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Cultivating critical thinking habits in Electrical Engineering flipped classrooms

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Cultivating critical thinking habits through take-home tests in a flipped Electrical Engineering course

Abstract

Tackling complex engineering problems requires that students develop higher-order thinking skills that allow them to evaluate multiple sources of information and make informed and reasoned decisions that lead to the best solution. One particular course in which mastery in learning requires higher-order thinking is the nonlinear electrical circuit course offered to electrical and computer engineering students. Since analyzing the operation of nonlinear circuits often requires making assumptions, verifying or rejecting the assumptions and drawing conclusions, students usually struggle with making a clear connection between different steps of the circuit analysis or applying these steps to solving new problems.

Within the framework of a fully flipped circuit course, we studied the effect of take-home tests on the final exam grades of the enrolled students. The previous design of the course was based on a hybrid model of in-class lectures. In the new course design, all lecture content was recorded and students were asked to watch the videos before coming to class so they could participate in the in-class problem-solving activities and discussions. The take-home tests were synthesis level circuit problems that were usually composed of a few distinct concepts learned in the course. Solving these problems required higher-order thinking, and students were encouraged to work on these problems in groups. These tests were in addition to the in-class midterm and final exams.

In addition to the total grades on the in-class final exam taken by all students, the scores on one of the final exam problems that was specifically designed to assess students' abilities to solve conceptually challenging questions were included in this study. Students' feedback on their perception of the effectiveness of the take-home tests on their learning was also collected in mid and end of quarter surveys.

The results of our study show that during the Fall and Winter quarters of the 2018-2019 academic year, the average final exam grade for students who took the take-home tests was significantly higher than the average for students who opted out of the take-home tests. Furthermore, out of the total students who correctly answered the conceptually challenging questions on the final exams of the Fall and Winter quarters, 71% and 65% participated in the offered take-home tests, respectively.

Introduction

This study was conducted in a fully flipped junior-level core electrical circuits course to test the effect of take-home tests on improving students' critical thinking and mastery of course learning outcomes. The course covers an introduction to nonlinear circuit elements and their applications in designing and building functional analog and digital circuits. As is integrated into the learning outcomes, students in this course are expected to analyze circuit problems that are different from what they have seen in the class and use what they have learned in the course to design functional circuits that satisfy the specified criteria. As an example, after learning about the PN junction diodes and the structure of half-wave and full-wave rectifiers, they were asked to design a DC power supply that would provide a certain average dc output voltage with a ripple voltage less than the given maximum value.

Solving the design problems required students to develop a strong understanding of the material and achieve a mastery level in mapping the design criteria to the circuit configurations that they have studied in the course. To provide students with an opportunity to achieve this goal, a series of interventions were implemented in the course since the Spring quarter of 2018. The current study is part of the progressive investigation of the effect of these interventions.

The transition from a traditional lecture style to a fully flipped classroom style in this course started in Spring 2018. As reported in our previous paper[1], in the Spring quarter of 2018, some parts of the lecture material were recorded and offered to students in the format of screencast videos. Students were asked to watch the videos and answer the accompanying multiple-choice concept-check questions before coming to the class, and class time was spent partly on teaching the rest of the lecture material and partly on solving the discussion questions posed by the instructor. Two optional take-home tests were added to the course. One take-home test was posted before the midterm and the other one was posted after the midterm exam. Students were strongly encouraged to take the tests, but they all had the option of opting out of the take-home test. Each take-home test had a problem related to the course topic; but to solve the problem, students had to achieve a deeper understanding of the covered course material. Students were allowed and encouraged to collaborate with each other, identify potential resources and solicit help from each other. Some of these resources include their TAs and the Tutoring Center in the department. To help with minimizing the potential for violation of academic integrity and to encourage students to reflect on their proposed solutions, they were asked to prepare a screencast and verbally explain how they solved the problem in addition to submitting their written solutions.

As discussed in our previous study[1], the changes we applied to the course had a promising effect on students' performance in this course and a positive effect on their final exam grades. In addition, in the mid-quarter and end of quarter surveys in spring 2018, students cited the benefits of offering the lecture content in the video format including the opportunity to review the material before and after class and having extra practice and discussion time in class. In the surveys, students also recommended flipping the entire course by offering all the lecture content in the video format and spending the entire class time on solving problems and discussing the confusing points in the circuit problems. Since one offering of the prerequisite course to the current one was based on the flipped classroom method, several students were previously exposed to the flipped classroom structure.

