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Matura Paper 2020

Building an Analogue Modular Synthesizer

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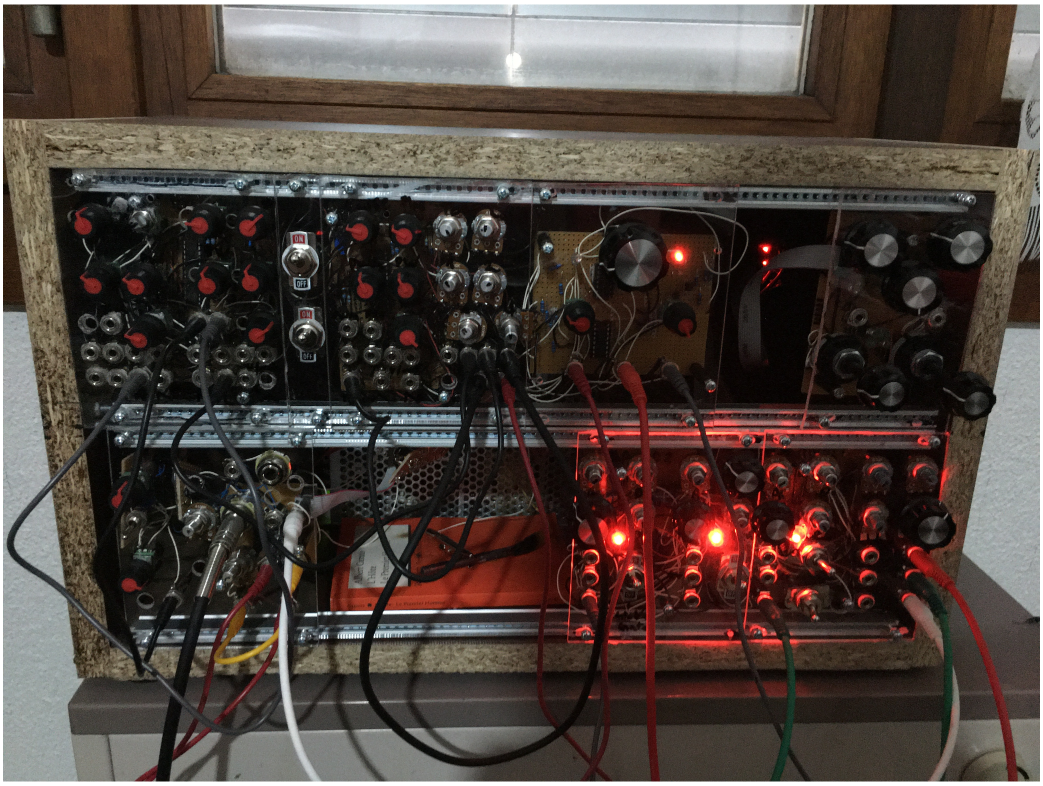

supervised by
Albert Kern

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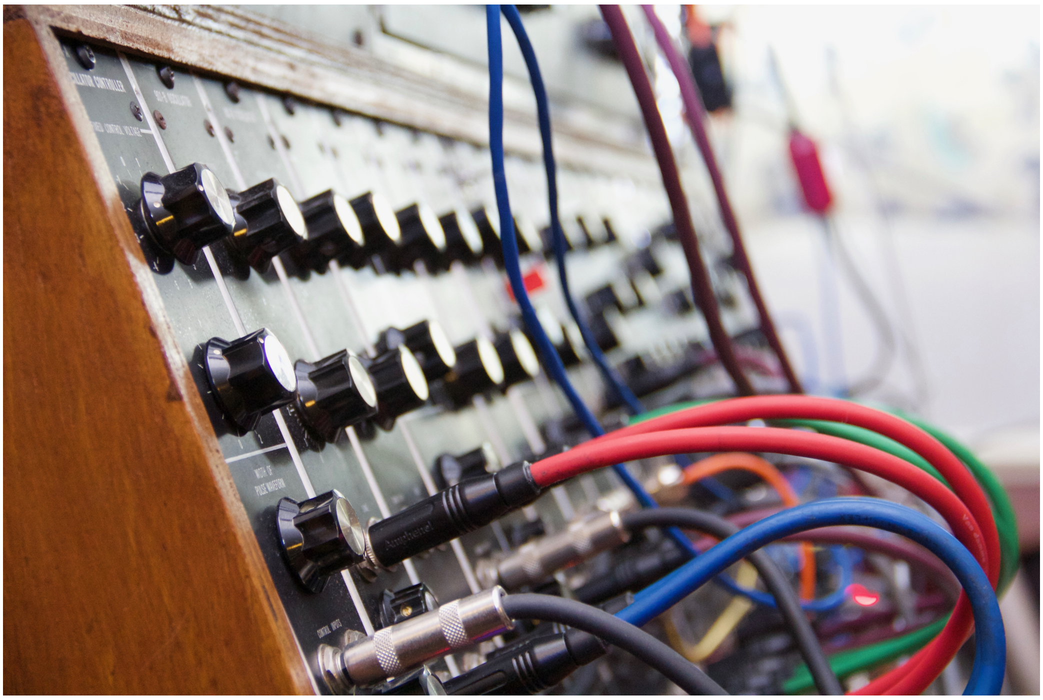


