# 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!

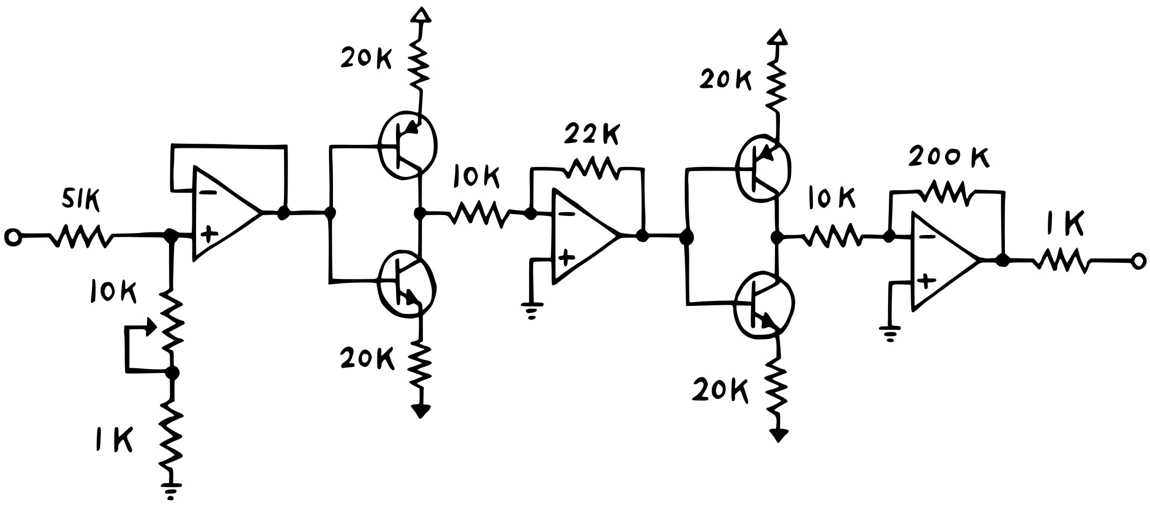
# TABLE OF CONTENTS



[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.

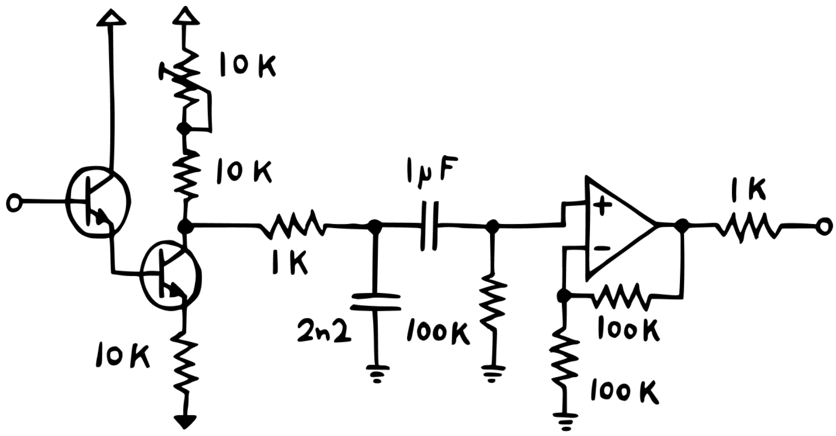
# THE mki x es.edu WAVEFOLDER

Even though wavefolding is more of a west coast synthesis concept, it's a great addition to the otherwise very east coast mki x es.edu DIY system. Why? Because it can provide a ton of unusual timbres for your patches: from a slight dash of brightness to harsh metallic drones. That's why I came up with this super simple BJT-based double wavefolder.



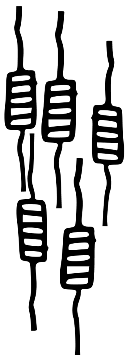
# THE mki x es.edu SAW-TO-TRI

Of course we'll need a suitable signal to fold – which, traditionally, has been either a sine or a triangle wave. And since the mki x es.edu VCO provides neither of those, we needed to do some extra work here. So I designed this super efficient little sawtooth-to-triangle converter that uses the same basic working principle as the main wavefolding circuit.



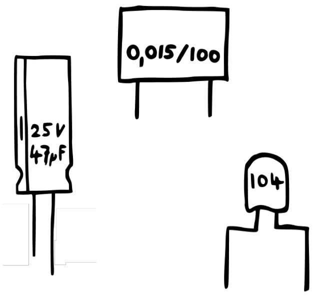
# BILL OF MATERIALS

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:



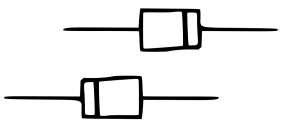
**An array of resistors.** The specific values (in ohms, which you should check for with a multimeter) are

| | |
|---|---|
| **220k** | x1 |
| **100k** | x3 |
| **51k** | x1 |
| **22k** | x1 |
| **20k** | x4 |
| **10k** | x4 |
| **1k** | x5 |
| **10 Ω** | x2 |




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

| | |
|---|---|
| **47 µF (electrolytic)** | x2 |
| **1 µF (1J63/foil)** | x1 |
| **100 nF (104/ceramic)** | x4 |
| **2.2 nF (2n2J100/foil)** | x2 |



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

**SB140[2] (schottky)** x2

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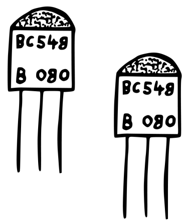
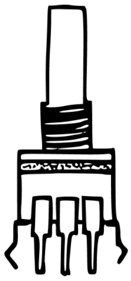
[2] Please note that these could also be a different model (e.g. 1N5818).



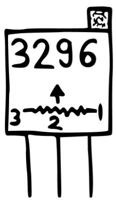

**A couple of transistors.** The specific model names (which are printed onto their bodies) are

**BC548 (NPN)** x4
**BC558 (PNP)** x2



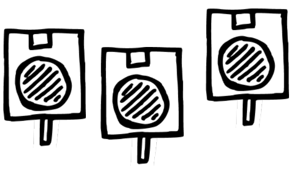
**One regular potentiometer.** The specific value (which may be encoded & printed onto its body) is

**10k (B103)** x1



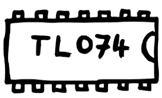

**A trimmer potentiometer.** The specific value (which is encoded & printed on top) is

**10k (W103)** x1



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

**Switched mono (black)** x3



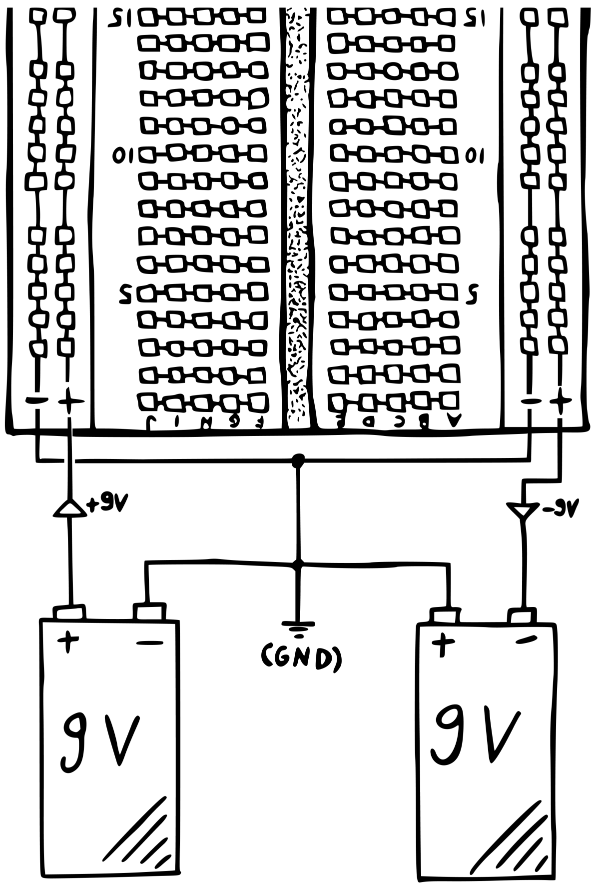

**A chip.** The specific model (which is printed onto its body) is

**TL074 (quad op amp)** 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.**[3] 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.[4]

**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.

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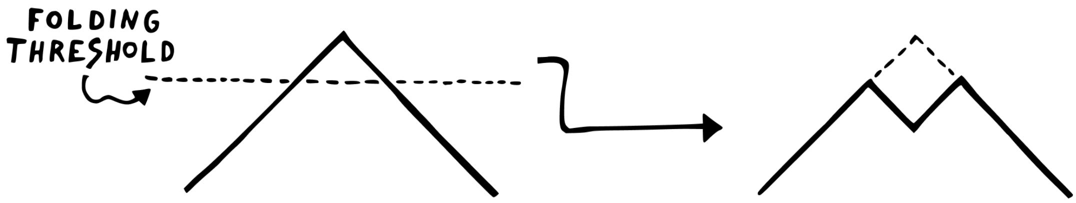
[3] Since all circuits in this manual were designed for a 12 V power supply, we assume that to be the default. Everything will still work roughly the same with 9 V, though.

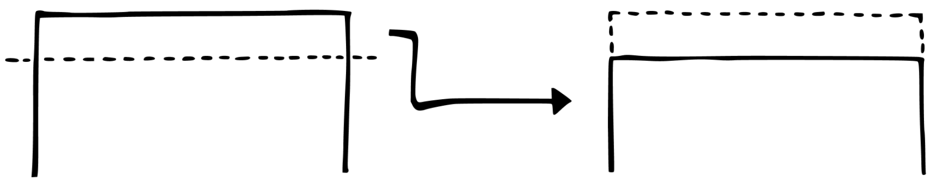
[4] This is a bit awkward because breadboards weren't really made with dual supply voltages in mind.

# WAVEFOLDING BASICS

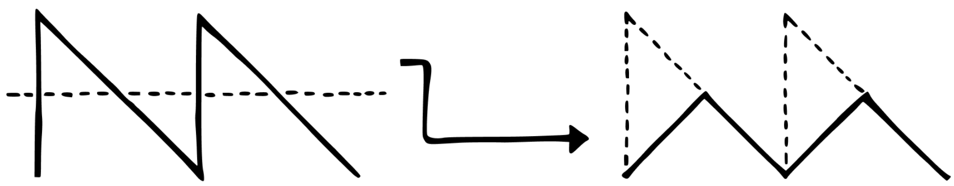
Before we can start designing our circuit, we'll first need to make sure we understand what wavefolding actually is. Thankfully, that term is pretty hard to misinterpret. **A wavefolder quite literally takes a waveform and folds it in on itself.** Here's what that would look like with a triangle wave as the input signal.




As you can see, everything above the folding threshold is folded inward – so that the tip of the original triangle now points down. In practice, this would create a bunch of additional overtones that give the resulting output an almost metallic feel.
Of course not all types of waveforms are equally suited as an input signal here. You won't gain anything by folding a square wave, for example – on the contrary, you'll just lose a bit of volume.

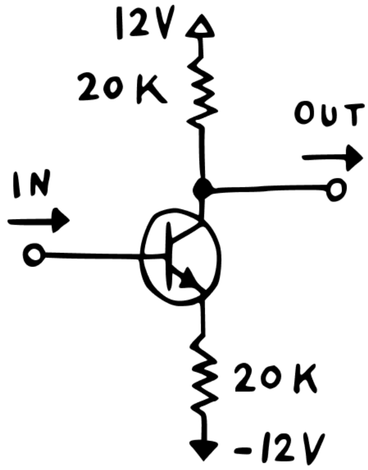


Try it with a sawtooth wave, though, and you'll notice that if you set the folding threshold just right, the result is actually a perfect triangle wave.



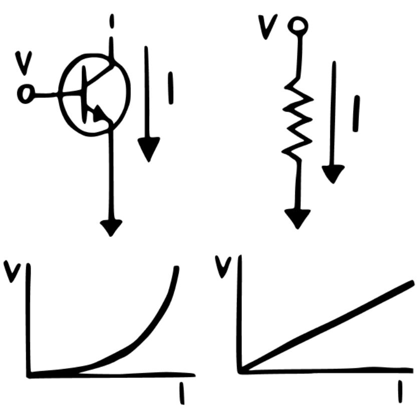
# THE SIMPLEST WAVEFOLDER

Okay, but how do we make this happen? The circuit will probably be quite complex, right? Yeah .. not really. All we need are three components: two same-value resistors and an NPN transistor.[5] If we set them up like this and send an oscillation into the transistor's base, we can pick up a folded version at the collector.




Now, if you've worked with NPN transistors before, you might say „hold on – how is this a wavefolder? It's just a bog-standard amplifier!" And you would be right. What's worse: it doesn't really amplify anything, since it has a gain of -1. So all it does is invert the input signal while keeping the volume the same.

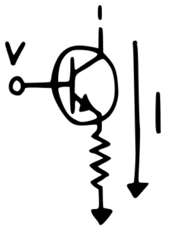
Then why do I call this a wavefolder? Because it is if you abuse it! To understand why and how, let's dissect this circuit step by step. Functionally, we can split it into two sections: the resistor up top and the transistor and resistor below. Let's start with the lower section.

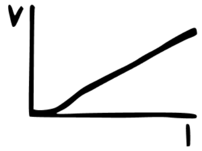



These two components in conjunction serve one simple purpose. **They're meant to convert voltage into current**. More precisely: the voltage we apply to the base into a current flowing through transistor and resistor. Okay, but what is the relation between those two variables?

Well, for the transistor on its own, the relation between base voltage and collector current is exponential. Conversely for the resistor, the relation between the voltage across it and the current flowing through it is strictly linear.

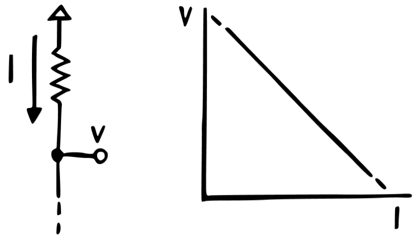
[5] Read more about resistors and transistors in the components & concepts appendix (page 28/37).



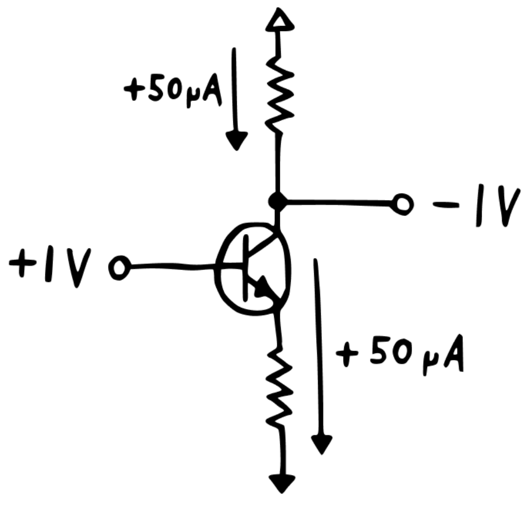

So when the components are paired up, we can see that their behaviors are clashing: while the transistor wants to ramp up its current throughput exponentially, the resistor only allows for a linear increase.

