Play-doh'ing with Circuits

Lesson Type: Module
Target Grade: Elementary/Middle School
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Semester: Spring 2017

Brief Overview

Circuits have become an integral necessity for our everyday lives. But how exactly do they work? This lesson will present a thorough walkthrough of just that. First, we will build a gigantic model circuit as a class to provide a foundation for thinking about what causes a circuit to work or not. Next, we will use conducting and insulating play-doh to test our model, to build circuits of our own, and to complete circuit challenges. Finally, we will explore just how cool circuits are by putting together real electrical components to create a piano made out of bananas!

Teaching Goals

At its core, the purpose of this lesson is to communicate:
- Circuits create a "river bed" that electrons can flow through to provide power.
  - Developing an intuition for electron flow and the paths that they can take through a given circuit.
- Open vs. Closed vs. Short circuits.
- Parallel vs. Series circuits.
- Conduction vs. Insulation.
- (Voltage, Current, Resistance.)
  - Ohm's Law: $V = IR$.
- With circuits, we can create some very fun technologies!

Agenda

- Module 0: Giant Model Circuit (10-15 min)
- Module 1: Play-doh'ing with Circuits (20-25 min)
      [Adapted from Wilcox, BEAM Fall 2013 and Roth-Johnson & Nguyen, UCLA BEAM]
- Module 2: Banana Piano! (20-30 min)

Throughout the lesson, continue to guide students in referring back to module 0 to help them understand why a certain circuit works or to help them debug a faulty circuit.

Module 0: Giant Model Circuits

Introduction
As a class, students will construct a giant circuit model. Mentors will help students in visualizing the flow of electrons in circuits and use this visualization as a basis for teaching concepts covered in later modules.

Materials
- 1 tennis ball per student
- 1 trash can / bin per class (find in classroom)
- 1 stack of books / obstacle per class (find in classroom)

Background/Notes for Mentors
In an electric current, moving electrons in a wire carry electric charge. We simplify this to mean that electrons themselves flow around the circuit and participate in the phenomena of current, voltage, and resistance. These ideas are further explained in the Background/Notes for Mentors section of the next module.

Material to Teach
Students will learn that circuits are analogous to river beds through which electrons can flow. Through this, they will see why circuits must be closed in order to work and will explore what happens when circuits are arranged in series vs. in parallel.

Procedure
Recommend constructing as a class. Your site may also choose to instead have a few student volunteers help demonstrate in front of the class or to split the class into multiple small groups and have a mentor lead each small group in building the model.

Also note that the evolution of our model circuit is a great example of the engineering process and how we take our current design, identify its flaws, present a solution, and repeat this analysis.

1. **Trash can golf.**
    a. **Unobstructed.** Give each student a tennis ball. Have the students stand in a line perpendicular to a bin placed a short distance away. When you say go, have students try to roll their tennis balls into the bin. They should not be allowed to throw because this will make your task of obstructing their shot much more difficult later. Count and record on the board how many tennis balls made it in. (You may choose to perform multiple trials if you wish.)
    b. **Slightly Obstructed.** Next, place a small stack of books or other obstacle between the line of students and the bin. When you say go, have students try to roll/toss their tennis balls into the bin. Count and record on the board how many tennis balls made it in.
    c. **Increasingly Obstructed.** Continue to increase the obstacles between the line of students and the bin and repeat this process until no more tennis balls make it into the bin.
    d. **Debrief.** Explain that the tennis balls represent electrons. Ask what happened when a small resistance was imposed. How about when the resistance was so great that no

tennis balls made it into the bin?

2. **Human circuit.**
   a. **Open linear circuit.** Collect back all the tennis balls and tell the students that we will now make a human circuit model. Have students stand in a line and have them link arms (or stand shoulder-to-should at the very least LOL). Have a mentor at one end start passing tennis balls down the line. Emphasize that students can only hold one tennis ball at a time and that they can't drop them! Also emphasize that the tennis balls can only flow in one direction! Soon, the tennis balls will start to build up at the end of the line and the student at the end should be confused about what to do with them all. Point out that this is clearly a problem and ask if there are any solutions to resolve this open circuit.
   b. **Closed circuit.** Now have the first and last people of the linear chain to link arms to close the circuit into a circle or closed loop. Now have the mentor pass a few tennis balls down the line and see that the electrons continue to circulate without problem. Again, emphasize that the tennis balls can only flow in one direction around the circuit. This observation is important in the next module since students will see that the LED's we are using will only work when it is connected in the proper direction.
   c. **Parallel circuit.** Now introduce a side path for the circuit such that one student now branches into two possible students and for another student to rejoin the two branches later downstream (you might have to unlink arms and just stand shoulder-to-shoulder at this point.) Now run the circuit again. What happens when the electron reaches the fork? Approximately half the electrons should go down one path while the other half travels down the other path. When the fork closes, the normal current is restored.

   Note: all of these circuits were short-circuits since there was never an opportunity for a voltage drop. We will extend this analogy when we introduce short-circuits in the next module.