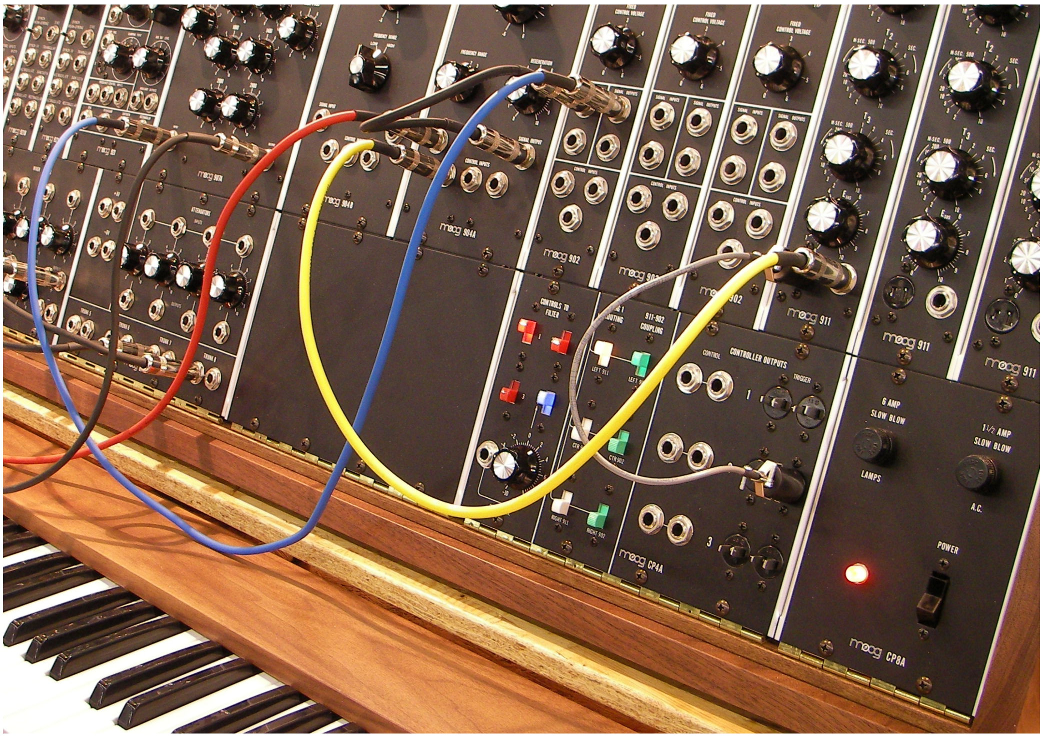
1 Preamble

1.1 Abstract

Designing and building an analogue modular synthesizer comes with a ton of challenges, setbacks and burned fingers. But even after numerous failures and catastrophes the amazement of seeing your own modular synthesizer flashing you with its bright red blinking LEDs and hearing the thunderous sounds coming out of the speaker undo all negative emotions. Not to downplay all the interesting and useful things that are to be learned while constructing such an electrical device. It is a long painstaking process, but in the end it is worth it.

1.2 What Is a Synthesizer?

A synthesizer is a musical instrument which creates sounds using electrical circuits unlike mechanical instruments. Traditionally synthesizers are controlled using a musical keyboard but there are also countless other ways of controlling a synthesizer. In a synthesizer (especially modular ones) there are a lot of possibilities in creating a sound. The sounds that synthesizers can produce have nearly no limit. It is possible to create creepy soundscapes and textures that send shivers down your spine or soft string like lead tones or just plain weird audio effects. A synthesizer is a fantastic tool to explore timbres and sound.


6 AMP
SLOW BLOW
LAMPS
POWER
moog CP8A
moog 911
CONTROLLER OUTPUTS
TRIGGER

2 Theory

2.1 Electrical Engineering Basics

To understand all the theory in this paper it is important to have a basic knowledge of electronics, which this section provides.

2.1.1 Crucial Electrical Components

Resistors

Resistors inhibit electrical current which makes them a very useful component in various circuits. In fact, they are one of the most prevalent components in circuitry. The most important rating of a resistor is its electrical resistance (R). The SI unit of resistance is the ohm (Ω). Another value of importance is the power rating (P). Energy cannot be destroyed so when a resistor draws current heat is generated. The power generated can be calculated using ohm's law ($V = R \cdot I, P = V \cdot I$):

$$P = R \cdot I^2 \quad (1)$$

It is important to never exceed the power rating of a resistor except if you want to experience the world's smallest light show.

