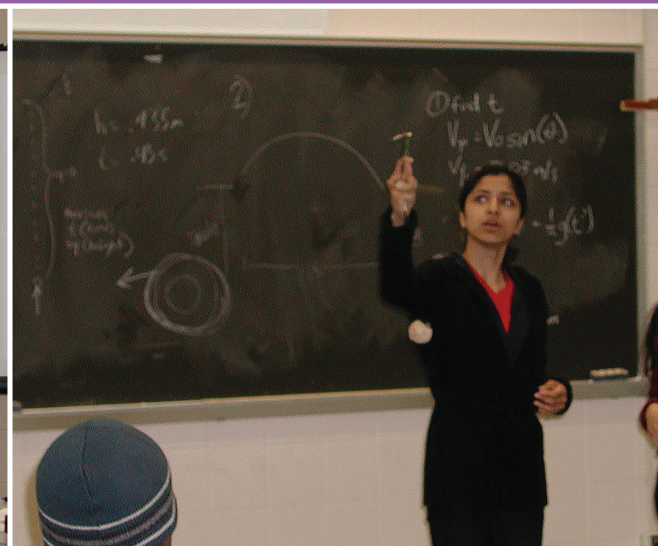




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REFRAMING THE NARRATIVE ON PHYSICS READINESS

Suzanne White Brahmia and Geraldine L. Cochran

Alternative undergraduate physics courses expand access to students and address socioeconomic barriers that prevent many of them from entering physics and engineering fields. The courses also help all students develop quantitative skills.



Isaac aspired to be an engineer. He excelled in every available math and science class, but his school didn't offer calculus. After graduating from high school as the class valedictorian, he enrolled in his state university. There, a math placement exam put him into precalculus, which made him ineligible for the calculus-based physics and chemistry courses required for an engineering degree. The academic placement would delay Isaac's graduation by at least a year.

Initially, Isaac pushed forward, even as he felt increasingly disconnected from the engineering track. The added financial cost of a fifth year to his family, however, ultimately led him to switch majors so that he could graduate in four years.

Although Isaac's case is a hypothetical example, many students we have advised and worked with have had similar experiences. To start taking physics courses—a common entry point for a math-based career path not only in physics but also in computer science, engineering, and the like—US students typically must enroll in or have completed calculus. The rigid requirement disproportionately affects students from socioeconomically disadvantaged districts, where access to advanced math is limited. In addition, the pandemic's disruption to education has had a similar disproportionate effect on them. The exclusion from physics is especially troubling given how little calculus is actually used in most introductory physics instruction.

Discussions around success in calculus-based physics often focus on student readiness—defined solely by the students' prior experience with calculus techniques as measured by placement tests—and are less focused on how well departments support the students admitted to their institution. Students labeled as underprepared are typically required to complete remedial math, which both extends the time it takes them to complete a degree and increases their costs. Some students persist; others are advised to change majors. Advisers usually place students in a physics class based solely on their university math-placement score. That thinking pushes away capable students for reasons unrelated to their potential.

This article examines evidence of unequal access to advanced math before college, explores the unintended gatekeeping function of placement tests, and reflects on the skills that are actually necessary for success in introductory physics. A compelling alternative to the current practice is the long-running, successful program at Rutgers University that expands access into physics while

strengthening the integration of calculus concepts into physics. More broadly, a national consortium is beginning to coordinate resources and support physics departments so that

outcomes for all students in introductory physics sequences can be improved.

Barriers to calculus-based physics

Who gets to take physics in college often depends less on students' ability to succeed and more on their access to math opportunities long before college begins.¹ Precollege education in the US is marked by unequal access to advanced coursework, particularly in math and physics. The gaps are shaped by broad structural inequities across school districts and are often tied to wealth inequality.

Some 21% of US public high school students in fall 2021 attended high-poverty schools, where at least three-quarters of students qualify for free or reduced-price lunch.² As shown in figure 1, students attending high-poverty schools are significantly less likely to have an option to take calculus in high school.

