An Integrated Mixed-signal Circuit Design Course Project

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Stephen Sandelin

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- A Novel Teaching Practice for an Analog Circuit Analysis Course

Abstract

In this paper, we present a novel teaching practice adopted in a sophomore-level circuit analysis course in the Electrical Engineering (EE) curriculum at Western Washington University. In particular, we have introduced a hands-on mixed-signal circuitry design project which integrates both analog circuits and digital electronics together. The students are asked to implement and demonstrate a pair of design goals that utilize knowledge and skills acquired in the circuit analysis course and a digital electronics course. The project also aligns perfectly with the schedules of these two sophomore courses which are taken by the same group of students in the same quarter. The objectives of the course project are twofold: First, to demonstrate how analog and digital design methodologies combine in the creation of mixed-signal designs. Secondly, to provide students hands-on opportunities to practice important design skills. The collaborative nature of this course project offers multiple benefits such as enabling students to apply knowledge and skills acquired from two different courses in the same quarter to design real-life circuits; bridging two different EE subjects together through engaging and fun circuits and providing a big picture view, and promoting students' motivation to continue pursuing the EE major. We have adopted this course project for two consecutive course offerings in fall 2018 and fall 2019, respectively. Student feedback in the form of survey questionnaires has confirmed that this pilot project has been successful. Per the survey results, most students feel their abilities of developing design solutions, constructing prototypes, and communicating the design process have improved, which indicates increased students' self-efficacy. Moreover, majority of students feel more motivated to continue with the EE major of study.

I Introduction

For most Electrical Engineering (EE) and Engineering curricula, analog circuitry and digital electronic devices are traditionally covered in separate courses[1]. The course projects and content in these subjects are often offered independently without coordination across these courses, which often lead to students' misperceiving these two subjects as completely different disciplines[1]. In real-life applications, mixed-signal circuits that combine both analog and digital components are becoming increasing popular and are often inevitable. It is important to bridge the gap between these two subjects.

Recently, some Engineering programs have experimented to introduce a single course that covers both analog and digital fundamentals to meet the needs of multidisciplinary curricula. For instance, for introductory level courses, the school of Engineering and Computer Science at Oakland University introduced a core course - Introduction to Electrical and Computer Engineering that covers the fundamentals of both digital and analog circuits interchangeably to all the Engineering students[1]. At Messiah College, a new Circuits I core course combining introductory analog and digital circuit theory was offered for a multi-disciplinary engineering curriculum[2]. The first half of the course focuses on analog circuit analysis topics and the second half introduces digital electronics.

For upper-level courses, the ECE Department at Lafayette College has introduced mixed-signal designs in their junior level electronics course sequence[3].

The EE curriculum in our institution at Western Washington University (WWU) follows a traditional course structure, i.e., the analog circuit analysis topics and the digital electronics topics are covered in separate courses. The sophomore EE students in our institution take the Circuit Analysis II course and the introductory Digital Electronics course in the fall quarter of their sophomore year for the same period of time.

Our solution to bridge the gap between the two course subjects, by taking advantage of the parallel nature (i.e., taken by students in the same quarter) of the course schedules, is to create an integrated hands-on course project that combines topics from both courses. Numerous studies have confirmed that hands-on coursework and learning by doing are effective teaching practices to enhance students' learning performance[4,5]. Through the collaboration and coordinator of the instructors of these two courses, we have developed a pilot course project that fuses topics from both courses and introduced the course project in the Circuit Analysis II course in fall 2018 and fall 2019, respectively. This approach of integrating course content from two separate courses that are offered in the same quarter (or semester) has not been widely reported in the literature.

In particular, the integrated course project focuses on mixed-signal designs involving RC circuit responses and various operation modes of a 555 timer. The design challenges are based upon the use of a 555 timer and a series of RC combinations, which incorporate both digital and analog elements. Each student is required to design the analog and digital circuity needed to configure and control the timer to produce desired output. The end results of this course project are two engaging and fun circuits highlighted as follows.

- The first one is a photo-Theremin which demonstrates the same concept as a traditional Theremin, of alternating the time constant of an oscillator circuit, to produce a Theremin like instrument that uses variations in light intensity instead of variation in local electric fields.
- The second circuit realizes the activation and de-activation sequencing as demonstrated by a bank of LEDs turning on and off sequentially.

