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Effects of In-class Hands-On Laboratories in a Large Enrollment, Multiple Section Blended Linear Circuits Course

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ABSTRACT

This paper examines the effects of hands-on learning in an undergraduate circuits class that is taught to non-majors; i.e., students outside of electrical and computing engineering. The course, ECE3710, is taught in a blended format facilitated by the video lectures prepared for two Massive Open Online Courses developed for the Coursera Platform. Because of the video content covered outside of class, the face-to-face portion of the class is enhanced with a number of active and collaborative learning techniques, including the inclusion of small-scale, mobile, hands-on labs. The assessment results show that the laboratory experiences play a significant role in the enhancement of student performance. The labs also have the benefit of improving students' confidence in course topics that are related to lab exercises.

Key words: Blended classroom, hands-on learning, electric circuits, MOOCs.

INTRODUCTION

In engineering education, proponents of reform generally agree that student engagement through use of hands-on work and collaborative problem-solving promotes critical thinking, communication, and creativity (ASEE, 2014; IEEE, 2014; NAE, 2008). The research on learning theory shows that facilitation of learning occurs when students are engaged with authentic experiences (Bransford, et al., 2000). Students who are taught with methodology grounded in active learning, cooperative learning, inquiry learning, problem-based learning, and just-in-time teaching are found to be more engaged with the course material, instructor, and/or peers (Smith, et al., 2005). New instructional technologies also keep students involved in their learning processes, engaged with the course material, and participating in meaningful discourse and exchanges with other students and instructor (Sandholtz, et al., 1997).

It is very challenging to incorporate substantive student engagement in large enrollment classes and multi-section classes that are taught by a team of instructors of different experience levels. Circuits courses taught to non-electrical engineering majors typically have some of the highest enrollments of any engineering course since they are required by so many majors. These service circuits courses typically cover a wide number of analysis methods and principles, attempting to build on rudimentary physics and math concepts acquired in pre-requisite courses. The combination of the jam-packed syllabus, inconsistent prior knowledge, and the resistance of non-majors to learn material outside their discipline all contribute to the difficulty of teaching this material effectively. Changes to the format of large-scale engineering courses, such as circuits for non-majors, may be very challenging but offers the greatest opportunity to impact a large number of students.

ECE3710 Circuits and Electronics is the Georgia Tech version of this circuits service course and is the focus of this paper. In particular, we will examine the impact of in-class hands-on laboratory experiences on student performance when these labs are implemented as part of a blended course format. Sections 1.1 and 1.2 motivate the study by giving background on blended learning and on hands-on laboratories. Section 2 describes the course structure and the in-class labs. Section 3 gives the methodology of the study at the results, and Section 4 is the summary.

Blended Learning

Starting in the summer of 2013, the Georgia Tech circuits and electronics course was redesigned in order to improve consistency across sections and to increase student engagement, especially through the addition of hands-on labs in the classroom. In order to accommodate the hands-on labs, a sequence of video modules was developed to deliver the majority of lecture material. This created time within the face-to-face (F2F) portion of the course for a variety of in-class activities, thus enhancing collaborative and active learning. The resulting course structure can be termed a “hybrid” or “blended” class, although terms like “flipped” and “inverted” are also used by some authors to refer to classes that combine some degree of F2F instruction with online, video content (Margulieux, et al., 2014). The Blended Learning Implementation Guide defines blended learning as

> *a formal educational program in which a student learns at least in part through the online delivery of content and instruction, with some element of student control over time, place, path, and pace, and at least in part at a supervised brick-and-mortar location away from home.* (Bailey, et al., 2013)

Twigg (2003) further classifies hybrid courses as being of four different types: (1) replacement (students watch videos outside of class to reduce in-class time), (2) supplemental (students access additional materials online with no in-class time reduction), (3) emporium (students have no required in-class time, but have access to an in-person resource center), and (4) buffet (students choose a combination of online or in-class activities). In the study discussed herein, students were still required to attend the same number and amount of F2F meeting times, so the adopted hybrid mode of delivery could be classified as being somewhere between "supplemental" and "replacement" in the spectrum of hybrid delivery modes (Zhao and Breslow, 2013; Biddix, et al, 2015).

There has been considerable research on the development and efficacy of hybrid or blended classes. According to Lack (2013), there are mixed findings regarding whether hybrid/blended learning is better or worse when compared to F2F or fully online delivery methods. However, given the enormous differences in what constitutes a hybrid or blended class, and given the wide range of research study designs, measures of success, and course subject matter, that is perhaps not surprising. A thorough review of research prior to 2010 (Means, et al, 2010) is modestly positive on the effectiveness of blended learning modes. A recent survey by Zhao and Breslow (2013) contained a summary of 42 studies using blended/hybrid courses. Although the subject matter and settings varied, many of the studies showed statistically significant improvement in learning for blended/hybrid classes vs classes that were either entirely F2F or online. Another relevant review article was recently presented by Bishop and Verleger (2013). Citing 83 references plus another 38 online sources, the authors list many perceived advantages of flipped classes, including the ability to combine learning theories that are quite different; namely active, problem-based learning, and instructional lectures based on behaviorist principles. They report that student perceptions of flipped classrooms are "somewhat mixed, but generally positive overall." Learning outcomes, however, have not shown significantly positive results. In fact, of all the references that they examined, only one (Day and Foley, 2006) showed significant improvement in scores on homework, projects, and tests, compared with traditional instruction. The authors strongly suggest that future research should be conducted, especially research that examines learning outcomes using controlled studies.

Blended learning is well-suited to STEM fields such as engineering because engineering education is heavy on classes that are dense in content; historically, engineering classes have been typified by the one-way delivery of content with little time or opportunity for discussion, questions, and collaboration. A good overview of developments of flipped or blended learning in engineering courses may be found in (Velegol, et al., 2015). They also report findings from their environmental engineering course; in particular, two different blended-course formats vs traditional F2F offerings of the same class. Among their results are recommendations on best practices on length of video modules, length of review or mini-lectures at the start of F2F classes, and types of in-class activities. Although the blended classes were received positively by the students, there was no statistically significant performance improvement on the final exam when compared to traditional delivery of the same course.