This means that the resistor is the bottleneck in our system: it throttles the transistor. **So for a given base voltage, the current flowing through transistor and resistor will be (almost) the same as the current flowing through just the resistor with the base voltage applied across it.** I say „almost“ because activating the transistor eats up a small but fixed amount of current – so it will always be a little bit lower.




Now let’s look at the upper part of our amplifier/wavefolder – which is just a single resistor connected to the positive rail. **That resistor serves the exact opposite purpose: convert current into voltage**. It works like this: the more current we pull through the resistor, the more the voltage below it will drop.

If we put this together with the lower half now, it should become clear why the voltage at the collector almost mirrors the voltage at the base. Because for every volt added to the base voltage, we push an additional 50 µA through the bottom resistor.[6]



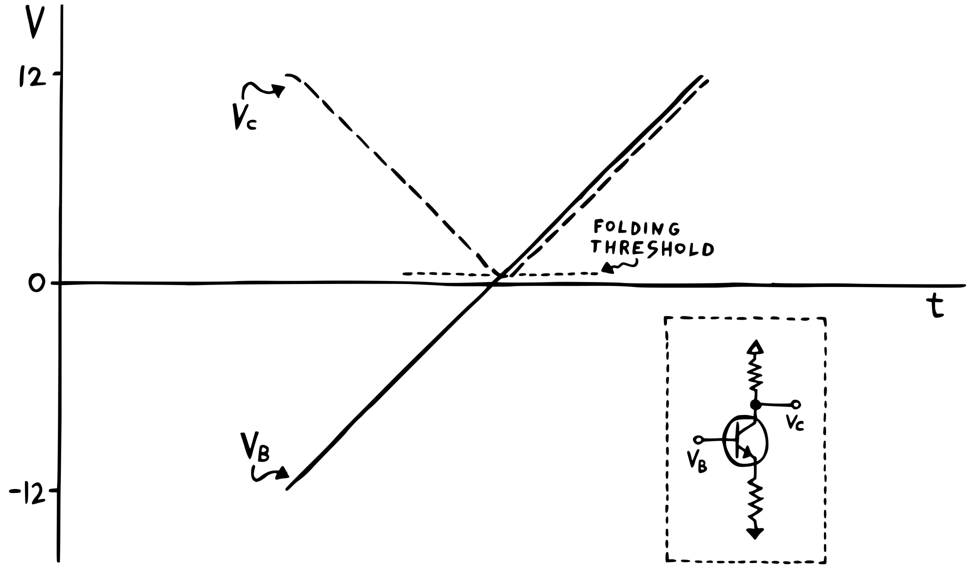

Which, in turn, means that we have to pull that current through the top resistor. **And because that resistor is of the same value as the one at the bottom, the voltage below it will drop by exactly 1 V**. There are two caveats here, though. First, the absolute collector voltage will be a small but fixed amount higher than the base voltage.

[6] You can try this chapter’s circuit in a simulator. I’ve already set it up for you right here: https://tinyurl.com/2hl93mas – you can change all values by double clicking on components.

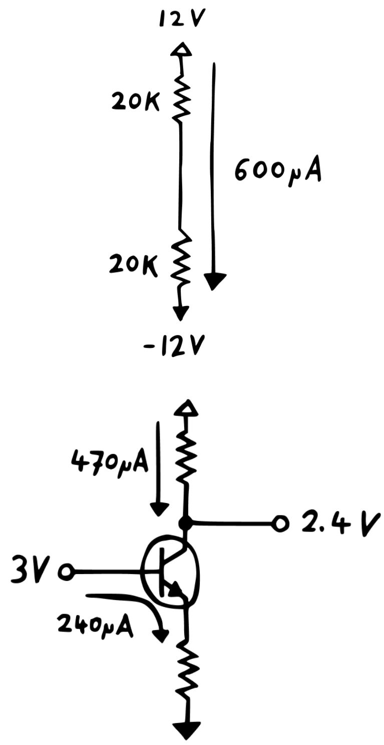
This is because, as we said earlier, the transistor eats up a bit of current while active. But second, and more importantly, this mechanism only works as long as the transistor can pull enough current into its collector.

# TRANSISTOR SATURATION

Let's look at our circuit's behavior using a quick graph. We'll imagine we steadily increase the base voltage ($V_B$) from -12 V all the way up to +12 V.




In the region between -12 V and around 450 mV, everything works as expected: the collector voltage ($V_C$) drops in sync with the base voltage. But after the base- and collector voltages meet, something strange happens: the collector voltage starts rising again. What's up with that?

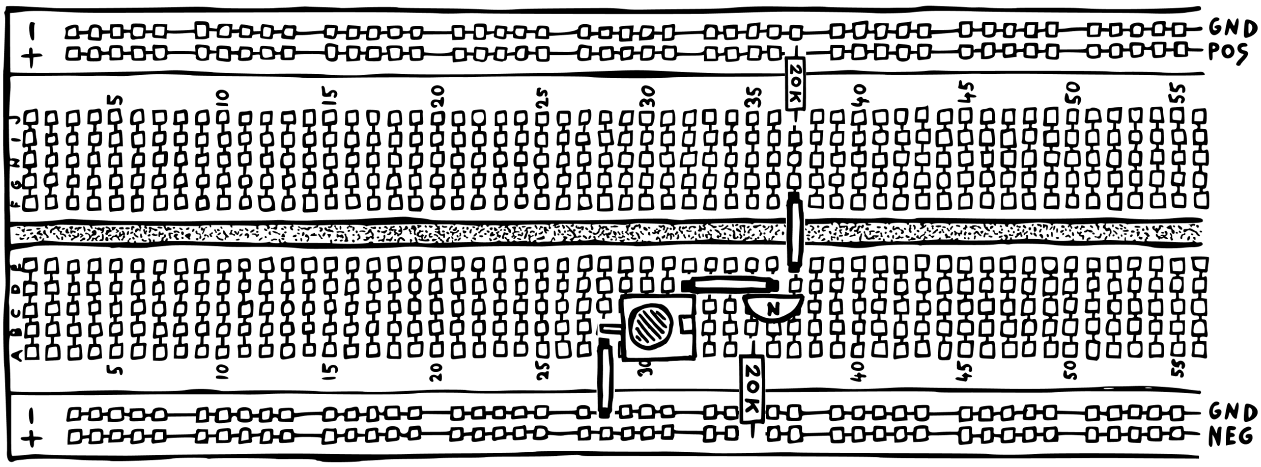



**Well, we've run into a phenomenon called transistor saturation**. This happens when we try to pull more current into the collector than is available. Think of it like this: If we'd remove the transistor from our circuit, we'd see 600 µA flow through both resistors. And we can't increase that current without bumping the voltage or reducing the resistance.

So as we push the base voltage above 450 mV, the transistor tries to blow past that 600 µA current limit. But since it can't get more current out of the top resistor, it'll switch to an alternate strategy.

**And that strategy is pulling large amounts of current into the base.** Which will not only cover the missing amount, but also increasingly substitute the current flowing into the collector. As a result, less current is pulled through the top resistor, and the voltage below it starts to rise. More precisely, for every volt added at the base, the collector voltage will rise by the same amount.

**This means that we have two distinct regions in our graph above: one where the collector voltage is roughly the inverse of the base voltage – and one where it's roughly the same.** So if we send an oscillation into the transistor's base, every part of the wave that crosses the 450 mV threshold will be folded over in the output.[7] To make sure this actually works, let's set it up on the breadboard.




If you now send a triangle, sine or sawtooth wave into the jack socket connected to the transistor's base while monitoring the voltage at the collector with an oscilloscope, you should see some folding happening.[8]

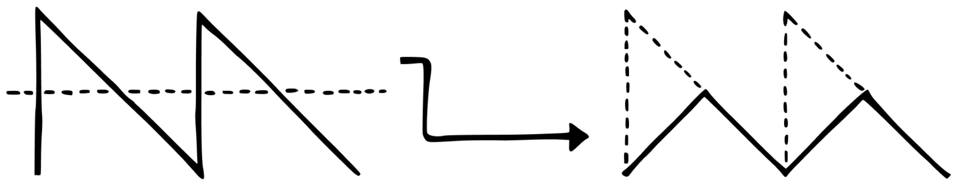
To make the effect easier to understand, I recommend you route the input through a mixer before sending it into the circuit. **That way, you can play with its volume to see what this does to the output.** (Spoiler: more volume means more noticeable folding – simply because a bigger part of the triangle is passing the folding threshold.)

[7] You can try this chapter's circuit in a simulator. I've already set it up for you right here: https://tinyurl.com/2zasufbu – you can change all values by double clicking on components.

[8] If you have the mki x es.edu VCF, you can get a sine wave by turning up the resonance all the way without any input signal.

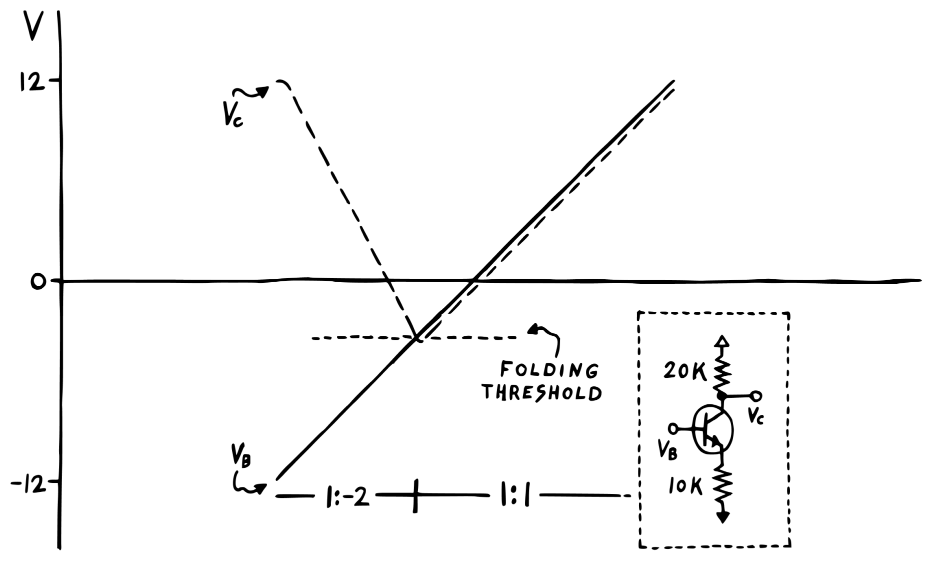
# SAW-TO-TRIANGLE BASICS

If you've used a sawtooth wave as your input signal, you probably noticed that at maximum volume, we almost fold it into a triangle! Since wavefolding generally sounds really good when applied to triangle waves (and because the mki x es.edu VCO does not have a triangle output), it makes sense to take a short detour here and talk about turning our circuit into a proper sawtooth-to-triangle converter.



To do that the ideal way, we'd have to add a ~450 mV offset to the sawtooth to center it around the folding threshold. This would give us a symmetrical, clean triangle at the output. Unfortunately, there isn't enough space on the module's PCB to pull this off, since it would require us to add another op amp IC. So we'll have to find an alternate approach with a smaller footprint.

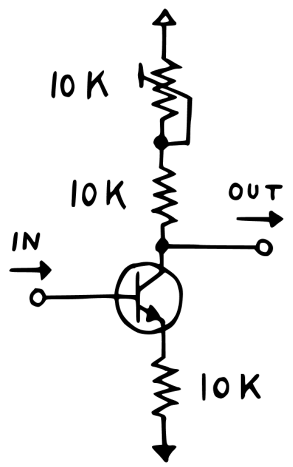
**And the alternate approach with the smallest footprint is changing the relation between the collector- and emitter resistors**. How does this work? Well, as we've seen before, if that relation is 1:1 (meaning that the resistance values are equal), the relation between base voltage and collector voltage is 1:1 (or 1:-1, depending on the region we're operating in) as well. Now, let's say we drop the emitter resistance to 10k, shifting the resistance relation to 1:2.



Interestingly, this doesn't result in a voltage relation of 1:(-)2 across the board. Instead, we get a 1:-2 relation in the non-saturated region, while the saturated region sticks with the 1:1 relation. But that's not all. As you can see in the graph, the folding threshold also drops noticeably, now sitting at about -3.5 V. Which is really interesting for us.

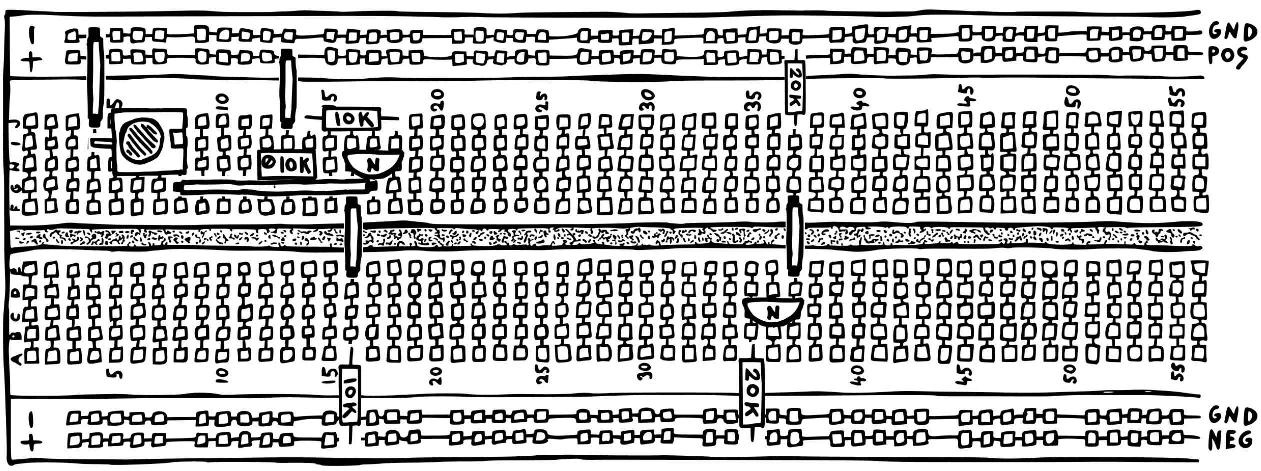
**Because instead of adding an offset to our input sawtooth, we could simply lower the folding threshold to make both line up perfectly**. Of course this would come with an unintended side-effect: if the voltage relations in the saturated and non-saturated regions differ, then our output triangle will be asymmetrical – since one side is going to be more slanted than the other.

Not ideal – but since we care about the small footprint here more than getting a perfect triangle output, it's a concession we can reasonably make. So next, let's think about the resistance value we're going to add at the transistor's collector. You might be tempted to just try a few different values here until you've found the correct one.