The collaborative nature of this course project offers multiple benefits, such as

1. Providing students hands-on experience in designing, analyzing, and testing mixed-signal circuits.
2. Enabling students to apply knowledge and skills acquired from two separate courses in the same quarter to design real-life circuits.
3. Bridging the gap of two different subjects of EE together through engaging circuits and providing a big picture view.
4. Promoting students' motivation to continue pursuing the EE major, which may help boost student retention.

To gauge the effectiveness of this teaching practice, we have collected students' feedback in term of survey questionnaires from students who took Circuit Analysis II in fall 2018 and fall2019. The survey results are overwhelmingly positive. The students feel that the project experience is worthwhile and beneficial. The survey results indicate increased students' self-efficacy, as most students have noted that their abilities regarding developing design solutions, constructing prototypes, and communicating the design process have improved. They also concur that the project experience further motivates them to pursue the EE major. We will elaborate the detailed survey questions and survey data statistics in a subsequent section in this paper.

The organization of the paper is as follows. We will first provide an overview of pertinent courses. Next we will describe the details of the integrated course project, followed by assessment results that demonstrate the effectiveness of the developed course project. Finally, we will conclude the paper with ideas for future improvement.

II Overview of Circuit Analysis II and Digital Electronics Coursework

The EE major courses at WWU begins in the winter quarter of the freshman year, as depicted in Table 1. Students first declare as EE pre-majors in order to take EE program courses. The pre-majors can apply for the EE program in June of the freshman year if they have taken a set of required courses as specified by the program's admission guidelines. Upon application, students will specify which concentration one would like to apply for. Currently the EE program at WWU offers two concentrations - Electronics and Energy. Students from both concentrations will take the same set of introductory core courses in their sophomore year.

Year / Major Status	**Course Number/Title and Quarter**
Freshman Year /EE Pre-majors	EE110 Introduction to EE, Winter EE111 Circuit Analysis I, Spring
Sophomore Year/EE majors	EE210 Circuit Analysis II, Fall EE233 Digital Electronics, Fall EE220 Electronics I, Winter EE 244 Embedded Microcontrollers I , Winter EE 310 Continuous Systems, Fall EE 333 Digital System Design, Fall

Table 1: EE Coursework for the Freshman Year and the Sophomore Year

The major topics covered in some of these EE courses are summarized in Table 2 below.

Course Number/Title	Major Topics Covered
EE111 Circuit Analysis I	DC circuit analysis techniques Network theorems Basics of op-amps
EE210 Circuit Analysis II	RC, RL, and RLC responses with DC sources AC circuit analysis techniques Frequency response and Bode plot AC power calculation Transformers Basics of three-phase circuits
EE233 Digital Electronics	Basic digital concepts Boolean algebra Digital devices Interfacing and the major functional units

Table 1: Major Topics Covered in Introductory EE Courses

Both Circuit Analysis II and Digital Electronics courses consist of weekly three-hour lectures and two-hour lab sessions. The laboratory activities are aimed to provide students hands-on practice on course content and to enhance students' understanding of important topics covered in lectures.

Given that the integrated course project is offered in the Circuit Analysis II class, we next provide some course information and desired learning outcomes of this course in Table 3 and Table 4.

Course information of EE210 Circuit Analysis II	
Prerequisite	MATH 204 (Elementary Linear Algebra) EE111 (Circuit Analysis I)
Textbook	"Electric Circuits", Nilsson J.W., Riedel S., Prentice Hall
# of Credits	4
Schedules	10 weeks with 3 hours of lecture and 2 hours of lab per week

Table 3: Course Information of EE210 Circuit Analysis II

Desire Learning Outcomes of EE210 Circuit Analysis II	
1.	Analyze RL, RC, and RLC switching circuits with DC sources
2.	Understand and competent in analyzing simple AC circuits using complex numbers, reactance, impedance, and phasors.
3.	Understand the concepts involved with power in AC circuits.

4.	Be able to design and analyze AC RLC circuits.
5.	Understand the concepts of frequency response and Bode plots.
6.	Have a basic ability to analyze 3- phase circuits.
7.	Be able to use appropriate tools for testing and analyzing AC circuits.
8.	Laboratory reports must be well written to meet the provided requirements.

Table 4: Desired Learning Outcomes of EE210 Circuit Analysis II

The attainment of these learning outcomes is assessed through combinations of students' performance on quizzes, midterm and final exams, and/or lab assignments and the course project.

