INTRO | mki x es.edu

Hey there, thanks for buying this DIY kit! We – **Erica Synths** and **Moritz Klein** – have developed it with one specific goal in mind: teaching people with little to no prior experience how to design analog synthesizer circuits from scratch. So what you'll find in the box is not simply meant to be soldered together and then disappear in your rack.

Instead, we want to take you through the circuit design process step by step, explaining every choice we've made and how it impacts the finished module. For that, we strongly suggest you follow along on a **breadboard[1],** which is a non-permanent circuit prototyping tool that allows you to experiment and play around with your components. To help you with this, we've included suggested breadboard layouts in select chapters.

In addition to this, you can also play around with most of the chapter's 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.

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, tools, and the process of putting the module together once you're done experimenting. 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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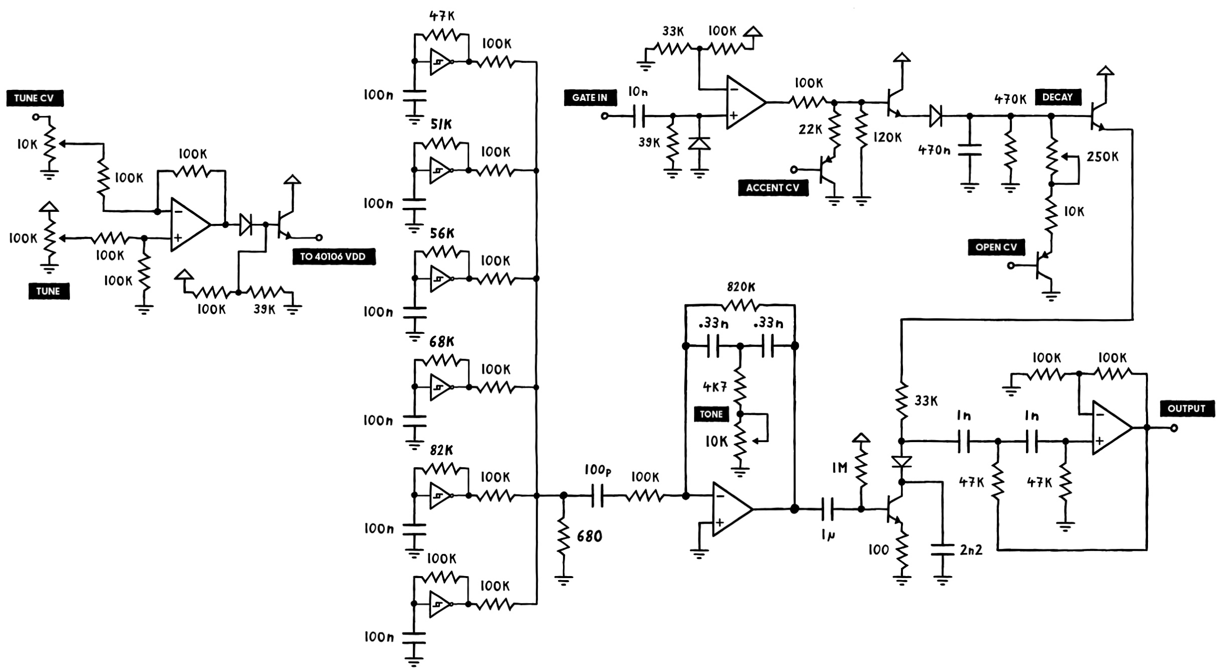
[1] Note that there is no breadboard included in this kit! You will also need a pack of jumper wires and two 9 V batteries with clips. These things are cheap & easy to find in your local electronics shop.

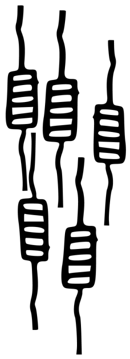
THE mki x es.edu HI-HAT

Synthesized, analog hi-hats are pretty fascinating. That’s because emulating any kind of cymbal using an analog circuit is tough, since the sound a real cymbal produces is not quite pure noise – but also not really harmonic.
Still, a couple classic drum machines like the Roland TR-606 and 808 took their best shot at it, with quite strange sounding results that I personally really like. So I decided to follow suit and came up with this simple, but very versatile and crunchy sounding hi-hat circuit.



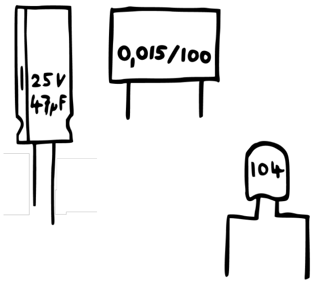
BILL OF MATERIALS

Before we start, please check if your kit contains all of the necessary components. In addition to a PCB, panel and power cable, your box should also contain:



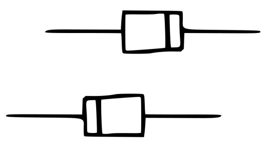
An array of resistors. The specific values (in ohms, which you should check for with a multimeter) are

1M	x1
820k	x1
470k	x1
120k	x1
100k	x18
82k	x1
68k	x1
56k	x1
51k	x1
47k	x3
39k	x2
33k	x2
22k	x1
10k	x1
4k7	x1
1k	x3
680Ω	x1
100Ω	x1
10Ω	x2



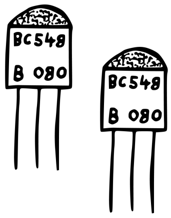
A bunch of capacitors. The specific values (which are printed onto their bodies) are

47µF (electrolytic)	x2
1µF (foil)	x1
470n (ceramic)	x1
100nF (ceramic)	x13
10nF (ceramic)	x1
2n2 (ceramic)	x1
1n (ceramic)	x2
330pF (ceramic)	x2
100pF (ceramic)	x1



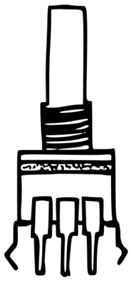
Some diodes. The specific model names (which are printed onto their bodies) are

1N4148 (signal)	x6
1N5819 (schottky)	x2



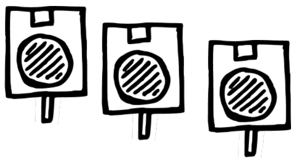
A couple of transistors. The specific model names (which are printed onto their bodies) are

BC558 (PNP)	x2
BC548/547 (NPN)	x4



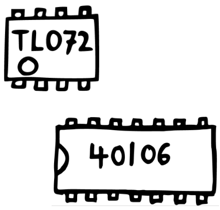
A handful of potentiometers. Their specific values (which may be encoded & printed onto their bodies) are

250k (B254) x1
100k (B104) x1
10k (B103) x2



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

Switched mono (black) x5



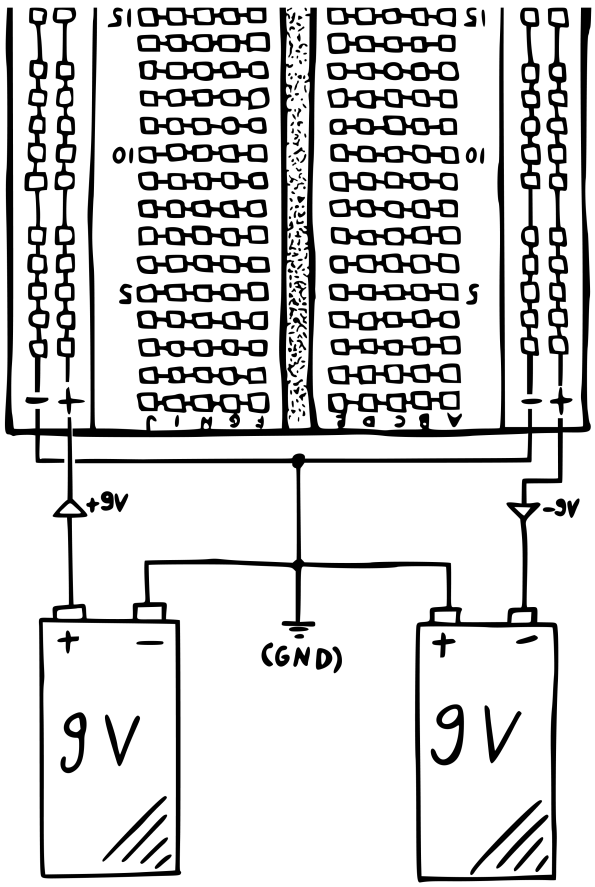
A couple chips. Their specific models (which are printed onto their bodies) are

TL072 (dual op amp)	x2
40106 (hex schmitt trigger inverter)	x1

You will also find a few sockets that are only relevant when assembling the module in the end.

POWERING YOUR BREADBOARD

Before we can start building, you'll need to find a way of providing your breadboard with power. Ideally, you'd use a dual 12 V power supply for this. Dual power supplies are great – and if you want to get serious about synth design, you should invest in one at some point. But what if you're just starting out, and you'd like to use batteries instead? Thankfully, that's totally doable. **You just need to connect two 9 V batteries to your breadboard like shown here.**[2] For this, you should use 9 V battery clips, which are cheap & widely available in every electronics shop.



By connecting the batteries like this, the row on the left side labeled **+** becomes your positive rail, the row on the right side labeled **+** becomes your negative rail, and both rows labeled **–** become your ground rails.[3]

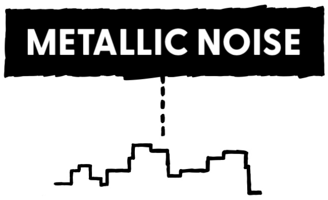
Please make sure you disconnect the batteries from your breadboard when you make changes to the circuit! Otherwise you run the risk of damaging components.

[2] Since the circuits in this manual were designed for a 12 V power supply, we assume that to be the default. Everything will still work roughly the same with 9 V, though.

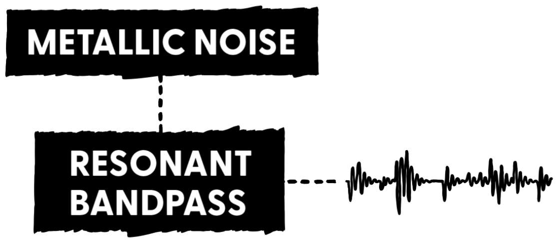
[3] This is a bit awkward because breadboards weren't really made with dual supply voltages in mind.

HI-HAT BASICS

To understand how it works, we'll start by identifying the different functional blocks that make up a classic analog hi-hat. First up: some sort of noise source. There are designs that go for simple white noise here, but I think this sounds a little basic and overly artificial.
That's because, as I said before, real cymbals produce a sound that's sort of half-way between pure noise and something faintly harmonic. **To get there, I took inspiration from Roland's implementation, which uses a very dissonant swarm of square wave oscillators to produce vaguely metallic sounding noise**.

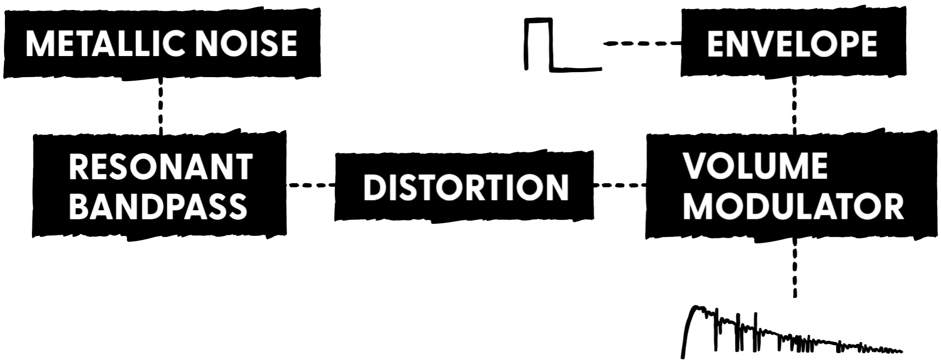


Next, we'll have to set up a filter to get rid of frequencies that real cymbal noise doesn't contain. Also, we'll want to emphasize some of the remaining frequencies to make the sound more sharp and biting. **So the filter will need to be resonant.**

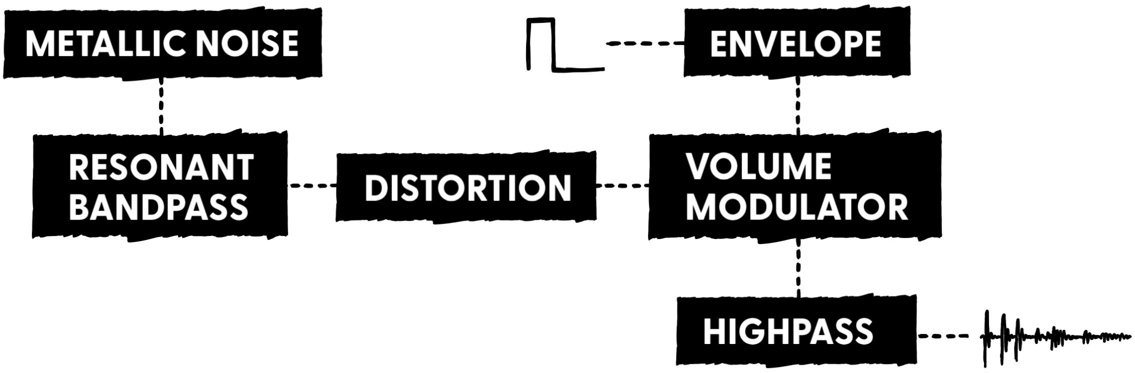


Since the harmonic content added by a resonant filter is usually not very complex, we'll then want to route our signal through some sort of distortion to add more crunch and metallic sheen.

After that, we'll have to shape the result into a quick burst – or a somewhat longer one, depending on whether the hi-hat should currently be open or closed. **For that, we'll use an amplifier which we'll control using an envelope generator**.



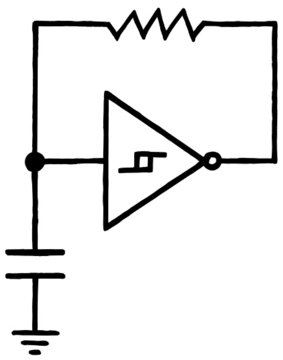
Finally, we'll apply another round of highpass filtering to get rid of any remaining low end in the signal.



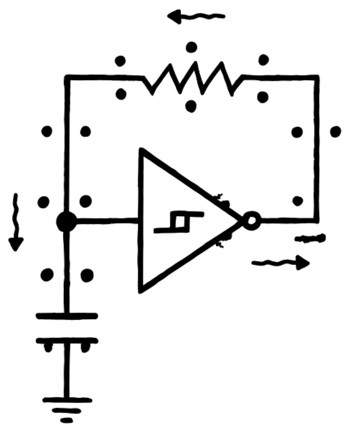
Next, we'll try to implement it in an actual circuit. We'll start by creating our noise source. **For that, we'll need a quick and efficient way to set up a swarm of square wave oscillators**.

INVERTER OSCILLATOR

Our best bet here is probably a schmitt trigger inverter-based solution, since it consists of just three parts per oscillator: the inverter, a capacitor, and a resistor.

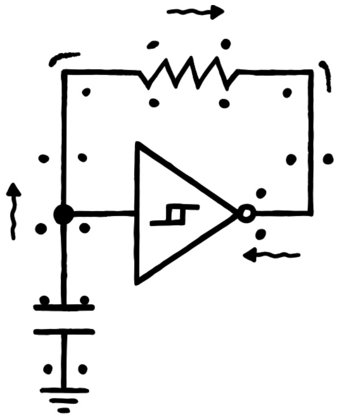


If you've built my DIY VCO, you'll mostly understand how this works. Still, here's a quick recap.[4] When we first flip the power switch, the capacitor will be empty and the voltage above it will be 0. **The schmitt trigger inverter will interpret this as a low input state, causing it to put its output 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, it'll 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.