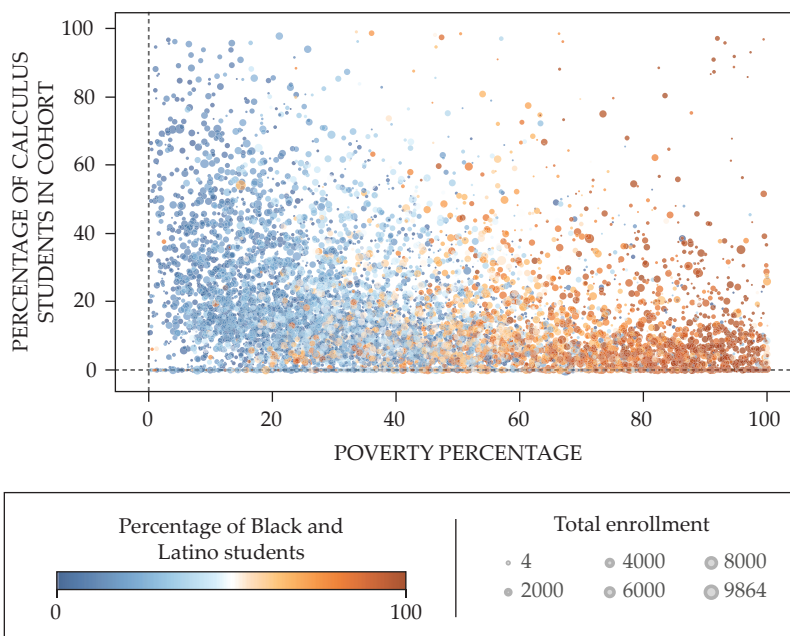


FIGURE 1. THE PERCENTAGES OF HIGH SCHOOL STUDENTS who enroll in calculus classes in US school districts depend in part on the poverty percentage in those districts. The size of the dots reflects the number of students enrolled in a school district, and colors represent the percentage of Black and Latino students. (Figure courtesy of Michael Marder, data from ref. 3.)

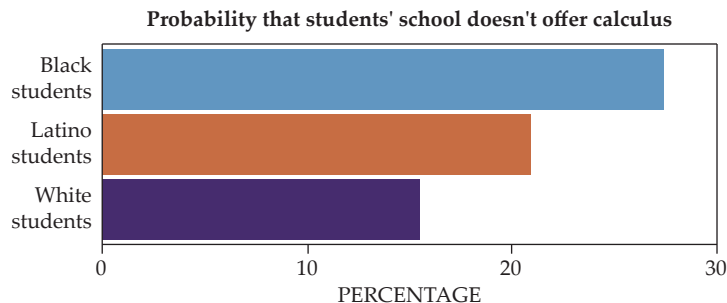


FIGURE 2. THE OPPORTUNITY TO TAKE CALCULUS in US public high schools is substantially different among students that identify primarily as Black, Latino, or white. (Data from Civil Rights Data Collection files for the years 2020–21 and 2021–22; available at <https://civilrightsdata.ed.gov/data>.)

The disparities are even more pronounced for Black and Latino students. In 2021, only 35% of US public high schools with predominantly Black and Latino students offered calculus compared with 54% of schools with lower enrollment of the two groups. That same year, the only mathematics courses available in some US public schools were at a level below Algebra 1.³ As shown in figure 2, Black students were nearly twice as likely as white students to attend a high school where calculus wasn't offered.

The differences in course availability are not merely academic; they shape college trajectories and limit access to STEM majors, which often require calculus as a prerequisite. Recognition of that context is essential to designing physics instruction and placement practices that do not penalize students for unequal access to opportunity.

The use of math placement tests to determine readiness for physics courses mirrors and reinforces inequities in educational opportunity. The tests tend to promote the fundamental attribution error made by instructors: that they interpret a student's lack of calculus preparation as a personal shortcoming rather than as a result of systemic barriers, such as unequal access to advanced math in high school.

Additionally, most placement tests emphasize procedural skills in algebra and trigonometry. Typical math problems

test a student's ability to rearrange equations without real-world context.

That kind of procedural competence is important, but excellence in math procedures shouldn't form the basis for inclusion in a physics course. Students' success in physics relies predominantly on their physics quantitative literacy (PQL): the ability to interpret equations, apply math in context, and connect math to physical meaning, all of which are best learned in a physics course.^{4,5} Such flexible, context-based reasoning is rarely taught in standard prerequisite math courses, yet it benefits all students regardless of prior preparation.⁶

Students who struggle with foundational algebra will need added support that is beyond the scope of a physics course. But for schools to rely on placement-test scores to determine readiness for physics is deeply flawed. Test scores often serve as rigid gates that filter out capable students and reinforce opportunity gaps. That sort of gatekeeping reflects a broken-student narrative—students must fix themselves to belong—when, in fact, many were never given a fair opportunity to begin with.

