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Integrating Design and Practical Applications into Linear Circuits Laboratories: Effects on Student Interest and Motivation

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Abstract

A sophomore-level introductory Linear Circuits course is a graduation requirement for multiple engineering majors at California State University, Chico. Historically, over 50% of students registered each semester have declared Mechanical Engineering majors. These students must also take two upper-division courses with a Linear Circuits prerequisite, but many don't consider the course content relevant or useful and exhibit low interest and motivation. Previously, all lab assignments only involved verification of principles such as Kirchhoff's Laws by breadboarding circuits and making measurements with multimeters and oscilloscopes. No opportunity for design or implementation of practical applications was offered, and students who already saw the course as boring and irrelevant had no reason to change their minds after completion.

Starting with the Fall 2018 semester, four new lab assignments were created to give students experience in designing circuits to meet performance criteria and building a working system. Since students still needed to learn how to breadboard circuits and use lab equipment, no changes were made to labs during the first half of the semester. The last four labs involved the design and implementation of an operational amplifier-based infrared security system with automatic day and night modes. An additional change for the Fall 2019 semester was the adoption of the portable Analog Devices ADALM2000 (M2k) Active Learning Module which includes DC power supplies, a waveform generator, and an oscilloscope.

Assessment of the applications-based lab assignment update was implemented by conducting Likert-scale student opinion surveys at both the beginning and end of the Fall 2019 semester. Start-of-semester surveys given to 104 students gathered feedback on how relevant and applicable the course content was to their majors (Question #1), their level of interest (Question #2), and motivation to study (Question #3). The same questions gathered feedback from the remaining 91 students at the end of the semester, except Question #2 was modified to ask about the change in their level of interest in course content after completing the security system.

Analysis of results of both surveys showed no statistically significant changes occurring across all majors for Question #1. For Question #2, statistical analysis was not performed because the response options were also changed, but 81.3% of students who completed the end-of-semester survey indicated that their level of interest in course topics had increased when compared to the beginning of the semester. However, analysis of Question #3 showed a statistically significant decrease in the motivation of Mechanical Engineering students to study more advanced topics related to Linear Circuits, with no significant change among other majors. Even though 64.7% of Mechanical Engineering students indicated that their level of interest increased, the difficult and abstract nature of circuit analysis likely limits their interests in further study to concepts only.

Most of the positive feedback regarding use of the ADALM2000 module was centered around students' ability to work on lab assignments and other projects on their own time. However, the acquisition cost of the module ($99 in Fall 2019) was a source of negative feedback.

Introduction and Background

The coverage of theory is always a vital part of any engineering course. However, focusing only on abstract theory without any real-world context does not show students why the content is important for them to learn, and reduced student motivation and engagement may result. Motivation and learning are enhanced when students can connect theory to tangible physical applications; therefore, the course must contain a suitable balance between these two areas [1]. Increases in student interest and retention rates are also evident when opportunities to design and build practical real-world applications are available, especially if offered early in students' undergraduate educations [2-5]. An additional issue is the relative scarcity of design activities in sophomore- and junior-level courses due to the heavy focus on the pre-requisite theory required for students to succeed in senior-level courses including capstone design projects [6].

To be successful as engineers, students must understand how to apply theory to real-world applications with numerous constraints as opposed to simply solving contrived pencil-and-paper problems. A focus on projects has been implemented in lower-division courses via guided multi-week laboratory exercises that enable students with a relatively limited theoretical background to participate in the design, testing, and implementation of functioning physical systems with real-world applications [7]. The project-based approach has also been found to be effective with students lacking any substantial formal background with circuits and electronics, where a hands-on "observations first, theory second" approach is used to educate students about basic concepts related to circuits as opposed to traditional lectures where students have no context in which to frame the material and as a consequence retain an insufficient amount [1, 8].

A sophomore-level introductory Linear Circuits course is a required pre-requisite for multiple upper-division courses for Electrical (EE), Mechatronic (MECA), Computer (CpE), and Mechanical (MECH) Engineering majors at California State University, Chico. The course covers foundational knowledge required for upper-division Electrical and Computer Engineering courses and includes the following topics:

- Passive circuit elements such as resistors, potentiometers, capacitors, and inductors.
- Voltage and current sources, both dependent and independent.
- Power and energy calculations.
- Circuit analysis with Ohm's Law, Kirchhoff's Laws and related methods such as Nodal and Mesh Analysis.
- Thévenin Equivalent Circuits and conditions for maximum power transfer to loads.
- Linear applications of ideal operational amplifiers.
- 1^{st}-order transient response of RC and RL circuits.
- AC steady-state circuits, phasors, and circuit analysis in frequency domain.
- Superposition concept and analysis methods.

Students concurrently enroll in a weekly 1-hour and 50-minute laboratory that gives them hands-on experience with circuit prototyping and use of laboratory equipment including multimeters, waveform generators, and oscilloscopes. The labs are also intended to reinforce the theory and concepts covered in lecture. During a typical semester, students will complete nine to ten separate laboratory assignments and summarize their findings by submitting written reports.

In previous semesters, there were no design activities in any of the laboratory assignments. None of the assignments gave students any sense of how or why the specific topics were necessary or useful in implementing real-world applications, since they were all "build the circuit and measure it" exercises. Students were given circuit diagrams and asked to perform theoretical calculations, then to construct the circuits on breadboards and verify that physically measured quantities matched their theoretical values. As a result, many students exhibited low levels of motivation and enthusiasm when performing the assignments during lab sessions.

These attitudes were particularly noticeable among the MECH majors since electric circuits are commonly seen by this student population as material that has minimal relevance to their major and future career [9-11]. Even though Linear Circuits is a pre-requisite course for two upper-division courses covering instrumentation and control systems and course topics are fundamental to implementing automation, many MECH students see circuits only as a graduation requirement to get checked off since their primary interests lie in the design and applications of mechanical systems. With no real-world applications in any of the lab assignments, MECH majors were not given any reason to change how they already perceived the relevance and usefulness of the course material. The lack of any design activities also did nothing to increase the interest and motivation of CpE, EE, and MECA majors, even though the course content was directly related to their chosen field of study. In addition, an opportunity to start helping students gain the skills required to meet ABET Criterion 3 Student Outcomes in upper-division courses was also missed.

To address some of these issues, a four-lab sequence was implemented which guided students through the design and construction of an operational amplifier-based infrared security system with an alarm buzzer and automatic day and night modes. The system is divided into four separate modules with each serving a different function. These lab assignments are the final assignments of the semester since students will need to have already gained a working knowledge of how to build circuit prototypes on breadboards and perform measurements with the lab equipment. Minimal changes were made to the first five to six lab assignments, which continued to cover the following topics:

- Resistor measurements and tolerances, series and parallel connections.
- Breadboarding of circuits and connections to power supplies.
- Verification of Kirchhoff's Laws and principles of voltage and current division.
- Thévenin's Theorem and maximum power transfer to loads.
- Use of multimeters, waveform generators and oscilloscopes.
- Inverting and non-inverting operational amplifier circuits.