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

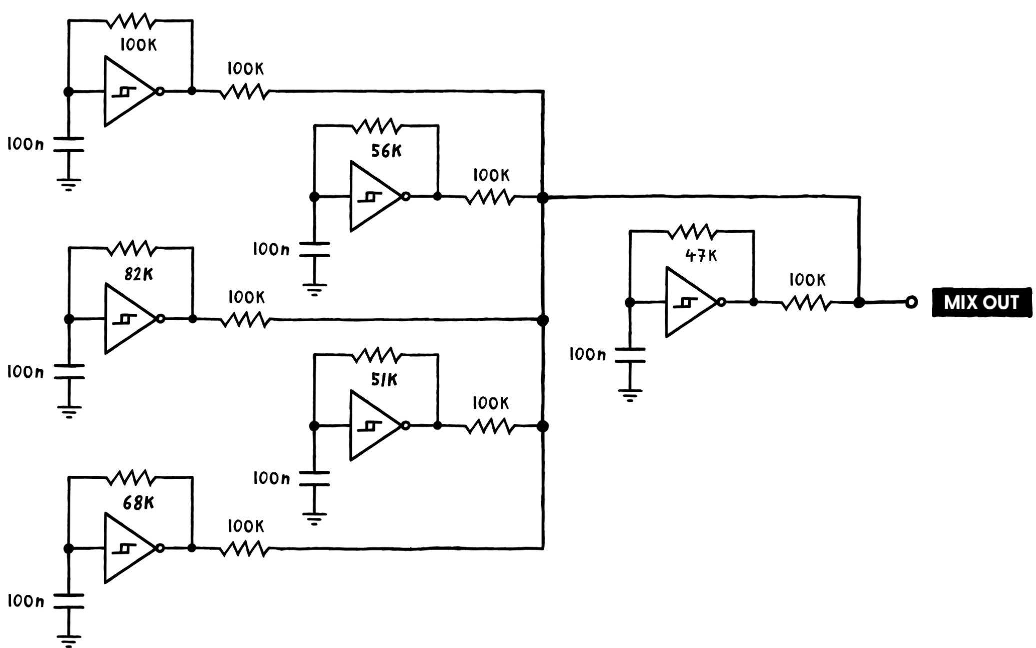


Until we hit the lower input threshold, the inverter latches into the low input state, and the whole process repeats. **At the inverter's output, this gives us a square wave whose frequency depends on the size of both resistor and capacitor: increasing either will decrease the frequency, cause it takes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

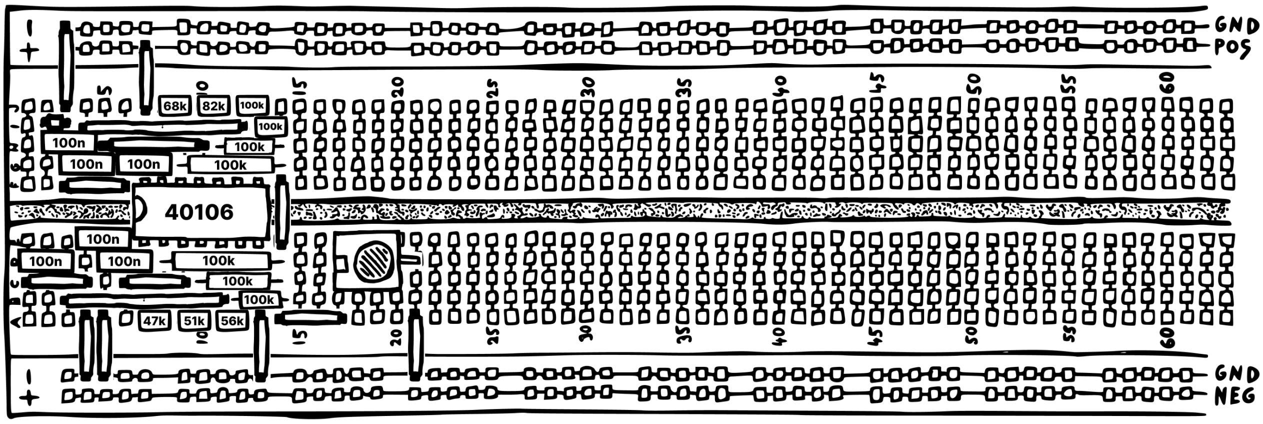
Knowing this, we can use a 40106 chip, which houses six individual schmitt trigger inverters, to set up six oscillators tuned to six different, dissonant pitches. Okay, but what pitches are we going to use, exactly? Well, to make our lives a little easier, we can simply adapt the values that Roland used in their TR-606 hi-hat. In ascending order, they tuned their six oscillators to (approximately) 245, 306, 365, 415, 437, and 619 Hz respectively.

Since I wanted to get something more chunky than the very high pitched 606 hats, I decided to shift all of those frequencies down by around 50%. Next, we'll need to pick capacitor and resistor values that give us these resulting frequencies. (Circuit simulators come in really handy here.)

With those values settled, all that's left is mashing the six oscillators together. **For this, we can go the lazy route and simply use six 100k resistors to create a passive mixer.**



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

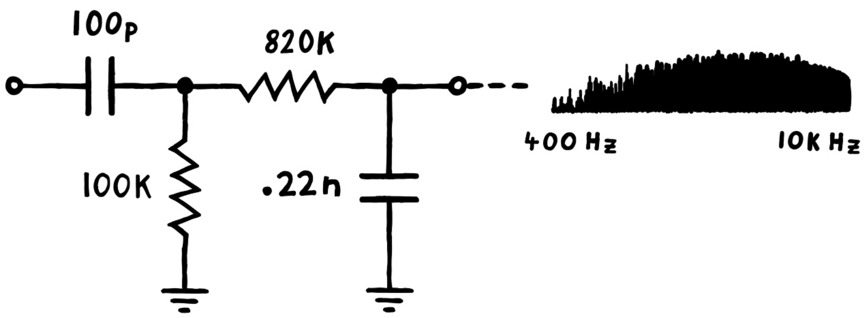


If you listen to the output through headphones, you should hear a dissonant, atonal swarm of bees. Just as expected! But it doesn’t really sound like a cymbal yet. One problem is the low end, but the high end is also a little too intense. **To deal with it, we’ll set up a filter that removes both low and high end frequencies at once.**

BANDPASS FILTER

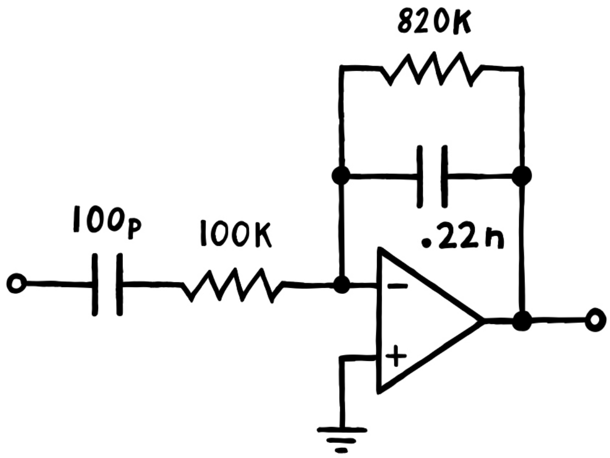
For that, we'll chain a simple passive highpass and a simple passive low pass together. If you need a refresher on how these work, I recommend reading the manual for my DIY VCF kit. **By selecting the right capacitor and resistor values, we can carve out the rough frequency band that is suitable for hi-hats.** Using a smaller resistor or capacitor in the highpass (on the left) will eliminate more of the low end, while using a bigger resistor or capacitor in the low pass (on the right) will kill more of the high end.

When playing around with this, I settled on a 100 pF cap combined with a 100k resistor for the highpass, and a .22n cap plus an 820k resistor for the low pass. Which gives us a frequency spectrum at the output that looks something like this: **a cut at around 400 Hz and a gentle drop starting at around 10 kHz.**



That's pretty close to what Roland used for their 808 and 606 hi-hats – I just decided to cut out a little bit more of the low end, since our mixed oscillators are more bottom-heavy overall.

Now, there is a small issue with this approach. Since the filter is passive, we'd lose a lot of volume at the output. **To fix this, we'll turn our passive bandpass into an active bandpass using an op amp.** To save a couple extra components (and more crucially, to be able to add resonance later), we'll go for an inverting configuration here. It works like this.



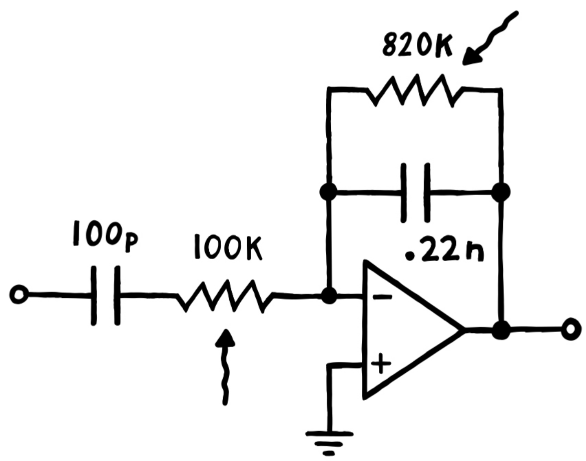
First, we ground the op amp's non-inverting input. Then, we take our highpass and we connect it to the inverting input. This might look a bit confusing, because we previously picked up the filter's output from after the capacitor, not the resistor. But in an inverting op amp setup like this, the inverting input acts as something we call a virtual ground node. **Meaning that it stays at (or very close to) 0 V during operation while also reading the input that will be amplified.** So for our filter, it doubles as the connection to ground for the resistor – and the output node for the filtered signal.

Next, we take our low pass and put it into the op amp's feedback path. Again, this setup might look a little confusing, because in the passive version, we applied the input signal to the resistor, while we connected the capacitor to ground and picked up the output from above it. **Here, since the inverting input doubles as a ground node and the filter's input, both the capacitor and resistor are connected to it.**

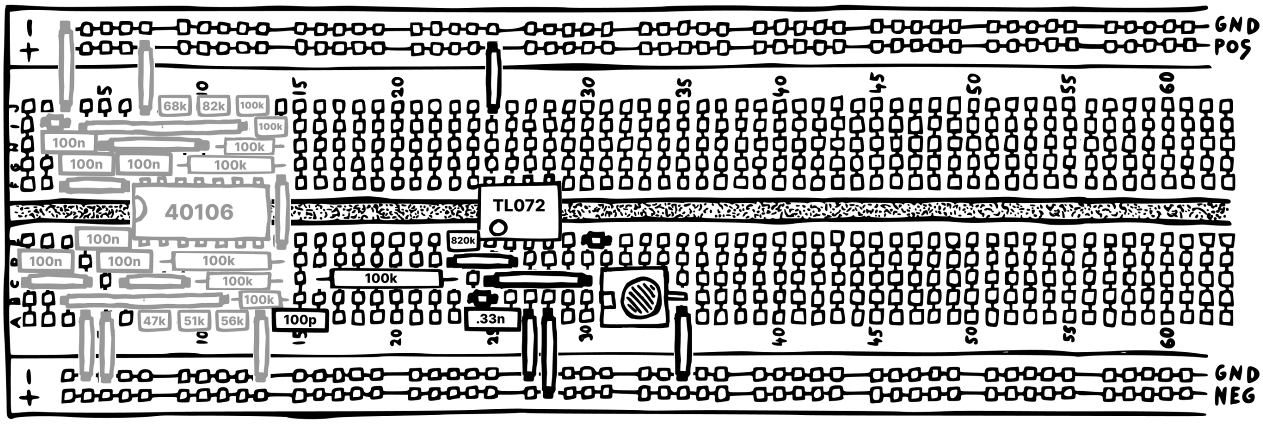
Finally, we've got to link the low pass output to the op amp's output, which completes the feedback path and allows the op amp to push and pull current through both filtering stages.

Okay, but how does this increase the output volume of our bandpass? That's the tricky part about this setup. Since the op amp does everything it can to keep its inverting input very close to 0 V, the impedances of both filter stages (that is, how hard it is to move current through them) matter. **If the impedance before the inverting input is low, but the impedance between that input and the op amp's output is high, a small change in the input signal requires a big change in voltage at the op amp's output to keep the inverting input close to 0 V.**

So the gain we apply to the filtered signal depends on the relation between the input impedance and the feedback impedance. Conveniently, with our chosen component values, that input impedance is about 3 times lower than the feedback impedance. **Meaning that we should get an output signal that's about 3 times louder than the one we'd have gotten from the passive version.**[5]



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

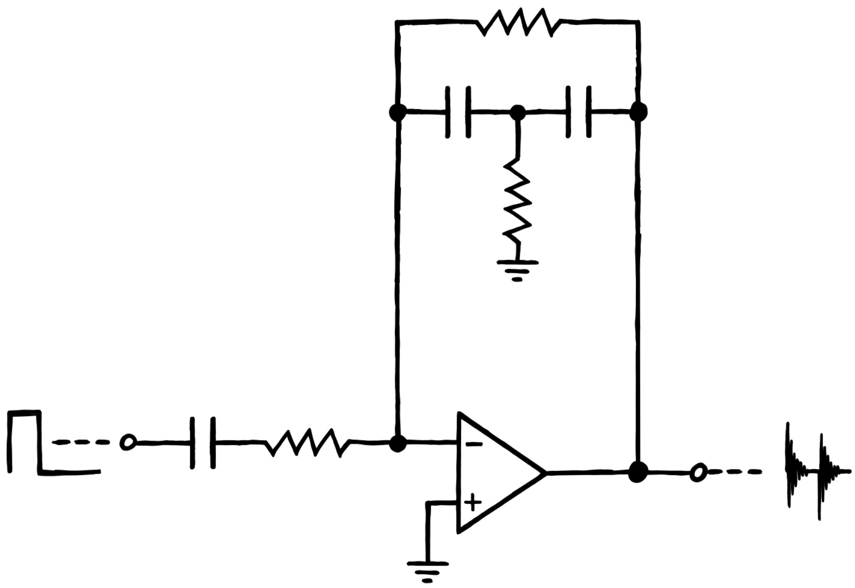


If you listen to this through headphones, the signal should be pretty loud.[6] Great!

[6] Note that since your kit does not contain a .22 nF capacitor, I swapped it for a .33 nF capacitor.

RESONANT BANDPASS

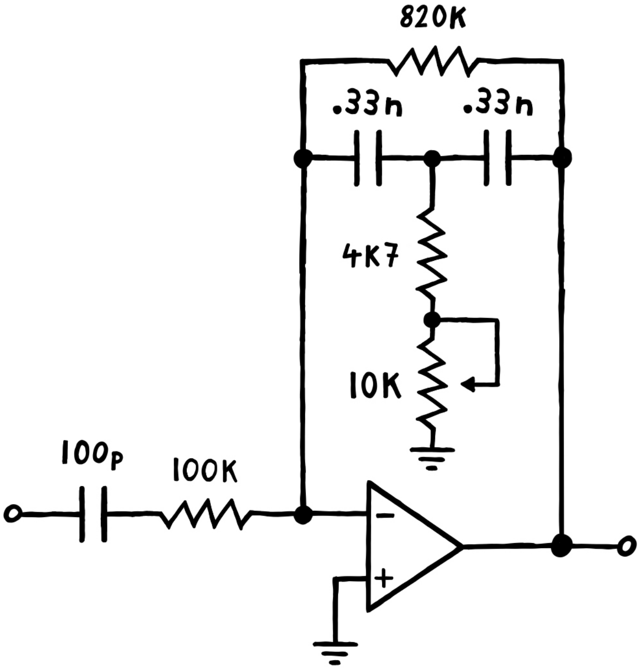
Next, we'll want to add some resonance to make the sound more sharp and biting. To get there, we only need to add two components: a capacitor and a resistor. If we insert them into the feedback path like this, then our filter will strongly emphasize the low pass stage's cutoff frequency.

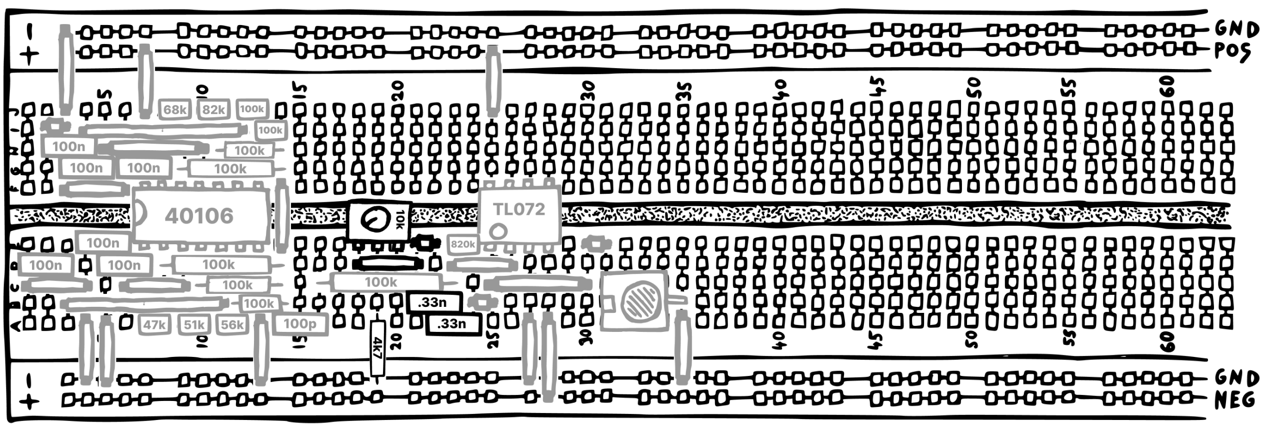


If you've built my DIY Kick Drum module, you'll recognize this structure as a bridged-t topology. In that kit's manual, I explain the mechanics behind this in detail, but here's the basic gist. Whenever the voltage at the inverting input changes, the op amp will try to neutralize that change by adjusting its output voltage. Previously, that process was very straightforward, because all the op amp had to do was charge (or discharge) the single capacitor in the feedback path.

Now, with the added cap and the resistance to ground between the two, things get pretty complicated, since both caps need to be charged and discharged – but they do so at very different speeds and they're interacting with one another in the process. As a result, the op amp over- and undershoots its target repeatedly as it struggles to stabilize the voltage at its inverting input. And the resulting oscillation that is added on top of the input signal is a perfect sine wave swinging at the low pass stages's cutoff frequency.

