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Project-Based Approach in an Electrical Circuits Theory Course - Bringing the Laboratory to a Large Classroom

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Abstract

Electrical Circuits Theory is a course that is required by many engineering disciplines at most universities and is often taught in a lecture-based approach. At the University of Oklahoma, an electrical circuits course was redesigned with a project-based focus in order to achieve additional learning goals that were considered important to the overall education of engineering students. Due to the large class sizes and lack of laboratory facilities, an inexpensive kit of parts and equipment was checked out to the students to support their hands-on circuit activities. The project was created to enhance students' understanding of the course topics and to improve their circuit design and team skills. By switching from a lecture-based to a project-based approach many planned and favorable outcomes were achieved. This paper describes the project, the study findings and shares future research steps. We plan to use the lessons learned from the project-based approach to improve the hands-on section of the course in future semesters. We trust our study will be beneficial to instructors, who are teaching an electrical circuits course and are interested in bringing the laboratory to a large classroom.

I. Background

Electrical Circuits is a required course for most undergraduate engineering major students. This course is often taught in a traditional lecture-based approach, which makes student engagement difficult. In addition to encouraging passive learning habits[1], this approach of static learning reduces students' autonomy and communications, lack of efficient organization and planning, and it provides less motivation for learning and creativity[2]. It is observed that in recent years, instructors of circuits course more often utilize active learning approaches to help students better understand complex circuit and physical-level phenomena. It is optimistic to see more instructors are no longer relying only on lecturing high level abstractions, but are prompt to involve students' minds and hands in projects, team work, circuits design, and student-centered activities. This active learning approach has proven to be effective for teaching circuits in several schools and to improve the quality of teaching/learning for circuit design in different electrical engineering courses. In addition to enhancing their understanding of design problems and skills, students who have been engaged in active learning environments claim to become more motivated and satisfied with their education. The following review of recent studies includes examples of different hands-on and active learning approaches in courses involving electrical circuits.

In one engineering school, a student-centered active learning approach was implemented because evidence-based educational research suggested that student-centered active learning can produce deeper conceptual learning than traditional lecturing. When active learning is conducted in an extensively group-based learning environment, students were found to develop various professional functioning knowledge skills; such as problem-solving, written and oral communication, independent learning, and team work[3]. A project based approach was also utilized in a Microelectronics circuit analysis and design course for undergraduate Electrical Engineering students. Findings from this study showed that the implementation of project-based learning motivated students and increased their autonomy and efficiency at the end of the project[1]. The project-based approach provides a successful mechanism to help students achieve high-level learning goals and deal with real problem-solving activities. The authors of this study suggest that in project-based learning, the instructor has a less central role, and students take more responsibility for their own learning, which results in higher student involvement and better understanding of circuits[1]. The project-based approach has also been utilized to teach an introductory circuit analysis course. In that traditional introductory course, the emphasis is on analysis techniques at the expense of instilling an intuitive understanding of the problem and the underlying engineering principles. In that course, the instructors introduced a hands-on design project to engage the students in the material and introduce the students to the excitement and breadth of the field of electronics. The study provided evidence that the project-based approach increased student interest in electronics and improved preparation for subsequent courses[4].

To overcome learning drawbacks from the traditional lecturing techniques, instructors of an analog electronic circuits' course implemented problem-based learning. In their study they used the approach not only to build on students' acquaintances, but also on their competences[5]. The authors of this study describe the course as an innovative course in electric circuit theory as they introduced systematic changes in lab instruction to make students understand the relationship between theory and real circuits. They integrated the lab sessions and the problem-solving sessions to give students new ways to handle the subject matter. Instead of focusing on what to report, the students in this course focused on what is to be learned as they made links between all the components in the course model. Over a two semester period student exam results showed similar outcomes as the traditional approach, but the communication skills and the learning motivation of the students were increased[5].

In another study, a laboratory-centered approach was utilized to introduce engineering students to electric devices and systems. First-year engineering students were engaged in open-ended design projects to explore and construct different types of electrical systems. Laboratory activities were selected to develop student intuition in electrical concepts, scientific fundamentals, provide a historical background, and demonstrate systems-level design issues. Using this approach for three years, the authors of the study observed an increase in student motivation and engagement, supported by a significant increase in Electrical and Computer Engineering enrollment[6]. Additionally, active student engagement methods such as tutorials and interactive lecture demonstrations allowing real-time display of experimental data also have been used in recitation sections and in a series of labs, focused on helping students to develop a better functional understanding[7].