Even among students who do enroll in calculus-based physics courses, disparities in preparation shape outcomes. About 75% of students who place into college calculus took it

Physics quantitative literacy

The following example, about the first law of thermodynamics, aims to assess an aspect of quantitative reasoning that is ubiquitous in physics.

The internal energy of a system can be increased by doing work on the system or by heating it, and it can be decreased by cooling the system or if the system does positive work on the environment. Which of the following equations represent(s) this relationship (U is the internal energy of

the system, Q is positive when energy flows into the system, and W is positive when work is done on the system)? **Choose all that apply.**

- $\Delta U = Q - W$
- $\Delta U = -Q + W$
- $\Delta U = Q + W$
- $-\Delta U = Q + W$
- $-\Delta U = Q - W$
- $-\Delta U = -Q + W$

Students are often challenged when asked to symbolize scalar quantities that take both positive and negative values and to interpret a change in a signed scalar quantity. Only about one-third of students at the end of their calculus-based physics sequence and only about two-thirds of physics majors by the end of their junior year answer this question correctly. The correct answer is C. (Example from S. White Brahmia et al., *Physics Inventory of Quantitative Literacy*, 2021.)

PHYSICS READINESS

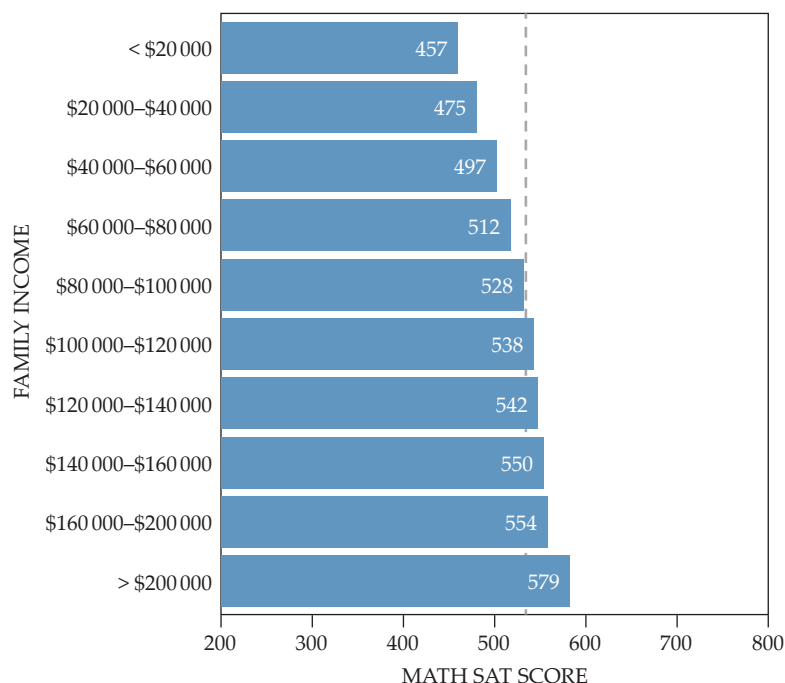


FIGURE 3. AVERAGE MATH SAT SCORES of student test takers in 2009 are correlated with family income. The College Board suggests that a score of 530 indicates college readiness, but students from households with an income under \$100 000 often score below that benchmark on average and require remedial coursework. (Chart adapted from ref. 8.)

in high school, which puts students without that opportunity at a disadvantage.⁶ One study across three selective institutions found that Analytical Physics exam scores are correlated with math SAT scores and prior physics experience⁷—both of which are tied to family income⁸ (see figure 3).

When course design aligns with student preparation, however, performance gaps shrink. After controlling for a student's socioeconomic status and SAT scores, researchers found that ethnic disparities in learning gains—the actual learning that was done during a course—were largely eliminated.⁹ Rather than asking who is prepared for physics, instructors should ask whether their courses are prepared for the students that their institutions enroll.

Preparing to teach all students

When instructors focus only on student readiness—rather than on how they can effectively support diverse learners—it can have unintended consequences. They often rely on metrics of mathematical readiness that are misaligned with the goals of physics courses, that reflect disparities in students' access to relevant high school courses rather than students' abilities, and that disproportionately affect Black and Latino students. The narrow focus on procedural mathematical preparation can also lead students to question whether they belong in physics at all.

Remediation-focused approaches, which address disparities in student access to precollege mathematics, often place the burden on students and leave the structural issues in

physics courses unexamined. Even valuable, well-intentioned supports, such as tutoring or bridge programs, require extra effort and time from students and leave the physics courses themselves unchanged. A more effective approach focuses on redesigning instruction to support a broad, diverse group of learners.

