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Introductory Circuits and Electronics Remote Labs: Design, Implementation, and Lessons Learned

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Abstract

In this paper we describe our re-design and delivery of an Introduction to Circuits and Electronics core undergraduate course at the University of Colorado Boulder. The course integrates take-home laboratory experiments designed to foster deep learning, enhance retention of complex concepts, and improve academic outcomes. The course was delivered for the first time during the Fall 2023 semester. In this paper, we present a number of remote laboratory experiments that were designed and assigned to students pursuing undergraduate degrees in Electrical Engineering, Electrical and Computer Engineering, Aerospace Engineering, and Biomedical Engineering. We discuss how we approached the challenges of delivering the same course content to a wide range of undergraduate students pursuing different majors. We share the lessons learned, successes and areas for future improvement of the course.

Why we developed take-home hands-on laboratories.

Our Electrical, Computer, and Energy Engineering (ECEE) Department at the University of Colorado Boulder offers a number of service courses to other departments, including, the sophomore circuits course, ECEN 2250: Introduction to Circuits and Electronics. The course covers the fundamental principles of circuit modeling and analysis including, ideal circuit elements, Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL), circuit analysis methods such as node voltage method, mesh current method, Thevenin and Norton equivalent circuits, the step, and natural responses of circuits with combinations of R, L and C elements, OpAmps, phasors, impedance, and analysis of simple filter circuits using voltage division.

Prior to the Fall 2023 semester, the ECEN 2250 course did not have a laboratory component. The first-time students got their hands on a physical circuit was in a subsequent course, ECEN 2270: Electronics Design Lab (EDL), in which students build an autonomous car that navigates a route defined by a line on the floor. While ECEN 2270 is a hands-on laboratory course, the exercises are all directed toward building a product, not exploring the fundamental principles of circuits.

When we were asked to teach the ECEN 2250 course for the first time, we believed that it was important to include a hands-on laboratory experience. However, we were constrained in not being able to change the course from a 3 to a 4-credits, could not change the meeting pattern of three, 50-minute sessions per week, and did not have physical laboratory space available for the 138 students to perform the hands-on laboratory assignments. In addition, given the high density of content in the established curriculum, we did not feel it was practical to sacrifice lecture time to do laboratory exercises in the classroom, even for one session per week.

During Covid, we had experimented in other courses such as Printed Circuit Board (PCB) Design, EDL and Capstone, by creating take-home lab kits that allowed students to perform laboratory experiments using equipment that fit into a shoebox. Lab sessions were literally conducted over zoom.

The take-home hands-on labs.

We decided to leverage this approach to create a series of take-home hands-on laboratory assignments that could be completed in a dorm room and given as part of the homework assignments. We cut by half the number of problems assigned in the homework and added two short labs each week. Generally, for a 3-credit course, we expect students to work about nine hours outside of class studying the textbook and working on homework problems. We decided to dedicate four of these hours to the new hands-on labs as part of the homework assignments.

A course kit containing commonly used elements, such as roles of wire, pliers, solderless bread board, resistor and capacitor component kits and a small box of electronics components including OpAmps, transistors, MOSFETs and a 555-timer chip (Lab 11: bonus lab) was built and made available for purchase to students enrolled in the course. Each kit also contained a digital multi meter (DMM). An example of the kit contents is shown in Figure 1. We selected the DMM Astro AI DM130B which we purchased in bulk on Amazon for $19. All students were required to purchase this kit for $120. To defray these costs, we used an open-source textbook at no cost to the students.