Module 1: Play-doh'ing with Circuits

Introduction
This module will be the main mechanism of teaching this lesson. We will take the concepts we modelled in the previous module and implement them using real electrical components. To make it easier and more fun to hook together, we will be using conductive play-doh instead of wires.

Materials (per group)
- 1/3 batch of Conducting dough *
- 1/3 batch of Insulating dough *
- 2 Ziplock Bags (to seal/contain doughs)
- 2 of 9V battery
- 3 of Alligator clip connectors and wires
- 3 of 10mm LEDs

* To be prepared by Logistics before site.

Background/Notes for Mentors
The battery provides a voltage and by the time the circuit loops around, that voltage must be all gone.

Each LED acts as a resistor and so the appropriate amount of voltage drop occurs to satisfy the aforementioned constraint. The reason for this is that since energy is conserved, $\Delta U_{battery} + \Delta U_{resistor1} + \Delta U_{resistor2} + \ldots = 0$. And since by definition $\Delta U = Q\Delta V$, dividing out charge Q from the first equation, we obtain the loop rule, $\Delta V_{battery} + \Delta V_{resistor1} + \Delta V_{resistor2} + \ldots = 0$, and complete this proof.

Consequently, when there are two LED's in series (one after the other), then each LED is only responsible for half of the necessary voltage drop. When two LED's are in parallel, each LED must be responsible for the fully amount of voltage drop since no matter which path is used, the condition that the voltage must be all gone by the time it returns to the battery must be satisfied.

Similarly, in parallel circuits, since each LED has a greater voltage drop than each when in series, at each LED, a greater amount of energy per unit of charge is left behind (since voltage is defined as energy per unit of charge). This is why the LED's in a simple parallel circuit glow brighter than those in a simple series circuit.

There are elegant and exact parallels between electrical energy and gravitational potential energy. Voltage is a difference in potential and can be thought of the "gh" in "U = mgh". Similarly, current is the flow rate of electrons and can be thought of as the "m" in "U = mgh". (More precisely, "m" corresponds to charge, but this exact analogy involves mass flux, which we will not discuss here.) Finally, resistance is analogous to frictional losses of an object falling. In both cases, frictional forces dissipate energy as heat, which is why a falling meteor or heavily wired computer can become hot.

Voltage, current, and resistance can be difficult concepts to grasp. Teach the different kinds of circuits first, then help students develop and intuition for electron flow and the paths that they can take. Finally, if students understand that, then take it a step further by formalizing their intuition into these three concepts. Given this parallel with gravitational potential energy, there are many analogies that can be used to explain these three concepts. Coming up with or searching online for such analogies that help explain one or more of these concepts is left as a pre-lab exercise. Two of these analogies will be presented in decal to supplement yours. Among these, choose your favorite to share with your students (too many analogies may cause even further confusion).

Material to Teach
Students will implement the modifications we made to our model in Module 0, learn the difference between conduction and insulation, and complete several circuit challenges to apply what they've learned!

Procedure
Note that LED's only work in one direction! If a seemingly correct circuit does not work, try flipping the LED. The positive end of the battery should feed into the longer prong of the LED
  1. **Introduction.** As a class, we will create several circuits together, determine whether they work or not, and refer to the illustration from Module 0 to understand why.
      a. **Closed Circuit.** Distribute materials and ask students to make two separate lumps out of their conductive play-doh. Plug both of the two wires from the battery pack and plug one into each of the lumps of dough. Take the LED and stick its prongs into the two balls of dough so as to bridge them. Make sure that the dough balls do not touch each other. (This scenario is explored in part c.) This is the standard closed circuit that we

ended with in Module 0. (If the circuit is setup as shown and it does not work, try flipping the LED.)
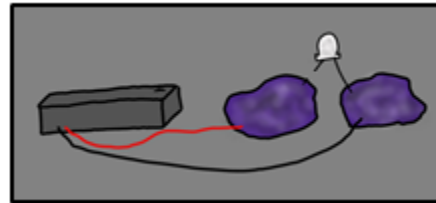
    i. Does the LED light up?
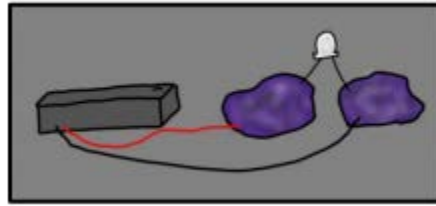
(Source: UCLA BEAM.)

b. **Open Circuit.** Pull one of the prongs of the LED out of its ball of dough. This leaves an open circuit.

    i. Does the LED light up?

    ii. Why or why not? Can you relate this back to the analogy presented in Module 0?