Which, to make things even more complicated, also depends on the resistance going to ground between the two caps. The relation, at least, is simple: the lower the resistance, the higher the cutoff frequency. **If we replace the single 2n2 cap we used previously with two 3n3 capacitors, and combine them with a 470 ohm resistor to ground, we should get a resonant peak at around 7 kHz**. And since it'd be nice to add some manual control for the tone here, we'll insert a 1k potentiometer between the resistor and ground. This should allow us to move the cutoff from 7 kHz all the way down to 4 kHz.[7]



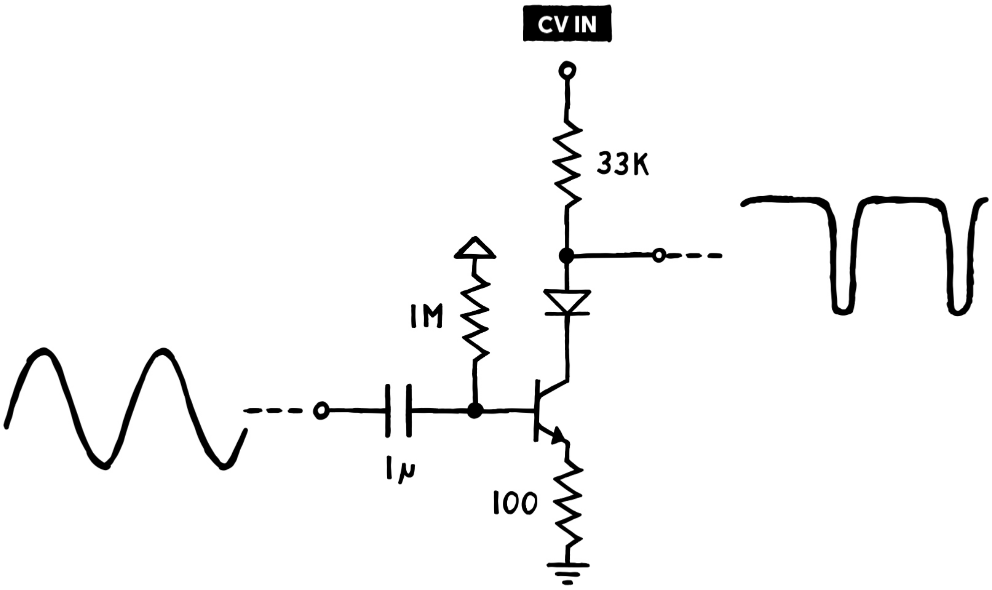


If you listen to this, it should sound much more sharp and aggressive. Cool!

[7] 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.

DISTORTION/VOLUME MODULATION

With the filtering and resonance sorted, I'd now like to add some crunch to our processed signal. And while we could use a dedicated distortion stage for this, there's a way more efficient solution. In Roland's 808 and 606 cymbal and hi-hat sections, they used something they dubbed the „swing type VCA" to modulate the signal's volume. **That VCA is so crude and bare bones that it adds a ton of distortion as a byproduc**t.
Which would be horrible for any other application – but in this case, it's essentially killing two birds with one stone: volume modulation and distortion in a single, efficient little block.

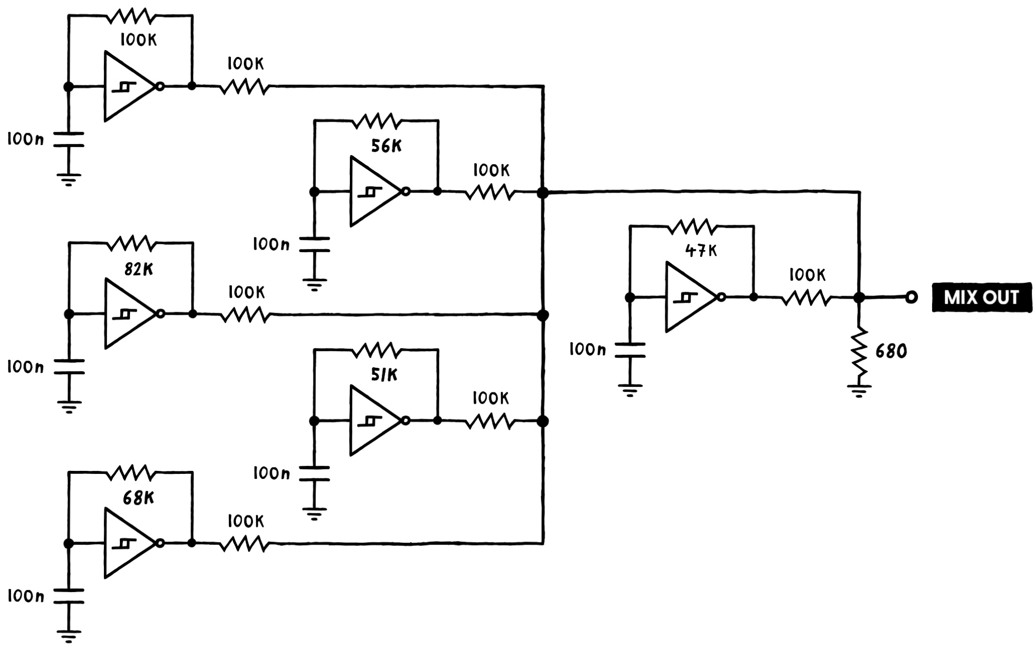


So let's take this block apart. The central piece is a simple NPN transistor, set up as a high gain amplifier. For that, we combine a big 33k collector resistor with a very small 100 ohms emitter resistor. (We'll ignore the diode for now.) Then, we bias our input using a capacitor followed by a big 1M resistor connecting the transistor's base to the positive rail. **This ensures that current is flowing through the transistor even if the signal is idling at ground level**.
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 – though with a huge gain. That huge gain is the key to the distortion added by the VCA. 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.

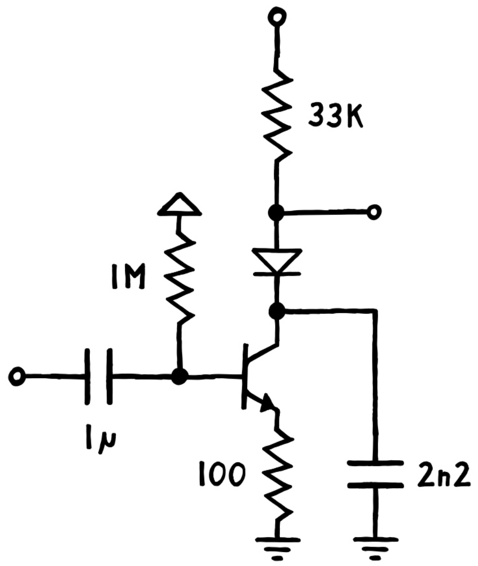
Alright, but what about the diode between the 33k resistor and the collector? Well, there's one small issue with this setup. If the control voltage is 0 and there is no diode there, current will flow into the base, out of the collector and towards that low voltage node. And as the input signal oscillates, 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 perfectly silent at 0 V control voltage**.

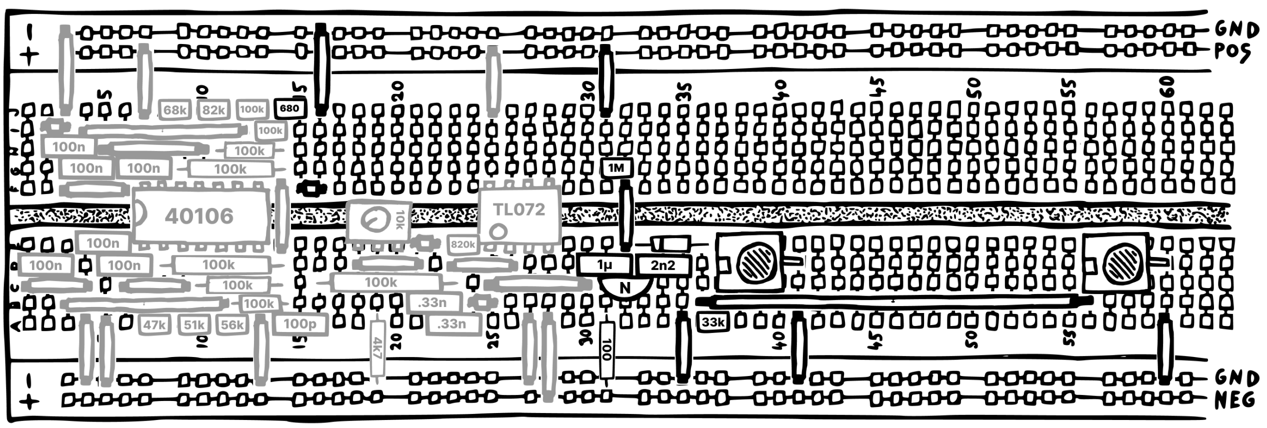
Heads up before you build and try this: with our filtered signal, we'll just get some very thin crackling at the VCA's output. What's up with that? Well, the issue is that our signal is just too loud going into the VCA. **This means that our transistor would mostly be stuck in its fully-on or fully-off state (also called saturation and cutoff), with the occasional, super quick transition**. Resulting in the thin crackle I just mentioned.

To fix it, we'll simply lower the volume of our oscillator mix. Right now, that mix is an almost 12 V peak-to-peak signal – which is very loud. So we'll insert a small 680 ohms resistor to ground after the passive mixer to scale that down to just about 400 mV peak-to-peak.



There's one small thing that bothers me about the raw sound coming out of the swing type VCA, though: you get some super high-pitched fizz that is introduced by the distortion. To fix it, we'll simply add a small 2n2 capacitor going to ground from the transistor's collector. **In combination with the 33k collector resistor, this will act like a very gentle low pass filter, taming the high end a little bit**.



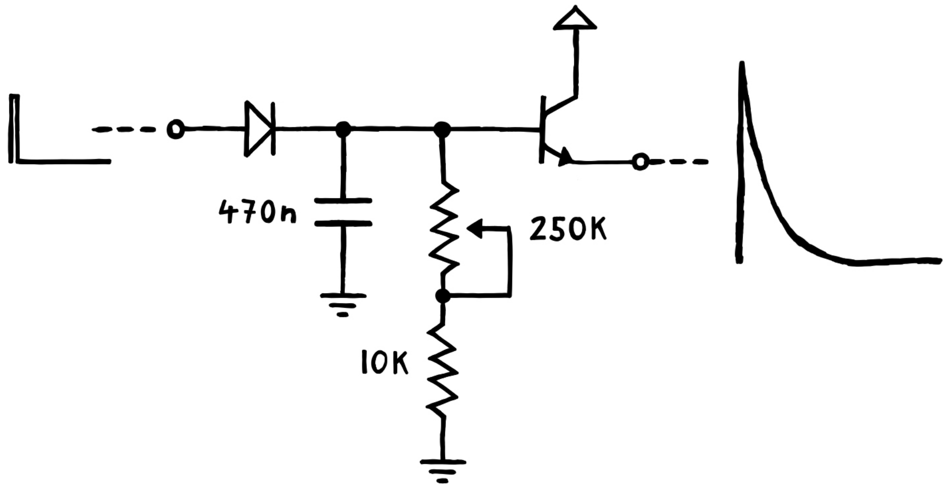


To properly test this, you'll need to send some form of control voltage into the VCA's CV input (on the left).[8] Once you do, you should hear the VCA open up and push out a pretty distorted version of the filtered signal. Great!

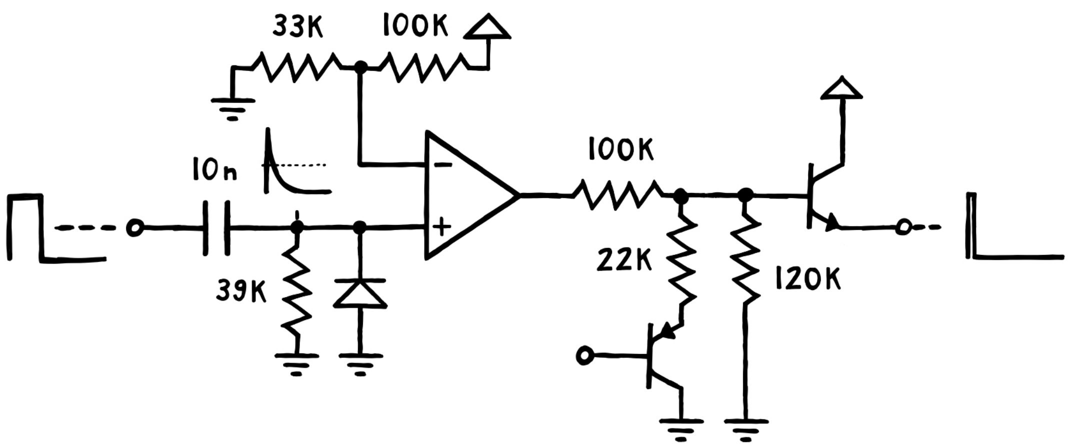
[8] You can try this chapter's circuits in a simulator. I've already set them up for you right here. You can change all values by double clicking on components.

ENVELOPE/GATE-TO-TRIGGER

So that's the VCA/distortion block down. Next up, we'll want to add a snappy envelope generator to drive our VCA and give us a quick, percussive hi-hat hit. For that, we can re-use the design I came up with for my kick drum circuit.



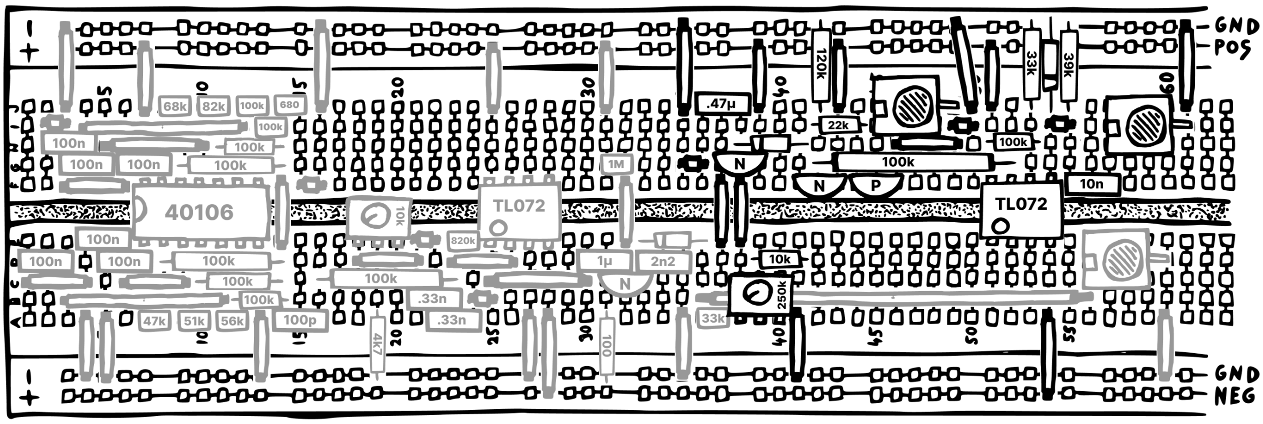
The basic version of that design consists of just five components: a diode, a capacitor, a potentiometer, a resistor and an NPN transistor. It works like this: **if we apply a short voltage pulse (also called a trigger) to the diode, the capacitor is filled up instantly and then slowly drained through the resistance to ground.** This creates a gradually falling voltage curve whose steepness only depends on the resistance we dial in using the potentiometer – since we're isolating the controlled discharging process from the rest of the circuit by setting the transistor up as a voltage buffer.
If we then connect the transistor to our VCA, we should get the percussive hit we were looking for. There's just one thing missing to be able to test this: a trigger. For that, we can again re-use something from my kick drum design: the gate-to-trigger converter.



This little circuit takes in a gate signal (from a sequencer or an LFO) and transforms it into a super short voltage pulse. For that, it combines a highpass filter with an op amp-based comparator. **That highpass transforms the gate into a quickly falling voltage curve – and the comparator then heavily distorts that curve into a pulse**.

To be able to adjust the trigger's size, we then route it through a little PNP transistor-based limiting circuit. It works like this: if we don't apply a voltage to the transistor's base, no current can flow through it, and the 12 V pulse is divided down to around 5 V by the 100k and 120k resistors.

Conversely, if we do apply a voltage to the base, then that transistor will pass exactly enough current to cap the trigger's size at that voltage. Giving us voltage control over the hi-hat's accent level. Great![9]

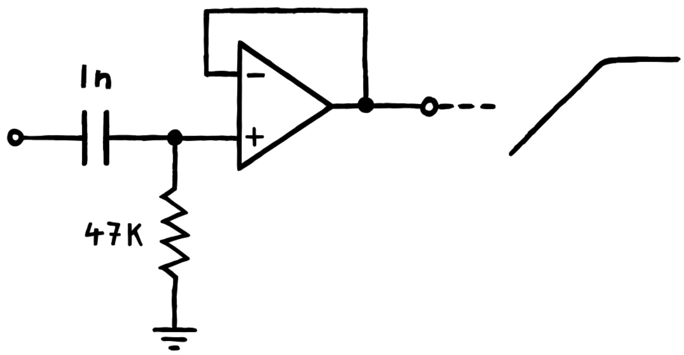


When testing this, start out without any accent CV applied. By playing around with the envelope's decay potentiometer, you should be able to influence the length of each hi-hat hit. Then, if you combine this with a CV sequence applied to the accent CV input, you should already get some interesting results.