Importance and Motivation for Hands-On Labs

Given the generally mixed results observed for blended/hybrid courses, it is natural to question the reasons for the variation in outcomes. We argue that the effectiveness of flipped or blended classes is dependent on the quality of experiences that are substituted for traditional in-class lectures. Un-burdened by the pressure of introducing and presenting new material in each class, the class times can be used in novel ways to improve and enhance student learning. One such activity is to introduce substantive laboratory experiences into a classroom environment, where the activity is "hands-on", that is, the students actually build and test circuits themselves.

We argue that authentic hands-on lab activities are very effective in improving student learning and retention of knowledge. Touch, in particular, may be underappreciated as a component in student learning since it can increase students' long-term memory and recall of the displayed phenomena. Experiential learning, such as hands-on experiments, can influence memory and recall. According to the Levels-of-Processing theory (Craik and Lockhart, 1972), memory and recall are dependent on the depth of mental processing during the learning process. Deeper levels of thought result in more elaborate, persistent, and stronger memory traces than more superficial levels of thought. Likewise, memory is enhanced when multiple sensory modes are activated- vision, hearing, touch, and smell.

Well-designed hands-on experiments may be advantageous for learning because, by its very nature, it involves at the very least vision and touch; in the case of dynamic experiments such as one that is based on a guitar string (Ferri and Ferri, 2014), sounds that accompany different modes of operation may also play a role. The theory of memory encoding (Smith and Kosslyn, 2006) is also relevant to hands-on learning. According to this theory, encoding is the essential first step to creating a new memory, allowing the formation of a construct that can be recalled from short-term or long-term memory. The four senses of vision, hearing, touch, and smell are processed with different parts of the brain; for example, tactile encoding is associated with the somatosensory cortex of the brain (Crawley, et al., 1998). Tactile sensing of physical experiments may reduce the cognitive load of a learner's working memory and thus support more complex understandings (Zacharia and de Jong, 2014). According to the theory, each sensory modality (visual, auditory, touch) has its own processing channel in the brain. Thus, the cognitive load during learning could be reduced either because touch sensory input can transfer the same information with the sensory input transferred through the visual or the auditory channels (same information is distributed to more than one processing channels), or because the touch sensory channel transfers different (but complementary) information to the sensory input transferred through the visual or auditory channels. This may be the reason that concepts reinforced through hands-on experiments are retained much more effectively than concepts learned through traditional or even active learning techniques in the lecture classroom.

One of the often-cited reasons for requiring experiments and laboratories in science and engineering education is to "enhance conceptual understanding" (Ma and Nickerson, 2006). And as active learning methods, it might be expected that hands-on experiences will always outperform traditional or passive learning methods. Unfortunately, the benefits of hands-on learning are not always realized due to poorly designed experiments (Hofstein and Lunetta, 2004; Abdulwahed and Nagy, 2009; Menekse, et al., 2013; Koretsky, et al., 2011). Hands-on activities that are done without opportunities for reflection and metacognition have missed the opportunity to create deeper understanding (Hofstein and Lunetta, 2004). Shavelson, et al. (2005) refer to four different types of knowledge: declarative knowledge ("knowing that"), procedural knowledge ("knowing how"), schematic knowledge ("knowing why"), and strategic knowledge ("knowing when, where, and how our knowledge applies"). This framework provides a useful way of evaluating laboratory experiences; what is typically termed "inquiry based laboratory exercises," are ones that reach the higher levels of the knowledge taxonomy (Koretsky, et al., 2011). Pre-labs and other types of preparation are also important as identified in Kolb's experiential learning cycle (Kolb, 1984; Abdulwahed and Nagy, 2009).

Traditionally, engineering laboratories have given students an opportunity to learn through observation, to examine the accuracy of theoretical models, and for the development of professional skills of value in engineering industries. The role of laboratory experiences in engineering is summarized in several references, for example (Feisel and Rosa, 2005; Ma and Nickerson, 2006; Koretsky, et al., 2011). One of the drawbacks of physical experiments is the increasing complexity and expense of laboratory equipment. In order to give students a taste of the current state-of-the-art in industry and in graduate research labs, university faculty have sought to acquire highly accurate and sophisticated tools, which must be housed in dedicated laboratory spaces and maintained by teaching assistants who can demonstrate their use to undergraduate students. In contrast, the laboratory experiences used in this study are purposely designed to be portable, affordable, and student owned. The portability and affordability of these small experimental platforms opens up the possibility of reaching students in non-traditional settings, such as in standard classrooms as well as in traditional asynchronous distance learning modes.

DESCRIPTION OF THE COURSE

ECE3710 is a junior-level circuits and electronics course for non-ECE majors at the Georgia Institute of Technology. There are 400-450 students enrolled in the course each semester in fall and in spring terms, separated into nine sections. During the summer term, there are 130-150 students in three sections. Four majors require the course: aerospace, biomedical, mechanical, and material science engineering. A few other engineering students take the course as an elective. ECE3710 is classified as a two-credit hour lecture course without a lab component. It is a very intensive course starting from the topic of Ohm's Law and ending with transistors.

Prior to the intervention discussed in this paper, ECE3710 suffered from inconsistency across sections in both coverage and grades. The instructors who taught the course in 2012 were sent a survey asking them to identify which topics out of 27 in the syllabus that they omitted. The median number of omitted topics among the 7 instructors was 7.0 or 26% of the material that should have been covered. Comparing omitted topics between sections showed a mismatch in topics covered of up to 50%. Class GPAs were in the typical range of 2.5-3.7 with curves applied inconsistently.

In order to improve consistency across sections, add in-class hands-on activities, and encourage student engagement, the course was converted from a traditional lecture style in Summer 2013 into a blended course style where students watch online videos prior to the class period. The course was blended using two Massive Open Online Courses (MOOCs), *Linear Circuits* and *Introduction to Electronics*, both developed at Georgia Tech specifically for ECE3710. The MOOCs are hosted by Coursera (coursera.org) and use the Coursera learning management system for students to watch the lecture videos and do automatically-graded homework assignments. A Piazza discussion forum is linked for students from the Coursera site. The MOOCs are run separately to both a public audience and to the on-campus students enrolled in ECE3710. The Georgia Tech Linear Circuits MOOC has been run four times synchronized with the public offering of the course where both sets of students share the same lectures, homework assignments, and Piazza discussion forum.