Even though ABET evaluation does not occur in this course, it is beneficial to incorporate activities that give students the tools to succeed in upper-division coursework and attain the required student outcomes according to the ABET Accreditation Criteria. The learning objectives related to the four-lab sequence address Student Outcomes #1 and #6 in ABET Criterion 3. Outcome #1 is concerned with the ability of students to solve complex problems using principles of engineering, science, and mathematics. Outcome #6 addresses the ability of students to conduct experiments, analyze their results, and arrive at valid conclusions [12].

Security System Circuits: Theory and Design

The interaction between the four modules and the function of each is shown in Figure 1. Each module introduces a different operational amplifier application beyond the typical inverting and non-inverting amplifier circuits covered in introductory Linear Circuits courses. Modules #1 through #3 require students to design some portion of the circuit according to listed constraints or performance targets. The typical design challenge is to determine one or more component values needed to meet given specifications for the voltages and/or currents required for proper operation of devices such as infrared emitters.

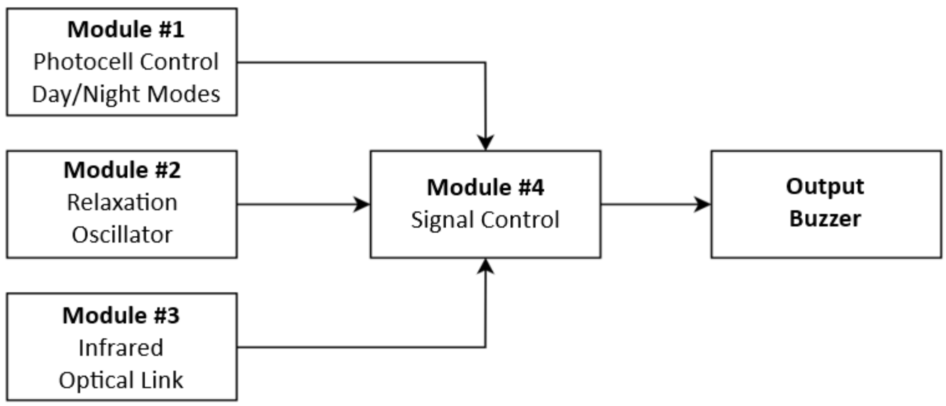

Figure 1: Block Diagram of Infrared Security System

During discussion of each module in lecture, students are also introduced to concepts that reach beyond the typical introductory Linear Circuits curriculum such as the binary number system, the differences between analog and digital signals and applications, logic gates, pull-down and pull-up resistors, set-reset latches, pn-junction diodes, and various non-linear applications of op-amp circuits such as comparators and oscillators. These additions to the course content are intended to give the MECH students an introduction to concepts and electronic components that they would not otherwise receive in the rest of their courses.

This system emulates the behavior of commercially available outdoor perimeter security systems which are deployed in locations such as outdoor yards of lumber and hardware stores. Intrusions are detected when the path of an infrared beam traveling between an emitter and photodetector is blocked. The behavior of the system can be summarized as follows:

- **Day mode**: photocell is exposed to ambient room lighting. The alarm remains silent until the beam path is blocked. Blockage of the beam path will cause the alarm buzzer to start beeping and continue until the blockage is removed. In this mode, the system functions like a door alarm that indicates when someone enters or exits a building.
- **Night mode**: photocell is covered by an object. In this mode, the alarm also remains silent until the beam path is blocked. Once this blockage occurs, the alarm buzzer will

continue beeping while the system is powered, regardless of whether the blockage is removed or the system goes into day mode. Like an actual burglar alarm, a user input is required to reset the system.

Students must show that their complete system exhibits the required functionality in both day and night modes. The only permitted external connection is to a DC power supply. Students are not permitted to use switches, buttons, or waveform generators to replicate signals from non-functional modules. LEDs are placed at the outputs of modules #1, #2, and #3 to give a visual indication of each module's output as a 1-bit binary signal.

Table 1 gives the Bill of Materials required to implement the security system. Students purchase lab kits that contain an assortment of standard resistor and capacitor values plus various integrated circuit chips for both digital and analog applications. To ensure proper operation of the system, operational amplifiers should be rail-to-rail capable and designed to work in single-supply mode from a 5 V power supply. The Microchip MCP6004 op-amp was selected for this application because it meets both criteria [13].

Table 1: Bill of Materials for Infrared Security System

Item Description	Part Number	Quantity
Quad Operational Amplifier, Rail-to-Rail Capable	MCP6004	2
Quad 2-input AND Logic Gate	74HCT08	1
Set-Reset Latch, NOR-type	CD4043B	1
Audio Piezo Indicator, self-driven	AI-1441-TWT-12V-R	1
Cadmium Sulfide Photocell	PDV-P8103	1
Infrared Emitter, 940 nm	IR1503	1
Photodiode	OP999	1
2-pin Red LED	Various	3
Diode, pn-junction	1N4148	2
Push Button	Various	1
Resistors and Capacitors	Various	
Breadboard	Various	1

Module #1: Photocell Control, Design and Operation

A cadmium sulfide photocell is used to sense large changes in the ambient light level of the circuit's location. The photocell functions as a light-sensitive variable resistor with possible resistance values as low as a few hundred ohms in bright light to several mega-ohms in total darkness. Figure 2 shows the circuit diagram for this module with the variable photocell resistance represented by R_{PC}. An op-amp comparator implements an analog-digital converter (ADC) with a single binary bit as the output. The lack of a negative feedback connection between the op-amp output and inverting input causes the amplifier to always be in either positive or negative saturation with outputs of 5 V or 0 V, respectively.

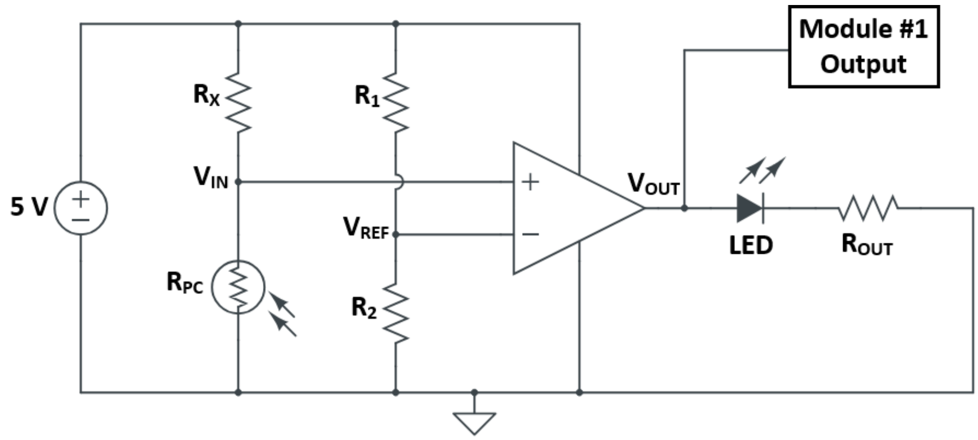

Figure 2: Circuit Diagram for Module #1, Photocell Control

In Figure 2, the resistors R_1 and R_2 form a voltage divider that provides a reference voltage of V_{REF} = 2.5 V. R_X and R_{PC} form a second voltage divider with the value of V_{IN} varying according to changes in R_{PC}. Two outputs are possible according to the following input conditions:

- $V_{IN} < V_{REF}$: day mode, V_{OUT} = 0 V, LED off.
- $V_{IN} > V_{REF}$: night mode, V_{OUT} = 5 V, LED on.