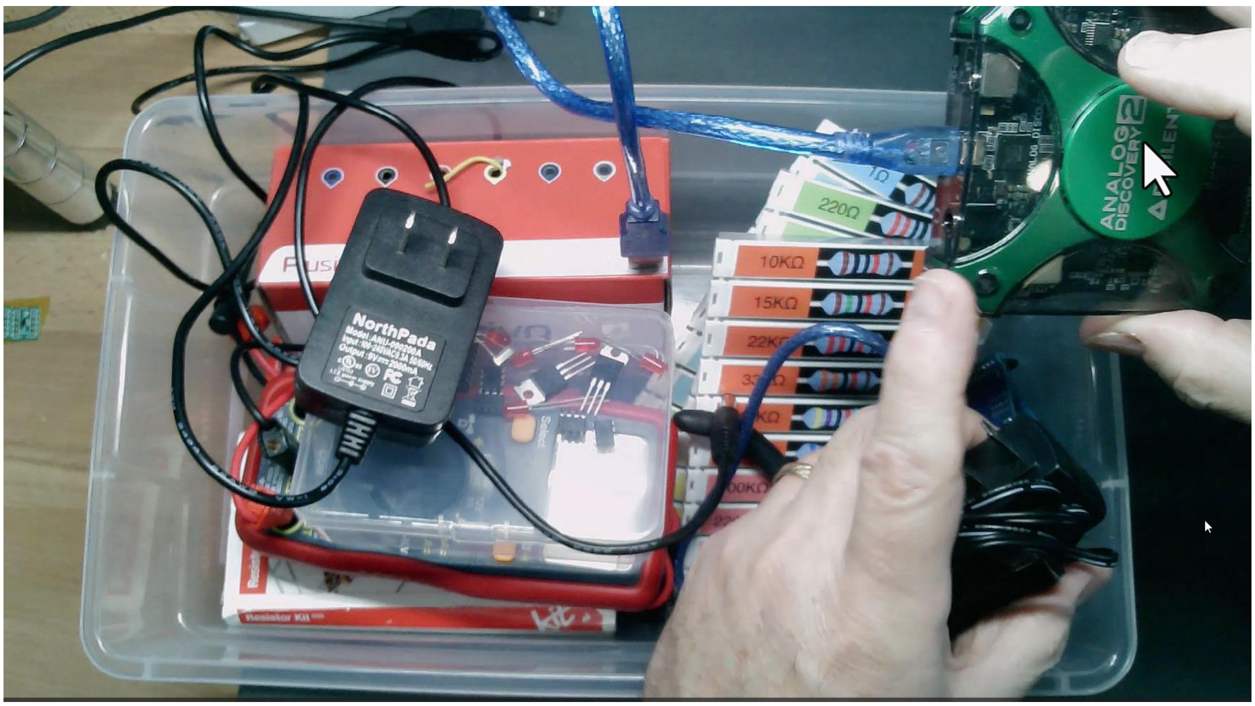

Figure 1. Example of the take-home kit, taken from the video.

In addition, all ECEE undergraduate students are given a Digilent Analog Discovery 3 scope to keep and use in other courses. Non-ECEE students enrolled in ECEN 2250 were allowed to rent an AD3 scope for the semester for $25.

A series of 10 labs with two experiments each were created that demonstrated the principles introduced in the lecture. A 15-to-30-minute video was created for each lab part that showed how to complete each experiment using only the parts in the kit. The videos were posted on a google drive and the lab manual contained a link to each video at the beginning of the description of the experiment. All the important information about the lab and how to perform the measurements and interpret the results were included in the lab. The lab manual had prompt questions and the description of what should be reported in the lab report.

All measurements were performed with either the DMM or the AD3 scope. Students were asked to complete the labs at home as homework and then write up a brief 2-page lab report taking pictures of their circuits and including screen shots of the scope traces. These were graded by the TAs.

In addition to the hands-on measurements, some of the labs also used LTSPICE to simulate circuits. In particular, the labs used LTSPICE to simulate the step response of RL, RC and RLC circuits and plot the impedance profile of RLC circuits in series and parallel. When possible, we had students build a circuit, measure the step response, bring this measurement into LTSPICE and compare directly the measured voltage to the simulated voltage.

The following is a list of the eleven labs and the two experiments in each lab we ended up with:

Lab 1: exploring the lab kit and testing the DMM and scope.

Lab 2: testing the continuity of the solderless breadboard and building a simple resistor, LED circuit.

Lab 3: testing ohm's law and measuring really small resistances.

Lab 4: how not to blow up a resistor and measuring the output Thevenin resistance of power supplies.

Lab 5: building an OpAmp follower circuit and a transimpedance amplifier for a photo diode.

Lab 6: building a capacitance and inductance meter in LTSPICE and exploring the equivalent capacitance and inductance of series and parallel circuits.

Lab 7: measure and simulate the step response of RC circuits.

Lab 8: measure and simulate the step response of an RLC circuit.

Lab 9: simulating and measuring the impedance of ideal and real RLC circuit elements in the frequency domain.

