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Identifying Bottlenecks in Undergraduate Engineering Mathematics: Calculus I through Differential Equations

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Abstract

A significant amount of research has investigated calculus as a barrier to student success and persistence in engineering school. Very little research, however, has investigated the mathematics courses that follow calculus I. These courses are built upon concepts and skills that are learned in the first semester and introduce more advanced material, building up a strong basis for math-dependent, domain-specific engineering courses. This paper investigates the longitudinal progress of two cohorts of students through the mathematics sequence at the University of Louisville's J.B. Speed School of Engineering, identifying both semesters and courses that have high levels of student repetition and attrition. Two student populations within the cohorts are considered: those who take calculus in their first semester, and those who require a remedial calculus intervention semester before taking calculus. This study adds to the literature by focusing on bottlenecks in mathematics sequences beyond calculus, providing insight into engineering school retention rates beyond the first-year.

Introduction

Engineering retention is multifaceted and complex, and a great number of research studies have investigated when and why students leave engineering school. Reasons range from intrinsic psychological factors such as high test anxiety or low self-efficacy to social factors such as a weak sense of belonging or parents without a college degree. One major factor in many studies is high-school preparation in mathematics, which has been shown to predict student success in engineering school [1, 2, 3]. It is also widely acknowledged that calculus in particular is a significant barrier for many undergraduate engineers, because many students who do not perform well in their first semester of mathematics do not stay in an engineering major [4, 5]. This is a significant challenge for all engineering schools, since calculus is the basis for higher level engineering concepts, and is therefore generally taught at the beginning of engineering programs.

It is important to study first year student retention in engineering programs because of the large number of reasons that students may leave in their first year. However, it is also important to look at longer success rates of students. Undergraduate engineering programs are rigorous throughout, and students need to gain base knowledge in mathematics, the sciences, and problem-solving as well as specific field-based knowledge in order to have an engineering career. This does not occur in a single semester or even a single year.

At the University of Louisville (UofL) J.B. Speed School of Engineering, the mathematics sequence includes three, 4-credit-hour courses of engineering-based calculus, (*Engineering Analysis I, II and III*), followed by a 2-credit-hour course in differential equations (*Differential*

Equations for Engineering). *Engineering Analysis I* begins with an algebra review, progresses through limits, and then follows the development and use of differentiation and integration to solve engineering problems. Engineering problems are pulled from all disciplines and include topics of motion, related rates, optimization, moments and centers of mass. *Engineering Analysis II* progresses to the development and use of: integration techniques, transcendental functions, vectors in three dimensions, polar coordinates, and power series to solve engineering problems. Again, engineering problems are sampled from many fields and include work, hydrostatic force, statics, heating, cooling, and catenaries. *Engineering Analysis III* covers partial derivatives, Lagrange multipliers, Fourier series, vector-valued functions, and multiple integrals. Engineering problems include topics in thermodynamics, motion, fluid flow, curl, flux, and divergence. *Differential Equations for Engineering* teaches first and higher-order differential equations (DE), systems of DE, partial DE, difference equations, numerical methods, Laplace transforms, and engineering applications involving mechanical vibrations, electrical circuits, impact forces and mixing.

Passing all four mathematics classes is required for students to obtain an engineering degree. The first three courses follow similar schedules: the class meets 5 times a week with exams on Tuesdays and exam-review days on Thursdays throughout the semester. The final course meets twice a week, with five-to-seven exams spaced throughout the semester. This emphasis on performance allows students and professors to monitor participation and learning of the great amount of material covered in the lectures. In the first semester, the first three weeks are also used as a diagnostic of mathematics preparation. If a student has an exam average below 50% on the first three exams, they are advised to drop out of *Engineering Analysis I* and register instead for *Introductory Calculus*. This course covers algebra, geometry, trigonometry and functions and prepares students with skills needed in calculus.

