Active Learning and Engagement in Mechanics of Solids

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Active Learning and Engagement in Solid Mechanics

Abstract

A flipped classroom approach was applied to a solid mechanics course at a public state-funded national research university in Fall 2014. All course material was organized into lecture/flipped classroom pairings. Lecture time was used to explain and introduce new concepts, with limited problem solving. Students prepared for flipped classroom sessions by watching a series of videos demonstrating problem solving techniques. During flipped classroom meetings, students self-organized into teams of 4 to work assigned problems at whiteboards with instructor guidance and feedback. The flipped classroom led to a small increase in average student achievement, which was assessed by comparing exam scores to a consistent exam from a previous semester. Lower performing students were more successful in the flipped classroom, while the performance of high achieving students did not change appreciably. Based on course evaluations, the student response to the flipped classroom was overwhelmingly positive; however, some negative perceptions were expressed. Ongoing research will assess whether holding students more accountable for flipped classroom preparation and accomplishments can lead to greater student achievement.

Introduction

Pedagogical changes in engineering education have been slow to change, despite the noted improvements to student learning from relatively novel teaching techniques[1]. A recent report from the Proceedings of the National Academy of Science, indicated that active learning pedagogies, regardless of which pedagogy, created learning environment where students were more engaged with course material and showed significantly better learning outcomes[1]. Active learning is loosely defined as any instructional technique that requires students to do meaningful activities and think about what they are doing[2]. Practices that are traditionally classified as active learning include collaborative learning, cooperative learning, and problem-based learning.

One instructional model that can facilitate active learning is the flipped classroom. In the flipped classroom, instruction is moved from class time to out of class time for students, and interactive lessons are moved into the classroom[3]. While the flipped classroom is gaining traction in engineering classrooms[4], there has been limited documentation of the effectiveness of the flipped classrooms within the specific subcultures of engineering. This work serves to add to and expand the initial insights into flipped classrooms in engineering mechanics by presenting outcomes-based evidence for an introductory course in solid mechanics. Engineering degree programs such as mechanical engineering, civil engineering, materials engineering, and geological engineering generally require such a course in the sophomore/junior year. The course may be known as “Strength of Materials”, “Mechanics of Materials”, “Mechanics of Solids”, to name a few, and develops a foundational technical knowledge base that is later expanded upon on with applications specific to the major.

The Learning Environment of the Flipped Classroom Experiment

The flipped classroom approach was applied to a solid mechanics course at a public state-funded national research university in Fall 2014. This institution has above average enrollments of students who self-identify as Hispanic (14%) and multi-ethnic (5%) when compared to national averages[5]. The engineering program also has lower than national average numbers for African American students.

While traditional diversity measures of this institution may not stand out, invisible measures of diversity, such as socio-economic status, make this institution unique. Students tend to come from low socio-economic status; 24% of our students are Pell grant eligible with household incomes under $30,000. The state subsidizes the cost of education to in-state students by providing a reduction in tuition of approximately 90% relative to the full cost of tuition to out-of-state students. The in-state tuition is one of the lowest in the country among four year national research universities, and provides access to engineering for a high number of students who may not otherwise afford it. Students coming from low-income backgrounds often suffer from a number of disadvantages when compared to their more affluent peers. The low-income status of many students drives them to seek additional funding through external employment, leaving students with little time for study outside of the classroom. In addition, 5% of engineering students are over the age of 30 and potentially have to support their families in addition to their studies. Living off campus is common among all students; such students have less access to study and support groups, which leads to the creation of a dispersed community of practice. Research has shown that having a weak community of practice, negatively influences students feelings of belonging and learning[6].

Overall, the state has a low rate of funding for education, suggesting that its students start out less prepared for college coursework in engineering relative to the national average. In addition, the university and engineering program admission standards create an environment that allow students to pursue engineering even when they have not met basic math pre-requisites, putting them immediately behind.