Lab 10: simulating and measuring the Bode response of low and high pass RC filters.

Lab 11: bonus lab: design, construct and measure a 555 astable oscillator circuit.

What did not work.

In addition to informal anecdotal feedback from students during office hours, we used two google surveys to solicit feedback from the entire class. This identified two initial problems. First was hiccups in the lab kit. Creating the kit and finalizing the BOM a month before class started was enough time to acquire the parts and create the kits. However, with the large number of kits that were required for this course and for ten other labs courses in the department, mistakes always happened. A part in stock was substituted for a part in the BOM when the new parts ran out, or some parts were missing, or the vendor supplied the wrong IC and this was added to the kit without verifying. All the kits were not available to students until the middle of the second week.

Even though a check list of correct parts was provided to students, and the videos had the specific parts displayed and illustrated, students unfamiliar with the kits with no previous lab experience, had difficulty figuring out what was an error in the kit from what was something they were doing wrong. Not having adequate in-class contact between instructors and students to quickly identify kit problems wasted some student’s time.

Of course, many students waited until the day before the labs were due to open up their kit to discover missing items. This created a delay between identifying the problem and getting it fixed. For some students who got their kits late, they were not able to complete the first lab until the end of the third week. They didn't get feedback from their first lab report until the end of the fourth week. This was too long a feedback cycle.

In the future, our electronics store (Estore) that distributes kits, will be stocked before the course starts and we will require students to purchase the kit and complete the first lab in the first week. This way these start-up problems will be resolved by the end of the first week.

The second problem we uncovered through the survey was about the excessive time students spent on the labs. Initially, we included four short experiments in each lab, anticipating students would spend 3-4 hours completing the labs. We grossly underestimated the time students would need to complete the labs. After four weeks, the overwhelming response from students was these labs were taking closer to 6-8 hours to complete. We revised all the future labs and reduced them each to only two experiments per lab, so it was under 4 hours to complete, including watching the videos. In the second survey sent out, there were no reported issues with any of the labs.

While the TAs graded the lab reports, we noticed in spot checking some of the reports that they were clearly written using ChatGPT. The sentence structure was complex, filled with expressive adjectives and while there were a lot of words, they often contained a low density of information. We sent out a warning to students that anyone using Chat GPT for the labs reports would be given a zero and no future labs would be accepted unless they convinced the staff they would not use ChatGPT for future labs. This seemed to stop this habit.

For our 138 enrolled students, we had seven TAs, including juniors, seniors and a few graduate students. This meant there were about 20 students assigned per TA. Grading the homework problems, the take-home lab reports and holding in-person office hours exceeded the allocated 10 hours a week available for most of the TAs. This meant that though they thought they were experienced in circuits, they did not have time to view the lab videos and perform the labs themselves.

They quickly discovered that they were unable to answer most of the questions students asked about the labs. This was because they did not understand the measurements or the equipment, and that even though they had taken the Circuits I or equivalent course, they could not apply the principles to the specific labs. Our upper division students and many of the graduate students coming into our MSEE program did not have adequate lab experience to know how to debug real world problems.

For example, a common problem students encountered was that they forgot to power the opAmp with the +/- 5 v supply available on the AD3. As part of the debug process, we always recommended measuring the voltage on the power rails as part of the debug process. Students did not read this step and TAs did not think about it. Another common problem was selecting the wrong resistor which throws off the voltage expected in a voltage divider or in setting the gain of a circuit. Double checking component values was on the list of things to check when in debug mode, but students and TAs did not pay attention to the list.

This is a difficult problem to fix. We were unable to increase the number of TAs for this course, as even seven was seen as too many for a class size of 138. We had a restricted pool of TA candidates to draw from and many did not have any lab experience. At the beginning of the course, not all the labs had been developed. However, now that the lab manual and all the lab videos are completed, we will require all TAs to view the videos and complete the labs for themselves over either the winter or summer break before the class starts. In addition, we will draw heavily from the students who have already taken the hands-on labs as future teaching assistants.

What worked

At the end of the semester, we conducted a survey and reviewed feedback forms. The students' responses about the hands-on labs fell into a bimodal distribution. Some students felt they were too much work, and they did not gain anything of value from them. The other distribution of students found them of great value and loved the labs. They felt they learned more about circuits from the labs than from the homework problems.

