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During the COVID-19 pandemic, I took the opportunity to redesign our introductory circuitry labs to be based on the Arduino microprocessors. The versatility and portability of these devices afforded an opportunity to introduce students to concepts of voltage, current, and resistance within an exploratory context. The course is the second semester of a year-long introductory calculus-based sequence at a small liberal arts college. The 16 students were predominantly members of our Early College elite public high school, many of whom are already envisioning STEM career paths. The course schedule has three classroom sessions a week, as well as a weekly laboratory experiment. For these experiments, I developed a scaffolded sequence of six laboratory activities, choosing an Arduino board that was specifically designed for education. The students' enthusiasm and engagement increased dramatically with their mastery of this technology.

The function of Arduinos

Arduinos present an inexpensive opportunity to bring electronics design to the beginning student.[1] These circuit boards were originally developed by Massimo Banzi and team to allow beginners and tinkerers to create multiple-purpose circuits without having to rebuild circuits completely to execute a new function.[2] The educational power of these tools has been widely recognized for physics and engineering classes as well as for the home enthusiast. They have been used to support inquiry-based advanced lab sequences,[3] modeling framework labs,[4] and project-based physics labs.[5] It is possible to use them with smartphones to record and process experimental data.[6] The Arduinos' compact size, low cost, and flexibility made them particularly attractive for a lab sequence during the COVID-19 pandemic, as I had to require students to carry out some experiments at home on short notice. Each student received an Arduino, a simple electronics kit, and a classic multimeter. With this equipment, the students could carry out most of the labs either at home or on campus.

There are many models of Arduino boards with different features, depending on the intended usage, but all following similar layouts. Most boards contain a 5-V DC output pin, a 3.3-V DC output pin, multiple ground pins, six analog voltage input pins, and 12 digital pins that can be configured for input or output. Although any model could be used for these experiments, I found the Maker UNO by Cytron[7] to be particularly well suited for introductory circuit labs. In addition to being cheap, it has many simple circuits that a beginner would want to execute already built in. Each digital output pin has already been linked to a built-in light-emitting diode (LED). In addition, a speaker has been connected to pin 8 and a built-in button to pin 2. With a standard Arduino, to learn how to switch an LED on and off, the student must wire up an external LED (in the correct polarity and in series with a resistor to limit current). I wanted the first experience to focus on how to get the Arduino to carry out simple tasks, and not have the student have to worry (yet) about concepts like polarity, resistance, complete circuits, limiting current, or how the holes in a breadboard are connected. The Maker UNO allowed beginners to get familiar with the functioning of the unit before trying to wire up any circuits, which can avoid short circuits, blowing LEDs, and any number of other mistakes that can damage the device.[8] None of the boards used in my spring 2022 class were damaged.

Another advantage to using the Arduinos for introductory circuit labs is that all the programs to carry out the necessary tasks come standard with the free software development environment. Functions to carry out specific tasks (such as "play a note" or "respond to the button being pushed") can be copied and pasted into new programs without needing to write everything from scratch. By the end of the first session, a student with no prior experience was able to get the board to play the Imperial March from Star Wars, blinking a different light for each note, in response to a button press. Scaffolded tasks introduce programming concepts such as for loops (to turn lights on and off in sequence or play a melody), serial output for numerical or graphical monitoring, and if/then blocks. My students had already been modeling dynamical systems numerically with VPython,[9] and they found it easy to grasp the syntax of the Arduino C-based code.[10]

Description of lab sequence

Once the students have learned how to program an Arduino, they are ready to begin learning about circuits. For Lab 2, I stepped away from the Arduino to have them develop a working model of resistance by testing Ohm's law. I used variable-voltage power supplies that we already had in stock (the cheap kits did not include such power supplies). The Arduinos cannot provide variable DC voltage on their own.[11] It's therefore easier to have students begin with standard power supplies and multimeters to learn to test for a linear relationship between voltage and current with a collection of devices. In addition to resistive circuit elements, I had them test an incandescent bulb and an LED, because it's important for them to see that not everything follows Ohm's law. It was also helpful to have them play with a large-scale variable resistor, to see that by sliding the contact point back and forth, they changed the resistance of the device by altering the length of the wire that the current flows through. These activities helped them model resistance as a relationship between applied voltage and resulting current.

