A Project-Based Approach to Teaching Introductory Circuit Analysis

Andrew Sterian, Bogdan Adamczyk, and M.M. Azizur Rahman
Grand Valley State University, Grand Rapids, Michigan
steriana@gvsu.edu, adamczyb@gvsu.edu, rahmana@gvsu.edu

Abstract - **We present a project-based approach to teaching an introductory circuit analysis course. Traditional introductory courses emphasize analysis techniques at the expense of instilling an intuitive understanding of the problem and the underlying engineering principles. We propose that an introductory circuit analysis course should teach the inter-relationships of current, voltage, power, resistance, inductance, and capacitance both mathematically and intuitively, since much of practical circuit design is not linear and cannot be reduced to linear circuit analysis problems. The fundamentals of linear circuit analysis remain important for working with linearized models of devices and for developing closed-form solutions that develop intuitive understanding of simple circuits. We describe a revision to our Circuit Analysis I course that balances both the theoretical and intuitive aspects of circuit analysis. We have also introduced a hands-on design project to engage the students in the material and to unify the laboratory exercises. The course project also introduces students to the excitement and breadth of the field of electronics, including a basic understanding of practical devices such as diodes, transistors, oscillators, and amplifiers. We present evidence that this project-based approach has benefits that include increased student interest in electronics and improved student preparation for subsequent courses.**

Index Terms – Introductory circuit analysis, Practice-oriented education, Project-based learning, Student engagement and retention.

INTRODUCTION

Our School of Engineering offers a 4-year ABET-accredited program that has an integrated co-operative education component and includes emphases in electrical engineering, computer engineering, mechanical engineering, and product design and manufacturing engineering. In recognition of our local industries' need for broadly-educated, highly competent engineers the first two years of coursework for all four of our emphases is nearly the same. Thus, all of our engineering students are required to take an introductory circuit analysis course (EGR214, Circuit Analysis I) which is normally scheduled in their second year of study, after having completed two courses in calculus and one physics course that introduces the fundamentals of charge and electricity. The circuit analysis course is directly assessed every semester using student evaluations and end-of-semester departmental review, and indirectly assessed through downstream courses that build upon the course material, as well as survey data from our co-op employers and graduating senior exit surveys. Since it is the only introductory circuit analysis course in our school, it is not a service course.

Until 2007, our circuit analysis course was fairly traditional, adhering to a standard sequence of topics found in several popular texts [1]-[2]:

1) Review of Basic Circuit Concepts and Laws
2) Node Voltage Analysis, Mesh Current Analysis
3) Source Transformations
4) Thévenin and Norton Theorems
5) Linearity and Superposition
6) Operational Amplifiers
7) Inductance, Capacitance, *RL* and *RC* Circuits
8) Other Topics (e.g., AC analysis)

The major benefit of this approach was that each subsequent topic builds upon the previous one. Each new method of circuit analysis utilizes the previously introduced techniques reinforcing the students' understanding of the material. Specifically, node voltage and mesh current techniques utilize the basic circuit laws: Ohm's law and Kirchhoff's voltage and current laws. Thévenin and Norton techniques often require the use of node and voltage methods to determine open-circuit voltage, short-circuit current and the source resistance. First-order circuit analysis techniques make use of the Thévenin and Norton theorems to determine the circuit response.

The drawback of this approach is that during the first part of the semester, the laboratory activities often amount to verifying the analysis techniques by creating purely resistive circuits and measuring appropriate voltages and currents. The first "practical" circuit can only be built when operational amplifiers are introduced, and the truly interesting practical circuits can be designed only after the topics of RC and RL circuits are explained. This usually happens during the second half, towards the end of the semester, greatly limiting the student's exposure to practical circuits and devices. Students that enrolled in our program because of an interest in electronics are disappointed that by the end of their second year of study they still haven't done anything "cool", and students in the non-ECE emphases are not left with much practical knowledge that they can apply to subsequent courses.