In the next section, we will present the developed integrated course projects in detail.

III the Integrated Mixed-signal Design Course Project

Design Goals:

This course project is aimed to demonstrate how analog and digital design methodologies combine in the creation of a mixed-signal design. The students are asked to implement and demonstrate a pair of design goals that utilize knowledge and skills acquired in EE111/EE210 Circuit Analysis I & II classes and EE233 Digital Electronics class. The design challenges are based on the use of a 555 timer and a series of RC combinations, which incorporate both digital and analog elements. In this course project, each student is required to design the analog and digital circuitry needed to configure and control the timer to produce the desired outputs for two different circuits.

The outcomes of each student' design in this course project are two circuits with potential real-life applications, as highlighted below.

- Circuit #1 is a photo-Theremin which demonstrates the same concept as a traditional Theremin, of alternating the time constant of an oscillator circuit, to produce a Theremin like instrument that uses variations in light intensity instead of variation in local electric fields. The circuit schematic is depicted in Figure 1.
- Circuit #2 is an activation and de-activation sequencer as demonstrated by a bank of LEDs turning on and off sequentially. The schematic of this circuit is depicted in Figure 3.

For each circuit design, students need to meet several design challenges under certain constraints. Detailed design specifications, design objectives, constraints, and deliverables will be elaborated in this section.

Project Schedules:

The course project was assigned to students in EE210 class in the 7th week of the fall quarter after the 555 timer and its functionalities were discussed in EE233. Prior to this, students in EE210 learned the topics related to the analog circuitry portion such as DC&AC circuit analysis techniques and RC circuit responses.

During the four-week span upon the end of the fall quarter, each student independently worked on the project to accomplish several deliverables by the specified deadlines, as specified in Section III.A and Section III.B.

III.A Detailed Description of Circuit #1 Design

As depicted in Figure 1, the first circuit is a photo-Theremin which uses of a 555 timer operating in an astable multivibrator mode. Moreover, the timer oscillates between two states (VCC and GND) at some rate that is determined by an external timing circuit. Specifically, the timer is in an oscillator configuration whose frequency can be determined by the RC circuit formed by R1, R2 and C1.

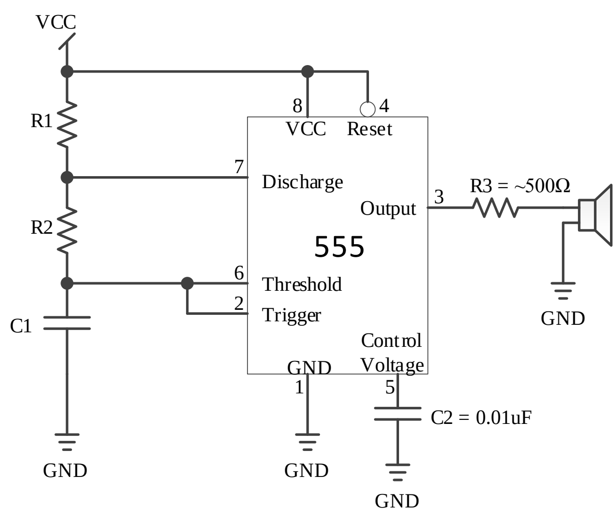

Figure 1: Astable Multivibrator Configuration for the Photo-Theremin Circuit Design

Figure 2 shows the voltage waveform of C1 and the 555 timer output voltage waveform at pin 3 with the assumption of R1=R2. Note that students should be able to derive these waveforms given their knowledge learned in EE233 class and EE210. The details of the 555 timer operation theory is omitted in this paper. As shown in Figure 2, the 555 timer output is a square wave. Further, the rise time “tr”of the voltage across C1 determines the time the output is high and the fall time “tf” across C1 determines the time the output is low. Therefore, the sum of those delays will yield the frequency of the output square wave. Also, note that the charge and discharge levels of the capacitor voltage are bounded, not by VCC and GND, but by 2/3 VCC and 1/3 VCC. With equal resistance on R1 and R2, the duty cycle will be 2:1 or 66% on and 33% off. This is good enough for a tone.