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

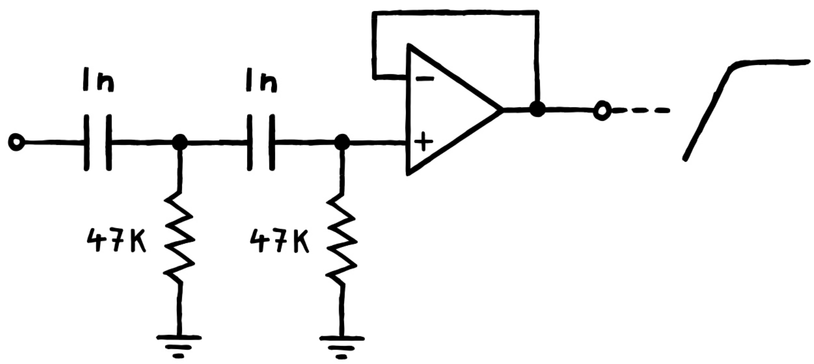
HIGHPASS FILTER

Still, our hi-hat is sounding a little too chunky for my taste. That's because our VCA didn't just add a little fizzy distortion – but also plenty of low end. So let's add another highpass filter to complete our signal chain.



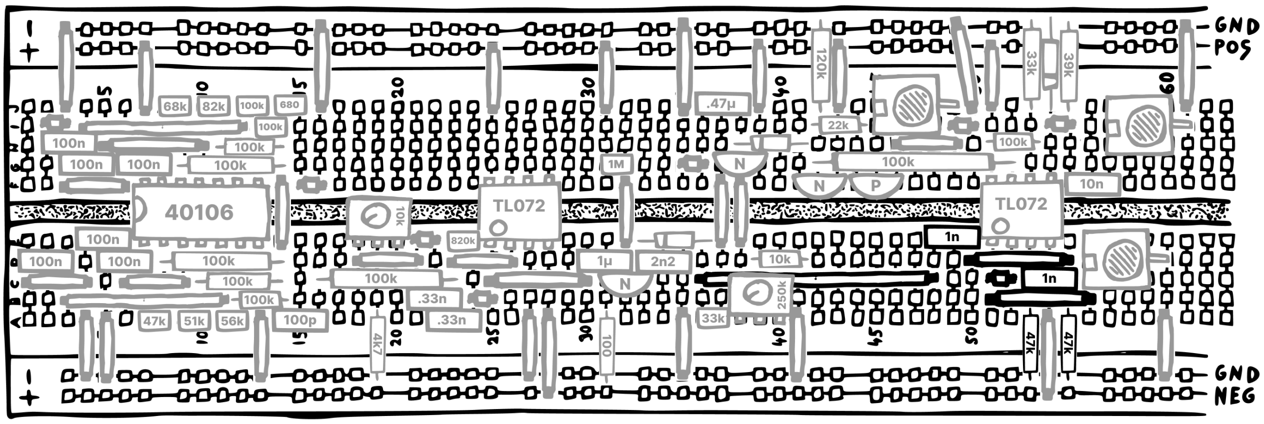
We'll start off with a simple active highpass filter, which we get by buffering a passive highpass using an op amp. **If we combine a 1 nF cap with a 47k resistor, we get a cutoff frequency of about 3.4 kHz, which should get rid of most of the chunkiness**. The buffer then ensures that the output voltage stays the same by keeping the output impedance low.

If you tried this with our signal, the result would be a little less chunky. But not significantly so. That's because our filter is what we call a single stage highpass, which means that it has a 6 dB per octave roll-off. This is pretty mellow, so a lot of frequency content below the cutoff point makes it into the output. To make this slope more steep, we can simply add another highpass stage with the same component values.



This way, we get a second order highpass filter, which should have a steeper 12 dB per octave roll-off (while keeping the cutoff frequency the same).[10]

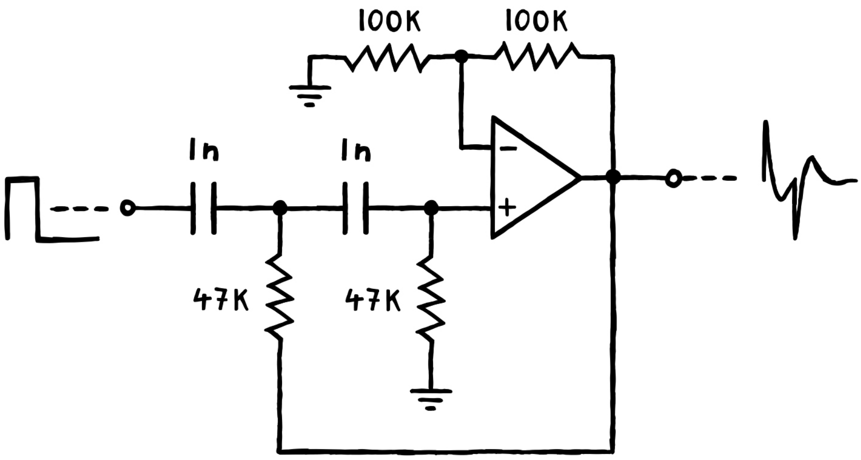
[10] You can try this chapter's circuits in a simulator. I've already set them up for you right here. You can change all values by double clicking on components.



And while this does get rid of the low-end more effectively, I think it could honestly use a bit more bite.

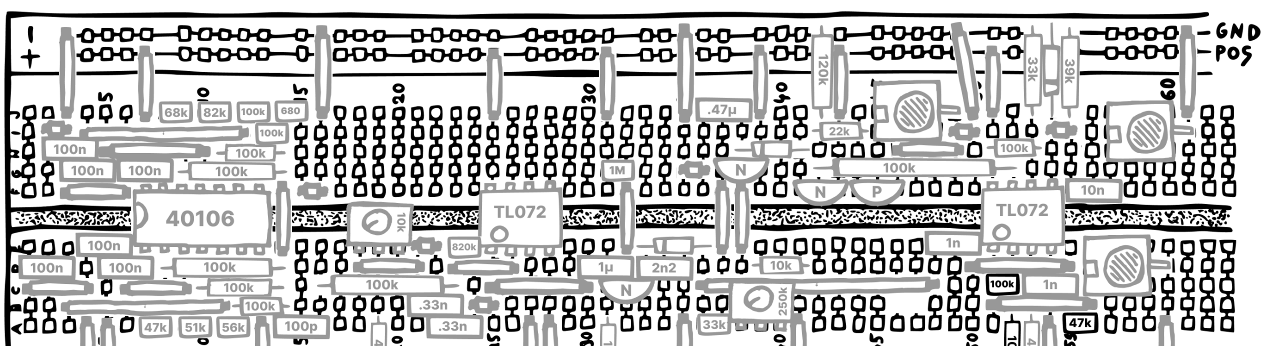
RESONANT HIGHPASS

To fix this, we'll simply make our highpass filter resonant. That way, we emphasize the frequencies around the cutoff point, which should hopefully give us a little more of that metallic ringing. Alright, but how do we make our setup resonant? Easy: we just have to connect the first 47k resistor to the op amp's output. **This way, we introduce positive feedback to the system, because the filter's output is routed back into the first filter stage**.



This destabilizes the filter's operation, leading to the same over- and undershooting behavior we saw previously in our resonant bandpass. We call this setup a Sallen-Key filter, by the way. One caveat, though. Since our op amp previously had a gain of 1 (since we set it up as a straight buffer), the amount of resonance added would've been pretty minimal.

To push it a little, we just have to increase the gain by putting a voltage divider into the op amp's feedback path. With a 100k/100k divider, we bump that gain to a factor of 2, which should be plenty.

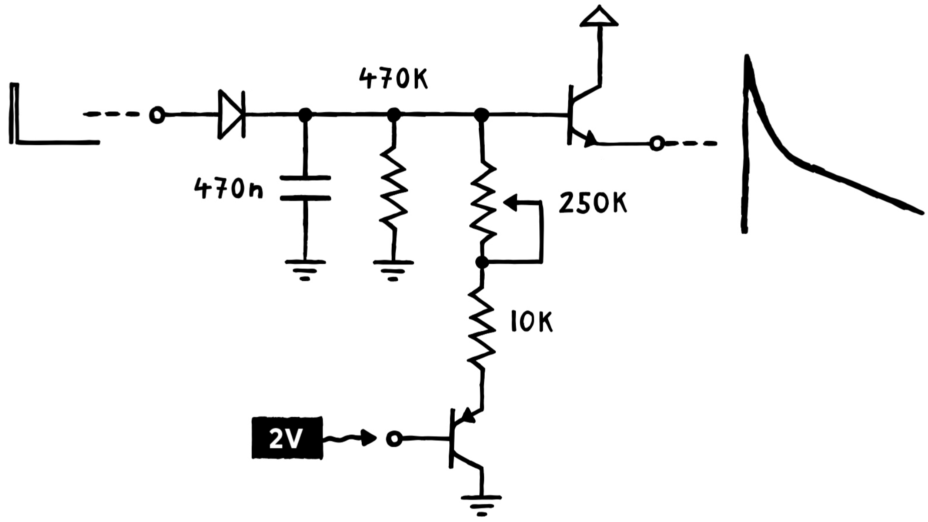


If you test this, it should sound pretty nice and metallic.[11] Great! Next, I'd suggest that you try to control the accent level with a sequencer and tweak the tone & decay levels a bit. I'd say that we now have a perfectly fine hi-hat circuit. But there are two extra features that I'd like to add: a way to open the hi-hat – and a way to control its pitch.

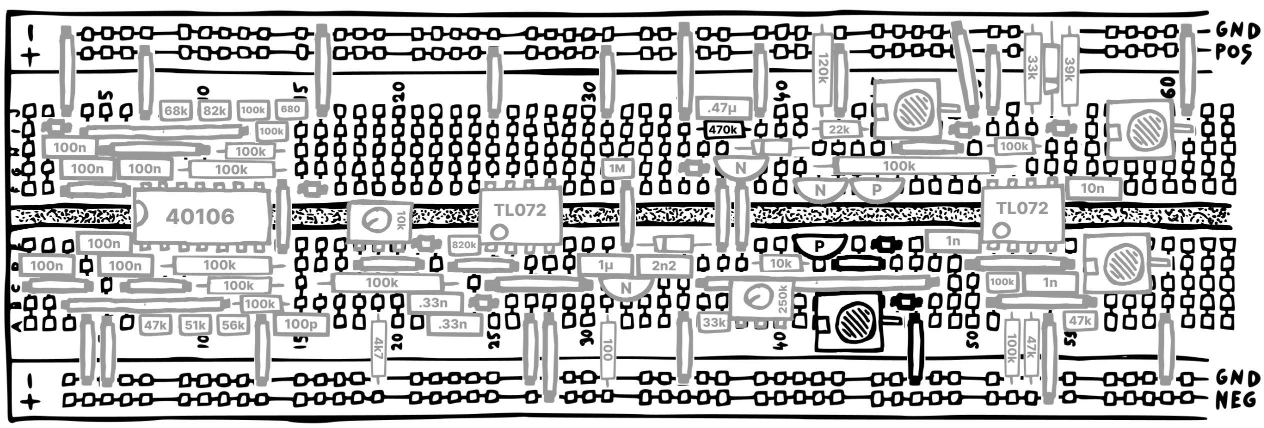
[11] You can try this chapter's circuits in a simulator. I've already set them up for you right here. You can change all values by double clicking on components.

OPEN HI-HAT

Let's start with the former. In Roland's 606 and 808 designs, they basically set up the open hi-hat as an additional voice – meaning that they introduced another trigger input and another envelope generator to get the job done. For our circuit, I don't think we need to go through all that, to be honest. **Instead, I'd like to make our hi-hat's decay voltage controllable, so we can open the hi-hat by applying a voltage**. Here's how that would work.



If we add a PNP transistor between the envelope's resistance and ground, and then apply a voltage to its base, the capacitor cannot fully discharge – and so the hi-hat stays open. And the higher the base voltage, the louder the persistent sound. **Since a real open hi-hat still decays in volume over time, though, we'll want to introduce an alternate, high-resistance path for our capacitor to discharge through**.
In my experiments, a 470k resistor worked well here, since it gave me a gentle drop in volume at the tail end of the open hi-hat sound.

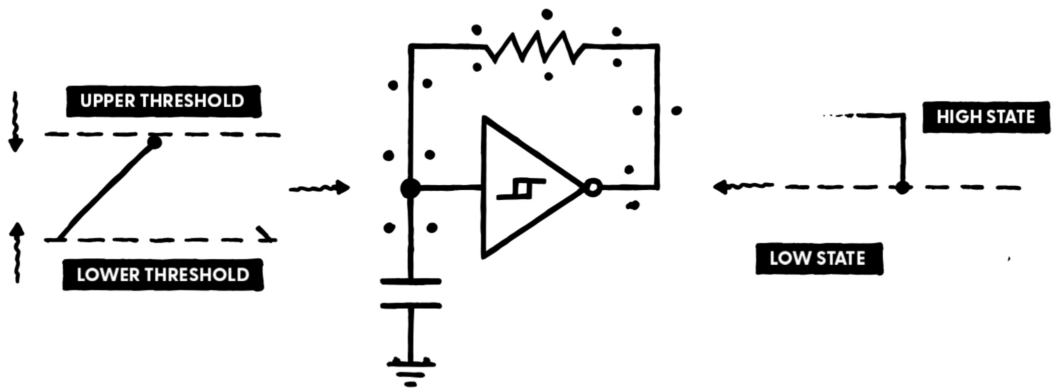


To trigger the open hat, connect the new CV input to your sequencer's velocity or pitch output.[12] If you're interested, try removing the 470k resistor and listen for the difference in the sound's tail end.

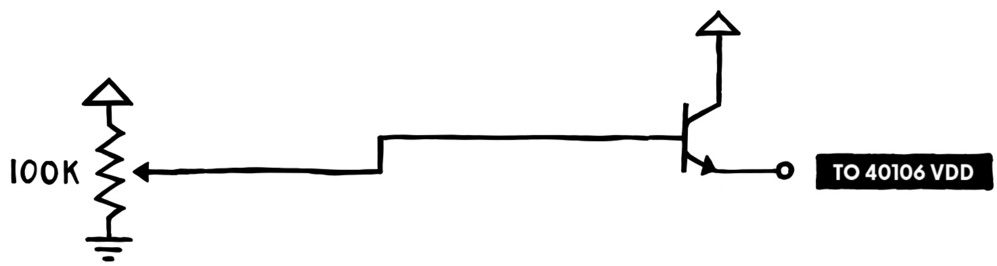
[12] You can try this chapter's circuit in a simulator. I've already set it up for you right here. You can change all values by double clicking on components.

TUNE CONTROL

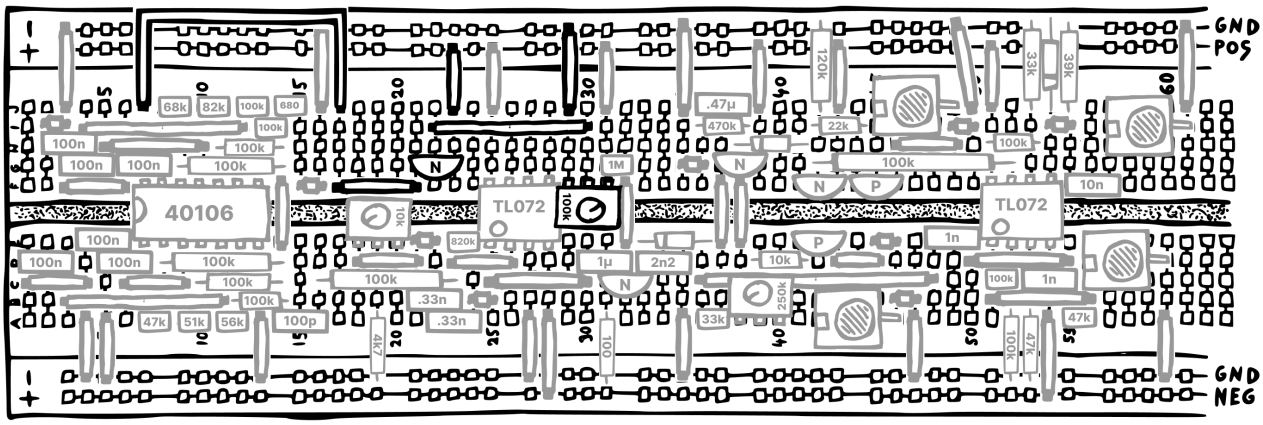
Alright, so this leaves only the tune control – which is a little tricky, because ideally, we want to shift the frequencies of all six oscillators up or down by the same amount at the same time. **Unfortunately, those frequencies are determined by the capacitor and resistor values in each individual oscillator core.** So we'd have to find a way to manipulate all resistor (or capacitor) values at the same time – right? Lucky for us, there is an alternate, hidden option: reducing the 40106 chip's supply voltage.
That's because the upper and lower voltage thresholds that the chip sets internally to process the input depend on the supply voltage. If it drops, the thresholds move closer together.