The ideal "flight plan" for students is to take the four required mathematics courses in the first four semesters of engineering school: Fall 1, Spring 1, Summer 1 and Fall 2. The engineering school is year-round, and it is expected that engineering students enroll in courses over the summer semester. In the spring of year 2, students are expected to have a cooperative internship (Co-op), where they work at an engineering company for a semester. Co-op is considered important real-world experience, and three semesters are required for graduation. Students are allowed to repeat and replace up to four courses to improve their grades, however, a single repetition results in a semester delay in the flight plan. A single repetition of a course either delays the first Co-op semester or delays enrollment in *Differential Equations for Engineering*. Both of these are significant interruptions to course flow. Students who take *Introductory Calculus* in the first fall semester are behind by one semester in the flight plan, and any repetitions beyond this create additional delays. This repetition then ends up being costly for students, who pay for additional credit hours and require more time as a student. It is also a problem for the engineering departments that have more students in their classrooms than are graduating each year.

This paper reviews students' progression through the entire mathematics sequence at the UofL's engineering school from two consecutive cohorts (first-time, full-time freshmen in 2012 and 2013) with respect to retention or attrition from the engineering program, progress through the sequence, and repetition in various courses. Students who participated in the remedial *Introductory Calculus* course were of particular interest, to see if the early calculus intervention either enabled curriculum completion or prevented it due to the staggered timeline of requirements. The objective of this paper is to identify later challenges within the engineering mathematics sequence by looking at longitudinal data. This analysis adds to the literature by providing data on the longitudinal progress of students through an entire engineering mathematics curriculum, as opposed to static retention rates after the first year for the engineering school as a whole. Additionally, it generates ideas for future studies with respect to mathematics instruction that target program completion in this undergraduate engineering school.

Analysis

Student grades and registration data were acquired for two cohorts: those entering the engineering school in Fall 2012 ($N = 452$) and Fall 2013 ($N = 525$) that were First Time, Full Time. Data was available from the entering semester through spring semester of 2016. Students were excluded from the analysis if they: did not register for a mathematics course in the first semester and subsequently transferred out of the engineering school ($N = 18$), or entered with some mathematics credit or for any reason did not begin the sequence with *Engineering Analysis I* or *Introductory Calculus* ($N = 30$). The remaining students were included in the analysis (2012: 419, 2013: 510).

The data was reviewed separately by cohort year (2012 and 2013) and split by initial course (*Engineering Analysis I* and *Introductory Calculus*). A python program was written to process the data, storing each element of the data separately. For each student, fields were collected for semesters, courses and grades. These fields were then used for the analysis.

Student Retention

Retention percentages over time, by semester, are shown in Figure 1 below. As shown in the figure, retention is very similar between the two cohorts. For both cohorts, retention is much lower for the students who start in *Introductory Calculus* (IC) versus the students who start in *Engineering Analysis I* (EA). At the beginning of the second year, retention rates are statistically significantly lower for IC students (IC: 55%, EA: 83%, $Z = 9.130$, $p < .001$). For both IC and EA students, the largest drop in retention, is in the spring semester of the first year.

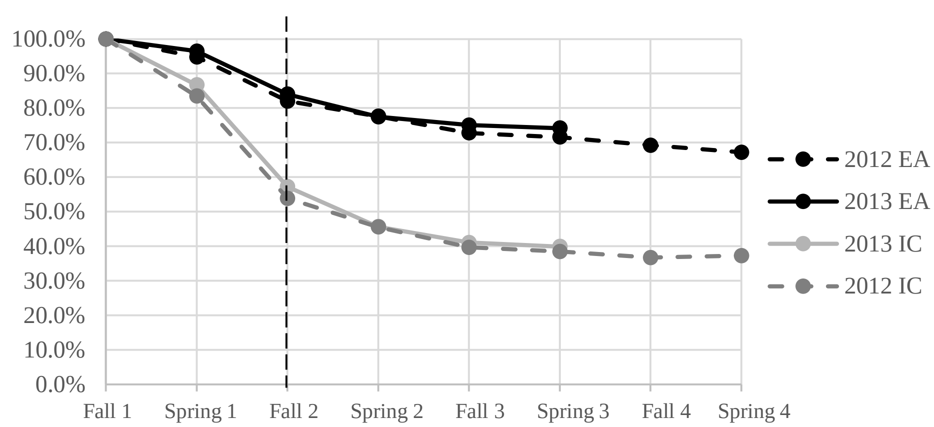

Figure 1: Retention over Time.