Capacitors

Capacitors store electric charge. They can be charged and discharged at impressive frequencies making them ideal for time related circuity. How much charge a capacitor can hold depends on its capacitance (C). Electrical charge Q is equal to capacitance C times voltage V ($Q = C \cdot V$). The SI unit of capacitance is Farad (F). Most capacitors have a capacitance in the range of $1pF$ to $470\mu F$. Capacitors also have a voltage rating which shouldn't be exceeded. Certain capacitors (for example electrolytic capacitors) are polarised, meaning that one lead must be connected to a positive and the other to a negative voltage. Otherwise the capacitor would act like a small firework.
When you connect a resistor to a charged capacitor it will discharge exponentially depending on the resistance of the resistor as well as the capacitance and the voltage of the capacitor. The voltage after a certain time can be calculated using following equation:

$$V_C = V_0 \cdot e^{-\frac{t}{RC}} \quad (2)$$

Capacitors are found in many time related circuits but also in power supplies to reduce ripples and noise in the rectified output.

Diodes

Diodes are semiconductor components that act like electrical one way streets. They let electrical current flow in one direction but not the other. Popular applications are reverse polarity protection and rectifier circuits (circuits that turn signals into rectangle signals).

Transistors

Transistors are often described as electrical switches, which is true for a variety of transistor types although another useful application is the amplification of signals.

Operational Amplifiers - OpAmps

Operational Amplifiers (short, OpAmp) are integrated circuits that can amplify a voltage by a certain gain. OpAmps have two inputs, an inverting input and a non-inverting input. There are numerous applications for OpAmps making them a very widespread component in electronics.

Inverting Amplifier

One of the most common operational amplifier circuits is the inverting amplifier (see figure 1). In this circuit the input voltage gets amplified by the gain Av (which is defined by resistors R_{In} and R_F) and inverted. The output voltage can be calculated using following formula:

$$V_{\text{Out}} = -\frac{R_F}{R_{\text{In}}} \cdot V_{\text{In}} \tag{3}$$

Summing Amplifier

Another very useful operational amplifier circuit is the summing amplifier. Its function is the summing of different voltages to one output voltage (as seen in formula 4). The circuit consists of a feedback resistor (R_F) and a resistor for each voltage input (R_{In}) setting the bias of the input.

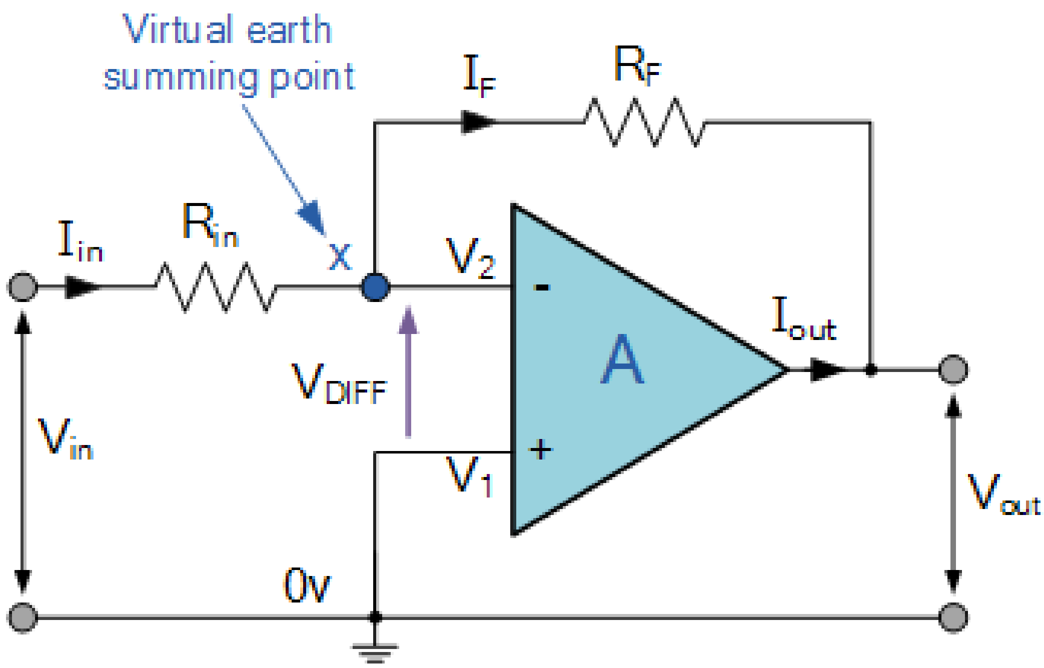


Figure 1: Inverting Amplifier Circuit

$$V_{\text{Out}} = \frac{R_F}{R_{\text{In 1}}} V_{\text{In 1}} + \frac{R_F}{R_{\text{In 2}}} V_{\text{In 2}} + \ldots + \frac{R_F}{R_{\text{In n}}} V_{\text{In n}} \tag{4}$$