For example, many electromechanical devices (e.g., motors, valves, solenoids) are controlled by a relatively basic transistor circuit with a catch diode added for protection (Figure 1) and the understanding of this circuit is useful for our students in the mechanical engineering and product design and manufacturing emphases. But transistors and diodes are non-linear devices hence are not included in the topic list of a traditional circuit analysis course, which focuses on linear circuits.

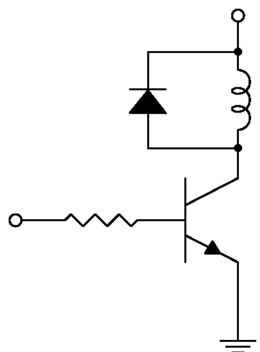

FIGURE 1
TRANSISTOR SWITCHING CIRCUIT FOR AN INDUCTIVE LOAD

Our main goals in redesigning the introductory circuit analysis course were to make the course relevant, practical, and engaging while still providing the necessary fundamentals to support the upper two years of study. The implementation plan for this course change was to:

- introduce RL, RC, and op-amp circuits as early in the semester as possible
- introduce diodes and transistors at a basic level
- introduce a design project
- implement just-in-time laboratories that were tightly coupled with the lectures
- have the laboratories support the design project

The details of the implementation changes are described in the next section.

A secondary goal for the course redesign was to introduce a design project into the sophomore year of study. As freshmen, students are given a design project in the EGR101 Introduction to Engineering course. Major design projects for all engineering disciplines are included in the junior year, and a capstone senior design project is prominent in the senior year. However, until 2007 we did not have any design experience for students in the sophomore year.

Our concerns about making traditional electrical engineering topics relevant for non-EE majors are not unique (see [3] for example), nor are our desires to ensure that the course material is seen by the students as practical and relevant [4]-[5]. There have been several efforts to integrate a design project into an introductory circuit analysis course [6]-[8] as well as proponents of tight temporal coupling between the lectures and laboratories [9].

NEW COURSE STRUCTURE

I. Topic Sequence

Students do not need much more knowledge beyond Ohm's Law and Kirchhoff's Laws in order to analyze simple circuits, thus we introduce "interesting" components such as operational amplifiers, capacitors, and inductors as early as possible in the course. These components enable equally interesting laboratories and also set the stage for applying these components to a design project. The remaining fundamental concepts (formal node/mesh analysis, source transformations, superposition, etc.) can be addressed in the second half of the course. By doing so, we achieve the additional benefit of having the students already somewhat proficient in circuit analysis so that they can appreciate the more advanced topics and relate them to actual practical circuits. Although we are still experimenting with the optimal sequence of topics, the one-semester course roughly splits into two parts of about 6 weeks each (with two weeks reserved for exams, special topics, etc.). The first half is an introduction to practical circuits, and the second half presents the more theoretical concepts. The following sequence of topics reflects our most current thinking:

<u>Part I</u>

- Voltage, current, resistance, power, energy
- Ohm's Law, Kirchhoff's Laws
- Node analysis (informal), element voltages
- Operational amplifiers (DC only)
- Capacitors and RC circuits
- Inductors and RL circuits
- Diodes and Transistors

<u>Part II</u>

- Node analysis, mesh analysis
- Dependent sources
- Source transformations
- Thévenin and Norton theorems
- Linearity and superposition
- AC analysis and complex numbers

Diodes and transistors are presented without reference to the underlying semiconductor structure as that is addressed in other courses taken by electrical engineering students only. We also do not delve into the depth of detail that is possible with these devices; for example, we only consider transistors as being fully on or fully off, not as active linear amplifiers. This approach is well matched to the needs of non-ECE students in the class who will most likely use transistors as switches, while still exposing ECE students to transistors such that their subsequent electronics course, which does examine the transistor in detail, comes more easily.

II. Laboratories

We do not have a formal laboratory manual for the circuit analysis course because we believe that the lectures need to be very closely connected in time with the labs (obviously, preceding them). The labs are written only in the week preceding the laboratory activity in order to ensure that they are relevant to the current week's lectures. This just-in-time approach allows us great flexibility in experimenting with the sequence of course topics, and to be responsive to unexpected events during the semester.

