INTRO | LABOR

Hey there, thanks for purchasing **MKI x ES Labor**! We – Erica Synths and Moritz Klein, with help from Dr. Shalom D. Ruben, teaching professor for engineering at the University of Colorado – have developed it as a fully-featured circuit design playground and a powerful electronics learning tool, all in one. So no matter if you're a complete beginner looking to get started in electronics & circuit design or a DIY synth veteran in need of a more streamlined way to prototype your ideas – Labor has you covered.

This manual will first guide you through the assembly process, give you a rundown of the features, and then supply you with a couple example circuits you can set up to explore what Labor can do. In addition to this, you can also play around with those circuits in a circuit simulator called **CircuitJS**. CircuitJS runs in your browser. You'll find weblinks in the footnotes which will direct you to an instance that already has example circuits set up for you. We strongly encourage you to fiddle with the component values and general structure of those circuits to get a better understanding of the concepts we're laying out.

Once you're done with the basic circuits in this manual, consider investing in one of our **MKI x ES.EDU DIY synth kits**! They're compatible with your Labor and come with detailed manuals like this one, allowing you to set up and learn about fully-fledged synthesizer circuits like VCOs, VCFs, Sequencers and more.

Generally, this manual is intended to be read and worked through front to back, but there were a few things we felt should go into a dedicated appendix. These are general vignettes on electronic components, concepts and tools. Don't hesitate to check in there whenever you think you're missing an important piece of information. Most importantly though: have fun!

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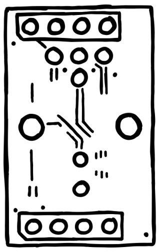
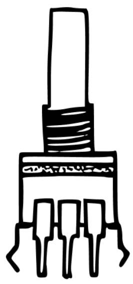
BILL OF MATERIALS

We ship Labor as a **partial DIY kit**. This means that while some parts of the device come pre-assembled, you'll have to put others together yourself. Before we get started on that, let's make sure that your kit contains all the necessary components. In the box, you should find:



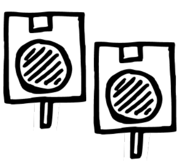
A couple PCBs. The specific model names (which are printed onto the boards) are

EDULAB Main PCB	x1
EDUPRTP Fixed Controls PCB	x1
EDUPNLF Free Space PCB	x1
EDUPNLB Breadboard PCB	x1
EDUPNLM Multipurpose Controls PCB	x1
EDUPOT Potentiometer/Socket adapter PCB	x24
EDUSW Switch/Button adapter PCB	x16



A bunch of potentiometers. The specific values (which are encoded & printed onto their body) are

B1M	x2
B250K	x1
B100K	x5
B50K	x1
B10K	x2
B5K	x1
B1K	x1

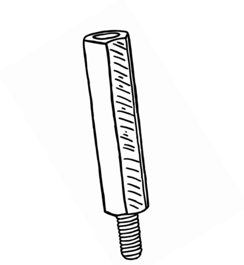


A few jack sockets. The specific models (which you can identify by their color) are

Switched mono (black) x5

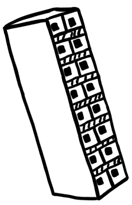
Some switches. The specific models (which you can identify by the number of connectors on their underside) are

Single pole (ON – ON)/(ON – OFF)	x1
Double pole (ON – OFF – ON)	x1



A couple spacers. The specific types are

3x11mm int./int.	x6
3x11mm int./ext.	x2
3x23mm int./ext.	x2
3x23 int./int.	x2



A bunch of connector elements. The specific types are

16-pin female header	x8
4-pin female header	x36
8-pin female header	x3
40-pin male connector	x4

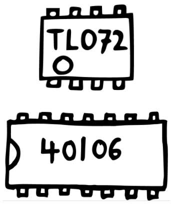
A couple LEDs (light emitting diodes). The specific model (which you can identify by measuring their body's width) is

3mm (red)	x2

And…

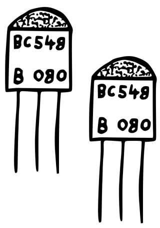
830 Point Breadboard	x1
Labor plywood base	x1
Breadboarding cable set	x1
12V 1A wall wart	x1
Screw M3X6 Phillips black	x28

If you decided to buy the **full kit** (instead of the basic version), your box will also include:



A couple chips. Their specific models (which are printed onto their bodies) are

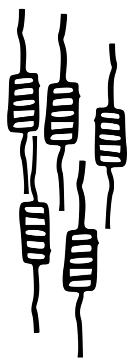
TL072 (dual op amp)	x2
TL074 (quad op amp)	x2
40106 (hex schmitt trigger inverter)	x2
4017 (decade counter)	x2
4015 (dual shift register)	x2



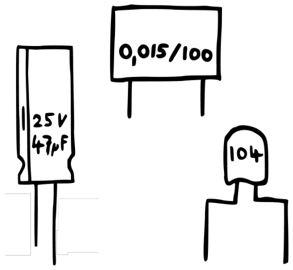
A couple of transistors. The specific model names (which are printed onto their bodies) are

BC548 (NPN)	x10
BC558 (PNP)	x10

An array of resistors. The specific values (in ohms, which you can check for with a multimeter) are

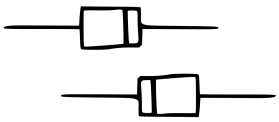


1M	x5
470k	x2
100k	x10
82k	x2
68k	x5
47k	x5
33k	x5
27k	x2
22k	x5
14k	x2
10k	x10
4k7	x2
2k	x5
1k	x10



A bunch of capacitors. The specific values (which may be encoded and printed onto their bodies) are

1µF	x2
470nF	x1
100nF	x5
10nF	x2
2.2nF	x2
1nF	x5



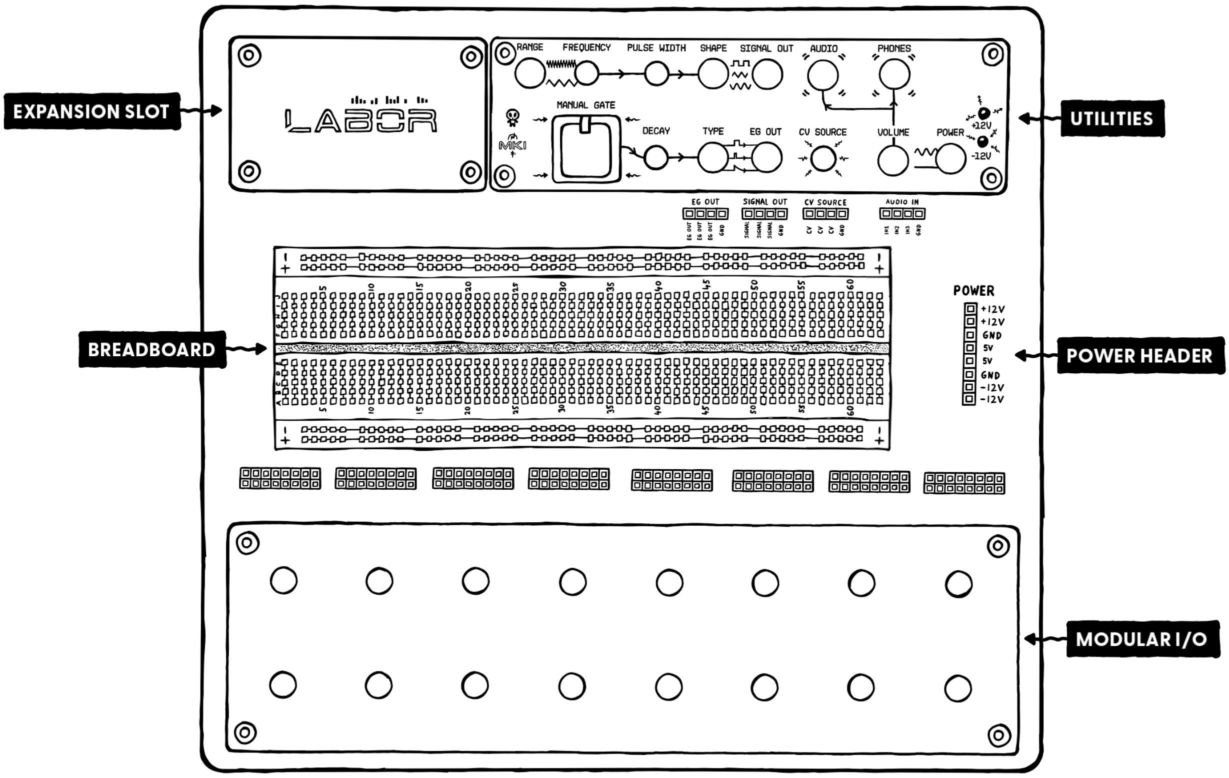
Some diodes. The specific model names (which are printed onto their bodies) are

1N4148 (signal)	x10

A couple more LEDs (light emitting diodes). The specific model (which you can identify by measuring their body's width) is

3mm (red)	x5

LABOR FEATURES



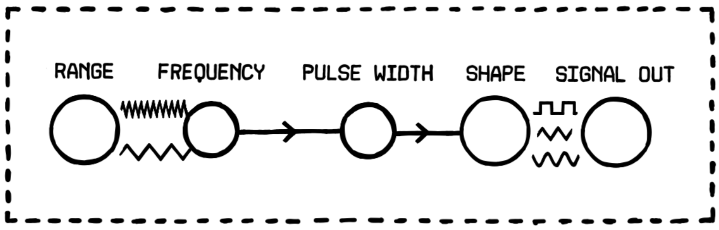
Labor comes equipped with everything you need for prototyping your circuits. In the center, there's a standard 830 tie point **breadboard**. This is where you'll insert your non-interfacing components like resistors, capacitors, diodes, and ICs. Right next to the breadboard, you'll find a **power header**. Here, you can grab any of the four available supply voltages (12 V, 5 V, 0 V, -12 V) and connect them to the breadboard's power rails.

At the bottom of the device, there's a **modular interfacing section**. This is where you'll insert all of your interfacing components like potentiometers, jack sockets, and switches. Those components' connectors are then routed to the interfacing headers at the top of the interfacing section. From here, you can conveniently connect them to any point on your breadboard using the bundled jumper cables. You can find more information on how this works in the next chapter.

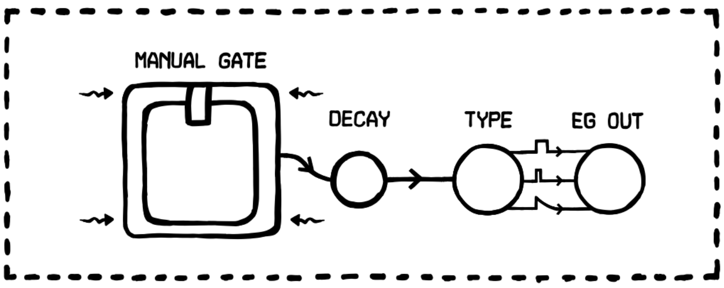
At the top of the device, there's a **utility section** that houses a couple useful circuit design tools. First up, we've got a **power switch** on the very right. Once you've plugged your Labor into the wall using the the included wall wart, you can turn the device on by flipping that power switch. There are two status indicator LEDs: one for the 12 V rail, and one for the -12 V rail. Both should light up, indicating that the power supply works as expected.