While retention rates remain lower for the IC students, the *change* in retention, better described as attrition rate, is much less after the first year. The attrition rates after the first year are similar for EA and IC students. This can be seen clearly in Figure 2.

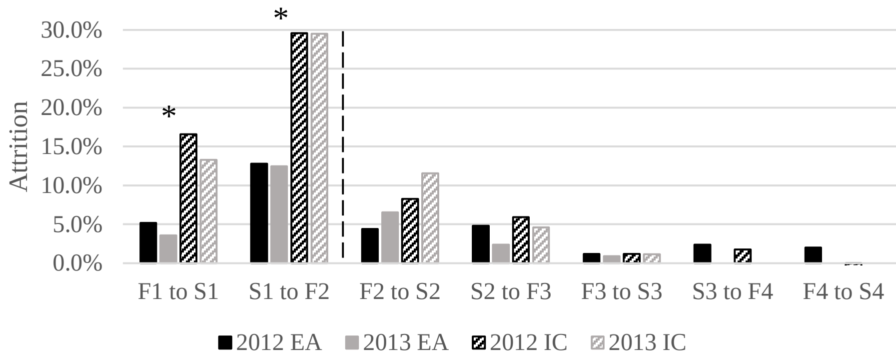

Figure 2: Attrition over Time.

These two charts showing retention and attrition rates over time by semester indicate that the largest changes occur in the first year. Once students enter the fall of their second year, they are much more likely to remain in the engineering school.

This assessment of student retention over time is important, but it does not provide the full picture. The other goal of this analysis was to address retention with respect to the mathematics sequence. For example, the IC students take different mathematics courses in a given semester than EA students because of the additional semester required at the beginning. Therefore, the similarity between IC and EA in attrition after the second year indicates that the later attrition is not solely caused by the courses themselves. This is further investigated in the next section.

Retention and Completion of the Mathematics Sequence

To understand the impact of specific math courses on retention, we looked at students' progression through the math sequence course by course. We tallied the number of students who continued to the next course, who repeated the same course, and who left the engineering school. These were not mutually exclusive groups – some students who repeated a course later left the engineering school, while others who repeated, continued. Also a few students did not enroll in the next course, but also did not leave the engineering school. These students are not tallied beyond their most advanced math course enrollment. The results are summarized in a flow chart that can be read as follows:

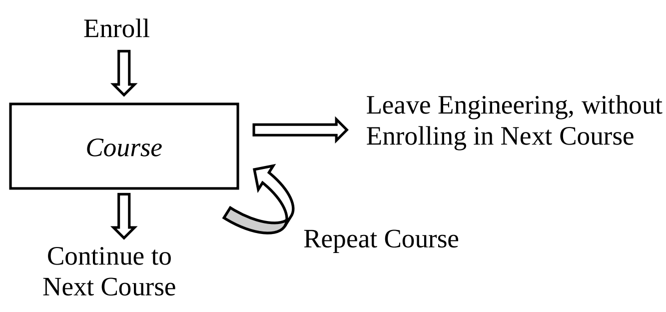

Figure 3: Recirculation Diagram Key

It is important to note that these figures do not describe progress through the sequence with respect to time. While some students move straight through the sequence, many repeat courses and fall behind by a semester. Some students repeat courses more than once, but the

