Implementing Projects in Calculus on a Large Scale at the University of South Florida

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Introduction

It is widely agreed upon that there is a significant need to increase the numbers of well-trained scientists, mathematicians, and engineers to meet the demands of an increasingly technological workplace in the United States and around the world. In particular, the President's Council of Advisors on Science and Technology report (Olson & Riordan, 2012) suggests that increasing the percentage of science, technology, engineering, and mathematics (STEM) graduates even by a relatively small percentage would have a big impact.

Many colleges and universities have been working on retention in STEM using a variety of strategies. At the University of South Florida (USF), as part of an NSF-funded STEM Talent Expansion Program (STEP) grant, we decided to try a number of approaches focused on student success in calculus, which is a gateway course with high failure rates. One approach in Engineering and Life Sciences Calculus I involved using undergraduate peer leaders to facilitate students working in groups of 3 or 4 on highly structured guided inquiry activities following the Process Oriented Guided Inquiry Learning (POGIL) model, and building a successful approach previously implemented in chemistry (Lewis & Lewis, 2005, 2008). The results of that intervention and related data analysis are described in Bénéteau et al. (2016). Another approach was to replace the final exam in Engineering and Life Sciences Calculus II and III courses by a real-world project. This approach differs from what is traditionally called project-based learning, PBL (Blumenfeld et al., 1991; Savery, 2015; Thomas, 2000). This term has sometimes been used interchangeably with another PBL, problem-based learning (Hmelo-Silver, 2004; Savery, 2015; Tawfik, 2015). Both PBLs can be defined as learning models with an emphasis on creating high levels of motivation and cognitive skill development in students working on open and complex problems with facilitation (Mills & Treagust, 2003; Williams & Williams, 1994). There has been some overlap in the use of the terms problem and project in prior literature; however, there are subtle differences between the PBL approaches (Hmelo-Silver, 2004; Mills & Treagust, 2003; Perrenet, Bouhuijs, & Smits, 2000). Ultimately, project-based learning has been considered to be more readily applicable to engineering education at the post-secondary level (Mills & Treagust, 2003), but activities drawing from the two PBL approaches have been developed to promote deep understanding for 5th graders (Barron et al., 1998). Regarding effectiveness, meta-analyses have found that problem-based learning can foster positive student attitudes and improve performance, especially in areas that are aligned to the intervention (rather than on general tests) (Dochy, Segers, Van den Bossche, & Gijbels, 2003; Gijbels, Dochy, Van den Bossche, & Segers, 2005; Shin & Kim, 2013; Strobel & Van Barneveld, 2009). Project-based learning is mostly reported in k-12 education (Boaler, 2002; Marx et al., 1994). Very few implementations have been reported in college calculus courses (Milligan, 2007). In the studied setting, the project-option curriculum is different than either PBL setting and is unique in that the faculty do not modify lectures or classroom discussions, but simply replace an exam with a project that the student has to work on outside of class. More detail on how the projects are implemented is given below. One advantage of this approach is the relative ease of implementation, since faculty can continue to use the teaching techniques and strategies they are comfortable with.

The premises of this approach were that offering students the option of replacing their final exam with a project (hereafter referred to as the project option) could: (1) stimulate student engagement by allowing them to link calculus with their particular interests; (2) increase personal attention from faculty members (and project advisors if they were not faculty) that might lead to increased student learning; (3) incorporate an active approach to learning; (4) prepare students for later work in industry by giving them practice with modeling; (5) enable contact with other professors or people in industry, leading to increased marketability. Preliminary implementations of this approach are described in Abramovich & Grinshpan (2008) and Grinshpan (2005).

In March 2007, David Milligan defended a Ph.D. dissertation in the College of Education at USF on real-world application projects in collegiate mathematics education (Milligan, 2007). From an extensive literature review into conceptually similar teaching approaches, he concluded that project options were unique in their employment at USF. Upon comparing project and non-project (final exam) groups, mathematical proficiency was found to be on a similar level for both groups before starting the project work or final exam preparation. Afterwards, project students reported higher levels of course satisfaction and an improved positive perception of mathematics. On average, project students spent about twice as much time preparing their projects as non-project students did in preparing for their final exam.
Since that time, the project option has continued to be offered for wider populations enrolled in calculus courses at USF and was specifically chosen as a key approach for expansion within STEP grant activities. The previous work did provide quantitative and qualitative information supporting the benefits of intervention, but failed to find a significant effect on math proficiency (Milligan, 2007). In considering whether to interpret the failure to find a significant effect as evidence of a true lack of impact, several issues with the statistical analysis emerged: first, t-tests were performed multiple times, with each course section interpreted separately; second, the sample size was small, leading to a lack of statistical power; and third, students' previous aptitude might have had an impact on the outcome measure that should have been taken into account. Seeking evidence of impact for the wider-scale implementation of the project option for calculus at USF necessitated an approach to analysis that would eliminate or control for most of these problematic issues. For example, by combining data from multiple sections, we could gain more power to examine evidence for an intervention effect as well as determine how such an effect might vary by sex or race/ethnicity, which is desirable from an equity perspective. Further, we could choose a short-term and a longer-term outcome measure that would determine impact on student retention and progression in STEM majors, our main goal for expanding the approach as part of the STEP activities. In this article, therefore, we examine the effect of the project option

on pass rates in Calculus II and III and retention in junior level course work, when implemented on a large scale by multiple professors in many sections.

