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Improving student learning in calculus through applications

C.Y. Young^{a*}, M. Georgiopoulos^b, S.C. Hagen^c, C.L. Geiger^d, M.A. Dagley-Falls^e, A.L. Islas^a, P.J. Ramsey^f, P.M. Lancey^g, R.A. Straney^g, D.S. Forde^h and E.E. Bradbury^a

^aDepartment of Mathematics, University of Central Florida, Orlando 32816, USA; ^bDepartment of Electrical Engineering and Computer Science, University of Central Florida, Orlando 32816, USA; ^cDepartment of Civil, Environmental, and Construction

Engineering, University of Central Florida, Orlando 32816, USA; ^dDepartment of Chemistry, University of Central Florida, Orlando 32816, USA; ^eCollege of Engineering and Computer Science, University of Central Florida, Orlando 32816, USA; ^fOffice of Institutional Research, University of Central Florida, Orlando 32816, USA; ^gOffice of Operational Excellence and Assessment Support, University of Central Florida, Orlando 32816, USA; ^hDepartment of Psychology, University of Central Florida, Orlando 32816, USA

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Nationally only 40% of the incoming freshmen Science, Technology, Engineering and Mathematics (STEM) majors are successful in earning a STEM degree. The University of Central Florida (UCF) EXCEL programme is a National Science Foundation funded STEM Talent Expansion Programme whose goal is to increase the number of UCF STEM graduates. One of the key requirements for STEM majors is a strong foundation in Calculus. To improve student learning in calculus, the EXCEL programme developed two special courses at the freshman level called Applications of Calculus I (Apps I) and Applications of Calculus II (Apps II). Apps I and II are one-credit classes that are co-requisites for Calculus I and II. These classes are teams taught by science and engineering professors whose goal is to demonstrate to students where the calculus topics they are learning appear in upper level science and engineering classes as well as how faculty use calculus in their STEM research programmes. This article outlines the process used in producing the educational materials for the Apps I and II courses, and it also discusses the assessment results pertaining to this specific EXCEL activity. Pre- and post-tests conducted with experimental and control groups indicate significant improvement in student learning in Calculus II as a direct result of the application courses.

Keywords: STEM retention; applications in calculus; enquiry-based learning

1. Introduction

The University of Central Florida (UCF) EXCEL programme is funded (2006–2010) by the National Science Foundation (NSF) under the auspices of Science,

^{*}Corresponding author. Email: cyyoung@mail.ucf.edu

Technology, Engineering and Mathematics Talent Expansion Programme (STEP) with the goal of increasing the number of US citizens obtaining a BS degree in Science, Technology, Engineering, or Mathematics (STEM).

In the book *Talking About Leaving, Why Undergraduates Leave the Sciences* [1], a list of reasons has been provided, such as: (1) discouraged/loss of confidence due to low grades in early years, (2) morale undermined by competitive STEM culture, (3) curriculum overload, fast pace overwhelming, (4) poor teaching by STEM faculty, (5) inadequate advising or help with academic programmes and (6) loss of interest in STEM, e.g. 'turned off by science'.

The UCF EXCEL programme addresses all of these reasons that affect student retention in STEM. In particular, to address reasons 1 (low grades in early years, i.e. calculus) and 6 (loss of interest in science and engineering), EXCEL has developed two one-credit courses that are taught in tandem with Calculus I and II, called *Applications of Calculus I and II (Apps I and II)*.

These courses were developed as a result of studies that have shown that students increase their appreciation of calculus through applications in science and engineering as well as improve learning of mathematics through applications [2–18]. Six science and engineering faculty, in coordination with the math faculty who teach the calculus topics, team teach the Apps I and II courses. In Apps I and II, faculty demonstrate to students how a particular calculus topic is used in their future science and engineering courses or how the professor uses it in their own research. For example, an aerospace engineer helps students discover the concept of a limit while determining the best material for a cooling fin in a computer; a chemist has hands on demonstrations with reaction rates when discussing derivatives; a molecular biologist discusses how he uses integration in his cancer research. Pre- and-post tests on the six calculus topics that the Apps I and II courses address are administered to both the experimental group (EXCEL students) and the control group (a group of non-EXCEL students with similar academic backgrounds as the EXCEL students). The pre- and post-tests are graded by EXCEL-funded graduate students who are trained by the Faculty Center for Teaching and Learning at UCF. The grading follows a rubric developed by the EXCEL mathematics faculty. This article discusses the process used to produce the educational materials for the Apps I and II courses and the assessment results.