Engineering Analysis I Group

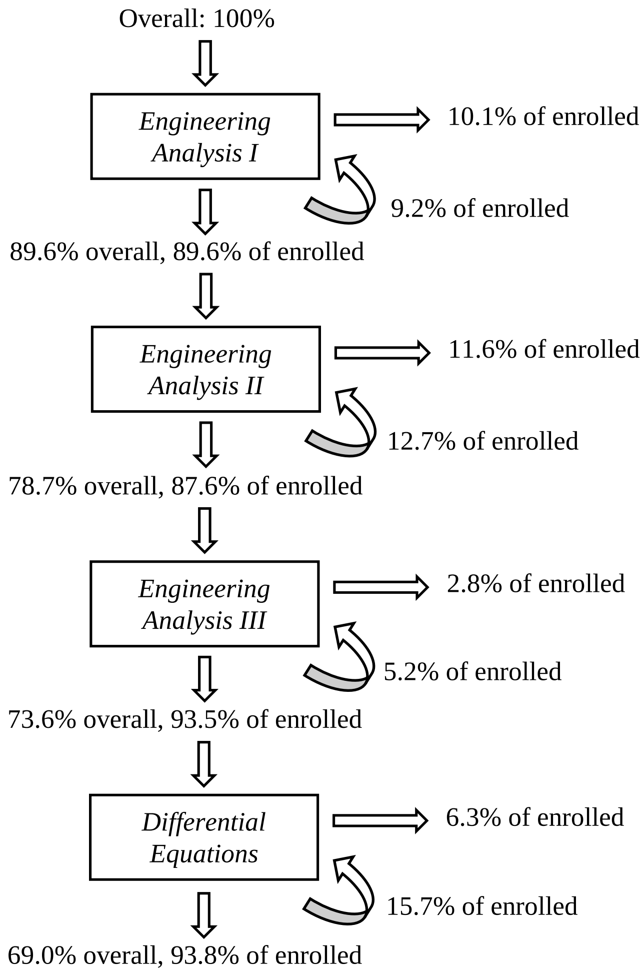

Figure 4: EA Student Progress through the Mathematics Sequence.

students who repeat the course are only counted once. The diagram merely shows how many students have had to repeat the course, how many end up moving on to the next course, and how many do not take another course and drop out of the engineering school.

Similar to the results of retention over time, the pattern of student progression through the sequence was very similar between the two cohorts. Results are presented as percentages of students in both cohorts for EA students and IC students in Figure 4 and Figure 5 respectively. For details on the individual cohorts, see Appendix A.

Of the group of students who started in *Engineering Analysis I*, 89.6% continued to *Engineering Analysis II*, 78.3% continued to *Engineering Analysis III*, 73.6% continued to *Differential Equations for Engineering*, and 69.0% completed the sequence. The more informative data appears when we look at the percentage of students who continue with respect to the number of students who enrolled in each course. The progression between courses was as follows: 89.6%, 87.4%, 94.1%, 93.7%. These percentages show that there is never 100%

continuation from course to course, but once the students reach *Engineering Analysis III*, they are much less likely to leave the engineering school.

In comparison, Figure 5 shows the progress for the students that start in *Introductory Calculus.* These students continue through the sequence with the following percentages (continuation to next course based on enrollment in that course): 76.6%, 60.3%, 90.8%, 88.4% and 83.2%. These values are lower than those for the EA students, indicating that even the students who pass the *Introductory Calculus* course are more likely to leave the engineering school as they progress through the math sequence.

Additionally, these results show that, similar to the EA students, after the *third* course, in this case after they reach *Engineering Analysis II*, students are much less likely to leave the engineering school. The dependence of student dropout rates on the numerical progress through the sequence (lower rates after the third course) rather than which course in the sequence (e.g. after Engineering Analysis I, II, or III) reinforces the previous finding that student attrition is likely due to something besides the required math courses.

