## Introduction

In this lab, you'll create an electronic piano out of everyday electronics, such as resistors, capacitors, and buzzers. We'll walk you through the design process and calculations needed to create our design, before finally implementing it using a breadboard.

Sound is a mechanical wave produced by vibrations, which travel through a medium until sensed by our ears. An acoustic piano creates tones by pressing down on the keys which in turn strike strings, creating sound waves through vibration. Modern electric keyboards create tones through playback of pre-recorded sounds, which are modulated by how hard the keys are pressed. The piano in this lab will produce tones by first producing a square wave with a 555 Timer IC, then converting the square wave into a sound wave using a piezo buzzer.

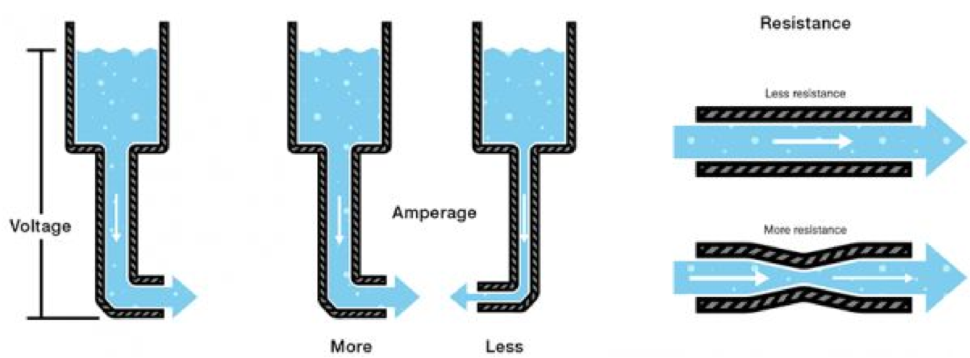
If you're familiar with any of these topics, feel free to skip ahead!

## Electricity Overview: Voltage, Resistance, Current, and Ohm's Law

In a circuit, an electric current will only flow if there is a path from high electric potential (think positively charged) to a lower potential (think negatively charged). We can quantify this using the ideas of voltage, resistance, and current:

- Voltage (V) is the magnitude of the difference between the electric potentials, and is measured in volts (V).
- Current (I) is the rate at which the charges travel through the path, and is measured in Amps (A).
- Resistance (R) is a measure of how much the path opposes the flow of current, and is measured in Ohms (Ω).

A familiar analogy might be water flowing down through a pipe. Here, water is driven by gravity from a higher place to a lower place. Using this framework, voltage would be the difference in height between the start and the end of the pipe. Current would be how fast the water flows in the pipe. Resistance would be factors such as the pipe's radius; if the pipe is thinner, less water can flow at any given time.




The water pipe analogy. Taken from https://forums.factorio.com/viewtopic.php?t=33963

The relationship between these three quantities is given by Ohm's Law: **V=IR**.

Alternatively, Ohm's Law says that a component with 1Ω of resistance will have a potential difference of 1V across if the current is 1A.

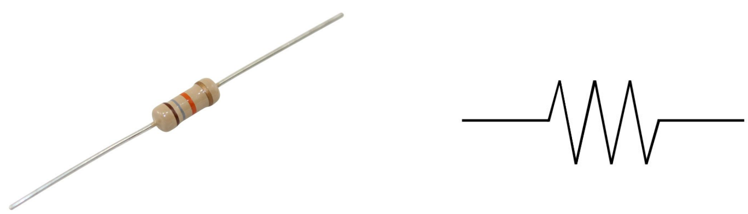
Ohm's Law tells us that:

- If resistance is constant, then increasing voltage increases current .
- If voltage is constant, then increasing resistance decreases current.
- If current is constant, then increasing voltage increases resistance.

These relationships hold true in both directions.

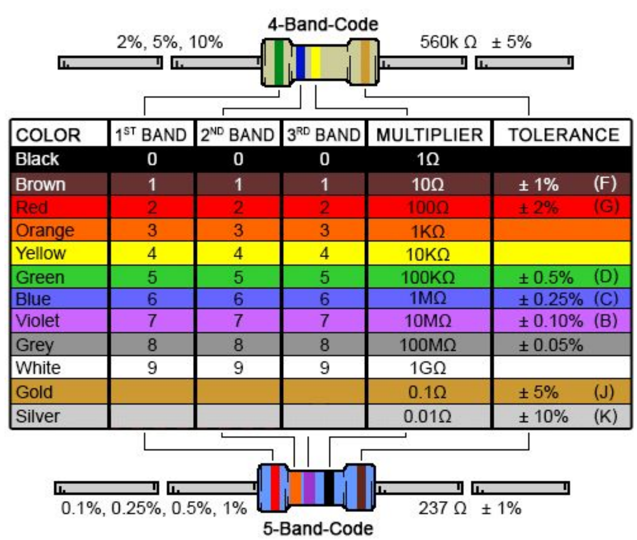
## Parts Overview: Resistors

To control the flow of electric current throughout our circuit, we'll use resistors. Resistors are conductors surrounded by an insulator, meaning that electric current will still flow, but it will be slowed down by the size and nature of the resistor's material.



A resistor component, and its schematic symbol.

Resistors are available in many ratings, so it is important to choose the right component: if there's too much resistance in a circuit, not enough current will flow and parts will not function correctly. On the other hand, if there's too little resistance in a circuit, there will be too much current flow and parts can break. Resistors are color coded by their values. A table of this system can be found below, but won't be needed for this lab.

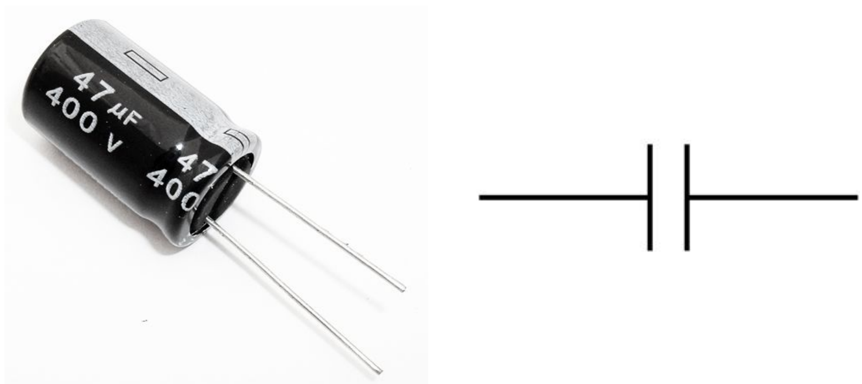



| COLOR | 1ST BAND | 2ND BAND | 3RD BAND | MULTIPLIER | TOLERANCE |
|---|---|---|---|---|---|
| Black | 0 | 0 | 0 | 1Ω | |
| Brown | 1 | 1 | 1 | 10Ω | ± 1% (F) |
| Red | 2 | 2 | 2 | 100Ω | ± 2% (G) |
| Orange | 3 | 3 | 3 | 1KΩ | |
| Yellow | 4 | 4 | 4 | 10KΩ | |
| Green | 5 | 5 | 5 | 100KΩ | ± 0.5% (D) |
| Blue | 6 | 6 | 6 | 1MΩ | ± 0.25% (C) |
| Violet | 7 | 7 | 7 | 10MΩ | ± 0.10% (B) |
| Grey | 8 | 8 | 8 | 100MΩ | ± 0.05% |
| White | 9 | 9 | 9 | 1GΩ | |
| Gold | | | | 0.1Ω | ± 5% (J) |
| Silver | | | | 0.01Ω | ± 10% (K) |

Resistor color codes. Taken from Digikey.