The in-class components of the course include a two-minute quiz at the beginning of the class, worksheets, instructor mini-lectures, and hands-on labs. The quizzes are based on the video lectures that are assigned for that day and serve two purposes: to test knowledge of basic concepts and to ensure that students are keeping up with the online lectures. The worksheets allow students to gain practice by working collaboratively with each other and interacting with the instructor. Most of the worksheets give practice on basic problem-solving skills, but a few have open-ended scenarios that focus on higher-level thinking tasks. The instructor's mini-lectures usually scaffold the worksheets by working some similar problems beforehand or by giving students guidance on how to approach the problems. The instructor also performs some just-in-time lectures during worksheet time to address concepts that are causing confusion. Over the duration of the semester, there are six in-class hands-on labs that are performed in pairs on student-owned data acquisition boards and parts kits. The effect of the in-class labs on student learning is the focus of this paper, so they are discussed separately in the next section.

The blended learning environment and instructor cooperation across sections promoted consistency among the sections. In addition to the video lectures, homework problems, and labs being common among sections of ECE3710, the tests are common and are given at a time when all students from all sections can attend. Each problem is graded by one instructor for all students in all sections to ensure consistent grading. When creating the tests, all the instructors review it to ensure that it is clearly worded, can be worked in a reasonable time, and is at an appropriate level for the course. The test composition is about 80% on problems and about 20% on short answer multiple choice questions. These short answer/multiple choice questions allow for testing on simple basic concepts, phenomena seen in the experiments, and on higher-level thinking.

After eight semesters and over 2600 students of ECE3710 taught in the blended course format, we have developed some best practices derived from instructor feedback, student surveys, and a data-based evolution of the course structure and course components. Student reaction to the first two offerings of the blended format of the course was mixed, with many student complaints centered on overall workload and technology glitches on the videos and online assignments. The glitches were corrected prior to the second offering of the course. Student workload was reduced by modifying the type and number of student deliverables, improving the course resources, and explicitly instructing students on how to take a course in this format. In terms of student deliverables, the online quizzes were eliminated, and in-class worksheets were added in place of some of the homework problems. The course resources were improved by adding approximately 100 videos of sample worked problems and revising the videos on the most confusing topics in order to show more details or to change the approach presented. These revisions were based on feedback from test performance and from the discussion forum posts, which helped to identify topics that caused the most confusion and what was the source of that confusion. An example of a strategy for success that we starting giving to the class was for them to take notes while watching the lecture videos. Many students think that they can re-watch the videos at any time and do not bother to take notes. This tends to increase time spent on the course because they spend more time rewatching videos than they would have spent taking notes. Also, test studying is harder without notes. We do not have data on the workload prior to the conversion to a blended format and cannot make a comparison. However, the average student workload over the last three offerings of the course has been 6.3 hours/week, which is close to the target of 6 hours/week. After all of the course modifications, the student response now shows an appreciation for the videos, the time spent in class working problems, and a very positive response to the in-class labs.

During that same eight semester time period, 32 different instructors have taught the course in the blended format. Of these, 5 are faculty members and 27 are advanced PhD students. In addition, the course resources were used by 4 different faculty members to teach ECE2040, the circuits course for ECE majors, in a blended format. Determining an effective mix of time to devote to each of the possible in-class activities is more difficult than just using a standard lecture format, so there is a learning curve for instructors new to blended classes. With mentorship from experienced instructors, the new instructors generally take two to three weeks to become comfortable and find their own routine with a blended style of learning. Once they teach the class once, the workload for their second offering is no higher than it would be for any other class. The overwhelming success of ECE3710 resulted in biomedical engineering to add it as a requirement to their degree in 2015 and another major, industrial and systems engineering, to add it as one of their preferred technical electives.

A more detailed description of how the MOOC was used to blend ECE3710 is given in (Ferri, et al., 2014) along with a concept inventory assessment that shows that consistency across sections was achieved after the course was blended. The data-driven feedback mechanism for how the blended course components and structure were changed in order to improve student learning and to reduce student workload (time-on-task in the course) is given in (Ferri, et al., 2015). The effects of the in-class hands-on labs on student performance and student attitude is not covered in these prior papers and is instead the focus of this paper.

Hands-On Labs

The main objectives of the labs are to enhance student learning of the basic concepts and to increase student confidence in practical application of the theoretical content of the course. Six class periods are taken up by the labs, which constitutes 20% of the in-class lecture periods (recall that this is a two-credit hour course). Converting the course to a blended format freed up the in-class time needed to implement the labs. Since this course is considered a lecture course, the labs need to be integrated with the lecture material, done in a standard classroom environment, and performed in a 50-minute time period. No special classrooms are used for ECE3710; most of the classrooms used for the course contain rows of long tables with chairs all facing a whiteboard at the

Figure 1. Typical classroom setting during an in-class hands-on lab.

front of the room. Each room holds fifty to sixty students. Figure 1 shows the classroom environment of a typical class during an in-class lab period. Figure 2 shows the interaction of students with an instructor during a lab session. The labs all require instructor sign off, where the instructor verifies that the students understand the concepts. (See https://www.youtube.com/watch?v=FVIcjBVjlp4)

A key to success of in-class hands-on labs is to craft the experience to have an impact on learning without undo time and effort for either the instructors or students. To ease logistics for the instructors in ECE3710, students must own their own experimental platform and materials and are responsible from bringing these supplies to the classroom. The students are required to purchase a National Instruments myDAQ board and a parts kit that is assembled and sold by the ECE department. The myDAQ and associated software has approximately the same cost as a textbook and converts a student laptop into a whole suite of electrical engineering instruments: a function generator, a digital multimeter, an oscilloscope, a Bode plot tool, and a spectrum analyzer. Students work in pairs on the labs, so they may share the device. The parts kits, costing $10 each, consist of a breadboard, wiring kit, and various resistors, capacitors, inductors, diodes, op amp, and potentiometers. The school orders the parts

Figure 2. Instructor interacting with students during an in-class hands-on lab.

at bulk and educational discounts and hires undergraduate assistants to put together the kits and to distribute them. The parts kit price is set so that there is no net cost or financial gain to the department.