The power supply has one hidden, but very important extra feature. If you accidentally create a short circuit, it will refuse to turn on to protect your components. In that case, the status indicator LEDs will stay dark even after you flip the power switch. **If that happens,**

immediately remove the power plug from the device, check your circuit and fix the short. (People often accidentally mix up the positive and negative supply rail connections on a chip – this also creates a de-facto short circuit.) Be sure to always turn your device off when you make modifications to the circuit! Also, the short circuit protection is not 100% failsafe. Don't rely on it exclusively – make sure you always double check your circuit before turning the device on!
Next up, at the top left, we've got a free running square, triangle and sine **oscillator.**

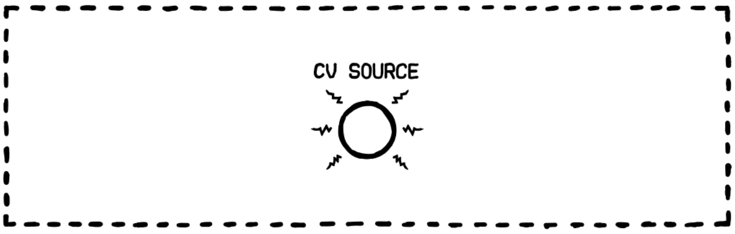


Use the **RANGE** switch to toggle between LFO and audio rate mode. (The former is great for testing modulation, while the latter gives you an audio signal to send through a filter, distortion circuit etc.) You can then set the oscillator's pitch via the **FREQUENCY** knob.
The next section allows you to select & control the oscillator's waveshape. Use the **SHAPE** switch to choose between square, triangle, and sine. If you've selected square, you can also manipulate its width via the **PULSE WIDTH** knob.
You can pick up the oscillator's output from either the **SIGNAL OUT** jack socket (for use with external gear), or from the **SIGNAL OUT** header (for use with your breadboarded circuit). Next up in the utility section, we've got a manual **gate/trigger/envelope generator**.

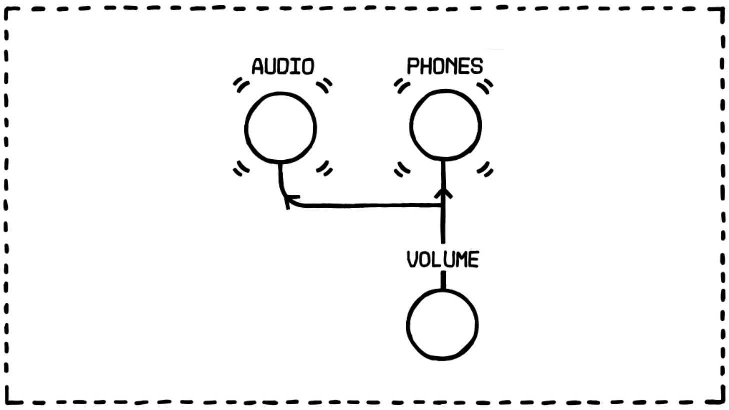


It's controlled by the mechanical push button labeled **MANUAL GATE**. Use the **TYPE** switch to select an output type, then press the button to trigger the generator. The button's LED will light up in sync with the output voltage generated. If you selected the envelope type, you can additionally control its decay via the **DECAY** knob.
Like the oscillator, the gate/trigger/envelope generator has two types of output: one jack socket labeled **EG OUT** for driving external gear, and a header labeled **EG OUT** for connecting the generator to your breadboarded circuit.

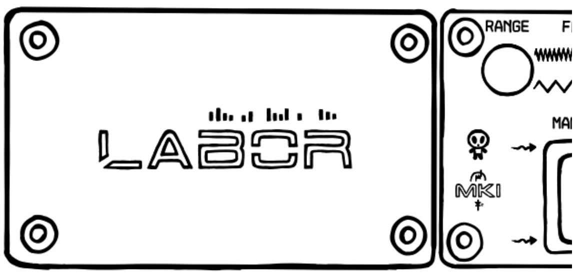
Next to the generator, there's a buffered variable **CV source**.



It can produce any voltage between -8 V and 8 V, and it's controlled via the knob labeled **CV SOURCE**. You can pick up its output from the header labeled **CV SOURCE.** Further to the right, you'll find the integrated **output amplifier** section.



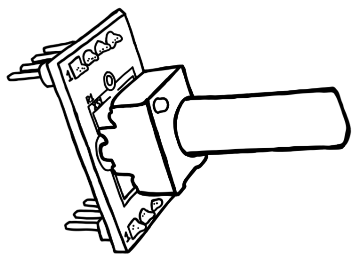
If you connect a signal from the breadboard to the header labeled **AUDIO IN**, you can pick up an amplified version at the jack sockets labeled **AUDIO** and **PHONES.** (The former sends out a line level signal, while the latter is able to drive headphones.) You can control the output volume via the knob labeled **VOLUME.** Finally, next to the utility section, you'll find Labor's **expansion slot.**

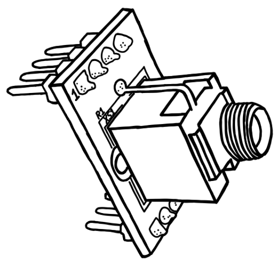


Here, you can insert useful mini-devices that we sell separately. If you don't have any devices to plug in right now, use the included **protection panel** to cover the slot.

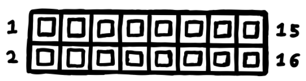
MODULAR INTERFACING SECTION CLOSE-UP

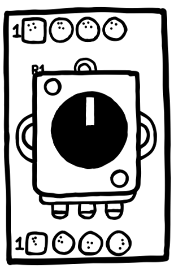
Before you can insert your potentiometers, sockets and switches into Labor's modular interfacing section, you'll first need to solder them to the included adapter mini-PCBs. (This is described in detail in the assembly guide section above.) Afterwards, they should look something like this.

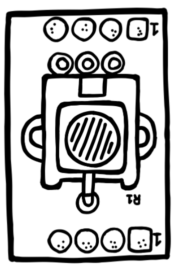




Using the 2x4 pins below the PCBs, you can now plug your interfacing elements into the 2x4 headers at the bottom of the device. You'll notice that there are some helpful notes on the device itself that explain how the individual interfacing elements are connected to the headers above. We'll break this down by looking at an example.

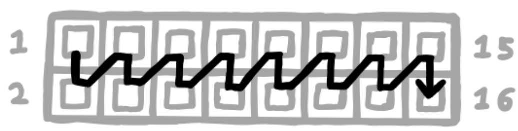


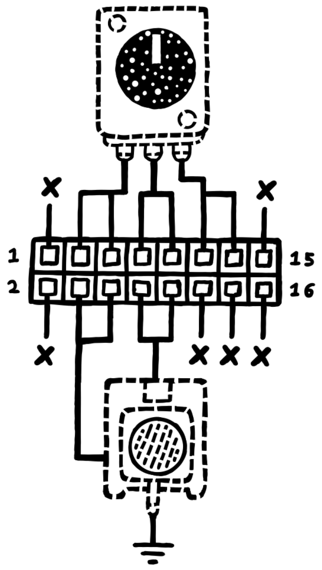




Let's assume that we've inserted a potentiometer into the top slot, and a jack socket into the bottom slot of an I/O column. The text on your Labor will tell you that for the potentiometer, **CCW** (left pin) is connected to pins 3 and 5, **WIPER** (middle pin) is connected to pins 7 and 9, and **CW** (right pin) is connected to pins 11 and 13. Similarly, it will tell you that for the jack socket, **TIP** (signal pin) is connected to pins 7 and 9, and **LUG** (switching pin for the default input) is connected to pins 3 and 5.

Okay, but what does this mean in practice? Simple: next to the 16-pin header, you'll find the numbers 1, 2, 15, and 16. These indicate that the individual pins are numbered in a zig-zag pattern.

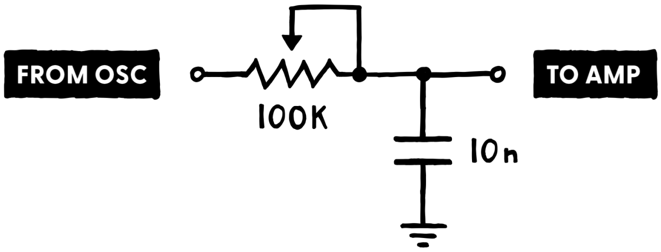




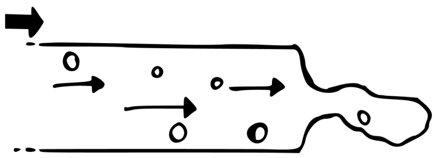
Knowing this, we can work out which pin connects where for our pot & socket – see the illustration on the left. Any pins marked with an **X** are inactive and don't connect anywhere. Note that the jack socket is automatically hooked up to the ground rail – no need to handle this yourself. Using the included jumper cables, you can now connect your interfacing elements to any point on the breadboard.
You can also plug push buttons, single pole switches and double pole switches into Labor's modular interfacing section. For info on how their pins are wired to the interfacing header, check the instructions on the device itself.

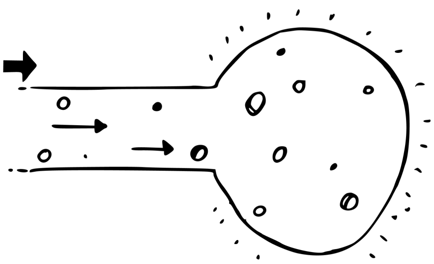
EXAMPLE CIRCUITS: LOW PASS FILTER

To do a first test with your Labor, let's set up a simple passive low pass filter. All we need for this are two components: a potentiometer and a capacitor.

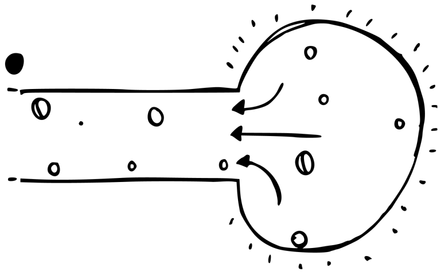


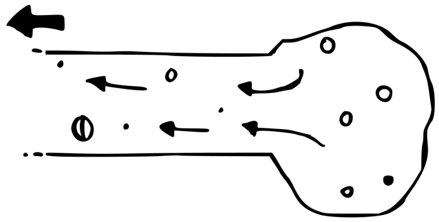
If we arrange them like this, any signal we feed into the input on the left will have its overtones removed to varying degrees, depending on the amount of resistance we dial in. In case you're confused as to how this works: let's dissect this little circuit. First of all, we'll take a look at what a resistor (i.e. our potentiometer) does in this scenario.
Resistors, if you don't know, basically act like narrow pipes that you can use to connect two points in your circuit. Their resistance value, measured in ohms, determines how strongly they restrict the flow of current. **So by using a resistor to connect two points in our circuit, we are restricting the flow of electricity between them**.
This by itself, without the capacitor, would not achieve anything in regards to our waveform. As long as no current is actually flowing out of our output, no current is passing through the resistor. And this means that the voltage applied to the input just gets transmitted as-is. So the voltage on the right will always be exactly the same as the voltage on the left. Even if the resistor is really, really strong.





But as soon as we introduce that capacitor, our circuit suddenly behaves very differently. **And that's because capacitors basically act like balloons that you can attach to some point in your circuit**. These balloons come in different sizes, ranging from very tiny to pretty huge. We measure that in a unit called farad.
As these balloons are filled with electrical charge, they begin to expand. **And just like with a real balloon, it will get harder and harder to push more charge in as the balloon starts pushing back increasingly**. Once the force we apply exactly matches the ballon's responding force, no current will flow anymore – the balloon is „full“.

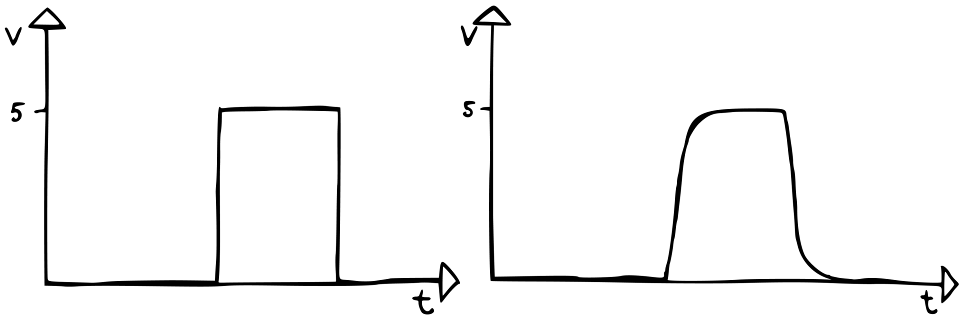




But note that „full“ in this context simply means as full as the given pressure can force it to be. If we were now to increase the pressure, the balloon would fill up even more – until the forces are balanced again. Of course we can’t do this indefinitely. At some point, the balloon will pop – just like a capacitor can explode if you push it too far.

But let’s assume that we’re staying well within specifications. **Then once we stop pushing current into it, the filled balloon will push its contents back into the circuit.** As more and more current leaves, the pressure (i.e. voltage) within the balloon will drop. Until the two forces are once again balanced.