Description of the Project Option

Developing projects

In sections implementing projects, individual students chose whether to do a project or take the final exam. In doing so, they chose a project advisor who was not the calculus instructor; this project advisor was typically a faculty member in a science or engineering department, or was a supervisor at the student's place of employment. Two of the co-PIs (an engineer and a biologist; hereafter co-PI advisors) were often the first resource for students seeking project advisors in those areas; they sometimes referred students to colleagues as potential project advisors, and sometimes acted as project advisors themselves. Projects were evaluated by both the project advisor and the calculus instructor.

Useful projects need to be clearly defined, conceptually straightforward, and mathematically tractable given the level of students' mathematical training. Moreover, the questions underlying the projects need to be sufficiently interesting that the students are able to stay motivated. The co-PI advisors took on primary responsibility for developing suitable projects, and their basic approaches are described below, but it is important to note that there is no single way to develop projects meeting these requirements, and faculty had much leeway. The decision to offer projects was voluntary on the part of calculus instructors, although verbal encouragement was provided by the department and by colleagues working on the STEP grant. Ten instructors who were not otherwise involved made the choice to implement projects in their calculus classes.

For engineering projects, the co-PI advisor found it effective to develop in advance a list of problems that he could assign to students. By contrast, for life sciences, the co-PI advisor found it valuable to suggest projects that corresponded to students' varying interests and mathematical abilities as determined via an individual interview process. These differing approaches stemmed partly from cultural differences between the disciplines – with life sciences students often weaker in mathematical training – and partly from the fact that the engineering problems all involved well-defined and well-known theory, while tractable life sciences problems frequently are more exploratory in nature. We also provided students with several online resources to help convey ideas for projects; these included a wiki with listings of ideas for life sciences projects, a listing of titles of all projects completed since the outset of our work, and an online journal of papers based on what we judged as the best student projects from past terms. These resources can be found at http://shell.cas.usf.edu/math/mug/ and http://scholarcommons.usf.edu/ujmm/.

Most students needed to consult with their project advisors at least twice before submitting rough drafts of their papers. We encouraged project advisors to set their own limits on time invested with the students. Some consultations were conducted by email, while others took place in person. Some of them involved discussion of mathematical technique; others focused on refining the problem being addressed by the student.

We provided students with a basic template for their papers, specifying that they include a cover page, abstract, table of contents, motivation for the problem addressed, mathematical description and approach to the solution, results and discussion, conclusions and recommendations, literature cited, and appendices (detailed calculations or computer code).

These advising sessions with students were challenging as well as rewarding in many ways. Box A describes the experiences of our two co-PI advisors.

How were projects assessed?

Projects were assessed both by the project advisors and the calculus instructor, but only the latter provided a grade. The project advisors were asked to provide answers to these questions:

1. How independently did the student work?
2. How clearly did the student provide a context for the work? (Put differently, how good was the introduction?)
3. How clearly did the student write out and define the terms in the equations?
4. How clearly did the student describe the methods used to analyze the problem?
5. (Optional) What do you think is the quality of the student's mathematical analysis?
6. Overall, how well does the student understand what he/she has done?

These questions were intended to allow the calculus instructor to focus on the mathematics as such, and to relieve them of some of the burden from interpreting a problem in an applied field with which they might have limited familiarity. It was necessary to keep the project advisor's assessments purely advisory, since the instructor of record for the course is the only one who can assign grades. Individual instructors determined their own criteria for grading.

What was the impact of the project option on students?

We wanted to examine how the project option impacted student retention in calculus classes as well as follow-up courses. More specifically, the main aims of our study were to answer the following questions.

1. How well do students perform in project-option calculus sections, as indicated by pass rate and withdrawal rate, in comparison to concurrent non-project-option sections and to historical sections before the implementation? Do the results differ when broken down by sex and race/ethnicity?
2. How does completing a project affect the overall throughput in key follow-up courses between students who did, and those who did not submit projects, respectively, in the project option sections?

The answer to the first question is important because it can provide evidence as to whether the implementation of project-option calculus courses helps students to pass the course, and thus help the department to make data-driven decisions about continuing the project-option courses. The answer to the second question can offer information for students about whether the choice of completing a project can better prepare them to pass key follow-up courses in their majors. In what follows, we give detail on the methods and results of the data analysis performed.

Methods

Participants

Participants in this study were all students enrolled in courses of Engineering, Calculus II and Calculus III at the University of South Florida, a large southeastern U.S. public research university. A roster file was obtained from the registrar's office for students enrolled in these courses and follow-up courses from spring 2003 to spring 2015. Information was retrieved for each student regarding demographic background (e.g., race, sex), SAT score and course grade. The identity of sections in which the project option was implemented and the names of students who submitted projects in those sections during the relevant period were provided by the course instructors, and merged with the roster file.