In developing the labs for this course, we decided upon some experiment design criteria that are based partly on logistics (as mentioned in the previous paragraph) and partly on using the results of learning theory on laboratory experiences discussed in Section 1.2. The goal is to make the most impact on learning in the course while satisfying practical considerations. The hands-on labs must:

- target concepts that are hard to understand by theory alone
- be well integrated with the theory taught in the class
- have a low learning curve for both instructors and students
- provide scaffolding for students who are novices to the equipment
- require students to relate theory to experiments
- have build, test, troubleshoot, analyze, and exploration activities, and when possible, design activities
- be doable in a 50 minute lecture period (by most students)

In the prelab done before class, students analyze a circuit using the methods taught in the lectures. The lab itself has step-by-step instructions for building the actual circuit and taking measurements. Students are asked to compare their theoretical results with the experimental results and explain differences. Many of the circuits are built with potentiometers so that students can see the effect of varying resistance on the measured outputs. The labs require an instructor sign-off and do not require a formal lab write-up, just the lab worksheet. The instructors attend two lab sessions of other instructors' classes in addition to their own so that there are three instructors in the classroom handling 50 students working mostly in pairs (with a few solo students). There are some exploratory and open-ended activities in the labs, but the 50-minute time frame of a standard class period limits the extent of those types of activities because of the wide variation in student skills and speed in completing the labs. In focus group sessions, students expressed overwhelming desire to keep the detailed step-by-step instructions rather than adding more open-ended exploration because they are such novices with the skills needed, and they need the extra basic practice to gain confidence.

A brief description of the six labs and the concepts covered is given next.

1. Resistors and Basic Circuits (learning how to use a digital multimeter, breadboards, measuring current, resistors in series and in parallel, voltage divider lab)
2. Resistive Circuits and Sensor Conditioning and Calibration (reinforcement of mesh/node analysis, use of potentiometers, working with sensor circuits by building a Wheatstone bridge to improve resolution of a sensor and calibration of a position sensor)
3. First and Second-Order Responses (RC time constants, RLC underdamped and overdamped responses and effect of resistance on behavior, introduction to op amps and the need for a buffer circuit)
4. AC Circuits and Frequency Responses (AC steady-state sinusoidal circuit analysis, frequency response, Bode plots)
5. Op Amp Filter (op amps and their use in filtering, filtering of 60 Hz measurement noise in a signal)
6. AC to DC Conversion (the use of a full-wave rectifier and smoothing capacitor, the effect of diode turn-on voltage)

The lab content and instructions have evolved over several semesters in order to reduce confusion, improve the focus on the concepts, and adjust the time for completion. Some photos of circuits on the breadboards were added along with the schematics, and tedious steps that diluted the emphasis were removed. In the most recent semester, we starting doing the pre-lab as an in-class worksheet.

METHODS AND RESULTS

The hypothesis of this study is that student performance is enhanced by the use of hands-on labs in the face-to-face portion of a blended class. Also of interest is how the magnitude of gains in performance differs with respect to students of different overall achievement levels and how the confidence levels of students in subject topics is impacted by the labs. The structure of the study uses a quasi-experimental design predicated upon both quantitative and qualitative methodologies. A total of 741 students participated in the study, 389 in the fall semester of 2013 and 352 in the fall semester of 2014. In each case, students were distributed across nine sections of the *Circuits and Electronics* course each taught by a different instructor (with the exception two sections of the course in fall 2014 that had the same instructor). Overall, participants in each term of the course completed two midterms, a final exam, 6 laboratory activity worksheets, homework problems, and a demographic survey. Exams, homework, and labs were common across all sections. Homework problems were completed on-line and graded automatically with no partial credit but with students receiving up to five chances to resubmit their answers. Exams were given outside of standard class periods at a common time for all sections. Students in the fall 2013 study completed online quizzes and a Circuits Concept Inventory (CCI) (Evans, et al., 2013) and students in the fall 2014 study completed pre and post surveys on course content. All points earned on tests and assignments were converted to percentages based on the total possible number of points.

Analysis of Test Performance, 2013

In our regression model for predicting students' achievement using the data collected in fall 2013, the dependent variable was the students' final exam score, and the independent variables were CCI pretest score, whether the student was male, whether the instructor had teaching experience, whether the course was required for the students' major, and the average laboratory percentage score. In specifying the model, interactivity with MOOC platform video viewing, number of online quizzes completed, and scores for completed online quizzes never proved significant. Average scores were determined for each of these, but these were also not significant. These variables were dropped from the analyses. An *a priori* statistical power analysis was conducted to determine the minimum sample size needed to test for effects of medium size (Cohen, 1988). For univariate analyses, the estimated sample of 25 is needed. For multivariate analyses, a sample size of 26 was determined. Results reveal that a sample of 286 students is sufficient to detect an effect in our analyses. Equivalent groups were established by comparing CCI pretest scores across sections of the course. Scores were not statistically different across sections. For the CCI, final exam, and 6 laboratory activity sheets, Cronbach's alpha (Cronbach, 1951) was calculated to assess the internal

Variable	M	SD	Minimum	Maximum
CCI pretest score, 0-100	48.02	11.79	10.71	100.00
Male student dummy (1=yes; 0=female)	.83	.38		
Instructor experience dummy (1=yes; 0=no, novice)	.47	.50		
Required course for major	.78	.41		
Average laboratory score	91.67	8.22	13.33	100.00

Table 1. Means and Proportions of Central Tendencies and Dispersion for Variables Predicting Students' Achievement (N=289).

consistency of items and was found to be α =.81, α =.79, and α =.71, respectively. For the CCI, final exam, and laboratory activity sheets, scores on the tests were determined as a measure of criterion validity and correlations were $r = .37$ ($p < .05$) or higher.