As a result, the College of Engineering has high attrition and a low degree completion rate. Recently compiled statistics show that the college freshman to junior retention rate (freshman declared engineering majors that are retained to junior status) has varied from 44 to 60% over the past 10 years. Core engineering courses in the sophomore year (statics, dynamics and solid mechanics) serve as gate-keeper courses for the engineering degree programs. These courses require C or better to advance to follow-on courses. Students find these courses to be technically challenging, since they are first asked to think like engineers. These courses accommodate enrollments of 100–300 students each semester, and thus may be inherently lacking attention to individual students and a personalized feel that is intrinsically motivating to students[7]. The rate of withdrawal or non-participation (students that accept an F without taking the final) by the end of the semester varies from 5-10% (e.g. 8.5%, 6.1% and 8.3% for recent offerings of the solid mechanics course).

While internal surveys have indicated a strong reliance on direct instruction as the primary pedagogy throughout the college, some courses have begun to incorporate active learning practices. The solid mechanics course discussed here first incorporated interactive response systems (i.e., clickers) into the lectures in 2011. Such systems allow students to respond to questions or problems posed during class time, which encourage their active thinking and are also used to provide instant feedback as to how well students grasp the comments. These interactive response systems have been used every semester in solid mechanics since Fall 2013, regardless of the instructor. Discussion sections, facilitated by teaching assistants (TAs), were implemented and have been ongoing since Fall 2012. The TAs have been encouraged to facilitate instructor-guided student problem solving practice during these discussions, rather than working problems at board, which leads to a very passive mode of learning. However, a high level of quality control has not been implemented. In Fall 2013, the instructor experimented with team-based learning as formally defined by Michaelsen[8-10]. About 1/3 of the content was delivered team-based learning style, which was concluded to be a sub-optimal approach for the specific objectives of this course.

In Fall 2014, the solid mechanics course was significantly re-designed using a flipped classroom approach. The cornerstone of the approach was to use class time for student teams to solve problems at whiteboards with instructor guidance. The objectives of this paper are to evaluate student learning outcomes relative to previous semesters, to discuss student evaluation and perception of the course, and to critically assess successes and failures and lay out a plan for improvement.

Course Objectives and Conduct in Fall 2014

For the solid mechanics course, one of the major student learning objectives is for students to organize, approach, and solve multi-step engineering problems that are applications of course specific technical content knowledge. This objective maps to ABET learning outcomes A: ability to apply knowledge of mathematics, science and engineering, and E: ability to identify, formulate, and solve engineering problems. For rigorous assessment, the exams in this course are 100% written problems that allow the graders to evaluate the student thought-process in working problems from start to finish, and are graded against a rubric that assigns points for applying the correct steps and calculation accuracy at each step of the process. The assessment method has been consistent in this experiment, with some changes to the exam timeline and final exam approach that are discussed below.

The following summarizes the elements of the course that were re-designed for Fall 2014. First, all course material was organized into lecture/flipped classroom pairings. For each pairing, the lecture time was used to explain and introduce new concepts, with limited problem solving. Feedback was obtained intermittently through the interactive response system to assess whether students were absorbing the concepts. Students were asked to prepare for the follow-on flipped classroom session by watching video clips (20-30 minutes total) demonstrating the solution of 2-4 problems related to the new concepts. The video clips were recorded by the instructor using a tablet PC; and showed the solutions being written over a power point template with a voiceover narrative explanation. Unlike the classroom, students could watch at their own pace, opt to re-watch parts they had difficulty understanding or skip over parts that seemed elementary. At the start of the flipped classroom session, students were given the opportunity to ask clarification questions about the video solutions, and were given a short review question using the interactive response system. Following the instructions, students self-organized into teams of 4 to work assigned problems at the whiteboards. Some of the problems worked during these sessions had been formally assigned as homework (giving students a head start) while others were given for extra practice. Students teams worked at their own pace, while the instructors and TAs walked around, observed the effort, answered questions, and redirected teams as necessary. Student teams were encouraged to rotate the role of scribe among the team members, obtain confirmation of accuracy from an instructor or TA after completing a problem, and take pictures of the work for later reference.