II. ENGR 2431 Course History

Although the above examples of active learning approaches have proven to be effective for teaching circuits in several engineering schools, introductory electrical circuits courses are still often taught in a lecture-based format with no laboratory component. For Electrical or

Computer Engineering (ECE) students this usually is not a major problem as later in the curriculum they typically take multiple hands-on lab courses that build on the theory learned in the introductory circuits course. However, for engineering students with other majors, there is often little to no hands-on laboratory experience with circuits in their other courses and these students never have the opportunity to design and build circuits.

At the University of Oklahoma the course that introduces electrical circuits to non-ECE majors is taught in a different structure than most institutions. The three-credit hour, 16 week course material is broken up into three distinct, one-credit hour courses that are taught in series, with each one lasting between 5 and 6 weeks. The first in the sequence, and the focus of this paper, is ENGR 2431 - *DC Circuits*. The second is ENGR 3431 – *Electromechanical Systems* and the third is ENGR 2531 – *AC Circuits*. Course descriptions and the engineering majors that take each course is shown in Table I below. In order to cover the additional content that is not normally covered in a circuits course, some of the highly specialized circuit's topics, such as dependent sources and supernode/supermesh solving methods, are left out of these courses. While this paper focuses only on ENGR 2431, a previous publication explains ENGR 3431 in greater detail[8].

Table I – Course Descriptions for ENGR 2431, ENGR 3431, and ENGR 2531

ENGR 2431: DC Circuits	ENGR 3431: Electromechanical Systems	ENGR 2531: AC Circuits
"Introduction to basic principles of electrical circuits. Topics include DC circuit analysis, DC transients, static electrical fields, static magnetic fields, capacitors, inductors, and filters."	"Introduction to basic principles of electromechanical systems. Topics include electric machines and motors, physical principles of sensing and actuation, types of sensors and actuators, digital logic gates, signal conditioning, A/D and D/A conversion, and interfacing and communication protocols."	"Introduction to intermediate principles of electrical circuits. Topics include basic complex algebra, AC Circuit analysis, resonance, AC transients, transformers, and electronics (diodes, operational amplifiers)."
Disciplines taking the individual course modules are as follows:		
Industrial, Civil, Architectural, Environmental, Chemical, Mechanical	Chemical, Mechanical	Mechanical
These three courses are taught sequentially in the following order:		
First 3rd of semester	Middle 3rd of semester	Last 3rd of semester

ENGR 2431 covers the majority of the electrical topics that were included in the morning session of the Fundamentals of Engineering (FE) Exam before it changed formats in January, 2014. This was one of the original reasons that four of the majors only included ENGR 2431 into their curriculum and replaced ENGR 3431 and 2531 with other courses. With the FE Exam changing to a discipline specific format in 2014, which didn't include most of the ECE topics for the majors of the students taking ENGR 2431, a shift in focus to include new learning goals was needed. Originally the only learning goal for ENGR 2431 was *Content*

Learning. The sole focus of the lecture-based course was to help the students learn the content included in the FE Exam so their chance of passing would rise. With the FE Exam motivation, no longer a central focus, the course was redesigned with new learning goals.

III. ENGR 2431 New Project-Based Course Design

The idea to switch to a project-based approach in ENGR 2431 was first conceived at an Olin College workshop that focused on designing projects for better student engagement. The idea of designing a project for ENGR 2431 that could benefit the students in other ways than just the *Content Learning* goal was ideal since these students were not ECE majors and the content learned in the course might not apply directly to their engineering careers. Based on the topics covered in the course and the type of project that was envisioned, the following four learning goals were specified for the project designed for ENGR 2431:

- Content Learning
- Design/Creativity
- Hands-On Skills
- Teaming/Collaboration

A description of the project and the assessment of the learning goals of the first implementation of the project are included in the later sections of this paper. Before continuing to the details of the project, obstacles to its implementation are discussed. The largest challenge and primary reason that a project was not previously considered for the course was the incredibly large class size. The class sizes have gradually increased over the last several years to the point that there were a combined 282 students in the spring and fall 2015 semesters. With so many students it was difficult to envision a hands-on project. The second major issue was the lack of lab space and equipment. When designing the project, we created an inexpensive kit to be checked out to the students that would allow them to have the flexibility to work on the project activities anywhere instead of in a predetermined lab space. The third challenge was the shortened timeframe of the course with a duration of less than 6 full weeks. The next section explains how these challenges were overcome to create a project in ENGR 2431.