And if the thresholds move closer together, then we have to move less current through the resistor and into/out of the capacitor during each wavecycle to reach them. Which should speed up the oscillation. Okay, but don't the inverters' output voltages also drop if the supply voltage drops? And wouldn't that cancel out the effect of moving those thresholds closer together?
In theory: yes. If you look at the chip's datasheet, it claims that the relation between supply voltage, output voltage, and thresholds is always the same. **But in practice, curiously, the thresholds move closer together faster than the output voltages drop.**
So let's try to exploit this! For that, we'll first set up a variable voltage divider. Because its output impedance varies wildly as we turn the potentiometer's knob, we'll then want to buffer it with an NPN transistor set up as an emitter follower.



Next, we take the result and apply it to the 40106's positive supply pin. This way, the transistor will give the chip just enough current so that the supply voltage stays locked to the variable voltage divider's output.



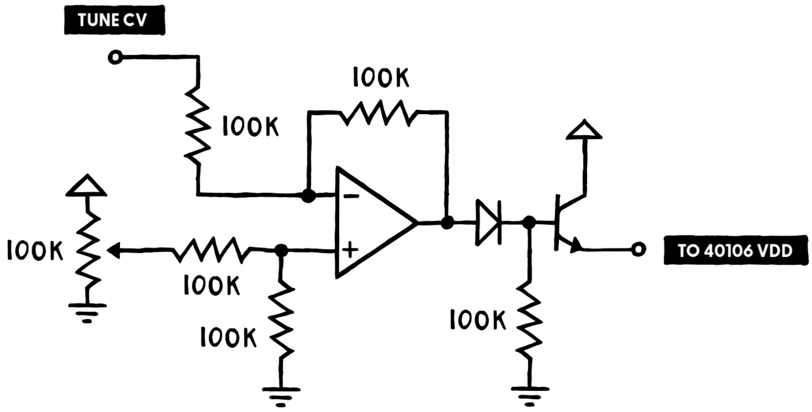
If you now turn the tune knob, you should be able to increase the pitches for all six oscillators. Now, if you tweak this control in combination with the tone knob, you can get a bunch of different feeling hi-hat sounds out of our little circuit.

TUNE CV

But why stop at manual tune control? Since we're already using a voltage to set the oscillators' frequencies, why not go the extra mile and also add a tune CV input? **All we have to do to make that happen is somehow combine an external voltage with the one coming from our variable voltage divider – before we buffer the result with our emitter follower**.

One slight issue, though. Traditionally, you'd expect a tune CV input to increase the pitch as the input voltage goes up. But with our idea, it would actually work the opposite way – since a higher supply voltage for the chip means lower pitch. To fix it, we'll simply subtract the control voltage from our manually set one – instead of adding it. This way, if the CV increases, the resulting voltage decreases, and the pitch rises.

For that, we'll use a simple op amp-based voltage subtractor. It does exactly what we're after: subtract one voltage from the other and set its output to the resulting voltage.

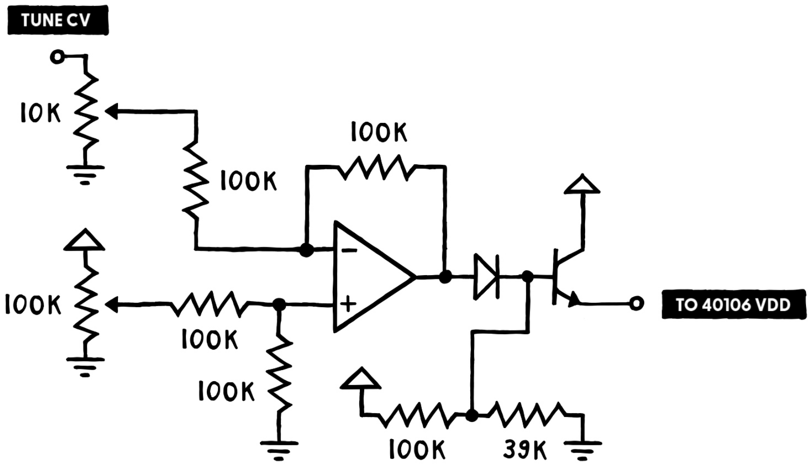


Before we send that voltage into the transistor's base, we need to take a pretty crucial protective measure, though. Since we supply our op amps with +/-12 V, the output can go negative if the CV is higher than the manually set voltage. **And if the output goes too far below the 0 V-line, the transistor will break down and allow current to be pulled into the emitter**. Which could damage our 40106 chip.

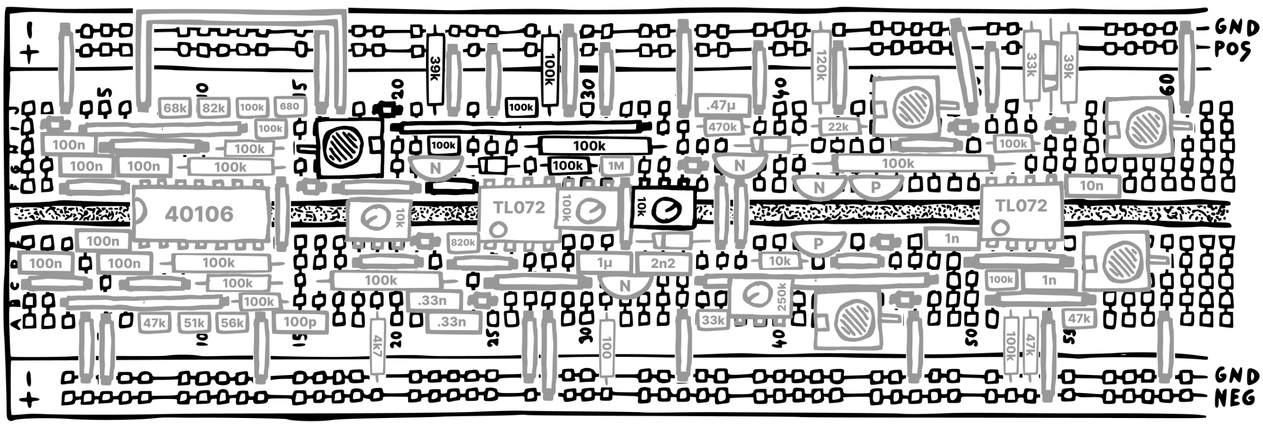
To prevent this, we simply insert a diode between the op amp's output and the transistor's base, which will block any current from flowing in the reverse direction. Then, we add a 100k resistor to ground at the base to keep the node from floating when the diode is blocking.

And while this would work in principle, we'd get some unexpected behavior towards the top end of the tuning range: the hi-hat would go almost completely silent. What's up with that? Simple: as soon as the 40106's supply voltage drops to 0 V, the chip stops operating at all. In fact, the minimum supply voltage specified in the datasheet is 3 V!

So we need to make sure that we never drop it lower than that. How do we pull this off? Simple: by raising the pull-down voltage we set after the diode. Right now, it's fixed at 0 V. But if we replace this 100k to ground with a voltage divider that produces roundabout 3 V and connect the NPN's base to it, then the voltage at that node can never drop below those 3 V.



That's because if the op amp's output voltage tries to pull it lower, the diode will block. Great! There's one more adjustment I decided to make, though. **With the previous setup, the hi-hat's pitch would change quite dramatically in response to a small change in CV**. In some situations, this might be what you want, but in others, you'd like to modulate the pitch in more subtle ways.
To account for this, we add a simple attenuator to the tune CV input, allowing us to adjust the effect's intensity on the fly.[13]



And with this, our hi-hat is complete. Once you're done experimenting, dig out the panel and PCB from the kit, heat up your soldering iron and get to building. You can find more information on how to populate the board & how to solder in the enclosed appendix.

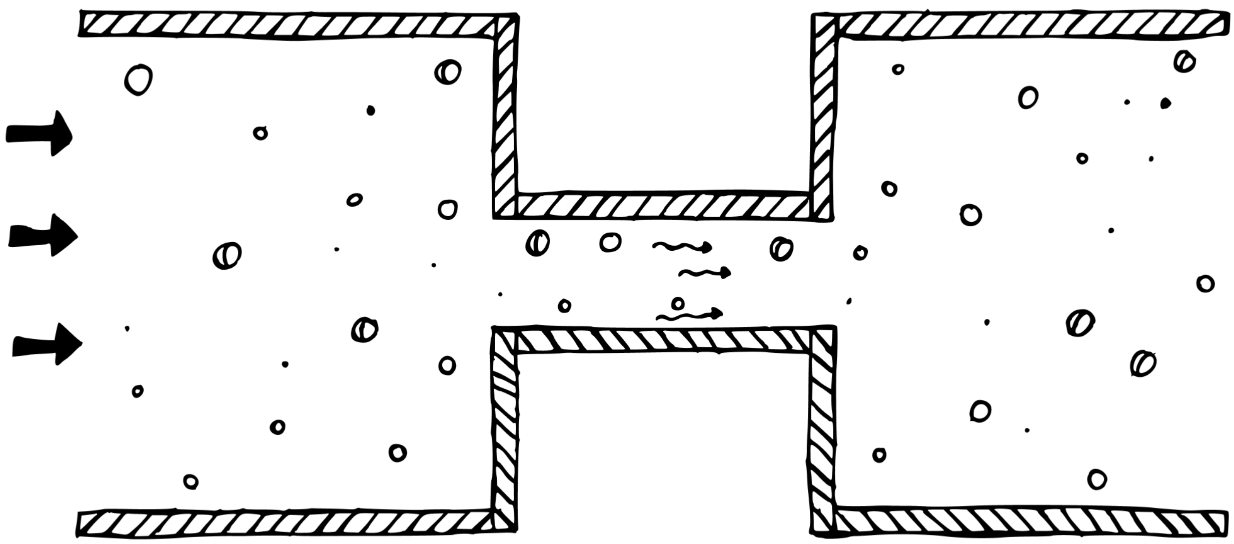
[13] You can try this chapter's circuit in a simulator. I've already set it up for you right here. You can change all values by double clicking on components.

COMPONENTS & CONCEPTS APPENDIX

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

THE BASICS: RESISTANCE, VOLTAGE, CURRENT

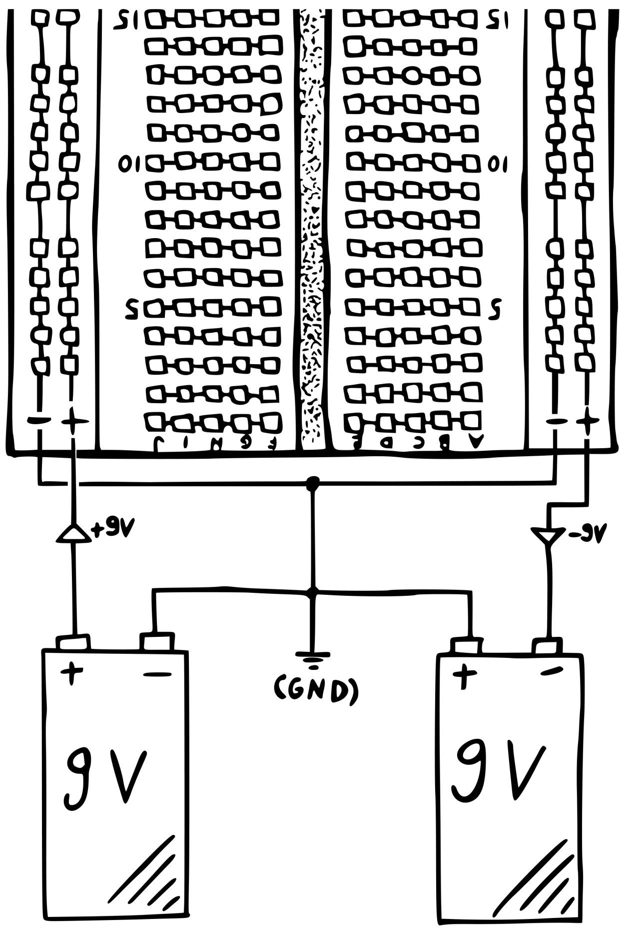
There are three main properties we're interested in when talking about electronic circuits: resistance, voltage and current. To make these less abstract, we can use a common beginner's metaphor and compare the flow of electrons to the flow of water through a pipe.



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**.

USING TWO 9 V BATTERIES AS A DUAL POWER SUPPLY

Dual power supplies are great – and if you want to get serious about synth design, you should invest in one at some point. But what if you're just starting out, and you'd like to use batteries instead? Thankfully that's totally doable. **You just need to connect two 9 V batteries like shown here.** For this, you should use 9 V battery clips, which are cheap & widely available in every electronics shop.

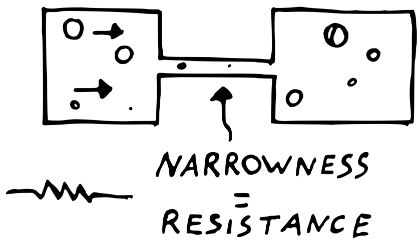


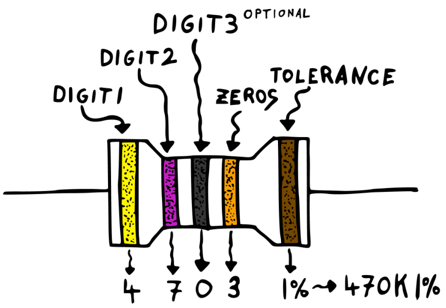
By connecting the batteries like this, the positive terminal of the left battery becomes your +9 V, while the negative terminal of the right is now your –9 V, and the other two combine to become your new ground.[14] **Please make sure you disconnect the batteries from your breadboard when you make changes to the circuit!** Otherwise you run the risk of damaging components.

[14] If you're struggling with setting this up, you can watch me do it here.

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[15] – along with the resistor's tolerance rating. In addition to that, the resistor itself is also colored. Sometimes, depending on who made the resistor, this will be an additional tolerance indicator.

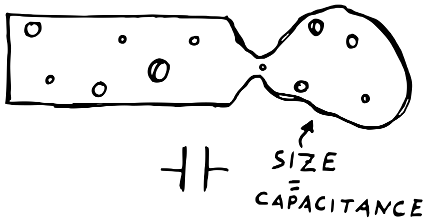
For the resistors in this kit, a yellow body tells you that the actual resistance value might be ±5 % off. A dark blue body indicates ±1 % tolerance. Some kits will also contain light blue ± 0.1% resistors to avoid the need for manual resistor matching.

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

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

CAPACITORS

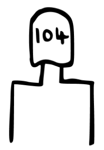
A capacitor is a bit like a balloon that you can attach to the open end of a pipe. If there's some pressure in the pipe, the balloon will fill up with water until the pressure equalizes. (Since the balloon needs some space to expand into, both of the capacitor's legs need to be connected to points in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

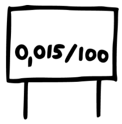


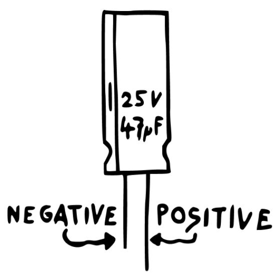
Then, should the pressure in the pipe drop, the balloon releases the water it stored into the pipe. The maximum size of the balloon is determined by the capacitor's capacitance, which we measure in farad (F). There are quite a few different types of capacitors: electrolytic, foil, ceramic, tantalum etc. 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 this circuit.







Ceramic capacitors usually come in disk- or pillow-like cases, are non-polarized and typically encode their capacitance value.[16] 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.[17]

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.

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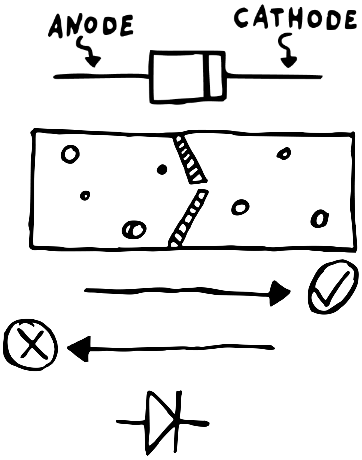
[16] For a detailed breakdown, look up ceramic capacitor value code. There are also calculation tools available.

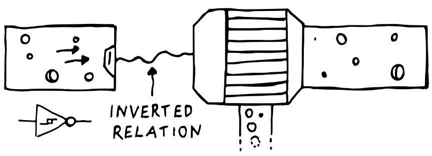
[17] If yours do encode their values, same idea applies here – look up film capacitor value code.

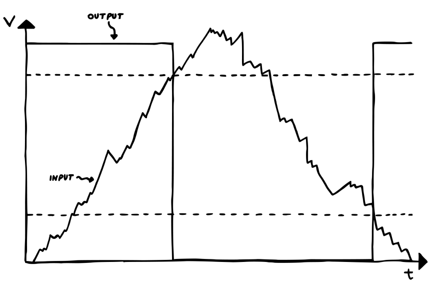
DIODES



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.