Following the successful results in Spring 2018, the completely flipped classroom model was adopted for the Fall 2018 and Winter 2019 offerings of the course. All the lecture content was recorded and offered to the students in the video format, and more in-depth quizzes, similar to the homework (HW) problems, were added to the lecture videos. Students were asked to solve these quizzes after watching the videos and before coming to the lecture. More discussion and multiple-choice iClicker questions were integrated into the lectures. Other than a few minutes for reviewing the content of the lecture videos at the beginning of every class, all the class time was spent on students solving and discussing the designed lecture questions. Three and two take-home tests were administered in the Fall 2018 and Winter 2019 quarters, respectively. The other course components including the HWs, labs, and a midterm and final exam, were similar to the Spring 2018 quarter.

In this study, the test and control groups were composed of ECE 65 students in the Fall 2018 and Winter 2019 quarters who took the take-home tests and the ones who opted out of taking the tests. The final exam grades and the survey results were used as the assessment tools for analyzing the effectiveness of the take-home tests in the revised and fully flipped course in the Fall and Winter quarters. Our guiding research question reflects the transformation of the course; we aim to assess the impact of the course design, and more specifically take-home tests, on developing critical thinking skills.

Literature review

Innovation in engineering education

According to the Center for the Advancement of Engineering Education (CAEE), engineering students who enter the discipline should have a high level of preparedness when it comes to their motivation to learn, a deep understanding of the real-world considerations of working as an engineer, and how critical thinking and social and emotional competencies are essential to solve problems and generate technological innovations.[2] Although it is well-recognized that such skills are important in professional contexts, there is some evidence that traditional engineering education does not effectively foster the growth of critical thinking skills and creativity in engineering students.[3] Research in engineering education has focused considerable effort on investigating more effective teaching methods to target these skills.[4] To contextualize the present research, a review of literature on critical thinking is provided alongside a review of scholarship examining the effect that flipped classrooms and varied assessment practices have upon student outcomes in engineering education.

Critical thinking in engineering education

In recent years, higher education institutions have increasingly emphasized critical thinking skills as a central outcome of undergraduate education. Although definitions of critical thinking vary across disciplines, a proposed definition in the context of engineering is the ability to move freely between drawing on concrete, contextual knowledge and abstract and reflective knowledge as needed.[5] Many definitions of critical thinking share a reflective element, emphasizing the ability to analyze and evaluate different approaches to a problem and self-regulate performance.[6–8]

Flexibility is also a hallmark of critical thinking in an engineering context. Adaptive expertise, or the ability to apply prior knowledge to novel and open-ended problems, is critical in responding effectively to design challenges.[9] Students must be able to think creatively throughout the design process.[10,11] Problems that students face in the engineering workforce are far more complex, and far less structured, than those they typically encounter in educational contexts, and there has been a call for an increased emphasis on problem-based learning in engineering classrooms to bridge that gap.[12]

Recognizing that this ability to solve complex problems calls on a host of interrelated skills, Lucas & Hanson propose a "habits of mind" approach in educating student engineers. These habits of mind are organized into six distinct categories: Systems-Thinking, Adapting, Problem Finding, Creative Problem-Solving, Visualizing, and Improving. Rather than fixed abilities, the authors emphasize that these habits of mind represent areas of continuous learning and improvement.[13] Critical thinking in the context of engineering education research has emerged as a multifaceted skill set that emphasizes adaptability, and the ability to solve problems by effectively synthesizing prior experience, diverse sources of knowledge, and the social resources of a team.