Repetition

Repetition results for EA students show that two courses in particular have a high percentage of repetition: *Engineering Analysis II* (12.5%), and *Differential Equations* (14.7%). IC students on the other hand have high repetition rates for all three of the more advanced courses: Engineering Analysis II, 31.0%; Engineering Analysis III, 20.1%; and Differential Equations, 15.2%. Repetition values tend to be higher for IC students. This indicates that even after taking a remedial course, these students are less likely to pass the more advanced courses than EA students, just like they are also more likely to leave the engineering school. It is possible then that repeats are indicative of student motivation or study strategies rather than prior knowledge.

However, the large percentages of repeats for EA students likely occur when the students are seeing new material. Many high schools teach calculus, if not AP calculus, giving students an introduction to their first course in college. The second course, however, should be new material for all. Additionally, *Differential Equations* is a course that is unlike the previous courses and has few opportunities for transfer from calculus. So, it is possible that the high levels of repetition are due to students having to learn new material.

Additionally, the two courses are similar in several ways. First, topics may appear as distinct, unrelated entities. Neither is algorithmic. Both courses teach solution methods for many types of equations: specific integral types in EAII and specific differential equation forms in DE. Students often feel that they must learn a greater quantity of material in these courses, although it is the same quantity but has a less linear conceptual progression. Also due to the piecewise subject material, exams require a different type of skill from students: the ability for students to determine which concept to use at any given time. Students must recognize and categorize problems prior to starting a solution procedure. It is possible that these two courses require different, recognition and categorization-based processes that are new and yet untrained. If this is the case, strategic modifications or interventions could target the cognitive process of learning and recognition.

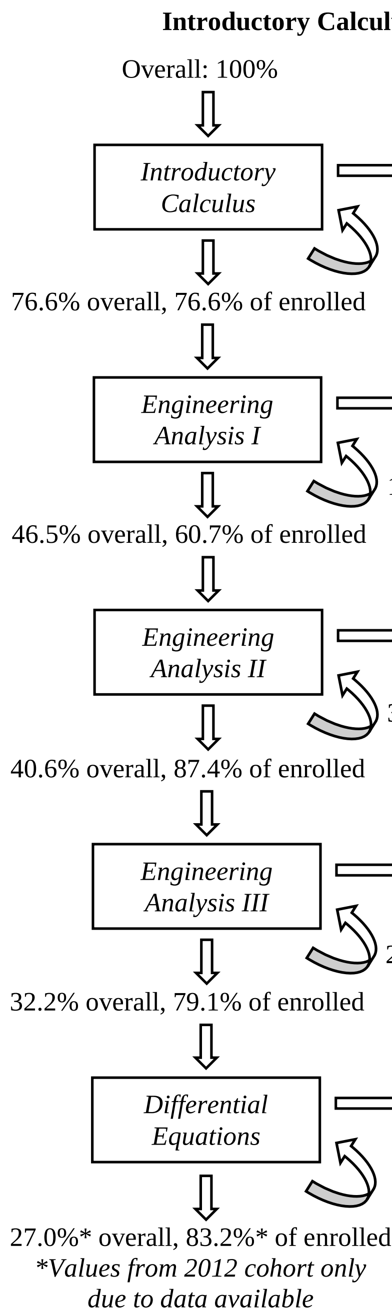

Figure 5: IC Student Progress through the Mathematics Sequence.

Discussion

There is a difference between a barrier that results in a high attrition rate, and a bottleneck that causes students to have to repeat a course. It has been shown here that in general, most of the attrition occurs in or just after the first year, however repetition is high in courses that are in the first year as well as the second. There are also differences between causes of attrition in the first year versus in the long-term. Students who continue into the second year of engineering school are much less likely to leave engineering, despite any difficult courses they may face. Both retention and repetition are therefore important when reviewing student progress through a multiple-semester math sequence to get reflections on the engineering program as a whole. This analysis can identify problem areas to address more specifically.