Cadmium sulfide photocells exhibit a large variation in resistance values even if components from the same batch are exposed to identical light intensity levels [14]. Students must measure the resistance of their photocell both under ambient room lighting conditions and with an object covering the photocell. Covering the photocell with a finger is sufficient for night mode, even though R_{PC} remains low due to light penetrating through fingers and the photocell's base. This lab assignment contains the following design tasks:

- Based on the measured value of R_{PC} with the photocell exposed in day mode, calculate the value of R_X so that $V_{IN} \approx 1$ V.
- Calculate R_1 and R_2 to meet the following specifications:
    - Current flowing through R_1 and R_2 is in the range of 2 mA to 10 mA, assuming an ideal op-amp with zero current at both input terminals.
    - V_{REF} = 2.5 V with a tolerance of +/- 5%.
- Calculate R_{OUT} so that the LED current is in the range of 4 mA to 6 mA if the output voltage of the op-amp is 5 V in night mode and the voltage drop across the LED is 1.7 V when turned on.

If calculations produce non-standard resistor values, then students are asked to come as close as possible to their calculated values by using series and parallel resistor combinations. Use of resistive decade boxes and potentiometers is prohibited to prevent students from using trial and error to find the correct resistance values instead of performing design calculations.

Module #2: Relaxation Oscillator, Design and Operation

This module implements an RC relaxation oscillator that runs continuously. The circuit is based on an inverting Schmitt Trigger which alternately charges and discharges a capacitor through a resistor. To operate in single-supply mode, a reference voltage of V_{REF} = 2.5 V must be supplied which is implemented using a voltage divider and a buffer op-amp with unity gain. Figure 3 shows the circuit diagram for this module.

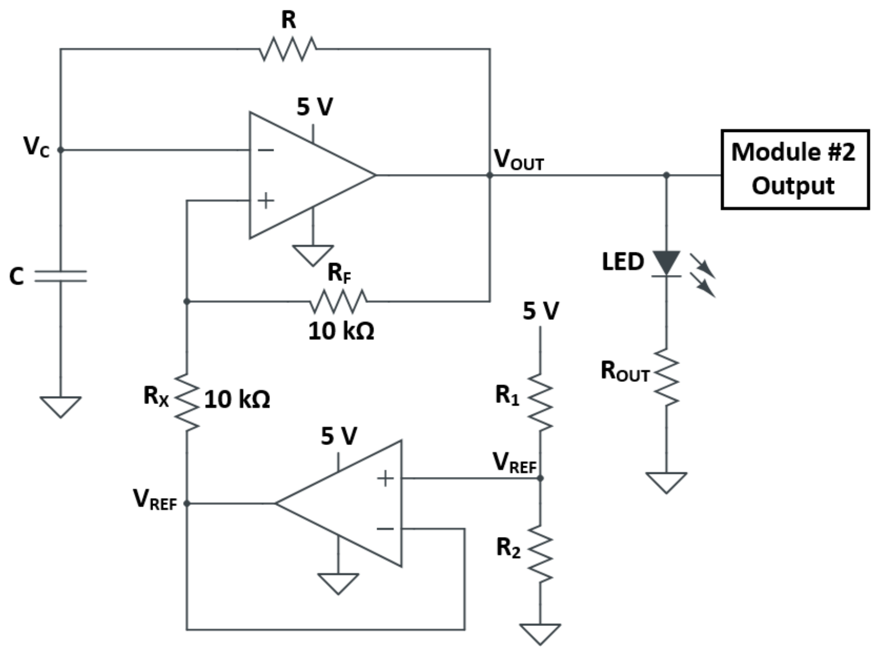

Figure 3: Circuit Diagram for Module 2, Relaxation Oscillator

Although the value of V_{REF} for this module is the same as Module #1, students were still asked to implement a separate voltage divider and buffer op-amp to avoid implementing a loaded voltage divider, where variations in load resistance will cause V_{REF} to also vary.

This module outputs a square wave with a 50% duty cycle which is used to switch the self-driven alarm buzzer on and off at around the same beep rate as a smoke detector. Equation 1 from [15] that relates the oscillation frequency f_0 to component values is provided to students:

$$\boldsymbol{f_0 = \frac{1}{2RC\, ln\left(1+\frac{2R_X}{R_F}\right)}} \tag{1}$$

This lab assignment contains the following design tasks:

- Using Equation 1, determine the capacitor value required to implement the oscillator with a value of f_0 in the range of 2 Hz to 6 Hz if R ≥ 10 kΩ. The use of standard capacitor and resistor values is also required and combinations are permitted.
- Calculate R_1 and R_2 so that V_{REF} = 2.5 V and the current flowing through both resistors is between 2 mA to 10 mA. In this case, students could use the results from Module #1.
- Calculate R_{OUT} so that the LED current is in the range of 4 mA to 6 mA if V_{OUT} = 5 V during a high output and the voltage drop across the LED is 1.7 V when turned on. The results from Module #1 could be used here again.

As a rail-to-rail capable op-amp, the MCP6004 datasheet states that the output voltage swing will be within 25 mV of the boundaries of both power supply and ground [13]. Students use oscilloscopes to simultaneously display the output and capacitor charge and discharge waveforms and verify these values. A discussion of the observed relationship between the capacitor voltage and changes in the oscillator output is expected in their lab reports.

Module #3: Infrared Optical Link, Design and Operation

The optical link consists of a small infrared LED which must be aligned tip-to-tip with a photodiode. The small photodiode current is converted to a voltage and amplified using a trans-impedance amplifier (TIA). However, the TIA output (V_{TIA}) is still an analog signal with a magnitude that depends on alignment of the emitter and photodiode and whether the beam path is obstructed. A binary signal with two possible states is needed from this module:

- V_{OUT} = 0 V: beam path is clear.
- V_{OUT} = 5 V: beam path is blocked.

These criteria are at odds with the TIA output characteristics, since blockage of the beam path will cause the photodiode current to drop to a minimum, resulting in $V_{TIA} \approx 0$ V. To solve this issue, a second inverting Schmitt Trigger is used for output from this module. An op-amp comparator could also be used here, but this lab assignment also covers the concept of hysteresis and how to reduce the possibility of rapid oscillation of a digital output between states when a noisy analog input signal hovers around the reference voltage level of a comparator. This module is separated into two sections, with Figure 4 showing the section containing the optical link and TIA and Figure 5 showing the inverting Schmitt Trigger. The two circuits are built and tested separately before being connected at node X.

Like the Schmitt Trigger used in the RC oscillator in Module #2, a non-zero reference voltage is required for the circuit in Figure 4. Equation #2 is used to determine the value of R_F based on the desired hysteresis value of the inverting Schmitt Trigger [15].

$$|V_{TH} - V_{TL}| = \frac{2V_S R_X}{R_F + R_X} \qquad (2)$$

In Equation #2, V_{TH} is the input voltage that causes the Schmitt Trigger output to switch from logic high to logic low. When the input voltage falls below V_{TH} to V_{TL}, the Schmitt Trigger output will switch from logic low to logic high. Since the sinusoidal signal used to test the circuit is specified to have a DC offset of 2.5 V, the same value must be used as the reference voltage V_{REF} since this value is midway between V_{TH} and V_{TL}. This lab assignment contains the following design tasks:

- Use Equation #2 to determine the value of R_F required to implement the inverting Schmitt Trigger with a hysteresis value between 0.5 V and 1 V, assuming R_X = 10 kΩ and V_S = 5 V.
- Calculate the value of R_E that will result in an emitter current between 15 mA and 25 mA if the voltage drop across the emitter is 1.3 V when it is turned on.