Active learning cultivates critical thinking skills

Active learning techniques, as well as pedagogies that encourage students to apply their knowledge to authentic engineering problems, have been found to be effective in fostering increased critical thinking abilities in engineering students.[14–17] In one study, an inquiry-based learning framework led to improved analytical skills and an improved ability of students to situate their knowledge in social contexts.[18] In another study, problem-based learning, combined with reflective writing, was found to be effective in improving several elements of students' critical thinking skills.[19] Additional studies have examined the effect of explicitly teaching critical thinking skills in undergraduate courses.[20–22] Active learning techniques developed specifically to target higher-order thinking skills can provide some of the benefits of problem-based learning with a lower time commitment.[16]

Flipped classrooms in engineering

When designing a course, well-aligned learning outcomes are essential for students to access and practice the skills in their field.[23] A flipped learning environment allows students to access material before class that would traditionally be taught during the face to face classroom session. Students can access this class material through several different modalities such as a pre-recorded video lecture. The participants are then able to analyze the material in their own time and work on specific tasks that require higher conceptual understanding while in class.[24]

Current literature that examines the course design process for a flipped classroom suggests this model is well suited to engineering education, as it allows students to be active in problem-based learning activities and constructivist paradigms.[25] Research suggests that a flipped classroom creates a learning environment in which complex problem-solving can occur and contribute to a student's critical thinking and interpersonal skills.[26,27] Multiple studies that have compared student learning in traditional engineering classrooms to learning in flipped engineering classrooms have reported statistically significant learning gains for students in the flipped environment.[28]

To align with new instructional methods, it is important that assessments also reflect authentic engineering problems.[29,30] Take-home tests may be especially effective in assessing higher-order thinking skills because of the increased opportunity for reflection.[31] In one study, students reported that group take-home tests encouraged high-level knowledge synthesis and the development of interpersonal skills.[32] The present study aims to fill a gap in the literature by evaluating the impact of a collaborative take-home test on student critical thinking skills in a fully flipped engineering classroom.

Methods

Setting

This study was conducted at UC San Diego, a large public research-intensive university in the The United States, with an approved IRB project. The course, ECE 65, was offered in the Fall and Winter quarters of 2018 and 2019. The course was taught in three weekly 50-minute class sessions. The same instructor taught the course in both quarters covering the same topics. The Fall quarter had 68 students enrolled and the Winter quarter had 136 students enrolled. All students attended the same lecture hall in each quarter. There were two students in Fall 2018 and three students in Winter 2019 quarters who retook the course. This course enrolls sophomores, juniors, and seniors. This is largely a result of the varying requirements of different majors within the Electrical and Computer Engineering Department at UC San Diego. For some majors, there are prerequisites to this course. For majors that do not have a prerequisite, students can take the course early in their curriculum. Table 1 shows the breakdown of students by gender and year in the program.

Table 1. The number of students and their college year.

Quarter	Total	Female	Male	1st year	2nd year	3rd year	4th+ year
Fall 2018	68	9	59	0	11	29	28
Winter 2019	136	19	117	0	15	92	30

Student selection into treatment conditions

In both Fall 2018 and Winter 2019, students were given the choice of whether or not to attempt take-home (TH) tests. Students were not randomly assigned to the control and treatment groups who would take the take-home tests or the group who would opt out of taking the take-home tests. The exams, if attempted, would collectively count for 15% of the overall course grade (in lieu of those same percentage points coming from in-class exams: 5% from the midterm and 10% from the final). In Fall, there were three take-home exams (worth 5% each), and in Winter, there were two take-home tests (the first worth 5%, and the second worth 10%). At the end of both courses, course grades for each student were computed using both grading schemas (with the 15% in question coming from the in-class exams *and* the take-home tests) and the higher of the two scores was assigned. While the grade breakdown and both options of the grade distribution (including and excluding the take-home exam grades) were given to the students at the beginning of the quarter, in both quarters, students were highly encouraged to take the take-home exams. In both quarters, students were asked to prepare a 5-10 minute screencast (video recording of their solutions) explaining their thought process and how they solved the problem. Free screencasting software and the related tutorials were provided to students on the course website. Students were allowed and encouraged to collaborate with each other in solving the take-home problems. In addition, they were welcome to seek help from their course TAs or the tutors at the department's Tutoring Center. Students ultimately submitted individual solutions and individually prepared screencasts.

In both quarters, all students were asked a question about their confidence in solving unfamiliar problems. They were presented with the statement "I think I can solve a circuit problem if I have not seen a similar one before" and were asked to what extent they agreed with it on a five-point scale from "strongly agree" to "strongly disagree".