Instead of requiring students to complete remedial math before enrolling in physics, departments can embed their course sequences with PQL. That integration helps students develop the ability to interpret equations, explain physical quantities, and connect math relationships to real-world phenomena. Optional instructor-led support courses or extended, credit-bearing pathways that integrate PQL into instruction offer a more inclusive and effective alternative. They are beneficial to students with various levels of preparation.

A sensible starting point for integrating PQL support is to examine how instructors use math in introductory physics.

Most problem-solving exercises in introductory physics courses in the US don't require calculus, even in courses that are designated as calculus based.¹⁰ Yet reasoning about core calculus ideas—for example, variation, rate of change, and accumulation—is essential for students who are learning for the first time about dozens of physics quantities, including force, momentum, and energy.

Compared with a traditional, familiar math course that provides context-free practice, a course with contextual physics quantities requires a different approach from students and instructors.^{4,11} Conceptual quantitative skills are rarely outcomes of traditional calculus instruction, which tends to focus on symbolic manipulation for solving math problems,¹¹ most of which are irrelevant in physics. Moreover, the math structures that physicists depend on—basic operations with simple function types like linear and inverse proportionalities and quadratic polynomials—are more widely accessible to students than are advanced techniques such as integration by partial fractions. By emphasizing how physical quantities and their relationships to each other can be constructed and symbolized, instructors can better support all students in developing meaningful mathematical reasoning in physics. (See the box for an example that tests PQL.)

For physics instructors, the lesson is clear: By identifying when students need PQL-specific skills and weaving those skills into courses, they can boost learning without lowering expectations.⁵ Instructors who use that approach report im-

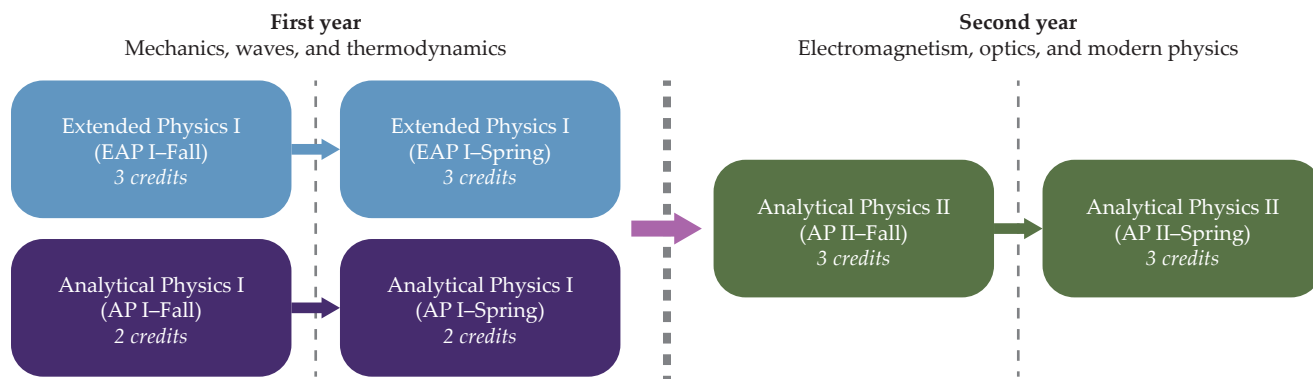


FIGURE 4. TWO PHYSICS SEQUENCES are available to undergraduate students at Rutgers University. The standard Analytical Physics (AP) pathway requires a calculus placement test. For students who lack the opportunity to take calculus in high school, the Extended Analytical Physics (EAP) sequence incorporates calculus-based reasoning and includes additional time for them to develop skills in physical quantitative literacy. By the end of the first year, all students are prepared for the second-year physics courses. A separate honors track is not shown. (Figure adapted from ref. 13.)

proved outcomes for all students.¹² Many physics departments already offer honors programs for students that are well prepared by their precollege physics and calculus courses. Why not invest in students who lack access to those courses? The challenge isn't fixing students—it's designing courses that help all of them thrive.

One extended course model removes the calculus prerequisite and adds credit hours for students to develop PQL at the same time that they are learning the course's core physics content. The Extended Analytical Physics (EAP) program at Rutgers demonstrates how that model works in practice.