(Source: UCLA BEAM.)

c. **Short Circuit.** Restore the circuit back to the closed state by reinserting the LED correctly. But now, push the two dough balls so that they touch each other. Here, the current passes through the dough and bypasses the LED since the LED has a higher resistance.

    i. Does the LED light up?

    ii. What's the problem with this circuit? What are all the possible paths that electrons can take in this circuit?

    iii. To help relate this back to our simulation: Imagine that we used Easter eggs instead and that the battery's job was to fill the eggs with candy while the lightbulb's job was to take out and eat the candy so that it had energy to power its light. What happens then if a filled egg returns to the battery?
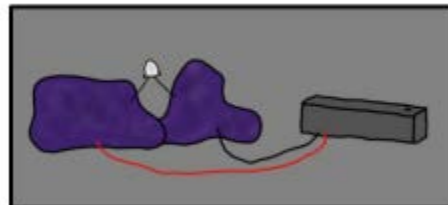

(Source: UCLA BEAM.)

d. **Insulated Circuit.** Restore the circuit back to the closed state. Replace both

conductive doughs with the insulating doughs.
  i. Does the LED light up?
  ii. How are insulators affecting the flow of electrons and the paths that electrons are taking?
  iii. What are some examples of insulators and conductors that you know of?
    1. (A good insulator is air!)
  iv. Why are insulators important for working with circuits?
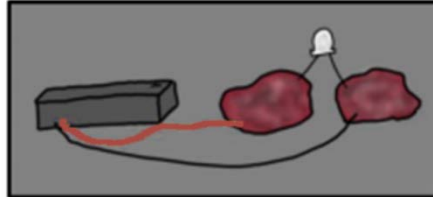
(Adapted from: UCLA BEAM.)

2. **Circuit Challenges!** Now, students will work in small groups or individually to complete the following challenges. Give students one challenge at a time and give them a new one once they are done. Feel free to give hints if a student is stuck for more than 7-10 minutes. You may also invent your own challenges.
   a. Have 2 LEDs light up equally bright.
      i. Solution: 2 LED's either all in parallel or all in series.
   b. If part (a) was solved using a parallel circuit, repeat the challenge but make both LEDs dimmer than they are now. If part (a) was solved using a series circuit, repeat the challenge but make both LEDs brighter than they are now.
      i. Solution: The remaining solution from part (a).
   c. Have 3 LEDs light up equally bright.
      i. Solution: 3 LED's either all in parallel or all in series.
   d. Have 1 LED bright and 2 LED's equally dimmer.
      i. Solution: Put 2 LED's in series and put that block in parallel with a third LED.

Module 2: Banana Piano!

Introduction
We will now apply what we've learned to create an exciting piano made out of bananas! This will help students to realize that the same circuits that we've learned about in the last two modules are used in real inventions that we use in our everyday lives!

Materials (quantities below multiplied by the number of Chromebooks available per site)
- 1 Chromebook
- 1 Arduino Uno Board
- 1 lead (cord) to connect Arduino to USB port on Chromebook
- 5 resistors
- 6 alligator clip connectors
- 11 mini connecting wires
- 1 bread board

- 5 bananas

Suggested that Logistics prepare one working circuit per site, and perhaps more for younger sites.

Background/Notes for Mentors

The main premise of why this can work is that bananas contain water and thus we can hook it up as part of a circuit. Note that there is a wire coming from a port called GND, which means 'ground.' To use the piano, students should hold the wire coming from GND in one hand, and touch a banana with their other hand. Essentially, the student becomes a part of the circuit as well in order to complete it. We are working with only 5 Volts here so there is no electrical danger, although it may be a good idea to emphasize that playing with electricity and circuits can be dangerous at higher voltages.

When we do not touch the banana and the GND together, then there is only one closed circuit in place but the software knows that at this resistance, the maximum resistance that this circuit can reach, a sound should not be played. However, when we do touch the banana and GND together, we close a second loop and thus create a circuit with resistors in parallel. This lowers the effective resistance of the circuit, and this lower resistance is detected by the software and triggers the appropriate pitch.

In terms of parts, the bread board is a long rectangular grid of holes through which wires can be inserted. Refer to the diagram below to see which holes are connected together; plugging in wires to holes in each group will link those wires together.
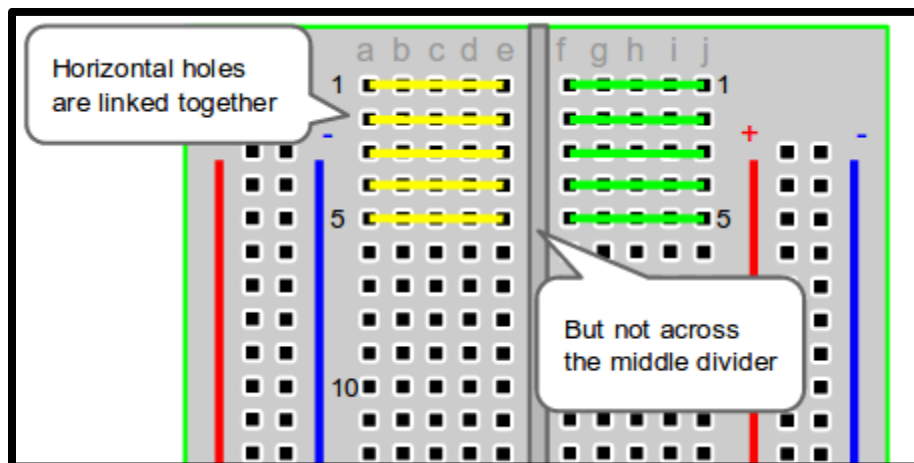

(Source: envato tuts+.)