The laboratories also serve as teaching tools that support the course project. By the time the students begin working on the project in earnest (at about the mid-point of the course), they will have already seen many of the sub-circuits for their design in previous laboratories. We present examples of this approach in the next section.

As an example, Table 1 shows the week-by-week sequence of lecture topics and laboratories that were conducted in the Winter 2008 semester. Some of the laboratories (such as the ones in Weeks 6, 8, 11, and 12) not only reinforced the previous week's lecture material but also introduced circuits relevant to the students' design project (described in the next section).

The laboratories and the course project work together to develop the intuitive insight into electronic circuits that we are attempting to develop. Figure 2 shows three circuits that students were required to build and analyze as part of a laboratory conducted in the Winter 2007 and Fall 2007 semesters. The laboratory gives students hands-on experience with the circuit shown in Figure 1, and also compares three methods of handling inductor "kickback voltage" that occurs during switching: simple resistor, catch diode, and catch diode with zener diode for faster turn-off. By taking measurements of the kickback voltage and turn-off time the students develop an intuition for the individual components, as well as for the circuit as a whole.

Our students benefit from a laboratory that is open whenever it is not scheduled. Card-key access allows students to enter the laboratory and use the equipment and supplies at any hour of any day. This allows students to work at their own pace (within reason) knowing that if they do not finish a lab within the three hours allotted to their lab section then they may return later, when the lab is not in use. A laboratory assistant holds open lab consulting hours once a week.

III. Course Project

The course project is assigned at mid-semester. It is graded by the laboratory instructors and is used to form the laboratory grade (20% of the overall course grade). Students work in teams of two within each laboratory section to design and implement a "simple" electronic circuit (simple for experienced faculty, still quite challenging for students in an introductory course). Details of the two course projects conducted so far are presented in the next section.

Students are expected to perform the following tasks:

- Design the complete project schematic
- Draw the schematic using the Eagle schematic capture package [10]
- Draw the PCB layout, also using Eagle
- Submit the PCB layout for manufacturing by the School of Engineering
- Purchase necessary electronic components
- Solder components to the PCB
- Test and debug the circuit

The second half of the semester is clearly a busy one, and the homework and laboratory report load is reduced in order to allow students to concentrate on the project. Eagle is not formally taught in either lecture or laboratory, but instructional videos are available that demonstrate to students enough of the software to be able to complete the project. ECE students further develop Eagle usage skills in their junior year.

The costs of the projects are nominal, and students have not yet complained about having to pay for their own components ($15-$20 per student). The School of Engineering pays for manufacturing the PCB's, which are limited in size to a few square inches so that all of the students' PCB's may be panelized as a single job.

PROJECT EXAMPLES

Two projects have been conducted so far, a Coil Gun project (Winter 2007 and Fall 2007) and a Handbell project (Winter 2008). The first project was competitive, the second collaborative. The second project is currently in progress thus no assessment of its success is available.

I. Coil Gun

In Winter and Fall 2007 the students were required to build an electromagnetic projectile launcher, or coil gun. The fundamental components in this design were a coil (inductor), energy storage capacitors, switching transistor, and timing circuit. Thus, although the components involved were fairly simple, the project itself was a good demonstration of a practical electronic circuit.

This project specifically developed the students' intuition for capacitance, inductance, resistance, voltage, and current. In designing their own coil the students were required to consider trade-offs in peak current, applied voltage, coil inductance, coil length, and so on. Several laboratories throughout the semester developed the necessary sub-circuits so that the coil itself was the major component to be designed by the students. The remainder of the design involved the intelligent integration of circuits they had seen in laboratory activities.

The project was constrained by allowing no more than 100 joules of energy storage, and required an electronic component cost of no more than $25.