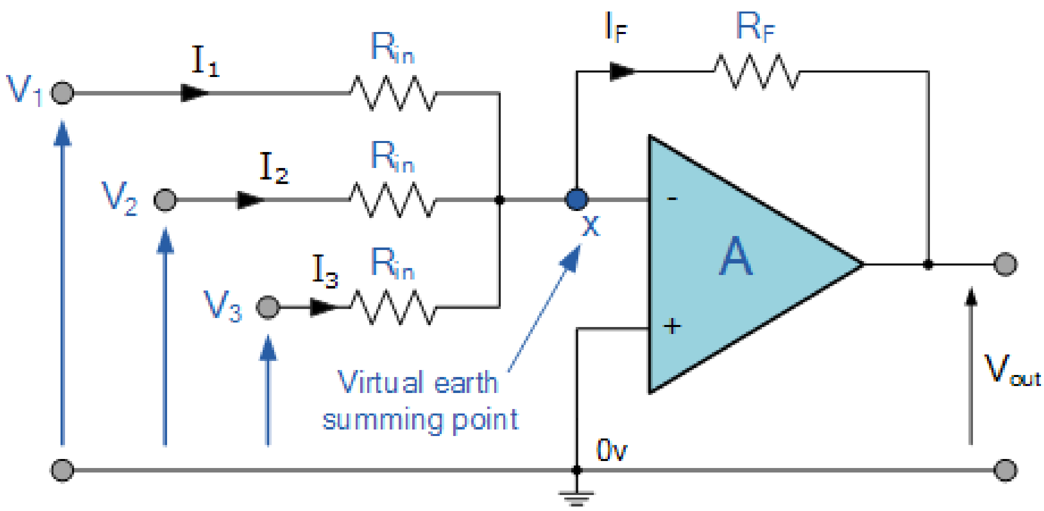


Figure 2: Summing Amplifier Circuit

2.2 Analogue Modular Synthesizer

What does analogue mean?

Analogue means that the synthesizer contains no digital circuitry. This specification is especially important regarding the oscillator because waveforms from analogue oscillators have slight imperfections unlike digital oscillators (although there are analogue oscillator emulators) which makes them harmonically richer. Analogue circuits also have the tendency to slightly distort and saturate the signal resulting in a warmer sound.

What makes a synth modular?

A modular synthesizer has no internal connections between modules. Connections are achieved via patch cables allowing for more possibilities in creating a sound (also called a patch).

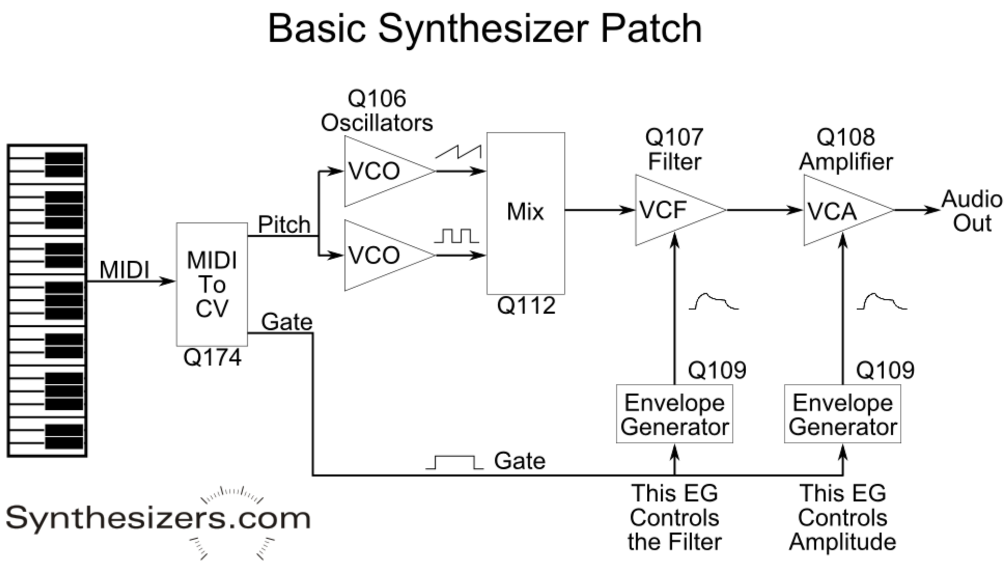


Figure 3: Basic Synthesizer Signal Chain

2.2.1 Modules and Their Application

There are countless different modules and new ones are constantly being developed. The most essential of these modules are listed here.

The Oscillator

The oscillator is arguably the most important module of a synthesizer. It is where the actual sound waves are synthesised, where the signal chain begins. A simple oscillator usually works by charging a capacitor and quickly discharging it when a certain threshold charge is reached and repeating this cycle over and over again which in return results in an oscillation.

Waveforms

An oscillator can synthesise different waveforms with distinct timbres. The most common waveforms being:

- Sine wave - Contains no overtones (multiples of the fundamental frequency of the signal), just the fundamental.
- Square wave - Contains only even overtones.
- Triangle wave - Contains weak even overtones.
- Sawtooth wave - Contains even and odd overtones.