The evaluation conducted in this work seeks to focus on the reorganization of the technical content delivery described above. However, additional changes to the course may have also influenced the student learning outcomes. First, a stricter but more transparent rubric was applied to the homework grading that emphasized importance of the problem solving procedure. For instance, students were required to summarize the problem statement in their own words, identify known values and the desired solution quantities with units, draw complete/labeled supporting sketches and diagrams as needed, show all equations in symbolic form, show calculations in detail, track units through the calculations, box final answers with 2-4 significant digits and clear indication of signs, and perform a sanity check to identify obvious errors. This rubric was loosely based on the work of Grigg and Benson[11], which explored the ways in which successful engineering students solved engineering problems. Some - but not all - of these steps were assessed more rigorously on exams. Second, a change in examination strategy led to realignment of course topics to exams. In the past, about 75% of the material was covered and tested in three exams prior to the final. The final exam contained about half new material (from the final 25% of the course) and about half comprehensive questions from the entire course. In the re-designed course, all material was presented and tested in 3 exams prior to the end of the course. Exam 3 was graded quickly and returned to the students with their tabulated course average (percentage). The final two class meetings were reserved for a final exam review. The final exam, which was optional, was broken into 3 parts paralleling the 3 exams. In the final exam, students were given the opportunity to improve their score on any or all 3 of the exams, and likewise improve their tabulated course average. Finally, the course was divided into two sections so that the lecture size was somewhat smaller (70 compared to 90-150 in prior semesters). Section 1 was taught by an experienced instructor and Section 2 was taught by a less experienced graduate student TA. Both worked together with other student TAs to facilitate the flipped classroom sessions.

The following elements of the re-designed course were consistent with previous semesters. The interactive response system was used during lectures. However, the questions in the re-designed course were largely conceptual and less calculation-based questions were incorporated. The same textbook has been used since Fall 2013; individual homework assignments were due approximately semi-weekly and incorporated online exercises for concept mastery and problems requiring multi-step solutions with detailed calculations. The exam style (discussed previously) and difficulty was consistent with previous semesters, to the extent possible. Since Fall 2013, the course has incorporated laboratory demonstrations and required student lab reports with data analysis.

Student Achievement in the Flipped Classroom

To assess student learning outcomes, we restricted our investigation to directly comparing Exam 1 performance in Fall 2013 and Fall 2014, for a few reasons. First, Exam 1 covered the same material and same difficulty of questions over this time period. However, due to the realignment of course topics to exams, Exams 2 and 3 covered different material. The topics that students historically performed the worst on were moved from Exam 3 to Exam 2. Furthermore, student behaviors and practices during the second half of the course deviated from ideal practices (discussed later). Finally, the final exam performance could not be evaluated as a measure of the flipped classroom due to the changes in the overall examination strategy.

In Figure 1, student scores on Exam 1 have been converted to probability density functions based on the sample mean and standard deviation of the score set, assuming a normal distribution.