Statistical analyses compared students in three groups: 1) the students in project-option sections, 2) the students in concurrent sections where the project option was not offered (concurrent non-project-option group), and 3) the students in historical sections prior to the implementation (historical group). The cutoff points for grouping are fall 2008 for Engineering Calculus II and spring 2009 for Engineering Calculus III. Students that are enrolled in these courses before the cutoffs, were considered to be in the historical group. Because night sections typically enroll different sorts of students than day sections, here we report on the day sections only. Sections offered during fall or spring semesters were included, but not those offered during summer semesters. While we include descriptive information above regarding the way in which project advisors approached students in Calculus for Life Sciences, we do not include that course in the analysis because the project option in Calculus for Life Sciences pre-dates the STEP project and there are no natural comparison groups.

Pass and withdrawal rates were used as outcome measures for group comparisons. Students with grades of "C" or better were considered to pass, corresponding to requirements for earning an Engineering B.S. degree. Students who withdrew from the class prior to a date set by the Registrar for dropping without academic penalty (typically the end of ninth week of a term) were considered to have withdrawn. Overall throughput was calculated as the proportions of students who passed the follow-up courses, out of the total number of students who submitted projects and those who did not, respectively, in the project-option sections.

We calculated the numbers of students and sections, percentages of female and underrepresented minority (Black and Hispanic) students, and SAT math scores for project options, concurrent, and historical groups. To address the first research question, we graphed the mean pass and withdrawal rates with their 95% confidence intervals for each group and each course, using SAS 9.3. We also graphed mean pass and withdrawal rates (and CIs), to explore whether the effect of the project option was related to sex and/or to race/ethnicity.

For research question two, we tracked students with and without projects submitted in the project-option sections, and report the throughput rate into the follow-up courses. In addition to Calculus III, we chose two follow-up courses (Thermodynamics and Electrical Systems) because they require calculus courses, are offered by the College of Engineering, and are required by most B.S. programs in engineering. At present, the College of Engineering offers eight B.S. programs (Chemical, Civil, Computer, Electrical, Industrial, General, Computer Engineering, Computer Science and Information Technology). All these programs, except Information Technology, require the completion of Engineering Calculus II and III. All of the engineering degrees require either Thermodynamics and Electrical Systems or both. Students majoring in Chemical Engineering need to take Thermodynamics, but not Electrical Systems. Students majoring in Computer and Electrical Engineering need to take Electrical Systems, but not Thermodynamics. Students majoring in Civil or Industrial Engineering need to take both Thermodynamics and Electrical Systems. By tracking these two courses, therefore, we can capture data on all students following the different pathways toward engineering degrees. Because most students take the follow-up courses within two years, it is reasonable to track students in the project-option sections through spring 2013, as they have had enough time to enter the follow-up courses. If students attempted a course multiple times, we analyzed the grade for the last attempt.

Group	Number of students	Number of sections	% female	% minority	Mean SAT math score (SD)
Engineering Calculus II					
Project-option	1589	29	21.1	24.3	617 (70)
Concurrent non-project-option	1405	26	19.2	26.8	608 (71)
Historical	2316	45	19.0	21.9	605 (76)
Engineering Calculus III					
Project-option	1431	26	18.2	24.4	619 (75)
Concurrent non-project-option	825	15	21.8	24.3	620 (73)
Historical	1870	36	17.8	21.8	607 (77)

Table 1. Student demographic information in each group for each course.

Group	n	% female	Asian	Black	Hispanic	White	% Minority	SATM (SD)
Engineering Calculus II								
Did a project	314	81 (26%)	17	23	55	188	25%	609 (76)
Did not do a project	1068	222 (21%)	78	74	183	660	24%	620 (68)
Engineering Calculus III								
Did a project	230	59 (26%)	17	19	42	137	27%	605 (71)
Did not do a project	898	157 (17%)	85	54	158	530	24%	624 (76)

Table 2. Characteristics of students (not) doing projects in project-option sections, up to Spring 2013. SATM is the mean score on math SATs. Minority means Black or Hispanic.

To examine the pass rates in the three comparison groups, their potential relationship with sex and race/ethnicity, and their interactions, we used logistic regression. SAS (Version 9.4) was used for the analysis. To identify satisfactory models, we first fit a saturated model (which includes all possible predictors and their interactions). We then deleted interaction terms and used likelihood ratio tests to evaluate the fit of the reduced models, retaining the most parsimonious model that provides an accurate fit, using the p-value from a likelihood ratio test ($p < 0.05$) as our criterion.

Results

Background Information

As shown in Table 1, the percentage of female students in the classes ranged from 18 to 22, and the percentage of underrepresented minority (Black and Hispanic) ranges from 22 to 27 across groups. The data indicate that the sexes, races, and ethnicities were about as well represented between those who did and did not do projects. Table 1 shows that the maximum among-group difference in mean SAT math score is 13 points; as the standard deviation is greater than 70 for each group, we conclude that there are no sizable differences among groups in SAT math scores.