IV. *Project Infinity* Description

Rather than just teaching students how to analyze circuits like in the original ENGR 2431 course, the new course contains a project that was implemented to teach students how to design, simulate, construct, and perform calculations on circuits. The project was named *Project Infinity* based on our rational that non-ECE students typically will forget how to perform difficult circuit theory calculations over time, but being exposed to design and construction of circuits on a breadboard and the opportunity to make measurements with a Multimeter are skills that we hope will stick with them for a long time. We created a kit of parts and equipment that were checked out to each group of two students. The kit contained a Multimeter, breadboard, AA battery cages, hand-tools, jumper wires, and components. The components included are resistors, capacitors, inductors, LEDs, SPST switches, potentiometers, switching diodes, and various types of sensors. LEDs, diodes, and sensors are discussed in more detail in the follow on courses (ENGR 2531, 3431) so introducing them in the first course formed a solid background for the students who would take the later courses. By including these additional components, we also aimed to make the circuit activities more interesting.

The project is broken up into three parts that correspond to the different topical areas covered in the course. Module 1 covers the basics of DC circuits such as combining resistors, Ohms law, and Kirchhoff's laws. Module 2 covers advanced DC circuits such as multiple loop circuits, Thevenin equivalent circuits, and superposition solving techniques. Module 3 introduces the addition of capacitors and inductors to DC circuits. Students learn to perform both transient and steady state analysis on circuits that include capacitors and inductors. Table II shows a brief description of each of the activities included in the three parts of the project. Even though there is no mention of calculations in Table II the students were required to compare the calculated result to the measurements on most of the activities.

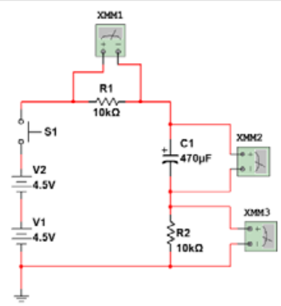
Table II – Project Infinity Activity Description

Module 1 Activity Descriptions
Make voltage measurements with the Multimeter
Make resistance measurements with the Multimeter
Build a circuit on a breadboard and make current measurements with the Multimeter
Build a circuit with a potentiometer.
Design and build a circuit with a potentiometer to achieve a set voltage
Simulate and build a circuit with a SPST switch
Simulate and build a circuit that includes an LED
Build a circuit with a switching diode
Build a circuit with a photo-resistive light sensor and a LED
Build a complicated circuit and then reduce it to a circuit with only one resistor
Design and build a complicated circuit and modify resistors to achieve a set voltage
Module 2 Activity Descriptions
Simulate and build a 2 loop circuit including multiple resistors and a diode
Simulate and build a 3 loop circuit including multiple resistors and a LED
Design a dimmer circuit using multiple resistors, potentiometer, a switch, and a LED
Build a multiple loop circuit with a potentiometer and a thermistor
Design and build a circuit that demonstrates superposition with multiple voltage sources
Design and build a circuit that demonstrates Thevenin Equivalent circuit theory
Module 3 Activity Descriptions
Build a circuit with a switch, capacitor, and resistors to demonstrate steady state analysis.
Build a circuit with a switch, capacitors, and resistors to demonstrate DC transient analysis.
Simulate and build a store/release circuit that charges capacitors and discharges across a LED
Build a RLC circuit to demonstrate steady state analysis
Build a Low Pass Filter RC circuit and show how DC is passed through
Build a High Pass Filter RC circuit and show how DC is blocked
Build a RC circuit that utilizes a photo-resistive sensor to change the voltage to a set range

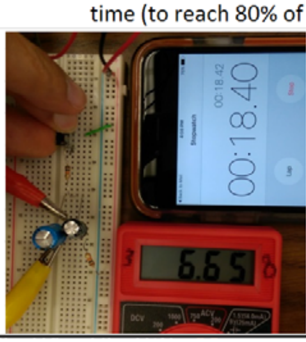
There are three Excel templates that each group of 2 students fills out as they work through the activities. By using an Excel template, measurement errors can be automatically calculated, which makes grading much more efficient. The three Excel Template reports have the following grade breakdown: Part 1 Report (10 points), Part 2 Report (10 points), and a Final Report that includes parts 1, 2, and 3 (70 points – 20 for part 1, 20 for part 2, and 30 for part 3). The reason it is broken up into 3 parts is to allow the students to receive feedback from parts 1 and 2 reports and fix any problems and resubmit them in the final report drop box. With this resubmittal system the project was set up where the students would get a good grade if they did the required work. An example of the activity description and the information that is included in the students' report submissions is shown in Figure 1.

2b) RC Circuit Transient Analysis – Calculate how long it should take for the capacitor to charge to 80% of the combined battery voltage (Vs = Vbatt1 + Vbatt2). Measure the capacitor voltage as the switch is pressed (and held down) and use a stop watch to verify it reaches 80% of Vs closely to the calculation. You should get within a few seconds between calculated and measured.