For Lab 3, I wanted them to combine their understanding of Ohm's law and programming the Arduino to create an ohmmeter. Their experience with the visible operation of the variable resistor put them in a good position to understand the inner workings of a potentiometer. I tasked them to take a standard resistor from the previous week (for which they have a well-measured resistance R) and connect it in series with the potentiometer between 5 V and ground, as shown in

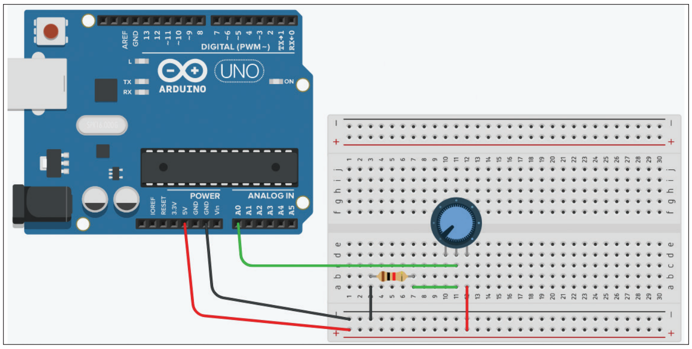

Fig. 1. Schematic diagram for using the Arduino as a multimeter in Lab 3. The 5-V pin is wired to one of the side pins on the potentiometer (red lines). The middle pin connects to a resistor with known resistance (green line). The other side of the resistor is connected to ground (black lines). The third pin of the potentiometer is not used. The potential difference from ground across the known resistor is measured at pin A0 (green line). The ratio of this voltage to the known resistance yields the current in the circuit. The voltage drop across the potentiometer divided by this current reveals the resistance of the potentiometer. These numbers can be calculated and displayed in the serial monitor or graphed in the serial plotter as the student turns the dial on the potentiometer. Image created with TinkerCAD.

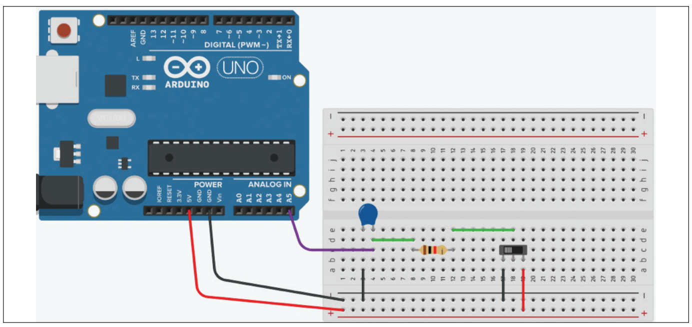

Fig. 2. Schematic diagram for testing the charging/discharging of the RC circuit. Red lines represent wires connected to the 5-V pin, while black lines represent wires connected to ground. The positive side of the capacitor (blue) is read at pin A5 with the purple wire, and the green wires connect the resistor to the capacitor and to either 5 V or ground, depending on the setting of the toggle switch. See Ref. 13 for more detail on this experiment. Image created with TinkerCAD.

Fig. 1. By measuring the voltage U at the midpoint between the two elements, they calculated the current $I = U/R$ and the resistance of the potentiometer: $R_{pot} = (V - U)/I$. On the software side, they learned how to print the voltage from a particular analog input pin to the serial monitor (or plot it to a time series graph). They could print or plot these numbers and then watch the output change as they turned the dial on the potentiometer.[12]

Once they turned their Arduino into an ohmmeter, Lab 4 required them to use their Arduino circuit to measure the resistances of other items (assuming, of course, that those items are indeed ohmic resistors). They replaced the potentiometer with a photoresistor and saw how the resistance of the device changed with illumination. They used the inverse-square law to test whether the relationship between light intensity and resistance was linear (it was not). They could also relatively quickly test hypotheses about how resistors combined in series or in parallel (they carried out these experiments before we covered that material in class, so they did not have a prediction ready to hand and had to reason a hypothesis out themselves). By building their own ohmmeter, they could hold an operational definition of resistance in their heads while applying the concept to different situations, without the "magic" of a device simply giving them a number, as a multimeter would.

In Lab 5, I tasked them to apply their skills to modeling the charging and discharging of a capacitor. This experiment was written up effectively by Galeriu et al.,[13] so I will not explain it in detail here. A possible circuit layout is presented in Fig. 2, using a switch to either charge or discharge the capacitor as desired. By this point in the semester, the classroom part of the course had caught up with the labs, so they knew to test for an exponential relationship with a timescale of RC. By choosing R and C to give reasonable time constants, they could easily see the charge/discharge cycle on the monitor as they flipped the switch.