There's a problem with that approach, though. **Every transistor is different from the next when it comes to its "natural" folding threshold (i.e. the one we're getting with equal resistor values)**. The 450 mV we've been assuming so far are just a rough average.

This means that the added resistance working for your specific transistor will not work for most others. So we'll go with an adjustable solution instead and use a precision trimmer set up as a variable resistor.[9] Since the correct resistance value will be somewhere between 10k and 20k, a 10k trimmer should work just fine.[10]



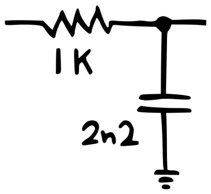

[9] Read more about trimmer potentiometers in the components & concepts appendix (page 32).

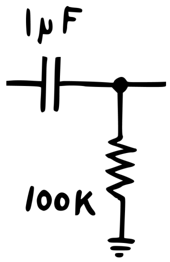
[10] You can try this chapter's circuit in a simulator. I've already set it up for you right here: https://tinyurl.com/2lzo9abh – you can change all values by double clicking on components.

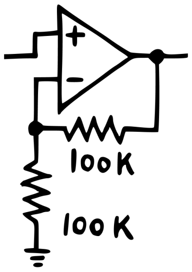
After you’ve set this up, send a sawtooth wave into the jack socket, while monitoring the collector voltage on your oscilloscope. Next, play with the trimmer until the gap between the rising and falling slopes disappears.

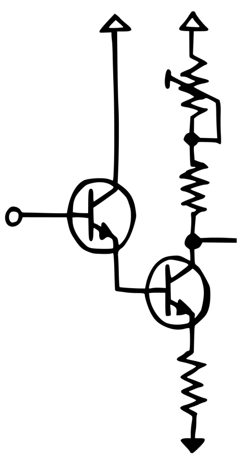
# PROCESSED & BUFFERED TRIANGLE

Got a good-looking triangle out of this? Great! Next, try in- and decreasing the input signal's frequency. You'll probably notice that your triangle suddenly doesn't look so good anymore. That's because of slight shifts in the sawtooth wave's vertical offset across the full frequency range. These are a typical byproduct of AC coupling, which the mki x es.edu VCO uses to center its output around the 0 V line.[11]



Unfortunately, there's not much we can do to prevent this from happening. So instead, we'll rely on a simple, but effective fix: **applying a low-pass filter to our saw-to-tri converter's output**. This will cause the gap between the triangle's sides to be smoothed, resulting in less noticeable buzz in the output signal. In my experiments, combining a 1k series resistor with a 2.2 nF capacitor to ground gave me decent enough results.

Next, we'll need to make sure that our triangle is centered around the 0 V-line. For that, we'll follow the lead of our VCO and use AC coupling again. So after the low pass filter, we'll set up a 1 µF capacitor, followed by a 100k resistor to ground.

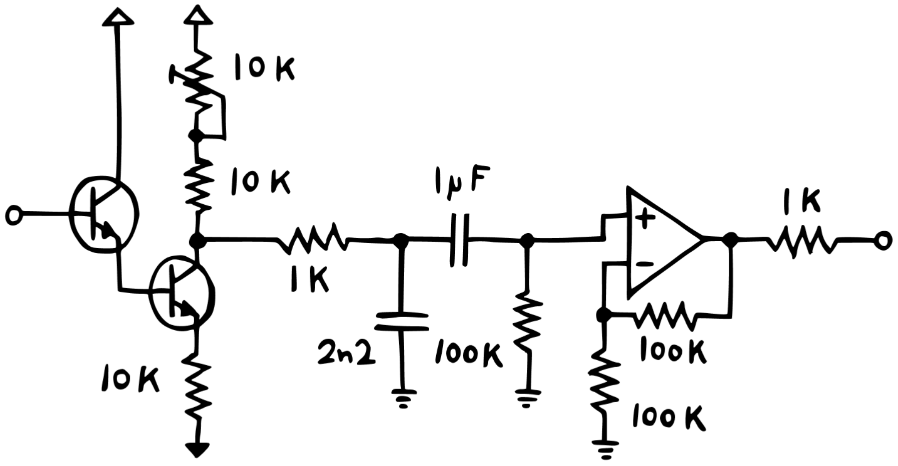
Then, we want to buffer & boost the signal to avoid loading effects and get the output up to the standard 10 V peak-to-peak. Since folding the input has slashed its volume in half, we'll use a non-inverting op amp-based amplifier with a gain of 2 here.[12]

Finally, we should try and increase the converter's input impedance a bit. Right now, we're drawing up to 1 mA from our VCO – which is quite a lot of current. To get that number down to more reasonable levels, we'll use a nifty little trick: **set up a second NPN transistor as a voltage buffer**. If we connect its emitter to the main transistor's base, its collector to the positive rail, and its base to our input sawtooth wave, the buffer transistor will replicate that sawtooth at its emitter, while pulling the necessary current directly from the power rail. This way, we reduce our peak current draw from the VCO to just 10 µA.

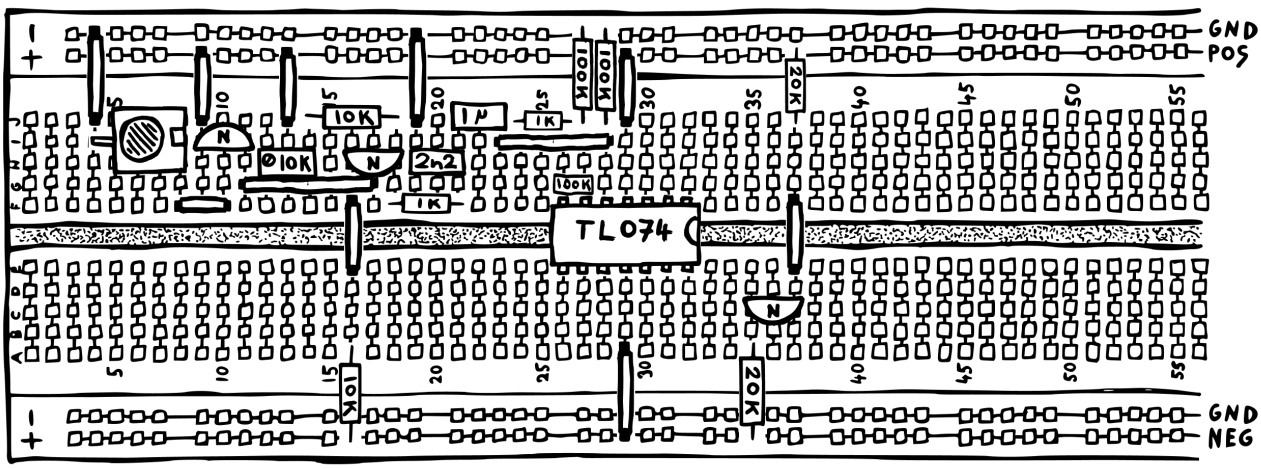
[11] Read more about AC coupling in the components & concepts appendix (page 33).

[12] Read more about op amps in the components & concepts appendix (page 34).

And here's what the whole thing put together looks like.[13]




Note that the buffer transistor will add a bit of a negative offset to the input sawtooth – so once you've set this up, you'll have to fiddle with the trimmer again to get the best results. For the op-amp, we'll be using a TL074 IC, which is four op-amps in a single chip. **Make sure that you set it up exactly as shown here – if you reverse the power connections, it will heat up and die!**




To check on your triangle, connect your oscilloscope to the op amp's output.

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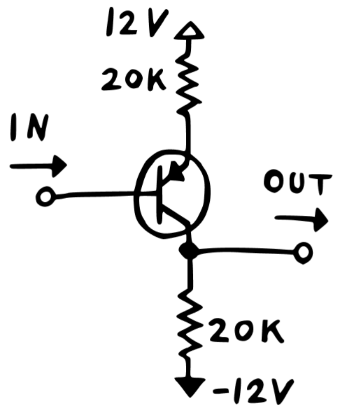
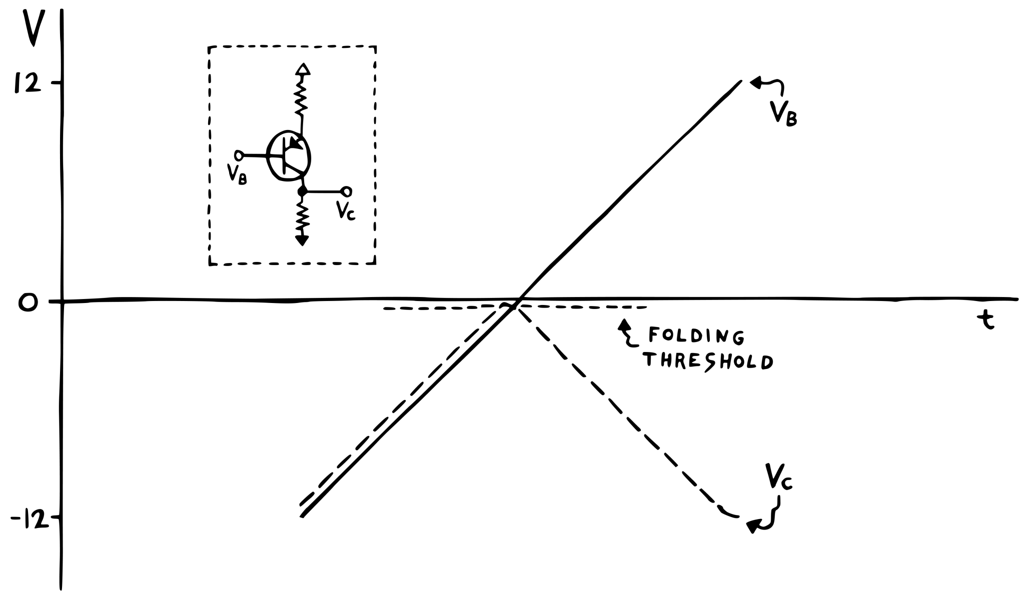
[13] You can try this chapter's circuit in a simulator. I've already set it up for you right here: https://tinyurl.com/2nwyf4fk – you can change all values by double clicking on components.

# PNP WAVEFOLDER

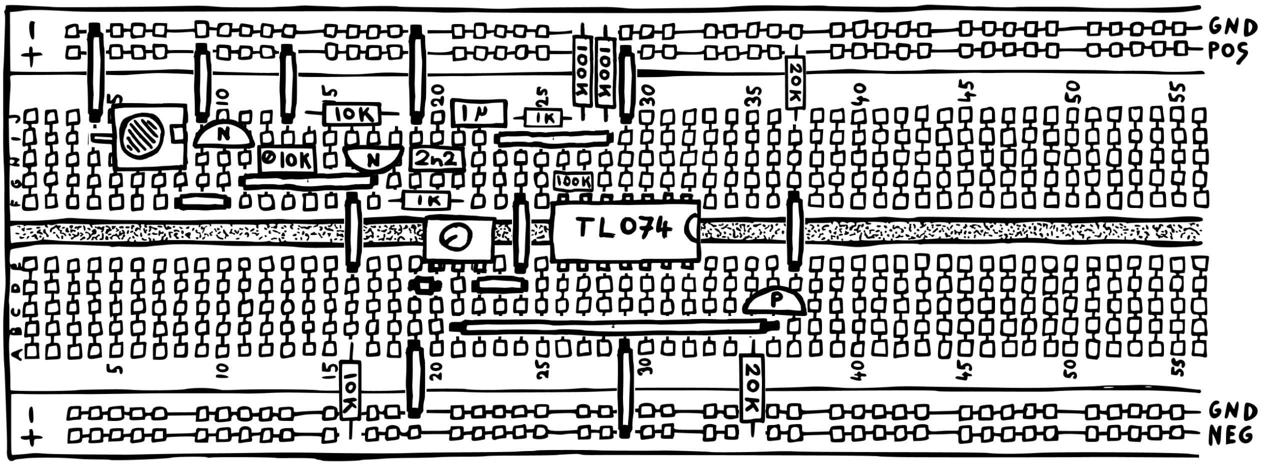
Now that we've got a decent triangle wave, let's get back to our wavefolder. The problem with our design so far is that it only affects the bottom of the output waveform. **In a traditional wavefolder, you'd want to fold both the bottom and the top, though.** To get there, we'll first check out an alternate version of our circuit that folds just the top of the output waveform.




As you can see, the only real difference here is in the type of transistor we're using. I've simply replaced the NPN with a PNP transistor. **And since the PNP transistor is basically just the NPN transistor's bizarro twin brother, everything about it is inverted.** Collector and emitter switch positions, and the current flowing through them increases as the base voltage decreases.
So if we look at the relation between base- and collector voltage for this circuit with another graph, we can see that the two regions are switched.



In the space between +12 V and -450 mV, the collector voltage rises as the base voltage drops. And once they meet, they both start dropping together. **So if we use our triangle wave as an input here, we should get an output with a folded top.**[14] To be able to vary the volume of the input, we'll also set up a simple, temporary attenuator using the 10k potentiometer from your kit.

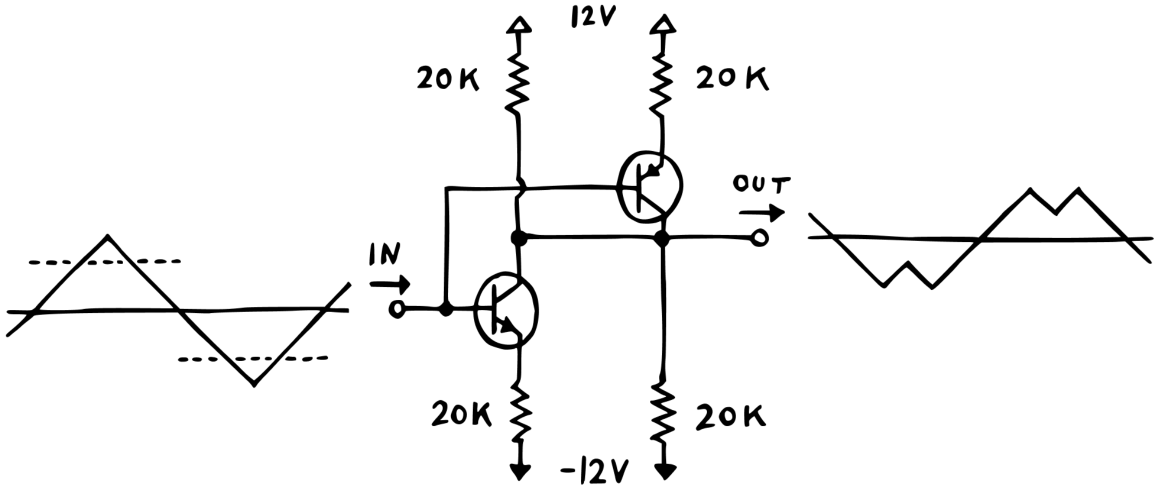



Once you've set this up, try fiddling with the potentiometer. You should see the shape of the output signal change as the folding effect gets more intense.