2. EXCEL specifics

The goal of the EXCEL project is to increase UCF's retention rates in STEM disciplines, thereby increasing the number of students graduating with a STEM degree. In this process, an increase in the percentages of under-represented groups (women and minorities) graduating with STEM degrees is expected since UCF has high percentages of minorities and women in STEM disciplines. UCF's data indicate that the incoming summer/fall 2009 'First Time in College' (FTIC's) STEM cohort is composed of 25% minorities and 36% women.

In order to achieve EXCEL's goal, the project has two primary objectives. The first objective is to attract 200 students per year from the higher attrition STEM freshmen group into the EXCEL programme (EXCEL participants). The higher attrition STEM freshmen group is defined to be the group of freshmen who are

declared STEM majors and have math SAT scores belonging to second and third quartile of math SAT scores of all STEM students entering UCF. UCF Institutional Research data show that this group of students typically experience higher STEM attrition, due to their performance in mathematics. The second objective is to increase the number of students remaining in STEM majors by increasing UCF retention rates from the current 50% rate to the projected 75%.

To achieve the first objective, the EXCEL programme directors, faculty and staff have embarked (since the inception of the project in January of 2006) in an aggressive marketing campaign to inform UCF STEM applicants and their parents of the benefits in participating in the EXCEL programme at UCF (e.g. guaranteed on-campus housing, block scheduling, exposure to the applications of calculus from early on in their college careers, tutoring and personalized attention at the EXCEL centre). In 2010, the EXCEL programme received approximately 750 applications for 200 slots and there has been an increasing trend of student applications for the programme from its initiation year (2006) to the present.

To achieve the second objective, the EXCEL faculty have designed a set of educational activities that are focused on the cornerstone courses of Calculus I and II. In particular, one of the innovations of this EXCEL programme is the introduction of the applications of calculus classes that are taught by science and engineering faculty who emphasize the importance of calculus topics in both STEM coursework and their own research areas. Through this sequence of applications of calculus classes, it is expected that EXCEL students will have more concrete examples of the topics covered in their calculus classes and their time on task with calculus concepts will be increased. EXCEL students have access to the EXCEL centre, a 1200 square foot lab where they can study alone, study together, or get personalized tutoring by any of the 10 graduate students hired to support the EXCEL programme. Finally, EXCEL students are block scheduled in Pre-Calculus, Calculus I and Calculus II in addition to the Apps I and Apps II courses. EXCEL graduate student mentors carefully monitor student progress on a weekly basis so that any observed deficiencies can be immediately addressed. The block-scheduling structure of classes offered in the first year of the EXCEL student cohort is as follows:

- Pre-Calculus or Calculus I and applications of Calculus I in the fall semester of the freshman year,
- Calculus I and applications of Calculus I or Calculus II and applications of Calculus II in the spring semester of the freshman year.

A pictorial that shows the sequence of EXCEL classes planned for an EXCEL cohort (starting in the fall of an academic year) is shown in Figure 1. The bold-faced mathematics courses are EXCEL only sections. Note that the EXCEL cohort is divided into two groups. The group that is not calculus ready is placed in the Pre-Calculus class for fall, and the group that is calculus ready is placed in the Calculus I class for fall. A math placement test is required of all EXCEL applicants and this test determines the appropriate math placement of the incoming cohort (Pre-Calculus ready or Calculus I ready). The applications of calculus classes are new classes that were introduced into the undergraduate curriculum in order to facilitate the appreciation of calculus topics, and they are co-taught by a number of science and



Figure 1. A pictorial illustration of the sequence of the common EXCEL courses taken by an EXCEL cohort. Calculus classes that are bold-faced are classes blocked for EXCEL students and taught by EXCEL faculty. Courses that are italicized are new courses that have been introduced by the EXCEL programme and taught/supervised by EXCEL faculty.

engineering faculty. Many of the EXCEL students follow up the Apps courses with an undergraduate research experiences (UREs) which gives students the opportunity to experience, first hand, the research that STEM faculty are conducting at UCF.