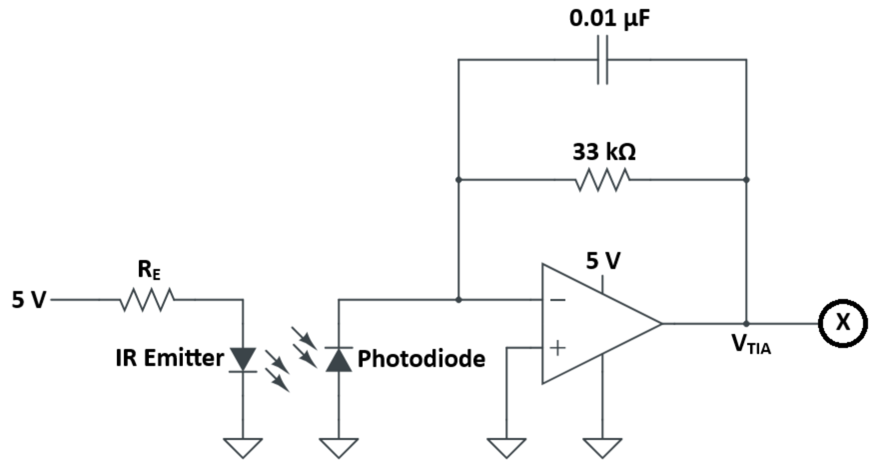

Figure 4: Optical Link and Trans-Impedance Amplifier section, Module #3

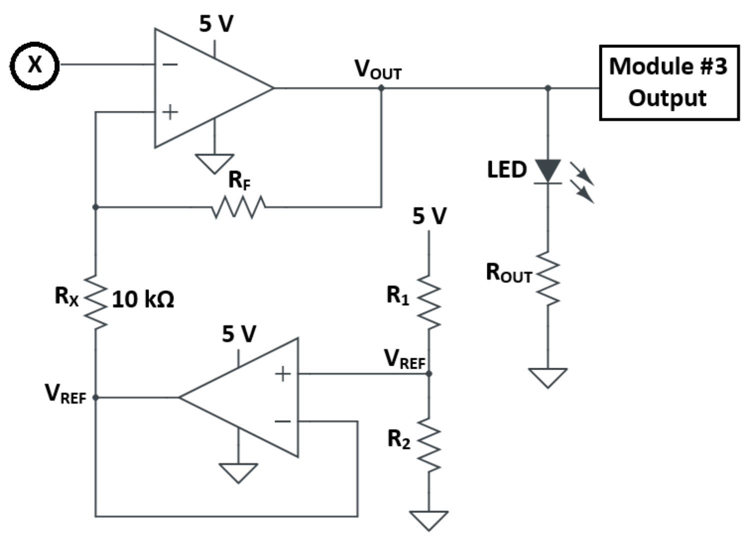

Figure 5: Schmitt Trigger and Reference Voltage Section, Module #3

This lab experiment was subdivided into two parts with students being asked to construct and verify the operation of the inverting Schmitt Trigger in Figure 5 before connecting its input to the output of the amplifier circuit in Figure 4. Hysteresis measurements are performed by connecting a waveform generator to the Schmitt Trigger's input. The test signal is a sine wave with a frequency of 100 Hz, amplitude of 2.5 V, and DC offset of 2.5 V. If the Schmitt Trigger is working properly, a distinct difference in the input voltage values at the intersections of the input and output waveforms can be seen on an oscilloscope display as shown in Figure 6.

Before connecting the TIA to the Schmitt Trigger input, students must verify correct operation of the optical link and TIA by measuring V_{TIA} with a multimeter while using an opaque object to intermittently block the emitter output from reaching the photodiode. Specifications for this output are:

- Beam path clear: $V_{TIA} > 4.5$ V.
- Beam path blocked: $V_{TIA} < 0.5$ V.

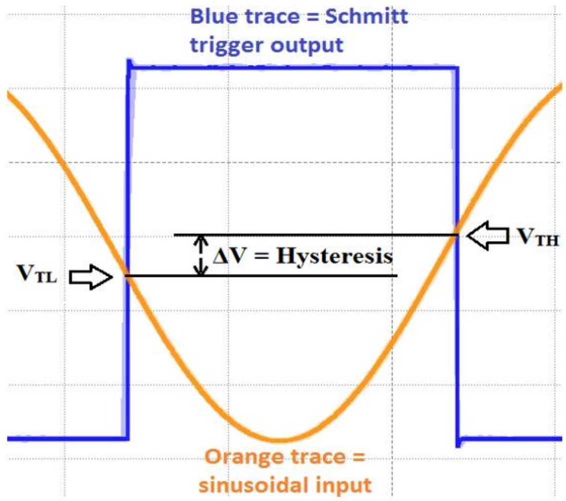

Figure 6: Example oscilloscope measurement of Schmitt Trigger hysteresis.

Students commonly encounter issues with $V_{TIA} < 2.5$ V when the beam path is clear. The most common cause is misalignment of the infrared emitter and photodiode. Both components must be aligned tip-to-tip with sufficient space left between them so that an opaque object can be used to block the beam. Another common issue is reversing the photodiode polarity which causes the theoretical output of the TIA to always be negative. Since all op-amps in this system are operated in positive single-supply mode, a negative output is not possible, and V_{TIA} will always remain around 0 V. Once the correct operation of both circuits has been verified, students are asked to connect the nodes marked X in Figures 4 and 5 and verify that the module output is correct when the beam path is blocked vs. clear.

Module #4: Signal Control, Design and Operation

This module takes the output signals from the other three modules and decides whether the oscillator signal from Module #2 passes through to the alarm buzzer. The system functionality requires that once the infrared beam path is blocked in night mode, the alarm buzzer will continue to sound regardless of whether the blockage is removed and/or the system goes into day mode. This feature is implemented using a CD4043 set-reset latch, where the conditions of “beam blocked” and “night mode” cause a true input to the “set” pin of the latch. The “set” condition can only be cleared by pressing the button, which is connected to the “reset” input of the latch. Figure 7 shows the circuit diagram for this module including locations of inputs from Modules #1, #2, and #3.

Three 2-input AND gates use the state of one input to determine whether the signal present on the other input passes through to the output of the gate. G_1 sends a logic high signal to the “set” input of the set-reset latch if the outputs of both Modules #1 and #3 are high, indicating that the beam path was blocked in night mode.

G_2 and G_3 both have one input connected to the oscillator signal from Module #2. The other input of G_2 is connected to the output Q of the set-reset latch. The oscillator output will appear at the output of G_2 if Q = 1. In the case of G_3, the oscillator signal will appear at this gate’s output if the beam path is blocked in day mode.