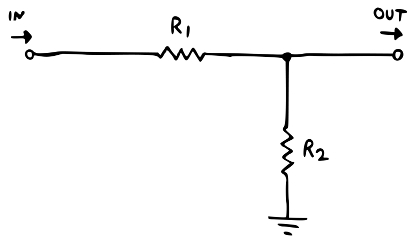
SCHMITT TRIGGER INVERTERS





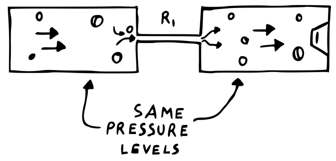
You can think of a Schmitt trigger inverter as two separate things. On the left, there's a sensor that measures the pressure inside an attached pipe. On the right, there is a water pump. This pump's operation is controlled by the sensor. Whenever the pressure probed by this sensor is below a certain 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

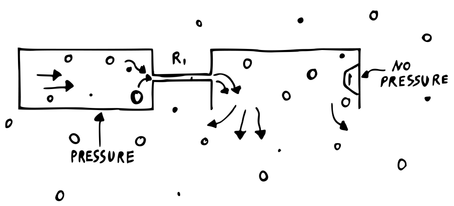


A voltage divider is really just two resistors set up like this: input on the left, output on the right. If R1 and R2 are of the same value, the output voltage will be half of what the input voltage is. How does it work?

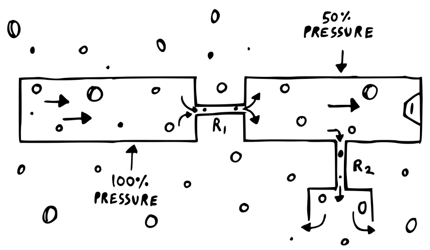
Let's use our analogy again: so we have a pipe on the left, where water is being pushed to the right with a specific amount of force. Attached to it is a narrow pipe, representing R1, followed by another wide pipe. Then at the bottom, there's another narrow pipe, representing R2, where water can exit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



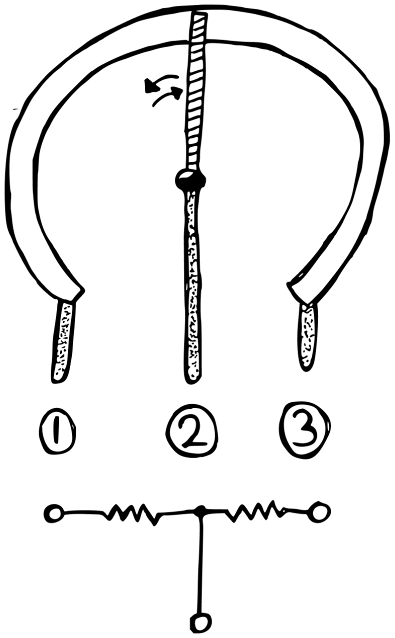
On the other hand, imagine R2 would just be a wide opening. Then **the pressure on the right would be 0**, because it'd all escape through that opening. But what happens if R2 is neither completely closed off nor wide open? Then the pressure would be retained to varying degrees, depending on the narrowness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

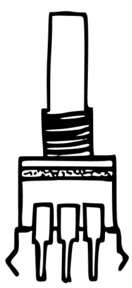
Potentiometers can be used as variable resistors that you control by turning a knob. But, and that's the handy part, they can also be set up as variable voltage dividers. To see how that works, let's imagine we open one up.

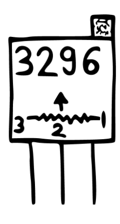


Inside, we would find two things: a round track of resistive material with connectors on both ends plus what's called a wiper. This wiper makes contact with the track and also has a connector. It can be moved to any position on the track. Now, the resistance value between the two track connectors is 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.





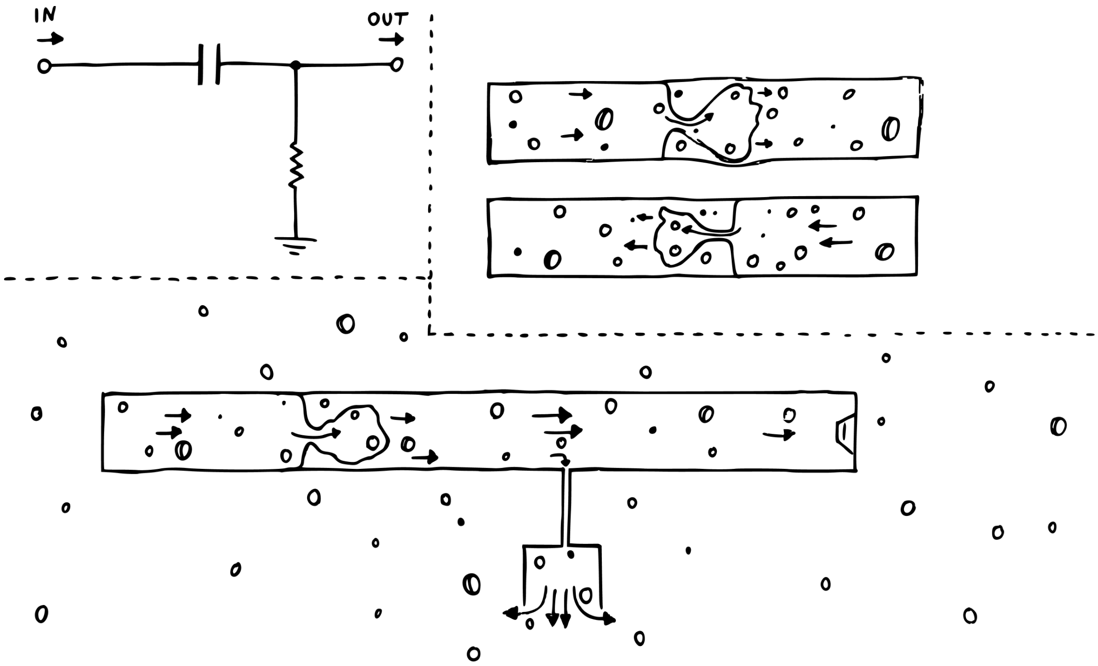
In these kits, you will encounter different types of potentiometers. First, there's the regular, full-size variant with a long shaft on top. These are used to implement user-facing controls on the module's panel and they usually – but not always – indicate their value directly on their casing. Sometimes, they'll use a similar encoding strategy as capacitors, though.[18]

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.

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

AC COUPLING

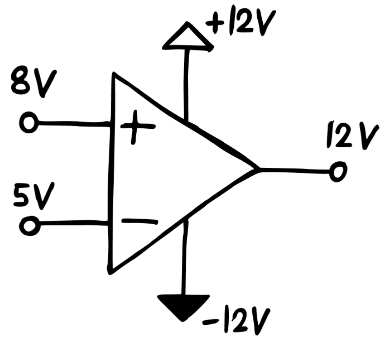
What is AC coupling – and how does it work? Imagine two adjacent pipes with a balloon between them. Now, no water can get from one pipe into the other, since it's blocked by the balloon. But, and that's the kicker, **water from one side can still push into the other by bending and stretching the balloon,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



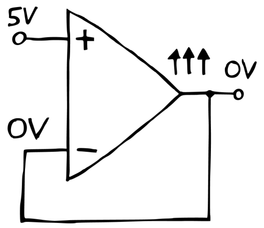
The key here is that op amps are essentially differential amplifiers. This means that they only amplify the difference between their two inputs – not each of them individually. If that sounds confusing, let's check out a quick example. So we'll imagine that one sensor – called the non-inverting input – 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.

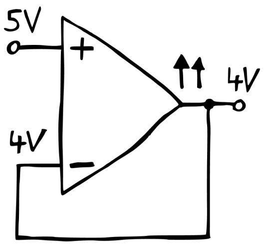
The handy thing though about op amp outputs is that they draw their power directly from the power source. This means that they can supply lots of current while keeping the voltage stable. **That's why we say an op amp has a very low output impedance**.

OP AMP BUFFERS/AMPLIFIERS

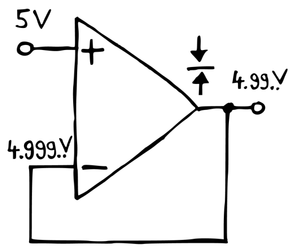
Buffering, in the world of electronics, means that we provide a perfect copy of a voltage without interfering with that voltage in the process. With an op amp-based buffer, the buffering process itself works like this. We use the non-inverting input to probe a voltage, while the inverting input connects 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.



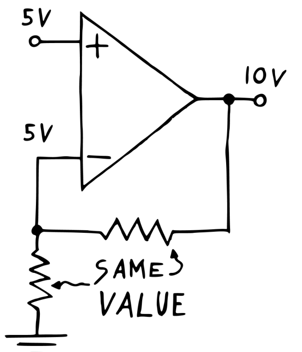
Before the op amp starts processing the voltages at its inputs, the output will be switched off. This means that **output and inverting input sit at 0 V at first**. So then, the op amp will subtract 0 from 5 and multiply the result by its gain. Finally, it will try and increase its output voltage to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



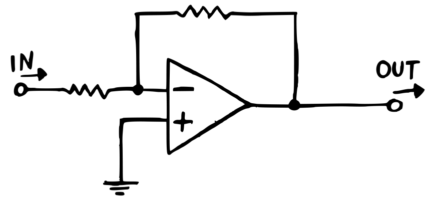
But as it's pushing up that output voltage, the **voltage at the inverting input will be raised simultaneously**. So the difference between the two inputs is shrinking down. Initially, this doesn't matter much because the gain is so large. As the voltage at the inverting input gets closer to 5 V though,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

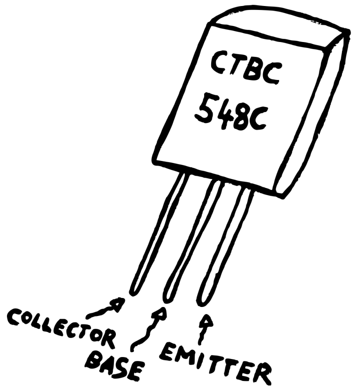
How does this work? Well, let's assume that we're applying a steady voltage of 5 V on the left. Then, as we already know, the op amp will subtract the inverting input's voltage from the non-inverting input's voltage, leaving us with a result of –5 V. Multiply that by the huge internal gain, and the op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

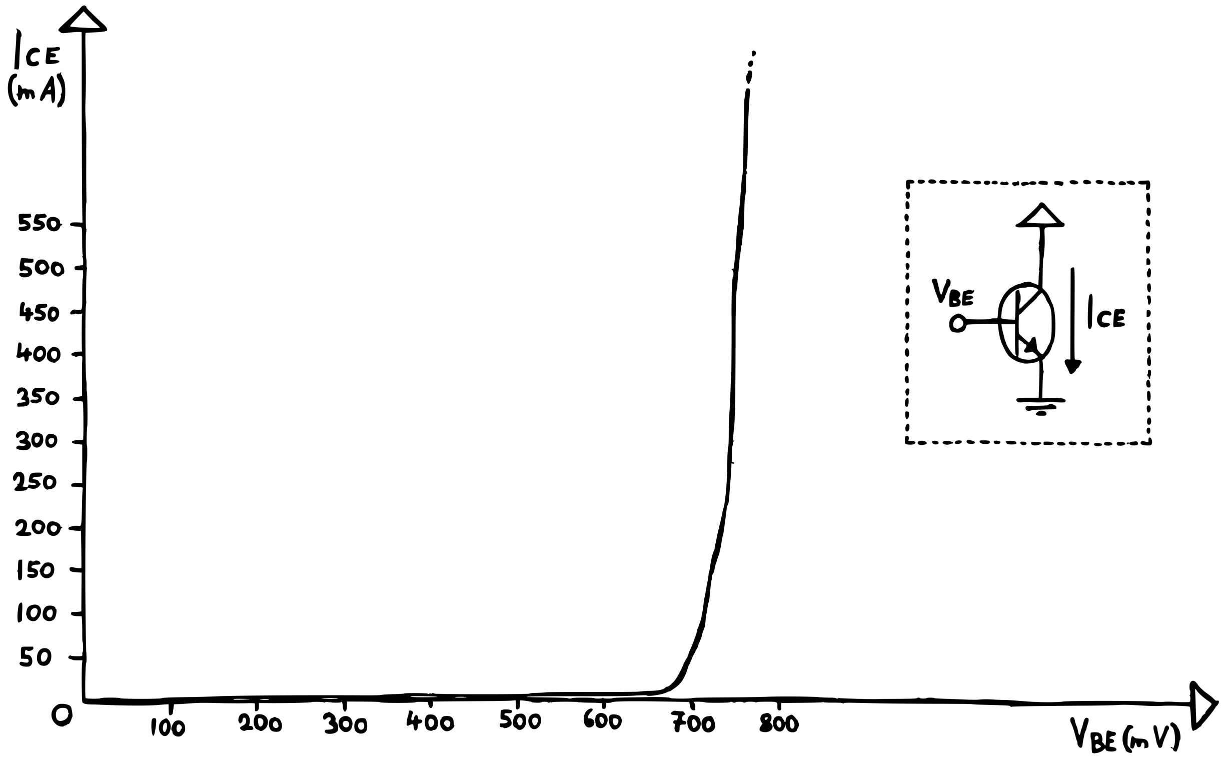
And that means that the voltage at the inverting input will be lowered to about 0 V, allowing our op-amp to settle on the current output voltage level. So while we read 5 V on the left, we'll now read a stable –5 V at the op amp's output. Congrats – we've built an inverting buffer! **If we want to turn 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.**[19] 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[20] 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.



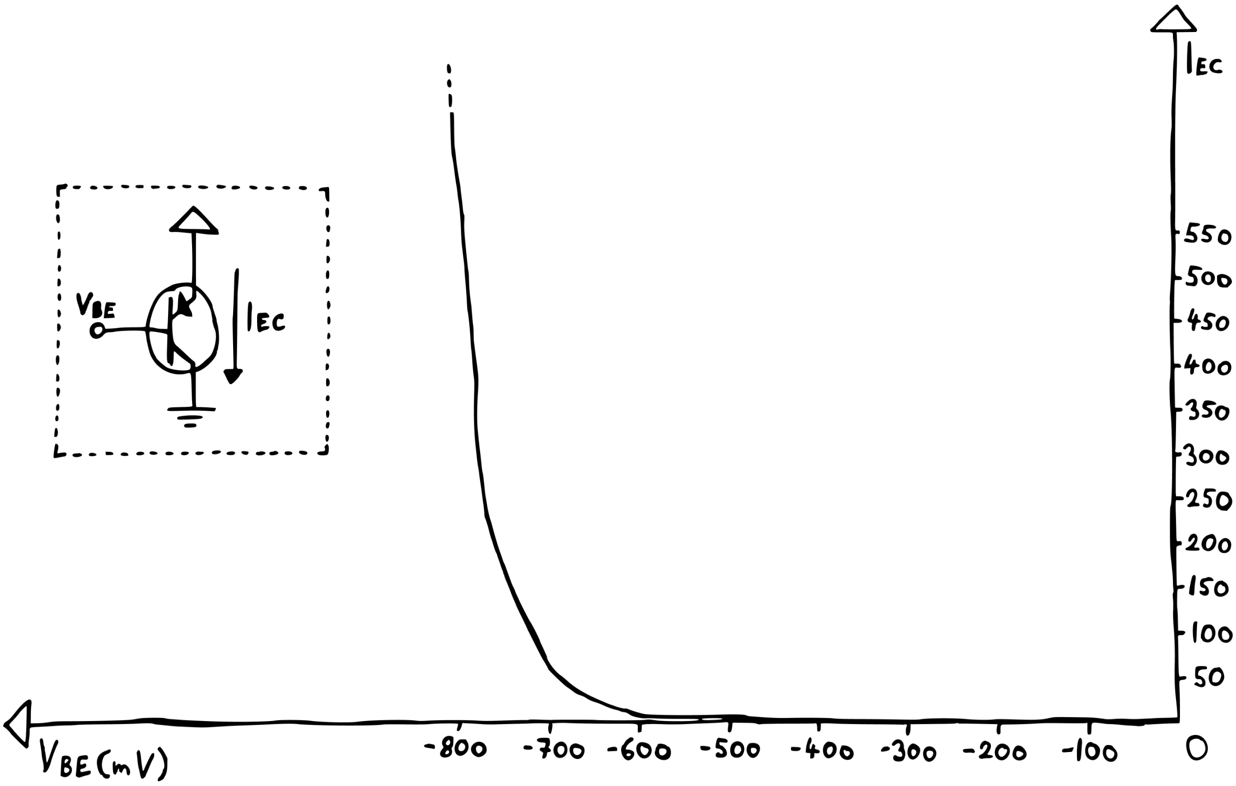
First, the relation between base voltage and collector current is exponential. Second, unlike a resistor, a BJT is not symmetrical – so we can't really reverse the direction of the

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

[20] 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**[21]. 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!

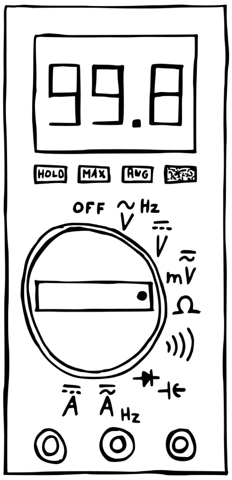


[21] Again, the voltage is measured between base and emitter.

TOOLS APPENDIX

There are two types of tools that will help you tremendously while designing a circuit: multimeters and oscilloscopes. In this appendix, we'll take a quick look at each of these and explore how to use them.