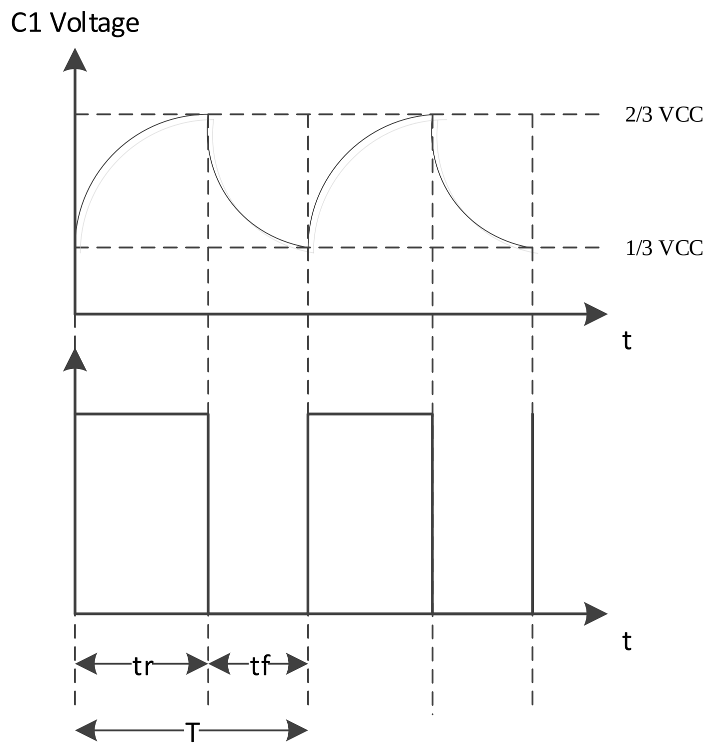

Figure 2: C1 Voltage (the top waveform) vs Vout at Pin 3 (the bottom waveform)

Design Challenge:

Each student needs to determine the values for R1, R2 and C1, in order to achieve an output frequency in the audio range.

Design Specifications:

- R1 and R2 are two photo-resistors due to the consideration of using photo-resistors to change the frequency of the output so the circuit behaves as a Photo-Theremin.
- To obtain the value of R1 or R2, students can measure the resistance of the photo-resistor at a medium level of light exposure to determine the "mid-point" resistance. This resistance will then go up or down from that point as a user move his or her hand in front of or away from the photo-resistors.
- To find C1, students need to determine the capacitance needed with the resistance measured to rise from 1/3 VCC to 2/3 VCC and to fall from 2/3 VCC to 1/3 VCC with VCC = 9V.

The design solutions require students to apply RC circuit response formulas covered in EE210 to find C1. There are different ways to determine C1 depending on whether one chooses to use the charging cycle or the discharging cycle. Students may choose any valid design method to get C1.

Design Solution Example:

Below is an example of the design solution for C1.

- Using the equation for RC step response to determine the value for C1, which can be found below:

$$V_c(t) = V_f + (V_i - V_f)e^{\frac{-t}{(R1+R2)*C1}}$$

R1=R2=1490 Ohm	Vf = 9 V	Vi = 3 V	t = ⅔T = 333 µs	Vc(⅔T) = 6 V

- Given the values of other parameters, C1 can be solved as

$$V_c(0.000333) = 6 = 9 + (3 - 9)e^{\frac{-0.000333}{2920*C1}}$$

  This then simplifies to C1=16.45 µF.

Note that the values for R1 and R2 in this example solution are based on a "medium light intensity" scenario.

Design Deliverables of Circuit #1:

- Week 1: Initial analysis of how to obtain R1,R2, and C1
- Week 2 and week 3:
  - Successful construction and demonstration of a working photo-Theremin circuit
  - Testing the circuit to verify the tone frequency
- Week 4: Completion of a written report

III.B Detailed Description of Circuit #2

As depicted in Figure 3, the second circuit is an activation and de-activation sequencer using a 555 timer, RC circuits, and a bank of LEDs. This circuit shows one way to sequence the switching on and off of power to parts of a circuit. The 555 timer can operate in a Mono-stable Multi-vibrator mode (a single, stable state) and can be triggered to go to the unstable state and remain there for a period of time. The circuit in Figure 3 demonstrates this mode.