Fully flipped classroom design

Prior to the start of the Fall quarter of 2018, the entire lecture content was recorded in the screencast format. The screencasts were 10-20 minute videos of the instructor teaching the concepts and solving circuit problems. Every lecture video covered a separate module in the course. In order for students to test their understanding of the lecture video material, they were asked to take a quiz after watching the videos. The quizzes were multiple-choice questions administered through the university's LMS (Learning Management System). Quiz problems were circuit problems similar to the HW problems, with the difference that some tips and instructions were added to the quiz problems to help students solve them independently. They were allowed to ask questions about quizzes on the Piazza discussion forum, but quiz related questions on Piazza were rare during both quarters. The quizzes were due one hour before the start of each lecture.

Students spent the in-class time solving circuit problems related to that day's lecture content, discussing their answers with their neighbors, and asking questions from the tutors and the instructor. In every class, 2-3 circuit problems were solved and reviewed. Some problems were designed in the format of multiple-choice questions (iClicker questions), and others were discussion problems. While iClicker questions provided a means to quickly gauge students' understanding of the course materials and competency in solving the circuit problems, their format was different from the midterm and final exams. To better align the in-class practice with the assessment format, some discussion questions were integrated into the lectures. For both iClicker and discussion problems, students had a few minutes to solve the problem, and then they were asked to explain their solutions to their neighbors and ask questions from the tutors or the instructor. In both quarters, a few tutors were hired to attend the lectures and participate in the students' discussions and respond to their questions. The ratio of tutors to students was 3 to 68 and 7 to 138 in the Fall and Winter quarters, respectively. The instructor and the tutors walked around the lecture hall during the lecture time to increase the proximity between students and the instructional team.

Other course components

Similar to the past quarters, the course had a lab component in the Fall 2018 and Winter 2019 quarters. In these labs, students built and tested the circuits that they studied in the course. In both quarters, three sets of HWs were assigned to students during the quarter. The Piazza discussion forum was used in both quarters in addition to the office hours to facilitate responding to the students' questions.

Results and analysis

We wanted to examine the effect of the take-home tests on student performance. Since opting-in to the take-home tests changed the dynamics of the students' overall course grades, we instead chose to look only at the scores on the final (in-class) exams. We paid specific attention to student performance on the most conceptually challenging questions on the final exams (which were similar to those students encountered on take-home tests and different from what students practiced in the lectures).

A number of students (9 in Fall and 2 in Winter) attempted only some of the take-home tests, did not complete them or earned very low scores, and so we set a performance threshold. In order to be considered in our analysis as having completed the take-home tests, a student's average score on them had to be above 50%. Two students in Fall 2018 and two in Winter 2019 did not take (or took alternate versions of) the final exam and their data was excluded from our analysis. This left 66 students' data for Fall and 134 students' data for Winter.

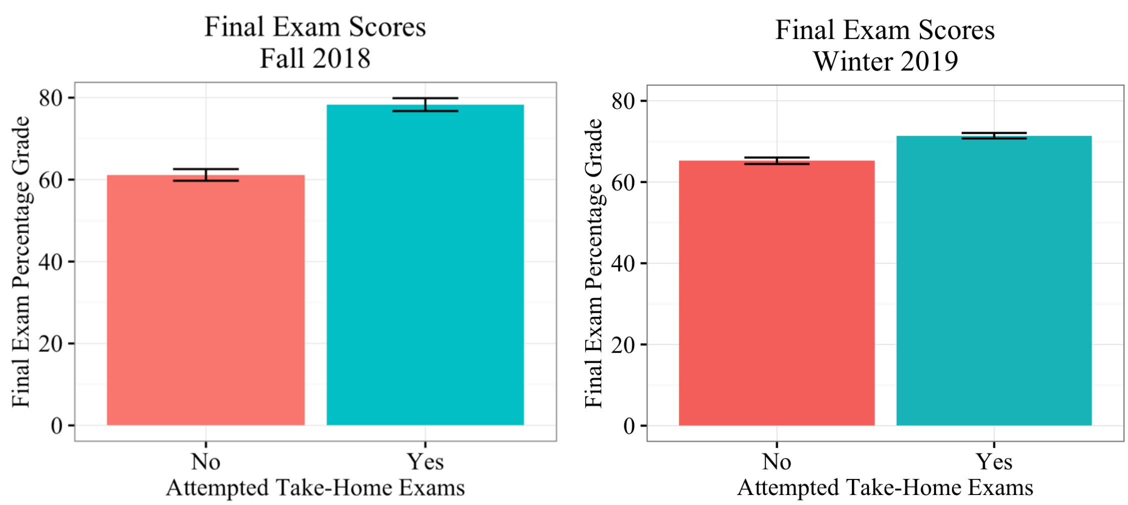

Fig. 2 Average final exam scores for Fall 2018 and Winter 2019 based on whether students attempted the take-home tests or not. Error bars represent standard error.