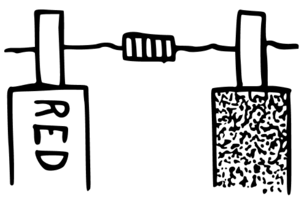
MULTIMETERS

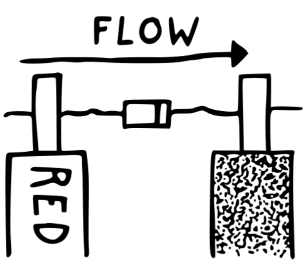


Multimeters come in different shapes and sizes, but the most common type is probably the hand-held, battery powered variant. It can measure a bunch of different things: voltage, current, resistance, continuity. Some have additional capabilities, allowing you to check capacitance, oscillation frequency or the forward voltage drop of a diode.

When shopping for one, you'll probably notice that there are really expensive models boasting about being TRUE RMS multimeters. For our purposes, this is really kind of irrelevant, so don't feel bad about going for a cheap model!

Using a multimeter is actually really straightforward. Simply attach two probes to your device – the one with a black cable traditionally plugs into the middle, while the red one goes into the right connector. Next, find whatever you want to measure and select the corresponding mode setting.



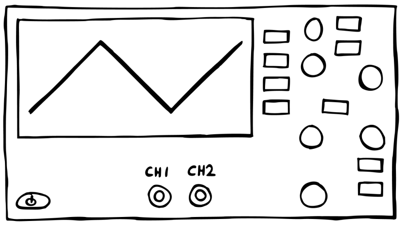


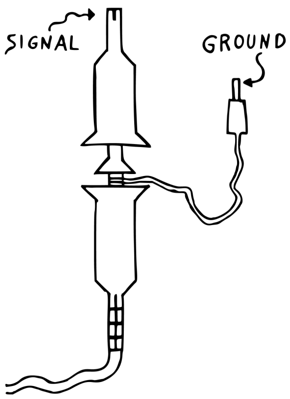
In some cases, it doesn't matter which probe you connect to which component leg or point in your circuit. This is true for testing resistors, non-polarized capacitors (foil/film, ceramic, teflon, glass etc.), continuity[22] or AC voltage.

In others, you'll have to be careful about which probe you connect where. For testing the forward voltage drop of a diode, for example, **the multimeter tries to push a current from the red to the black probe**. Here, you'll have to make sure the diode is oriented correctly, so that it doesn't block that current from flowing. For testing a DC voltage, you want to make sure the black probe is connected to ground, while you use the red one to actually take your measurement.

[22] Just a fancy word for saying that two points are electrically connected.

OSCILLOSCOPES



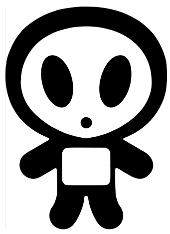


While multimeters are fairly cheap and compact, oscilloscopes are usually somewhat pricey and bulky. **If you're willing to make the investment, they are a huge help with the troubleshooting process, though**. Using one is, again, surprisingly straightforward – if you manage to work your way through the sometimes quite convoluted UI, especially on digital models.

To start using your scope, simply attach a probe to one of the channel inputs. These probes usually have two connectors on the other end: a big one that you operate by pulling the top part back – and a smaller one, which is usually a standard alligator clip. The latter needs to be connected to your circuit's ground rail, while you probe your oscillation with the former. Now what the oscilloscope will do is **monitor the voltage between the two connectors over time and draw it onto the screen as a graph**. Here, the x-axis is showing time, while the y-axis is showing voltage. You can use the device's scaling controls to zoom in on a specific part of your waveform.

Usually, digital oscilloscopes will also tell you a couple useful things about the signal you're currently viewing: minimum/maximum voltage level, oscillation frequency, signal offset. Some even offer a spectrum analyzer, which can be useful to check the frequencies contained in your signal.

BUILD GUIDE



MODULE ASSEMBLY APPENDIX

Before we start building, let's take a look at the complete **mki x es.edu Hi-Hats** schematics (see next page) that were used for the final module's design and PCB fabrication. Most components on the production schematics have denominations (a name – like R1, C1, VT1, VD1, etc.) and values next to them. Denominations help identify each component on the PCB, which is particularly useful during **calibration**, **modification** or **troubleshooting**.

XS4 is the **Trigger input** jack socket, **XS1** is the **Accent input** jack sockets; it requires +5V gate signal to initiate the accent. **XS2** is **the Tune CV input, XS3** is **the Decay CV input** (you can use CV to emulate open Hi-Hats) and **XS5** is the **Audio output** jack socket – these are the very same we've already been using on the breadboard for interfacing with other devices. In our designs, we use eurorack standard 3,5mm jack sockets (part number WQP-PJ301M-12).

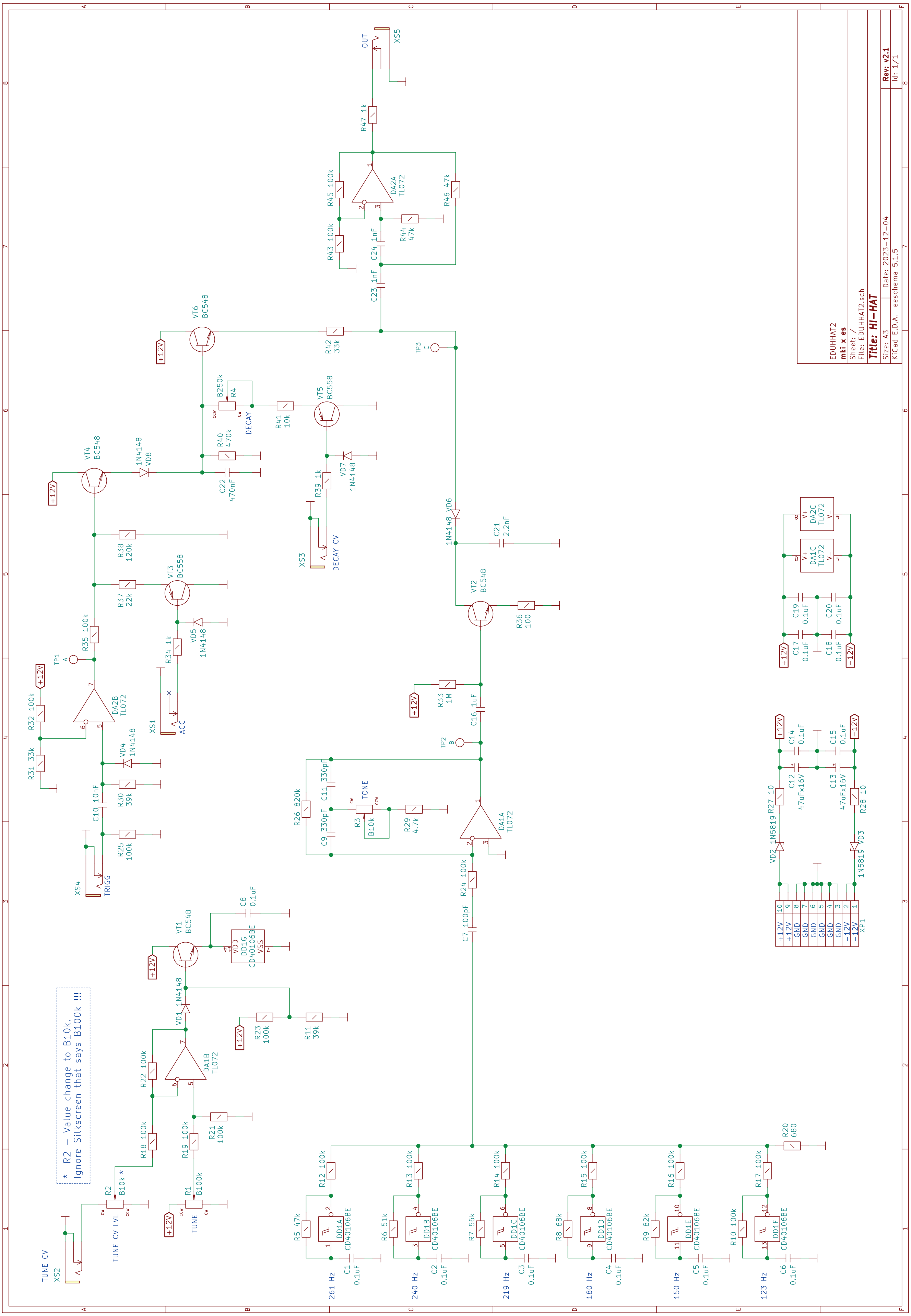
XP1 is a standard eurorack **power connector**. It's a 2x5 male pin header with a key (the black plastic shroud around the pins) to prevent accidental reverse polarity power supply connection. This is necessary because connecting the power incorrectly will permanently damage the module.

VD2 and VD3 are **schottky diodes** that double-secure the reverse polarity power supply protection. Diodes pass current only in one direction. Because the anode of VD1 is connected to +12 V on our power header, it'll only conduct if the connector is plugged in correctly. If a negative voltage is accidentally applied to the anode of VD2, it closes, and no current passes through. The same goes for VD2, which is connected to -12 V. Because schottky diodes have a low forward voltage drop, they are the most efficient choice for applications like this.

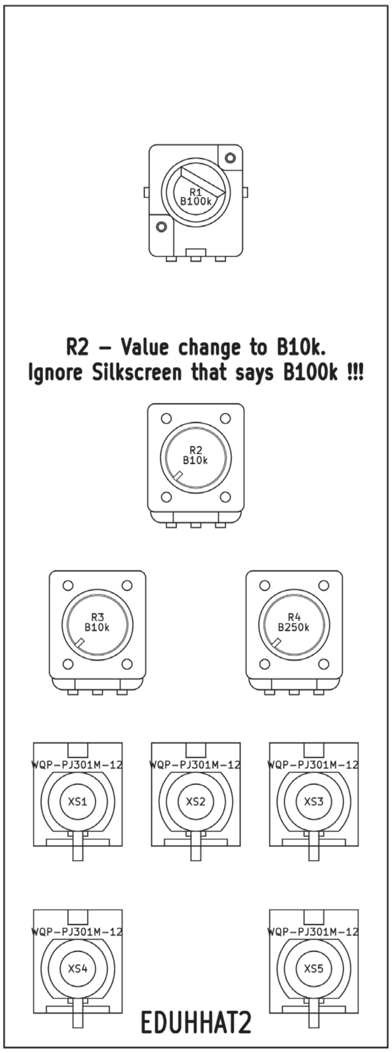
Next, we have two **10 Ohm resistors** (**R27** and **R28**) on the + and – 12 V rails, with **decoupling** (or **bypass**-) capacitors **C14, C15.** These capacitors serve as energy reservoirs that keep the module's internal supply voltages stable in case there are any fluctuations in the power supply of the entire modular system. In combination with R5 and R6, the large 47 microfarad pair (C12 and C13) compensates for low frequency fluctuations, while C4 and C5 filter out radio frequencies, high frequency spikes from switching power supplies and quick spikes created by other modules. Often another component – a **ferrite bead** – is used instead of a 10 Ohm resistor and there's no clear consensus among electronic designers which works best, but generally for analogue modules that work mostly in the audio frequency range (as opposed to digital ones that use microcontrollers running at 8 MHz frequencies and above), resistors are considered to be superior.

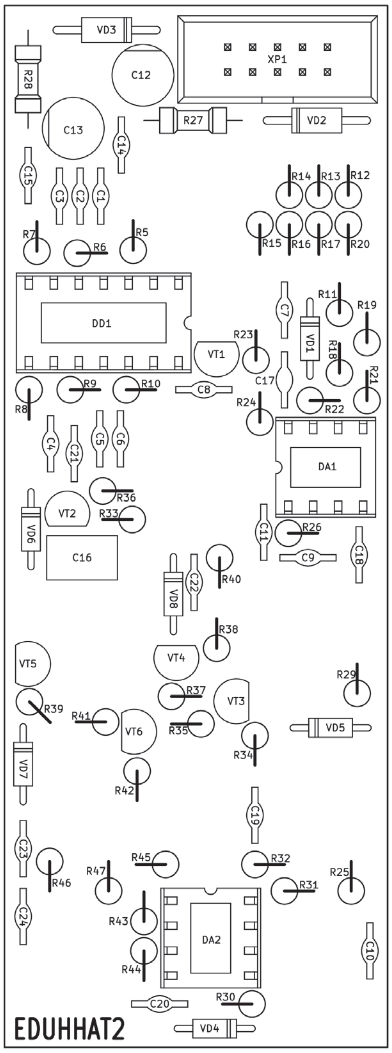
Another advantage of 10 Ohm resistors is that they will act like **slow "fuses"** in case there's an accidental short circuit somewhere on the PCB, or an integrated circuit (IC) is inserted backwards into a DIP socket. The resistor will get hot, begin smoking and finally break the connection. Even though they aren't really fuses, just having them there as fuse substitutes is pretty useful - **you'd rather lose a cent on a destroyed resistor than a few euros on destroyed ICs.**

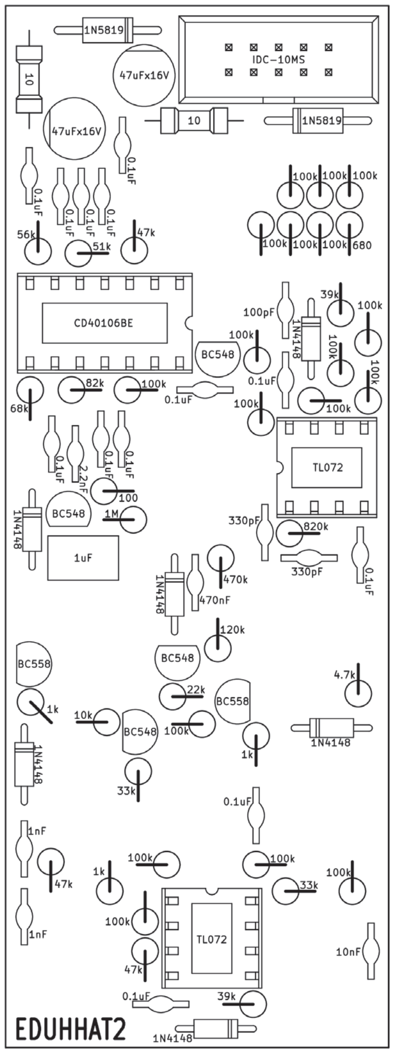
Capacitors **C17-C20** are additional decoupling capacitors. If you inspect the PCB, you'll see that these are placed as close to the power supply pins of the ICs as possible. For well-designed, larger PCBs you will find decoupling capacitors next to each IC. Like the others, their job is to simply compensate for any unwanted noise in the supply rails. If the input voltage drops, then these capacitors will be able to bridge the gap to keep the voltage at the IC stable. And vice-versa - if the voltage increases, then they'll be able to absorb the excess energy trying to flow through to the IC, which again keeps the voltage stable. Typically, 0.1 uF capacitors are used for this purpose.

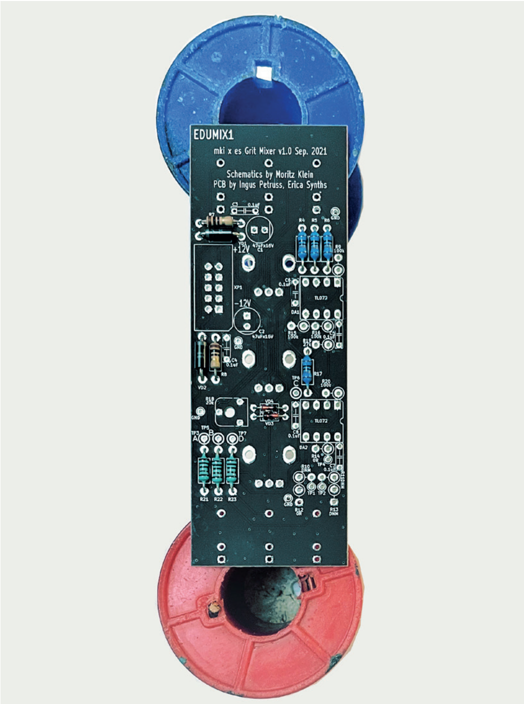

* R2 – Value change to B10k.
Ignore Silkscreen that says B100k !!!
EDUHHAT2
mki x es
Sheet: /
File: EDUHHAT2.sch
Title: HI-HAT
Size: A3
Date: 2023-12-04
KiCad E.D.A. eeschema 5.1.5
Rev: v2.1
Id: 1/1

Before you start soldering, we highly recommend printing out the part placement diagrams with designators and values and follow step-by step instructions below. Hi-Hats PCB is one of most densely populated PCB in our DIY.EDU line, so, this will help you to avoid mistakes in the build process.