In particular, the lab we got the most positive feedback on was building an RLC circuit and comparing its step response to a simulated RLC circuit. The students then adjusted the value of the L element in LTSPICE to get the best agreement. Figure 2 shows the circuit students built and the measurement and simulation initially brought into LTPSICE before the L value is optimized.

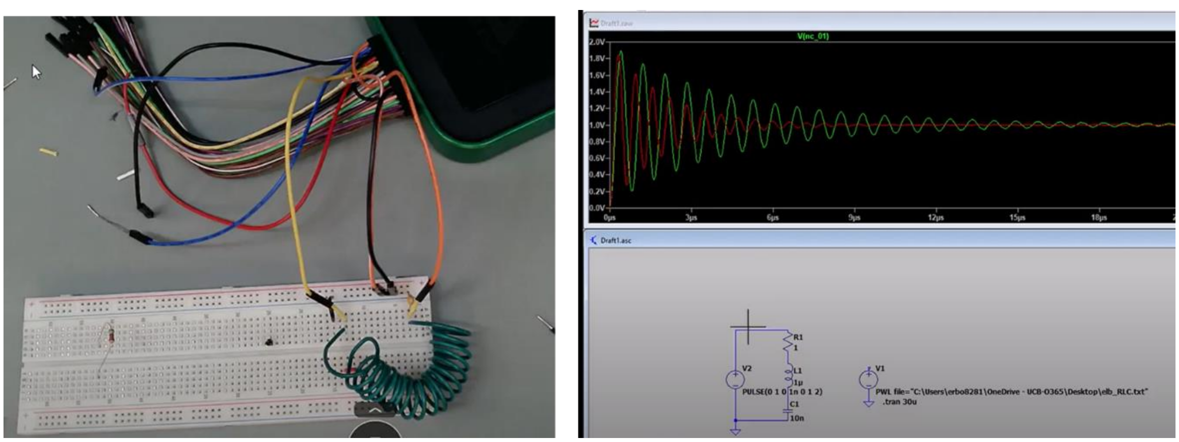

Figure 2. Left: the actual circuit students build, right: the measured data in red, imported into LTSPICE from the AD3 measurement and the simulated RLC response in green, before optimizing the inductor value. After optimization, the measurement and simulation are right on top of each other.

This lab enabled students to wind their own coil and calculate the loop inductance using a simple online calculator. They constructed the circuit, driven by a square wave source, saved the transient voltage measurement in a csv file, imported it into LTSPICE and compared the simulated response of an ideal RLC circuit to their measured voltage.

The overwhelming response was astonishment that they could get such great agreement between the physical thing they built and measured, and the ideal circuit they simulated. This demonstrated how powerful simple models and analysis were to describe real world circuits.

Creating the labs

The take-home hands-on labs were designed during the summer before the class began. This involved planning the labs to be consistent with the curriculum, creating the BOM, acquiring the inventory for up to 138 kits, assembling the kits, distributing the kits, writing the lab manual, and recording the videos.

We decided to record videos for the first five labs and hold off on the last five labs to get feedback from students. Even so, getting ready for the first day involved about 200 hours of preparation time. This broke down to about 100 hours of planning and 100 hours of execution. Once the overall outline for each lab was completed and all the parts finalized, it took about 10 hours to complete each lab. This included experimenting with what worked, creating the videos, and writing the lab manual.

Once the labs were released and we began to get feedback, we modified the labs to reduce the time spent and to simplify the lab report with clear instructions of what questions were to be answered and what measurements displayed in the report.

This meant that an additional 10 hours a week had to be spent in completing and distributing the remaining five labs during the semester, always keeping at least one week ahead of the class.

Conclusion

We developed a series of labs which could be completed at home, a part of the homework experience of sophomores in an introductory Circuits I course. Most of these students had no previous experience using a DMM or a scope and were able to master these instruments and perform sophisticated measurement-simulation correlation experiments by the end of the course. Even with the initial start-up problems, the take-home hands-on labs created for our Circuits I course were a success. As instructors, we felt the content delivered and the experience offered to students was worth the effort invested by the instructor, the TAs and the students.

The final impact will be evaluated over the next few semesters as many of these students take the follow-on courses in the curriculum.

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