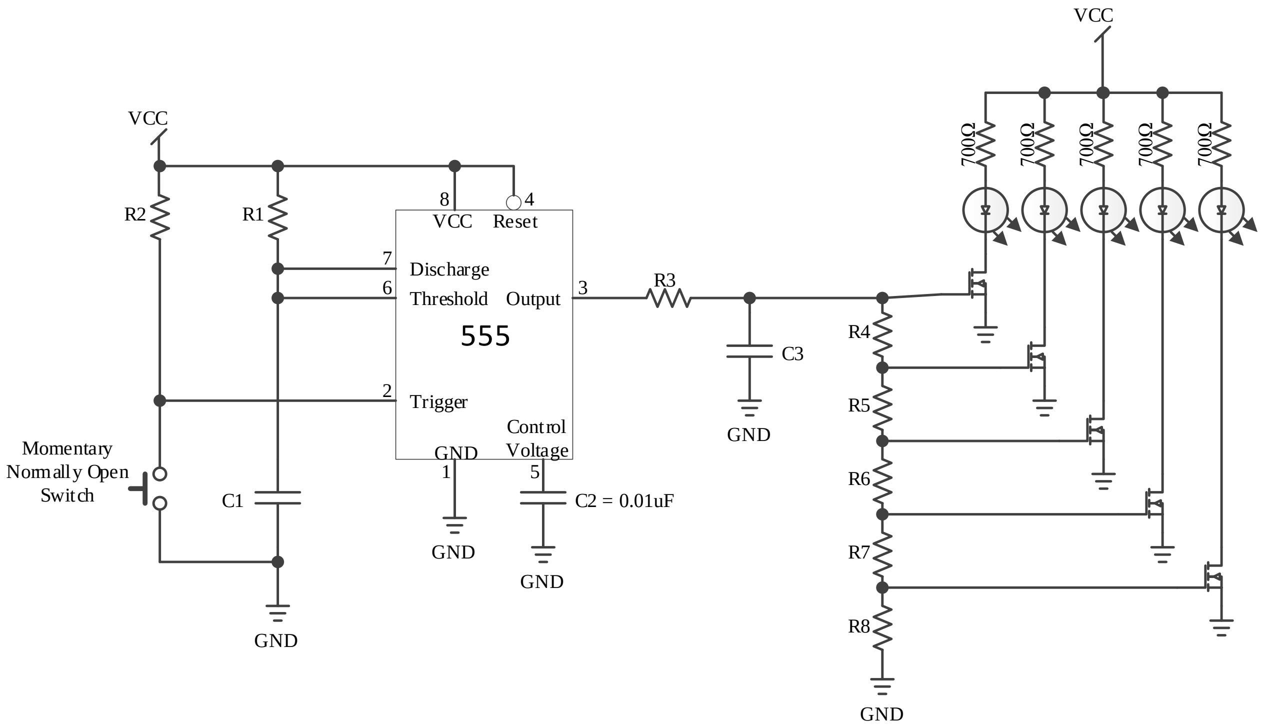

Figure 3: a 555 Timer-based Sequencer Circuit

Based on the 555 timer operation theory, we can derive the following voltage waveform and timing relationship as shown in Figure 4.