Going back to our filter circuit, let’s try and apply what we’ve just learned. We’ll keep track of the voltage levels at the input and output in these two graphs: input voltage on the left, output voltage on the right.



We now know that the resistor acts like a flow-restricting narrow pipe, while the capacitor acts like a charge-storing balloon. So let’s say that the input voltage suddenly jumps from 0 V to 5 V. Unlike before, that voltage will now cause current to flow through the resistor and into the capacitor, filling it up.

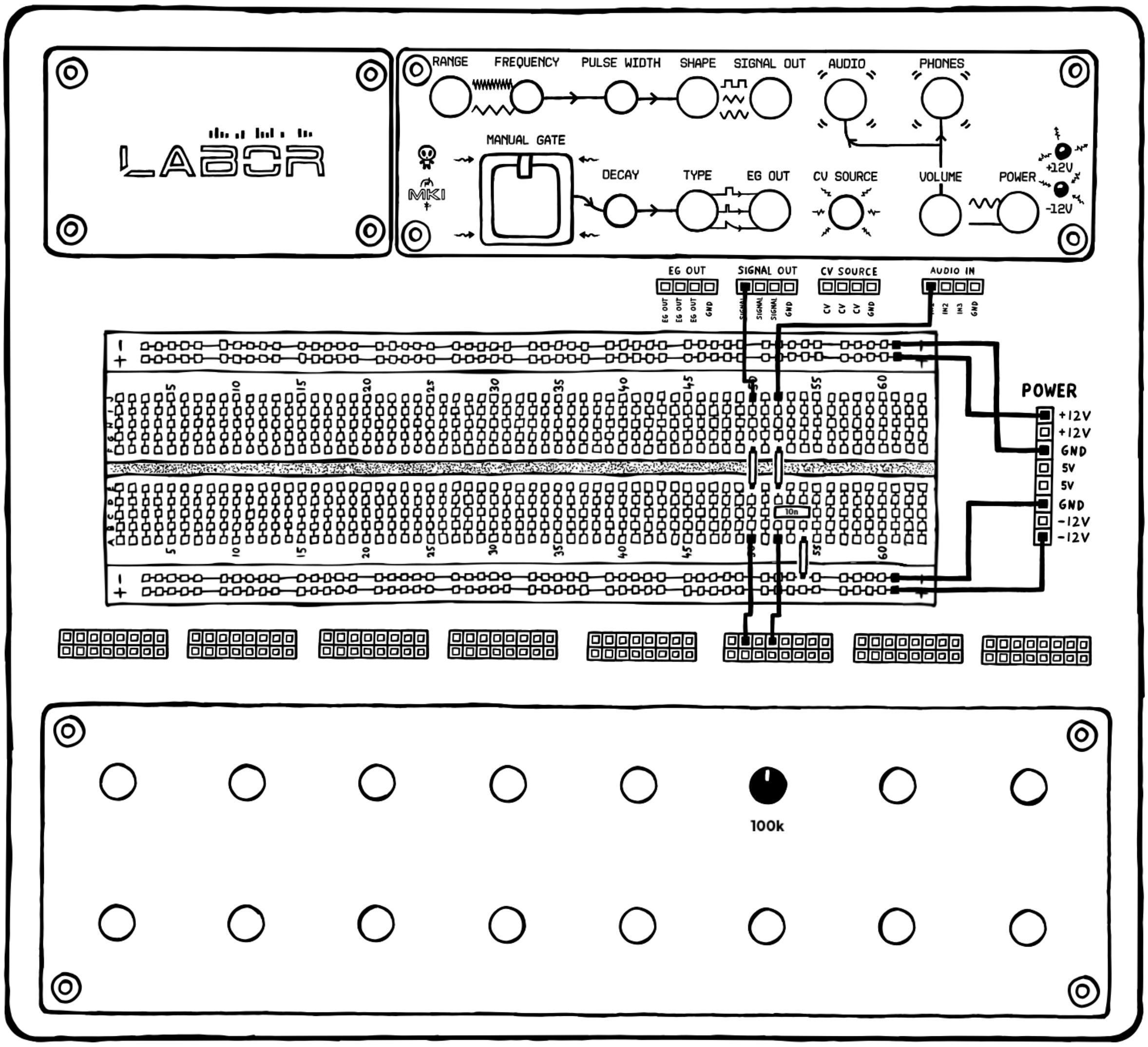
This means that the input voltage is no longer instantly transmitted to the output – because filling the capacitor up takes some time. Once it is full, we’ll read 5 V at the output. And the rate at which it fills up depends on two key factors: the size of the capacitor and the strength of the resistance. The bigger the capacitor, the longer it takes to fill it up. The weaker the resistance, the more current can flow and the quicker the capacitor is filled up.

Next, we’ll imagine that the input voltage suddenly drops to 0 V. This means that the capacitor will start pushing its contents back through the resistor, since there is no opposing force anymore. **While the capacitor is emptying, the output voltage is slowly declining – until it finally hits 0 V**. And again, the duration of that process depends on the capacitor’s size and the resistor’s strength.

You’ll notice that I’ve drawn a slight quirk into the way the output voltage ramps up and falls. **That’s because pushing current into the capacitor gets harder as we approach**

the maximum voltage level, and the voltage inside the capacitor gets weaker as it empties out.

The end result is a waveform that is decidedly less angular than the square wave we sent in.[1] Because of this, we can expect it to sound a lot less harsh. To try this for yourself, here's how you could set it up.



We grab Labor's oscillator from the **SIGNAL OUT** header, route it through the 100k potentiometer plugged into the interfacing section before connecting it back to the breadboard. Here, we then add a 10n capacitor going to ground, before routing the signal to the **AUDIO IN** header.

Once you've set this up, connect your headphones to the **PHONES** output, set the oscillator's waveform to square, the range to audio rate, and turn the filter potentiometer all the way to the left. You should hear a bright, buzzing sound. Now slowly turn the pot in

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[1] You can try this chapter's circuit in a simulator. I've already set it up for you right here. You can change all values by double clicking on components.

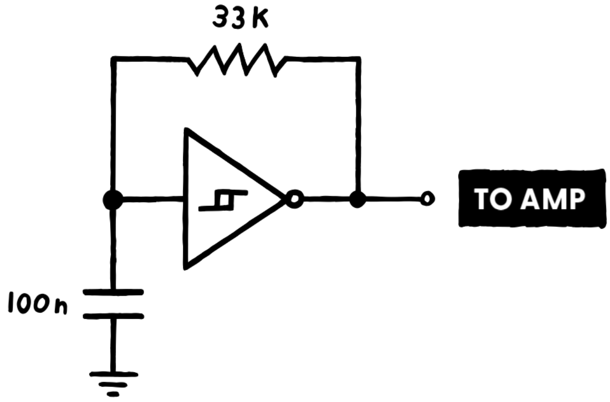
the other direction. The sound should gradually get less bright. This is because the high frequency content gets filtered out as the resistance increases.[2]

You'll notice that you cannot fully close the filter. Even if you turn the potentiometer all the way to the right, you can still hear the oscillator (though with far fewer overtones.) **As an optional challenge, think about how you could extend the filter's range so that it can be fully closed.** What would you have to change about the circuit? Also, is there a way to make this filter out low frequencies instead of high frequencies?

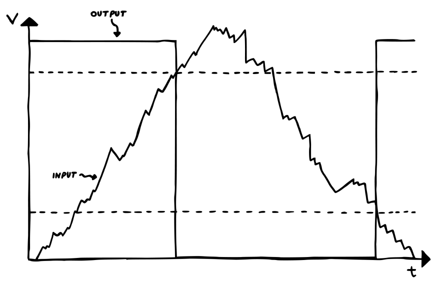
[2] If you've purchased the Oscilloscope Expansion, try looking at the output wave as you turn the potentiometer. You should see its edges get smoother, as if they're being sanded off.

EXAMPLE CIRCUITS: OSCILLATOR

Next, let’s try setting up a simple square wave oscillator ourselves. For this, we need three components: a schmitt trigger inverter, a resistor, and a capacitor.

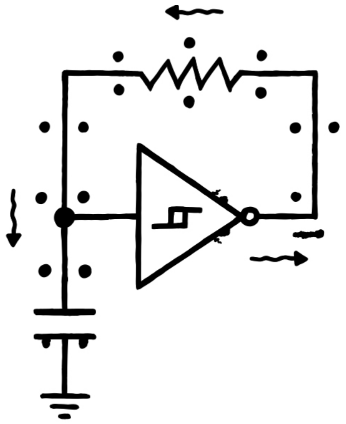


In case you don’t know what a schmitt trigger inverter does: you can think of it as two separate things. On the left, there’s a sensor that measures voltage. On the right, there is a current pump. The current pump’s operation is controlled by the sensor. Whenever the voltage probed by it is below a certain threshold, the current pump will be working. If the voltage is above a second threshold, the pump won’t be working.

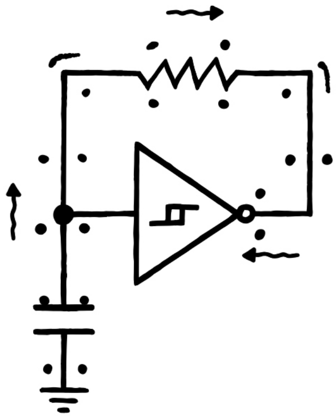


Here’s a quick graph to visualize that. The squiggly line represents the voltage at the input, while the solid line shows the voltage at the output. **So every time we cross the upper threshold on our way up, and the lower one on our way down, the output changes state**. One thing that’s very important to keep in mind: no current flows into the sensor! It’s really just sensing the voltage without affecting it.

With this in mind, let’s piece together how our oscillator works. When we first turn on the circuit, the capacitor will be empty and the voltage above it will be 0. **The schmitt trigger inverter will interpret this as a low input state, causing it to put its output into the high state**. Now, current flows from the chip’s output through the resistor and into the capacitor, filling it up. As it fills up, the voltage above it rises.



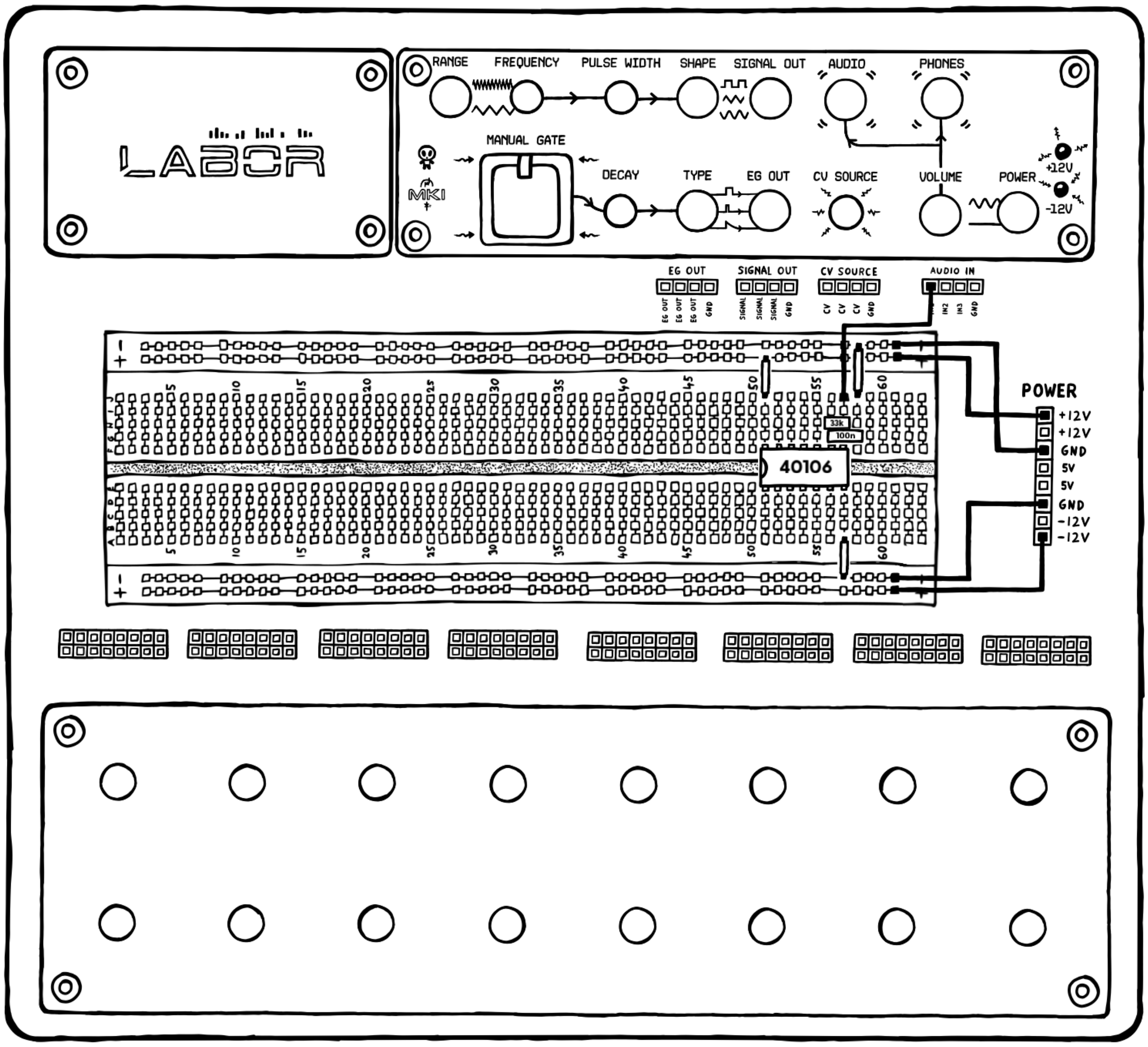
At some point, the voltage above the capacitor will cross the schmitt trigger inverter's upper input threshold, causing it to latch into the high input state. In response, it'll put its output into the low state. Because the capacitor voltage is now much higher than the inverter's output voltage, current will flow out of the cap and back into the output.