## Parts Overview: Capacitors

A capacitor is a component consisting of two plates which store opposite charges. In this sense, they're like a tiny battery; they're used to store electric charge. When a voltage is applied to it (such as being connected to a battery), a capacitor will store charge. When removed, it stores the charge and can act as a battery, allowing charge to flow across a voltage difference. A capacitor's ability to store charge is its capacitance (C), and is measured in Farads (F).




A capacitor component and its schematic symbol.

In this lab, we'll be using capacitors for their ability to charge and discharge small amounts of charge to smoothen out signals. During normal use, the capacitor will charge. When the voltage rapidly changes, such as when a button is pressed, the capacitor will discharge, reducing the spike. This use is known as bypassing.

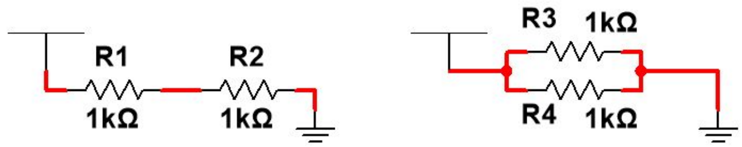
## Electricity Overview: Series and Parallel

In general, electricity will flow if there is a path from high potential to low potential. Here, we'll explore this in more depth through series and parallel connections and their connections to resistors.

In a series connection, one component is connected to the end of another. In this case, electricity will only have one path to flow through. In a parallel connection, components are connected on both sides. In this case, electricity will have multiple paths to travel through.

If two resistors are connected in series, they can be treated as a resistor with the sum of their resistances. (Rtotal = R1 + R2).

If two resistors are connected in parallel, they can be treated as a resistor with the following resistance: (1/Rtotal = 1/R1 + 1/R2)

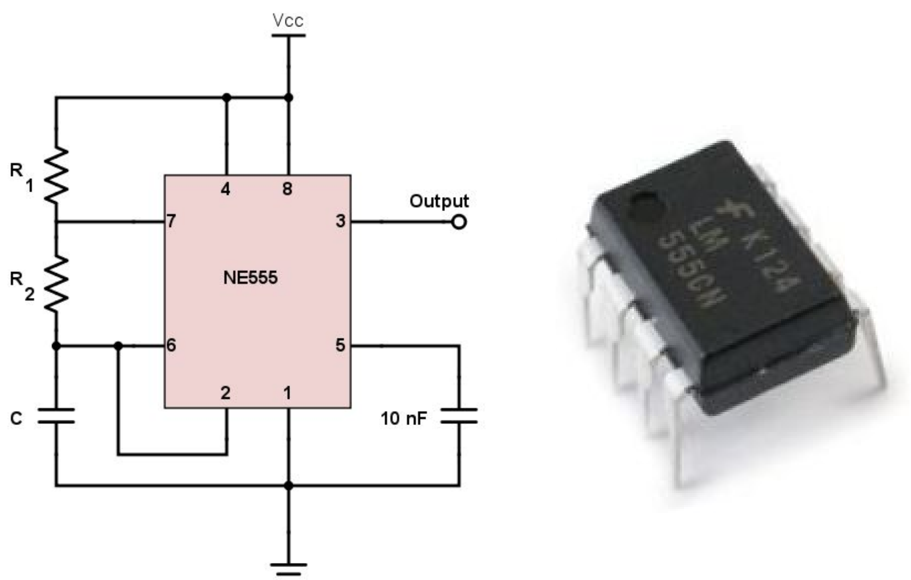



Series Connection
R = R1 + R2

Parallel Connection
1/R = 1/R3 + 1/R4

## Parts Overview: 555 Timer

The component we'll be using to create a square wave is a 555 Timer IC. ICs (integrated circuits) are premade chips meant to do a specific function. We chose the 555 Timer for this lab because it has an output that oscillates periodically, making it perfect to generate our waveform.




The schematic of a 555 timer wired as an astable multivibrator, and the 555 Timer IC.

The square wave is outputted from pin 3 (marked as *Output)*, and the period of the square wave changes based on the values of R1, R2, and C as denoted in the picture above.

The period of the output is denoted by **$T = \ln(2) * C * (R_1 + 2R_2)$.**
The frequency, therefore, is **$f = 1/T = 1/(\ln(2) * C * (R_1 + 2R_2))$.**

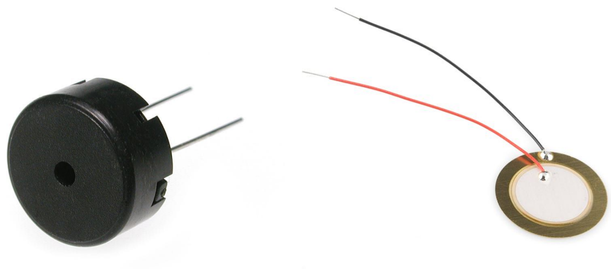
Here is a quick overview of what all of these pins do, though it's by no means necessary to complete the lab.

1. Ground: connects to ground reference.
2. Trigger: controls when the timer rises and falls along with 6 and 7.
3. Output: outputs a HIGH or LOW signal based on the state of the timer.
4. Reset: resets the timer's cycle when a LOW signal is inputted.
5. Control: can change the timer's cycle during use.
6. Threshold: controls when the timer rises and falls along with 2 and 7.

7. Discharge: controls when the timer rises and falls along with 2 and 6.
8. VCC: supplies power to the chip.

## Parts Overview: 555 Timer

Lastly, the component we will use to create sound is a piezo buzzer. A piezo buzzer contains a tiny ceramic that deforms whenever a voltage is placed across it. Therefore, if a square wave is placed across the buzzer, the ceramic will vibrate at the same frequency as the wave! This vibration creates a specific tone based on the frequency of the vibration.

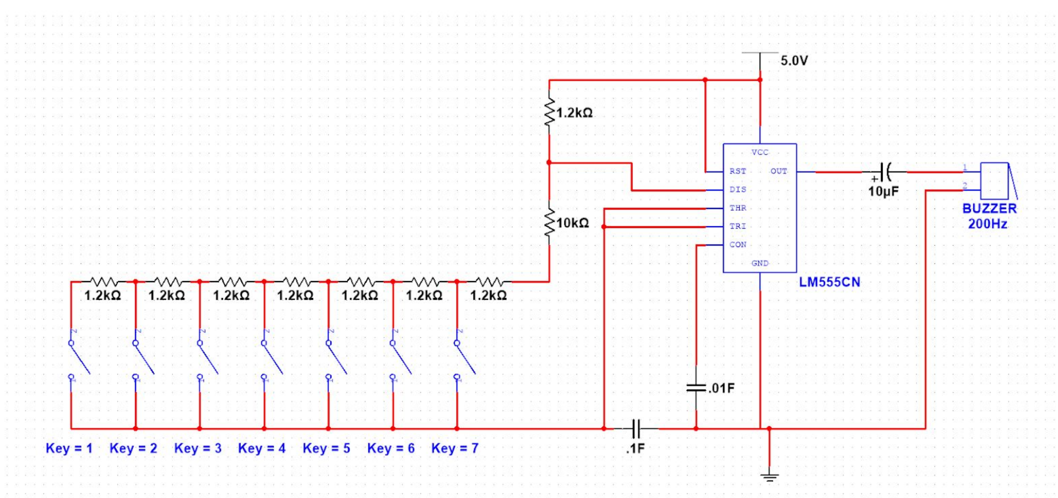


A piezo buzzer and the piezo filament.

## Putting It All Together: Making Sound from Electricity

Now that we know that a 555 timer creates waves based on its inputs and a piezo buzzer creates sound, we can make our electronic piano! To do this, we'll wire the piezo buzzer to the output of the 555 timer, which will create a square wave. To change the pitch of the sound, we need to change the frequency of the signal, which is given by **$1/(\ln(2) * C * (R_1 + 2R_2))$.** To change the frequency of the signals, we can change the values of $R_1$ and $R_2$ to get the frequencies we want.

