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Teaching Tips - Special Issue (COVID)

Teaching Electronic Circuit Fundamentals via Remote Laboratory Curriculum

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CHALLENGE STATEMENT

The course "Electrical Fundamentals" (EF) is a core requirement for all undergraduate students in our biomedical engineering program. The curriculum introduces general principles of device development for electronics-based bioinstrumentation, comprehensively covering foundational acquisition concepts for bioelectric signals. Laboratory-based learning modules provide hands-on experience with circuit fundamentals. We here introduce our six-hour lab curriculum for distance learning, which we developed in response to the COVID-19 outbreak.

The learning outcomes for the lab curriculum are twofold. The first learning outcome enables students to design and analyze basic electric circuits of resistors, capacitors and operational amplifiers (op-amps). The second learning outcome teaches students to interpret signal characteristics using core bioinstrumentation equipment, including oscilloscope, function generator and multimeter. Moreover, at this stage in the EF students' curriculum, the concept of filters is still in progress. Therefore, the lab curriculum builds up and deepens the theoretical concept of low- and high-pass filters through practical experimentation.

Traditionally, our EF labs are taught in studio-style on campus where groups of students learn to use oscilloscopes, function generators, multimeters and breadboards. Here, the challenge is to replace these precision instruments with affordable, reliable and portable components that students could safely and robustly assemble at home. Moreover, the material needs to be engaging to nurture student interest. Furthermore, some of our students have limited access to internet. To enable accessibility to all students, labs need to accommodate asynchronous learning. Finally, due to initial uncertainty during the COVID-19 outbreak, the lab curriculum needs to be designed such that single students can complete lab exercises independently, as opposed to working in groups.

NOVEL INITIATIVE

The remote lab curriculum is taught synchronously in three two-hour sessions. A ratio of 10 students per teacher is desirable for effective real-time troubleshooting. Therefore, for our large undergraduate cohort, we recruit "peer mentors," in addition to the EF instructor and teaching assistants. Peer mentors are outstanding undergraduate students who have previously taken the EF class, who are being mentored by the principal instructor, and who are now helping their peers with hands-on circuit troubleshooting.

Lessons utilize the Arduino Uno, a versatile tool that can be robustly employed in undergraduate engineering education ranging from foundational instruction to project-based learning and student competitions.[4,5,9] Here, the Arduino replaces three traditional pieces of laboratory-learning equipment, (1) the multimeter, (2) the function generator and (3) the multichannel oscilloscope.[1] We provide students with a customized Arduino kit, including breadboard and all circuit components. In addition, each student needs access to a laptop, internet and webcam.

For optimal learning outcomes, the current curriculum encourages synchronous learning. However, lab instructions are self-contained, enabling students to follow them independently should poor internet con-

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nectivity necessitate asynchronous learning. At the beginning of each lab session, the instructor demonstrates the following principles via synchronous teaching: how to assemble the circuit, how to upload code to the Arduino chip, how to use SerialPlotter to view and interpret time series data read in by Arduino, and how to further analyze these time series data in Excel and Matlab.

Following initial instruction, students then independently work through the lab instructions. Work is self-paced, but students are encouraged to finish within the two-hour time frame of the lab. To facilitate timely completion and to avoid having students get stuck on their own, the lab instructions provide milestones, frequently prompting students to submit photos of their circuit as well as numerical values or plotted time series, using private messaging to the instructional team. As problems arise, teachers then trouble-shoot with the students using synchronous video chat. Concepts taught by each milestone are completed before a new concept is introduced, reducing cognitive load and helping learning and retention.[6]

The curriculum consists of three take-home laboratory exercises. Lab 1 instructs students on component tolerances[7] and reviews basic circuit knowledge. Students learn how to use the Arduino as a multimeter to measure voltages, currents, and verify resistances of parallel-serial resistor circuits. In Lab 2, the Arduino functions both as function generator and multi-channel oscilloscope. Students learn about charge and discharge behavior of resistor–capacitor (RC) circuits and the time constant τ, laying the foundation for the concept of low-pass filtering. Lab 3 leverages sonification to teach active amplification using op-amp circuits. Op-amps are a challenging new concept for the majority of EF students. To motivate students, here, the output of the circuit is fed into a loudspeaker, allowing students to experience the tuning of RC circuits by hearing how the circuit filters sound, as well as listen to how loud music sounds when it is processed by op-amp circuits. All three lab exercises, as well as all components needed, are comprehensively explained in the laboratory instructions (see Supplements).

To illustrate the overall concept of Arduino-based learning of circuit fundamentals, we next explain Lab 2 in detail. The learning goal of Lab 2 is to understand charging and discharging of resistor–capacitor (*RC*) circuits. Students learn to use the voltage traces over *R* or *C* to estimate and verify the time constant τ, while also building up intuition about temporal and spectral filtering properties of the circuit. To illustrate temporal filtering properties of a serial *RC* circuit, students record both the generated input pulses and the voltage output of the circuit over *C*. Students then plot the charging and discharging curve, take fiduciary markers and estimate the decay constant τ. Students discover that for sufficiently slow pulse rates, the capacitor has enough time to charge and discharge. However, this behavior breaks down as the pulse rate increases. To estimate the maximum pulse rate that the *C* can robustly follow, students increase pulse rate on the function generator while monitoring the peak to peak voltage of the capacitor, $V_{C_{pp}}$, on the oscilloscope. Students then plot $V_{C_{pp}}$ as a function of pulse rate and observe how the $V_{C_{pp}}$ amplitude decreases with increasing pulse rate.