The Arduino Uno board allows us to receive inputs and send outputs via a software that can be uploaded to it.

Scratch is a code development environment that beginning programmers can use to write programs. The code given to you is already written and uploaded to the Arduino board. The basic program consists of a loop that runs forever (or until execution is halted by the user) and consistently checks if the voltage level for any of the banana inputs drops below its default value. If it does, then it will trigger a pitch before returning to its regular state. There are constants within each of the conditional if blocks. These constants can be calibrated if the values do not work well with the numbers shown in the box on the right hand side of scratch that looks like this below. In this case, the Analog2 and Analog3 inputs are both detecting a value of 1023 (when your bananas are properly setup, you

should see a value of 1023 in each analog input from 0 to 4). When the banana is touched and connected to GND, then this value of 1023 will significantly drop. The goal of the constants in the code then, is to ensure that it properly defines a value which the Analog inputs must drop below in order to trigger a pitch. A screenshot of Scratch and the code is also shown below. Note that the constants are located in the green code blocks and that it probably makes sense for all of these constants to be the same value (unlike what is shown here). Note also that in the magenta code blocks, you can choose from the dropdown menu new pitches (or even a new instrument in the magenta block above the orange forever loop).
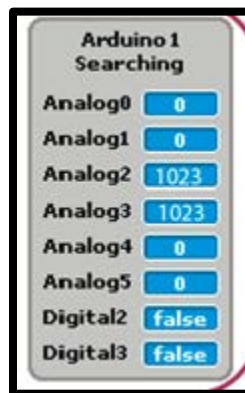
(Source: Loopy Computy.)
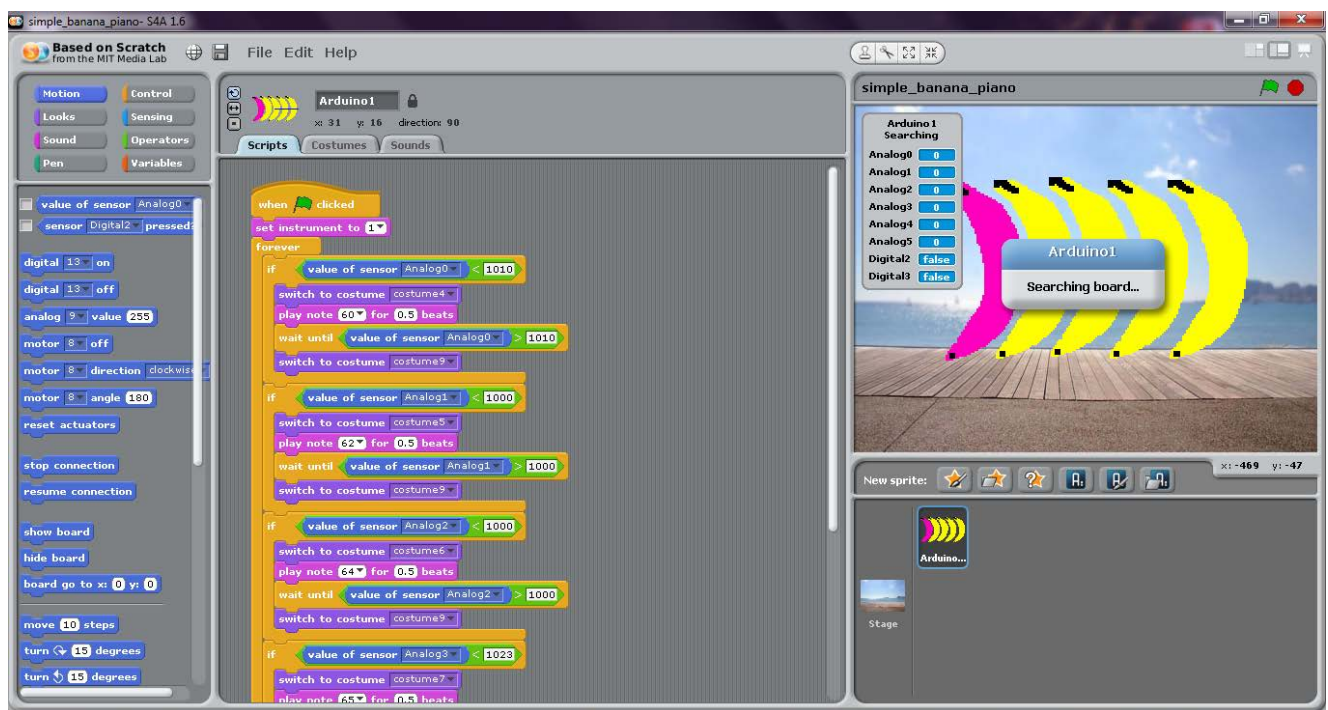
Material to Teach

If anything, students will witness the idea that we can add hardware to our circuits (mix and match electronic parts) to create the fun inventions that we interact with in our everyday lives.