To change $R_1$ and $R_2$, we can use buttons to turn resistors "on and off." The exact schematic we will use for this is shown below.




This design makes use of the fact that resistance in series can be treated as the sum of the resistances. By choosing where to anchor the circuit to ground, we change the effective resistance! Try it out for yourself.

## Calculating the Resistor Values for Pitch:

For this piano, we will make an octave from C4 (262 Hz) to C5 (523 Hz). The full list is given down below:

| | | | |
|---|---|---|---|
| C4 | 262 Hz | G4 | 392 Hz |
| D4 | 294 Hz | A5 | 440 Hz |
| E4 | 330 Hz | B5 | 494 Hz |
| F4 | 349 Hz | C5 | 523 Hz |

Given these frequencies and the equation for the frequency of the timer, we can begin to choose our resistor values. We will let C and $R_1$ stay constant, which means that the keys of our piano will determine the value of $R_2$. Let's let C = 1 uF (note that this is 10^-6) and $R_1$ = 1k ohm.

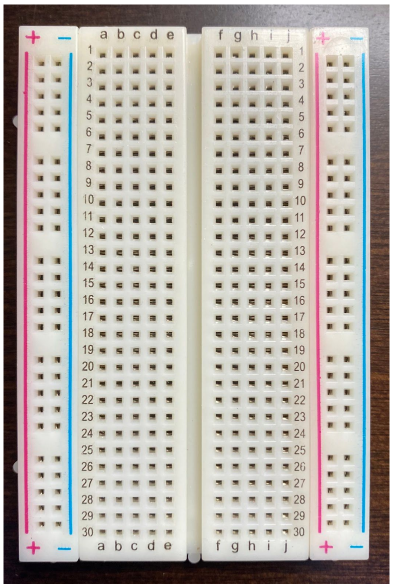
Hint 1: **$T = \ln(2) * C * (R_1 + 2R_2)$, $f = 1/T$.**
Hint 2: Because C5 has the greatest frequency, it will also have the smallest period. Therefore, C5 will need the least resistance, so start first by calculating the needed resistance for C5, then work your way up from there.

With our resistor values calculated, it's time to build our piano!

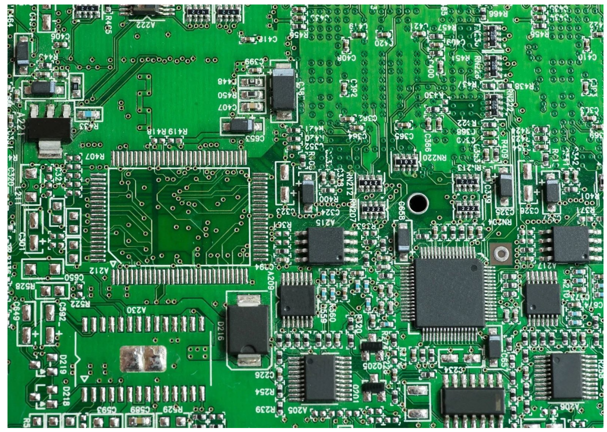
R1 = 880 ohm, R2 = 80 ohm, R3 =  180 ohm, R4 =  200 ohm, R5 = 230 ohm, R6 = 120 ohm, R7 = 270 ohm, R8 = 300 ohm
R1 refers to the resistance for C5. Then for B5, we need a total resistance of 960 ohms so we place R1 and R2 in series to get the desired total resistance. Same for the rest

## A Quick Introduction to Building Circuits and Breadboarding

Breadboarding is a fast and temporary way to prototype circuits, usually used to make sure a design works as desired before finalizing it in a product. As we build our electronic piano, we'll learn some breadboarding basics and become a little more familiar with reading schematic diagrams, which are a standard way of representing circuits so that anyone can read and build the designs they contain.

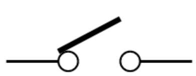


*A breadboard.*



*A printed circuit board - what you* don't *want to make a mistake on.*
*Image retrieved from [Makezine](Makezine).*

When we build circuits, we want to make sure we are building a complete path for current to flow, from power, or the positive (+) terminal to ground, the negative (-) terminal. When there are gaps in the circuit, the current cannot flow through, and that's when we call the circuit an *open circuit*. A circuit that has no breaks, like one that keeps a light on, is a *closed circuit*. In many cases, we want to be able to control when a circuit is on or off. In real life, for example, we don't usually want to keep a light turned on forever (that would be a waste of energy), so we use switches, which control when a circuit is open or closed. It's just like how your light switch works - when you press the switch, the circuit closes and your light turns on. Otherwise, the circuit is open and you remain in a dark room.

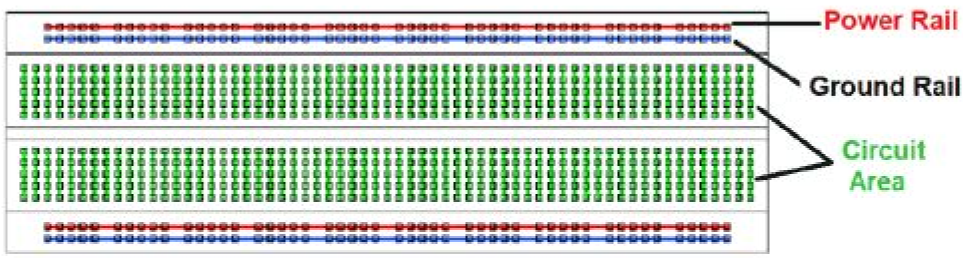


*A schematic representation of a switch.*

*A switch component. They can come in many forms, but all essentially do the same thing.*

We'll be using a lot of switches in our circuit to make up the keys of our piano. Now, let's get to the real breadboarding!

If you take a look at your breadboard, you'll see two red and blue lines, and several numbered rows. The red and blue lines mark the power and ground rails in the breadboard–these lines are all connected down the column, so anything you put in the power rail will be connected to everything else in the power rail, and the same goes for the ground rail. The numbered rows are a little different. Instead of vertical connections, these connections are horizontal, and do not extend across the gap in the middle. These connections are made by strips of conductive material under the board that run in those directions. Feel free to ask for help if you don't understand something!