At the end of the semester, the student teams competed against each other to see which design could launch a 3cm 1/8" steel projectile the longest distance. The winning entry, shown in Figure 3, achieved a distance of 54 feet. Most interesting is that this entry was constructed by two non-

TABLE 1
SEQUENCE OF LECTURES AND LABORATORIES IN WINTER 2008

Week Number	Lecture Topics	Laboratory
1	Voltage, current, resistance, Ohm's Law	Introduction to Laboratory Equipment, Ohm's Law
2	Kirchhoff's Laws, node analysis	Introduction to Function Generators and Oscilloscopes
3	Mesh analysis, Op-amps	Node Voltage Analysis / Spice simulation
4	Op-amp circuits, Capacitors	Op-amps Inverting Amplifier
5	RC circuits, Exam #1	Capacitors / RC Circuits
6	Inductors, RL circuits	Astable multivibrator using an op-amp and capacitor
7	Source transformations, Thévenin/Norton theorems	Inductors / RL Circuits
8	Diodes, Exam #2	The Bridge-Tied Load (op-amp audio amplifier project)
9	Spring break	Spring break – (week 2 of amplifier project)
10	Diodes, NPN transistors	Diodes / Zener diode shunt regulator
11	NPN/PNP transistors	Transistors / Transistor-based tilt sensor
12	Transistors, Linear regulator, Exam #3	Transistors / Linear regulator
13	Complex numbers	Soldering Instruction
14	AC analysis	Project construction / testing
15	AC analysis	Project demonstrations