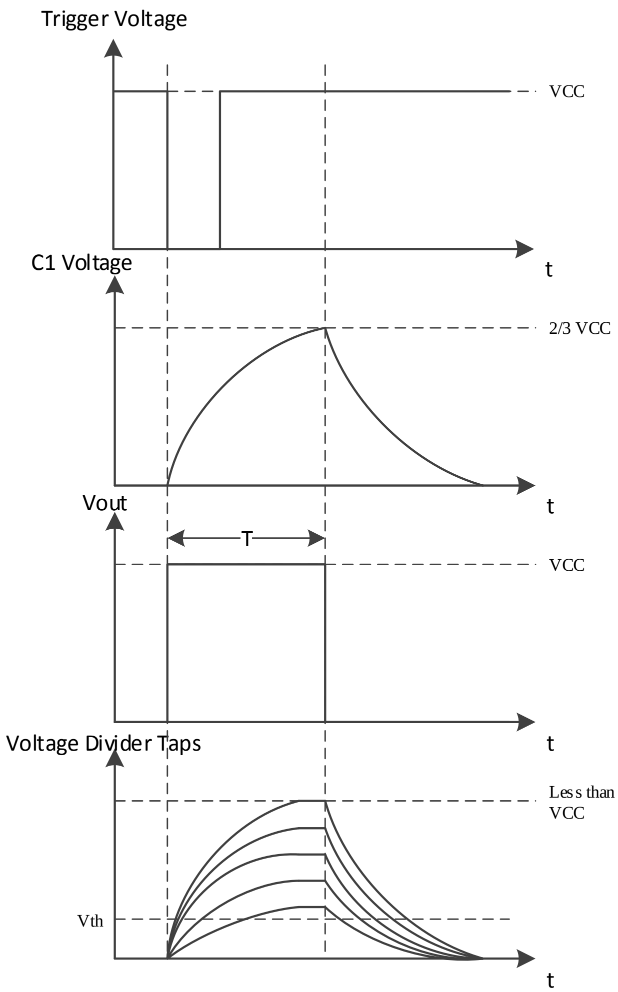

Figure 4: Timing Waveforms at Each Stage

Note that R4 to R8 form the voltage divider taps. Vout is the voltage at pin 3 of the timer. Vth is the threshold voltage to turn on a NMOS switch that connects each resistor of the voltage divider and the corresponding LED.

Design Challenge:

The design challenge for circuit #2 is three-fold.

- First, determine R1 to achieve an output pulse time of approximately 2.6-2.8 seconds, given a value of 4.7uF for C1.
- Second, determine R3 to achieve a charge and discharge time across C3 of approximately 2 seconds, given a value of 4.7uF for C3.
- Finally, determine R4 to R8 for the voltage divider. This is a two-part problem since the total resistance of the divider will form a voltage divider with R3 and limit the maximum voltage that C3 can be charged to. The timing of the sequence is not critical, but it must be obvious to an observer that the LEDs are being illuminated one at a time.

Design Specifications:

- R2 is a pullup resistor, a value of around 3KΩ works well.
- The capacitors C1 and C3 are 4.7uF.
- The NMOS switches are BS107 small signal MOSFETs.
- To simply the design, use the assumption of R4=R5=R6=R7=R8. But the actual R8 might need to be larger than the other resistors in the divider ladder to raise the voltage level at the voltage divider taps used to switch the outputs.

The design solutions for the sequencer circuit again involve applying RC circuit response formulas and other circuit analysis techniques. The solution process is more challenging than the photo-Theremin circuit. There are different alternative design methods in order to obtain the required values. Students can choose whichever method that is convenient for them to use.

Design Solution Example:

Table 5 shows the results of a design solution for the sequencer circuit and an actual circuit is shown in Figure 6. The details of how to obtain these values are omitted in this paper.

R1 = 500k Ohm	R4 = 24k Ohm	R7 = 24k Ohm	C1 = 4.7 µF*
R2 = 3k Ohm*	R5 = 24k Ohm	R8 = 150k Ohm	C2 = 0.01 µF*
R3 = 82k Ohm	R6 = 24k Ohm	*= Value given	C3 = 4.7 µF*
VCC = 9 V			

Table 5: a Design Solution for Various Component Values of the Sequencer Circuit

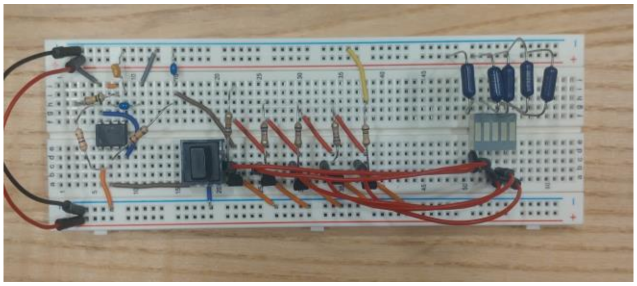

Figure 6: Picture of an Actual Sequencer Circuit

Design Deliverables of Circuit #2:

- Week 2: Initial analysis of how to obtain R1, R3, and R4 to R8 for the sequencer circuit
- Week 3 and week 4: Successful construction and demonstration of a working sequencer circuit
- Week 4: Completion of a written report

IV Assessment Results of the Integrated Course Project

To gauge the effectiveness and impact of the integrated course project, we have collected survey questionnaires from students who took EE210 and EE233 in fall 2018 and fall 2019. Students' feedback help assess how students feel about the course project experience, as well as whether this teaching practice is effective and achieves the projected benefits. We acknowledge that the assessment data collected in this work are subjective data based upon students' perceptions about the project experience. Other assessment measures such as grades of exams would be more objective. We plan to include students' grades in our future data collection and assessment.

Assessment Data Collection:

Each student who took EE210 in fall 2018 and fall 2019 was asked to respond to ten questions with each question having five possible answers. Each answer was mapped to a numerical value, specifically, 1-strongly disagree, 2-disagree, 3- no opinion, 4-agree, 5-strongly agree.