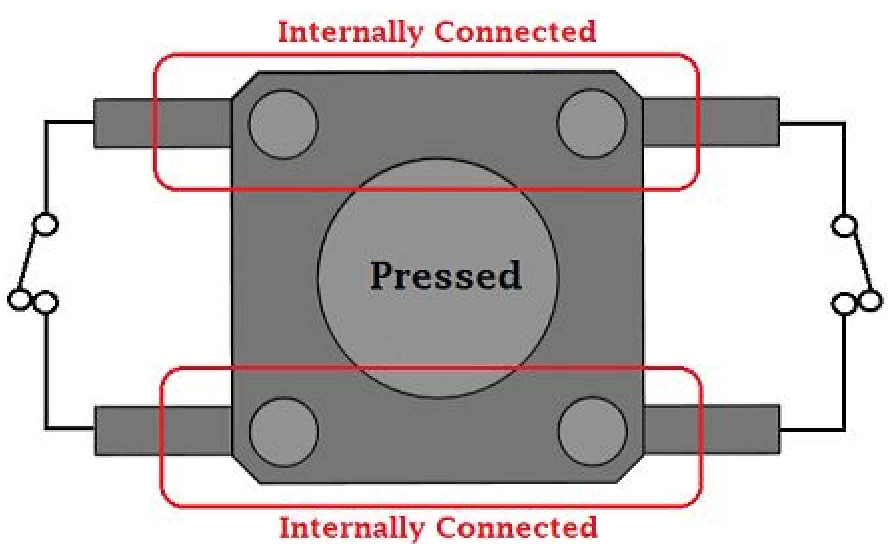



*Retrieved from [Components101]*

## Building Our First Circuit

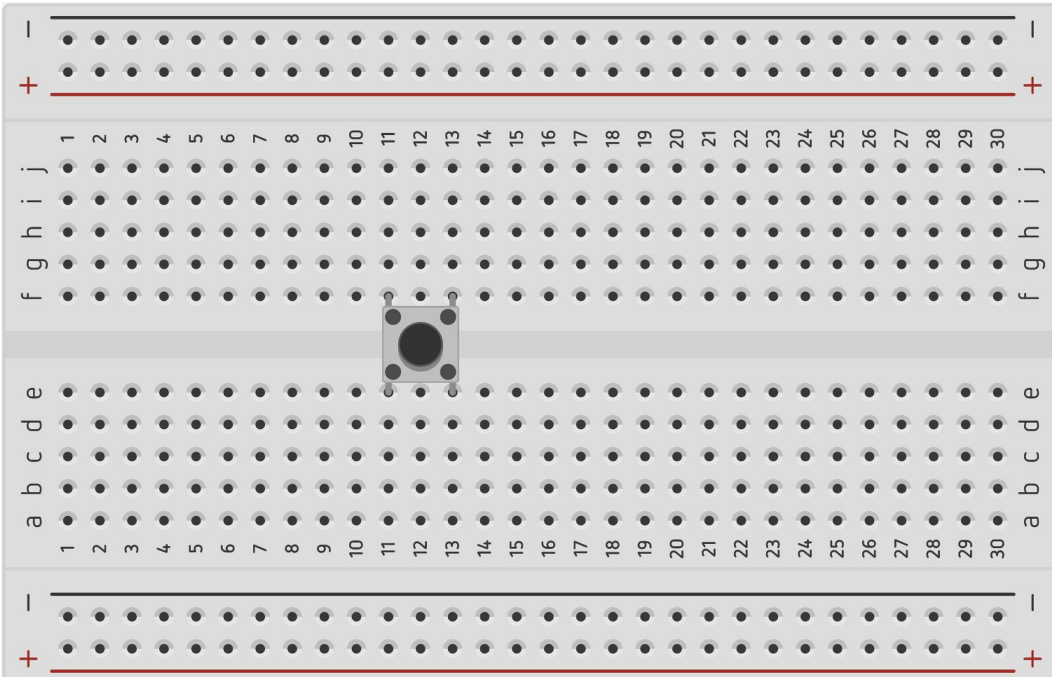
Before we begin building our electronic piano, we'll put together a simple circuit to familiarize ourselves with breadboarding and the parts we'll be using today. If you have breadboarded before and feel comfortable with the following exercise, feel free to skip this section and move on to "An Overview of Our Design."

Our aim for this practice circuit is to control an LED (light-emitting diode) with a push button switch. Although a push button switch might seem slightly more complicated than the switch we looked at previously because of its four pins, it works in the same way, but with internal connections as in the image below. It just gives us more room to work with!

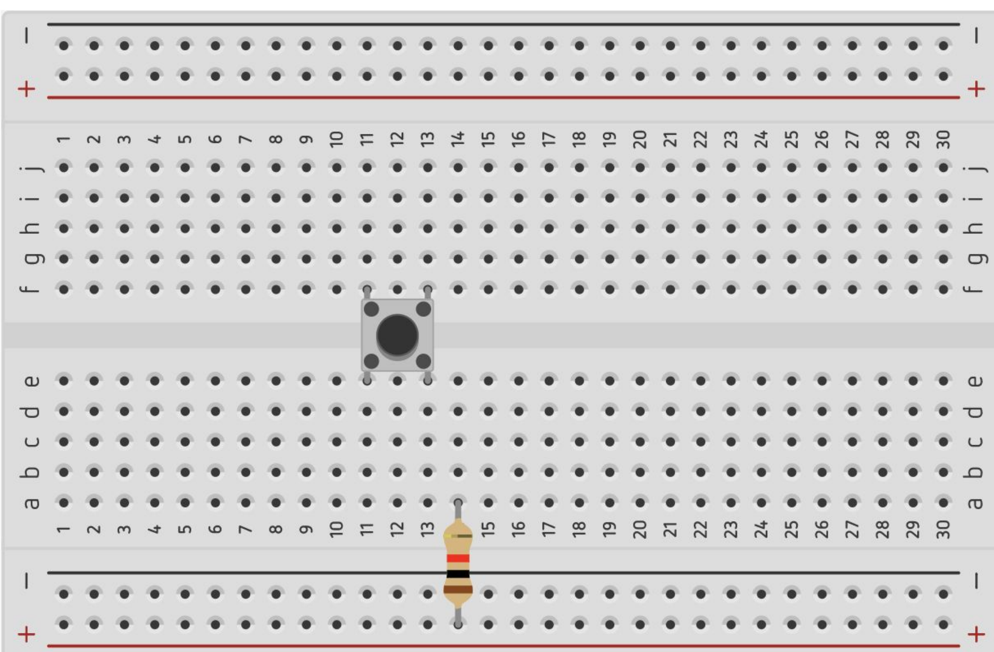



*The internal workings of a push button switch. Retrieved from [Components101].*

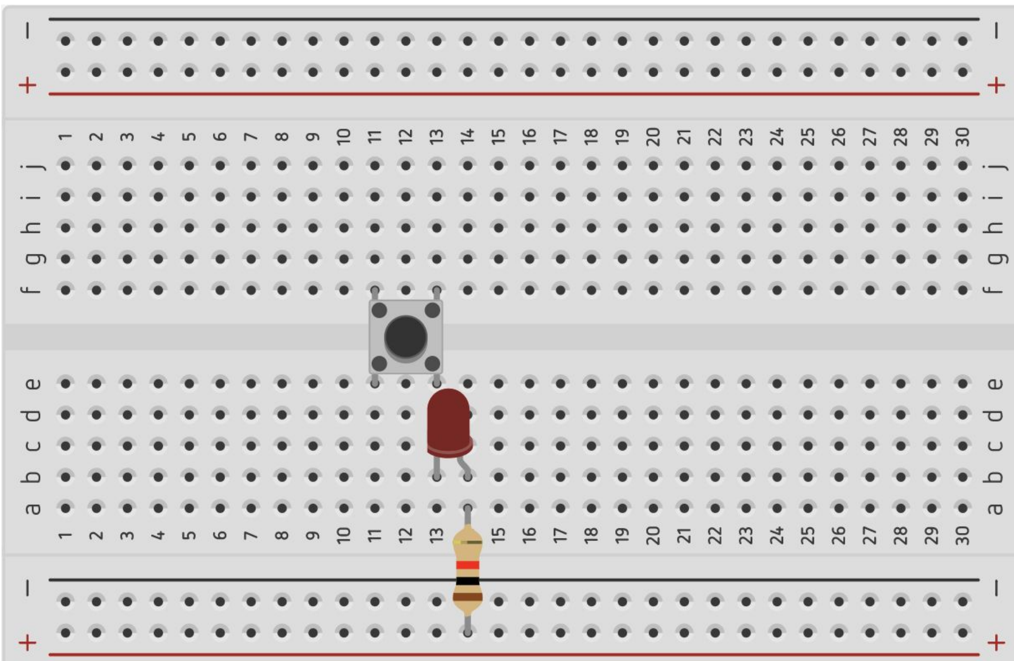
We'll first put our push button somewhere on our breadboard, across the channel separating the two halves in the middle, so that the legs do not connect to themselves. When you press the legs into the holes on the breadboard, make sure they go in firmly, or they might not connect to the conductive material in the breadboard that will connect all of our components together.