[14] You can try this chapter's circuit in a simulator. I've already set it up for you right here: https://tinyurl.com/2eemmvv8 – you can change all values by double clicking on components.

# TOP/BOTTOM WAVEFOLDER

Now the question is: how do we combine the NPN- and PNP folding circuits into one? Lucky for us, it's actually pretty straightforward. **All we have to do is wire them together like shown here: base connects to base and collector connects to collector**.

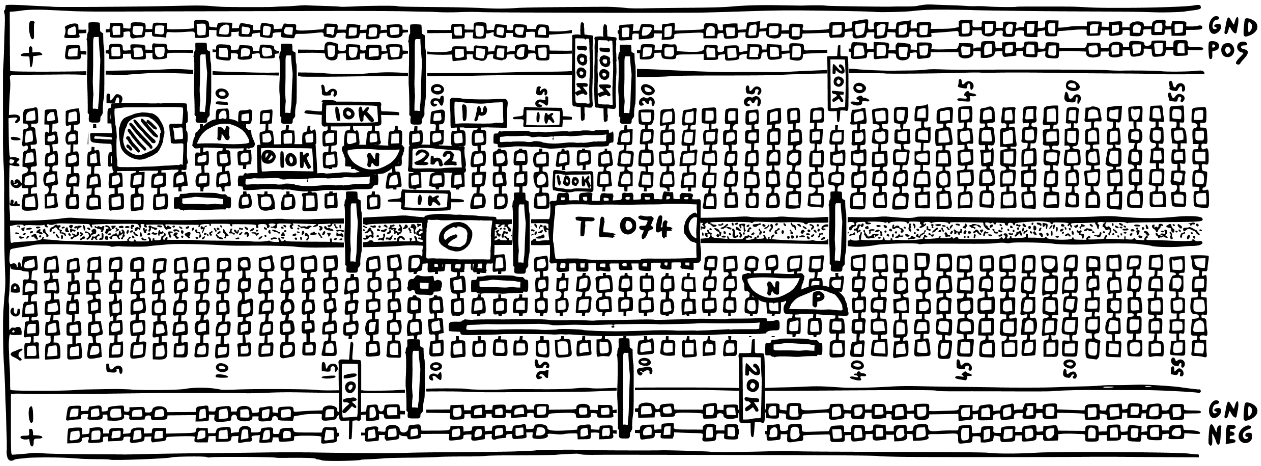



If we then send in our triangle wave on the left, we can pick up a top- and bottom-folded output on the right. It works like this: at 0 V base voltage, without a connection between the collectors, the NPN's collector would sit at +700 mV, while the PNP's collector would sit at -700 mV. **Wire them together, and we get 0 V – since the two voltages cancel each other out**.

Now, if we increase the base voltage, the NPN transistor will open up, while the PNP closes down, leaving us with a current deficit at the collectors. This forces us to pull more current from the positive rail through the 20k resistor, which, in turn, will cause the voltage at the collectors to drop. At least until we run into the NPN's folding threshold. Because then, that NPN goes into saturation and the collector voltage starts climbing up again.

And the same idea applies in reverse if we decrease the base voltage from the 0 V line. The NPN will close down, while the PNP opens up – so we pull less current through the 20k resistor and the voltage rises. Until we hit the PNP's folding threshold, it goes into saturation and the collector voltage starts dropping again. **This way, we get two folding thresholds – one slightly above and one slightly below the 0 V-line.**[15]

[15] You can try this chapter's circuit in a simulator. I've already set it up for you right here: https://tinyurl.com/2op694aw – you can change all values by double clicking on components.



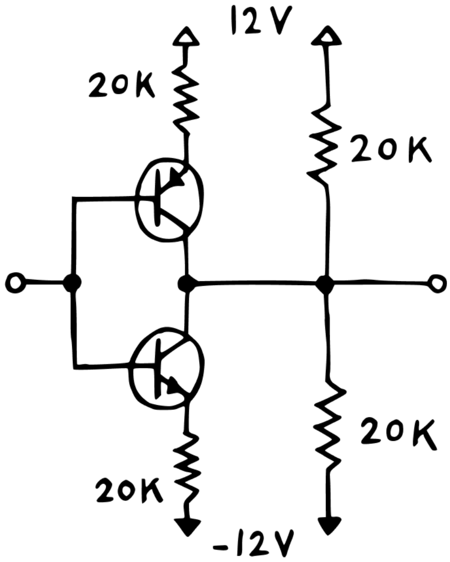

If you again check on the voltage at the two transistors' collectors with your oscilloscope, you should see both the top and bottom of the input triangle get folded over.[16] Perfect! So how do we listen to this now? **Unfortunately, we can't just attach an output socket to the transistors' collectors, since that would mess with the core mechanism by pulling more current through it.**

Okay, so we'll simply route the voltage through a non-inverting op amp buffer connected to an output socket, right? While that would work, there's an alternate approach that helps us streamline our design a bit.

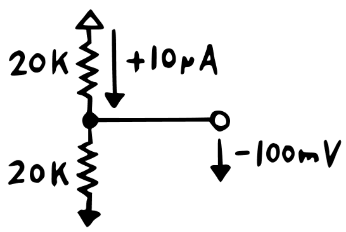
[16] If you don't, try turning the input attenuator way down. The effect is clearest at about 5-10% input volume.

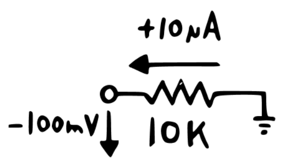
# BUFFERED WAVEFOLDER

To get there, let's first clean up the existing schematic while keeping the circuit itself the same. We'll move the two transistors directly on top of each other. Then, we'll pull both collector resistors over to the right.




This leaves us with these two vertical paths on and between which current flows. Let's take a closer look at the one on the right.

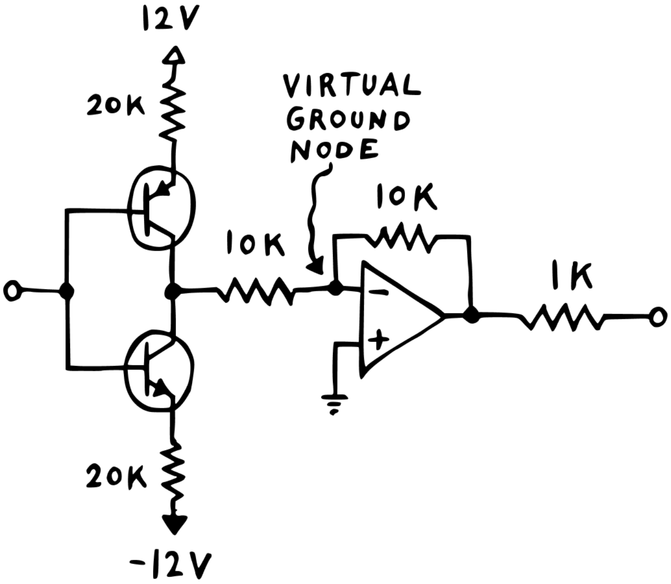



Since this is a 50% voltage divider between +12 V and -12 V, the central node sits at 0 V. At least until we start drawing current from it. Then, the voltage will drop by 100 mV for every additional 10 µA we pull through the top resistor.

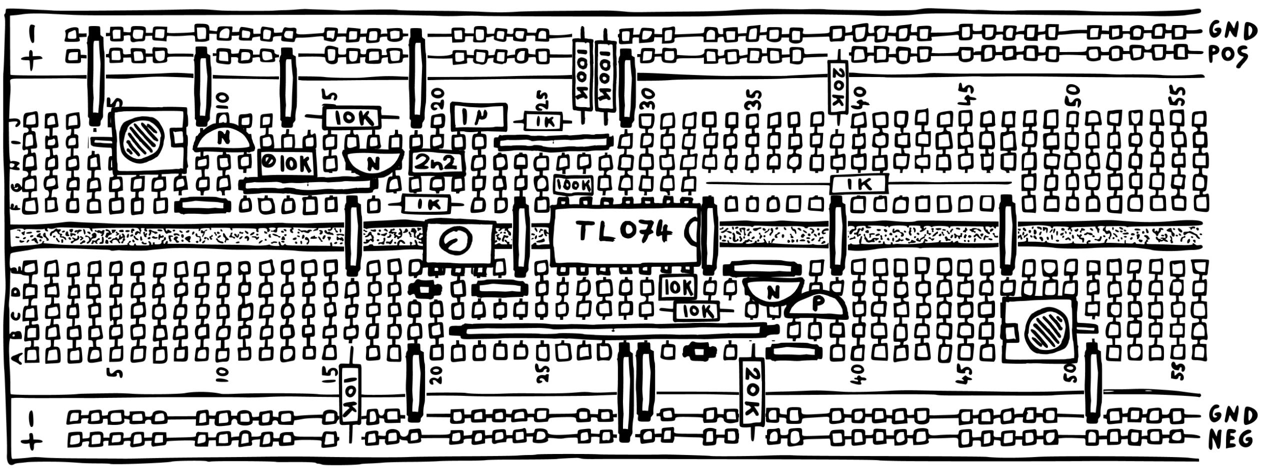
**Interestingly, we can get exactly the same behavior from a single 10k resistor to ground**: if we don't pull current through it, the voltage on the other side is 0 V. And if we do, the voltage drops by 100 mV for every 10 µA we pull. Great! So we could simply replace the two 20ks with a single 10k to ground and save ourselves a resistor.

But we can take the optimization even further. We'll use an inverting buffer to buffer the collector voltage – instead of a non-inverting one.




This approach has two benefits. First: we undo the inversion that the wavefolding stage applies to the input signal. So the output will be in phase with the input again. **And second, the new 10k resistor gets to work double duty: it's providing the extra current for our two transistors – and it's playing its role as input resistor for the inverting buffer**.

This works because in an inverting buffer, the op amp's inverting input is what we call a virtual ground node: it behaves just like a path to ground without actually being one. So connecting the collectors to the op amp's inverting input through a 10k is functionally the same as connecting them straight to ground here.[17]

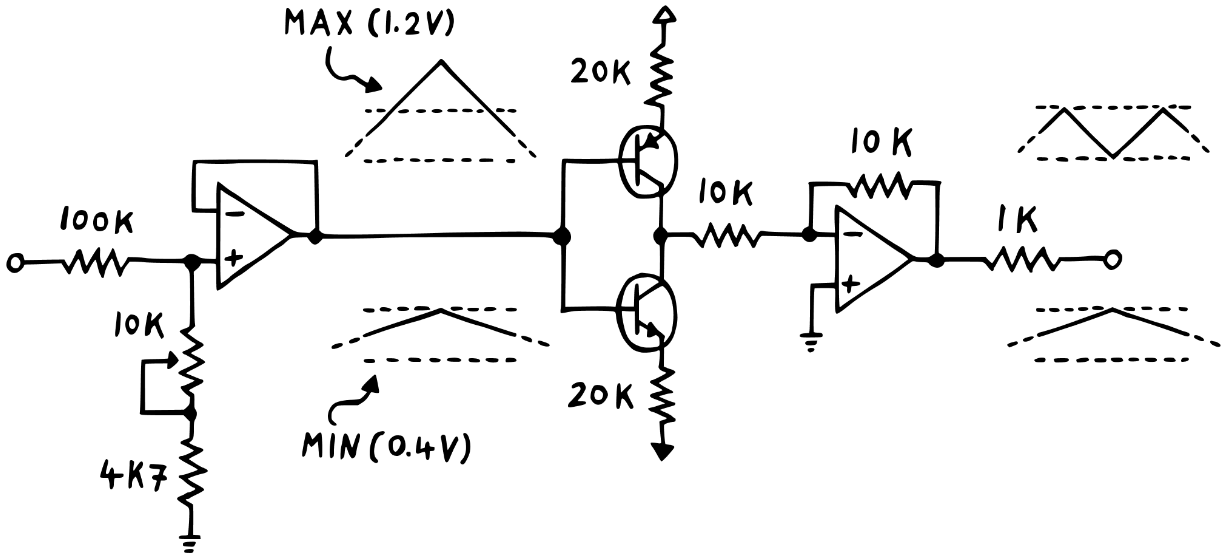



With this change, you can finally listen to the output. By adjusting the input volume, you can again change the effect's intensity. If you check the output on the oscilloscope, you'll see how it crosses the folding thresholds a second time at maximum volume – but doesn't get folded. That's because we're just going deeper and deeper into saturation of the same transistor.

[17] You can try this chapter's circuit in a simulator. I've already set it up for you right here: https://tinyurl.com/2ehwyz2q – you can change all values by double clicking on components.

# INPUT STAGE

Great! But since using our existing attenuator feels pretty clunky and imprecise, we should come up with a slightly more elaborate solution.




For that, it makes sense to restrict the input volume's range somewhat. If the intensity knob is dialed all the way down, you'd expect the input signal to just pass through the circuit unaffected instead of going completely silent.

Also, it would be great if the output volume stayed the same, no matter the set intensity. We can achieve this if we make sure that the signal always fits nicely between the two folding thresholds. **This means that the minimum input volume should be just shy of crossing the thresholds, while the maximum should be just shy of crossing them a second time**. Ideally, we would use a fixed 100k input resistance, followed by a 10k potentiometer and a 4k7 baseline resistance to ground here.[18]

Given a 10 V peak-to-peak input, this outputs a range of 0,4 to 1,2 V peak-to-peak, which fits between the two thresholds nicely. Before sending the result into our wavefolding stage, we have to buffer it with an op amp to avoid loading effects.[19]

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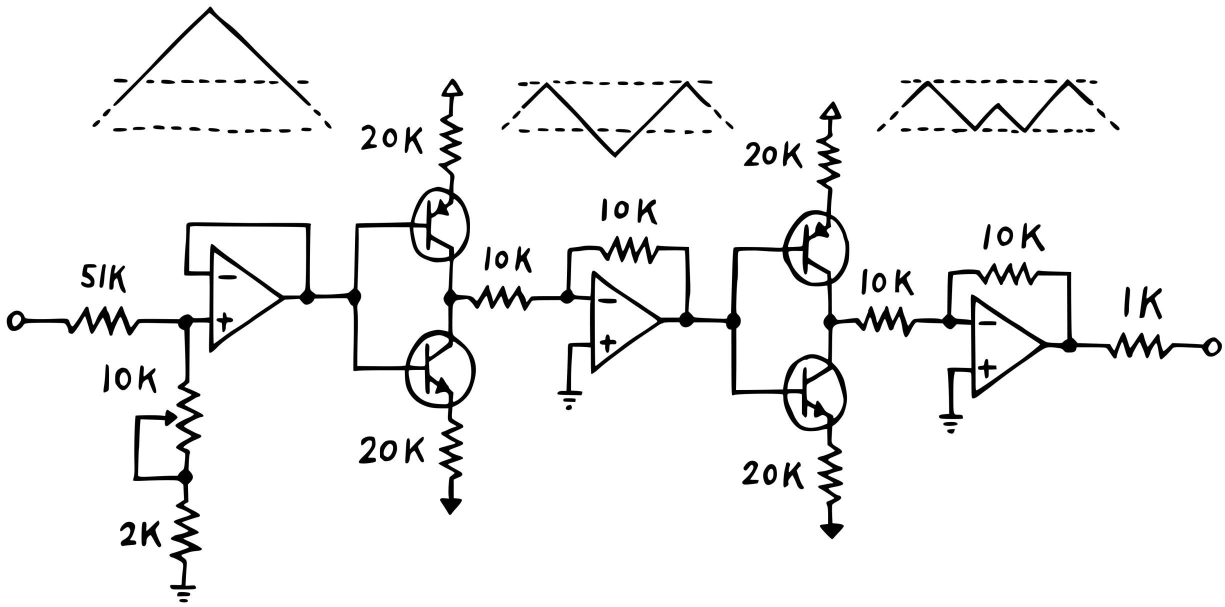
[18] Unfortunately, your kit doesn't contain extra 100k and 4k7 resistors – so we'll have to skip this step on the breadboard right now. Feel free to set it up yourself if you have those values in your stash.