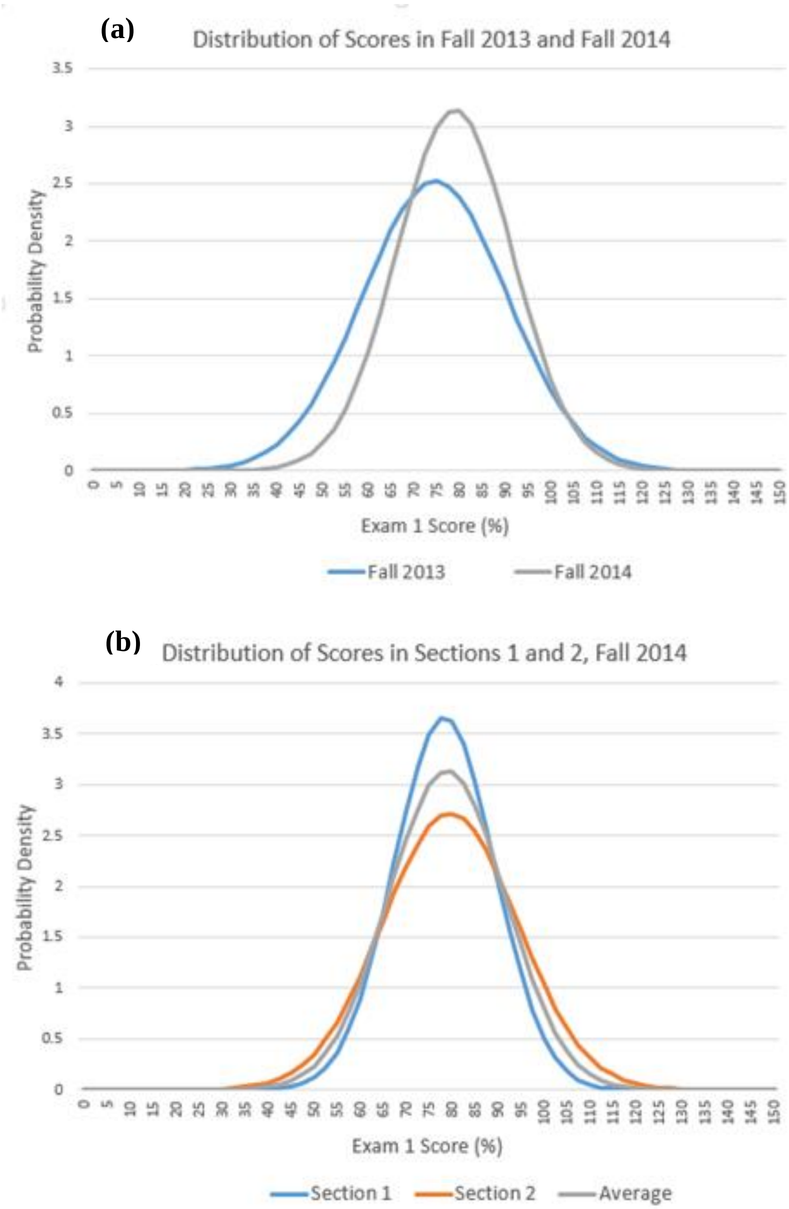

Figure 1. Distribution of Exam 1 scores (a) Fall 2013 and Fall 2014, (b) Sections 1 and 2 in Fall 2014

Figure 1(a) compares the overall distribution of scores from Fall 2013 and Fall 2014, while Figure 1(b) compares the distribution of Section 1 and 2 scores from Fall 2014. In Figure 2, we compare histograms of Exam 1 scores for the 3 score sets discussed in Figure 1. The histograms show the number of students scoring in each percentile range (0-10%, 10-20%, etc.). From Figure 1(a), the average Exam 1 score in Fall 2014 (78.9%) was slightly higher than in Fall 2013 (74.7%). Also noteworthy, the distribution of scores was narrower in Fall 2014 (standard deviation of 12.7% in Fall 2014 compared to 15.8% in Fall 2013). The histograms in Figure 2 show that the percentage of students performing very well – in the 90-100% range – did not increase (19.6% in Fall 2014 compared to 24.6% in Fall 2013). We attribute the decline in high performance to a stricter grading rubric in Fall 2014 that penalized students for lack of attention to process steps, clarity of presentation, and units more so than in years prior, although the students had been forewarned. More noteworthy, however, the percentage of students performing very poorly – less than 60% - declined sharply (7.1% in 2014 compared to 14.9% in Fall 2013). These data are consistent with what has been reported in the literature on active learning strategies – that learning outcomes for high performing students are not substantially different, while learning outcomes for lower performing students tend to be much improved (Freeman et al., 2014).