Table 2 shows demographic characteristics of students in both Engineering Calculus II and III, according to whether they did projects. While about 21% of students in the classes were women (Table 1), a slightly larger fraction of those doing projects (Table 2) were female. Similarly, minority students were slightly over-represented among those completing projects, as compared with the classes as a whole (Table 2).

Student Performance on Projects

Pass and withdrawal rates for each group in each course are given in Figures 1-2. For Engineering Calculus II, there were 2,316 students in the historical group, enrolled in 45 sections, with an average pass rate of 55.4% and average withdrawal rate of 22.7%. There were 1,405 students in the concurrent non-project-option group in 26 sections, with an average pass rate of 51.7%, and average withdrawal rate of 17.9%. There were 1,589 students in the project-option group in 29 sections, with an average pass rate of 63.9%, and average withdrawal rate of 13.5%. Overall, students in the project-option group performed better, as compared with the concurrent non-project and historical groups, who obtained a higher pass rate and lower withdrawal rate.

For Engineering Calculus III, there were 1,431 students in 26 sections of project-option calculus, with an average pass rate of 72.3%, and average withdrawal rate of 7.6% (Figure 2). There were 825 students in 15 sections of the concurrent non-project-option group, with an average pass rate of 69.4%, and average withdrawal rate of 10.3%. There were 1,870 students in 36 sections of the historical group with an average pass rate of 62.4%, and average withdrawal rate of 15.7%. Thus, students in

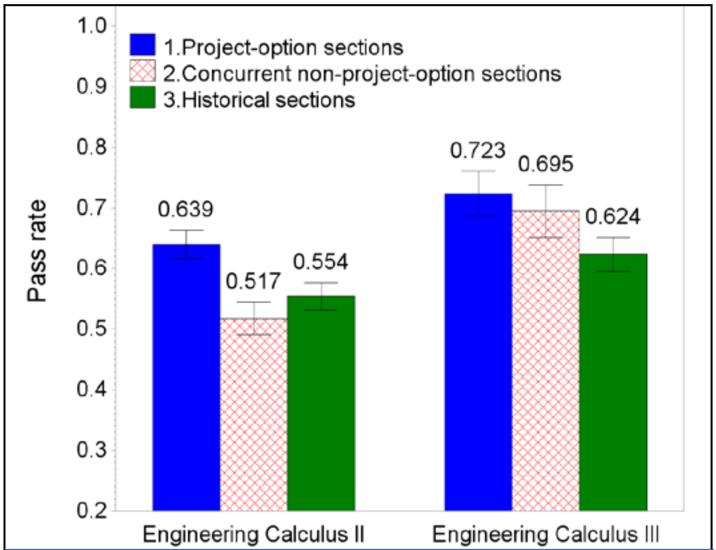

Figure 1. Average pass rates and their 95% confidence intervals, for project-option, concurrent non-project-option, and historical sections.

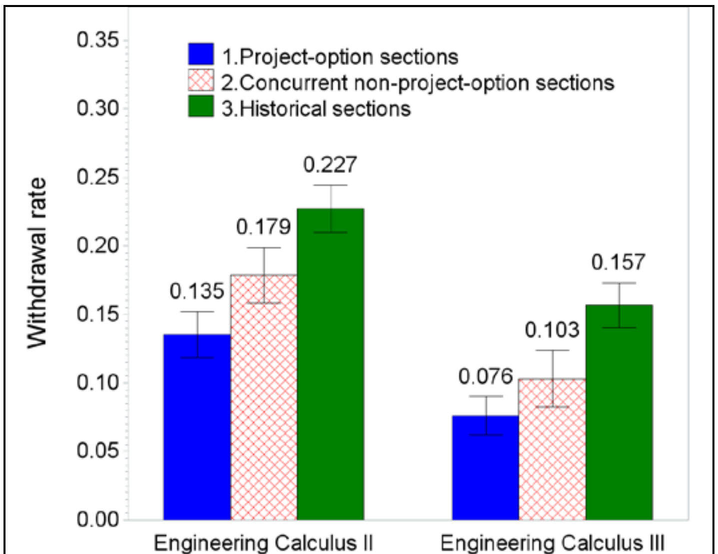

Figure 2. Average withdrawal rates and their 95% confidence interval, for project-option, concurrent non-project-option, and historical sections.