In order to evaluate the effects of take-home exams, we conducted Welch's Two-Sample t-tests. In Fall 2018, students who completed the take home tests earned significantly higher scores on the final exam (*M* = 78.3%, *SD* = 12.7%) than those that did not (*M* = 61.1%, *SD* = 11.6%), $t(47.5) = 2.88$, $p = .006$. In Winter 2019, the same pattern held: students who completed take home exams (*M*=71.4%, *SD*=9.8%) had higher final exam scores than those who did not (*M* = 65%, *SD* = 9.2%), $t(97.8) = 2.08$, $p = .04$. (See figure 2).

There was a challenging question on final exams which was designed to require critical thinking skills similar to those required to do well on the take-home tests. Although there was a range of student scores on these questions, we set a performance threshold designed to reflect whether or not students had mastered the challenging concept behind the question. For Fall 2018, students who scored above a 9/10 on the challenging question were considered to have mastered the concept, and for Winter 2019, students had to score a 7.5/10 or higher.

In order to examine whether completing the take-home tests influenced performance on the challenging questions on the final exams, we conducted chi squared tests for independence. For Fall 2018, the results suggested that completing the take-home tests and accurately answering the challenging question on the final were *not* independent from one another X^2 (1, *N* = 66) = 4.29, $p = .038$. The proportions of students who correctly answered the challenging question on the final exam differed between the students who completed the take-home tests (~58%) and those who did not (~32%), a greater difference than would be expected if these variables were unrelated. For Winter 2019, the results of the chi squared test did not reach significance, X^2 (1, *N* =134) = 0.23 $p = .63$, leaving us unable to conclude that completing the take-home tests and correctly answering the challenging question were related.

An additional finding in the Fall 2018 and Winter 2019 courses was the general shift in the confidence of the students in their ability to analyze and solve new circuit problems. In both quarters, we asked all students to respond to a question about their confidence in solving unfamiliar problems. Students were presented with the statement "I think I can solve a circuit problem if I have not seen a similar one before" and were asked to what extent they agreed with it on a five-point scale from "strongly agree" to "strongly disagree".

In Fall 2018, this question was posed to students in-class early in the quarter (n = 52), in-class after the first midterm (n = 37), and again on the online anonymous student survey administered by the university at the end of the course (n = 52). In Winter 2019, the question was asked at the beginning (n = 104) and the end of the quarter (n = 92). In both cases, the number of students who agreed with this statement dramatically increased throughout the quarter (see fig. 3). Student answers were assigned numbers, such that "strongly agree" was 2, "neither agree nor disagree" was 0 and "strongly disagree" was -2. In Fall 2018, the average answer at the beginning of the quarter was 0, 0.32 mid-quarter, and .94 at the end of the quarter. A Welch Two Sample t-test comparing the beginning and end of quarter results was highly significant, $t(94.3) = -4.65$, $p < .0001$. In Winter 2019, the average response went from 0.5 at the beginning of the quarter to .91 at the end, also highly significant, $t(189) = -7.52$, $p < .0001$.