The second objective of the EXCEL programme is to increase the rate of EXCEL students who graduate with a STEM degree from 50% to 75%. To achieve this objective, EXCEL has focused on a number of academic, advising and social activities that help in the creation of an EXCEL learning community consisting of faculty, staff, graduate students and cohorts (06–09 EXCEL students). The main goal of the EXCEL learning community is to increase the success of the EXCEL cohort in the first 2 years in college, thus attributing to the increase in retention rate of the EXCEL cohort within STEM. The goal is achieved, in part, by providing a small college atmosphere at the third largest university in America. The academic, advising and social activities planned by EXCEL cohorts are as follows:

- (1) group on-campus housing block;
- (2) an EXCEL-specific orientation;
- (3) welcoming parties at which faculty, staff and graduate students introduce what UCF has to offer to the EXCEL cohort;
- (4) EXCEL only sections of calculus classes (Pre-Calculus, Calculus I and II);
- (5) applications of Calculus I and II classes designed and taught by a number of science and engineering faculty to the EXCEL cohort;
- (6) advising offered on a regular basis (at the EXCEL centre) by the first year EXCEL academic advisor and other college advisors;
- (7) mathematics and science tutoring offered (at least 60 h per week) by graduate students at the EXCEL centre;
- (8) recitation sessions, offered at the EXCEL centre, led by the math professors who are instructors of the Pre-Calculus, Calculus I and Calculus II courses;
- (9) peer-tutoring sessions organized at the NIKE housing community (where EXCEL students reside) on Sunday through Thursday evenings;
- (10) undergraduate research experiences offered by UCF faculty to the interested EXCEL sophomore students.

The remainder of this article is devoted to Activity # 5 (development and teaching of the Apps I and II courses) and its impact on the EXCEL cohorts.

3. Development of applications of Calculus I and II

The applications of Calculus I and II courses are one-credit courses that meet one night a week for an hour. Students simultaneously are enrolled in the traditional Calculus I or II course, respectively. The Apps I and II courses are led by a STEM professor (instructor of record) who coordinates faculty (six STEM faculty are slated to co-teach each of the Apps I and Apps II courses) presentations. The six science and engineering professors each teach two consecutive weeks. Each professor who co-teaches in the Apps I and II courses produces a chapter in a book (called Apps I or Apps II book) and PowerPoint slides for his/her presentations are developed and delivered.

The development of the applications of Calculus book is led by Apps I and Apps II science and engineering faculty coordinators. They start with a list of core topics for Calculus I and Calculus II which are provided by mathematics faculty. Then, the Apps I and Apps II faculty coordinators share these topics with the six STEM faculty who are slated to co-teach the courses; each one of these faculty select one of these core Calculus I and II topics such that they can illustrate its usefulness both in higher level courses taught in their disciplines, and, in a general sense, in the research that they conduct.

The STEM faculty work with EXCEL math faculty to ensure consistency of notation for the book chapter and PowerPoint presentations that they produce. Additionally, a master schedule is developed by the math faculty to ensure that the calculus topic has been covered in the calculus course *prior* to it being covered in the Apps course. Figures 2 and 3 provide a lecture example and in-class assessment of an application topic covered in the *Apps I* course that focuses on cooling fins in personal computers, while illustrating the mathematical concept of limits is provided below and referred to as an Apps I module. The goal of this module is to illustrate the importance of limits in engineering analysis and to help students develop physical intuition (through discovery learning) as to why fins are useful, why they are manufactured utilizing aluminium or copper, and why they are effective in heat removal.