Traditionally, studio-style instruction in Lab 2 uses a function generator to send voltage traces as inputs to the circuit, consisting of pulses of variable repetition rate. Students then trace the circuit with a multichannel oscilloscope. Here, the Arduino functions both as multichannel oscilloscope and simplified function generator, using the same sampling period for both, with a precision of $\pm$ 50 μs. Specifically, using our custom code for Lab 2, the Arduino delivers a train of rectangular pulses (0 or 5 V, with 50% duty cycle and 100% modulation depth, from Arduino pin A1). An output voltage, across *R* or *C*, is simultaneously read in by the Arduino, sample by sample (from pin A0). The voltage traces of both the generated pulse train and the recorded measurements are then sent to the student's laptop via serial port. SerialPlotter, which is part of Arduino IDE on the laptop, then plots both voltage traces sample by sample, generating the type of trace that students would traditionally observe on a multi-channel oscilloscope. The numerical values of these voltage traces can then be copy-pasted into Excel or Matlab where students can use them to run detailed analysis, including estimating peak-to-peak voltages and time constants of the circuit.

Prior to uploading the code onto the Arduino chip, students can modify four parameters in the code: (1) the sampling period, (2) the total number of samples that the Arduino records and sends out (this limits the number of samples plotted, preventing the plot from rolling), (3) the pulse period (this adjusts the pulse widths of the output pulse train), and (4) the initial state of the capacitor (charged vs discharged). On their personal computer or laptop at home, every student opens the Arduino IDE, inspects the customized code and programs it onto the Arduino chip with the "upload" IDE function. To prevent lack of coding skills from interfering with the learning goals of the remote lab curriculum, students do not need to code. However, they are encouraged to inspect the Arduino code and special breakout sessions are offered to explain the code to interested students.

REFLECTION

The new remote training curriculum was implemented during Spring and Summer 2020 with two different instructors and 70 students. All students were able to complete all sections of all labs. Due to the *ad hoc* nature of this learning intervention, no formal learning outcome data were collected. Instead, student satisfaction was gathered from informal feedback, suggesting that the remote lab curriculum resulted in self-reported skill gains and overall high satisfaction.

A number of students commented that it felt empowering to build and trace circuits at home, with affordable materials, as compared to using expensive high-fidelity devices at the university. Consistent with prior work on enriched learning, the inclusion of a sonification experience *via* their own self-made loudspeaker to validate circuit functionality was particularly rewarding to many students.[11] Going forward, we will routinely use Arduino-based learning as a first step before introducing the professional oscilloscope and function generator devices.

Of note, at the onset of the pandemic, not all of our students had access to webcams. Instead of live, webcam-based circuit trouble-shooting, these students emailed us photographs of their circuits. However, we discovered that, aside from being an inefficient use of instructor time, email slows down the learning momentum.[10] We now mandate webcam-enabled laptops for our course.

Our undergraduate cohort includes a high proportion of underrepresented minority students, providing the kind of environment where utilization of peer mentors is a particularly promising method for nurturing BME undergraduate students in their professional and personal development.[8] Here, peer mentors allowed for effective trouble-shooting during labs. Moreover, peer mentors made students more comfortable to ask basic questions as well as help maintain a sense of community during social isolation due to the COVID-19 crisis. Furthermore, the peer mentors were able to deepen their knowledge of electronics by learning through teaching their peers. Both the students in class and the peer mentors reflected very positively on this experience.

In summary, when student access was limited during COVID-19, a novel Arduino-based intervention enabled remote teaching while satisfying original learning outcomes of the EF course. Students were able to measure key parameters of serial-parallel resistors, RC-circuits and op-amp circuits. Experiential learning via a custom Arduino kit demonstrated to students how they can build simple electronic circuits at home, while maintaining accessibility of EF teaching to all students. A lab format of initial instruction followed by prompting for "fill-in-the-blanks" milestone answers proved effective for remote learning with synchronous trouble-shooting of circuits. The use of sonification and peer mentoring further enriched student motivation. Informal course evaluations suggest that many students benefitted from the remote lab curriculum. Future work will need to formally test teaching effectiveness.[2,3]

ELECTRONIC SUPPLEMENTARY MATERIAL

The online version of this article (https://doi.org/10.1007/s43683-020-00008-x) contains supplementary material, which is available to authorized users.

AUTHORS' CONTRIBUTIONS

NA and AI developed the labs. AI and NA taught the labs. AI wrote the manuscript.

FUNDING

None.

DATA AVAILABILITY

Supplementary material is enclosed to this submission. All lab instructions are available via github.

CODE AVAILABILITY

All code is available via github.

SUPPLEMENTAL MATERIALS

All lab instructions and software tools are available on GitHub.[1]

CONFLICT OF INTEREST

None.

INFORMED CONSENT

The corresponding author accepts responsibility for releasing this material on behalf of any and all coauthors.

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