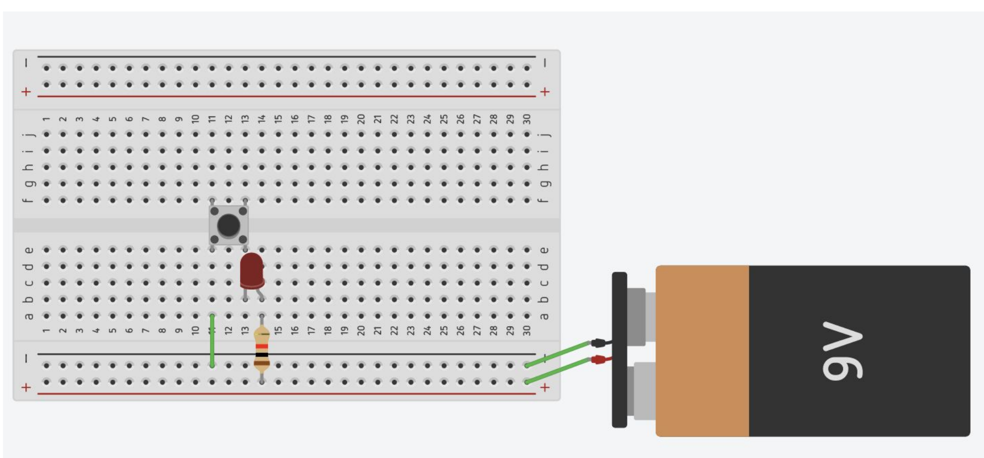
Connect a resistor from the power rail to an unoccupied row on the breadboard. This resistor will prevent our LED from burning out quickly.



Next, we will connect our LED, or the “light” of our circuit. Unlike resistors, for which orientation does not matter, LEDs can only be connected in one way, from the positive to the negative lead. The positive lead (or electrode) is the longer leg, while the negative electrode is the shorter leg. When you’re tracing your circuit, make sure that your LED has power going from its long to short legs. If you can’t figure out which leg is shorter, look for a flat edge on the outside of the LED, and that side will correspond to the negative lead. Connect the longer leg to the row with the resistor, and the shorter leg to a row with one of the legs of the push button switch.



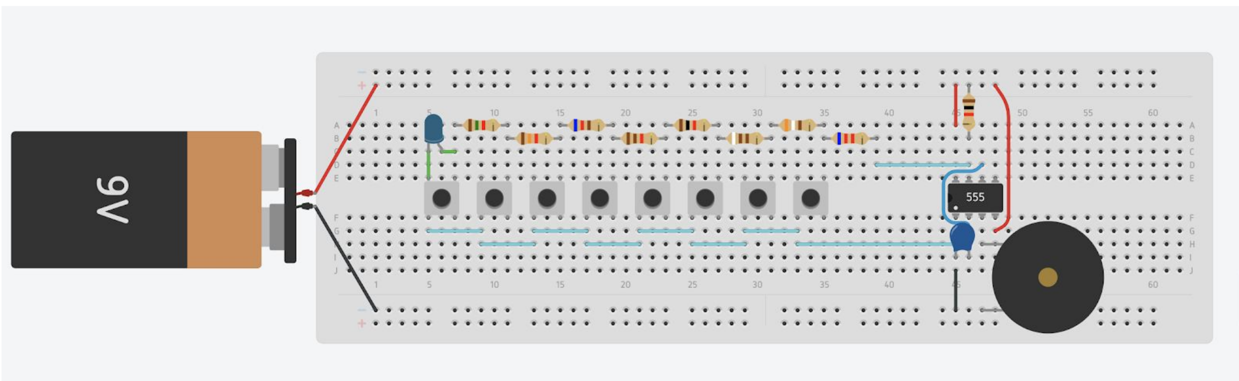
Finally, finish your circuit by connecting the other leg of the switch to ground with a wire, and connect your breadboard to a power supply.



Press the button and see what happens! If the LED doesn't light up, check that everything is connected firmly and in the correct rows, or try another LED. If that still doesn't work, call someone over for help. Now that we're a little more comfortable with using our breadboard and building circuits, it's time for the real project!

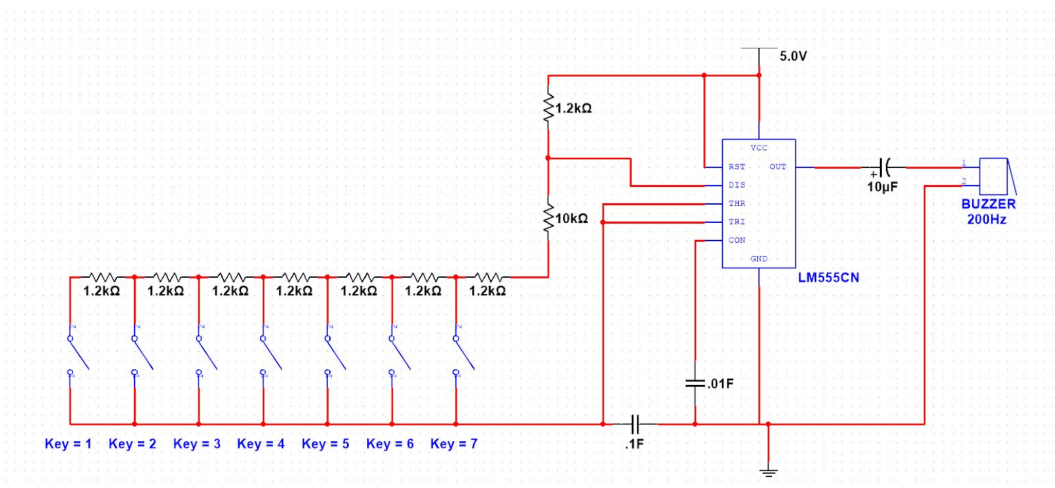
## An Overview of Our Design

At the end of today's lab, we'll have built something that looks like the image below. When the keys are pressed, you should be able to hear different tones from the buzzer. Ignore the many colors of the resistors for now–you'll be using the resistors with the values that you calculated in the previous part instead of the placeholder values that are just here to show you where to place the components.




*A model of the complete electronic piano we'll be building.*

The schematic for the our circuit would look something like this:

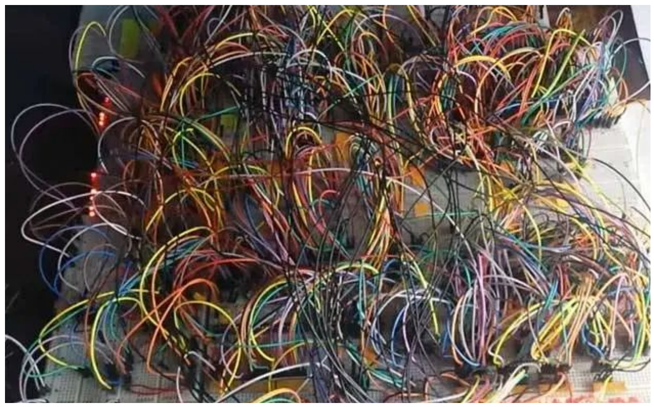



*A schematic diagram for an electronic piano.*

Note, however, that the above schematic has a few more components than the design we will be building today and different values. What's important is the block on the left with the parallel switches and resistors, and the LM555CN block, which is our 555 timer. We'll be building a simplified version of this circuit, but if you feel comfortable, feel free to try making the circuit above on your own later and compare the differences in sound!

Do you see how the schematic simplifies the model above, and lays everything out clearly so we don't just see a jumble of wires and components? Try comparing the components on both images, and see what overlaps and what doesn't!