2c) RC Circuit Transient Analysis – Put a 100µF in parallel with the 470 µF capacitor and repeat part 2b.



2c) RC Circuit (100uF || 470uF)	Calculation	Units	Measurement	Units	Measurement Error
time (to reach 80% of Vs)	18.35	sec	18.4	sec	-0.3%



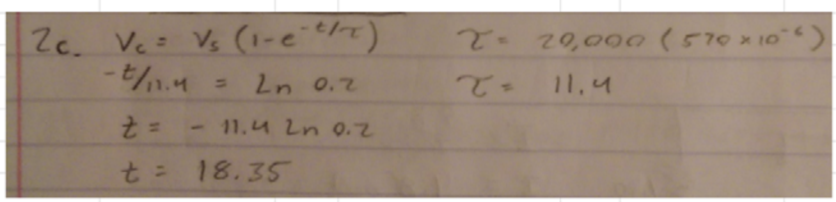


Figure 1: Module 3 – Part 2b and 2c activity description (top) and report template submission for Part 2c (bottom).

V. Students Perception of the Project- Survey Results

91 students participated in the survey in the Fall 2015 semester (N = 91). In the survey they responded to statements regarding their perceived value of the project. The first group of questions were statements that the students responded in a 5 point Likert scale where: 1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, and 5=Strongly Agree. Responses of 4 or 5 were considered positive responses. The survey data showed that the students felt the project positively affected many of the learning goals and overall the project was a good experience. The *Hands-On Skills* learning goal statement ("The project strengthened my hands-on skills") had a 97% positive response. The *Design/Creativity* learning goal statement ("The project strengthened my design skills") had a 73% positive response and the *Content Learning* goal statement ("The project contributed to my learning of the material") had a 74% positive response. The final question on the survey asked the students whether or not we

should do the project again next semester and 93% of the students that gave a definite answer responded favorably (79 yes and 6 no). Only 6 students gave an undecided answer. Most of the students who said no or were undecided stated the issue they had with the project was that it took too much time to complete. The survey statements also showed that the students felt the project was too time consuming and difficult. 66% had a positive response to the statement “The project took too much time to complete” and 74% had a positive response to the statement “The project was difficult”. It is encouraging that the project received highly successful survey results even while it was considered a rigorous project.

VI. Content Learning Assessment - Final Exam Comparison

Since the traditional course structure of ENGR 2431 didn’t have any activities that addressed the learning goals of *Teaming/Collaboration*, *Design/Creativity*, or *Hands-On Skills*, we were expecting improvements in these areas to naturally occur with the new project-based course design. The only concern we had was whether the fourth goal of *Content Learning* would be negatively affected. In order to assess this learning goal, a comparison of final exam scores between the traditional approach and the project based approach was performed. We need to mention here that in both years it was the same instructor teaching the course and the instructor is also one of the authors of this study. The same final exam was given in the fall 2013 semester (traditional lecture-based approach) and in fall 2015 semester (project-based approach) and the results were compared. We also have to clarify here that the final exams were not returned to the students and the solutions were not posted - in other words we ensured that no students had advance knowledge of the exam questions or solutions. In addition, the instructor used the same lecturing styles in delivering the subject material in both years.

Table III – ENGR Student Population and Average Final Exam Scores

	FALL 2013		FALL 2015	
Major	Students	% Cass	Students	%Class
Architectural	2	3.6%	7	7.1%
Chemical	15	27.3%	45	45.9%
Civil	12	21.8%	8	8.2%
Environmental	8	14.5%	6	6.1%
Industrial	12	21.8%	15	15.3%
Mechanical	6	10.9%	17	17.3%
Cohorts	Students	Final Exam	Students	Final Exam
All Students	55	76.4%	98	70.3%
Subset with Exam ≥ 60%	46	81.6%	73	78.1%

The ENGR 2431 final exam was made up of 20 multiple choice questions that are similar to the DC circuits questions that were on FE exams prior to 2014 (when DC circuit topics were required for all examinees). Our findings showed that the average grade for the final exam decreased by 6% from the Fall 2013 to the Fall 2015 cohorts. The *p*-value was calculated to be 0.031 using a two-tailed, unequal variance type T-Test. Using a significance level of $\alpha = 0.05$ this indicates that the decrease in exam score between the Fall 2013 and