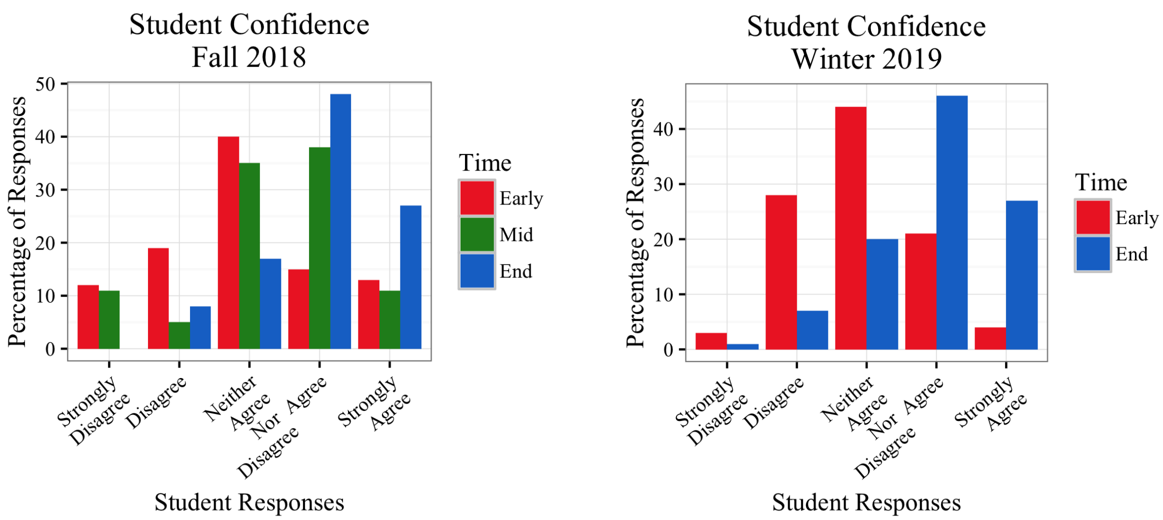

Fig. 3 Percentages of student responses to the question about solving an unfamiliar problem throughout Fall 2018 and at the beginning and ending of Winter 2019

Discussion

Improving critical thinking dispositions

We believe there were several factors affecting our examination of the challenging questions, and why the chi square tests differed in significance between quarters. A smaller percentage of students got this question correct overall in Winter 2019 (~ 37%) than did in Fall 2018 (~ 47%). This question might have been overly challenging in Winter, occluding the difference in understanding between the two groups. More specifically, the designed question for the Fall quarter was from the material that students had more practice with, however; the problem of the Winter quarter was from material that was not extensively practiced in class due to the time limitations and the course curriculum in the 2018-2019 academic year. Additionally, in Winter, there were only two take-home exams while in Fall there were three. It might be that three rounds of practice are significantly better than two at developing and maintaining the critical thinking skills necessary to tackle these questions. Research on spaced retrieval practice (often discussed in the literature as spaced practice versus massed practice) in a precalculus course for engineering students suggests this may be the case.[33]

While there was a difference in significance, it is not surprising that the take-home exams generally improved student success on the challenging question presented in the final exam. As previously defined, critical thinking skills in an engineering course rely heavily on flexibility and the ability to draw from appropriate types of knowledge in a given context.[5,9] Students who selected to complete the optional take-home tests would have an advantage in having practiced attempting a complex problem that extended beyond the types of problems they had collectively solved in the course.

Potential impact of integrated course design

Another consideration in assessing the critical thinking of students is the gradual improvement of the course design and development of course materials. The instructor has taught this class twice before and this paper captures the third and fourth time teaching this course. There have been intentional active learning techniques integrated in all iterations of the course, a gradual progression to a fully flipped course, improvements in assessments, and instructional improvements based on classroom observations and student feedback. While course materials were not explicitly assessed, this process of continuous improvement and feedback allowed the instructor to adapt the course to better meet the needs of students. Additionally, since active learning can support the development of critical thinking skills,[15,16] there are several elements of the course that complement the instructor's aim of cultivating critical thinking habits in her students.

The course design process informed the formative assessments integrated throughout the course. The instructor created new discussion questions and revised iClicker questions.[25] The intent of these questions was to give additional opportunities for students to practice circuit problems. More specifically, through solving in-class problems and participating in discussions, students practiced identifying patterns observable on the circuit configurations, formulating the goal of circuit analysis using the data provided in the problem statements, and writing KVL equations that would lead into the calculation of the target parameters. These formative assessments ultimately helped students develop a holistic approach to solving circuit problems.

There are a host of reasons why the completion of take-home tests could positively impact students' performance on challenging problems. The most obvious consideration is that students will have the practice of a challenging problem that requires application of knowledge beyond what has been presented during class time. Additionally, the process of completing the take-home test could have illuminated outside resources available to all students in the course. Several students cited utilizing the free tutoring services offered at the Tutoring Center in the department, for example. Having access and familiarity with these resources could have generally improved their success on course assessments. Finally, collaborative learning was encouraged and the take-home test was usually completed in groups. Working collectively on the take-home test could have yielded a stronger understanding of course materials through peer learning.