***Pro Tip:*** *When you're breadboarding, make sure to keep your wires short and neat, to make it easier to debug if something goes wrong and to see what you're doing. We don't ever want our breadboards to look like this!*

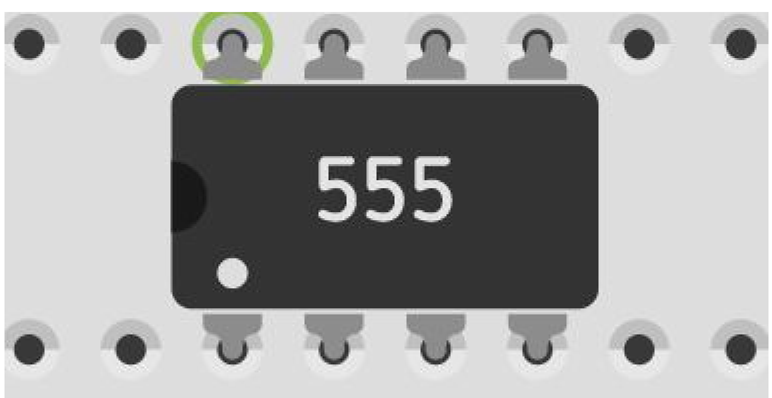


*A very messy, ugly breadboard. Retrieved from Hackaday.*

## Putting Together an Electronic Piano

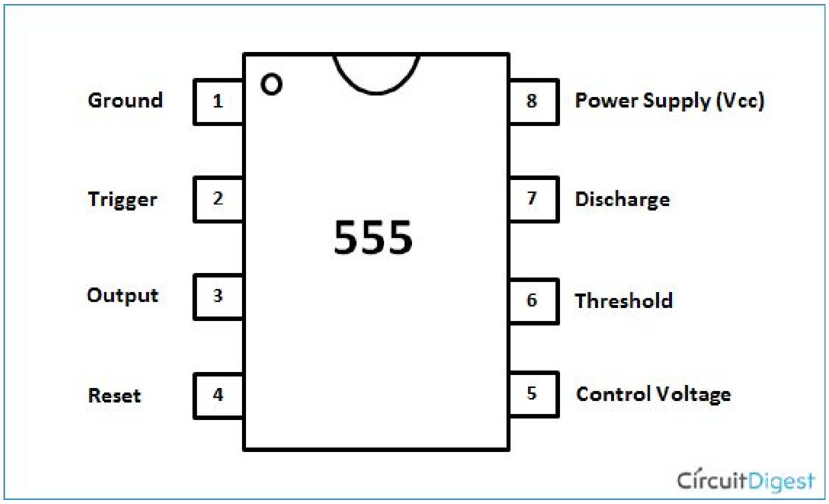
*If you ever get stuck on any part, make sure to raise your hand and call us over. We're here to help!*

The first thing we're going to do is insert our 555 timer into the breadboard. Press it down carefully, so all the legs line up and are firmly in the holes on the breadboard. We don't want to have a loose connection! To ensure each leg is in a separate row, make sure the black part of the integrated circuit chip lies in the gap between the two sets of rows in the breadboard. Notice the little curve-shaped notch on one end of the chip–that'll tell us which way we're oriented so we can figure out which leg is which!



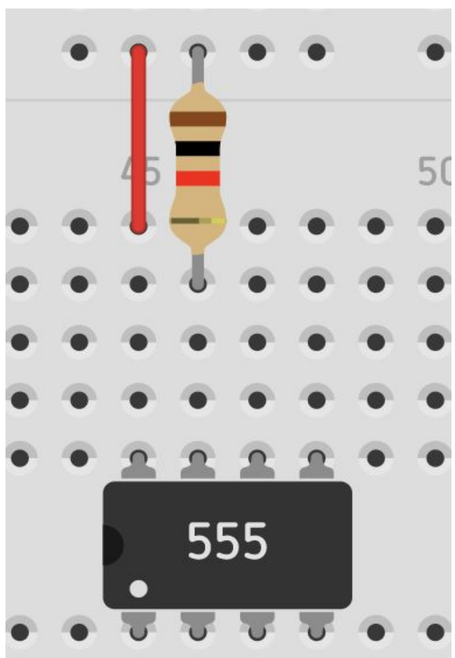

*Your board should look like this, but with real components!*

As a reminder, the legs of the chip correspond to these:

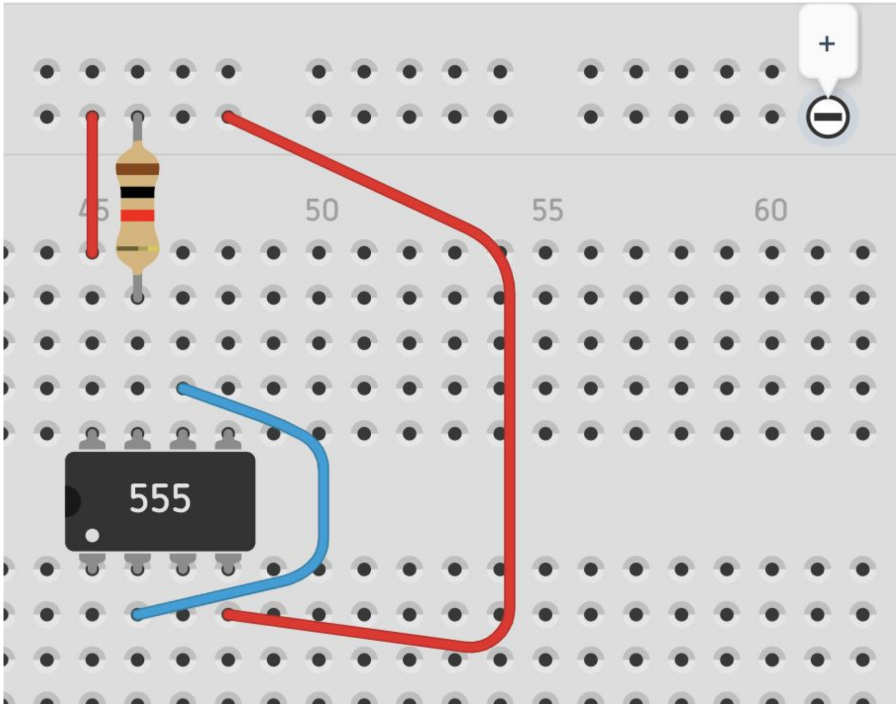



*The pin diagram of the 555 timer.*

First, connect the 8 pin and the 7 pin to the power rail with a wire and a 1kΩ resistor respectively, as shown below. Following the color chart for resistor values from before, we can see that the 1kΩ resistor has brown-black-red stripes. We can ignore the fourth gold stripe for this lab.

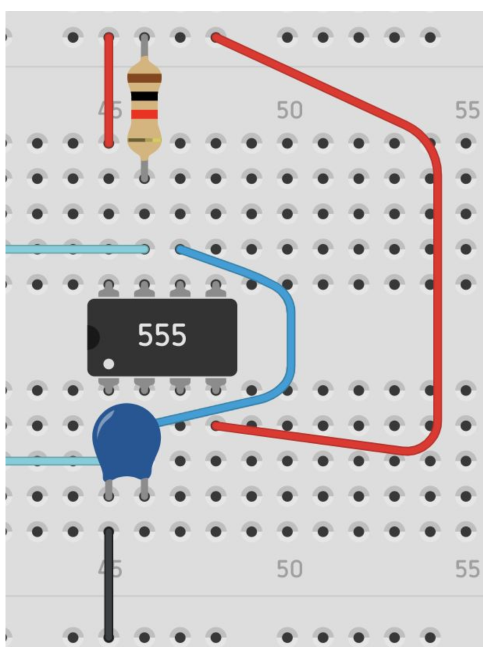



Next, connect pin 2 to pin 6 using a length of wire. Use the wire clippers to shorten and strip the wires to make them shorter as needed. Connect pin 4 to the power rail with another length of wire.