At this engineering school, attrition is a particularly high during and after the second semester. This is the same for the students who start on-track in the math sequence, taking *Engineering Analysis I*, and for those who must take the *Introductory Calculus* course prior to starting the sequence. This indicates that it is not the courses themselves that cause attrition, but rather the many internal and external psychological factors that impact first-year retention.

The data review also identified two courses that students frequently repeat: *Engineering Analysis II* and *Differential Equations*. There are many potential causes of this repetition, including but not limited to the novelty of the material, the new cognitive processes of recognition and categorization required for solutions, as well as motivation and study strategies. To reduce the number of repetitions, many possible teaching interventions could be investigated, such as deliberate practice of problem categorization, retrieval practice, or collaborative learning. These two courses each have unique issues as well as similarities. *Engineering Analysis II* has students dropping out as well as repeating the course, and *Differential Equations* has more students repeating the course more than once (not described in results thusfar, but observed in the construction of this paper). This indicates that each course may have specific issues. It is known that student performance and participation in *Differential Equations* suffers from it being a 2-credit hour course, for example. This reduces the amount of time that students can spend on the course, and also makes it more likely that they withdraw from the course because students can retain full-time status. One current intervention underway is flipping the *Differential Equations* course. On the other hand, since *Engineering Analysis II* has students both dropping out and repeating it, some careful analysis of the current structure of the course and in-class activities warrants more attention and reflection.

Conclusions

This paper reviewed two cohorts of students progressing through the mathematics sequence at the University of Louisville J. B. Speed School of Engineering. Data verified other research and showed that attrition is highest in and after the second semester, but it also identified some bottlenecks in later courses that cause students to repeat courses, possibly delaying their graduation dates. This analysis looked at a multidimensional dataset of student progress through the mathematics sequence (including semester-based and course-based progress and retention) in an enlightening way to identify bottlenecks in the longer timescale. Arriving at this procedure was nontrivial, and it is likely that other institutions would benefit from a similar approach. This procedure uniquely connects first-year-retention research to graduation rate research for engineering in a meaningful and descriptive way.

Future steps for this university are to target the bottleneck courses with interventions aimed at improving student pass rates and reducing the number of repetitions. As mentioned, a current intervention being used in *Differential Equations* is a flipped classroom. Others are needed specifically for *Engineering Analysis II.* The interventions will help students progress through the program and will relieve student backlog in some courses in the engineering school. This will optimize both students' and the university's resources and will allow the university to grow efficiently, providing students with the best possible education.