Table 1 summarizes the means, central tendencies and dispersion for the variables that were retained. Variables were selected from salient research in engineering. The R Square was .307 and indicates that the included variables taken together explain 30.7% of the variation in the final exam score. The only statistically significant predictors of performance on the final exam are the CCI pretests scores and the scores on the laboratory worksheets. The CCI pretest is an indication of how well prepared the students are for the course based on their prior knowledge, so the results make sense.

Analysis of Test Performance, 2014

Building upon the study done in fall of 2013 that showed that the laboratory grades are a predictor of final exam scores, a new study was done in fall of 2014 to assess the impact of the labs on students of different overall achievement levels in the class. The independent variables that were

Variable	Regression Coefficient	Beta	*t*	*p*
CCI pretest score	.304	.247	4.774	<.001
Male student dummy	3.545	.092	1.774	.077
Instructor experience dummy	1.180	.041	.784	.433
Required course for major	–2.542	–.072	–1.387	.167
Avg. laboratory score	.711	.403	7.683	<.001
(Constant)	–.909		7.683	.298

Table 2. The Regression Analysis (N=289).

found to be insignificant in the previous study were not included in this study. CCI tests were not used in fall 2014 because we needed a better match to the course topics in order to perform a finer grain analysis of the dependence of student performance on the laboratory experience.

In order to assess different aspects of performance, the final exam was designed to include ten multiple choice/short answer questions: four questions on concepts related to the experiments, Qe, four questions on concepts not related to the experiments, Qc, and two questions that were on higher level thinking, Qh. The Qc questions can be viewed as a control group. All questions were graded on a scale of 0-2 with exactly one question each in the Qe and Qc categories allowed to be given partial credit of 1 point while all the rest of the problems allowed no partial credit. How students did on the Qe questions relative to the Qc questions can be examined from the ratio Qe/Qc, where a score greater than 1 means that they did better on Qe. The questions were reviewed and modified accordingly by three professors who normally teach circuits courses at Georgia Tech, two of whom are not associated with this particular service course. Efforts were made so that the questions had the same level of difficulty, and inherent bias in the questions was mitigated by examining trends in Qe/Qc ratios for different levels of performers in the class rather than focusing solely on the raw scores.

The four basic concept questions that were not related to the labs, Qc, included questions on the following topics: (i) identifying the expression for the Thévenin equivalent resistor in a circuit, (ii) identifying the correct expression for the response of a second-order circuit given the differential equation, (iii) identifying transistor operating regimes on i-v curves, and (iv) identifying the condition under which a transistor is operating as an amplifier. An example of one of the problems is shown below:

Sample Qc question: "An RLC circuit has the following differential equation:

$$\frac{d^2V}{dt^2} + 200\frac{dV}{dt} + 12500V = 25000.$$

Which of the following is a valid expression for $V(t)$? (a) $K_1e^{100t} + K_2e^{50t}$, (b) $2 + K_1e^{-100t} + K_2e^{-50t}$, (c) $K_1e^{-100t} + K_2e^{-50t}$, (d) $K_1e^{-100t}\cos(50t + \theta)$, (e) $2 + K_1e^{-100t}\cos(50t + \theta)$, (f) none of the above"

The four basic concept questions that were related to concepts reinforced by labs, Qe, included questions on the following topics: (i) identifying a time constant from a plot, (ii) identifying the corner frequency from a Bode plot, (iii) identifying the steady-state output of a circuit given the sinusoidal input and a Bode plot, (iv) determining the turn-on voltage of a diode given the input and output curves of a full-wave rectifier.

Sample Qe question: "What is the time constant of the following output of an RC circuit? The input is a square wave with DC offset of 1v and peak-to-peak voltage of 2v. In order to get full credit, the answer needed to be in the range 0.15ms to 0.25ms. No partial credit was given.

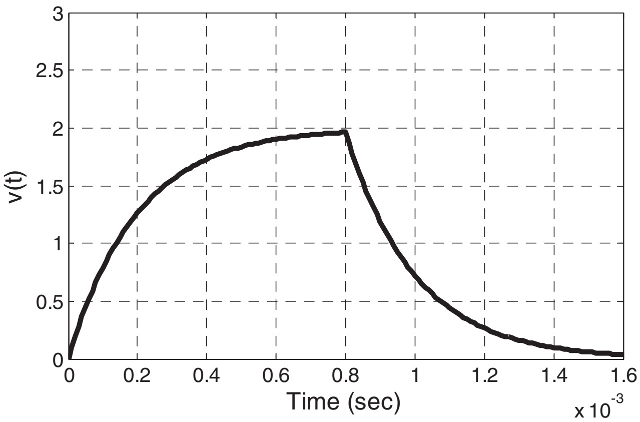

Figure 3. Plot of an RC circuit response, included in a Qe question.

The two higher-level thinking questions, Qh, were both multiple choice and included (i) one that required students to identify the analysis method that would be the easiest to use to solve a resistive circuit problem and (ii) one that asked the best filter design for a given sensor noise scenario.

A summary of the rankings of the problems in terms of their average scores is given in Table 3 (1=highest avg, and 10= lowest avg). The interspersion in the order of how well students did on the categories of problems gives some credibility to their fairness.

Tables 4–8 show the analysis of how students performed on these Qe and Qc questions. In the analysis, Qc is considered the control group while Qe is the group that relates to the intervention (the labs). In order to see if there is a pattern of student performance on Qe versus Qc questions relative to overall performance on this part of the exam, the students are split into groups according to the score on the multiple choice/short answer: 0-5, 6-10, etc. Table 4 displays the number of students in each group along with the mean Qc and Qe scores in each group. The ratio of the mean Qe to Qc scores for each group indicates how much better students did on the Qe questions versus the Qc questions. For example, students who scored 16-20 on that part of the test did 7.9% better on the Qe questions than the Qc questions. The next range, 11-15, shows the largest improvement in scores, 20.4%, in Qe versus Qc scores. A similar analysis was done on the medians in each score

Ranking	1	2	3	4	5	6	7	8	9	10
	Qc(iii)	Qh(i)	Qe(ii)	Qc(i)	Qe(iv)	Qe(iii)	Qe(i)	Qc(ii)	Qc(iv)	Qh(ii)

Table 3. Rankings of average scores on the multiple choice/short answer concept questions.

category, shown in Table 5. Statistical significance was examined using both a one-way ANOVA test and a Mann-Whitney test. The Mann-Whitney test is nonparametric and does not assume a normal distribution, so the results tend to be more conservative than the ANOVA test. The strength of the assumption of normal distribution in these results varies by population, so the result of both the Mann-Whitney test and the ANOVA test are given.