Until we hit the lower input threshold, the inverter latches into the low input state, and the whole process repeats. At the inverter's output, this gives us a square wave whose frequency depends on the size of both resistor and capacitor: increasing either will decrease the frequency, because it takes longer to charge and drain the cap.[3]

[3] You can try this chapter's circuit in a simulator. I've already set it up for you right here. You can change all values by double clicking on components.

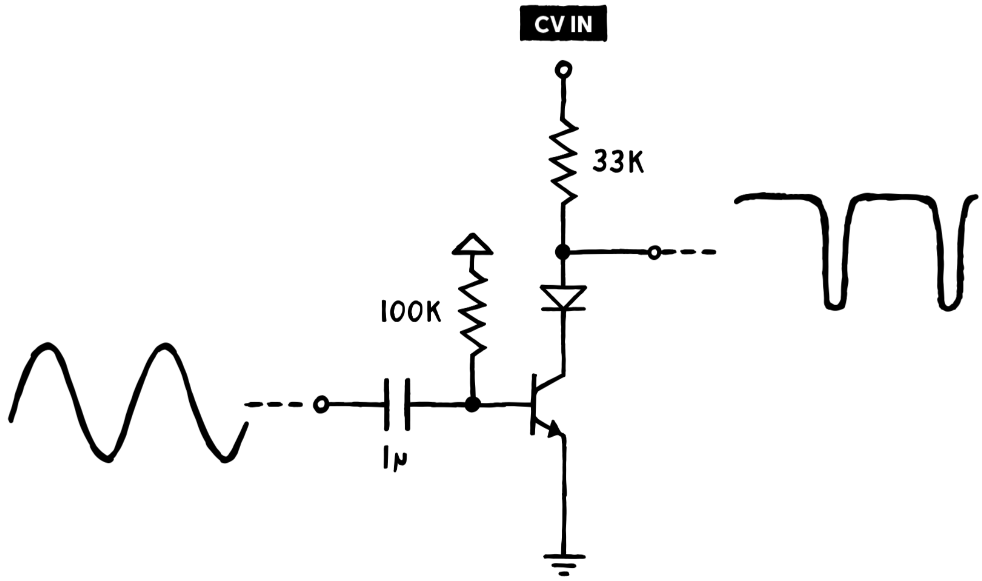
To try this out, here’s how you could set it up.



First, we plug a 40106 hex schmitt trigger inverter chip (which contains six individual schmitt trigger inverters) into the breadboard and connect it to +12 V and ground. Then, we add a 100 nF capacitor at one schmitt trigger inverter’s input. Connect its input and output using a 33k resistor and route the output to the **AUDIO IN** header, and we’re done. Once you’ve set this up, connect your headphones to the **PHONES** output. You should hear a bright, buzzing sound. **As an optional challenge, think about how you could change the oscillator’s pitch**. Is there any way you could make it higher or lower? Also, is there a way to change the pitch on the fly?

EXAMPLE CIRCUITS: CRUDE VCA

Next, let's set up a circuit that allows us to test your Labor's envelope generator: a simple, crude VCA (**V**oltage **C**ontrolled **A**mplifier). For this, we need five components: a transistor, two resistors, a capacitor and a diode.



To understand how it works, let's take this circuit apart. The central piece is a generic NPN transistor, set up as a high gain amplifier. For that, we connect its collector to the positive rail via a 33k resistor. (We'll ignore the diode for now.) Then, we bias our input upwards using a 1 µF capacitor followed by a big 100k resistor also connecting the transistor's base to the positive rail. **This ensures that current is flowing through the transistor even if the input signal currently at or slightly below the 0 V-line**.
That current can then be manipulated by the signal pushing against and or pulling at the capacitor. The transistor in turn replicates those changes in voltage at its collector by opening up and closing down – though with a huge gain. Because of this huge gain, this VCA adds a ton of distortion to its output. **Basically, any tiny change in voltage at the input results in a big change in voltage at the collector.** So any signal that's not extremely low in volume will be transformed into a harsh, distorted pulse wave.
That pulse wave's amplitude, and that's the kicker, is then determined by the control voltage we apply to the 33k resistor. Simply because it sets the maximum voltage that we can get below that resistor when the transistor is fully closed. **So by lowering the control voltage, we lower the volume of our output signal.**[4]

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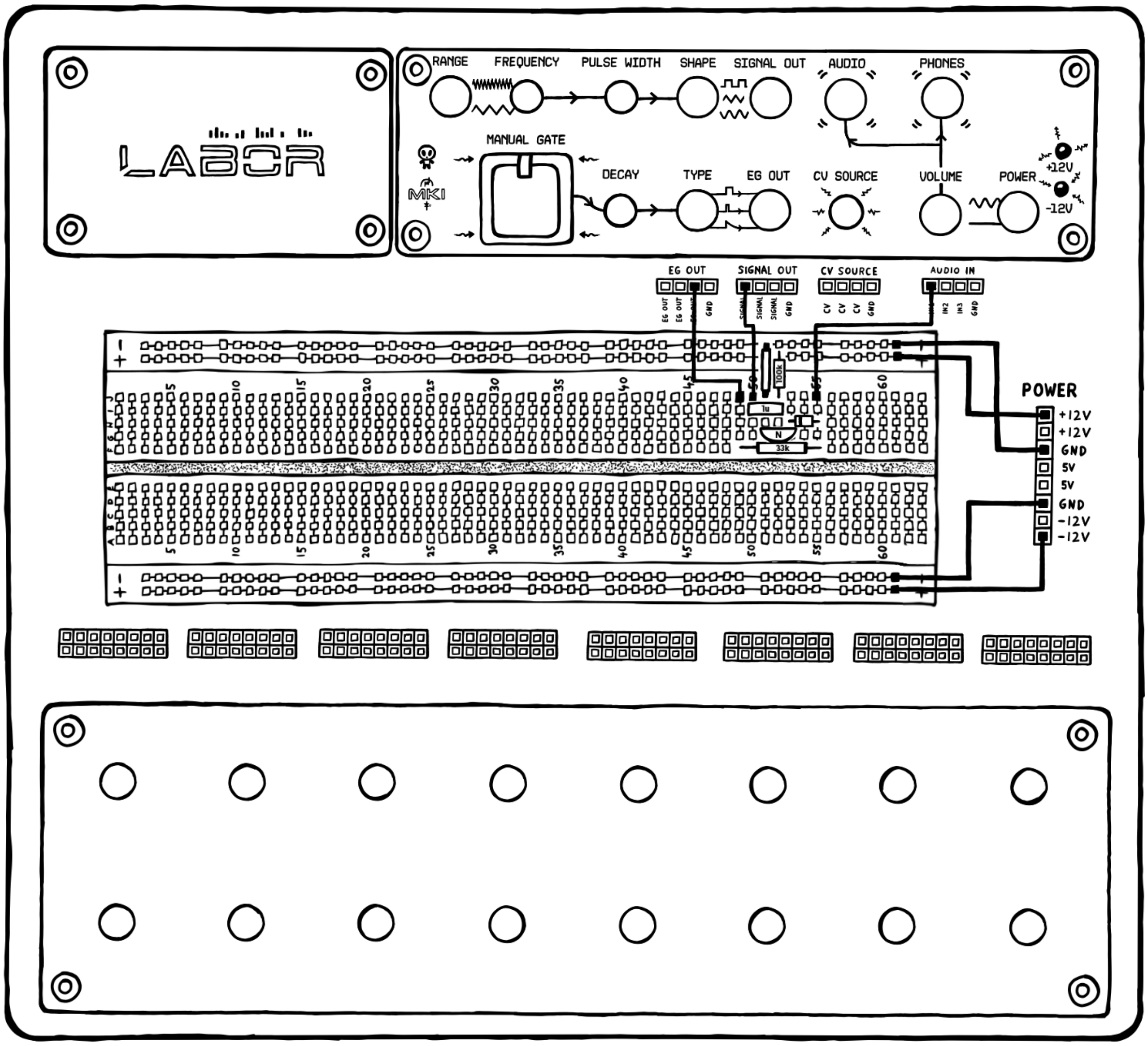
[4] You can try this chapter's circuit in a simulator. I've already set it up for you right here. You can change all values by double clicking on components.

Alright, but what about the diode between the 33k resistor and the collector? Well, there's one small issue with this setup. **If the control voltage is 0 and there is no diode there, current will flow into the base, out of the collector and towards that low voltage node**. And as the input signal oscillates, so will that current flow. Resulting in an audible signal at the VCA's output. By putting the diode here, we stop that from happening – and our VCA will be mostly silent at 0 V control voltage. To try this out, here's how you could set it up.



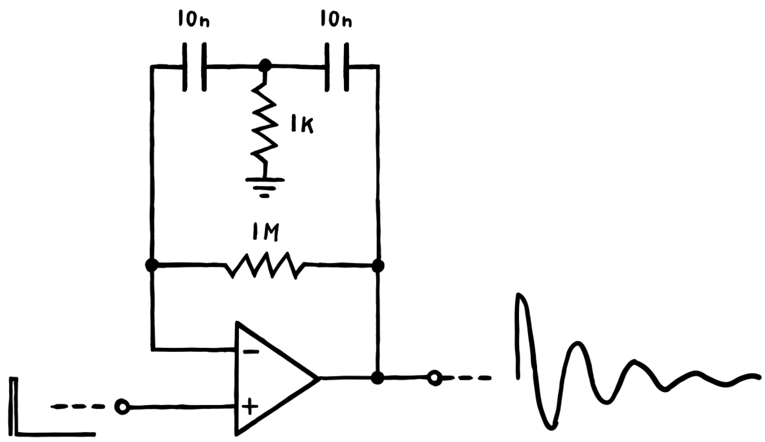
First, we grab Labor's oscillator from the **SIGNAL OUT** header and route it through a 1 µF capacitor on the breadboard. On the other side, add the NPN transistor, connect its base to the positive rail using a 100k resistor and its emitter to ground. Next, grab Labor's envelope generator from the **EG OUT** header and connect it to the transistor's collector via a 33k resistor and a 1N4148 small signal diode. Finally, connect the VCA's output to the header labeled **AUDIO IN**.