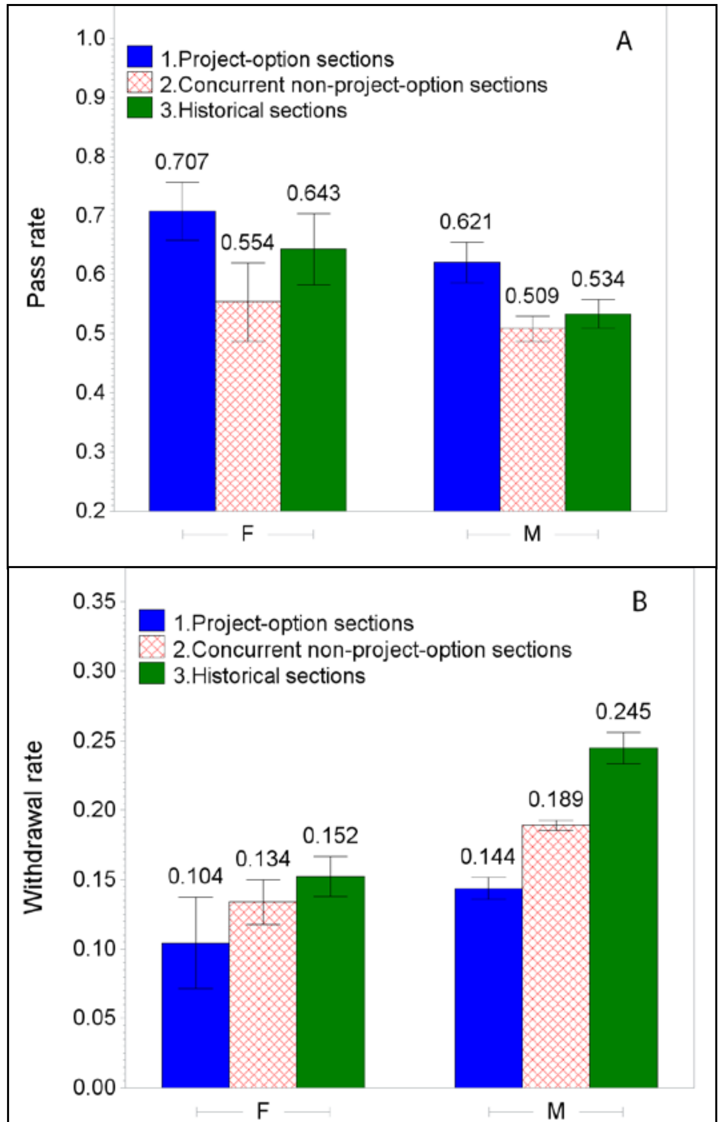

Figure 3. Course effect breakdown by sex for Engineering Calculus II. Bars give 95% CIs. A: pass rate by sex; B: withdrawal rate by sex.

the project option calculus group performed better – with higher pass and lower withdrawal rates – than those in the concurrent non-project and historical groups.

In Engineering Calculus II, for each instructional group, females performed better than males, with higher pass rates and lower withdrawal rates (Figure 3). The same is true for Engineering Calculus III (Figure 4). Therefore, project option calculus may help both sexes in similar ways.

For Engineering Calculus II, project-option sections consistently had higher pass rates for all races and ethnicities (Figure 5). The between-instructional-groups differences are significant for all races and ethnicities except Hispanics (Table 3).

However, in Engineering Calculus III (Figure 6), the project-option sections do not show a consistent effect on pass rate for all races. The overlapping 95% CI indicate that the observed difference is not significant.

Analysis of the logistic regression models showed that no interaction terms were statistically significant. In other words, there is no evidence that the intervention effect varies for each sex, race, and ethnicity. Accordingly, we report only main-effect models. Table 3 gives parameter estimates for those models, for each class.

The logistic regression analysis (Table 3) shows that students in the project-option group passed Engineering Calculus II significantly more often than students in the concurrent non-project and historical groups, even after taking into account gender and race. Students in the concurrent non-project section have a 39% lower odds of passing, as compared with those in project sections. The historical control students show a 29% lower odds of passing. This effect was also present for students in Engineering Calculus III; the odds of passing are 14% lower for those in concurrent non-project sections, and 36% lower for those in historical sections. The between-group differences are significant only for the current vs. historical comparison (Table 3).

Follow up analysis at the individual level

Students completing projects in Engineering Calculus II had a greater chance of entering and passing the follow-up courses, as expected (Table 4). The fraction entering each of the follow-up classes was greater for students who completed projects than for students who did not. Pass rates for those completing projects were nearly identical to pass rates for those who did not, in Calculus III and Thermodynamics, and were slightly lower in Electrical Systems. Total throughput of students from Calculus II through all three follow-up classes was greater for those completing projects.

A similar picture emerges for the two follow-up classes to Calculus III (Table 5). Students completing projects in Calculus III were more likely to enroll in both Thermodynamics and Electrical Systems, and the pass rates for both classes were very slightly greater for students who had submitted projects in Calculus III. The throughput was substantially greater among students who submitted projects (Table 5).