2015 cohorts is statistically significant. This average decline was caused primarily by a larger number of students who scored lower than 60% on the exam in the Fall 2015 semester. The "Subset" row listed in Table III above shows the number of students in each cohort who scored 60% or higher on the final exam. A change in the grading structure that resulted in a 4.6% higher overall grade going into the final exam for the Fall 2015 cohort is one plausible explanation of why 9% more students in the Fall 2015 semester scored less than a 60% on the exam and why the grades on the exam were lower in general. This 4.6% pre-final grade increase for the Fall 2015 cohort is also statistically significant with a 0.028 *p*-value. The Fall 2015 cohort were able to accumulate higher grades due to the way the project-based course was graded with a resubmission system. In contrast the Fall 2013 course design included challenging quizzes that significantly lowered the average grades. With higher grades going into the final exam many students in the Fall 2015 cohort might have been demotivated to prepare for the final exam as rigorously as the Fall 2013 cohort. It is interesting to note that when looking at only the final exam scores from the "Subset" that scored 60% or higher on the final exam the decrease in average exam scores is no longer statistically significant ($p > 0.12$). This would support our alternative explanation that more students in the Fall 2015 cohort came in completely unprepared for the final exam because they thought they didn't need that high of a grade on the final to get the letter grade they desired in the class.

In order to further analyze the individual exam questions to see which topics the students did better on and worse on the "Subset" of students that made a 60% or higher on the exam will be used. Since the exam was multiple choice, with guessing allowed, including data for students with extremely low grades would reduce the confidence in the individual question data as many of the extremely low grades would have many more answers that were guesses. From the Subset group of students there were 8 of the 20 questions that had ± 10% change in correct answers and a *p*-value < 0.05. Four of these questions showed statistically significant improvement and four showed reductions, as shown in Table IV below. The four questions that showed improvement were from topics that were heavily emphasized in *Project Infinity* and the four that showed reduction were more of a theoretical nature that were not as clearly covered in the project.

Table IV – ENGR 2431 Final Exam Questions with Significant Changes in Results

Topics of Questions with > 10% grade change and p-value < 0.05	**% Change**	**p-value**
Topics for the 4 Questions with Statistically Significant **Improvements** in FA15		
Combining capacitors to find total capacitance	11.6%	0.015
Combining resistors to find equivalent resistance	20.8%	0.004
DC Steady State Analysis for RLC Circuits	14.0%	0.045
DC Transient Analysis for RL or RC Circuits	17.5%	0.017
Topics for the 4 Questions with Statistically Significant **Reductions** in FA15		
Resistor calculation from equation	-18.7%	0.003
Maximum power transfer	-37.4%	5.7E-06
Superposition solving method	-17.7%	0.023
Determining number of nodes in a circuit	-14.0%	0.011

It is encouraging that the four questions that showed improvement were from topics where students were required to build the circuit, take measurements, and theoretically solve the circuit to compare the calculated and measured results. This allowed the students to see the theory work in a real circuit and solidified the understanding of the topic. This is likely to be very important for the RL and RC transient analysis questions (shown in the fourth row of Table IV) because the concepts are difficult to grasp with only the theory. We feel that the theory will make more sense when the students see the capacitor, resistors, and inductors go through their charging and discharging cycles. The four questions that were negatively affected pointed to changes that need to be made to the project. The most glaring mistake was the *maximum power transfer* term was not used in the project and students likely didn't realize that the load resistor needed to be set equal to the Thevenin resistance to achieve maximum power transfer. This concept was discussed in lecture, but there was no homework or quiz where the students could practice solving a problem that included this terminology.

VIII. Conclusion

By changing our Introductory Circuits course from a lecture-based to a project-based approach we were able to introduce additional learning goals. The study findings clearly showed that students felt the project helped them improve their hands-on and design skills, while also contributing to their learning of the content. The teaming/collaboration learning goal was not directly assessed, but observations of the students' working together provided us with visual evidence that positive impact in this area was also achieved. In the next study we plan on evaluating the teaming/collaboration learning goal.

However, the study findings revealed unfavorable results when comparing exam scores of ENGR 2431 students who took the project-based version of the course in fall 2015 to the students who took the lecture-based version in fall 2013. While the students taking the project-based course answered some questions at a much greater success rate, overall the final exam grades decreased due to oversights in the project and course design. In future offerings of the course, quizzes will be given throughout the semester to improve content learning. Additionally, the project questions and activities will be modified to address some of the topics that the students scored poorly on in the final exam.

This study builds on the results of previous studies and provides additional evidence that favorable outcomes occur when implementing active learning concepts into a lecture-based circuits course. The lessons learned from this pilot study will be used to improve the hands-on segment of the ENGR 2431 course in future semesters. Due to the initial successes of this study, we also plan to introduce parts of this project into a circuits course for ECE majors in the near future. We trust our study could be beneficial to instructors who are teaching an electrical circuits course and are interested in bringing the laboratory to a large classroom.

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