VCO - Voltage Controlled Oscillator

The most common form of oscillator is the VCO. A VCO lets you modulate the pitch using a control voltage (CV). This makes controlling the synthesizer with a keyboard very easy, although for the most widespread convention of Volt per octave (V/oct) an exponential converter is needed inside of the VCO because the input voltage is linear but perceived pitch is not.

Envelope Generator - Adding the Fourth Dimension

Envelope generators create a control voltage in response to a gate/trigger signal. The generated signal typically consists of four stages (see figure 5):

- Attack stage: The voltage ramps up to the peak.
- Decay stage: The voltage drops to desired sustain level.
- Sustain stage: The voltage rests on set level until key is released.
- Release stage: The voltage ramps down to $0V$.

An envelope generator is almost always used to modulate the volume of the synth so that the note does not go on forever.

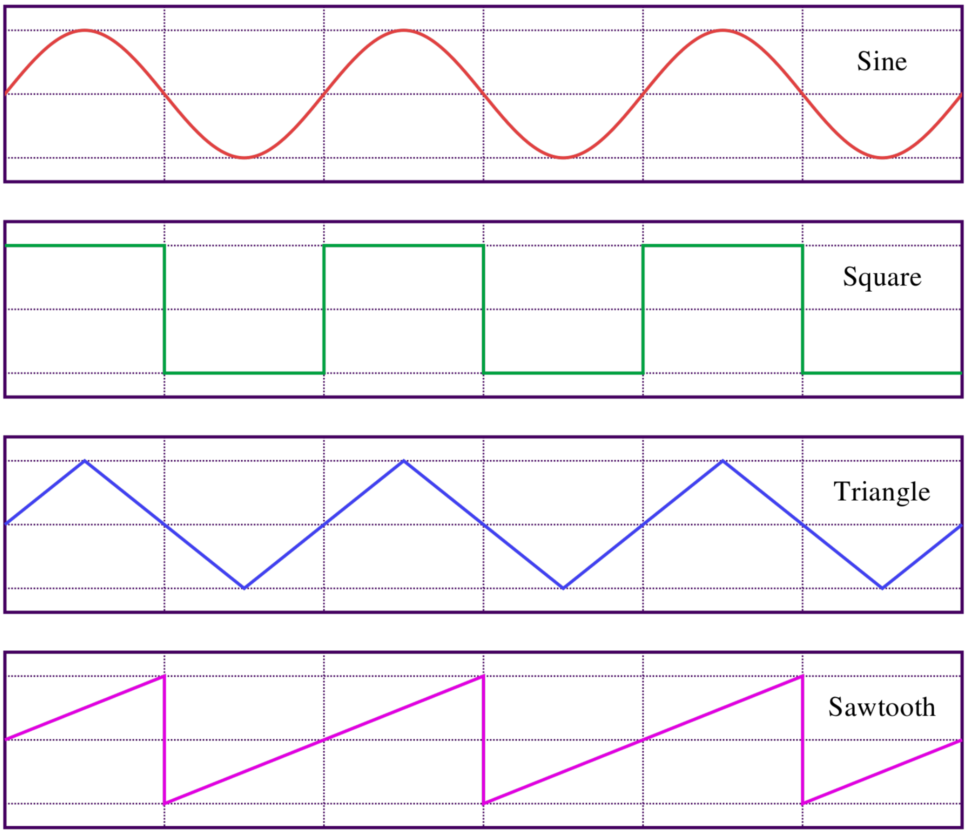


Figure 4: Common waveforms

Voltage Controlled Amplifier - VCA

Usually it is not desirable that a note is never-ending which means that the volume has to be variable. VCAs allow the modulation of volume via a control voltage signal, for example from an envelope generator.

Filter - Less is more

The filter is one of the most crucial modules in subtractive synthesis (explained on page 11) as it allows for certain frequency bands to be cut out or tamed. The probably most common filter type is the (voltage controlled) low pass filter which cuts high frequencies but lets low frequencies pass at a desired cutoff frequency.