The results indicate that the top three groups of students (that is, all students who were above the 9th percentile) performed statistically better on basic concept questions that relate to labs versus basic concept questions that do not relate to labs - the gains in means were 7.9% to 20.4% for these student populations. Specifically, students in the upper two categories, score ranges of 11-15 and 16-20, performed statistically higher on the Qe versus Qc questions, with $p<0.05$. The Qe/Qc ratios in the second-lowest range, 6-10 overall score, is unity to slightly greater than one when considering both mean and medians, with p-values $0.05<p<0.1$ indicating that the performance on the Qe questions was statistically higher than that on Qc but at a higher p-value than the other results. The means and medians in the lowest performing group do show that students in this group did better on the Qc versus Qe questions, but the variance is such that the scores between Qe and Qc are statistically the same.

The labs seem to have the largest positive impact on students in the second-highest overall category. A possible reason for this trend is that there is a ceiling effect in the highest score range, 16-20, since students must have scored almost perfect in order to be in that range so there is less room for differences between the Qe and Qc scores. The lower two scoring categories correspond to weaker students in terms of understanding basic concepts in the course and also students who have lower motivation levels to perform additional course requirements such as labs.

Similar trends were seen when the data was analyzed by gender as seen in Tables 6 and 7, which include the subset of students in Table 4 and 5 who identified their gender on a survey. Specifically, the largest gains in Qe over Qc were achieved in the second-highest category, overall score of 11-16, for both genders. While the difference in the Qe versus Qc scores in the 11-16 category was

N	Overall Score	Mean Qc	Mean Qe	$\frac{\text{MeanQe}}{\text{MeanQc}}$	p-value*
48	16–20	6.604	7.125	1.079	0.041
151	11–15	4.781	5.755	1.204	<0.001
120	6–10	3.217	3.583	1.114	0.083
33	0–5	1.364	1.273	0.933	0.739

*ANOVA

Table 4. Mean Qc and Qe scores versus overall scores.

N	Overall Score	Median Qc	Median Qe	$\frac{\text{MeanQe}}{\text{MeanQc}}$	p-value*
48	16–20	6	8	1.33	<0.001
151	11–15	4	6	1.5	<0.001
120	6–10	4	4	1	0.059
33	0–5	2	1	0.5	0.356

*Mann-Whitney

Table 5. Median Scores for Qc and Qe versus overall scores.

statistically significant, there were fewer female students in the other scoring categories, yielding results that the Qc and Qe scores were statistically equivalent for those categories. The male population had statistically significant higher scores in Qe versus Qc in the upper two scoring categories and statistically equivalent grades in the lower two categories.

Another way of examining this data is to look at the relationship between course grade and the Qe/Qc ratio. In this case, the A students in the class had the highest average gain, 20.9%, in scores on the Qe versus Qc questions while the students in the D&F range did worse on the Qe versus Qc questions. Examining the ANOVA tests shows that A and B students, who comprise 72% of the students, scored statistically higher on Qe versus Qc questions while C and D/F students scores were statistically equivalent on those two types of questions.

Tables 4–8 all indicate that the vast majority of students in the class performed statistically better on basic concept questions that relate to labs versus basic concept questions that do not relate to labs. The lowest performing students had no statistical difference in scores between the two types of questions. It was mentioned previously that the student populations with the lowest performance had lower motivation levels for performing all of the lab activities. To examine this assertion, the box plots of the lab scores for the course are shown in Figure 4 for the student populations grouped by

N	Overall Score	Mean Qc	Mean Qe	$\frac{\text{MeanQe}}{\text{MeanQc}}$	p-value*
6	16–20	7.00	6.667	0.952	0.628
29	11–15	4.897	5.931	1.211	0.008
32	6–10	3.000	3.125	1.121	0.752
7	0–5	2.143	1.429	0.667	0.140

* ANOVA

Table 6. Mean Qc and Qe values separated by gender, female students.

N	Overall Score	Mean Qc	Mean Qe	MeanQe / MeanQc	p-value*
34	16–20	6.618	7.235	1.093	0.049
115	11–15	4.661	5.383	1.155	0.001
84	6–10	3.345	3.548	1.061	0.442
17	0–5	1.118	1.059	0.9474	0.877

*ANOVA

Table 7. Mean Qc and Qe values for male students.

their final course grade. For each population group, the box shows the middle 50% in the group with the "whiskers" showing the range of the upper and lower 25% groups. Outliers are indicated with a *. As expected, the medians (shown as a solid line in each box) are monotonically decreasing, and the variation in scores is increasing from the "A" students to the "D&F" students. Students in the lower grade ranges missed more labs. Also, the format of the labs allowed students to get most of the credit by completing the steps in the worksheet and writing the correct measurements without fully answering the higher-level thinking questions. The better students earned all the points on the labs, including credit for the higher-level thinking questions.

A regression analysis was done to determine if performance on the labs was a predictor of performance on the tests. Since some of the outliers identified in Figure 4 represent students who did not complete one or more labs, only those students who turned in all of the lab worksheets are included in the regression analysis. Other independent variables are chosen to be homework and in-class quizzes in order to determine their ability to predict the performance on tests. Other factors such as gender and major were excluded because they were found to be insignificant predictors of performance in the regression analysis on the fall 2013 data. Recall that the tests are common among all sections and are graded in a consistent manner (each problem is graded by a single person for

N	Course Grade	Mean Qc	Mean Qe	MeanQe / MeanQc	p-value*
142	A	5.064	6.121	1.209	0.001
120	B	4.153	4.542	1.094	0.02
63	C	2.906	3.343	1.151	0.290
33	D&F	2.759	2.414	0.875	0.753

* ANOVA

Table 8. Mean Qc and Qe values for students grouped by final course grade.