Once you've set this up, plug your headphones into the **PHONES** output, select the envelope setting on the switch labeled **TYPE** and turn up the knob labeled **DECAY**. Make sure the oscillator is operating in the audio range, select the sine wave option using the **SHAPE** switch, and press the **MANUAL GATE** button. You should hear the oscillator come in instantly and then fade away gradually.

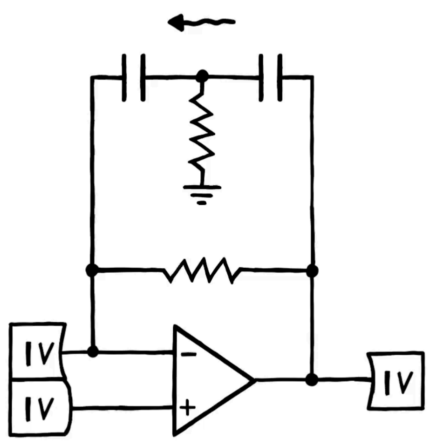
You'll notice that the signal doesn't really sound like a sine wave. This is because of the distortion added by the VCA. If you have the Oscilloscope Expansion, try looking at the VCA's output and compare it to the original sine wave. How does the VCA change the waveshape? **As an optional challenge, think about how you could reduce the amount of distortion added by the VCA**. Is there a way to smooth the output signal's edges a little?

EXAMPLE CIRCUITS: BRIDGED-T OSCILLATOR

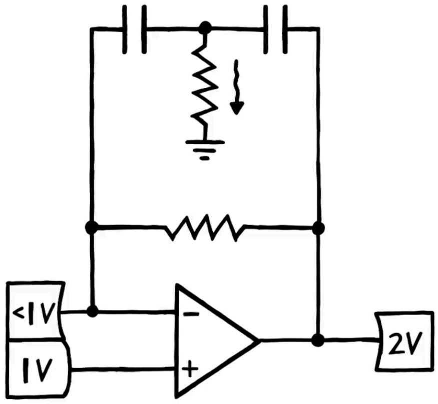
Finally, let's set up a circuit that allows us to test Labor's trigger generator: a bridged-t oscillator. It consists of just one op amp, two resistors and two capacitors. **Together, they form a strange sine wave oscillator that needs to be kickstarted by a voltage pulse to actually oscillate**. And even then, it won't continue oscillating (like other oscillators do), but quickly drop in volume and eventually die out completely. Which is ideal for creating simple percussive sounds.



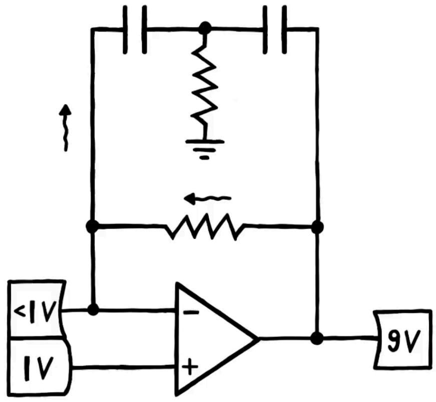
So let's look at how this works. We'll assume that the voltage at the op amp's non-inverting input quickly jumps from 0 to 1 V. Now, to reach a state of balance, the op amp will try to push the voltage at its inverting input up to 1 V as well. For that, it'll increase its output voltage to 1 V. Initially, this will work just fine, since that voltage pushes straight through the two capacitors and reaches the inverting input that way.



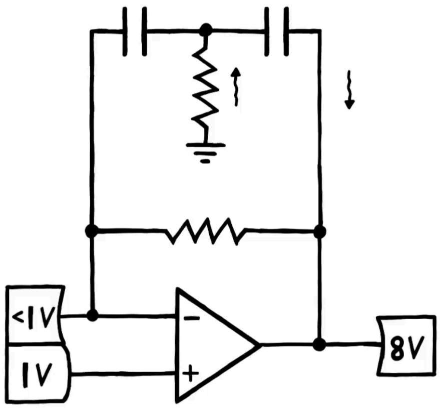
But because there is a resistor to ground between the two caps, we'll see current drain out from the first capacitor. Which means that the voltage applied to the second cap (and subsequently, the inverting input) will drop. To compensate, the op amp will raise its output voltage. **But as it does that, even more current is squeezed out of the first cap, forcing the op amp to push even harder**.



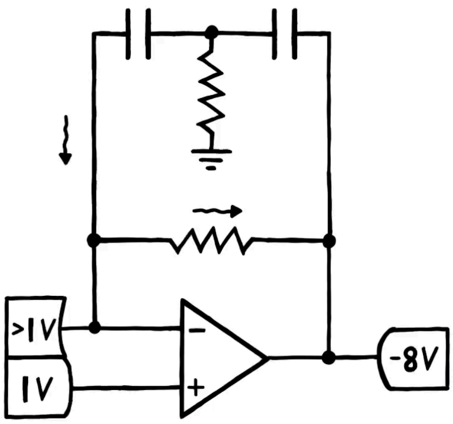
And this would continue until the op amp runs into the upper supply voltage – if it weren't for the bridge resistor between output and inverting input. **Because as the op amp pushes harder and harder, that resistor allows a small current to charge up the second cap from the other side**.



At some point, this process will add more voltage on the left as we lose on the right, causing the whole mechanism to kick into reverse gear. Now, the op amp will start dropping its output voltage to try and course correct. Only problem is that this will pull current out of the first cap, and subsequently up from ground, increasing the voltage between the two caps and also at the inverting input. Which forces the op amp to reduce its output voltage even further.



Eventually, we'll again reach a tipping point where the whole mechanism reverses. Only this time, it'll be at a slightly lower output voltage. **That's because with every charging and discharging cycle, we lose a bit of the momentum we initially put in**. The circuit behaves kind of like a pendulum that way.



And so the output it produces is a sine wave swinging around the non-inverting input voltage with a steadily decreasing amplitude. Which should give us a nice quick percussive hit. In order to tune it to a specific frequency, we have to choose the right combination of capacitor and resistor values. **This is a little tricky, since all of those values influence both frequency and decay at the same time.** Using two 10 nF capacitors, a 1M bridge resistor, and a 1k resistor going to ground should give us a woodblock-ish sound with a decently long decay.[5]
To kickstart the oscillator, we'll use Labor's trigger signal. Because the oscillator needs enough room to swing, we'll have to divide the trigger down. For that, we'll simply insert a 100k/10k voltage divider at the op amp's non-inverting input.

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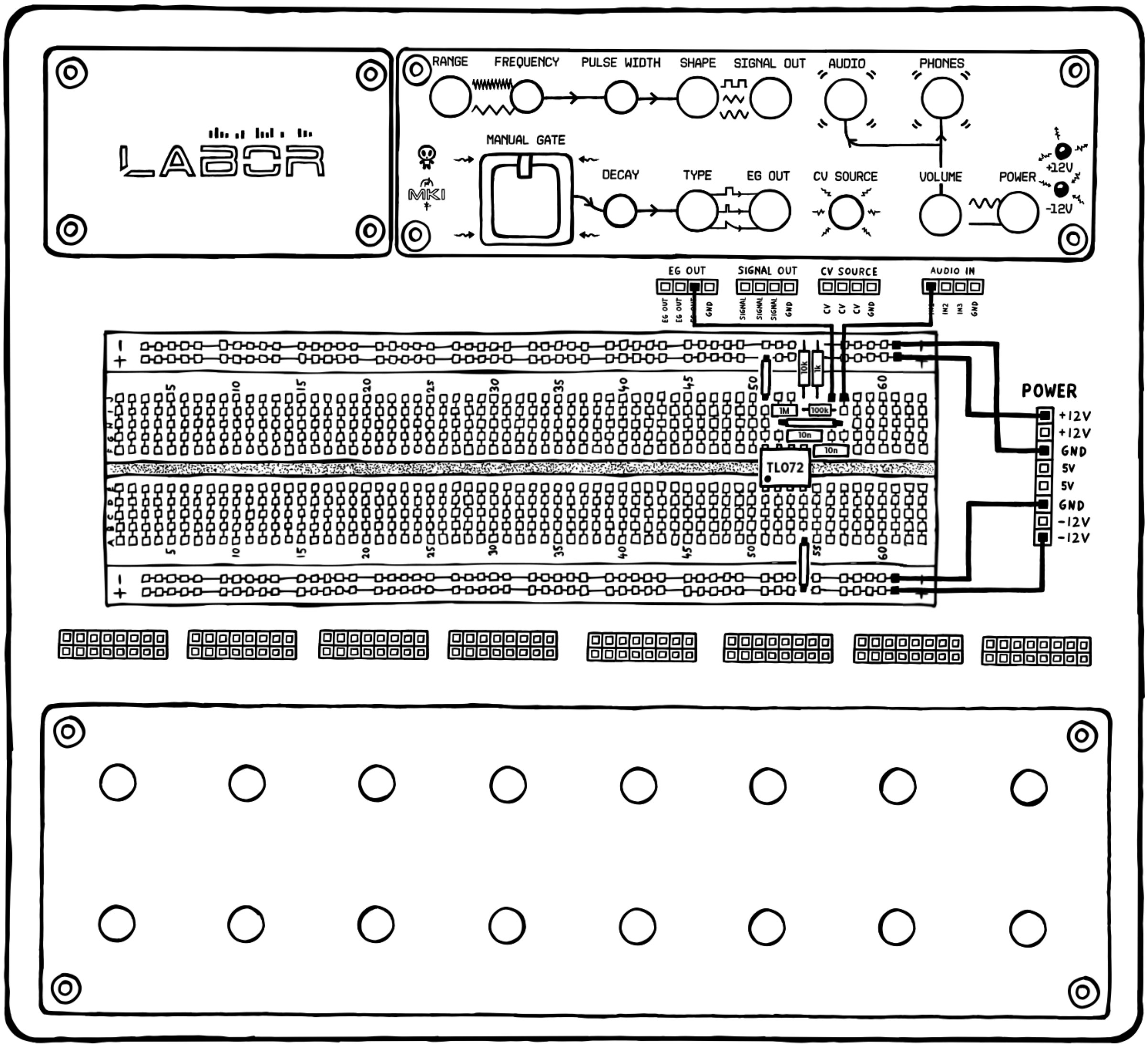
[5] You can try this chapter's circuit in a simulator. I've already set it up for you right here. You can change all values by double clicking on components.

To try this out, here's how you could set it up.

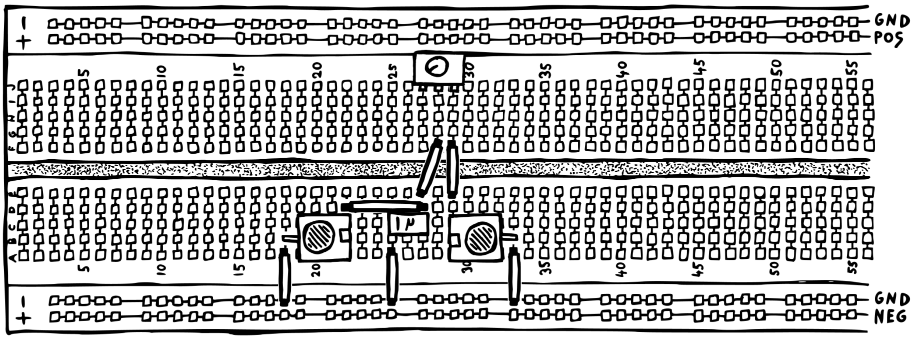


First, we'll set up a TL072 chip, which houses two generic op amps, and connect it to the positive and negative rail. Next, grab Labor's trigger from the header labeled **EG OUT** and connect it to the top op amp's non-inverting input via a 100k/10k voltage divider. Then, connect the op amp's inverting input and output via a 1M resistor – and also via the two 10 nF capacitors in series. Finally, add the 1k resistor to ground where the two caps meet and wire up the op amp's output to the **AUDIO IN** header.