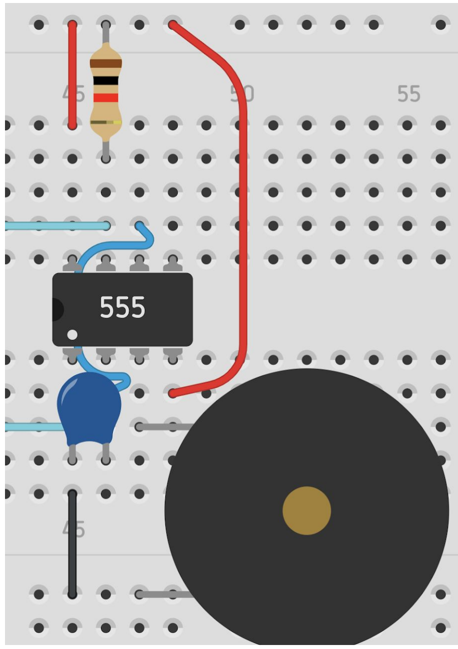



***Pro Tip:*** *You can connect the two power rails and ground rails with two wires, so you can use either rail instead of having wires go all across your breadboard. Then, you can avoid the long red wire in the image above.*

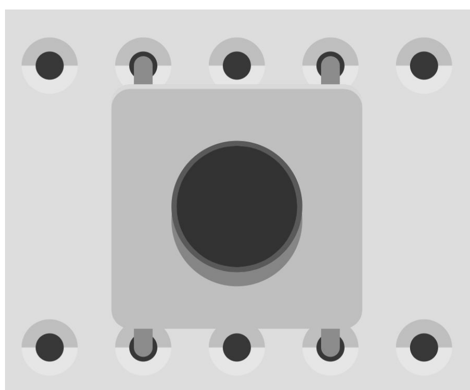
Connect pin 1 to the ground rail, and connect the capacitor between pins 1 and 2 of the 555 timer.



Now, it starts to get more exciting! Connect the positive wire of the piezo buzzer to pin 3 of the 555 timer, and the negative wire to ground.

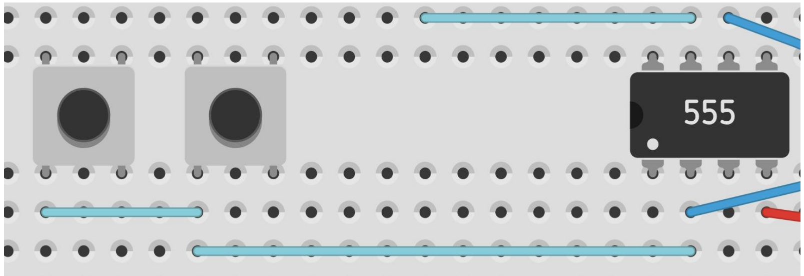



We're going to start inserting our switches, in parallel, which will make up the keys of our piano. Just like our 555 timer, the switches go in the gap between the two sets of row connections.

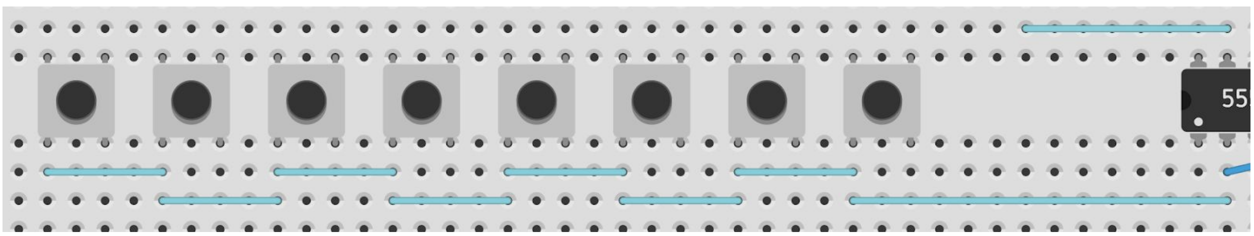


*One lonely button - just like this!*

We'll follow this switch with another one, and connect one of the legs of each switch together for them to be parallel. Connect one leg of just your first button with pin 2 of the 555 timer with a wire, as shown below.

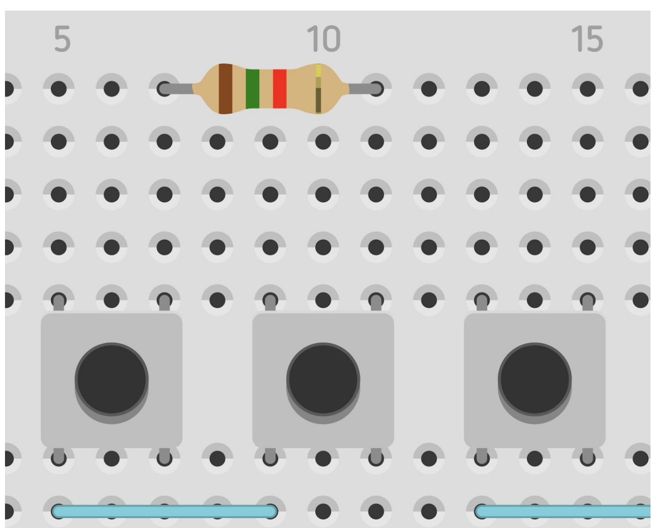



Do the same for each key you want on your piano, until all the buttons look something like this (note that they don't have to be so far away from the 555 timer if you want to keep your components closer together):



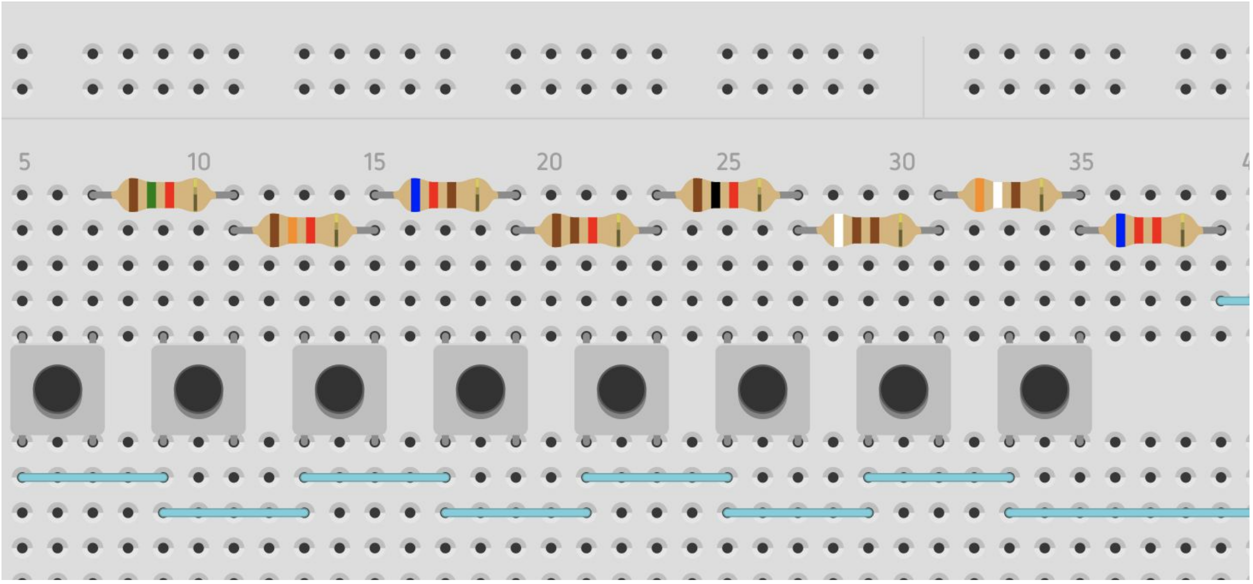
*Many, many buttons.*

Next, we'll start putting resistors in to create the different notes of our piano. Connect each resistor from the top-left pin of each switch to the top-left pin of the switch to its right.