Discussion and conclusion

This study examined data for all students enrolled in each affected course since 2003 at a large public university so that we can have good estimates of the effect of the intervention. For Calculus II, the project-option sections overall performed better than concurrent non-project option sections and historical sections, and this suggests the difference arises from the intervention. This implies that it is worthwhile to continue to offer project-options for students in engineering calculus courses. When considered by sex and race/ethnicity, the project-option sections outperformed their counterparts for each group; the probability of passing the course depends on student's demographic group. For Calculus III, the change in the intervention group is in the same direction, but was not statistically significant. This may be partly because there is a smaller sample size, or partly because students in Calculus III have, by definition, already passed through the filter of Calculus II, and so there may be less variance in student readiness for the course. Note that intervention benefitted each demographic group in a similar way. For each course, the observed variance in the implementation effect by sex and race might arise from random chances. Importantly, the intervention did not harm female students or underrepresented minorities.

We are not sure why the project option appears to be so successful. We suspect, however, that one component is the pedagogical aspect of the project option: students had discussions with their project advisors and their instructors, as well as with their classmates, which may have had an impact on the way they experienced the class. There may be alternative or additional factors. As different groups responded in different ways, it is worthy of further exploration how and why each group is influenced by each course, and take actions to improve the ongoing project-options.

On average, students who submitted projects were more likely to succeed in follow-up courses from both Calculus II and III. At one level, our results suggest that this is largely because more students submitting projects were likely to attempt the follow-up courses, not because they were more successful if they did attempt the courses.

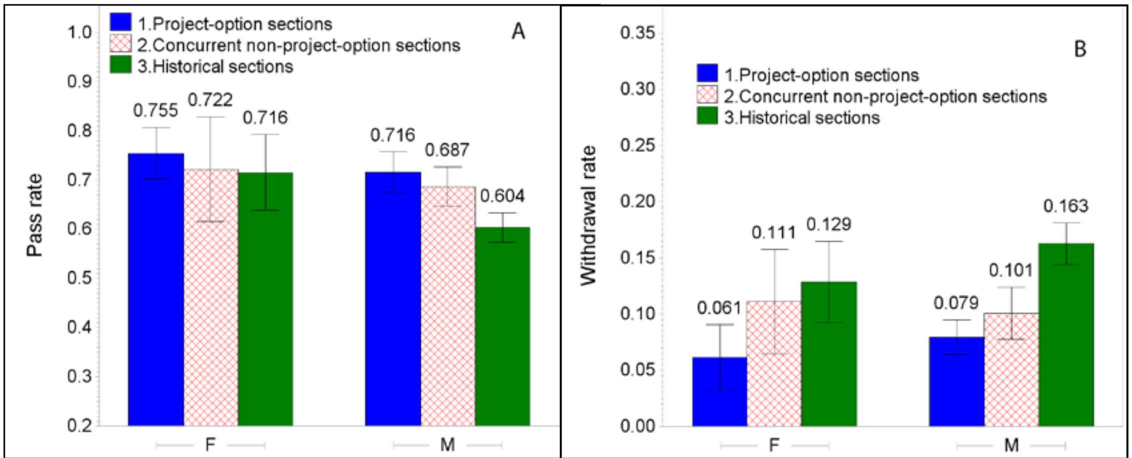

Figure 4. Course effect breakdown by sex for Engineering Calculus III. Bars give 95% CIs. A: pass rate by sex, B: withdrawal rate by sex.

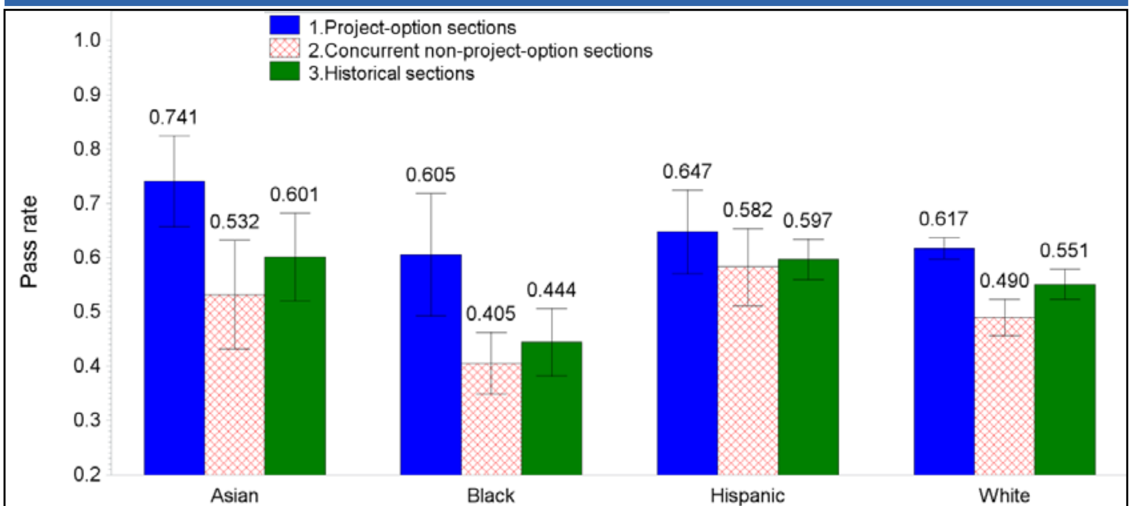

Figure 5. Mean pass rate and 95% CI for Engineering Calculus II, by race/ethnicity.