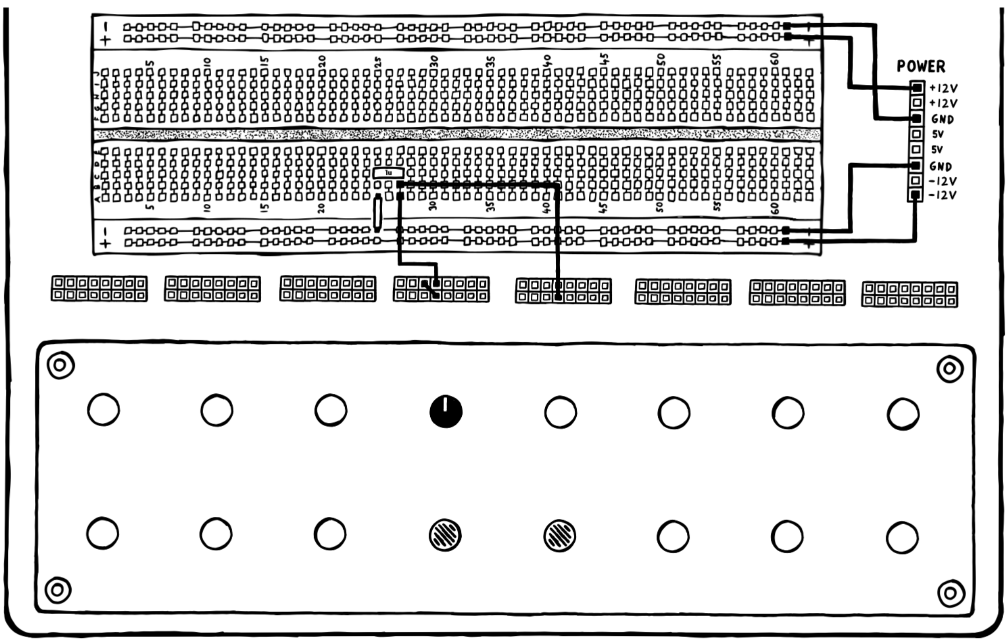
Once you've set this up, plug your headphones into the **PHONES** output and select the trigger setting on the switch labeled **TYPE**. Press the **MANUAL GATE** button. You should hear a sound resembling a woodblock. As an optional challenge, think about how you could change the pitch of the sound. Is there a way to adjust it on the fly?

USING OUR DIY KITS WITH LABOR

In the manuals for our **MKI x ES.EDU DIY** kits, you'll find suggested breadboard layouts at the end of most chapters. You can replicate them as-is on your Labor, but to get the most out of it, we recommend that you handle the interfacing elements like jack sockets, potentiometers and switches via Labor's modular interfacing section instead. Here's a quick example. Let's assume that we've got this suggested breadboard layout using two sockets and a potentiometer.



Then in order to adapt it to your Labor, you'll want to plug both jack sockets and the potentiometer into the modular interfacing section instead and connect them to the board using jumper cables. Be aware that you do not need to connect your sockets to ground manually – the modular interfacing section is taking care of that for you internally. **Also, make sure to use the potentiometers and sockets that come with your Labor kit for this! If you solder the DIY kit's interfacing elements to the Labor adapter mini-PCBs, you cannot use them to assemble the DIY eurorack module later!**

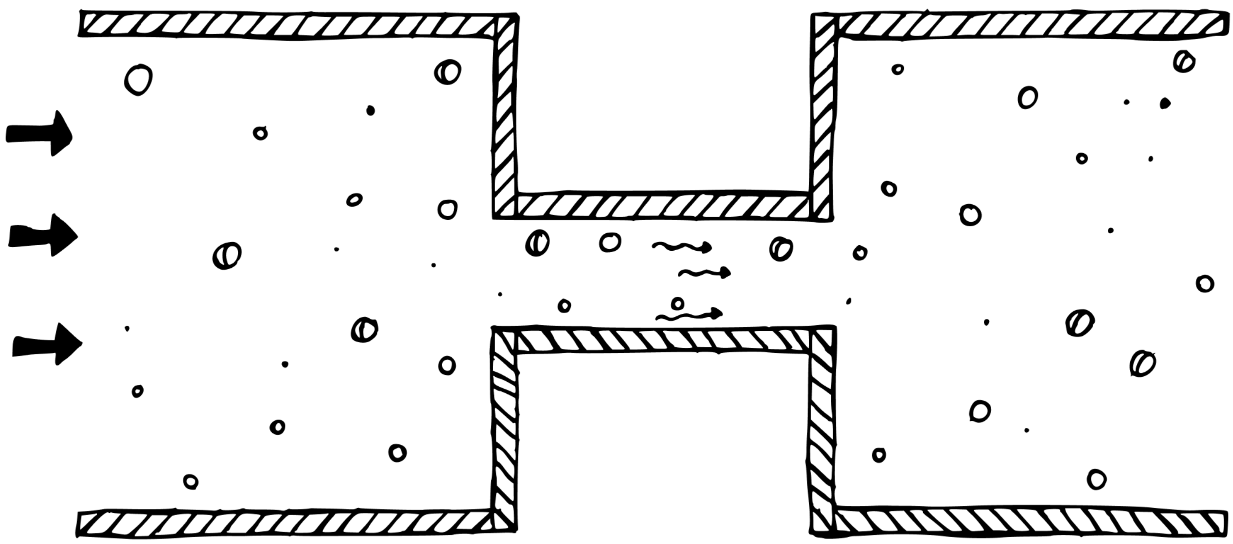


COMPONENTS & CONCEPTS APPENDIX

In this section, we'll take a closer look at the components and elemental circuit design concepts we're using to design our circuits. Check these whenever the main manual moves a bit too fast for you!

THE BASICS: RESISTANCE, VOLTAGE, CURRENT

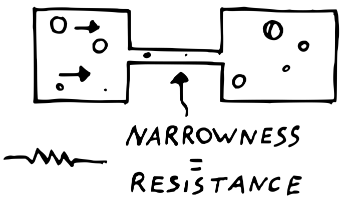
There are three main properties we're interested in when talking about electronic circuits: resistance, voltage and current. To make these less abstract, we can use a common beginner's metaphor and compare the flow of electrons to the flow of water through a pipe.

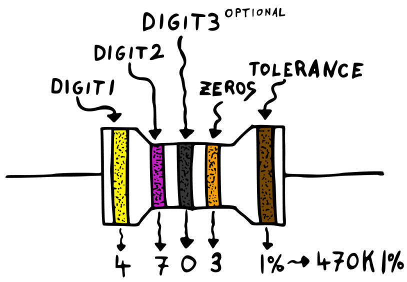


In that metaphor, resistance would be the width of a pipe. The wider it is, the more water can travel through it at once, and the easier it is to push a set amount from one end to the other. Current would then describe the flow, while voltage would describe the pressure pushing the water through the pipe. You can probably see how all three properties are interlinked: **more voltage increases the current, while more resistance to that voltage in turn decreases the current.**

RESISTORS

While a conductive wire is like a very big pipe where lots of water can pass through, **a resistor is like a narrow pipe that restricts the amount of water that can flow**. The narrowness of that pipe is equivalent to the resistance value, measured in ohms (Ω). The higher that value, the tighter the pipe.





Resistors have two distinctive properties: linearity and symmetry. Linearity, in this context, means that for a doubling in voltage, the current flowing will double as well. Symmetry means that the direction of flow doesn't matter – resistors work the same either way.

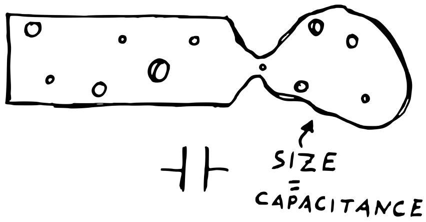
On a real-life resistor, you'll notice that its value is not printed on the outside – like it is with other components. Instead, it is indicated by colored stripes[6] – along with the resistor's tolerance rating.

While in the long run, learning these color codes will be quite helpful, you can also simply use a multimeter to determine a resistor's value.

[6] For a detailed breakdown, look up resistor color coding. There are also calculation tools available.

CAPACITORS

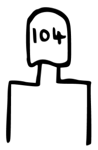
A capacitor is a bit like a balloon that you can attach to the open end of a pipe. If there's some pressure in the pipe, the balloon will fill up with water until the pressure equalizes. (Since the balloon needs some space to expand into, both of the capacitor's legs need to be connected to points in your circuit.)



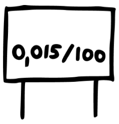
Then, should the pressure in the pipe drop, the balloon releases the water it stored into the pipe. The maximum size of the balloon is determined by the capacitor's capacitance, which we measure in farad (F). There are quite a few different types of capacitors: electrolytic, foil, ceramic, tantalum etc. They all have their unique properties and ideal usage scenarios – but the most important distinction is if they are polarized or not.

You shouldn't use polarized capacitors against their polarization (applying a negative voltage to their positive terminal and vice versa) – so they're out for most audio-related uses like AC coupling, high- & low-pass filters etc.

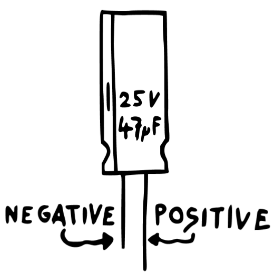
Unlike resistors, capacitors have their capacitance value printed onto their casing, sometimes together with a maximum operating voltage. **Be extra careful here!** That voltage rating is important. Your capacitors can actually explode if you exceed it! So they should be able to withstand the maximum voltage used in your circuit. If they're rated higher – even better, since it will increase their lifespan. No worries though: the capacitors in this kit are carefully chosen to work properly in our circuits.



Ceramic capacitors usually come in disk- or pillow-like cases, are non-polarized and typically encode their capacitance value.[7] Annoyingly, they rarely indicate their voltage rating – so you'll have to note it down when buying them.



Film capacitors come in rectangular, boxy cases, are non-polarized and sometimes, but not always, directly indicate their capacitance value and their voltage rating without any form of encoding.[8]

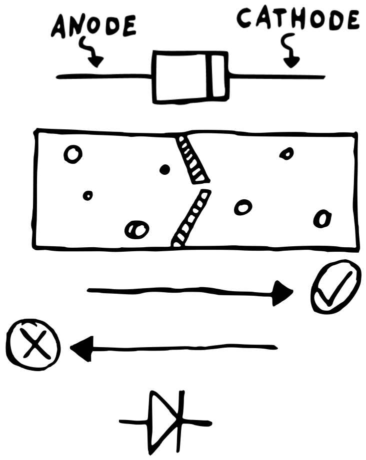


Electrolytic capacitors can be identified by their cylinder shape and silver top, and they usually directly indicate their capacitance value and their voltage rating. They are polarized – so make sure you put them into your circuit in the correct orientation.

[7] For a detailed breakdown, look up ceramic capacitor value code. There are also calculation tools available.

[8] If yours do encode their values, same idea applies here – look up film capacitor value code.

DIODES

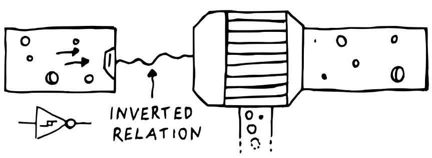


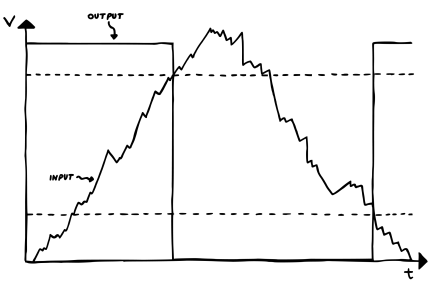
Diodes are basically like one-way valves. Current can only pass through in one direction – from anode to cathode. That direction is indicated by the arrow in the diode symbol and by a black stripe on the diode's casing. So any current trying to move in the opposite direction is blocked from flowing.

There are a few quirks here, though. For one, the diode will only open up if the pushing force is strong enough. Generally, people say that's 0.7 V**,** but in reality, it's usually a bit lower. Also, diodes don't open up abruptly – they start conducting even at much lower voltages, although just slightly.

There are a lot of different diode types: Zener, Schottky, rectifier, small signal etc. They all have their unique properties and ideal usage scenarios – but usually, a generic 1N4148 small signal diode will get the job done.