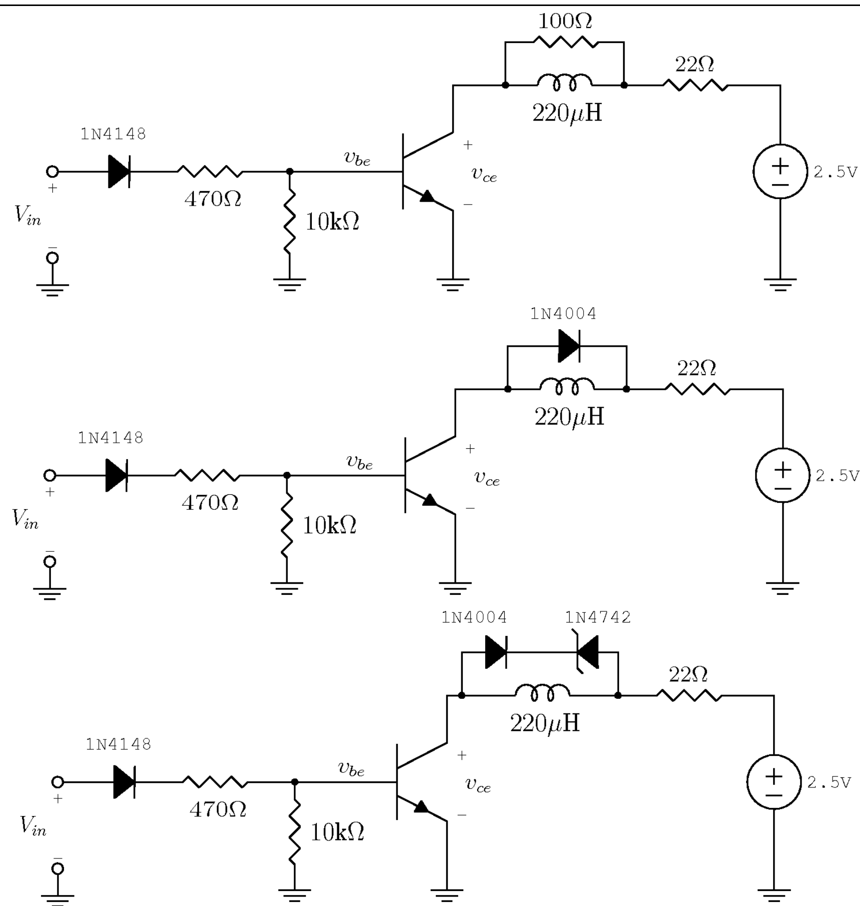

FIGURE 2
THREE INDUCTIVE-LOAD SWITCHING CIRCUITS STUDIED IN ONE LABORATORY

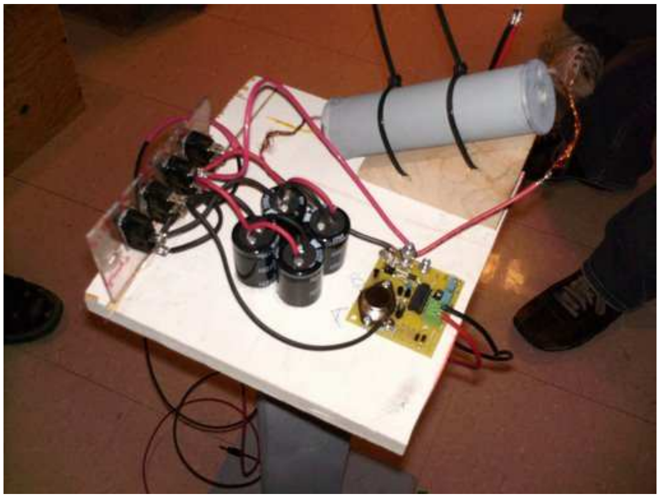

FIGURE 3
WINNING COIL GUN PROJECT IMPLEMENTATION FROM WINTER 2007

ECE students. Many students were comfortable enough in their understanding of capacitors to design their own voltage doubling schemes (using mechanical switches) to increase the applied voltage to their coil guns.

Student feedback for this project was generally positive, with the time investment required being the most common complaint. Other negative comments included the fact that the course was different from previous semesters, the need for more fine-grained deadlines to ensure students finished the project on time, and more detailed grading rubrics for various aspects of the project.

The positive comments were very encouraging as they suggest that many of the goals of the course redesign were met. Some of these comments were as follows:

"The coil gun project was very involved but the course was planned very well and the sequence of events was extremely logical."

"The course project applied many things that were learned during the class which was very helpful."

"The course project was a good hands-on way to understand all the basic principles that were learned in the course instead of just reading about them."

"I learned a lot from the project. I never thought I would be able to design and put together a circuit board myself; it was actually pretty cool. I have a new found respect for circuits."

In addition to these comments, several junior-level students watching the coil gun competition informally complained that they did not have the opportunity to take this course in the new project-based format.

We are also seeing the preliminary effects of the course project on downstream courses. In Fall 2007 the Dynamics course taken by mechanical/manufacturing engineering students included a course project in which some students, on their own initiative, designed and built circuits to assist in the project's operation. In Fall 2007, faculty also noticed that the design and implementation skills of junior level students were better for students who took Circuit Analysis I in the project-based format compared to those who took it in the traditional format.

II. Handbells

In Winter 2008 we are trying a new project, the design of electronic handbells. Each handbell is an oscillator tuned to a particular frequency that drives a small speaker. The handbell uses a tilt sensor that only activates the circuit when the handbell is in a horizontal position. Each group of two students will build four identical handbells, so that a laboratory section will be able to form a handbell choir and perform a musical piece by the end of the semester.

The handbell circuit comprises:

- an oscillator circuit – students can use the one developed in the laboratory of Week 6 (as shown in Table 1)
- an audio amplifier circuit, demonstrated in the laboratory of Week 8
- a tilt sensor and transistor amplifier, demonstrated in the laboratory of Week 11
- a voltage regulator, demonstrated in the laboratory of Week 12

The design component of this project mostly demands the selection of appropriate resistor values for each of the sub-circuits. In doing so, students need to understand the operation of op-amp inverting and non-inverting amplifier circuits, an op-amp-based astable multivibrator, and a two-stage current amplifier using bipolar junction transistors. The circuit is easily simulated using a Spice simulator.