A case study in New Jersey

Since 1986, Rutgers' department of physics and astronomy has supported mathematically underprepared engineering students through the EAP program.^{13–15} Launched with state and federal funding, the program aims to address the mismatch between New Jersey's diverse population and the STEM-graduate population at its flagship university. The students who enroll in precollege calculus in New Jersey public schools mirror the national trend shown in figure 1, and those students are primarily from affluent districts with few Black and Latino students. To address the disparity, Rutgers created a parallel physics pathway that allows students who are not placed into calculus to stay on track for engineering degrees. The Rutgers program was already unusual in 1986: It split the mechanics sequence across two semesters to make room for the increasing demand for first-year programming courses.

The EAP pathway, shown in figure 4, is an introductory physics sequence for engineering majors who place in a math course below calculus.¹³ It spans three or four semesters and totals 9 or 12 credit hours, depending on the major. Typically, students take EAP I in fall and spring, which prepares them for the standard Analytical Physics (AP) II course in the following fall—for some majors, a second AP II course may be

taken in the spring. The alternative EAP pathway complements the standard AP sequence, which also runs three or four semesters with 7 or 10 credits. Since its launch, EAP enrollment has grown from 90 students annually to approximately 300, compared with the 900 students who are in the AP sequence each year. Most students remain in either the EAP or AP sequence, although some switch pathways.

Students in the EAP pathway take an additional credit hour each semester of the first year for deeper engagement with physics concepts and PQL. Importantly, the course does not teach remedial math; instead, it helps students understand how algebra, precalculus, and introductory calculus concepts apply in physics contexts and introduces PQL topics as needed.

The program has broadened access to STEM degrees for students from diverse educational backgrounds. Figure 5 illustrates how the EAP is meeting its objectives. Degree completion for all students is boosted by the gains among women and those from historically underrepresented groups in STEM. Compared with the two years before the EAP's implementation, the number of underrepresented minority students who complete STEM degrees in six years has increased by about 50%.¹³ A 10-year follow-up study of Rutgers first-year students that pass the introductory physics sequence yielded similar results.

The strength and longevity of the EAP model lies in implicit structures that build student agency in a rigorous scientific community:

► **Flexible entry.** Placement scores help inform what courses students take, but they can choose or switch pathways through the start of the spring semester of the first year to maintain control over their courses.

► **Representative instructors.** The faculty instructors and leaders of the EAP program include members from underrepresented groups in physics who serve as role models for students.