SCHMITT TRIGGER INVERTERS

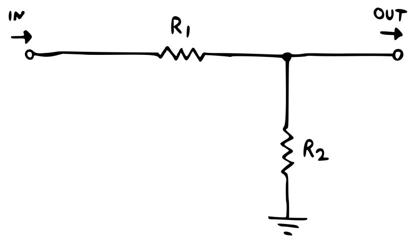




You can think of a Schmitt trigger inverter as two separate things. On the left, there's a sensor that measures the pressure inside an attached pipe. On the right, there is a water pump. This pump's operation is controlled by the sensor. Whenever the pressure probed by this sensor is below a certain threshold, the pump will be working. If the pressure is above a second threshold, the pump won't be working.

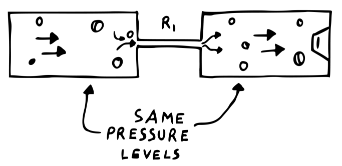
Here's a quick graph to visualize that. The squiggly line represents the voltage at the input, while the dotted line shows the voltage at the output. So every time we cross the upper threshold on our way up, and the lower one on our way down, the output changes its state. One thing that's very important to keep in mind: no current flows into the sensor! It's really just sensing the voltage without affecting it.

VOLTAGE DIVIDERS

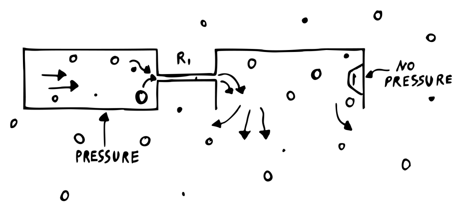


A voltage divider is really just two resistors set up like this: input on the left, output on the right. If R1 and R2 are of the same value, the output voltage will be half of what the input voltage is. How does it work?

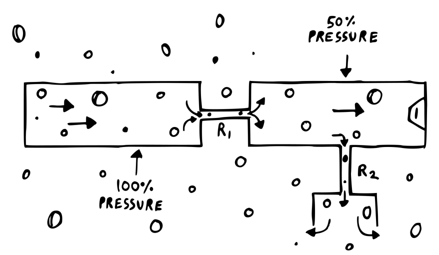
Let's use our analogy again: so we have a pipe on the left, where water is being pushed to the right with a specific amount of force. Attached to it is a narrow pipe, representing R1, followed by another wide pipe. Then at the bottom, there's another narrow pipe, representing R2, where water can exit the pipe system. Finally, imagine we've set up a sensor measuring the voltage in the right hand pipe.



First, think about what would happen if R2 was completely sealed off. Our sensor would tell us that **the pressure on the right side is exactly the same as the pressure on the left**. Because the pushing force has nowhere else to go.



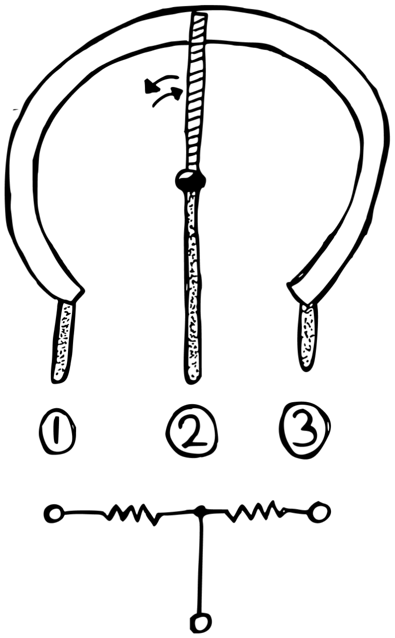
On the other hand, imagine R2 would just be a wide opening. Then **the pressure on the right would be 0**, because it'd all escape through that opening. But what happens if R2 is neither completely closed off nor wide open? Then the pressure would be retained to varying degrees, depending on the narrowness of the two resistor paths.



If pipe R1 is wide and pipe R2 is narrow, most of the pressure will be retained. But if it's the reverse, the pressure level will be only a tiny fraction. And if R1 and R2 are identical, **the pressure will be exactly half of what we send in**.

POTENTIOMETERS

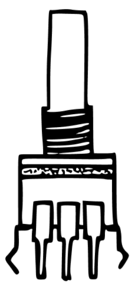
Potentiometers can be used as variable resistors that you control by turning a knob. But, and that's the handy part, they can also be set up as variable voltage dividers. To see how that works, let's imagine we open one up.

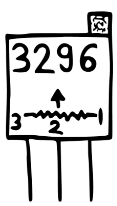


Inside, we would find two things: a round track of resistive material with connectors on both ends plus what's called a wiper. This wiper makes contact with the track and also has a connector. It can be moved to any position on the track. Now, the resistance value between the two track connectors is always going to stay exactly the same. That's why it's used to identify a potentiometer: as a 10k, 20k, 100k etc. But if you look at the resistance between either of those connectors and the wiper connector, you'll find that this is completely dependent on the wiper's position.

The logic here is really simple: **the closer the wiper is to a track connector, the lower the resistance is going to be between the two**. So if the wiper is dead in the middle, you'll have 50 % of the total resistance between each track connector and the wiper.

From here, you can move it in either direction and thereby shift the ratio between the two resistances to be whatever you want it to be. By now, you might be able to see how that relates to our voltage divider. If we send our input signal to connector 1 while grounding connector 3, we can pick up our output signal from the wiper. Then by turning the potentiometer's knob, we can adjust the voltage level from 0 to the input voltage – and anything in between.





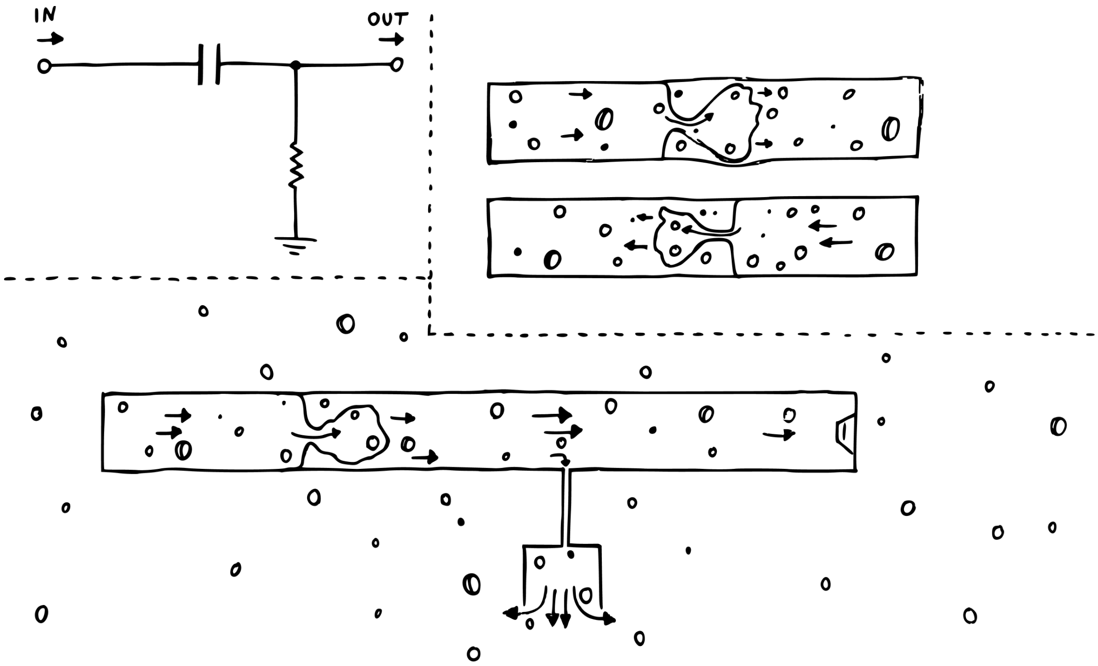
In our DIY kits, you will encounter different types of potentiometers. First, there's the regular, full-size variant with a long shaft on top. These are used to implement user-facing controls on the module's panel and they usually – but not always – indicate their value directly on their casing. Sometimes, they'll use a similar encoding strategy as capacitors, though.[9]

Second, we've got the trimmer potentiometer, which is usually much smaller and doesn't sport a shaft on top. Instead, these have a small screw head which is supposed to be used for one-time set-and-forget calibrations. Trimmers usually encode their value.

[9] Look up potentiometer value code for a detailed breakdown.

AC COUPLING

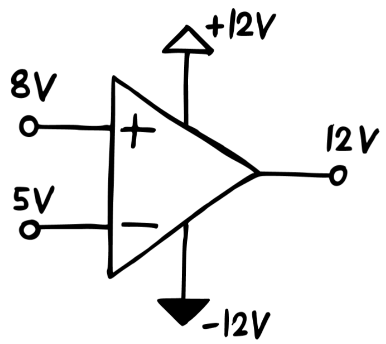
What is AC coupling – and how does it work? Imagine two adjacent pipes with a balloon between them. Now, no water can get from one pipe into the other, since it's blocked by the balloon. But, and that's the kicker, **water from one side can still push into the other by bending and stretching the balloon, causing a flow by displacement**.



Next, we'll bring in a resistor after the coupling point, going straight to ground. **This acts like a kind of equalizing valve**. Now imagine we apply a steady 5 V from one side. Then on the other side, we'll read 0 V after a short amount of time. Why? Because we're pushing water into the balloon with a constant force, causing it to stretch into the other side, displacing some water. If we didn't have the equalizing valve there, we'd simply raise the pressure. But since we do have it, the excess water can drain out of the system. Until the pressure is neutralized, and no water is actively flowing anymore.
Okay, so now imagine that the voltage on the left hand side starts oscillating, let's say between 4 V and 6 V. When we start to go below 5 V, the balloon will begin contracting, basically pulling the water to the left. This will create a negative voltage level in the right hand pipe – like as if you're sucking on a straw, making the voltage there drop below 0 V. Then, once the pressure on the other side rises above 5 V, the balloon will inflate and stretch out again, pushing water to the right. And the pressure in the right hand pipe will go positive, making the voltage rise above 0 V. **We've re-centered our oscillation around the 0 V line.** Okay, but what about the resistor? If current can escape through it, doesn't that mess with our oscillation? Well, technically yes, but practically, we're choosing a narrow enough pipe to make the effect on quick pressure changes negligible!

OP AMPS

Op amps might seem intimidating at first, but they're actually quite easy to understand and use. The basic concept is this: every op amp has two inputs and one output. Think of those inputs like voltage sensors. You can attach them to any point in your circuit and they will detect the voltage there without interfering. **No current flows into the op amps inputs – that's why we say their input impedance is very high**. Near infinite, actually. Okay, but why are there two of them?



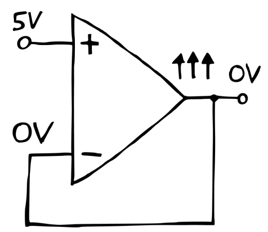
The key here is that op amps are essentially differential amplifiers. This means that they only amplify the difference between their two inputs – not each of them individually. If that sounds confusing, let's check out a quick example. So we'll imagine that one sensor – called the non-inverting input – is reading 8 V from somewhere. The other sensor – called the inverting input – reads 5 V. Then, as a first step, the op amp will subtract the inverting input's value from the non-inverting input's value. Leaving us with a result of 3. (Because 8 minus 5 is 3.) **This result then gets multiplied by a very large number – called the op amp's gain**. Finally, the op amp will try to push out a voltage that corresponds to that multiplication's result.

But of course, the op amp is limited here by the voltages that we supply it with. If we give it –12 V as a minimum and +12 V as a maximum, the highest it can go will be +12 V. So in our example, even though the result of that multiplication would be huge, the op amp will simply push out 12 V here and call it a day.

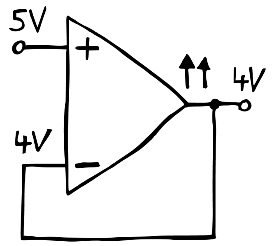
The handy thing though about op amp outputs is that they draw their power directly from the power source. This means that they can supply lots of current while keeping the voltage stable. **That's why we say an op amp has a very low output impedance**.

OP AMP BUFFERS/AMPLIFIERS

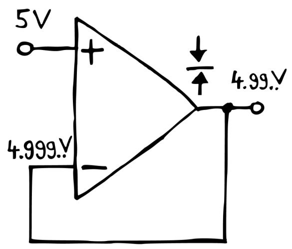
Buffering, in the world of electronics, means that we provide a perfect copy of a voltage without interfering with that voltage in the process. With an op amp-based buffer, the buffering process itself works like this. We use the non-inverting input to probe a voltage, while the inverting input connects straight to the op amp's output. **This creates what we call a negative feedback loop**. Think of it this way. We apply a specific voltage level to the non-inverting input – let's say 5 V.