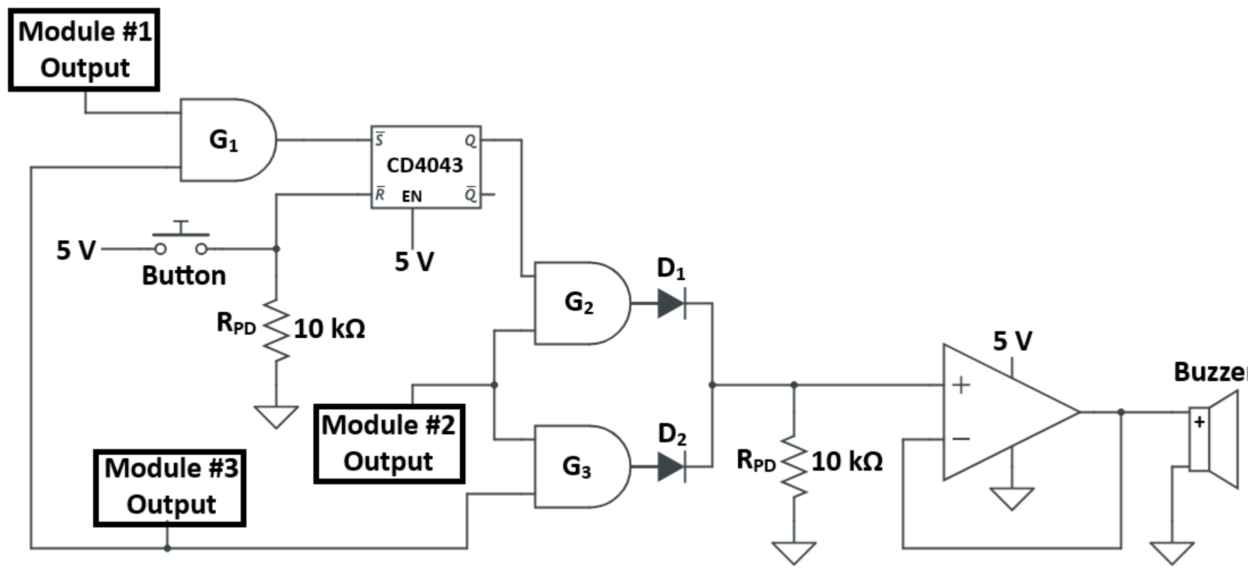

Figure 7: Circuit Diagram for Module #4

Two pn-junction diodes are used to isolate the outputs of G_2 and G_3 from each other. In day mode with Q = 0, the output of G_2 will always be 0 but the output of G_3 follows the oscillator signal when the beam path is blocked and the two outputs will be in conflict. The voltage drop across the forward-biased diode does not reduce the diode output below the minimum input voltage of 3 V required to turn on the buzzer [16]. The diodes could be replaced with a two-input OR gate, but diodes were used so that a conceptual discussion of their properties and behavior could be tied to a practical application, particularly for MECH majors who do not take any semiconductor electronics courses.

An additional discussion of the circumstances that require the use of pull-up and pull-down resistors is also covered in lecture. The buffer amplifier powering the buzzer is not required since the input current to the buzzer is substantially below the maximum output current from the AND gate. However, it is included to provide a discussion of the importance of ensuring that input and output power requirements and limitations are considered when connecting components together and how some components such as sensors have very limited power output capabilities.

No design tasks are assigned for this module. In lieu of this activity, students are asked to review the provided datasheets for the set-reset latch [17] and Quad 2-input AND gate [18] and answer a set of questions regarding device parameters such as maximum supply voltages and input/output currents.

Use of Portable Laboratory Equipment

The Fall 2019 semester marked the adoption of the Analog Devices ADALM2000 (M2K) Active Learning Module in all the Linear Circuits I laboratory activities [19]. This module combines all typical benchtop lab equipment such as function generators, oscilloscopes, logic analyzers, voltmeters, and DC power supplies into a single package that is slightly larger than a typical smartphone and connects to a personal computer with a USB interface. Previously, all students completed assignments using benchtop lab equipment within a 1-hour and 50-minute lab session.

The time limits induced a significant amount of stress and anxiety and hindered learning. To avoid losing sign-off points, students would often attempt to force circuits to work by randomly changing connections and hoping to get lucky as opposed to taking the time to perform systematic debugging. The use of the M2k module enabled students to work on the lab assignments on their own time which allows for deeper learning since the time pressure is significantly reduced.

An additional update to lab procedures was the expectation that all students would have spent some time working on the lab assignment before coming to lab, rather than starting from scratch at the beginning of the lab period and being required to finish everything by the end. This has also enabled an increase in the content depth of the lab assignments with the intention of giving students additional preparation for upper-division coursework.

To enhance the accuracy of AC measurements and give students experience with using typical BNC connector-based equipment, a BNC adapter board for the Digilent Analog Discovery 2 [20] and a set of oscilloscope probes were also included in the lab kits. The Analog Discovery 2 was a competing product which had the same equipment features and pinouts as the M2k module so the Digilent BNC adapter board could also be used with the M2k.

At the start of the Fall 2019 semester, the M2k module was priced at $99 plus tax and shipping, so students were asked to purchase their own modules. Realizing the cost burden on students, the department purchased a large quantity of modules during the Fall 2019 semester and has been loaning them out to students on a semester basis.

Survey Questions and Research Methods

Assessment of the impact of the series of project-based labs was conducted using Likert-scale survey questions which gave students five answer choices to each question. Institutional Review Board (IRB) approval was obtained prior to administering survey instruments. Participating students signed an informed consent form which stated that all data would be collected anonymously, participation was voluntary, and no reward or penalty would be applied to their course grades regardless of their responses or lack thereof. Surveys were given at both the beginning and end of the Fall 2019 semester to enable an evaluation of the change in perceptions toward course content from all majors enrolled in the course. The initial survey was given at the first lab meeting during the second week of the semester, and the final survey was given during the last lab meeting before Finals Week. Both surveys were distributed and collected as hard copies in lab sessions instead of being conducted online, which maximized response rates.

At the beginning of the semester, a total of 104 students completed the start-of-semester survey. However, 13 students had stopped attending during the semester for various reasons, leaving a total of 91 students completing the end-of-semester survey. Students were told that surveys would be anonymous, so no identifiers were used on survey instruments. This means that start-of-semester surveys from students who were not present to complete the end-of-semester survey could not be removed from the datasets, leaving unequal before-and-after sample sizes for both MECH and MECA majors as shown in Table 1.

Table 1: Survey Completion Rates by Major		
Major	**Start of Semester**	**End of Semester**
Computer Engineering	$n = 15$	$n = 15$
Electrical Engineering	$n = 24$	$n = 24$
Mechanical Engineering	$n = 43$	$n = 34$
Mechatronic Engineering	$n = 22$	$n = 18$

Table 2 shows the survey questions regarding student opinions about course topics that were administered at the start of the semester, along with the Likert-scale response options for each question. An additional question (not shown) asked students to select which major they had declared so that responses could be segregated and analyzed by major.