Figure 1(b) shows that student performance varied non-negligibly in Fall 2014 Section 1 – led by the experienced instructor – compared to Section 2 – led by the graduate student. Section 2 earned a slightly higher average (79.6% compared to 78.3%) with more high performers but also more low performers (see Figure 1). We are unsure whether the distributions are truly statistically different, but if so they could possibly be a combination of inherent differences in student composition, exam difficulty, and instructor experience. Higher performing students may have been more likely to enroll in Section 2 (8 am) compared to Section 1 (10 am), but attendance was also lower in Section 2 due to its early time. Lower performing or less motivated students enrolled in the 8am course may have been more likely to withdraw from the course early due to the meeting time, and may have led to the increased grades of the section. The exam problems for the sections were consistent, but not identical. Most of the scoring discrepancy between the two sections can be attributed to a problem that we interpret as being more difficult for Section 1 compared to Section 2. The exams for each section were graded comparably, with the experienced instructor grading half of the problems and the graduate student grading the other half for each exam, with both following an agreed upon grading rubric.

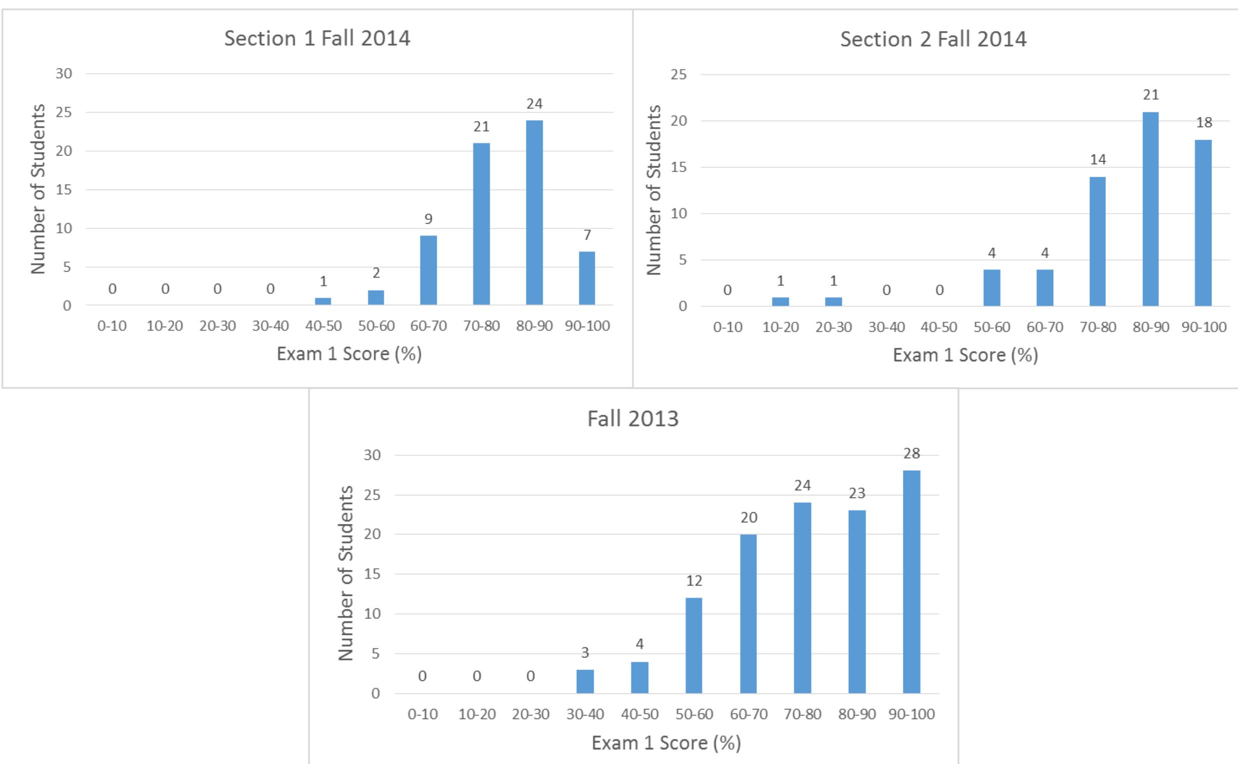

Figure 2. Histograms of Exam 1 scores for Sections 1 and 2 in Fall 2014 and Fall 2013