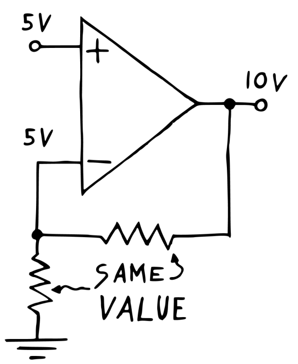
Before the op amp starts processing the voltages at its inputs, the output will be switched off. This means that **output and inverting input sit at 0 V at first**. So then, the op amp will subtract 0 from 5 and multiply the result by its gain. Finally, it will try and increase its output voltage to match the calculation's outcome.



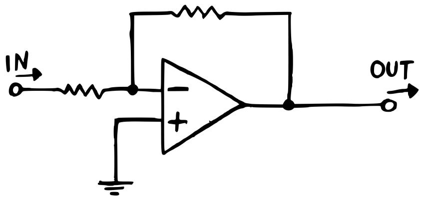
But as it's pushing up that output voltage, the **voltage at the inverting input will be raised simultaneously**. So the difference between the two inputs is shrinking down. Initially, this doesn't matter much because the gain is so large. As the voltage at the inverting input gets closer to 5 V though, the difference will shrink so much that in relation, the gain suddenly isn't so large anymore.



Then, the output will **stabilize at a voltage level that is a tiny bit below 5 V**, so that the difference between the two inputs multiplied by the huge gain gives us exactly that voltage slightly below 5 V. And this process simply loops forever, keeping everything stable through negative feedback. Now if the voltage at the non-inverting input changes, that feedback loop would ensure that the output voltage is always following. So that's why this configuration works as a buffer: the **output is simply following the input**.



How about amplifying a signal though? To do that, we'll have to turn our buffer into a proper non-inverting amplifier. We can do that by replacing the straight connection between inverting input and output with a voltage divider, forcing the op amp to work harder. Here's how that works. Say we feed our non-inverting input a voltage of 5 V. Now, **the output needs to push out 10 V in order to get the voltage at the inverting input up to 5 V**. We call this setup a non-inverting



amplifier because the output signal is in phase with the input.

For an inverting buffer/amplifier, the input signal is no longer applied to the non-inverting input. Instead, that input is tied directly to ground. So it'll just sit at 0 V the entire time. The real action, then, is happening at the inverting input. Here, we first send in our waveform through a resistor. Then, the inverting input is connected to the op amp's output through another resistor of the same value.

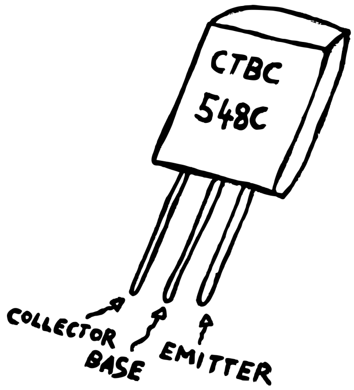
How does this work? Well, let's assume that we're applying a steady voltage of 5 V on the left. Then, as we already know, the op amp will subtract the inverting input's voltage from the non-inverting input's voltage, leaving us with a result of –5 V. Multiply that by the huge internal gain, and the op amp will try to massively decrease the voltage at its output.

But as it's doing that, an increasingly larger current will flow through both resistors and into the output. Now, as long as the pushing voltage on the left is stronger than the pulling voltage on the right, some potential (e.g. a non-zero voltage) will remain at the inverting input. Once the output reaches about –5 V though, we'll enter a state of balance. Since both resistors are of the same value, the pushing force on the left is fighting the exact same resistance as the pulling force on the right. **So all of the current being pushed through one resistor is instantly being pulled through the other**.

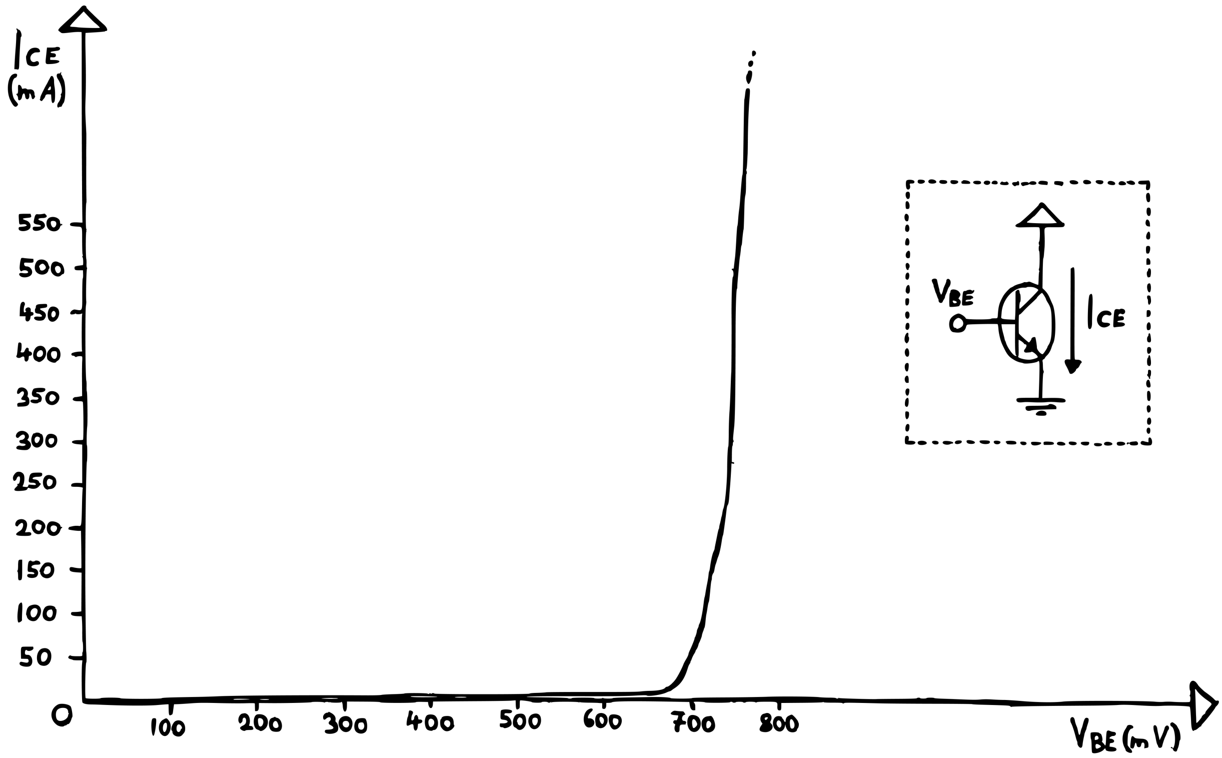
And that means that the voltage at the inverting input will be lowered to about 0 V, allowing our op-amp to settle on the current output voltage level. So while we read 5 V on the left, we'll now read a stable –5 V at the op amp's output. Congrats – we've built an inverting buffer! **If we want to turn it into a proper amplifier, we'll simply have to change the relation between the two resistances**. By doing this, we can either increase (if you increase the right-hand resistor's value) or reduce (if you increase the left-hand resistor's value) the gain to our heart's content.

BIPOLAR JUNCTION TRANSISTORS

Bipolar junction transistors (or BJTs for short) come in two flavors: NPN and PNP. This refers to how the device is built internally and how it'll behave in a circuit. Apart from that, they look pretty much identical: a small black half-cylinder with three legs.



Let's take a look at the more commonly used NPN variant first. Here's how we distinguish between its three legs. **There's a collector, a base and an emitter.**[10] All three serve a specific purpose, and the basic idea is that you control the current flow between collector and emitter by applying a small voltage[11] to the base. The relation is simple: **more base voltage equals more collector current**. Drop it down to 0 V and the transistor will be completely closed off. Sounds simple – but there are four important quirks to this.



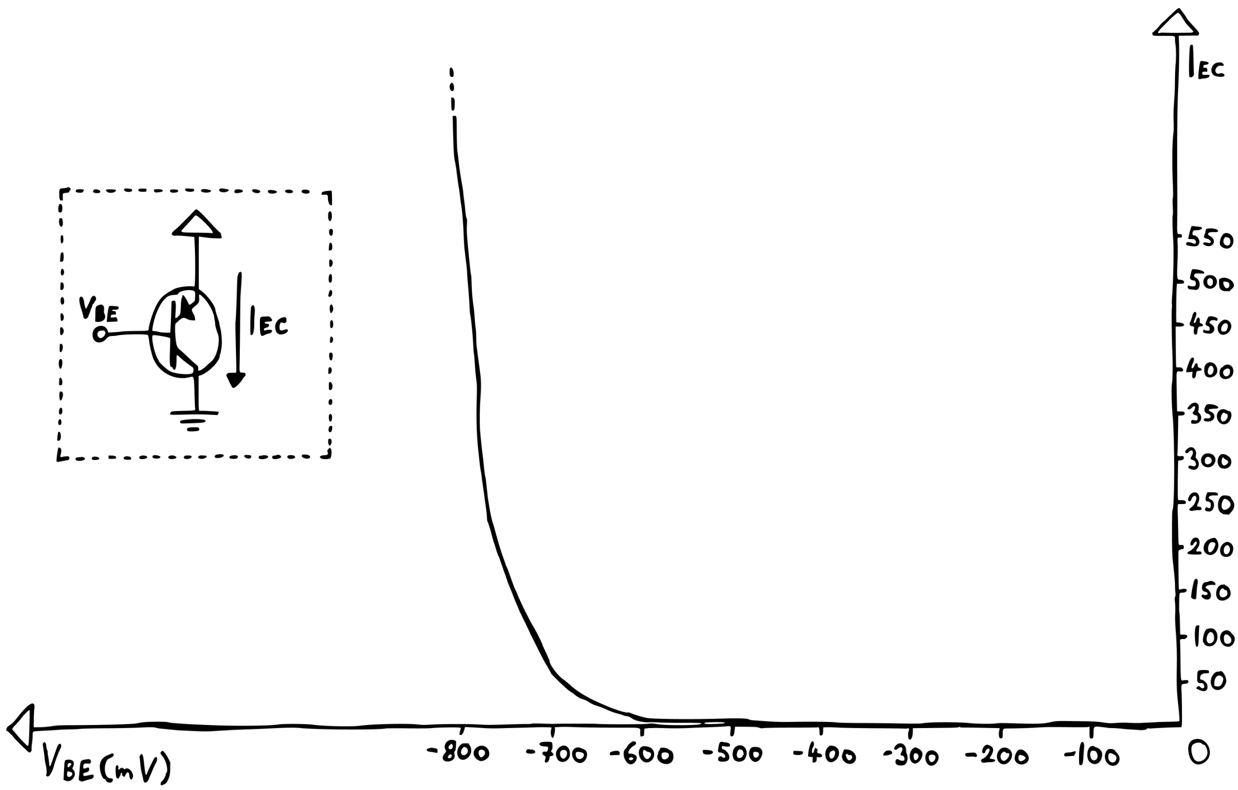
First, the relation between base voltage and collector current is exponential. Second, unlike a resistor, a BJT is not symmetrical – so we can't really reverse the direction of the

[10] Please note that the pinout shown here only applies for the BC series of transistors. Others, like the 2N series, allocate their pins differently.

[11] The voltage is measured between base and emitter. So „a small voltage" effectively means a small voltage **difference** between base and emitter!

collector current. (At least not without some unwanted side effects.) Third, also unlike a resistor, a BJT is not a linear device. Meaning that a change in collector voltage will not affect the collector current. And fourth, the collector current is affected by the transistor's temperature! The more it heats up, the more current will flow.

Now, for the PNP transistor, all of the above applies, too – except for two little details. Unlike with the NPN, **the PNP transistor decreases its collector current when the voltage at its base increases**[12]. So you have to bring the base voltage below the emitter to open the transistor up. Also, that collector current flows out of, not into the collector!



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12 Again, the voltage is measured between base and emitter.