Intermediate students may also become more confident in their abilities to assemble a circuit from a diagram and to ensure that all principles taught from our model in Module 0 hold consistent.

The most advanced students may be able to interact with both the hardware components in front of them as well as the software aspect presented through the Scratch development environment on the Chromebook. If students demonstrate interest in fiddling around with the software aspect, encourage them to calibrate the constants and to even rearrange code blocks.

Procedure

Elementary school sites do not need to worry about teaching circuit assembly or the code, treat it more as a hands-on demo. Middle school sites have more flexibility in choosing what aspects they would like to teach and what challenges they would like to present to their students.

1. **Assembly.** Connect the circuit as shown below. You may want to draw the diagram on the board and have students work together to piece the circuit together. Note that there should be a wire going into the 5V port of the Arduino board, which is the one that splits into parallel resistors and bananas. There is another wire going into GND (ground); when a student holds this wire and touches a banana, it will close that circuit and allow the software loaded onto the Arduino board to respond with a sound clip. Make sure to walk through this process with your students slowly.
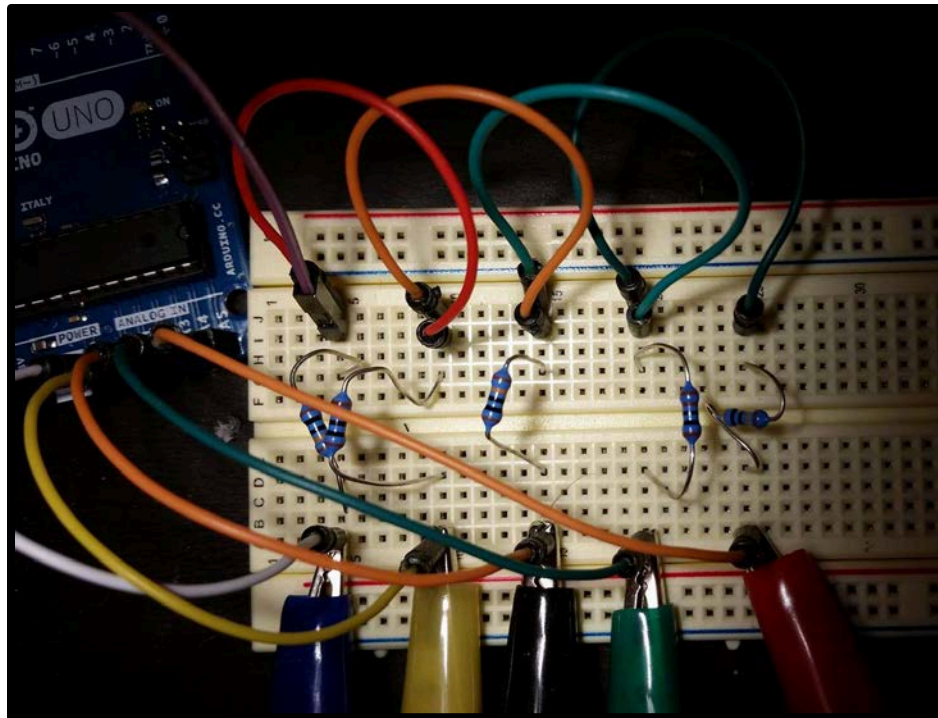

  a. Specifically (note coordinate system on bread board):
- Send voltage to all 5 bananas:
  1. Wire between Arduino 5V to bread board I5.
  2. Wire between bread board J5 to I10.
  3. J10 to I15.
  4. J15 to I20.
  5. J20 to I25.
- Resistors for each path:
  1. Resistor between bread board G5 to bread board D5.
  2. Resistor between G10 to D10.