Using MATHCAD and having students 'guess' and compute values, we follow through a progression of integration of key mathematical concepts taking the student from the abstract idea of a limit to calculation and interpretation within a visual environment, effectively analysing a particular engineering problem.

During the presentation of this module, a student participates, through appropriately posed questions by the instructor, in a number of meaningful activities: (1) taking the limit of the average rate of change to arrive at the instantaneous rate of change, (2) using a limit to define e, the natural base of logarithms, the exponential function and its derivative, (3) illustrating the difference between dependent and independent variables in the equation for the temperature, while enforcing concepts of units associated with variables, (4) applying the concept of the limit of the equation for the temperature as x tends to zero (the temperature)



Figure 2. A pictorial illustration of the cooling fan in a computer and how it cools is used by Dr Alain Kassab in the applications of Calculus I course.

The entire grade for the course is based on clicker questions that students answer in class. An example of a clicker question (and the correct answer) is provided to the right.



Figure 3. Selected slides used by Professor Kassab in the Apps I course to illustrate the 'cooling of fins' application.

at the base of the fin) and to infinity (the tip of a very long fin), (5) introducing a physical relation, Fourier's law of heat conduction, relating the rate of cooling to the instantaneous rate of change of the temperature with respect to space, (6) that the derivative of the exponential function is an exponential function (an important rule in calculus), (7) introducing a variety of fin candidate materials and having students select materials based on resulting temperature profiles and fin effectiveness and (8) trying to take a limit a $\Delta x \rightarrow 0$ numerically and realizing the inherent limitations due to round-off and machine precision, therefore enforcing the importance of

analytical methods in a world pervaded by computation. The following are examples of PowerPoint slides from an Apps I class.







Limits and rate of change: temperature in a cooling fin (cont'd)

 Using the symbolic manipulator in MATHCAD (actually the MAPLE symbolic manipulator engine), we find indeed that

$$\lim_{n \to 0} \frac{e^{-\lambda \cdot h} - 1}{h} \to -\lambda$$

Leads us to the general result that for the function

h





The entire grade for the course is based on clicker questions that students answer in class. An example of a clicker question (and the correct answer) is provided to the right.

4. Assessment of applications of Calculus I and II

The effectiveness of the Apps I and II courses is assessed in two main ways: (1) preand post-tests on Calculus I and Calculus II topics given to both experimental (EXCEL) and control groups and (2) the EXCEL group is provided with an Apps I and II questionnaire through which students give feedback to the assessment team about the Apps I and II courses. This assessment was applied to all of the Calculus I and II courses taught to EXCEL students since the inception of the EXCEL programme (2006). Data have been collected for the years 2006–2009. We have chosen to provide analysis of the data pertaining to the EXCEL 2006 cohort who took these classes in the fall 2006 and spring 2007 as this class is currently graduating with STEM degrees.

4.1. Preliminaries: Calculus I and II pre- and post-tests

As mentioned above, in order to assess the mathematical knowledge acquired from students as part of the EXCEL programme, we administered a knowledge-based Calculus I pre- and post-tests during fall 2006 semester, and a knowledge-based Calculus II pre- and post-test during spring 2007 semester. The same calculus test was administered to both the EXCEL group and to a control group of students. The control group consisted of students with similar demographics (majors, math SAT scores, etc.) who were enrolled in Calculus I in the fall of 2006 and Calculus II in the spring of 2007 but did not participate in the EXCEL programme.

The questions were drawn from various Calculus topics taught throughout the semester and were chosen by a member of the UCF Math Department faculty. The same questions were given to the students at the beginning and end of the semester.

Test question	Calculus I	Calculus II	
1	6	5	
2	1	5	
3	3	5	
4	4	5	
5	4	5	
6	5	5	
7	3	5	
Total	26	35	

Table 1. The maximum number of points for each question on the test as part of the pre- and post-tests for Calculus I (fall 2006) and Calculus II (spring 2007) courses.