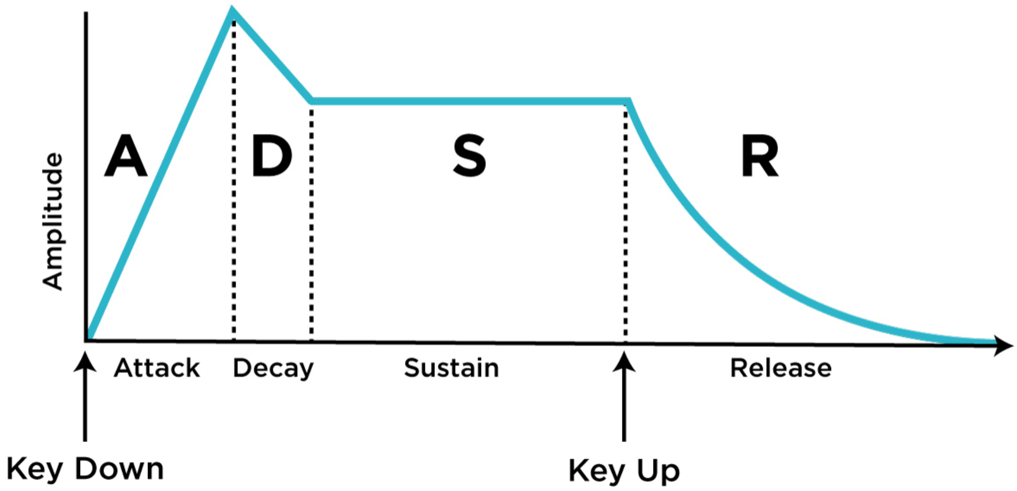


Figure 5: ADSR Envelope

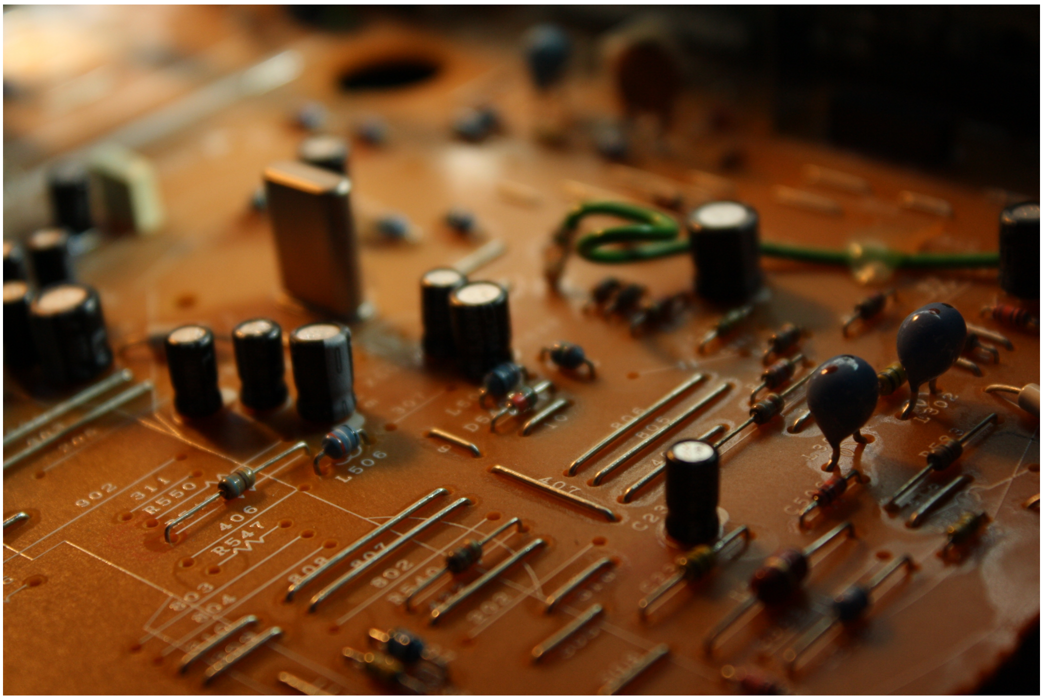
2.3 Forms of Synthesis

Subtractive

Subtractive synthesis works on the principle that we have a harmonically rich signal of which certain frequencies get cut or altered.

Additive

Additive synthesis works in exactly the opposite way of subtractive synthesis. In additive synthesis harmonically rich sounds are created by adding numerous sine waves of different frequencies on top of each other.



3 Construction of a Modular Synthesizer

3.1 Idea

I already knew what I wanted to do long before we had to choose a matura project subject. I wanted to do something that combined my two most profound interests: Music and electrical engineering. I have always wanted to have a hardware synthesizer but did not have the finances to buy one. That is how I got the idea to make an analogue modular synthesizer. Analogue because I fancy the sound of analogue gear over the sound of digital counterparts and I chose to build a modular system instead of a hardwired synthesizer because I enjoy having a lot of possibilities to alter the sound and create interesting textures.

3.2 Planning

The first thing that I did was to plan everything out. I reflected about which modules I wanted to build and decided that I would like to construct 3 VCOs (Voltage Controlled Oscillator), 3 ADSRs (Attack-Decay-Sustain-Release), a VCF (Voltage Controlled Filter), 4 VCAs (Voltage Controlled Amplifier), a unique drone module, an eight-channel audio mixer, 2 LFOs (Low Frequency Oscillator), a distortion module and a sequencer. This selection turned out to be slightly overambitious but I managed to build everything except the drone and sequencer module. Additionally, the 4 VCAs were lowered to 2 and the mixer only has four channels.

Something that I was unsure of was the question if I should etch PCBs (printed circuit boards) indirectly via a company or if I should build the circuits completely from scratch using stripboard. I left this open at the moment because I did not think it would matter all that much.