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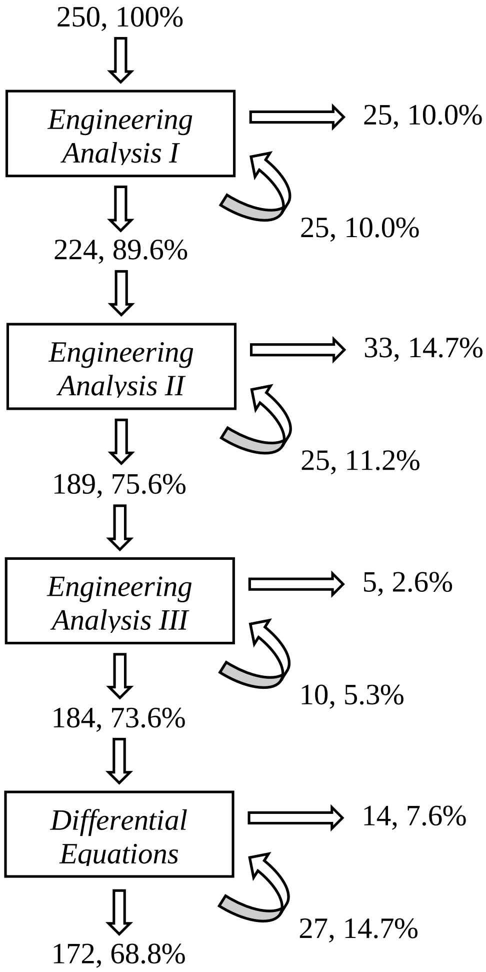
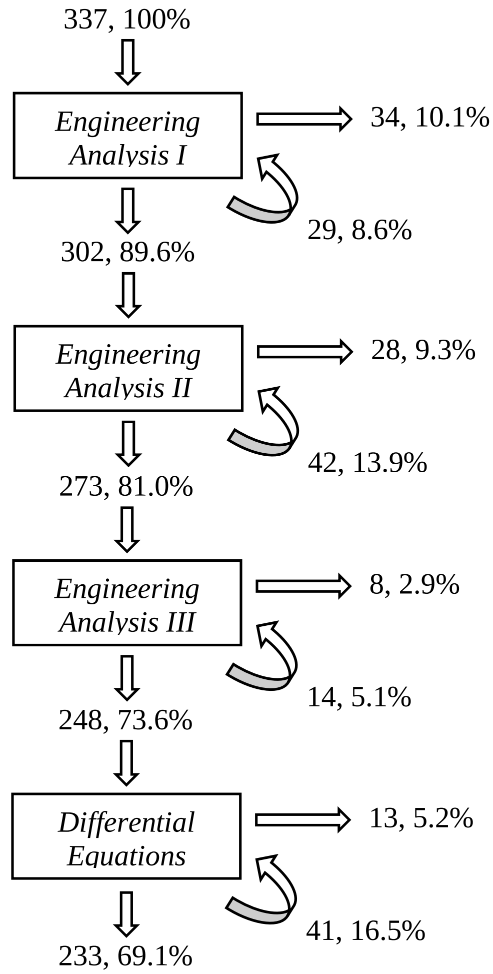
Appendix A

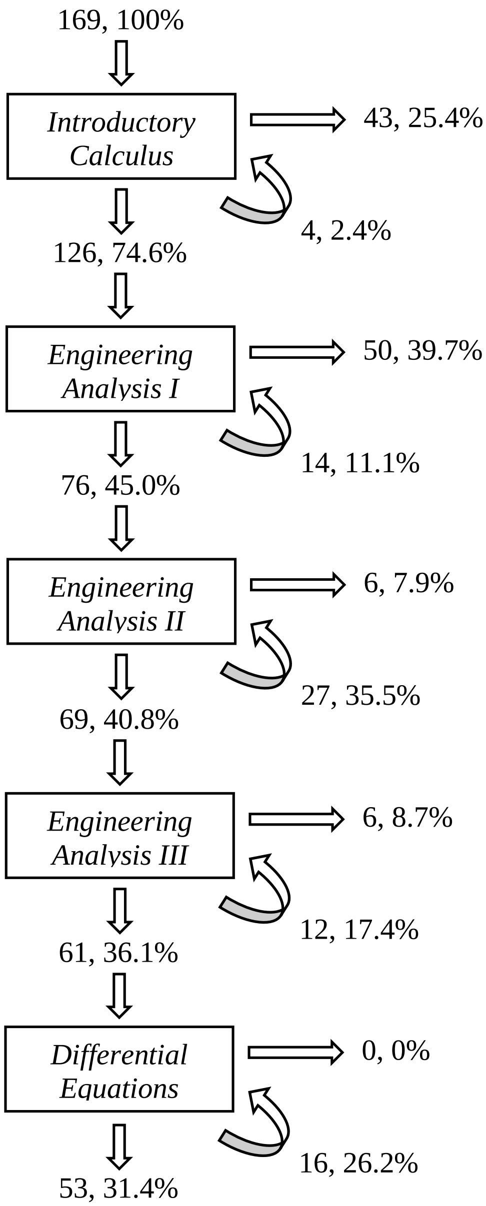
Engineering Analysis I Group
2012 Cohort



Engineering Analysis I Group
2013 Cohort



Introductory Calculus Group
2012 Cohort



Introductory Calculus Group
2013 Cohort