Student Satisfaction

Student course evaluations administered at the end of the semester indicated an overwhelmingly positive response to the course revisions in Fall 2014 compared to the prior year. The average scores for both Overall Course Quality and Instructor Effectiveness were 4.61/5 for Section 1 and 4.46/5 for Section 2. The Fall 2014 averages were the highest that the experienced instructor had ever received for this course.

Student comments provided additional insight into student perceptions of the course. Overall, 23 students in Section 1 and 22 students in Section 2 wrote a specific comment. The number of comments that could be interpreted as overwhelmingly positive was 14 of 23 for Section 1 and 11 of 22 for Section 2. The nature of these comments were "best course", "overall great experience", "really liked the flipped classroom", etc. While the response was strongly positive for both sections, a few negative reactions to the flipped classroom were expressed. We sorted these by students that expressed strong dislike over the flipped classroom (1 in Section 1 and 4 in Section 2) and students that perceived the flipped classroom took more of their time than a traditional approach (1 in Section 1 and 3 in Section 2).

The rate of negative feedback was higher in Section 2 with the graduate student instructor. As discussed above, Section 2 contained more high performers, which could indicate that Section 2 was composed of more students that had achieved success under traditional learning techniques, and thus were resistant to the flipped classroom. Upon reflection, we believe that students in both sections were similarly educated about the benefit of the flipped classroom at the beginning of the semester. However, a few students in Section 2 vocally expressed dislike of the approach after some time had passed. An effective response would have been to reinforce the theory and benefits of the active learning approach; however, the graduate student instructor was unsure of how to respond in this situation. As such, the exchange may have negatively influenced the overall student perception in Section 2. Regarding the time commitment, our intention was that the additional preparation required of the students (watching video examples) should be offset by the time saved completing some of the homework in class.

Evaluation of Alternative Examination Strategy

The alternative examination strategy for the course provides an interesting opportunity for evaluation of student motivation and improvement. The model was described to the authors by Dr. Furse, who conducts an online training program to help new instructors implement flipped classroom approaches[12]. Recall that the examination strategy allowed students to attempt Parts 1, 2 and/or 3 of the final exam to improve their scores on Exams 1, 2 and 3, respectively. The strategy is expected to provide extra motivation to perform well on the first attempt in order to opt out of the final. For the final exam, students can optimize their time, focus on the exam materials that they struggled with most, learn from their mistakes, and improve their scores.

After Exam 3 was graded, students were given a cumulative course average (percentage), and the minimum letter grade that would be associated with that percentage. Based on this information, students could estimate the potential improvement to their grade and devise a strategy for retake. Disappointingly, many students settled for grades in the B and C range without attempting to improve them. However, their willingness to attempt improving their grade may have been influenced by more pressing needs for attention to other courses[13]. Table 1 lists statistics on retake attempts for each section separately and the two sections combined for each exam. The statistics include the number of students attempting the retake (Number Attempted), the number of students who improved their score (Number Improved), the percentage of students who improved their score (Percentage Improved, and the averages of the first attempt (First Attempt Average) and the retake (Retake Average) among students who attempted the retake only. Overall, the retake success rate was high, with 79% of students improving their scores, and the average improvement a little greater than 10%. Section 2 students had extra time to prepare, with a final exam scheduled on Monday compared to the previous Friday for Section 1. This influenced the retake rate only slightly (82 attempts in Section 2 compared to 77 attempts in Section 1) and did not lead to a higher success rate (77% in Section 2 compared to 81% in Section 1). Following the retake, the average scores were still much lower for Exam 2 – which contained the most difficult material for the course – compared to the other two exams.