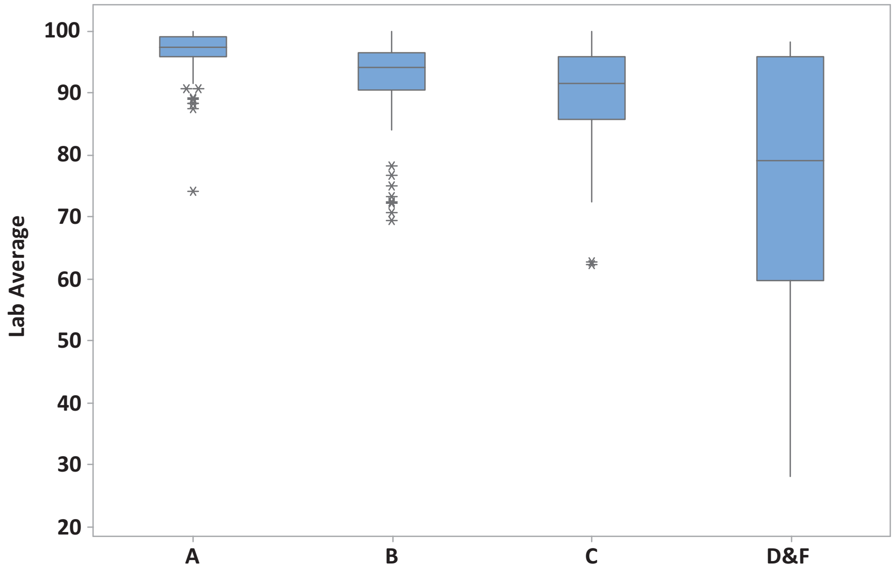

Figure 4. Box plot of the lab averages for students in populations grouped by final grade in the course, showing the median, middle 50%, upper and lower quartiles, and outliers (*).

all students). The dependent variable is the average of the two tests and final exam, (Exam Avg). The number of students in the model is N=332.

The regression model is

$$\text{Exam Avg} = -2.92 + 0.2242\ \text{Hwk Avg} + 0.263\ \text{Lab Avg} + 0.3284\ \text{Quiz Avg}$$

The R-Squared value is 26.2% indicating that 26.2% of the variation in the exam averages is due to the independent variables.

From the results, performance on the labs (by students who completed all the labs) is a predictor of the performance on the exams with $p<0.05$. The Quiz Avg has the largest coefficient, so it is the strongest predictor of test performance. This result is to be expected since students' scores

Independent Variables	Coef (β)	SE Coef	t-value	p-Value
Hwk Avg	0.2242	0.0402	5.58	<0.001
Lab Avg	0.263	0.115	2.28	0.023
Quiz Avg	0.3284	0.0643	5.10	<0.001

Table 9. Regression analysis for determining performance on tests.

on the daily quizzes relate to how well they keep up with the material from the online lectures and how well they understand the basic concepts. The Lab Avg is the second strongest predictor and the Hwk Avg is the weakest, though all of the coefficients are similar in value.

Analysis of Student Surveys

Student self-perceived competence in the subject matter was assessed by surveys in which students were asked to rate their level of understanding on specific topics in the course on a scale of 1 to 4 (1 = no understanding, 2= minimal understanding, 3=moderate understanding, and 4=solid understanding). Self-perceived competence in topics relates to the confidence in those topics. Both pre and post surveys were completed and gains were analyzed. The mean responses and their 95% confidence intervals from the post-survey are shown in Figure 5 with topics displayed in order of occurrence in the course, with Ohm's Law on the left being the first topic and logic gates being the last (Ferri, et al., 2015). The first three topics were covered in Physics II, the prerequisite for ECE3710 and show higher-levels of confidence. The rest of the topics are all rated in the range of approximately 3.0-3.5. The tight interval bounds and the small variation among topics is an indication of the consistency among topics and students in the course. Unrelated to the laboratory component emphasized in this paper but interesting from a blended course perspective, the same survey was taken for a different course, ECE2040, the circuits class for ECE majors. The results of the survey were compared for one blended section of the class and two traditionally taught sections of the same course taught the same semester. The blended section used the same online materials and some of the same in-class labs as used for ECE3710. In those results, described in (Ferri, et al., 2015), the confidence levels of the topics started dropping off significantly about 2/3 of the way through the term in both of the traditional-style courses. The blended version of ECE2040 maintained the same level of consistency across topics as displayed in Figure 5 for ECE3710. A drop off as the semester nears the end in the traditionally-taught classes would be expected since the topics tend to be more complex and students tend to be more overwhelmed late in the term. This phenomena did not occur in ECE3710 nor did it occur in the blended version ECE2040.

In order to examine the relationship between the labs and the confidence levels, the topics were grouped into ones that were reinforced through the labs (I) and ones that were not related to the labs (II). The gains in the ratings from the pre-survey to the post-survey were determined, and the corresponding means and medians for the aggregate groups (I) and (II) are shown in Tables 10 and 11.

The results indicate that the student self-perceived competence (that is, student confidence) in topics that were reinforced by a lab had a higher gain than topics that were not reinforced by the labs. The largest difference in gains between category I and category II was for the B students, which represented the middle group of students (119 students had higher grades and 52 students had lower

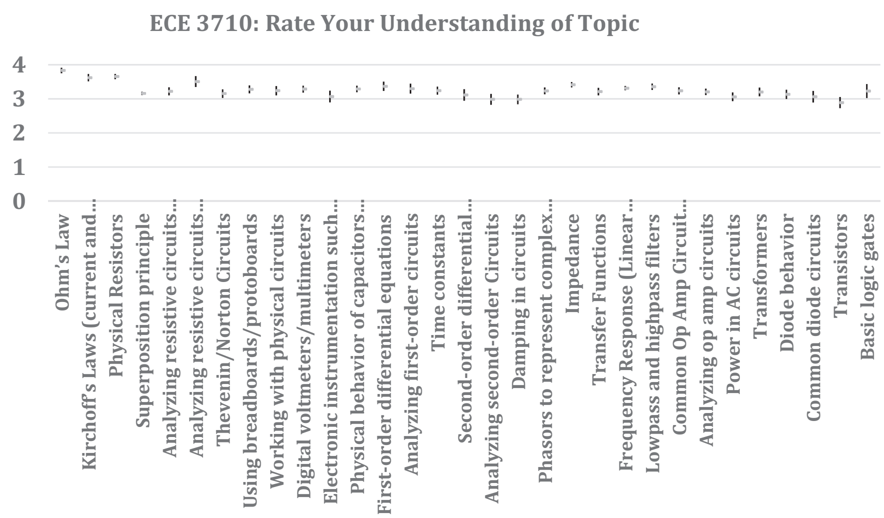

Figure 5. Post survey results of course topics displayed in order of occurrence in the course. Rating is from 1=no understanding to 4 =solid understanding. N = 310.