Table 2. Sample sizes of the Control and EXCEL groups. It is important to note that over 1000 students take Calculus I and II at UCF every year. The control group has more students than reported in this table because some faculty teaching non-EXCEL sections of calculus choose not to participate in the pre- and posttest assessments.

Course	Control	EXCEL	
Calculus I	110	157	
Calculus II	23	61	

The pre-test was given on the first day of class, and the post-test was a part of the students' final exam.

Taking into account that one grader may introduce biased scores, two trained graders were used to assign a rating or score to each answer given by the students. The high inter-rater reliability of the graders on both the pre-test (r = 0.82) and posttest (r = 0.92) indicate that there was high consistency in the ratings given by the two graders. Both graders used the same rubric to rate the answers to each question for all the students across pre- and post-tests. The rubric was created by the faculty member who proposed the questions. The maximum possible score for each question is given in Table 1.

For our analysis, we only considered students who took both the pre-and posttests. The resulting sample size is given in Table 2. (However, we do include those students that do not complete either of the calculus courses in our final retention rate calculations.)

Some of the cases included in the data analysis had missing scores for one or more questions. This may have been due to the fact that the grader did not have the corresponding page for that question or that the copy was unintelligible. If N/A was entered for a particular question from both graders, the cell was left blank resulting in missing data. In other words, they were stricken from the data. For each test, the total scores assigned by the two graders were averaged and used as the official total scores in the data analysis.

Calculus II group	N	Pre-test mean	Pre-test SD	Post-test mean	Post-test SD
Control	23	0.59	0.848	19.28	8.16
EXCEL	61	0.73	1.06	24.02	7.72

Table 3. Mean and SD for each group (Control or EXCEL) for the pre- and post-tests for Calculus II in spring 2007.

4.2. Calculus I pre- and post-tests

To ensure that prior student knowledge of calculus was not interfering with the results of EXCEL and control group comparison, the average skill level upon entering the course for both groups were statistically compared. The EXCEL group had mean pre-test and post-test scores of 3.94 and 10.81 with standard deviations (SDs) of 1.71 and 4.83, respectively. The control group had mean pre- and post-scores of 4.01 and 11.01 with respective SDs, 1.92 and 4.04. An independent sample *t*-test conducted to compare pre-test scores for both groups (2006 EXCEL group and 2006 control group) indicated that the pre-test scores were essentially the same for both the control and EXCEL groups [t (265) = 0.35, p = 0.73]. The magnitude of the differences in the means was negligible (η^2 = 0.0005).

To compare how the two groups improved from pre-test to post-test, we conducted a 2×2 mixed between-within-subjects analysis of variance. This analysis indicated that there was no significant difference in change of knowledge test scores, over time for the control and EXCEL groups. This is shown by the interaction effect in the multivariate test, which was not statistically significant [Wilks' lambda = 1, F(1, 265) = 0.047, p = 0.829].

4.3. Calculus II pre- and post-tests

For the Calculus II data (spring 2007), we conducted the same analysis as in Calculus I. The test score means and SDs for each group (EXCEL and control groups who took Calculus II in the spring 2007) are given in Table 3.

The students' pre-test scores were statistically the same for both the control and EXCEL groups [t (82) = -0.579, p = 0.564]. The magnitude of the differences in the means was very small ($\eta^2 = 0.004$).

Finally, there was a significant difference in change of knowledge test scores over time for the control and EXCEL groups (Figure 4). More specifically, the improvement in scores (from pre- to post-test) is much larger for the EXCEL group than the control group. This was shown by the interaction effect in the multivariate test which was statistically significant [Wilks' lambda = 0.93, F(1,82) = 5.89, p < 0.05, multivariate partial $\eta^2 = 0.07$].