Table 2: Start-of-Semester Survey Questions	
Question	**Response Options**
#1A: How relevant/applicable do you think the material covered in Linear Circuits I is to your major?	Very relevant
	Somewhat relevant
	Neutral
	Somewhat irrelevant
	Completely irrelevant
#2A: How would you rate your level of interest in the material/topics covered in Linear Circuits I?	Very interested
	Somewhat interested
	Neutral
	Somewhat disinterested
	Not at all interested
#3A: How motivated do you feel to study the material/topics covered in Linear Circuits I?	Very motivated
	Somewhat motivated
	Neutral
	Somewhat unmotivated
	Not at all motivated

Table 3 shows the survey questions regarding student opinions about course topics that were administered at the end of the semester, along with the Likert-scale response options for each question. In comparison to Table 2, Questions #1A and #1B are identical. Questions #2A and #2B still focused on student interest, but Question #2A asked students about their baseline level of interest at the beginning of the semester while Question #2B asked students about the **change** in their level of interest after completing the application-based labs. Due to this difference, Questions #2A and #2B do not have the same response options.

Questions #3A and #3B focus on student motivation, both at the beginning and end of the semester, and have the same response options. Question #4 asked students to comment on their experiences using the Analog Devices ADALM2000 Active Learning Module to complete lab assignments both during scheduled lab sessions and outside of lab.

Table 3: End-of-Semester Survey Questions

Question	Response Options
#1B: How relevant/applicable do you think the material covered in Linear Circuits I is to your major?	Very relevant
	Somewhat relevant
	Neutral
	Somewhat irrelevant
	Completely irrelevant
#2B: How would you rate the **change** in your level of interest in the material/topics covered in Linear Circuits I as of right now versus at the beginning of the Fall 2019 semester?	Much more interested
	More interested
	No change
	Less interested
	Much less interested
#3B: After designing and assembling the infrared security system in lab, how motivated do you feel to study more advanced concepts based on material covered in Linear Circuits I (either in a future course or on your own time?)	Very motivated
	Somewhat motivated
	Neutral
	Somewhat unmotivated
	Not at all motivated
#4: How did the use of the Analog Devices ADALM2000 Active Learning Module (M2K) affect your overall learning experience in the EECE 211L labs? Did you find the use of portable equipment beneficial/useful, or would you rather have performed all lab work during scheduled lab sessions using benchtop equipment at no additional cost?	Open-ended answer: fill in blank text box with handwritten response.

Survey Results and Data

Figure 8 shows the responses to Question #1A (start-of-semester survey) and Question #1B (end-of-semester survey) respectively: *"How relevant/applicable do you think the material covered in Linear Circuits I is to your major?"* A much higher response in the "Very relevant" category can be seen on both surveys when comparing CpE, EE, and MECA majors to MECH majors.

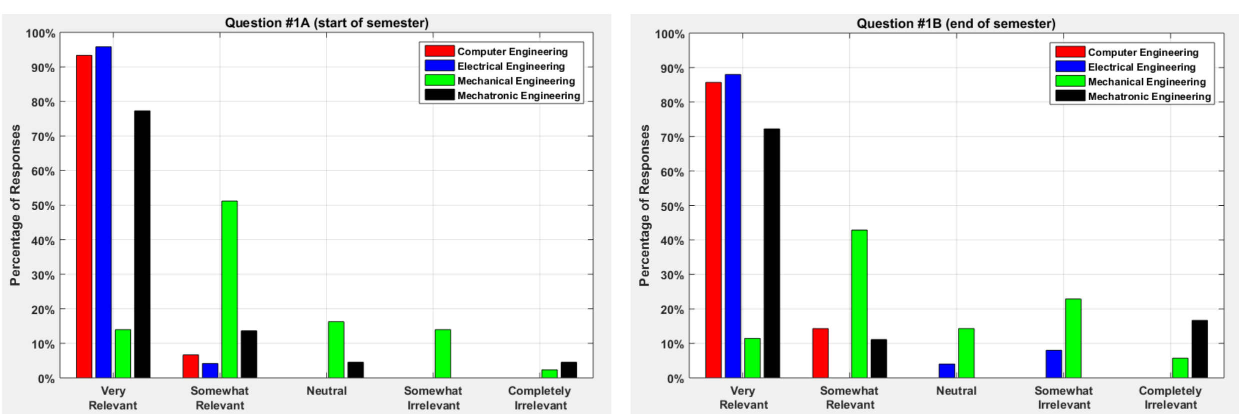

Figure 8: Responses to Questions #1A and #1B.

Figure 9 shows the responses to Question #2A (start-of-semester survey): *"How would you rate your level of interest in the material/topics covered in Linear Circuits I?"* and Question #2B which forms the follow-up question on this topic for the end-of semester survey: *"How would you rate the **change** in your level of interest in the material/topics covered in Linear Circuits I as of right now versus at the beginning of the Fall 2019 semester?"* A significant positive impact appears for all majors on Question #2B, with a large majority of students from all majors selecting "More interested" or "Much more interested."

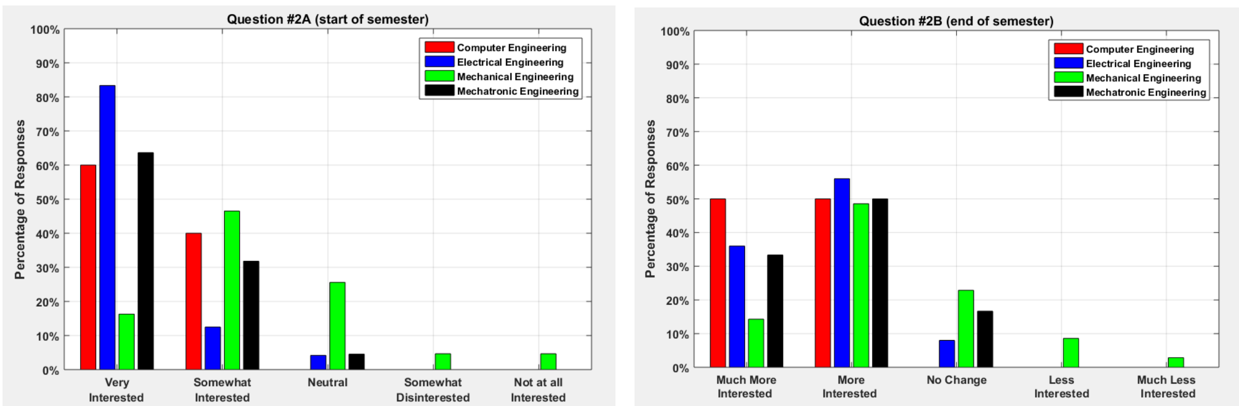

Figure 9: Reponses to Questions #2A and #2B.

Figure 10 shows the responses to Question #3A (start-of-semester survey): *"How motivated do you feel to study the material/topics covered in Linear Circuits I?"* and Question #3B which forms the follow-up question on this topic for the end-of semester survey: "*After designing and assembling the infrared security system in lab, how motivated do you feel to study more advanced concepts based on material covered in Linear Circuits I (either in a future course or on your own time?)"* The majority of EE, CpE, and MECA majors continue to respond in the "Very motivated" and "Somewhat motivated" categories at the end of the semester, while a distinct trend toward lower motivation overall can be seen in the MECH majors.