The handbell circuit that the students are being steered towards is not necessarily optimal, e.g., an LM386 audio amplifier device could be used instead of the op-amp circuitry presented to the students. The goal, however, is to have the students put their knowledge into practice, and they do so by building a circuit with well-understood components that have been taught in lectures and laboratories, not by using "magic chips".

DISCUSSION

The integration of a project in an introductory circuit analysis course in the School of Engineering was presented. Although projects are integrated into many of our courses, at all levels, a sophomore-level project is necessarily different from projects at the junior and senior levels. In Table 2 we present a comparison between our sophomore-level circuit analysis project and existing projects in the freshman, junior, and senior years. We believe that the project we have integrated into the circuit analysis course fills an important gap in the educational development of our students.

ACKNOWLEDGMENT

The authors would like to acknowledge the Padnos College of Engineering and Computing for their continuing support of our course development efforts.

REFERENCES

[1] Nilsson, J.W. and Riedel, S.A. *Electric Circuits*, Pearson Prentice Hall, Upper Saddle River, NJ, 8th Ed., 2008.

[2] Thomas, R.E., Rosa, A.J. *The Analysis and Design of Linear Circuits*, John Wiley & Sons, Inc., New York, NY, 3rd Ed., 2001.

[3] Zekavat, S.A., Sandu, C., Archer, G., Hungwe, K. "An evaluation of the teaching approach for the interdisciplinary course Electrical Engineering for Non-Majors", *Proceedings of the 2004 ASEE Annual Conference & Exposition*, Salt Lake City, Utah, June 2004.

[4] Bordogna, J., Fromm, E., Ernst, E.W. "Engineering Education: Innovation Through Integration", Journal of Engineering Education, Vol. 82 Issue 1, January 1993, pp. 3-8.

[5] Brown, A., Ybarra, G., Massoud, H., Board, J., Holmes, J., *et. al.* "Redesign of the Core Curriculum at Duke University", *Proceedings of the 2006 ASEE Annual Conference & Exposition*, Chicago, Illinois, June 2006.

[6] Evans, A., Davies, T., Wilks, S. "Is your laboratory a turn-off?", International Journal of Electrical Engineering Education, Vol. 39 Issue 3, July 2002, pp. 284-291.

[7] Firebaugh, S., Jenkins, B., Ciezki, J. "A Comprehensive Laboratory Design Project for Teaching Advanced Circuit Analysis", *Proceedings of the 2004 ASEE Annual Conference & Exposition*, Salt Lake City, Utah, June 2004.

[8] Jenkins, B., Field, C.T. "Practical circuit design in an elementary circuit theory lab", *Proceedings of the 2000 ASEE Annual Conference & Exposition*, St. Louis, Missouri, June 2000.

[9] Gravé, I. "Integrated Course-Lab-Studio Environment for Circuits and Electronics Courses at Elizabethtown College", *Proceedings of the 2005 ASEE Annual Conference & Exposition*, Portland, OR, June 2005.

[10] http://www.cadsoft.de, Eagle Schematic/PCB CAD software

AUTHOR INFORMATION

Andrew Sterian, Associate Professor, Padnos College of Engineering and Computing, Grand Valley State University, steriana@gvsu.edu.

Bogdan Adamczyk, Associate Professor, Padnos College of Engineering and Computing, Grand Valley State University, adamczyb@gvsu.edu.

M.M. Azizur Rahman, Associate Professor, Padnos College of Engineering and Computing, Grand Valley State University, rahmana@gvsu.edu.

TABLE 2
COMPARISON OF PROJECT ATTRIBUTES BY YEAR

	Freshman Year	**Sophomore Year**	**Junior Year**	**Senior Year**
Duration	Multiple, small projects	One half-semester project	One whole-semester project	One two-semester project
Mentorship	Faculty	Faculty	Primarily faculty, some industry	Primarily industry, some faculty
Design Challenge	Low	Medium	High	Very High
Diversity of Projects	All projects the same	All projects the same	All projects different	All projects different
Impact of Project Failure	Low	Medium	High	No graduation