Table 1. Exam Retake Attempts, Success Rates, and Averages

		Number Attempted	Number Improved	Percentage Improved	First Attempt Average	Retake Average
Exam 1	Section 1	23	19	83%	71.1%	86.2%
	Section 2	26	20	77%	69.6%	83.3%
	Combined	49	39	80%	70.3%	84.7%
Exam 2	Section 1	31	26	84%	64.3%	75.6%
	Section 2	23	15	65%	66.0%	72.3%
	Combined	54	41	76%	65.0%	74.2%
Exam 3	Section 1	23	17	74%	68.8%	76.3%
	Section 2	33	28	85%	70.2%	84.0%
	Combined	56	45	80%	69.6%	80.8%

Critical Assessment of Implementation and Plan for Improvement

Students were observed to exhibit very favorable practices during the first third of the class, and Exam 1 scores are believed to reflect such practices. However, performance on Exams 2 and 3 declined compared to Exam 1; the average scores for the two sections combined were 72.7% on Exam 2 and 75.2% on Exam 3 compared to 78.9% on Exam 1. Some of the decline is explained by the fact that material on Exams 2 and 3 is more difficult for students, and the trends from Fall 2014 echo historical trends. Nevertheless, student behaviors and practices were altered from ideal practices in the latter 2/3 of the course. First, the rate of watching the video examples steadily declined as students became busier; this was evident by documenting the number of times each video was watched. Second, lower levels of student engagement in the flipped classroom were observed as time passed. For instance, some team members appeared not to follow or pay attention to the team effort at the board. In some teams, the same student was observed to assume the role of the scribe all the time. As a result, the ability of the student teams to successfully complete problems within the allotted time was observed to decline.

Upon reflection, we feel that the instructors adjusted their behavior to compensate for the lack of student preparation. Specifically, at the start of flipped classroom sessions, the instructors gave guidance to help the teams solve the problems rather than let them fail if they were not properly prepared. A non-compensating approach may have helped the teams get back on track, or may have just led to further frustration on the part of the students. Furthermore, we observed that the ratio of 7 or 8 teams per one instructor that was implemented during some of the sessions was too high. In this case, the instructor could not continuously visit all teams in a timely manner. Due to a desire to complete all the problems, teams would erase their solution and move on to a new problem without confirmation that their solution was correct. Later discussion would sometimes reveal that the answer was not correct, but with no mechanism to analyze the solution and identify the errors.

To address the perceived shortcomings of the student behavior, we have made some changes in the course structure for Spring 2015, which is currently underway. The most significant changes have been implemented to hold students more accountable for their preparation and their accomplishments in the flipped classroom. To assess preparation, periodic pop quizzes will be administered that include questions that can likely be answered only by students that have watched the videos and listened to the instructor narrative (5% of overall grade). To assess the in-class productivity, problems considered in the flipped classroom are assigned as a separate teamwork assignment, and are designed to be finished within the hour. The process to receive credit for the teamwork is very simple if the teams finish their work during class time, which enhances motivation to be prepared. To receive credit for the teamwork, teams must submit photos of their boardwork that identify the scribe (to document that they are rotating the role of scribe) and identify all team members present (students must be present to receive credit for the teamwork). Students must attempt at least 2 problems during the class meeting and a TA must sign off on at least one (confirming clarity of solution and accuracy). To compensate for the teamwork assignments, individual homework assignments have been substantially shortened.