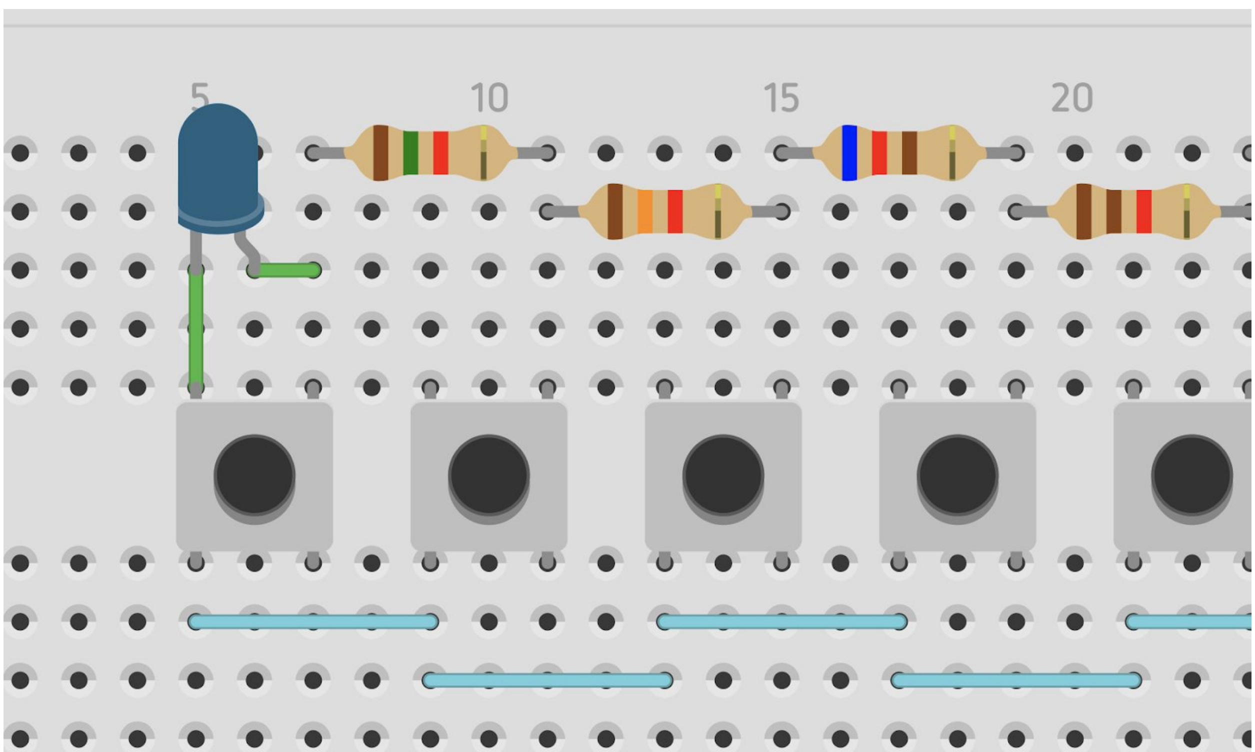



*Use the resistors with the values you calculated!*

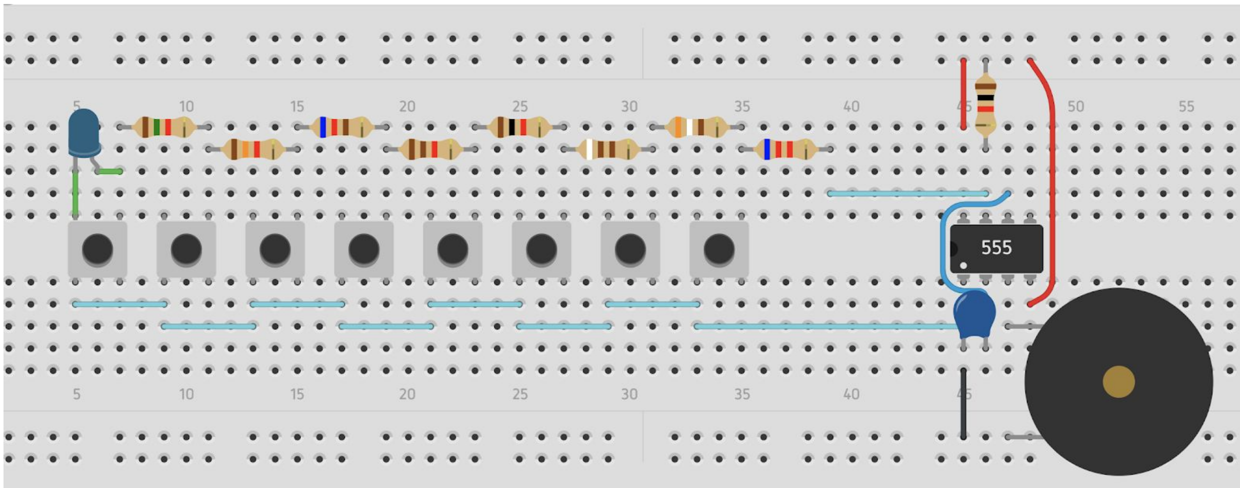
After you put in all the resistors, your circuit should look similar to the model below. When you get to the last resistor, you can either connect the resistor directly from the switch to pin 7 of the 555 timer or connect it to any unoccupied row, and then connect that row to pin 7 with a wire (as shown in our model).




Just for fun, we can connect an LED to our last switch, which will light up whenever we press a key. Connect the long leg of the LED to the row with the last resistor in it (or you can insert it into an empty row and then connect it with a wire as in our model, which is slightly messier), and the short leg to the top-right leg of the switch.

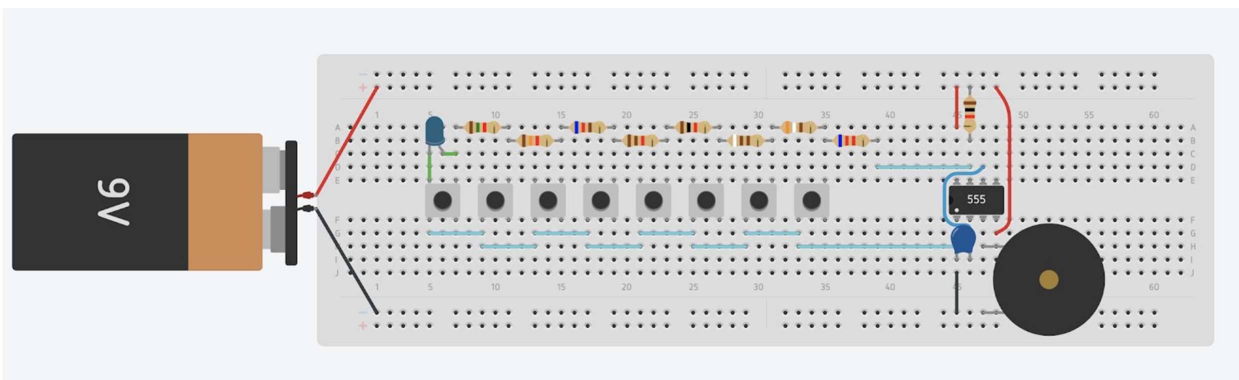



Our circuit should now look like this:




*Almost done!*

Finally, we connect our circuit to a power supply (either a battery or with long red and black wires directly to the power supply in the lab), and test out our circuit!




*Time for some musical fun!*

Press the keys and listen for a sound. If you can't hear anything and the LED doesn't light up, make sure there are no loose wires and that each component is connected securely to the right row. Check your power supply connections. If that still doesn't work, call someone over for help.

Congratulations! You just built your own electronic piano! Try composing your newest masterpiece on your new instrument, and have fun with it!