The next step was to plan out the design of the casing. After thinking about certain more complex designs I eventually opted for a simple design inspired by the Doepfer A-100 Analog Modular System (See figure 6).

Finally I thought about the power supply. After some reflection and research I came to the decision to get a power supply with the voltages $+12V$, $-12V$ and $5V$ because these are the voltages most modules nowadays use.

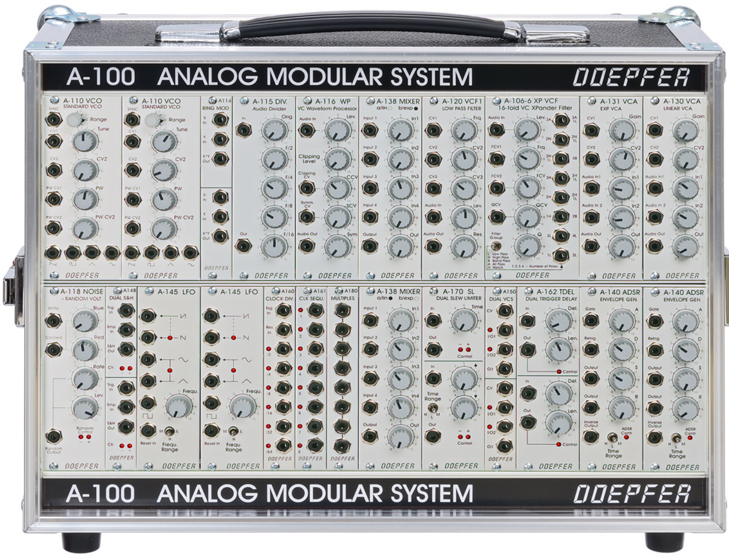


Figure 6: DOEPFER A-100 Analog Modular System

3.3 Research and Design

Circuits

I started my research by searching for fitting circuit designs for my modules. I had to make sure that every circuit worked with the voltages I chose ($+12V$, $-12V$, $+5V$), had the desired features and was not too complex of a circuit. This took quite a while but eventually I found what I was looking for.

VCO

After some time looking for a schematic of a VCO with atleast a sawtooth and a pulse output as well as sync (A slave oscillator gets reset with every period of a master oscillator) and FM (Frequency Modulation) I finally found a fitting circuit from Cellular and Molecular Biology graduate and synthesizer enthusiast Yves Usson. He has quite a lot of good schematics on his website[1], one of which is a VCO with sawtooth, pulse, triangle and sine output as well as sync and FM capabilities[2].

[1] https://yusynth.net
[2] Schematic in appendix - figure 7

ADSR Envelope Generator

Whilst stumbling around various synthesizer forums I ran across a website of a man named René Schmitz[3] on which I found an ADSR envelope design[4] that was not all too complicated but had independent potentiometers and promised to have very snappy decay times, so I opted for this design.

Low Pass VCF

On the website of the Englishman Sam Battle[5] I found a fitting design for a Low Pass VCF modelled after the Korg MS-20 VCF. Sam Battle's design is actually a slight modification of a René Schmitz design. What caught my eye about this circuit was the simplicity and the fact that there was already a stripboard design on the website[6].

VCA

In my research I stumbled across a website[7] about a modular synthesizer where I found a simple VCA. Because there was nothing special I was looking for in the VCA I just went with this design.

LFO

Regarding the LFO I was looking for a triangle and rectangle output and decent frequency range. Eventually I found what I was looking for on the website of David Haillant. It promised a range switch and my desired waveforms all in an uncomplicated design[8].

Distortion Module

The distortion was completely designed by me. It consists of a first amplification stage using an OpAmp. In this stage I can already rectify the signal by setting the gain at a level which causes the signal to exceed the power supply voltage and thus get rectified. After this stage there is a hard clip circuit (rectifies the signal at a certain voltage threshold) with selectable diodes which can

[3] https://www.schmitzbitz.de
[4] schematic in appendix - figure 8
[5] https://www.lookmumnocomputer.com
[6] Stripboard design in appendix - figure 10
[7] http://www.bergfotron.synth.net/
[8] Schematic in appendix - figure 9

create more unique distortion effects. The last stage is another amplification stage where the signal can be amplified to a reasonable signal level.

3.4 Construction

3.4.1 Casing

The construction of the rack was more of a challenge than I expected. The first mistake happened when I bought the wood for the casing because after a while I realised that I miscalculated the dimensions because I used the wrong panel thickness in my calculation. Fortunately I noticed that really only two panels did not fit so I just sawed the excess off instead of buying new panels. This resulted in a slightly smaller case but that was the worst of it.