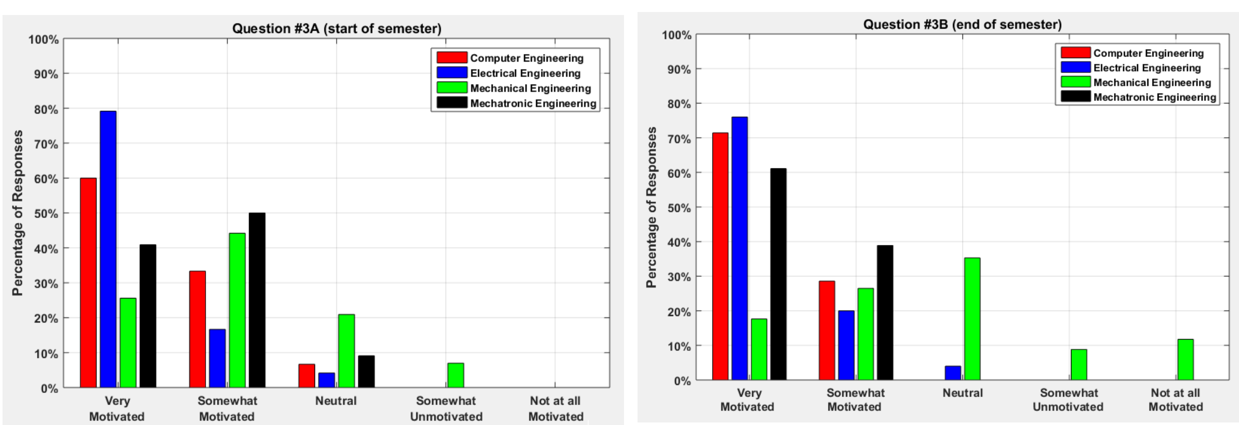

Figure 10: Responses to Questions #3A and #3B.

Statistical Analysis of Survey Responses

Since the lower-division sequences of courses required for the major in both EE and CpE are identical at Chico State, survey responses for both majors were combined. Significant differences exist in lower-division courses for MECH and MECA majors, so these responses were left separate. Evaluation of the internal consistency of survey responses was performed by calculating Cronbach's alpha for these three major categories on both surveys, with results shown in Table 4. All alpha values are above the minimum of 0.7, indicating that survey questions have sufficient internal consistency [21].

Table 4: Values of Cronbach's alpha		
Major	**Start of Semester survey**	**End of Semester survey**
Computer Engineering and Electrical Engineering	$\alpha = 0.803$	$\alpha = 0.82$
Mechanical Engineering	$\alpha = 0.964$	$\alpha = 0.958$
Mechatronic Engineering	$\alpha = 0.864$	$\alpha = 0.766$

Shapiro-Wilk tests were conducted on responses to each survey question, segregated by the major or combination of majors shown in Table 4, to determine the level of normality and whether parametric or non-parametric statistical analysis methods would be more appropriate. Table 5 summarizes the results of all Shapiro-Wilk tests.

Table 5: Results of Shapiro-Wilk Tests		
Major	**Question**	**Result**
Computer Engineering and Electrical Engineering	#1A	$W = 0.233$, $p = 5.12\text{x}10^{-19}$
	#2A	$W = 0.579$, $p = 2.24\text{x}10^{-9}$
	#3A	$W = 0.609$, $p = 5.5\text{x}10^{-9}$
	#1B	$W = 0.388$, $p = 1.43\text{x}10^{-11}$
	#2B	$W = 0.738$, $p = 5.59\text{x}10^{-7}$
	#3B	$W = 0.579$, $p = 2.24\text{x}10^{-9}$
Mechanical Engineering	#1A	$W = 0.848$, $p = 5.49\text{x}10^{-5}$
	#2A	$W = 0.853$, $p = 7.45\text{x}10^{-5}$
	#3A	$W = 0.857$, $p = 9.22\text{x}10^{-5}$
	#1B	$W = 0.874$, $p = 0.001$
	#2B	$W = 0.863$, $p = 0.000556$
	#3B	$W = 0.898$, $p = 0.00395$
Mechatronic Engineering	#1A	$W = 0.503$, $p = 1.4\text{x}10^{-7}$
	#2A	$W = 0.677$, $p = 1.01\text{x}10^{-5}$
	#3A	$W = 0.773$, $p = 0.000198$
	#1B	$W = 0.55$, $p = 2.23\text{x}10^{-6}$
	#2B	$W = 0.807$, $p = 0.001907$
	#3B	$W = 0.624$, $p = 1.19\text{x}10^{-5}$

The results of the Shapiro-Wilk tests show that $p < 0.05$ for responses to all survey questions, indicating that none of these datasets have a normal distribution and are better treated as non-parametric for statistical analysis. Student populations at the start and end of the semester were treated as independent because there was no way to remove start-of-semester surveys from students who did not complete both. Mann-Whitney U and Kruskal-Wallis H tests were used to look for any statistically significant differences between start-of-semester and end-of-semester surveys. These tests were not run on Questions #2A and #2B due to the differences in response options. For Mann-Whitney U, a statistically significant difference is present when $p < 0.05$, and the same criteria is used for Kruskal-Wallis H, in addition to $\chi^2 > 3.841$, with this critical value corresponding to $\alpha = 0.05$ and 1 degree of freedom (df = 1) [22, 23]. Results of Mann-Whitney U and Kruskal-Wallis tests are shown in Table 6, with rows showing questions which have a statistically significant difference between surveys highlighted in beige.

Table 6: Results of Mann-Whitney U and Kruskal-Wallis H Tests

Major	Questions	Mann-Whitney U	Kruskal-Wallis H
Computer Engineering and Electrical Engineering	#1A and #1B	$p = 0.2187$	$\chi^2 = 1.5375$, $p = 0.215$
	#3A and #3B	$p = 0.7613$	$\chi^2 = 0.0963$, $p = 0.7563$
Mechanical Engineering	#1A and #1B	$p = 0.2779$	$\chi^2 = 1.189$, $p = 0.2754$
	#3A and #3B	$p = 0.02429$	$\chi^2 = 5.098$, $p = 0.02395$
Mechatronic Engineering	#1A and #1B	$p = 0.6285$	$\chi^2 = 0.252$, $p = 0.6159$
	#3A and #3B	$p = 0.1534$	$\chi^2 = 2.082$, $p = 0.1491$

The only statistically significant change shown in Table 6 is the comparison for Questions #3A and #3B in the Mechanical Engineering group relating to student motivation. However, the response percentages per option in Figure 10 show a decrease instead of the expected increase. Table 7 shows the changes that occurred on a percentage basis for the number of responses in each response option. A shift toward lower motivation occurs overall, with decreases in “Very motivated” and “Somewhat motivated” responses and increases in the other three categories.