The survey was anonymous. Students were asked to voluntarily specify some demographic information such as age group, gender, and concentration of study (Electronics or Energy)

The ten survey questions are listed below.
Q1: The project enhanced my understanding of RC circuit responses (such as time constant, final value, and initial values).
Q2: The project helped my understanding of the 555 timer and its different functions (or states).
Q3: Do you feel this project to fuse analog circuit with digital device (555 timer) is valuable?
Q4: Do you feel the experience of designing real-life circuits and making them work is valuable?
Q5: The project further motivated me to study these subjects and the EE program.
Q6: The project helped increase my ability to communicate the design process that I used.
Q7: The project helped increase my ability to develop design solutions.
Q8: The project helped increase my ability to construct a prototype, test it, and evaluate a design.
Q9: The design helped increase my ability to select the best possible design that meets design requirements.
Q10. The project allowed me to independently define required components and values.

There are total 48 responses with 17 from the fall 2018 class and 31 from the 2019 class. Table 6 shows a summary of the number of responses according to gender.

	Female	Male	Unspecified	Total
2018	1	16	0	17
2019	5	22	4	31

Table 6: # of Survey Responses according to Gender

Summary of Assessment Data:

The survey results are summarized in Table 7 with the mean and the standard deviation (STD) of each question. For comparison purpose, we also provide the survey statistics from the group of women students as well.

Questions	**2018**		**2019**		**Women Students**	
	Mean	**STD**	**Mean**	**STD**	**Mean**	**STD**
Q1	4.3	0.46	4.2	0.60	4.4	0.44
Q2	4.2	0.71	3.4	1.33	3.8	0.44
Q3	4.5	0.44	4.6	0.8	5	0.44
Q4	4.8	0.40	4.8	0.37	5	0.44
Q5	4.2	0.63	4.1	0.72	4	0.7
Q6	4.1	0.55	4.1	0.57	4.4	0.44
Q7	4.3	0.58	4.3	0.59	4.6	0.54
Q8	4.3	0.84	4.4	0.56	4.4	0.83
Q9	4.0	0.86	4.0	0.94	4	0.44
Q10	4.5	0.51	3.9	1.01	4.2	0.54

Table 7: Survey Data Summary from fall 2018 and fall 2019 Circuit Analysis II Classes

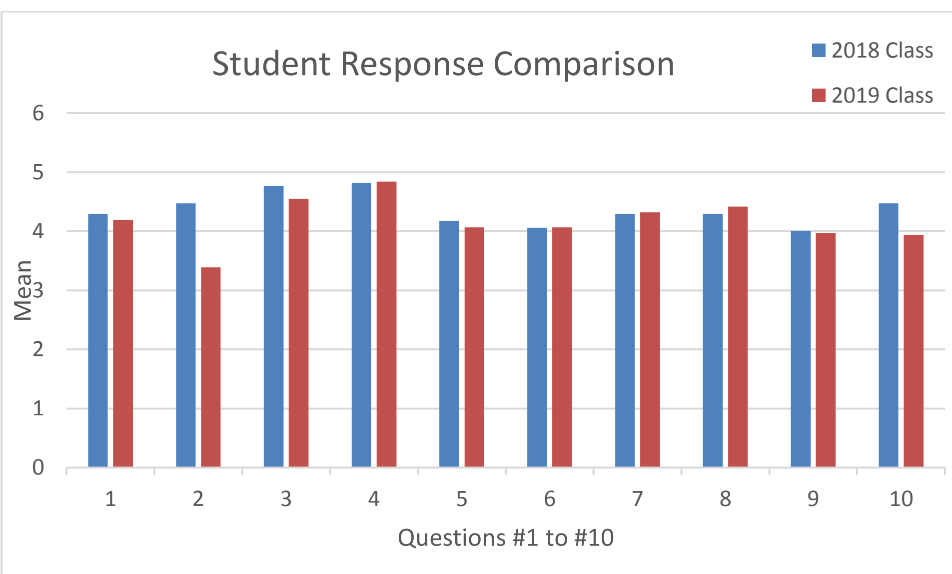

Figure 7: Student Responses Comparison between 2018 Class and 2019 Class

Assessment Results:

Based on the survey results presented in Table 7 and Figure 7, we have made a few key observations:

- Most students felt that the course project was a valuable experience.
- Majority concurred that the course project helped their understanding of the RC circuit responses and the 555 timer. However, a few students from the 2019 class noted that they would hope to have more lecture time to cover the 555 timer functionalities, as reflected from the relative lower mean value for Q2 compared to that from the 2018 class in Figure 7.
- Students also acknowledged that the course project experience motivated them to continue pursuing the EE major.
- Students felt their abilities to find design solutions, to prototype and test a circuit, and to select the best design that meets design requirements improved. This indicates increased students' self-efficacy which has been shown to correlate to the improvement in students' learning performance[6, 7].