[19] You can try this chapter's circuit in a simulator. I've already set it up for you right here: https://tinyurl.com/2j563omv – you can change all values by double clicking on components.

# DOUBLE WAVEFOLDER

Cool – but a single wavefolding stage sounds a bit too tame for my taste. **So let's fold the folded signal again!** For that, we'll simply add another wavefolding stage after the first one's output buffer.



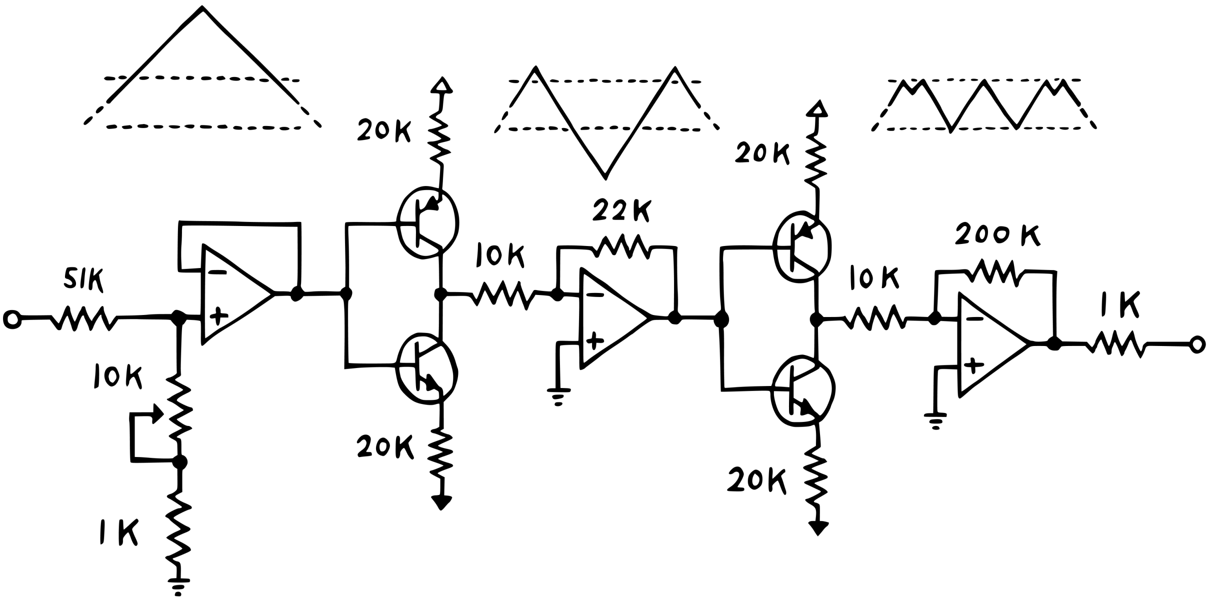

Then, we'll have to adjust the input attenuator's range. That's because we've previously made sure that the input signal doesn't cross the folding thresholds a second time. But in order for the additional stage to have any effect, it needs to. So we'll simply replace the 100k input resistor with a 51k – and the 4k7 baseline resistor with a 2k. **This roughly doubles the attenuator's range (while keeping the minimum volume the same), allowing us to boost the signal to the necessary levels.**[20][21]

[20] Again, your kit is unfortunately missing extra 10k & 2k resistors, so we'll also have to skip this step on the breadboard right now. Feel free to set it up yourself if you have those values in your stash.

[21] You can try this chapter's circuit in a simulator. I've already set it up for you right here: https://tinyurl.com/2myhymmp – you can change all values by double clicking on components.

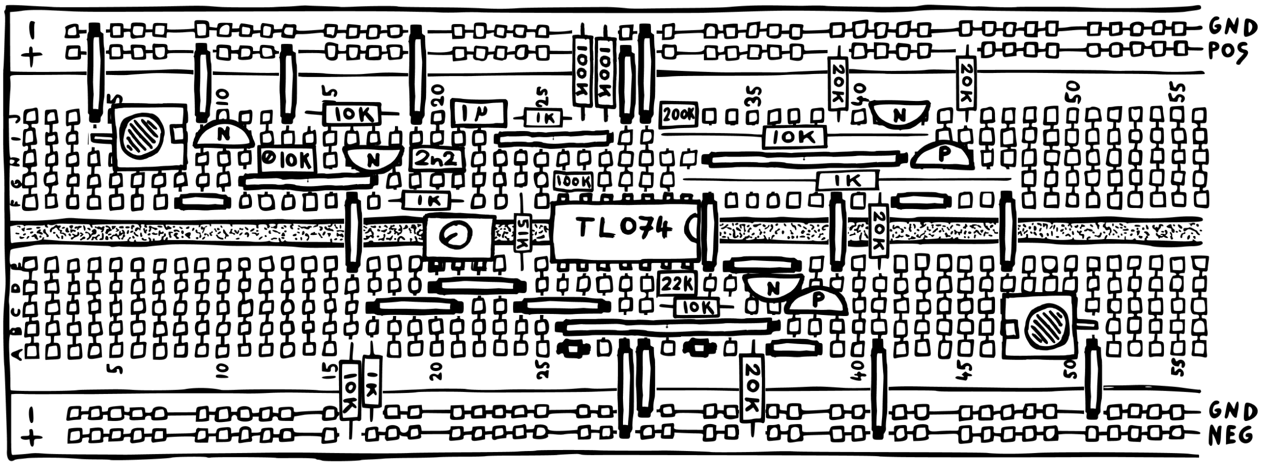
# 2.5x WAVEFOLDER

Now, a double wavefolder is nice, but I'd still like to add a bit more zing. For that, we just have to increase the gain of the first folding stage's output buffer. **Because if it's more than 1, the signal will get folded one additional time for free**.




Why is that? Because coming into the second stage, the signal will now wiggle across the thresholds one additional time. In my experiments, increasing the gain by a factor of around 2 gave me the best results. So we'll replace the 10k feedback resistor with a 22k.
Now, to keep our intensity knob's behavior the same, we'll have to adjust the attenuator's range. Because otherwise, the second stage will fold the signal even at minimum intensity. To avoid that, we'll halve the baseline resistance in the attenuator. **That way, at minimum intensity, the signal is occupying only half the area inside the first stage's folding thresholds**. Blow that up by a factor of 2, and the result should fit snugly between the second stage's folding thresholds again.
As a final touch, we'll get the circuit's output volume up to the standard 10 V peak-to-peak. For that, we just have to bump the second output buffer's gain to 20 by increasing its feedback resistance to 200k.[22]

[22] You can try this chapter's circuit in a simulator. I've already set it up for you right here: https://tinyurl.com/2krc36es – you can change all values by double clicking on components.




Once you’ve set this up, check if the signal does pass through unchanged at minimum intensity. Then, see what happens as you dial it up. You should get additional spikes in the output that make it sound even more harsh and metallic.

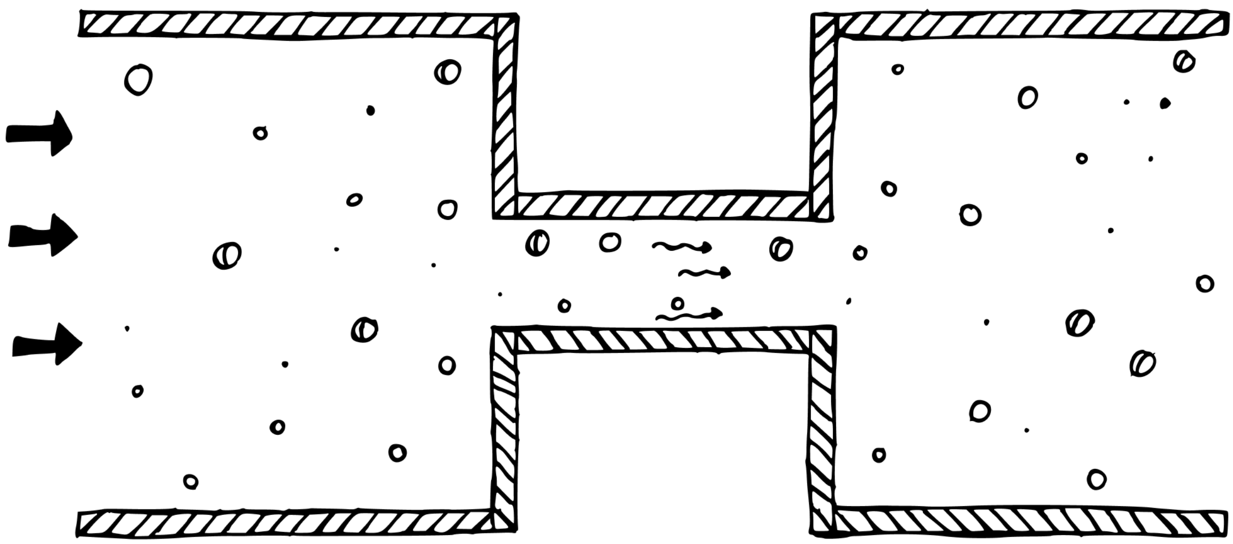
And with this, our wavefolder is done. Once you’re done experimenting, dig out the panel and PCB from the kit, heat up your soldering iron and get to building. You can find more information on how to populate the board & how to solder in the enclosed appendix.

# 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

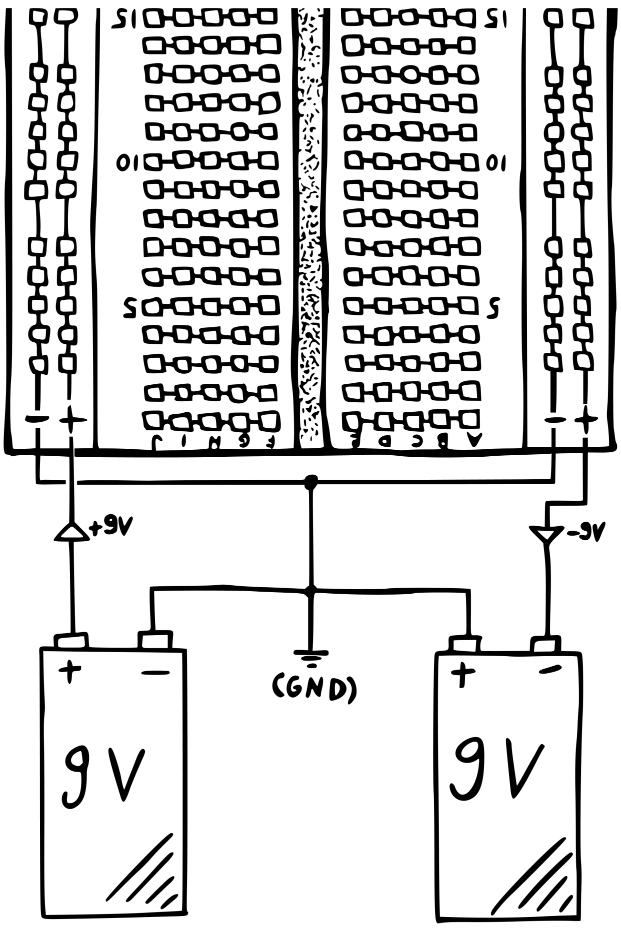
**There are three main properties we're interested in when talking about electronic circuits: resistance, voltage and current.** To make these less abstract, we can use a common beginner's metaphor and compare the flow of electrons to the flow of water through a pipe.



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.

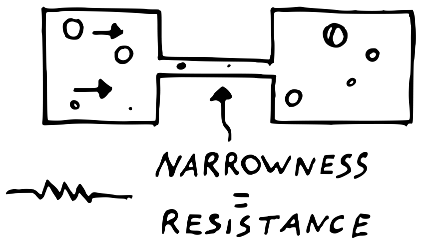


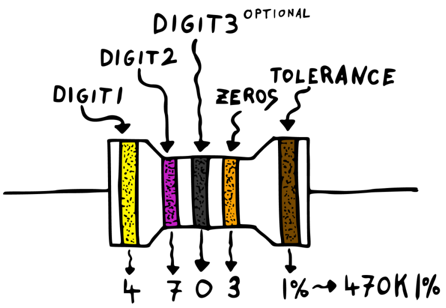

By connecting the batteries like this, the positive terminal of the left battery becomes your +9 V, while the negative terminal of the right is now your –9 V, and the other two combine to become your new ground.[23] **Please make sure you disconnect the batteries from your breadboard when you make changes to the circuit!** Otherwise you run the risk of damaging components.

[23] If you're struggling with setting this up, you can watch me do it here: https://youtu.be/XpMZoR3fgd0?t=742

# 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[24] – 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.

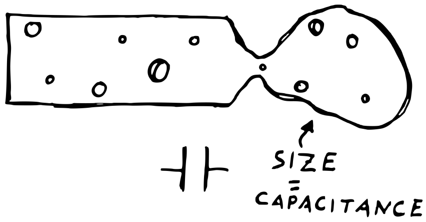
For the resistors in this kit, a yellow body tells you that the actual resistance value might be ±5 % off. A dark blue body indicates ±1 % tolerance. Some kits will also contain light blue ± 0.1% resistors to avoid the need for manual resistor matching.

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.