4.4. Surveys and focus groups

The assessment team also distributed a questionnaire to 187 EXCEL students who took the Apps I and II courses in fall 2006 and spring 2007 semesters. Some of the



Figure 4. The change in knowledge (over time) in the pre- and post- tests of the Calculus II class for the EXCEL and control groups. The bar chart shows that knowledge gained by the EXCEL group is larger than that acquired by the control group at/upon completion of the Calculus II course.

relevant student feedbacks obtained from this questionnaire are as follows:

- (1) 'Through the applications classes I know more about science and engineering disciplines' (89% said yes).
- (2) 'Applications classes helped me feel that I am a member of an EXCEL learning community' (68% said yes).

4.5. Summary of assessment

In spite of the fact that results were only provided above for the pre- and post-tests of Calculus I in fall 2006 and Calculus II in spring 2007, both of which pertain to the EXCEL 2006 cohort, the feedback from the analysis of the pre- and post-tests applied to other EXCEL cohorts (2007, 2008 and 2009) is very similar. That is, the pre- and post-tests applied to Calculus II concepts for these cohorts showed that increased math knowledge was demonstrated by the EXCEL cohorts compared to the control groups of students. The pre- and post-tests comparing the math knowledge of the EXCEL and control groups in Calculus I are inconclusive (sometimes the EXCEL group did better, sometimes worse and sometimes the groups did as well). The value of the Calculus II pre-test is that it demonstrates that both groups had no knowledge of the material before training began. Although the Apps II assessment results are clearly demonstrating success, it is possible that the result is cumulative and enhanced by the student participation in Apps I. In addition, the students who take Apps II are a subset of Apps I who are going to specific STEM fields (e.g. biology majors do not take Apps II). The Apps I and II questionnaires administered to EXCEL 2007-2009 groups also yielded very positive responses to questions 1 and 2, mentioned above for the EXCEL 2006 cohort.

5. Impact of EXCEL programme on retention rates

The EXCEL programme has many activities: cohort for math courses, graduate student mentors, tutoring in the EXCEL centre, Apps I and II courses, group



Figure 5. The bar graph shows the percentage of students who declared STEM majors as freshmen in fall 2006 and are still STEM majors in fall 2009. The EXCEL programme demonstrates a higher retention in general, and in specific underrepresented groups in STEM. T = total, M = Male, F = female, B = Blacks, H = Hispanics, B + H = Blacks and Hispanics.

housing block, recitation sections, EXCEL advisors, social activities, sophomore undergraduate research experiences, etc. All of these contribute to the overall goal of retaining more STEM majors. The following chart illustrates retention of STEM majors going into students' fourth year for the EXCEL 2006 and control 2006 cohorts; the retention rates shown in Figure 5 were produced at the beginning of fall 2009, 3 years after the EXCEL 2006 cohort was admitted to UCF.

Although we cannot determine which of the many EXCEL activities and how much each one of these activities are contributing to the increased student STEM retention rates, we believe that the sense of a learning community that the Apps I and II courses reinforce plays a very significant role in the improved retention rates observed for the EXCEL cohorts.

It is difficult to determine which of the many EXCEL educational activities are contributing to the higher STEM retention rates observed by EXCEL compared to the control group STEM retention rates. However, the consistently observed higher knowledge attained by EXCEL students in Calculus II and the highly positive responses of EXCEL students that they have a sense of a learning community provide enough evidence for us to claim that the Apps I and II courses are contributing to these observed higher retention rates.

6. Conclusions

The UCF EXCEL programme is increasing retention rates of undergraduates pursuing STEM degrees. The applications of calculus courses are key components of the programme. The pre- and post-test data suggest that Apps I does not significantly improve student learning in Calculus I, but Apps II significantly improves student learning in Calculus II. One of the possible reasons for why EXCEL students exhibit a significant benefit from the Apps II course is that, given enough time, the EXCEL educational interventions (including the Apps class) start having an impact on the EXCEL students, compared to the control group of students that has not had the opportunity to benefit from these interventions. Furthermore, one beneficial byproduct of the Apps I and II courses is that the Apps courses do significantly improve students' appreciation of science and engineering's dependence on calculus.

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