Students	I (labs)	II (no lab)	p-value*
All (N=251)	24.6%	9.6%	0.005
A (N=119)	33.3%	23.1%	0.19
B (N=80)	26.8%	4.7%	0.008
C (N=42)	2.0%	−14.6%	0.297
D&F (N=10)	−2.1%	−13.7%	0.863

*ANOVA test

Table 10. Mean gains in confidence for topics reinforced by the labs (I) and topics not related to the labs (II) for all students and for students grouped based on their final grade achieved.

Students	I (labs)	II (no lab)	p-value*
All (N=251)	28.6%	12.5%	0.002
A (N=119)	35.0%	25.0%	0.086
B (N=80)	28.6%	12.5%	0.007
C (N=42)	10.7%	−6.2%	0.219
D&F(N=10)	−3.6%	−6.2%	0.396

*Mann-Whitney test

Table 11. Median gains in confidence for topics reinforced by the labs (I) and topics not related to the labs (II) for all students and students grouped by final grade achieved.

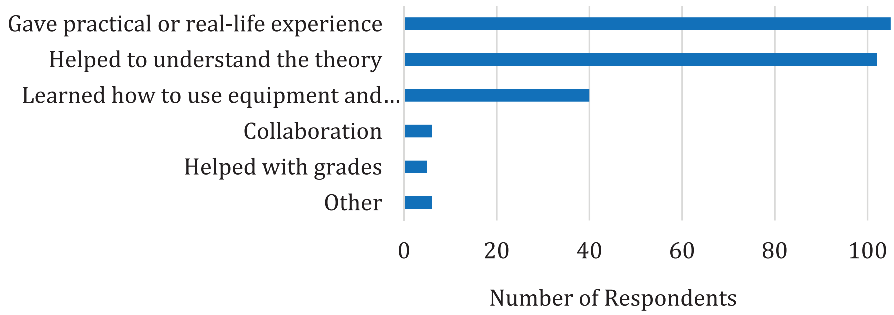

Figure 6. Free response answers to question on what was the most helpful part of the experiments, with answers grouped into categories.

grades than this population group). The A and the B student groups had statistically significant (with $p<0.1$) results showing higher gains for the lab-related topics versus the non-lab related topics, and the C-F students showed no significant difference in gain between the two categories of topics.

The post survey also had a free response question asking students to name one way that the labs helped them. The responses were very similar and fell into a few categories as shown in Figure 6 indicating that students felt that the labs equally gave them practical experience and helped them to learn the theory.

SUMMARY

By the very nature of blended classes, there is a great deal of variation in the way that the courses are structured, such as "replacement" and "supplemental" formats, and the types of activities that are included in the face-to-face portion of the class. To date, the literature on the effectiveness of blended and flipped classrooms has been fairly mixed, especially with regard to significant improvement in test scores. Part of the observed disparity in outcomes may stem from the large variations in how the face-to-face class time is used, with many of the course designs failing to take maximum advantage of active and collaborative learning techniques. In this paper, we present a study on the blended classroom format of a large enrollment, multi-section engineering course for non-majors; i.e., a course that is required of engineering majors outside of the primary subject area of electrical engineering. The out-of-class activities for the course, ECE 3710, include viewing online videos, doing online homework, and doing prelabs. The in-class activities include daily quizzes, collaborative worksheets, mini-lectures, and hands-on labs. The inclusion of these labs in a blended class and their impact on learning is the focus of this paper.

There is research-based evidence on the theory of learning that suggests that concepts reinforced through hands-on experiments are retained much more effectively than concepts learned through traditional or even standard active learning techniques. The depth of mental processing and the activation of multiple sensory modes – vision, hearing, and touch – affects memory and recall, thereby influencing learning and retention. Hands-on labs require multiple sensory modes, and the labs can be structured to include exploratory and reflection activities that trigger deeper mental processing. The hands-on labs developed for ECE3710 include a pre-lab where students do analytical studies, a laboratory procedure where a circuit is built and measurements taken, reflection questions where students must reconcile the experimental results with theory, and some exploratory activities. Because of new technology for portable, inexpensive data acquisition boards, students are able to own the experimental platforms that they use and to bring them to class to do the experiments at their desks in a regular classroom. Thus, the experiments can be tightly integrated with the lecture material and timed to be just before or just after the related theoretical material is introduced in class.

Our research reveals that hands-on activities show a positive impact on student learning and on student confidence for students in the middle and upper categories of performers. We examined performance on common tests given across all nine sections of the course and found that the performance on the labs is a predictor of the performance on the tests. A set of concept questions on the final exam included a control group, Qc (concepts not related to the experiments), and an experimental group, Qe (concepts related to the experiments). Examining both the means and the medians, students who performed better overall on the concept questions performed statistically better on the Qe than the Qc questions. Similarly, the students who earned an A or a B in the course performed statistically higher on the Qe versus Qc questions. The same trends appeared in the levels of confidence, with the greatest gains in confidence (from pre-survey to post-survey) on topics that were reinforced by the experiments. These gains in performance and in confidence were not seen by the lowest achieving students. Correspondingly, the lowest-achieving students had lower lab scores, often attributed to them not doing some of the labs and/or by completing only the measurements portion of the labs and not the higher-level thinking activities.

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