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

# CAPACITORS

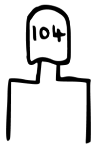
**A capacitor is a bit like a balloon that you can attach to the open end of a pipe.** If there's some pressure in the pipe, the balloon will fill up with water until the pressure equalizes. (Since the balloon needs some space to expand into, both of the capacitor's legs need to be connected to points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



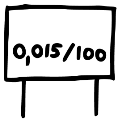

Then, should the pressure in the pipe drop, the balloon releases the water it stored into the pipe. The maximum size of the balloon is determined by the capacitor's capacitance, which we measure in farad (F). There are quite a few different types of capacitors: electrolytic, foil, ceramic, tantalum etc.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

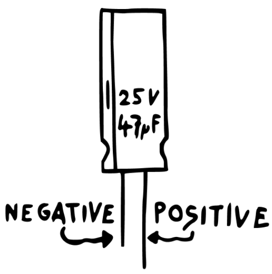
Unlike resistors, capacitors have their capacitance value printed onto their casing, sometimes together with a maximum operating voltage. **Be extra careful here!** That voltage rating is important. Your capacitors can actually explode if you exceed it! So they should be able to withstand the maximum 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.[25] 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.[26]




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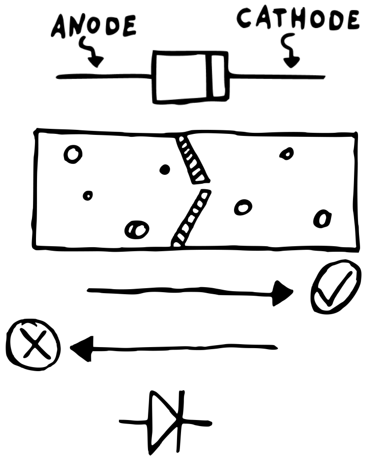
[25] For a detailed breakdown, look up ceramic capacitor value code. There are also calculation tools available.

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

# DIODES

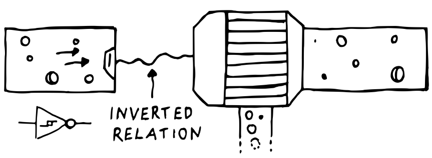


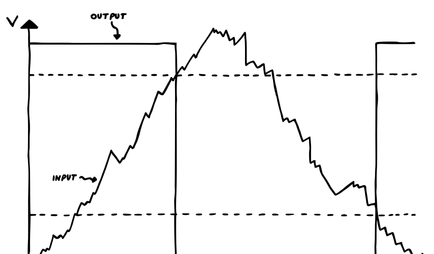

**Diodes are basically like one-way valves. Current can only pass through in one direction – from anode to cathode**. That direction is indicated by the arrow in the diode symbol and by a black stripe on the diode's casing. So any current trying to move in the opposite direction is blocked from flowing.

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

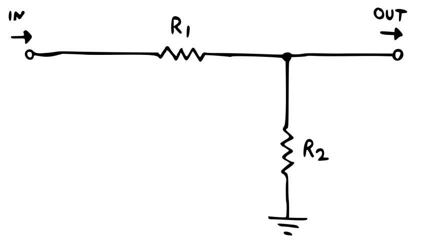



**You can think of a Schmitt trigger inverter as two separate things. On the left, there's a sensor that measures the pressure inside an attached pipe. On the right, there is a water pump**. This pump's operation is controlled by the sensor. Whenever the pressure probed by this sensor is below a certain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

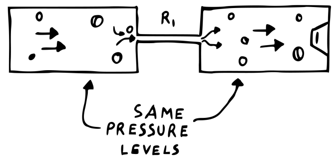
# VOLTAGE DIVIDERS



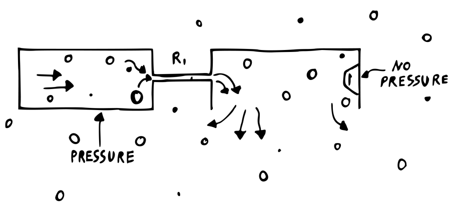

**A voltage divider is really just two resistors set up like this: input on the left, output on the right.** If R1 and R2 are of the same value, the output voltage will be half of what the input voltage is. How does it work?

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.

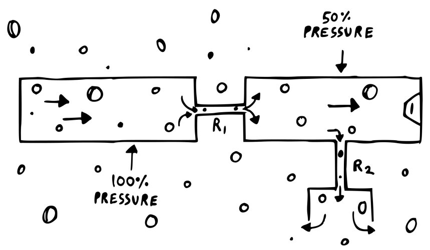
First, think about what would happen if R2 was completely sealed off. Our sensor would tell us that **the pressure on the right side is exactly the same as the pressure on the left**. Because the pushing force has nowhere else to go.




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.

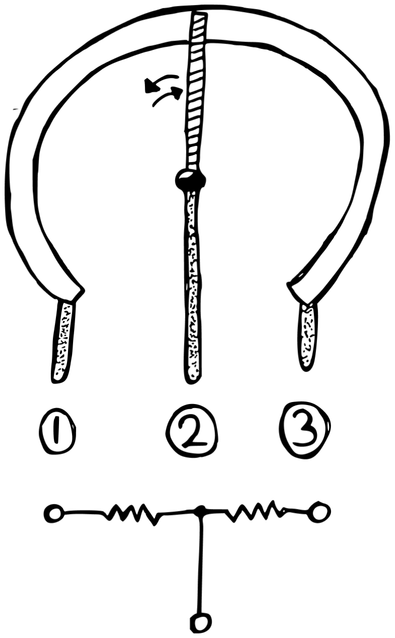



If pipe R1 is wide and pipe R2 is narrow, most of the pressure will be retained. But if it's the reverse, the pressure level will be only a tiny fraction. And if R1 and R2 are identical, **the pressure will be exactly half of what we send in**.



# POTENTIOMETERS

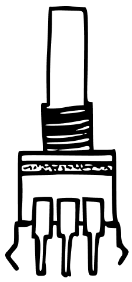
**Potentiometers can be used as variable resistors that you control by turning a knob. But, and that's the handy part, they can also be set up as variable voltage dividers.** To see how that works, let's imagine we open one up.

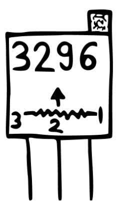



Inside, we would find two things: a round track of resistive material with connectors on both ends plus what's called a wiper. This wiper makes contact with the track and also has a connector. It can be moved to any position on the track. Now, the resistance value between the two track connectors is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





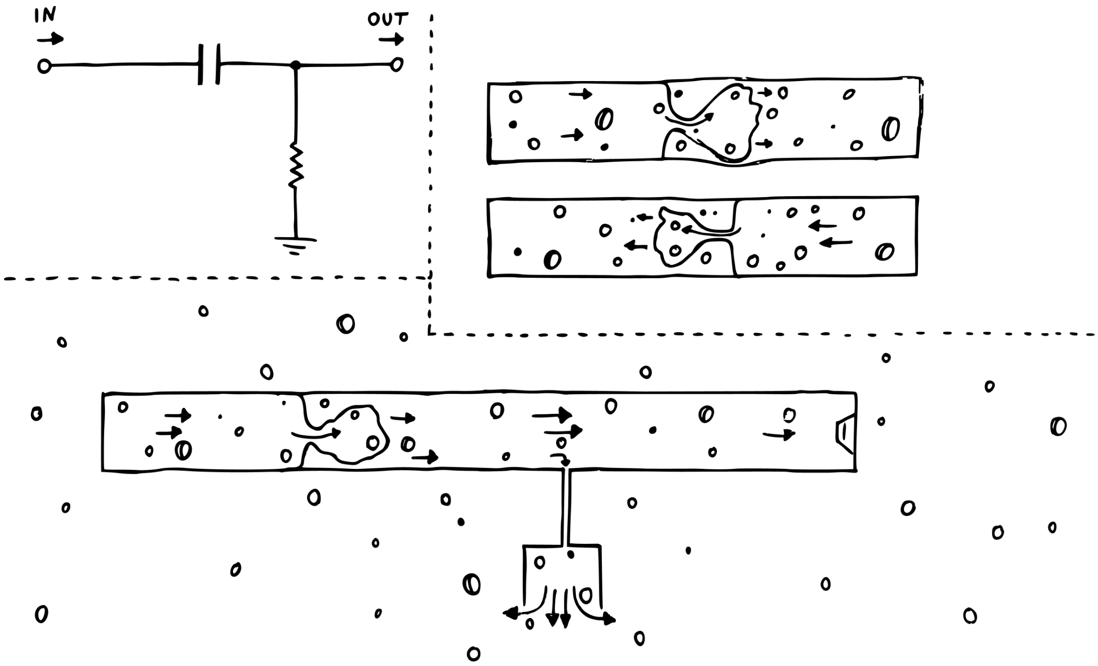

In these kits, you will encounter different types of potentiometers. First, there's the regular, full-size variant with a long shaft on top. These are used to implement user-facing controls on the module's panel and they usually – but not always – indicate their value directly on their casing. Sometimes, they'll use a similar encoding strategy as capacitors, though.[27]

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.

[27] 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**.

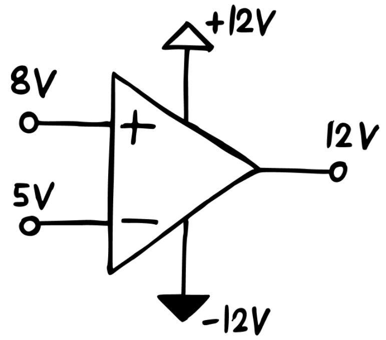



Next, we'll bring in a resistor after the coupling point, going straight to ground. **This acts like a kind of equalizing valve**. Now imagine we apply a steady 5 V from one side. Then on the other side, we'll read 0 V after a short amount of time. Why? Because we're pushing water into the balloon with 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?



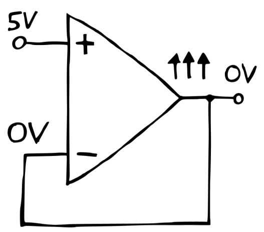

The key here is that op amps are essentially differential amplifiers. This means that they only amplify the difference between their two inputs – not each of them individually. If that sounds confusing, let's check out a quick example. So we'll imagine that one sensor – called the non-inverting input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

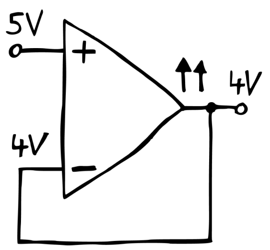
The handy thing though about op amp outputs is that they draw their power directly from the power source. This means that they can supply lots of current while keeping the voltage stable. **That's why we say an op amp has a very low output impedance**.

# OP AMP BUFFERS/AMPLIFIERS

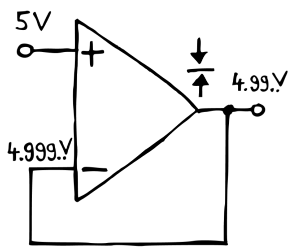
Buffering, in the world of electronics, means that we provide a perfect copy of a voltage without interfering with that voltage in the process. With an op amp-based buffer, the buffering process itself works like this. We use the non-inverting input to probe a voltage, while the inverting input connects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



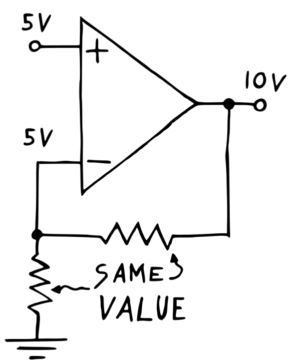

Before the op amp starts processing the voltages at its inputs, the output will be switched off. This means that **output and inverting input sit at 0 V at first**. So then, the op amp will subtract 0 from 5 and multiply the result by its gain. Finally, it will try and increase its output voltage to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



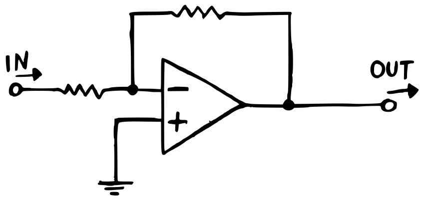

But as it's pushing up that output voltage, the **voltage at the inverting input will be raised simultaneously**. So the difference between the two inputs is shrinking down. Initially, this doesn't matter much because the gain is so large. As the voltage at the inverting input gets closer to 5 V though,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

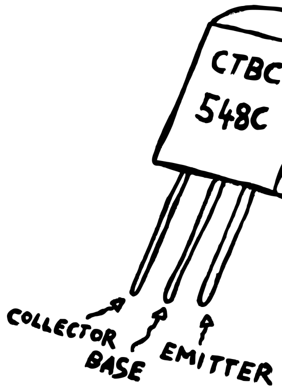
How does this work? Well, let's assume that we're applying a steady voltage of 5 V on the left. Then, as we already know, the op amp will subtract the inverting input's voltage from the non-inverting input's voltage, leaving us with a result of –5 V. Multiply that by the huge internal gain, and the op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

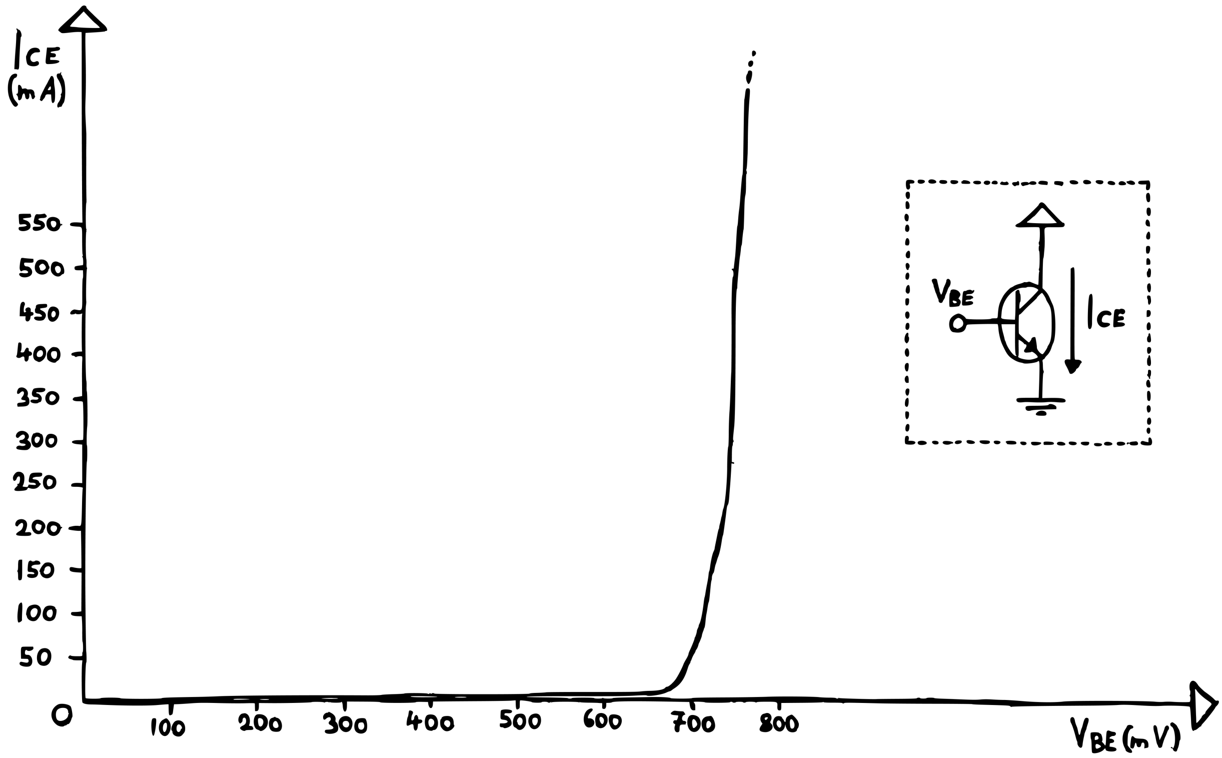
And that means that the voltage at the inverting input will be lowered to about 0 V, allowing our op-amp to settle on the current output voltage level. So while we read 5 V on the left, we'll now read a stable –5 V at the op amp's output. Congrats – we've built an inverting buffer! **If we want to turn 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.**[28] 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[29] 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