Table 7: Changes in response rates for Questions #3A and #3B, Mechanical Engineering

	Very motivated	Somewhat motivated	Neutral	Somewhat unmotivated	Not at all motivated
Start-of-semester	25.58%	44.19%	20.93%	6.98%	0%
End-of-semester	17.65%	26.47%	35.29%	8.82%	11.76%
Change	-7.93%	-17.72%	+14.36%	+1.84%	+11.76%

The factor most likely responsible for lowered motivation is the difficulty and frustration often encountered by students learning abstract circuit theory. Linear Circuits I courses at Chico State commonly have a DFW rate in the 20-30% range every semester regardless of course instructor. Students often underestimate how much practice is required to become moderately competent at circuit analysis; engagement is often limited to watching the instructor give examples on the board in class and copying homework assignment solutions found online without working through the problems. At the time of this study, Chegg and CourseHero were two frequently used online sources for solutions, but ChatGPT and similar AI-based tools are now preferred. This type of passive engagement often results in poor exam scores which can easily influence opinions about lab content, course topics, and even the EE and CpE majors themselves. However, lab assignments such as those described in this study give students opportunities to actively engage with the course material and increase their sense of accomplishment, since the final result is also a product of their own design effort.

Another potential factor in the lowered motivation of MECH students is the lack of any MECH-specific content in the lab assignments to show how these areas are related. However, including such content is problematic because significant lecture time would be needed to provide EE and CpE majors with the background on MECH topics needed to complete the lab assignments, which takes away from the time available to cover required course content. The effects of fatigue and burnout from heavy course loads and other personal obligations may also have a negative influence, the degree of which was not investigated in this study and is unknown.

No statistically significant changes in opinions about relevance of course content to the major or student motivation were noted for the EE/CpE and MECA groups. Students enrolled in these three majors already know that they will need to take multiple courses related to Linear Circuits, Electronics, and Embedded Systems. The responses to Questions #1A and #3A at the beginning of the semester already skewed heavily toward "Very relevant" and "Very motivated," so there was no room for any significant increase.

Student Feedback for Analog Devices ADALM2000 (M2k) Module

An additional open-ended survey question was given to gather feedback from students about their experiences using portable lab equipment that gave them the option to work on lab assignments outside of scheduled lab times. Students were asked to comment on whether they found the use of portable lab equipment to have a positive impact on their learning experiences in the labs and whether they would have rather performed all lab assignments during regularly scheduled lab sessions using benchtop equipment. The following are a sample of positive responses received from the survey question:

- "It was extremely beneficial to have the portable equipment. I think this allowed me to get more hands-on experience with the tools that I would have otherwise had, had I needed to depend on an open and available lab."
- "The M2k was great, taking it home and working out the labs there saved lots of time."
- "The M2k module was very useful for me, especially when working off campus. I prefer to use the M2k rather than the large benchtop equipment."

- “The portable equipment was useful for working at home with my partner. This was better than doing it all in lab.”

Nearly all the negative feedback was addressed toward the acquisition cost of the M2k module. Negative feedback in this area was often mixed with positive feedback with respect to the usefulness of the portable equipment as can be seen in the following comments:

- “The ADALM2000 was beneficial because we were able to finish most labs before the lab period. The added cost was not so great.”
- “Cost is a bit high considering I likely will not use it for another class. Having the ability to test prior to class time is nice though.”
- “The M2k module was very useful since it allowed my lab partner and I to work outside of scheduled lab time. It did hurt a little to have to purchase the module, however it is a worthwhile investment for future classes.”

Discussion and Conclusions

Reworking the last four laboratory assignments in an introductory Linear Circuits course gave students more opportunities to perform circuit design tasks and implement a realistic practical application instead of only building circuits according to diagrams and confirming theoretical calculations by making measurements. The variety of components included in the system introduced students to non-linear applications of operational amplifiers as well as digital logic elements and diodes. Use of a microcontroller would greatly lower component counts and simplify the system, but covering related topics in lecture would take too much time away from required course content since Linear Circuits I has no Embedded Systems or programming prerequisites.

Electrical, Computer, and Mechatronic Engineering majors already had very high levels of motivation and interest at the beginning of the semester as expected, since Linear Circuits is a core course in these majors. As a result, there was little room for motivation and interest to increase any further, and no statistically significant changes were noted for these majors. For Mechanical Engineering majors, lower levels of motivation and interest than other majors were already present at the beginning of the semester, and a statistically significant decrease ($p < 0.05$ for both Mann-Whitney U and Kruskal-Wallis H) occurred at the end of the semester instead of the expected increase. However, 64.7% of Mechanical Engineering majors indicated that they were more interested in circuits and related topics at the end of the semester than they were at the beginning, which is a very positive result. It is likely that this interest extends only to learning about how circuits and electronics are used in electro-mechanical systems on a conceptual level and does not include learning how to perform the related analysis and design required for implementation. This is not considered a significant issue because the intent behind the redesign of lab assignments was to give students more opportunities to perform design tasks and see how theory is used to implement practical applications, not to convince them to all switch to Computer or Electrical Engineering if they had declared other majors.

This study represents a preliminary investigation into the impacts on student motivation and learning when practical applications and design activities are included in labs. However, the impact of this study is limited by several factors. The small sample sizes precluded formation of a control group, so it was not possible to perform the same surveys with students enrolled in lab sections that had no changes to lab assignments. The impact of small sample sizes was further exacerbated by eight fewer Mechanical Engineering majors and four fewer Mechatronic Engineering majors taking the end-of-semester surveys. Follow-up on the same student population as they progressed through upper-division Circuits and Electronics courses would have been beneficial but difficult due to the constant rotation of different faculty teaching those courses every semester. However, the COVID-19 pandemic and shift to 100% virtual instruction for all labs and lectures in the middle of the Spring 2020 semester dashed all chances of any meaningful follow-up with this student cohort. Very few students found this shift to have a positive impact on their learning experiences, and comparisons between online and in-person courses would not have been meaningful, especially with lockdowns, economic impacts, and pandemic deaths creating multiple additional confounding variables. The extreme increase in workload caused by transitioning all courses and labs to fully online in the middle of the semester with only a few days' notice also meant that it would not have been reasonable to request participation from other faculty in continuing this research longitudinally.

The Analog Devices ADALM2000 (M2k) module was appreciated by students because it enabled them to work on lab assignments and other projects without having to find a time when lab rooms were available. The most consistent negative feedback was regarding the module's cost of $99 during the Fall 2019 semester. Since the M2k now retails for over $240 as of the time of this writing [19], requiring students to purchase the module with their own funds has the potential to create significant Socioeconomic Equity issues with disproportionate impacts on lower-income students. MECH students would also have little use for the module after completing Linear Circuits I due to the lack of upper-division circuits courses required for their major. If labs are scheduled in-person and on campus, justification for requiring students to purchase the modules is reduced further, especially if lab rooms with a full complement of benchtop equipment are available.

Since the M2k module's cost has more than doubled since Fall 2019, departments considering purchasing a large number of modules to loan to students should determine whether they can absorb the ongoing cost of replacing modules that are either returned non-functional or not returned at all. Placing holds on student accounts in these cases will not be 100% effective, because there are multiple reasons that students may drop out without any plans to return. There is also the risk of equipment being discontinued, such as the Digilent Analog Discovery 2 which was an identical product to the M2k but is now out of production [24].

Despite these issues, the use of portable instrumentation should be strongly considered for circuits labs that are taught online. Circuit simulation platforms such as Tinkercad and LTSpice have their uses, but software simulations are not a direct replacement for hands-on experience with physical components. This equipment enables students to get the same hands-on experience with circuit construction, measurement, and troubleshooting that they would receive during in-person instruction.

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