3. G15 to D15.
4. G20 to D20.
5. G25 to D25.
- Wires back to Arduino inputs:
  1. Wire between bread board A5 to Arduino A0.
  2. Wire between bread board A10 to Arduino A1.
  3. Bread board A15 to Arduino A2.
  4. Bread board A20 to Arduino A3.
  5. Bread board A25 to Arduino A4.
- Alligator clip wires to bananas:
  1. Loosen the wire at bread board A5 and clip an alligator clip wire to it and reinserting it as shown below.
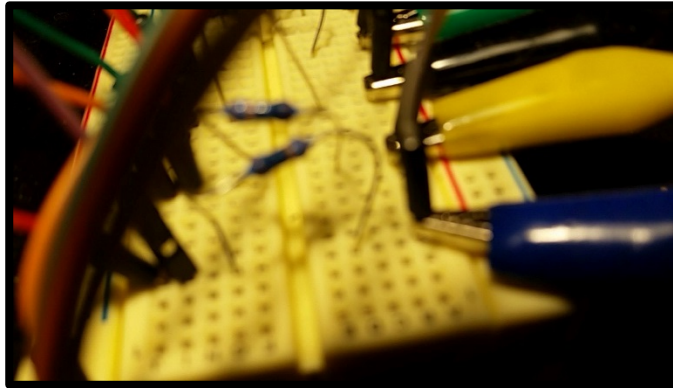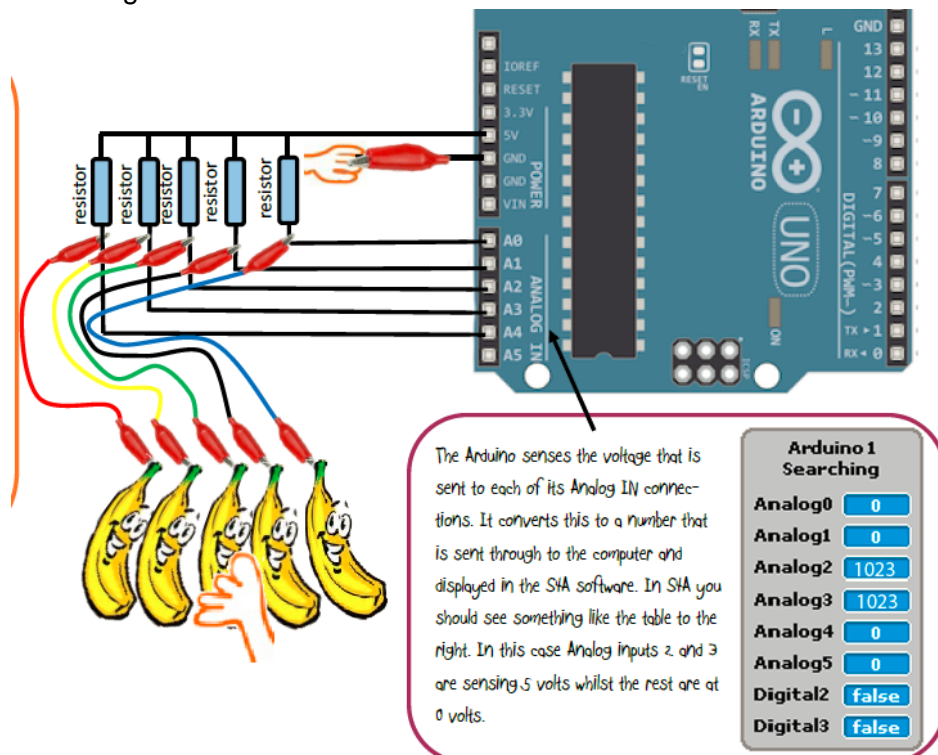

  2. Repeat with new alligator clip wires for positions A10, A15, A20, A25.
  3. Attach a banana to the remaining end of each alligator clip wire (from its stem).
- USB cable into large port on Arduino and into USB port of Chromebook

2. **Starting the Chromebook**. Turn the Chromebook on with the power button. When the screen with the exclamation point appears saying OS verification is off, DO NOT touch any keys and DO NOT turn off developer mode. Wait for it to start up.
   a. When the Chrome logon page appears, browse as guest.
   b. When the internet browser appears, Press Ctrl + Alt + T to bring up the terminal.
   c. Type: `shell`
   d. Type: `sudo startunity`
   e. Linux will now appear. Find and open the Scratch4Arduino program.
   f. Open "simple_banana_piano.sb" in Scratch4Arduino, which is the source code file. It should be located in the Downloads folder of the machine.
   g. Press the green flag in the top right corner of Scratch4Arduino to execute the code. (Make sure the Arduino device is connected to the Chromebook via the USB cable).
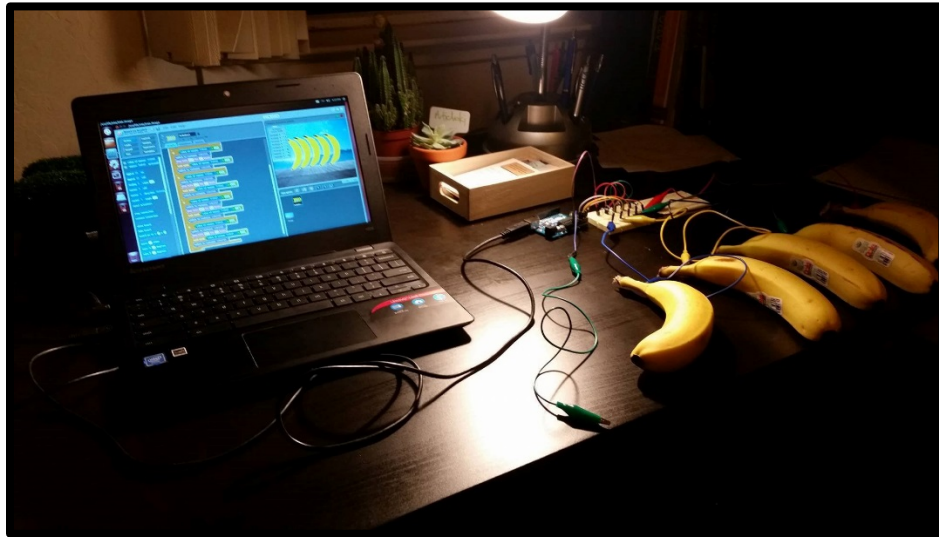
3. Be sure to ask questions and to continue reinforcing the concepts covered in the previous modules as students assemble and interact with the banana piano. Examples:
   a. What do you think a resistor does here?
   b. What is it called when we split a wire into multiple paths?
   c. How does wiring our circuit in parallel affect the flow of electrons?
   d. Why do the bananas only trigger a sound when they are touched?
   e. Why do you need to hold to wire leading to GND when you touch a banana in order to make a sound?
   f. Do you think bananas are conductors or insulators?