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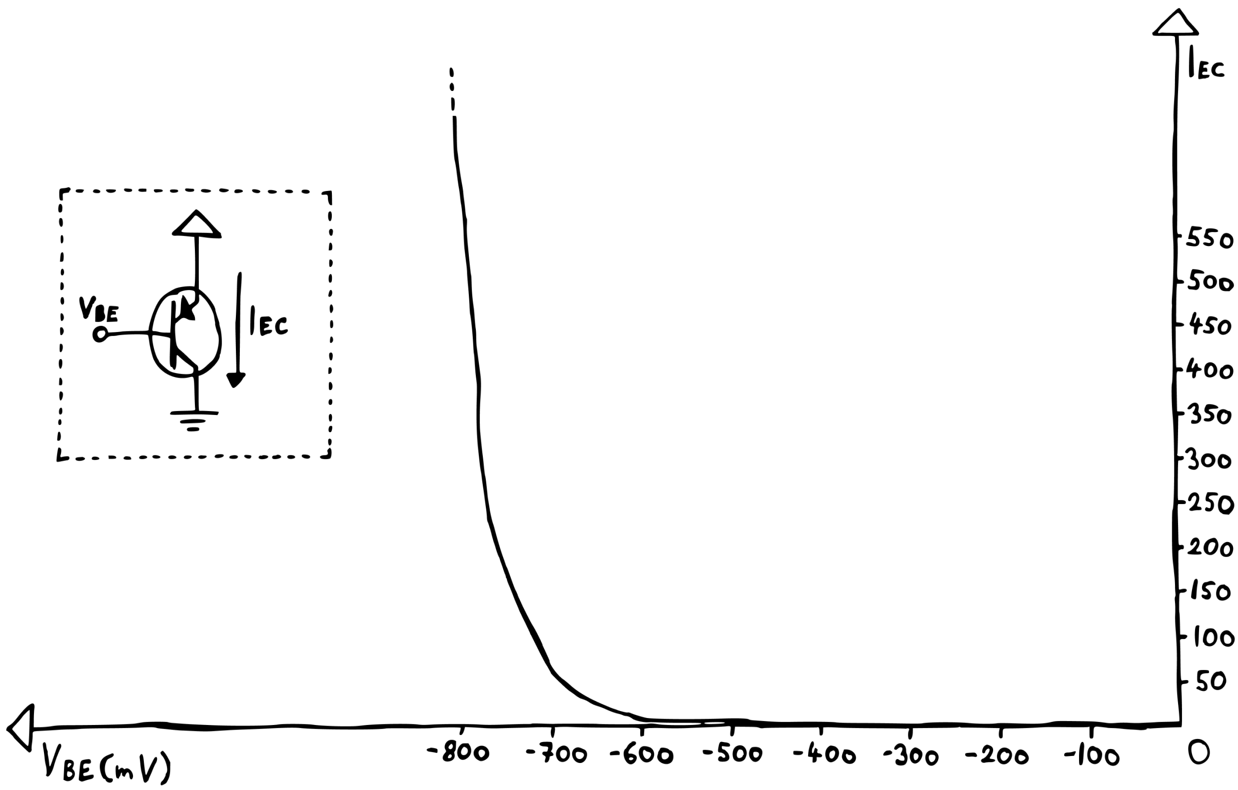
28 Please note that the pinout shown here only applies for the BC series of transistors. Others, like the 2N series, allocate their pins differently.

29 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**[30]. 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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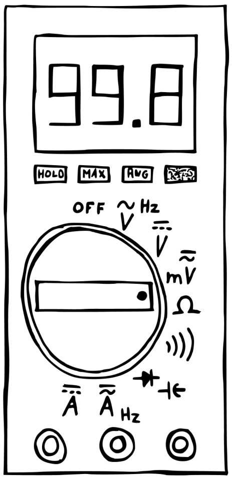
[30] Again, the voltage is measured between base and emitter.

# 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.

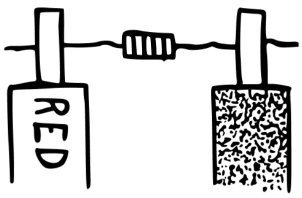
# MULTIMETERS

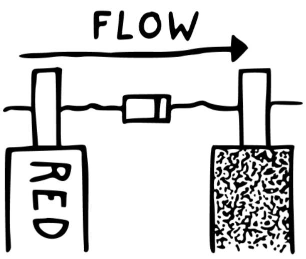



Multimeters come in different shapes and sizes, but the most common type is probably the hand-held, battery powered variant. It can measure a bunch of different things: voltage, current, resistance, continuity. Some have additional capabilities, allowing you to check capacitance, oscillation frequency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



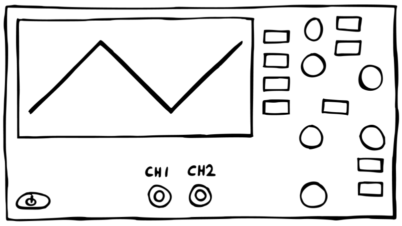



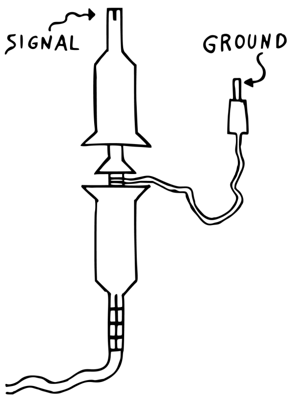

In some cases, it doesn't matter which probe you connect to which component leg or point in your circuit. This is true for testing resistors, non-polarized capacitors (foil/film, ceramic, teflon, glass etc.), continuity[31] or AC voltage.

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.

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

# OSCILLOSCOPES



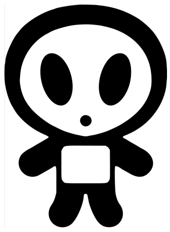




While multimeters are fairly cheap and compact, oscilloscopes are usually somewhat pricey and bulky. **If you're willing to make the investment, they are a huge help with the troubleshooting process, though**. Using one is, again, surprisingly straightforward – if you manage to work your way through 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 Wavefolder** schematics (see page 3) 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**.

**XS1 and XS2** are the **Audio input** jack sockets, **XS3** 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).

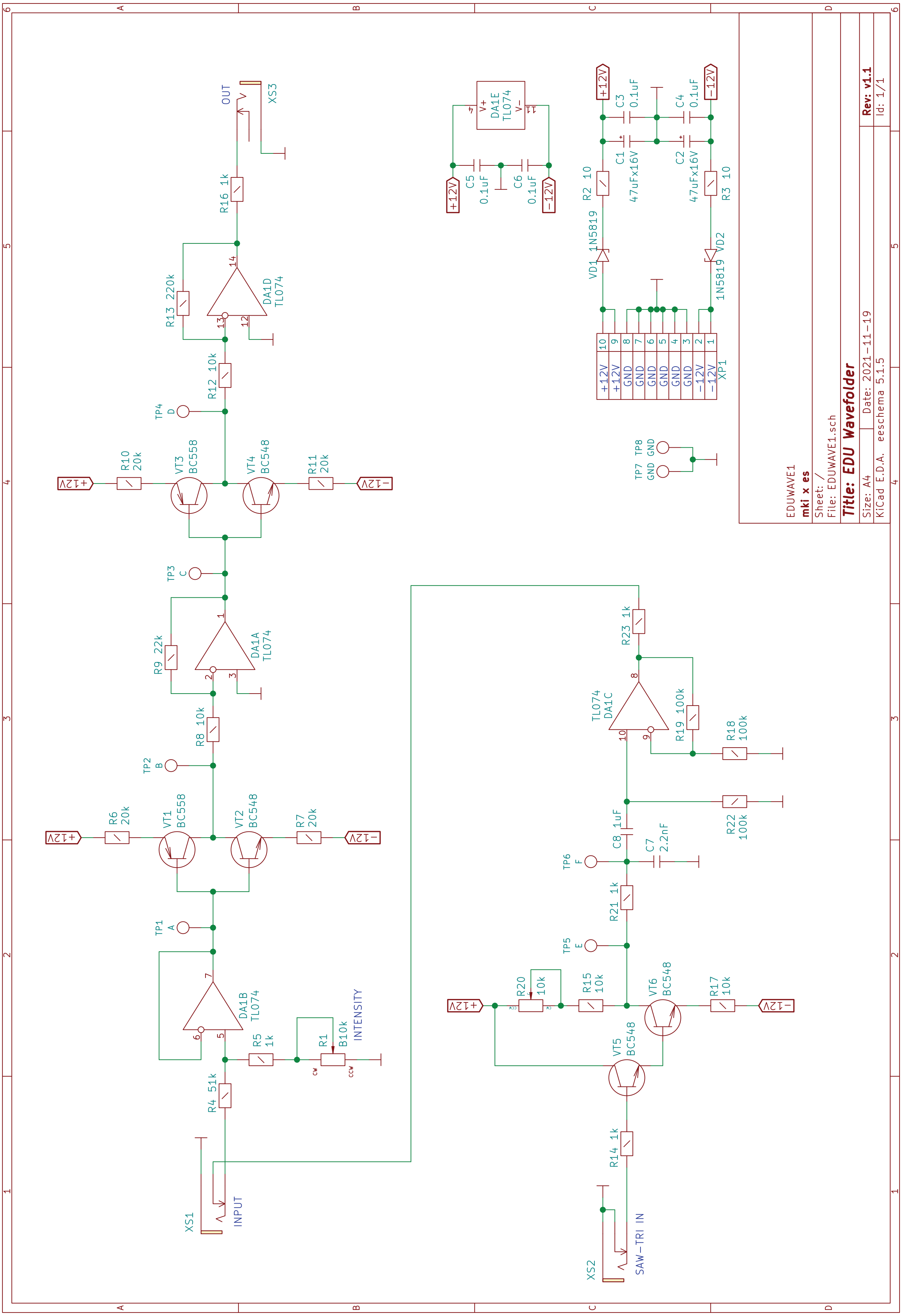
**XP1** is a standard eurorack **power connector**. It's a 2x5 male pin header with a key (the black plastic shroud around the pins) to prevent accidental reverse polarity power supply connection. This is necessary because connecting the power incorrectly will permanently damage the module.

**VD1 and VD2** 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** (**R2** and **R3**) on the + and – 12 V rails, with **decoupling** (or **bypass**-) capacitors **C1 – C4**. 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 (C1 and C2) compensates for low frequency fluctuations, while C3 and C4 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**.

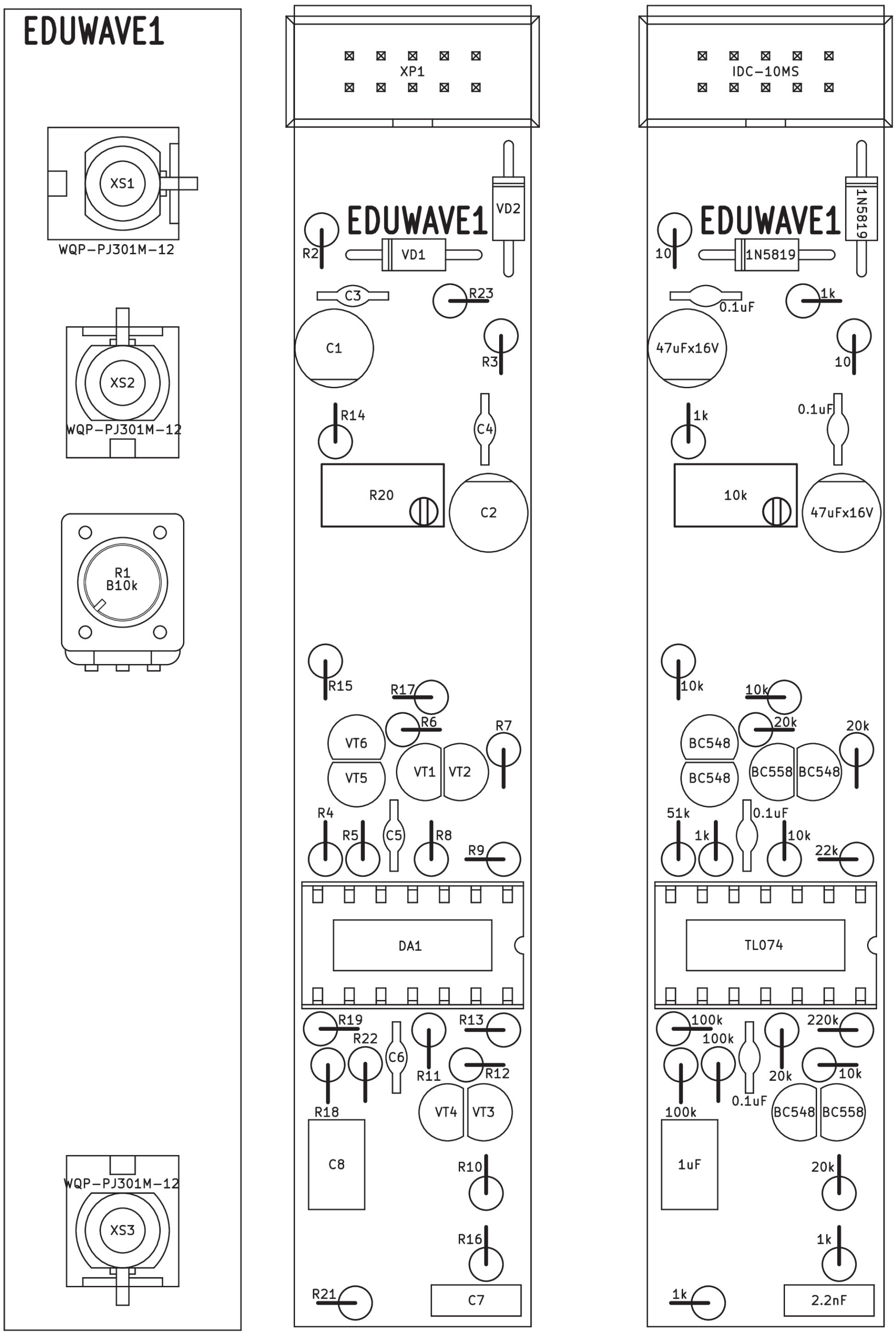
Capacitors **C5 and C6** are additional decoupling capacitors. If you inspect the PCB, you'll see that these are placed as close to the power supply pins of the ICs as possible. For well-designed, larger PCBs you will find decoupling capacitors next to each IC. Like the others, their job is to simply 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.