Assessing student confidence

While our study was focused on improving critical thinking skills, one of the general course findings was that students were more confident by the end of the course. There was a significant increase in students' self-reporting that they are able to solve a circuit problem even if they had not seen a similar problem before. The instructor has been building a classroom culture that values questioning and co-constructing of knowledge. There are several interwoven elements of the course that could have contributed to students' gaining confidence in their own abilities.

Limitations

One limitation of this work is the lack of random assignment into control and treatment groups: students *chose* to join the treatment group by attempting the take-home tests. This limitation precludes us from making strong causal claims, as there is the potential for selection bias to influence our results (i.e. students who chose to complete the take-home tests were students that would have performed well on the final exam regardless). In order to examine this possibility, we compared the GPAs of students who did and did not complete take-home tests using Welch Two Sample t-tests. The average GPAs of these groups were significantly different. In Fall, students who completed take-home tests had a higher average GPA (3.44) than students who did not (1), t(39.4) = 2.68, $p = .009$. In Winter, students who completed take-home tests also had a higher average GPA (3.34) than those who did not (3.01), t(94.8) = 3.93, $p < .01$. This limitation will be something to take into consideration for future studies and for course design considerations. Table 2 shows the average and median cumulative GPA of students in each group. In addition, the percentage of the students with lower cumulative GPA, relative to the average GPA in the class, is provided. As can be seen in Table 2, 42% and 48% of students whose GPA was below the average for the entire class in the Fall 2018 and Winter 2019, respectively, participated in the take-home tests.

Table 2. The average cumulative GPA of students in each group and the distribution of students with below-average GPA in different groups.

	Take-home tests (Fall)	No take-home tests (Fall)	Take-home tests (Winter)	No take-home tests (Winter)
Average cumulative GPA (out of 4.0) of the students in the group	3.44	3.11	3.34	3.01
Median cumulative GPA (out of 4.0)	3.61	3.13	3.39	3.02
Percent of students with a cumulative GPA below the class average in the group	42%	58%	48%	52%

Additionally, we are limited in our ability to connect responses between students who completed the mid-quarter feedback and end of quarter feedback because the survey at the end of the course was administered through the official campus teaching evaluation system, which does not include identifying information. Both surveys asked if students would be able to solve a circuit problem if they hadn't seen a similar problem and the number of students who believed that they could complete this type of problem increased in both quarters. We are able to report on general shifts and improvements in the confidence of critical thinking skills, but unable to correlate this data at the individual level and make claims regarding individual student transformation. While some of our limitations relate to the inability to follow the progress of individual students that does not completely explain why there was not a significant relationship between completing the take-home test and correctly answering the challenging question. This could be a result of a small effect size and something to continue to assess in future courses.

Conclusion

In sum, this study documents the progression of an ECE 65 into a fully flipped course. Through reflective course design, we are able to see progress towards developing critical thinking skills. Building upon the previous study[1], the integration of a flipped classroom alongside the take-home tests illustrates that completion of this assessment improves student performance on challenging circuit problems that require critical thinking.[34]

Future considerations

There is potential for further research on the development of critical thinking skills through coursework. One methodological consideration that we addressed is to have a randomized selection of students, or groups matched for GPAs take the take-home test in the future. By altering the way students are assigned to the two groups, we will be able to make stronger claims about potential connections to critical thinking skills and completion of the take-home test.

An area that is of particular interest for future studies is examining the effects of collaborative research and the role of peer learning. By documenting who completed assessments individually or collaboratively we can get a better sense of the impact of collaboration and compare the results of students who seek help from their peers with students who completed the assessments individually. Additionally, we would like to focus on the impact of peer learning on the take-home test. What are the experiences of students who worked collaboratively on the take-home test? How likely are students to seek help on this assessment? And where are they getting this support? By examining these questions and offering opportunities for students to share their reasoning for opting in or out of the take-home tests, we will have a broader understanding of their decision-making and explore connections between critical thinking and collaboration.

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