By copying and pasting the serial output into a spreadsheet, they could test whether the voltage at the readout pin was linear with time on a semilog scale and therefore exponential. They could then use the same experiment design to study the behavior of multiple capacitors in series or in parallel.[14]

As a final task, I wanted the students to integrate their Arduino work with other lab equipment, to grapple with questions of experiment design as well as ways that uncertainty can be hidden inside measuring devices. Our department uses the Vernier suite of electronic lab sensors,[15] and Vernier sells adapters[16] that enable their sensors to be connected to a standard breadboard. They provide instructions for how to wire these adapters to an Arduino,[17] as well as a code library of standard functions for reading and interpreting the voltages from their various sensors. With access to the code, I required students to change the value for the speed of sound in the code for the "Motion Detector," so they could see how the device changed a time delay to a distance measurement. The code for the force probe uses a linear relationship between the measured voltage and the output force numbers. I required students to apply a sequence of known forces and test this relationship. These activities forced the students to think about how the process of taking data inherently includes uncertainty, even when it looks like the sensor is printing out unambiguous numbers.[18]

The students can also program the Arduino to not only record data but respond to the data it receives. I challenged the students to brainstorm ways they might use sensors and processors together, like to record times when a photogate[19] is tripped or to sound an alarm if a Geiger counter rate gets too high. Students enjoyed the creative freedom to choose their own sensors and design their own experiments. For my purposes, it was sufficient to use Labs 6 and 7 for these activities: Lab 6 focused on analog devices such as force probes and light sensors, while Lab 7 had them working with digital devices such as radiation counters and photogates. These activities could easily be extended into further weeks, and they could also lead smoothly into a longer-term student-directed experimental project.

Student reactions and future plans

In both their lab reports and the anonymous end-of-semester evaluations, the 16 students were uniformly enthusiastic about these experiments. They appreciated the mix of directed tasks to learn the syntax and concepts and open-ended encouragement to explore their own questions: "I think other professors should make sure to allow students to test different ideas they have (as long as they're safe) outside of the required lab procedures. Doing so will let them build intuition for the device in general, rather than just follow the instructions for assignments." They were inspired by the potential for developing their own ideas: "the Arduino has a ton of creative freedom that can be explored. … There are a massive number of other gadgets that can be linked to it. I think it does a great job at integrating coding and electricity for beginners: the coding language is relatively simple, and the circuits became relatively easy once I got the hang of them." Another student shared, "Using the Arduinos has made me a stronger programmer, and it also has a lot of possibilities, as I can control what I want my circuit to do rather than just build it. I like how I can change the code to have the Arduino beep or blink if a certain threshold is passed [on an external] sensor, or see the live results and data from the Arduino's wide variety of built-in sensors, building upon previously created code or writing my own."

It was clear they perceived the tasks as interesting and useful, and I am looking forward to developing these labs further in future iterations of the course. It has long been a tradition in our department to allow students to carry out their experiments at times of their choosing. The flexibility and low cost of most of the equipment afforded the students the possibility of executing many of these experiments at home, which extended this empowerment. Some students found it difficult to collaborate remotely with their lab partners, since each of them were building their own circuits. It was challenging to analyze and debug their partners' circuits through a video feed. In contrast, sometimes the applications were easier or more fun for them to develop when they could create the tools in their own homes rather than the laboratory. They could measure the resistance of household objects or find ways that sensors could interact with their daily activities. Although I am not sure I will *require* them to work at home, it remains an intriguing option, if we need it.

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11. Although several of the digital output pins can produce an "analog output" that can dim an LED or run a motor at slower speeds, this is achieved by changing the duty cycle of a digital square wave, not by reducing the level of a DC voltage. You can "fake" a traditional resistance experiment this way, as a standard multimeter cannot respond fast enough to see the variation, and will therefore react to the AC wave as if it is an adjustable DC voltage, but that forces you either to be dishonest with the students about what's really going on or to try to help them understand concepts of AC current and duty cycle this early in the course. However, if a variable power supply is simply not available, this could be a workable substitute.
12. Although Arduinos do not provide built-in software data analysis tools, there are ways to pass recorded data to processing software beyond just copying and pasting into LoggerPro. See, e.g., Daniel Nichols, "Arduino-based data acquisition into Excel, LabVIEW, and Matlab," *Phys. Teach.* **55**, 226–227 (2017).
13. Calin Galeriu, Charyl Letson, and Geoffrey Esper, "An Arduino investigation of the RC circuit," *Phys. Teach.* **53**, 285–288 (2015).
14. Even if the exact relationship is not tested, it is very easy to see whether the time constant increases or decreases if they replace the capacitor with two or three identical elements in series or in parallel.
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18. See, e.g., Andrew J. Haugen and Nathan T. Moore, "A model for including Arduino microcontroller programming in the introductory physics lab," arXiv:1407.7613 [physics.ed-ph] for ways to structure modeling of the data-taking process.
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