	Parameter estimate (SE)	χ^2	Pr > χ^2	Odds ratio (95% CI)
Engineering Calculus II				
Intercept	0.86 (0.08)	111.45	< 0.0001	
Concurrent vs Project	-0.5 (0.08)	44.61	< 0.0001	0.61 (0.52, 0.7)
Historical vs Project	-0.34 (0.07)	26.02	< 0.0001	0.71 (0.62, 0.81)
Male vs Female	-0.38 (0.07)	27.01	< 0.0001	0.69 (0.6, 0.79)
Hispanic vs White	0.17 (0.08)	4.53	0.03	1.18 (1.01, 1.38)
Asian vs White	0.23 (0.11)	4.88	0.03	1.26 (1.03, 1.55)
Black vs White	-0.39 (0.1)	13.84	0.0002	0.68 (0.56, 0.83)
Engineering Calculus III				
Intercept	1.29 (0.1)	166.87	< 0.0001	
Concurrent vs Project	-0.15 (0.1)	2.42	0.12	0.86 (0.71, 1.04)
Historical vs Project	-0.45 (0.08)	35.06	< 0.0001	0.64 (0.55, 0.74)
Male vs Female	-0.35 (0.09)	15.45	< 0.0001	0.7 (0.59, 0.84)
Hispanic vs White	-0.09 (0.09)	0.87	0.35	0.92 (0.76, 1.1)
Asian vs White	0.04 (0.12)	0.08	0.77	1.04 (0.81, 1.32)
Black vs White	-0.38 (0.12)	9.21	0.002	0.69 (0.54, 0.88)

Table 3. Parameter estimates for logistic regression models of effect of demographic characteristics on pass rates.

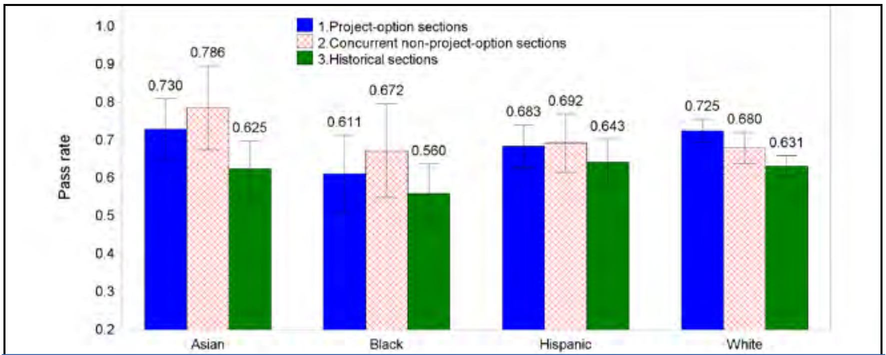

Figure 6. Mean pass rate and its 95% CI, for Engineering Calculus III, by race/ethnicity.

	N	Number entering	Fraction entering	Number passing	Fraction of those entering class who passed	Throughput (fraction passing, given completion of Calculus II)
Students in project-option Calculus II sections subsequently taking Calculus III						
Project submitted	314	238	0.76	210	0.88	0.67
Project not submitted	1068	657	0.62	579	0.88	0.54
Students in project-option Calculus II sections subsequently taking Thermodynamics						
Project submitted	314	160	0.51	140	0.88	0.45
Project not submitted	1068	392	0.37	348	0.89	0.33
Students in project-option Calculus II sections subsequently taking Electrical Systems						
Project submitted	314	160	0.51	136	0.85	0.43
Project not submitted	1068	392	0.37	361	0.92	0.34

Table 4. Performance of students in project-option Calculus II sections with respect to three follow-up classes.

	N	Number entering	Fraction entering	Number passing	Fraction of those entering class who passed	Throughput (fraction passing, given completion of Calculus III)
Students in project-option Calculus III sections subsequently taking Thermodynamics						
Project submitted	230	125	0.54	110	0.88	0.48
Project not submitted	898	415	0.46	362	0.87	0.4
Students in project-option Calculus III sections subsequently taking Electrical Systems						
Project submitted	230	148	0.64	133	0.9	0.58
Project not submitted	898	474	0.53	417	0.88	0.46

Table 5. Performance of students in project-option Calculus III sections with respect to two follow-up classes.

But this begs a number of questions: are these differences due to reasons such as the better performance in the affected calculus courses, or unmeasured factors such as motivation? In any case, there is little concern that the project option harms student retention in the long term. It will be interesting to investigate further the mechanisms by which the project-option affects subsequent performance.