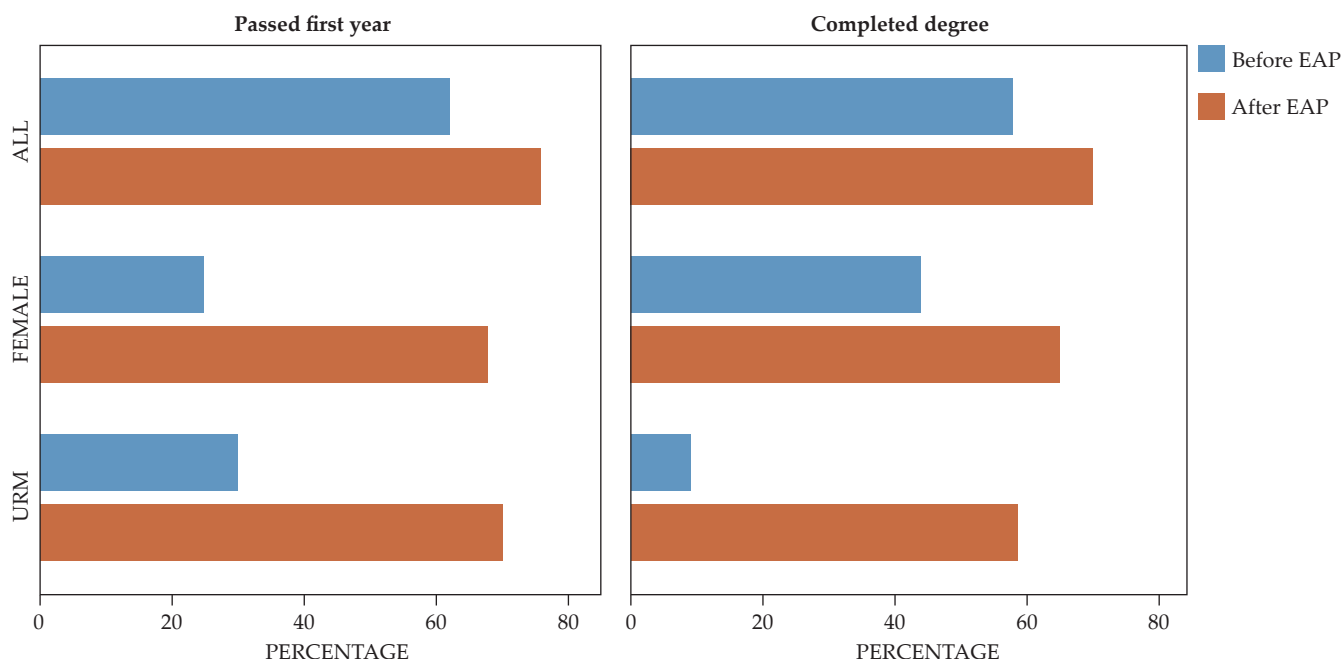


FIGURE 5. THE PERCENTAGES OF STUDENTS who passed first-year physics courses and who completed a STEM degree increased after the introduction of the Extended Analytical Physics (EAP) program at Rutgers University. Results are averaged over the two years before and over seven years after the program's introduction. The left group of bar graphs shows percentages of all students, female-identifying students, and students from underrepresented minority (URM) groups who passed first-year physics, regardless of the physics pathway they took. The right group of bar graphs shows similar results for students who earned STEM degrees within six years. A conservative estimate of uncertainty is about 4%. (Figure adapted from ref. 13.)

► **Supportive environment.** The program fosters a safe pedagogical space where students can take risks and learn from mistakes.

► **Deep learning focus.** Activities emphasize conceptual and procedural understanding of linear and inverse proportional relationships and extend that reasoning to other critical functions commonly found in physics models.

► **Calculus foundations without calculus.** Students explore core calculus ideas, such as quantities, rates of change, and accumulation, through accessible precalculus reasoning.¹¹

The Rutgers EAP model integrates PQL development into standard introductory physics by emphasizing quantitative reasoning that's rarely addressed in math courses but is essential for physics. Physical quantities, which are central to every physics model, are related through a few core equation types that occur across various contexts. Helping students identify the mathematical role of each quantity deepens their understanding of precalculus concepts and prepares them to engage with the scientific ideas that the quantities represent. Crucially, the reasoning is accessible to precalculus students and focuses on conceptual skills rather than on procedural calculus skills.

Developing PQL also means that students will be able to interpret symbols and letters as representations of measurable, variable quantities with units and often with direction

and sign. Vector quantities add representational complexity that requires students to be fluent with notation such as unit vectors, subscripts, and signed scalars. Those conventions convey essential information about orientation and reference frames, which are vital for students to accurately model physical systems and are suitable to introduce to students before they take calculus.

The Rutgers EAP program serves as a model for effective expanded access and sustained success. Some institutions of higher education are beginning to rethink introductory physics through an access lens. The Ohio State University now offers an extended course structure based on the Rutgers model. The structures at other schools tend to result in students taking an extra year. Given the financial strain of an additional year in college, it is critical to reevaluate access criteria for calculus-based physics and expand programs that effectively support those students.

Supporting all capable students

Efforts are underway to expand the Rutgers model to other US schools. The nascent NSF-funded network known as TIPSSS, or Transforming Introductory Physics Sequences to Support all Students (<https://u.osu.edu/tipsss>), aims to help connect departments and educators who are committed to rethinking introductory physics instruction for all driven,

capable students, regardless of what math courses they were able to take in high school.

Through its members, TIPSSS supports departmental transformation by adapting curricula and conducting studies on student learning and identity.¹⁶ TIPSSS resources promote PQL and help college-level instructors customize materials. It also offers a rare professional community for instructors who are driving change. TIPSSS is a step toward collective action—it connects departments that are committed to rethinking instruction and broadening access so physics becomes a path, not a barrier, to students' futures.

Meeting students where they are academically requires instructors to rethink long-standing course designs with sustained effort and institutional support. Research on PQL and programs like Rutgers' EAP show that improvement is possible. Physicists are natural problem solvers, but physics instructors cannot single-handedly fix the deep disparities in US precollege math education. That essential work is underway elsewhere and will take time. Meanwhile, we have agency. As university faculty, we can rethink the signals we send through course design and placement policies. Physics instructors share a commitment to unlocking student potential. Now we must ensure that our instruction supports all students—not just those fortunate enough to take physics and calculus in high school.

Isaac's story may be common, but it doesn't have to be the norm. What are we doing to make sure students like Isaac

aren't turned away before they've had a chance to pursue the futures they envision?

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