Additional Circuit Diagram:

The Arduino senses the voltage that is sent to each of its Analog IN connections. It converts this to a number that is sent through to the computer and displayed in the S4A software. In S4A you should see something like the table to the right. In this case Analog inputs 2 and 3 are sensing 5 volts whilst the rest are at 0 volts.

(Source: Loopy Computy.)

References

- Circuits with Friends, National Geographic. (http://www.nationalgeographic.org/activity/circuits-friends/)
- Squishy Circuits, John Wilcox, BEAM, Fall 2013.
- Squishy Circuits, Perry Roth-Johnson & Chris Nguyen, Building Engineers and Mentors, UC Los Angeles. (http://beam.ucla.edu/sites/default/files/docs/Squishy_Circuits.pdf)
- Squishy Circuits – Conductive Dough Recipe, Inspiring Our Youth, YouTube. (https://www.youtube.com/watch?v=Ud05YJMzm00)
- Conservation Laws in Circuits, North Carolina School of Science and Mathematics. (http://courses.ncssm.edu/apb10/resources/guides/G21-2.circuits_conservation.htm#summary)
- Lou A. Bloomfield, University of Virginia, Physics Central. (http://www.physicscentral.com/experiment/askaphysicist/physics-answer.cfm?uid=20080506030510)
- Banana Piano, Loopy Computy. (http://www.loopycomputy.com/banana-piano.html)

Summary Materials Table

Material	Amount per Group	Expected $$	Vendor (or online link)
Tennis Ball	1 per student		May substitute any other kind of throwable objects/balls.
Conducting Dough	1/3 batch * # of groups per site		Made by logistics from included recipe, below.
Insulating Dough	1/3 batch * # of groups per site		Made by logistics from included recipe, below.
Ziplock Bags (to store/seal Doughs)	2 large per site		
1 of 9V battery	2 * # of groups per site		
Alligator clip connectors and wires	3 * # of groups per site		https://www.amazon.com/uxcell-Double-ended-Alligator-Clips-Jumper/dp/B00D10KTLQ

10mm LEDs	3 * # of groups per site		
Chromebook	As available per site		Set up as specified in last 2 pages of this document.
Arduino Uno board	1 * # of Chromebooks per site		Set up as specified in last 2 pages of this document. https://store-usa.arduino.cc/products/a000066?utm_source=redirects&utm_medium=store.arduino.cc&utm_campaign=303_Redirects
Lead to connect Arduino to USB port on Chromebook	1 * # of Chromebooks per site		Comes with Arduino Uno
Resistors (2 MegaOhm) (Must be of this resistance)	5 * # of Chromebooks per site		https://www.amazon.com/NTE-Electronics-1W520-Composition-Resistance/dp/B008UTT8Y2/ref=sr_1_12?s=industrial&ie=UTF8&qid=1487756545&sr=1-12&keywords=2+megaohm+resistor
Alligator clip connectors and wires	6 * # of Chromebooks per site		https://www.amazon.com/uxcell-Double-ended-Alligator-Clips-Jumper/dp/B00D10KTLQ
Mini connecting wires (Male to Male 3")	11 * # of Chromebooks per site		https://www.adafruit.com/products/759
Bread board	1 * # of Chromebooks per site		https://www.amazon.com/Solderless-BreadBoard-tie-points-200PTS-

			Haobase/dp/B0195V3682/ref=pd_lpo_21_lp_t_4?_encoding=UTF8&psc=1&refRID=4S6HFPPJBDDRK0DJ3QRZ
Bananas	5 * # of Chromebooks per site		

**Conductive dough recipe** [https://www.youtube.com/watch?v=Ud05YJMzm00]
• 1 cup (tap) water
• 1 1/2 cups flour
• 1/4 cup salt
• 3 Tbsp. cream of tartar
• 1 Tbsp. vegetable oil
• Food coloring (one color)