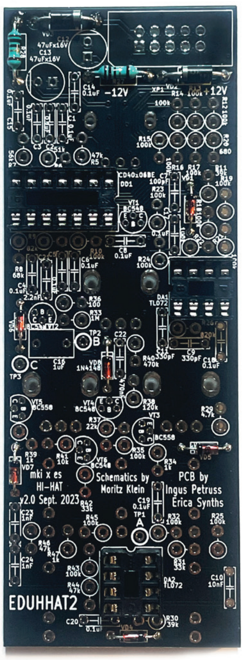








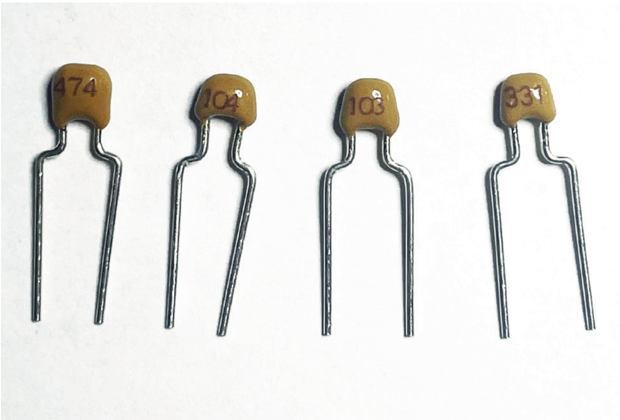
Place the Hi-Hats PCB in a PCB holder for soldering or simply on top of some spacers (I use two empty solder wire coils here).

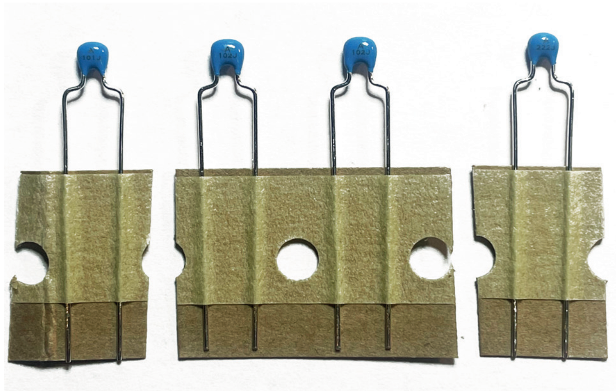


I usually start populating PCBs with lower, horizontally placed components. In this case, these are **10 Ohm resistors, switching diodes and the power protection diodes.** Bend the resistor leads and insert them in the relevant places according to the part placement diagram above. Next, insert the diodes. Remember – **when inserting the diodes, orientation is critical!** A thick white stripe on the PCB indicates the cathode of a diode – match it with the stripe on the component. Flip the PCB over and solder all components. Then, use pliers to cut off the excess leads.

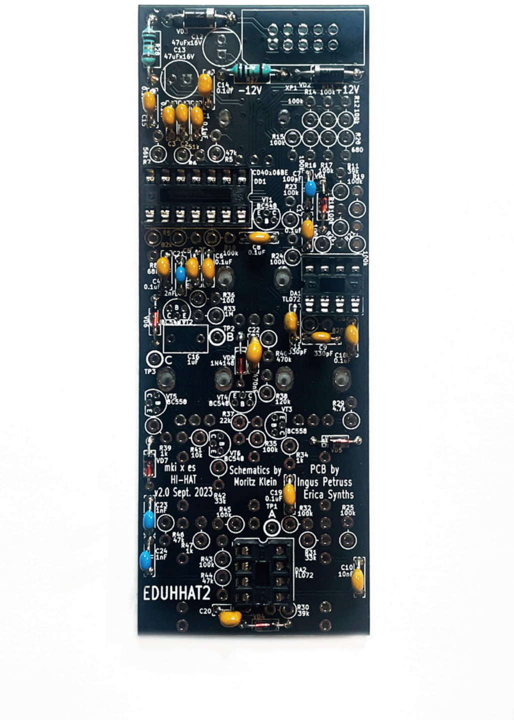
Also, **insert the first DIP socket**, hold it in place and solder one of the pins. Continue with the **next DIP socket.** Make sure the DIP sockets **are oriented correctly** – the notch on the socket should match the notch on the PCB's silkscreen. Now, turn the PCB around and solder all remaining pins of the DIP sockets.

Then proceed with the ceramic capacitors. Because ceramic capacitors look very similar, I recommend sorting them by values before you proceed with installing and soldering them. Yellow capacitors in the picture to the left are 470nF, 0,1uF, 10nF and 330pF, blue capacitors are 100pF, 1nF and 2,2nF.



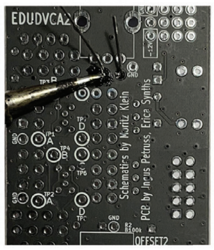


Start with soldering 0,1uF capacitors - place the PCB in your PCB holder or on spacers, insert the capacitors and solder them like you did with the resistors & diodes before. Now your PCB should look like this:

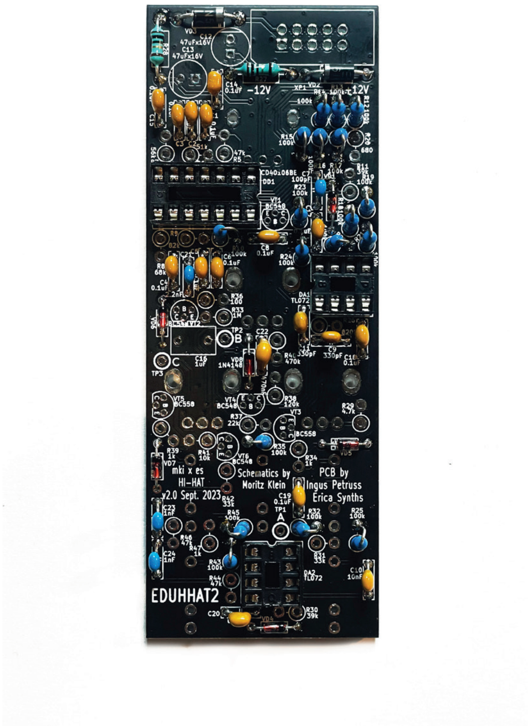


Then proceed with other capacitors. When completed, your PCB should look like this:

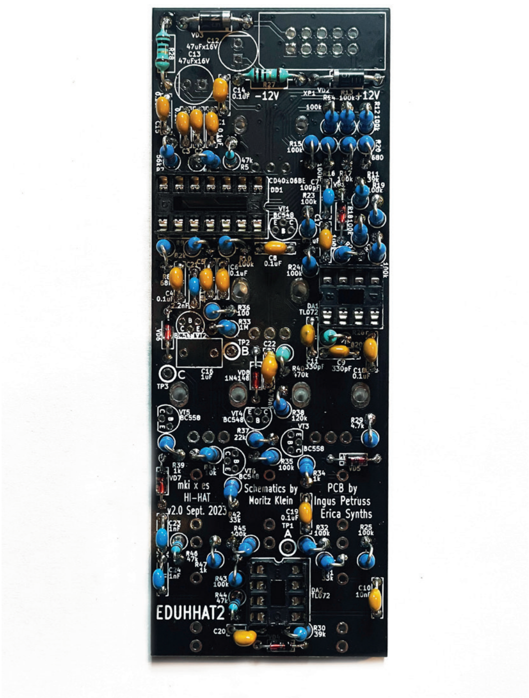
Now, let’s proceed with resistors! All components on the PCB have both their value and denomination printed onto the silkscreen. Resistors are particularly tricky because they are color coded, and sometimes colors are difficult to distinguish. If you are not sure about a resistor’s value, use a multimeter to double-check. In order to save space on the PCB most of resistors on the Hi-Hats module are vertically placed. The next step is to place & solder those. Bend a resistor’s legs so that its body is aligned with both legs and insert it in its designated spot. Then solder the longer lead from the top side of the PCB to secure it in place, turn the PCB around and solder the other lead from the bottom. You can insert several resistors at once. Once done with soldering, use pliers to cut off excess leads.



Let's start with 100 k resistors, because we have plenty of those. Once you have soldered all 100 k resistors, your PCB should look like this:



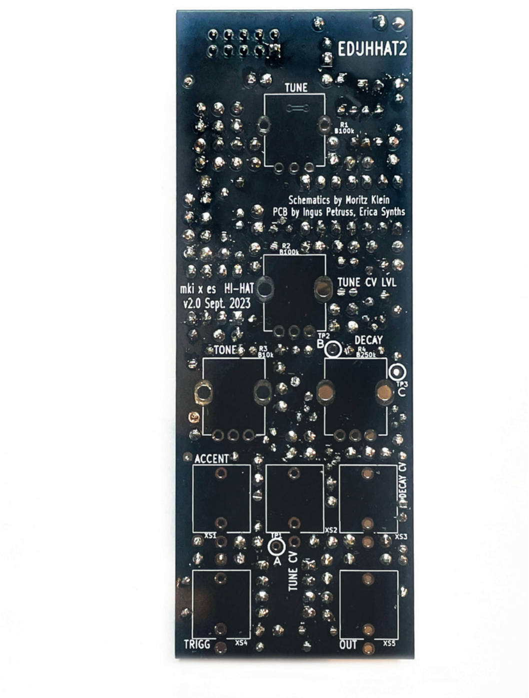
Then proceed with other resistors. Remember – if you are not sure about resistor values, use the multimeter to check! When al resistors are installed, your Hi-Hats PCB should look like this:



Next, insert and solder **transistors.** There are PNP and NPN transistors in the kit, therefore before soldering them, I highly recommend to sort them. Make sure you install them in correct places and pay attention on the orientation of the transistors – notch on the silkscreen has to match the flat part of the transistor.

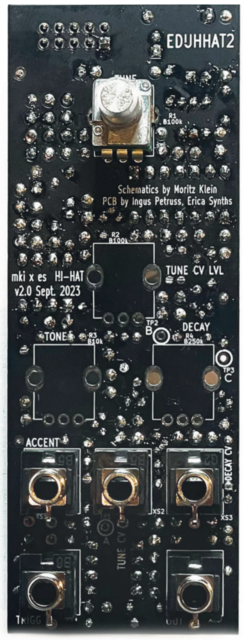
Now **insert & solder the electrolytic capacitors.** Electrolytic capacitors are bipolar, and you need to mind their orientation. The positive lead of each electrolytic capacitor is longer, and there is a minus stripe on the side of the capacitor's body to indicate the negative lead. On our PCBs, the positive pad for the capacitor has a square shape, and the negative lead should go into the pad next to the notch on the silkscreen.

Also, populate the 1 uF **film capacitor** and **2x5 PSU socket.** Make sure the orientation of the socket is as shown in the picture below – the arrow pointing to the first pin is aligned with a notch on the silkscreen. The key on the socket will be facing down the PCB. Now your PCB should look like this:

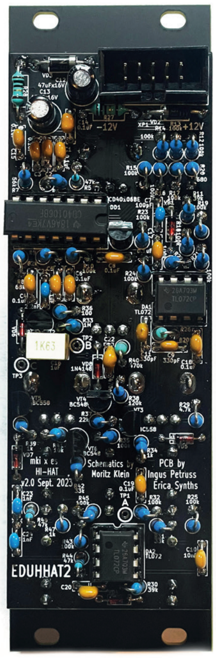


Now, turn the PCB around and inspect your solder joints. **Make sure all components are soldered properly and there are no cold solder joints or accidental shorts.** I noticed, I forgot to solder most of the pins of the PSU socket. Clean the PCB to remove extra flux, if necessary.

Insert the top potentiometer and jack sockets, then fit the panel to align components, you just installed, and solder them.



Insert other potentiometers, but don't solder them yet! **NB! There's a replacement in the kit - Tune CV potentiometer should be 10k, while the BOM and silkscreen on the PCB says 100k.** Fit the front panel, screw the nuts on the top potentiometer and jack sockets and make sure that the potentiometer shafts are aligned with the holes in the panel – and that they're able to rotate freely. Now, go ahead and solder the potentiometers.



Now, **insert the ICs into their respective DIP sockets.** Mind the orientation of the ICs – match the notch on each IC with the one on its socket.

Finally fit the Decay potentiometer knob and we are done!

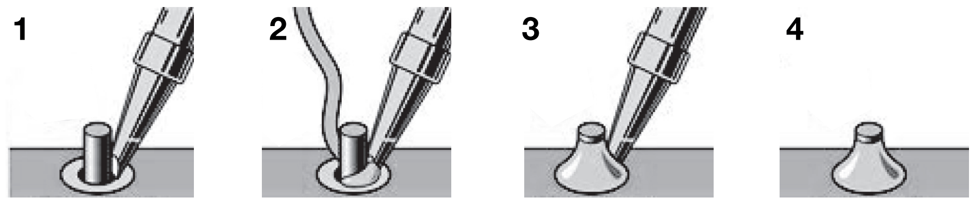
Congratulations! **You have completed the assembly of the mki x es.edu Hi-Hats module!** Connect it to your eurorack power supply and switch it on. If there's no "magic smoke", it's a good sign that your build was successful. The module doesn't need any calibration. Patch trigger signal (the gate output of your DIY.EDU Sequencer will work fine, but the Erica Synths Drum Sequencer is the best choice) to the input of the module and connect the output of the module to a mixer. You should hear the Hi-Hats sound. Turn gates on the sequencer on and off in order to achieve a desired Hi-Hats pattern and tweak some knobs on the module to observe change of the sound.

Enjoy!

SOLDERING APPENDIX

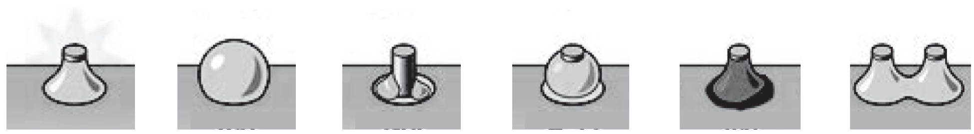
If you've never soldered before – or if your skills have become rusty – it's probably wise to check out some **THT** (through-hole technology) **soldering tutorials on YouTube**. The main thing you have to remember while soldering is that melted solder will flow towards higher temperature areas. So you need to make sure you apply equal heat to the component you are soldering and the solder pad on the PCB. The pad will typically absorb more heat (especially ground-connected pads which have more thermal mass), so keep your soldering iron closer to the pad on the PCB. It's critically important to dial in the right temperature on your soldering station. I found that about 320 °C is the optimal temperature for most of parts, while for larger elements like potentiometers and sockets, you may want to increase that temperature to **370 °C.**

Here's the recommended soldering sequence:



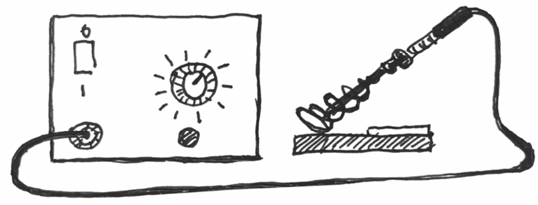
Heat part and pad 2 - 3 sec	Add solder	Continue heating 1 -2 sec.	Let cool

After you have completed soldering, inspect the solder joint:

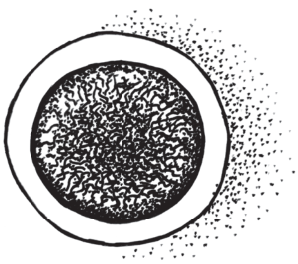


Perfect	Too much solder	Not enough solder	Cold joint	Too much heat	Short

DIY electronics is a great (and quite addictive) hobby, therefore we highly recommend you invest in good tools. In order to really enjoy soldering, you'll need:

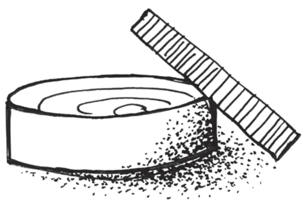


A decent soldering station. Top-of-the-line soldering stations (brands like Weller) will cost 200€ and above, but cheaper alternatives around 50€ are often good enough. Make sure your soldering station of choice comes with multiple differently-sized soldering iron tips. The most useful ones for DIY electronics are flat, 2mm wide tips.



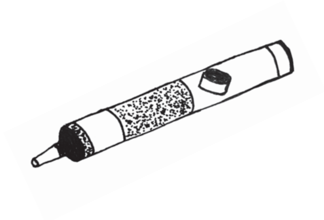
When heated up, the tips of soldering irons tend to oxidize. As a result, solder won't stick to them, so you'll need to clean your tip frequently. Most soldering stations come with a **damp sponge for cleaning the iron tips** – but there are also professional solder tip cleaners with **golden curls** (not really gold, so not as expensive as it sounds). These work much better because they do not cool down the iron.

Solder wire with flux. I find 0,7mm solder wire works best for DIY projects.

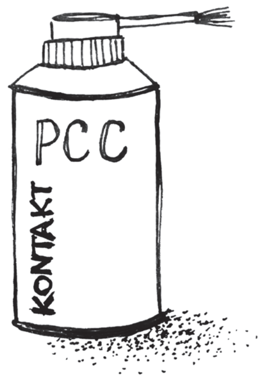


Some **soldering flux** paste or pen will be useful as well.

Cutting pliers. Use them to cut off excess component leads after soldering.



A solder suction pump. No matter how refined your soldering skills are, you will make mistakes. So when you'll inevitably need to de-solder components, you will also need to remove any remaining solder from the solder pads in order to insert new components.



Once you have finished soldering your PCB, it's recommended to remove excess flux from the solder joints. **A PCB cleaner** is the best way to go.

All of these tools can be found on major electronic components retailer websites, like Mouser, Farnell and at your local electronics shops. As you work your way towards more and more advanced projects, you'll need to expand your skillset and your tool belt – but the gratification will be much greater.

“No acting, no production, could take the place of that moment when you come out in the dark on to the stage and the drummer plays four beats on the hi-hat and then lights and music. It just takes your breath away. No words can do what music can.”

– Ken Stott