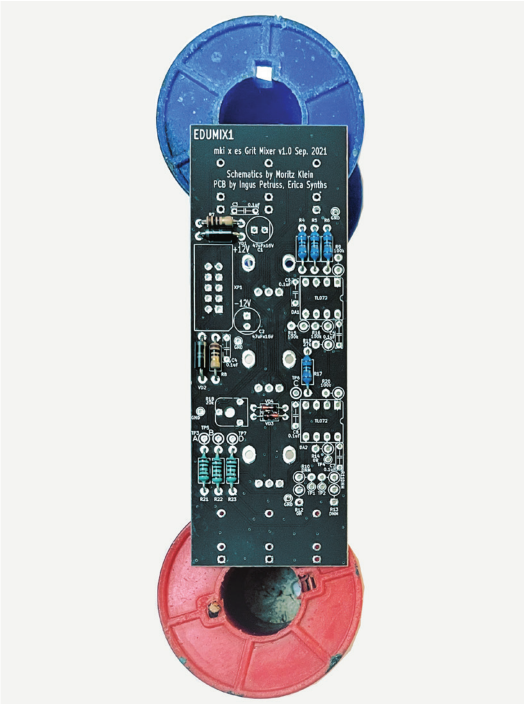


EDUWAVE1
mki x es
Sheet: /
File: EDUWAVE1.sch
Title: EDU Wavefolder
Size: A4
Date: 2021-11-19
KiCad E.D.A. eeschema 5.1.5
Rev: v1.1
Id: 1/1
INPUT
XS1
SAW-TRI IN
XS2
OUT
XS3
INTENSITY
R1 B10k
R4 51k
R5 1k
R6 20k
R7 20k
R8 10k
R9 22k
R10 20k
R11 20k
R12 10k
R13 220k
R14 1k
R15 10k
R16 1k
R17 10k
R18 100k
R19 100k
R20 10k
R21 1k
R22 100k
R23 1k
R2 10
R3 10
VT1 BC558
VT2 BC548
VT3 BC558
VT4 BC548
VT5 BC548
VT6 BC548
DA1A TL074
DA1B TL074
DA1C TL074
DA1D TL074
DA1E TL074
C1 47uFx16V
C2 47uFx16V
C3 0.1uF
C4 0.1uF
C5 0.1uF
C6 0.1uF
C7 2.2nF
C8 1uF
VD1 1N5819
VD2 1N5819
XP1
TP1 A
TP2 B
TP3 C
TP4 D
TP5 E
TP6 F
TP7 GND
TP8 GND
+12V
-12V

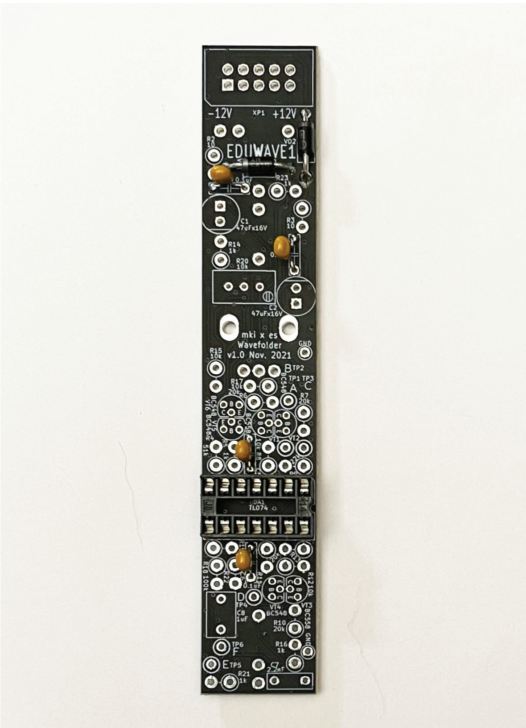

mki x es edu

**Before you start soldering**, we highly recommend printing out the following part placement diagrams with designators and values. Because some of our PCBs are rather densely populated, this will help you to avoid mistakes in the build process.





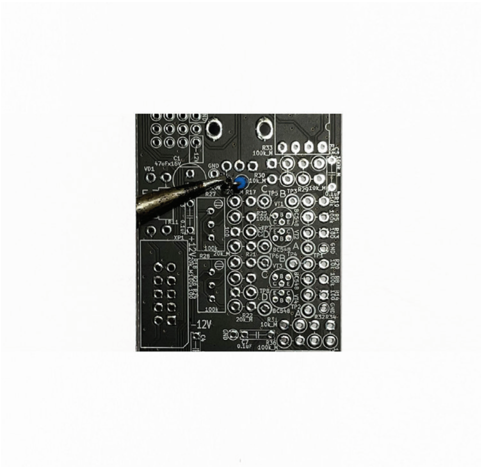

**Place the Mixer PCB in a PCB holder for soldering** or simply on top of some spacers (I use two empty solder wire coils here).

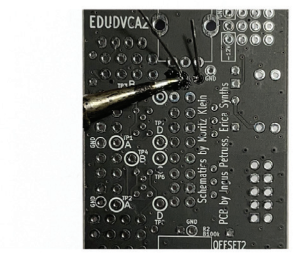


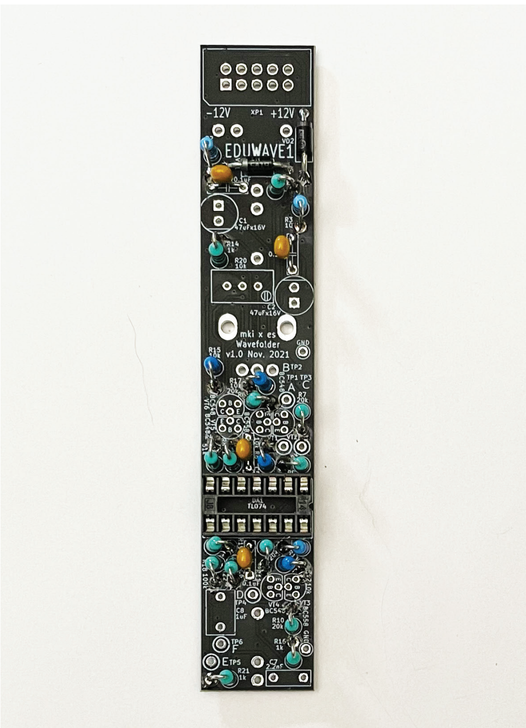

I usually start populating PCBs with lower, horizontally placed components. In this case, these are **power protection diodes**. Bend the diode leads and insert them in the relevant places according to the part placement diagram above. Remember – **when inserting the diodes, orientation is critical!** A thick white or black 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.

**Next, insert the DIP socket,** hold it in place and solder one of the pins. Make sure the DIP socket **is 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.** Place the PCB in your PCB holder or on spacers, insert the capacitors and solder them like you did with the diodes before. After this procedure PCB should look like this:

In order to save space on the PCB, some of our projects, including the Wavefolder, have **vertically placed resistors**. The next step is to place & solder those. All components on the PCB have both their value and denomination printed onto the silkscreen. If you are not sure about a resistor's value, use **a multimeter** to double-check. 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.

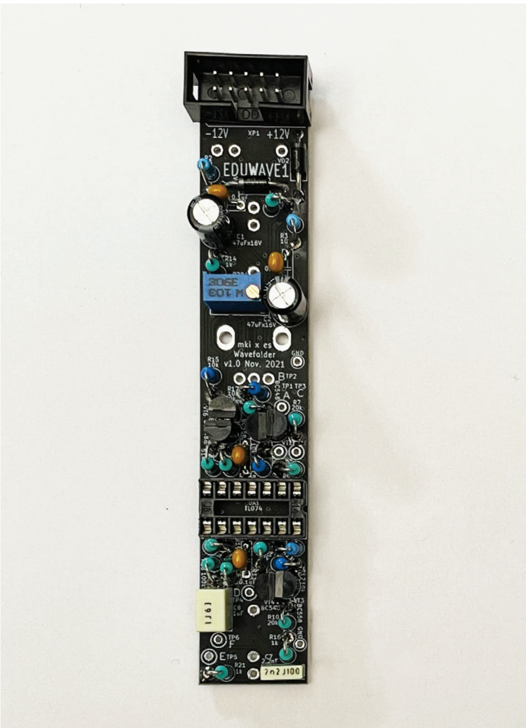






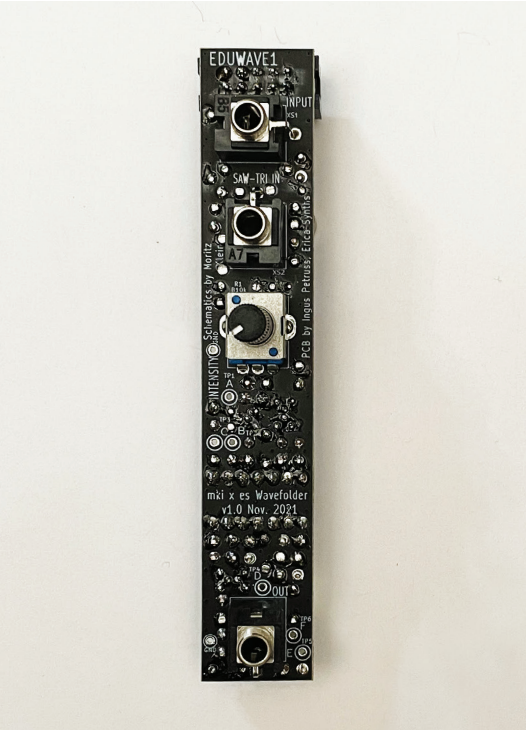
Once you are done with soldering all resistors, your PCB should look like this:


**Next up: 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.



Then insert and solder **the transistors**. Make sure you place correct transistors in relevant places (we use both NPN BC548 and PNP BC558) and align them with the marked outline on the silkscreen – **orientation is critically important here**. Also, insert film capacitors and solder them.

Then complete the component side of the Mixer PCB by soldering the **PSU socket and multiturn trimmer potentiometer**. 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 inwards 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**. Clean the PCB to remove extra flux, if necessary.

Insert **the jack sockets** and solder them. Then insert **the potentiometer**, **but don't solder it yet**! Fit the front panel and make sure that the potentiometer shaft is aligned with the holes in the panel – and that they're able to rotate freely. Now, go ahead and solder the potentiometer.


Then fit the **front panel** and fix it with the hex nuts.

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

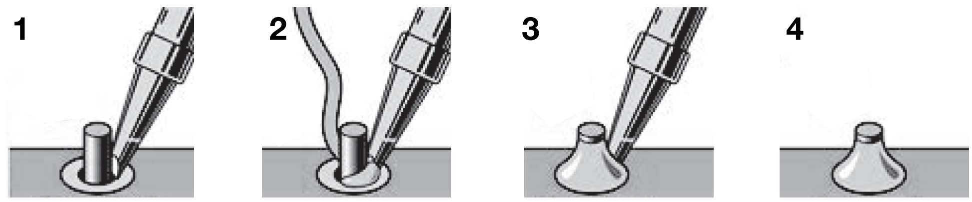
Congratulations! **You have completed the assembly of the mki x es.edu Wavefolder module!** Connect it to your eurorack power supply and switch it on. If there's no "magic smoke", it's a good sign that your build was successful. Patch the sawtooth signal from the  DIY.EDU VCO to the SAW-TRI input of the module and connect the OUT of the module to a mixer. You should hear some sound which timbre will change as you adjust the INTENSITY knob. Now you can proceed with calibration, which consists of adjusting the multiturn trimpot. Please, follow instructions above!

**Enjoy!**

# SOLDERING APPENDIX

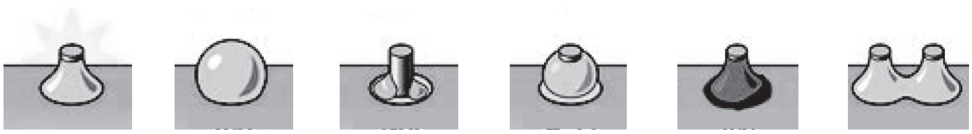
If you've never soldered before – or if your skills have become rusty – it's probably wise to check out some **THT** (through-hole technology) **soldering tutorials on YouTube**. The main thing you have to remember while soldering is that melted solder will flow towards higher temperature areas. So you 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:**



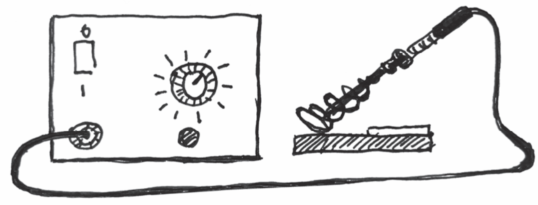

Heat part and pad 2 - 3 sec | Add solder | Continue heating 1 -2 sec. | Let cool

**After you have completed soldering, inspect the solder joint:**

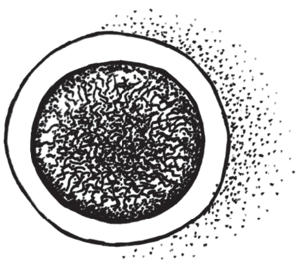


Perfect | Too much solder | Not enough solder | Cold joint | Too much heat | Short

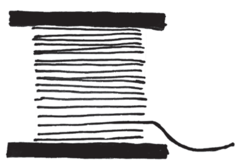
DIY electronics is a great (and quite addictive) hobby, therefore we highly recommend you invest in good tools. In order to really enjoy soldering, you'll need:



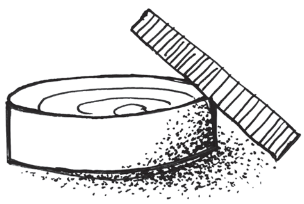
**A decent soldering station.** Top-of-the-line soldering stations (brands like Weller) will cost 200€ and above, but cheaper alternatives around 50€ are often good enough. Make sure your soldering station of choice comes with multiple differently-sized soldering iron tips. The most useful ones for DIY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

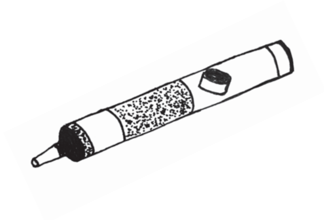


**Solder wire with flux**. I find 0,7mm solder wire works best for DIY projects.

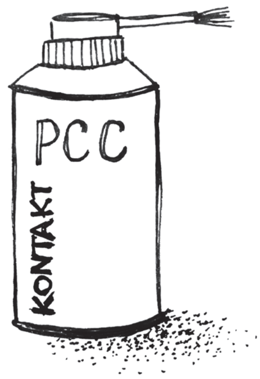


Some **soldering flux** paste or pen will be useful as well.

**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.

"If you want a thing done well, do it yourself."

– Napoleon Bonaparte