We also compare the responses from the women students and that from male students in 2019 class, as shown in Figure 8. Interestingly, for almost all categories, it appears that women students feel slightly more positive about the project experience than male students. We should note that the sample size of the women student group is relatively small.

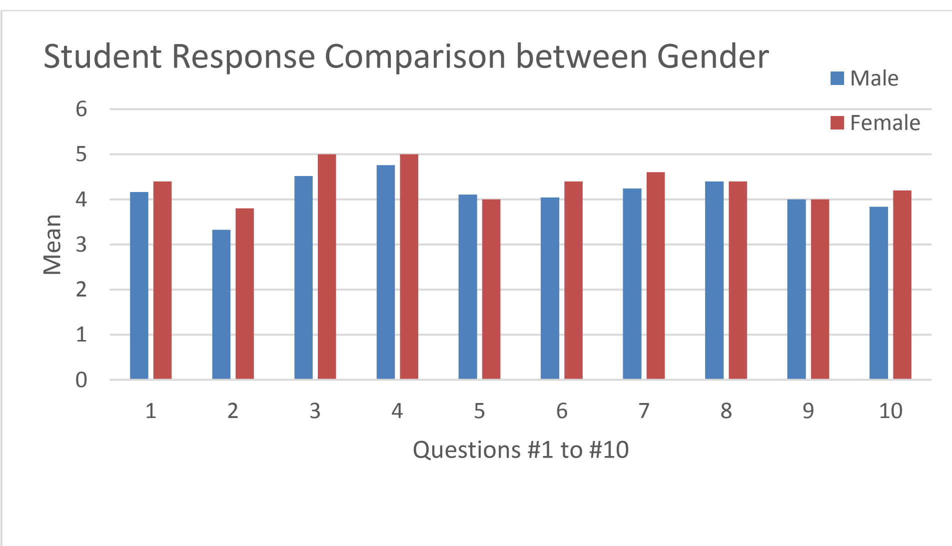

Figure 8: Student Response Comparison between Male and Female Students from 2019 Class

Some students provided encouraging written remarks, such as

- "I appreciate the crossover of EE210 and EE233."
- "I enjoyed bringing digital and analog together into a cumulative project."
- "The project was a good connection between EE233 and EE210. Enjoyed the project."

- “Was good combination of RC, digital, and overall hands-on application!”
- “Using the equations learned in class to apply on a very hands-on project is cool.”
- “ I find the project challenging and rewarding”
- “Please keep doing for the future years.”

Some also offered constructive suggestions for improvement, such as

- “I feel it could involve more digital electronics content in the project.”
- “It would be helpful to allocate one more lecture to go through more 555 timer functionalities and how the circuit design affects it.”

It would be interesting and meaningful to compare students’ perceptions on a non-integrated course project experience with those on the integrated course project experience. Note that we currently do not have assessment data for the case of students working on a non-integrated course project, i.e., a course project only involving analog circuitry and not combining any digital elements. In the future, we plan to adopt the “between group” method in Circuit Analysis II class. We will divide students into two groups, the experimental group and the control group. Students in the first group will work on a non-integrated course project and the second group of students will focus on the proposed integrated course project. The survey questions will be re-valuated and modified before we distribute the survey to both groups of students for assessment data collection and comparison.

V. Conclusions

In this paper, we present a novel teaching practice adopted in a circuit analysis II course through integrating analogy circuit and digital electronics into a single course project. The course project combines topics from a circuit analysis course and an introductory digital electronics course which are taken by EE sophomore students in the same quarter. The collaborative nature of the course project and the coordination of the two course schedules render multiple benefits. Students’ feedback has demonstrated the effectiveness of this integrated course project. Some of the future improvement ideas include adding AC circuitry and more digital electronics content in the course project.

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