Insulating dough recipe
• 1 1/2 cup flour
• 1/2 cup sugar
• 3 Tbsp. vegetable oil
• 1/2 cup deionized (or distilled) water
• 1 tsp. granulated alum (optional)
• Food coloring (a different color)

Procedure
1. Mix the flour, salt, cream of tartar, and vegetable oil in a medium sized pot.
2. Mix in a few drops of food coloring into the water and then pour the water into the medium sized pot.
3. Cook over medium heat and stir continuously.
4. The mixture will began to get chunky. Keep stirring vigorously until the mixture forms a ball in the middle of the pot.
5. Remove the dough from the pot into a bowl or onto a piece of wax paper. Let it cool for a few minutes.
6. Knead the dough with your hands. Ensure that the dough is thoroughly mixed and homogenous.
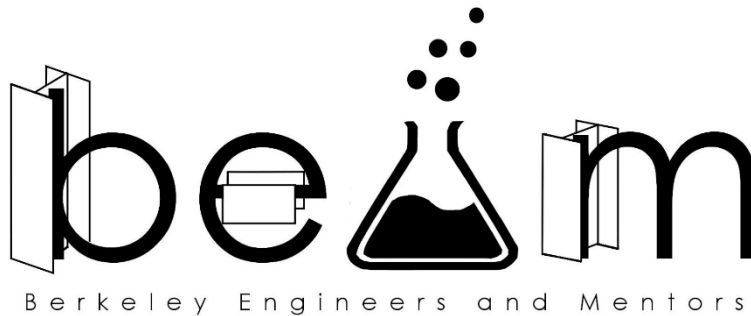
Technical Setup for the Banana Piano

Author: Matthew Sit
Semester: Spring 2016
Special thanks to Louis Chen for help in debugging these steps.

Enable Developer Mode

(Source: http://lifehacker.com/how-to-install-linux-on-a-chromebook-and-unlock-its-ful-509039343)

1. Once logged in to the Chromebook, press and hold Esc + Refresh + Power. This reboots in Recovery Mode.
2. Press Ctrl + D immediately when the yellow exclamation point screen shows up.
3. Press Enter and wait for the Chromebook to be reset (up to 15 minutes).
4. When red exclamation point appears, leave alone and wait until it reboots into Chrome OS.

Installing Linux on a Chromebook

(Source: http://lifehacker.com/how-to-install-linux-on-a-chromebook-and-unlock-its-ful-509039343)

1. Download Crouton from https://goo.gl/fd3zc onto the Chromebook into the Downloads folder.
2. Press Ctrl + Alt + T to bring up the terminal.
3. Type: `shell`
4. Type: `sudo sh -e ~/Downloads/crouton -t unity`
5. Wait until it installs. Enter a login name and password when prompted.
6. Type: `sudo startunity`

Installing Scratch

1. Return to Chrome OS. (If you are in Linux, Shut Down to return to Chrome OS.)
2. Go to http://s4a.cat/, click the Download tab at the top, and download the Linux (Debian) version to the Downloads folder.
3. Return to Linux (Steps 2, 3, 6 of Installing Linux on Chromebook section above).

4. Navigate to the Downloads folder, double click on the Installer package that you just downloaded and Install the Package.
5. Open the terminal in Linux. (XTerm)
6. Type: `sudo dpkg --add-architecture i386`
7. Type: `sudo apt-get update`
8. Check that you are in the Downloads folder by typing: `ls` If not, type: `cd ~/Downloads`
9. Type: `sudo dpkg -i S4A16.deb`
10. Type: `sudo apt-get -f install`
11. Type: `sudo apt-get install libsm6:i386 libice6:i386 libpulse-dev:i386`
12. Type (where `username` is the account username set in step 5 of previous section): `sudo usermod -a -G serial username`

Downloading the Banana Piano Source Code File
1. Return to Chrome OS. (If you are in Linux, Shut Down to return to Chrome OS.)
2. Go to and download http://www.loopycomputy.com/uploads/2/1/8/3/21834178/simple_banana_piano.sb to the Downloads folder.

Installing Scratch Firmware to Arduino
(Source: http://s4a.cat/)
1. Follow the instructions on http://s4a.cat/ under the section "Installing the Firmware into your Arduino." It is probably safest to just do this via a separate, personal laptop. Essentially, you will download the Arduino driver, download the Firmware needed, and upload it on to each Arduino board that is to be used. Once this is done, the Chromebooks will be able to talk to the Arduino boards.

Additional Notes
1. "Shutting Down" the Linux will return to Chrome OS. To return to Linux from Chrome OS:
   a. Press Ctrl + Alt + T to bring up the terminal.
   b. Type: `shell`
   c. Type: `sudo startunity`
2. When the laptop is booting up, it will show the exclamation point screen with the option to turn off developer mode. Emphasize to mentors that they should NOT do anything on this screen—just wait for it to pass over. Turning off developer mode will remove Linux from the machine and these steps will have to be performed all over again.