As in Fall 2014, students are allowed to self-organize into teams initially. To simplify the documentation process, the team assignments are recorded and students are required to maintain the same team composition. Knowing that team success can be influenced by team composition, the instructors/TAs will assess team dynamics and participation and reassign team members after the first third and second third of the course. Work has shown that the long-term establishment of teams can lead to students continually taking the same roles and not developing additional skills[14]. Additionally, work on teaming has indicated that cognitively diverse teams produce better solutions to problems[15]; as educators we wish to expose our students to many ways of thinking to help transform them into better problem solvers. Finally, a maximum ratio of 5 student teams per instructor/TA has been implemented in Spring 2015 to ensure the teams can be given adequate attention. This ratio was applied successfully during the Fall 2014 classroom sessions.

Challenges to Implementation

The flipped classroom approach implemented here, or any approach that involves providing instructor feedback to students on an individualized basis, requires significant resources. For Spring 2015, 175 students are enrolled in the solid mechanics course. For efficiency, all students attend the same lecture, and resources are focused on the flipped classroom sessions; the students have been split into 5 separate sections for the flipped classroom session with up to 40 students each. The instructor will have limited involvement in the flipped classroom sessions; rather, each session is moderated by two TAs with the maximum 5 teams to 1 TA ratio. Overall, 20 in-class instructor/TA hours are required per week to manage the flipped classroom (5 sections x 2 instructors x 2 class meetings per week). Four TAs have been hired to assist with the course, wherein 3 of the 4 are experienced from the previous semester. However, starting with a set of new TAs would inevitably require a significant time commitment from the instructor.

At this university, we have also encountered significant obstacles with regard to scheduling and classroom assignments. The solid mechanics course is designated in the catalogue as a 3 credit course with 3 lectures and 1 discussion section per week. In Fall 2014, the classroom was converted by installing temporary whiteboards on the walls around the room, so that the lecture room could be used for flipped classroom sessions. To handle the larger enrollment in Spring 2015, distinct separation of lectures and flipped classrooms (discussions) was needed. Upper administration has become involved to bend the rules, allowing the course to be scheduled as 2 lectures and 2 discussions per week in order to continue to evaluate the flipped classroom innovations. In addition, cross-campus scheduling demands do not allow for much consideration of specific classroom needs. To ensure that all flipped classroom sessions could be held in a suitable space, we renovated a classroom that was under the scheduling control of the department for this purpose.

In our opinion, our generation is on the cusp of a revolution in engineering education, with regards to technical content, professional skills, and delivery methods. To be on the forefront of innovation, engineering educators must be creative, adaptable, patient, and persistent. We hope that institutional structures will evolve to be more accommodating in time as the evidence of success for these innovations grows. To continue fostering institutional attitudes that foster the development of new educational pedagogies locally, future work will seek to generate persuasive evidence to convince administration that a flipped classroom technique not only delivers the same content knowledge but provides students with additional skills in the areas of teaming and problem solving.

Conclusions

This paper has described the implementation and assessment of a flipped classroom active learning strategy in an introductory solid mechanics course. The cornerstone of the strategy was to use class time for student teams to solve problems at whiteboards with instructor guidance. Analysis of student learning outcomes and student satisfaction has led to the following conclusions:

1. The flipped classroom led to a small increase in average student achievement, which was assessed by comparing exam scores to a consistent exam from a previous semester. Lower performing students were more successful in the flipped classroom, while the performance of high achieving students did not change appreciably.
2. Based on course evaluations, the student response to the flipped classroom was overwhelmingly positive. Negative perceptions of the flipped classroom were expressed more in one section compared to the other, suggesting that overall student perceptions may be influenced by vocal dissenters, and instructors must be prepared to reinforce the theory and expected benefit to retain student buy-in

3. For the latter 2/3 of the course, student success was negatively influenced by lack of student preparation and subsequent disengagement during the flipped classroom. Ongoing research will examine whether holding students more accountable for preparation and accomplishments in the flipped classroom will lead to greater success.
4. Flipped classroom strategies that involve providing instructor feedback to students on an individualized basis require significant resources. Scheduling and proper classroom setup can pose additional challenges. Institutions must adapt to accommodate the changing educational needs.

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