We found challenges at three different levels in the process of this research. These were problems at the student level, problems at the institutional level, and residual problems with individual faculty members. One broad problem with students is that most have little to no experience in modeling; consequently identifying an interesting project, and finding ways to make it mathematically tractable, are time-consuming (Box A). Motivating students to do the work – which can require more time than studying for an exam – is a challenge. It would be helpful to provide additional training to students or think about how the way we as instructors teach problem solving in class, can improve students' ability to model real-world problems. This last challenge is perhaps one of the advantages of the project-based teaching approach referred to in the introduction, in which daily classroom experiences are modified to include modeling. We suggest that simply offering a class that emphasizes modeling is not sufficient, and it can be useful to follow up on such student experiences with further training, such as might occur in capstone courses or undergraduate research. Indeed, some of the students involved in submitting projects in Calculus II or III did go on to do undergraduate research. On the other hand, anecdotal evidence from instructors shows that simply offering the project option can have a strong effect on student motivation and perception of mathematics. One instructor reported a student who seemed extremely weak mathematically, and struggled to hand in homework assignments on a regular basis, yet became interested in a project on economics that related to another class he was taking. He used very simple piecewise polynomial functions to model growth of various financial indicators related to the housing market. Although his modeling was fairly primitive (and somewhat unrealistic), he became extremely excited at the idea that he could apply some of his mathematical skills to an area that he was interested in, and this experience seemed to change his perception of the course and of mathematics.

The largest problem at the institutional level is the commitment to these projects. There must be some buy-in to the idea of faculty members spending substantial time advising students on their projects, and on grading the resulting papers. Unfortunately, with the end of our support from NSF, all but one our co-PI advisors will no longer have the time available to advise large numbers of students on projects. As a result, the use of projects as a replacement for final exams in calculus instruction will

Box A. Advising students on their projects.

Our co-PI advisors interacted with many students seeking to do projects, and found these interactions both interesting and challenging. They each provided a summary description of these interactions, especially those aimed at getting a student started on a project. Many students visited these advisors with vague ideas (at best) as to what they might do for a project. As a result, our co-PI advisors discussed with them questions like the following.

1. Are you already doing undergraduate research? If so, your research PI can probably suggest a project. *This is ideal because it ties calculus to something that the student is already interested in. An excellent example is a student who was doing research on drinking water filters for use in third world countries. We were able to frame a project around the time needed to filter a given amount of water.*
2. Do you have an internship or a job that requires some practice of mathematics? Your supervisor might be able to suggest a project. *This has the same advantage as (1) above.*
3. Do you have an idea for a project? If so, I can help you frame it into a project of the appropriate level. *Some students come in with an idea so easy that it could be done in a few minutes. Others come in with an idea suitable for a dissertation topic or a research career. Either way, we could often help them steer it to something at an appropriate level. Again, this had the advantage that they would already be interested in the topic. We did not allow students to completely define the problems by themselves, since there was the possibility that they were using a solved problem from somewhere. In order to ensure uniqueness, we always had a say in the problem definition.*
4. Have you taken any engineering (or biology) courses yet? If so, ask your former or current instructor to suggest a project. *This might result in a project in which they were not terribly interested. However, it would relate to their major and it would give them additional exposure to their departmental faculty. Since we did encounter some students who were unable to articulate any particular interest in research in their field of study, this seemed a way that they might find a project topic*.
5. What is your major? *We have lists of faculty from other departments who have been willing to supervise projects. This might be even further removed from a student's interest, but it does help them make contact early with departmental faculty, and it would be related to their major.*
6. What are your interests? *Many students in biology came in with no idea for a project, but were able to articulate interests about topics like growth of tumors, spread of invasive pests, finding appropriate dosage for drugs, or other topics. The key was to show them that these are inherently mathematical topics, and then to reduce the problem to an appropriate level. We were frequently able – if it was early enough in the semester – to help students develop projects on this basis. For example, one student came to our biology co-PI advisor and stated an interest in orthopedic injuries. After a bit of conversation, the co-PI advisor (who does not work in an area related to this) established that one question was explaining why some injuries are so much more severe than others. The co-PI advisor suggested beginning by asking a simple question: all else being equal, a large person falling will experience more force than a small person will. How much of that is due to their additional height (and thus acceleration), and how much to their additional weight? The student was able to develop that question into a successful project. Similarly, our engineering co-PI advisor was able to develop problem statements based on things such as blood glucose levels, peritoneal dialysis, and roller coasters because students were interested in them.*

likely be scaled back at our institution.

Even if there is institutional buy-in, evaluating projects – and doing so in a fairly even-handed way – is difficult for individual faculty members (Box A). How does a calculus instructor reasonably evaluate a stack of papers on topics covering a wide range of topics, in which they have no training? How do individual project advisors evaluate the mathematics? These are challenging problems, and so far we have no general answers.

These problems notwithstanding, we believe there is room for considerable optimism about project-based calculus instruction. To be sure, our data have some limitations: our study is observational; classes were not randomized to the project option, nor were students randomized to doing the project or not. Calculus instructors, project advisors, and instructors of follow-up courses all vary, and cannot be randomized. These are, alas, problems characteristiof most educational research. We suspect that our result – that project-based calculus can improve not only pass rates but subsequent success – is robust, but certainly our particular p-values and effect sizes may not be. A challenge to future research is finding ways to shed further light on these conclusions.

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