Problems with the Power Supply

When I first connected my power supply to the power plug the power LED kept blinking and the device kept making a high pitched noise synchronised with the blinking. Because the power supply had two settings, one for 230 V/AC and one for 120 V/AC I thought that this must be the problem so I changed the setting. Unfortunately this did not solve the problem, in fact it only made it worse because the electrolytic capacitor of the full bridge rectifier (which filters the signal and ensures a perfect DC-voltage even when a load is connected) nearly overheated. Defeated I went online and searched for answers and finally found my salvation on a YouTube video about a person having the same problem. Apparently the power supply needed a minimum current draw to work. So I connected an old computer fan and tried it again but that was not enough so I tried connecting small resistors which sadly also did not work, sometimes because they were not drawing enough current and sometimes because they overheated and shined a red light into my face. Eventually I resorted to a relatively extreme solution. I connected a graphite rod with alligator clips to the +5V and ground connectors of the power supply. It finally worked but I was forced to put the rod on something heat resistant because else it would have burned my house down (I used a book of french author Albert Camus).

3.4.2 Modules

General Module Building Procedure

In this section the general module building procedure is described using the LFO module as example.

Stripboard Design

First and foremost I always had to design a stripboard (a board with copper strips and holes to solder through-hole components into) layout. This was not a very hard task for this schematic[9] although it was sometimes a challenge to keep it compact.

Soldering and Assembly

The most painstaking and lengthy process was always the assembly. Countless burns and soldering fumes constantly tickling my lungs. Also connecting cables was always a flimsy task and very time consuming.
The first thing that I eventually always did after I built a routine was sketching the circuit onto the blank stripboard using a sharpie. Then I started soldering the jumper cables on the circuit as these were the most pesky to solder. Afterwards all other components were added part after part.
The most time consuming part was connecting all potentiometers, audio jacks and switches to the stripboard.
After the actual circuit was done I continued by cutting and drilling the panel piece. Finally the only thing that was left to do was attaching the circuit to the panel.

Voltage Controlled Oscillator

The stripboard design that I had to design for YuSynth's VCO[10] design was definitely the hardest out of all because it was also the most complex schematic. The assembly went relatively well but took a long time. Finally I could test it but there was nothing but disappointment. The only thing coming out of the output was a high pitched screech and a ton of noise. After a lengthy time of thinking I had the idea that maybe the JFET that I substituted with a MOSFET in enhancement mode could be the problem. Sadly this did not solve the problem

[9] Schematic in appendix - figure 9
[10] Schematic in appendix - figure 7

so out of time pressure I searched for an alternative and found one. An analogue to a classic oscillator IC - the CEM3340. I ordered 3 chips and found a fitting schematic[11] for the IC on https://www.lookmumnocomputer.com that I modified to my liking. Luckily this design worked instantly.

Voltage Controlled Low Pass Filter

The stripboard design was already given here which sped up the process quite a bit. Directly after assembly it unfortunately did not work correctly. It appeared that only the resonance part of the circuit was working. This was eventually fixed by checking all connections and re-soldering suspicious contacts.

ADSR Envelope

This was the design of René Schmitz. Sadly this design did not work for me at all. The output signal was negative and not behaving as it should. So I searched for other designs and found a similar one on YuSynth.net. This design eventually worked without a problem.

Voltage Controlled Amplifier

I tried to create a very compact stripboard design and more or less succeeded. There were not any problems while assembling this module and it also worked off the bat. But unfortunately one time I was not paying attention and accidentally reversed the polarity of the power supply resulting in damage to an IC. It still worked for a while but at one abrupt moment the IC suddenly shorted out and started to smoke. After that I embarrassingly had to rebuild the entire circuit.

Distortion module

Assembling and soldering this module was one of the most straightforward processes because it is a simple design. It worked as intended without any additional tweaking.

3.4.3 Conclusion and thoughts

The assembly of my own analogue modular synthesizer was quite a journey and an emotional rollercoaster at some points. I learned a lot and I am rather pleased

[11]Stripboard in appendix - figure 11

with the end result. I will keep modifying it and building new modules to get even more weird sounds as there is always a sound that has not been explored yet.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Pitch
Level
Cymbal

4 Appendix

4.1 List of figures

List of Figures

4.2 References and sources

- André Ruschkowski: Elektronische Klänge und musikalische Entdeckungen. Reclam, 2010.
- Figure 1: https://www.electronics-tutorials.ws/wp-content/uploads/2018/05/opamp-opamp6.gif, 17.10.2019.
- Figure 2: https://www.electronics-tutorials.ws/wp-content/uploads/2018/05/opamp-opamp11.gif, 17.10.2019.
- Figure 3: https://www.synthesizers.com/learn/synthpatch_1000.png, 19.01.2020.
- Figure 4: https://en.wikipedia.org/wiki/Waveform#/media/File:Waveforms.svg, 17.10.2019.
- Figure 5: https://d2wclktjr2mmlu.cloudfront.net/media/wysiwyg/articles/learning-synthesis-envelopes-1/ADSR_graf-2.jpg, 17.10.2019.

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- Figure 10: https://www.lookmumnocomputer.com/projects#/simple-filter, 19.10.2019.
- Figure 11: https://www.lookmumnocomputer.com/projects#/cem-3340-diy-simple, 19.10.2019.
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[12]Hjönk

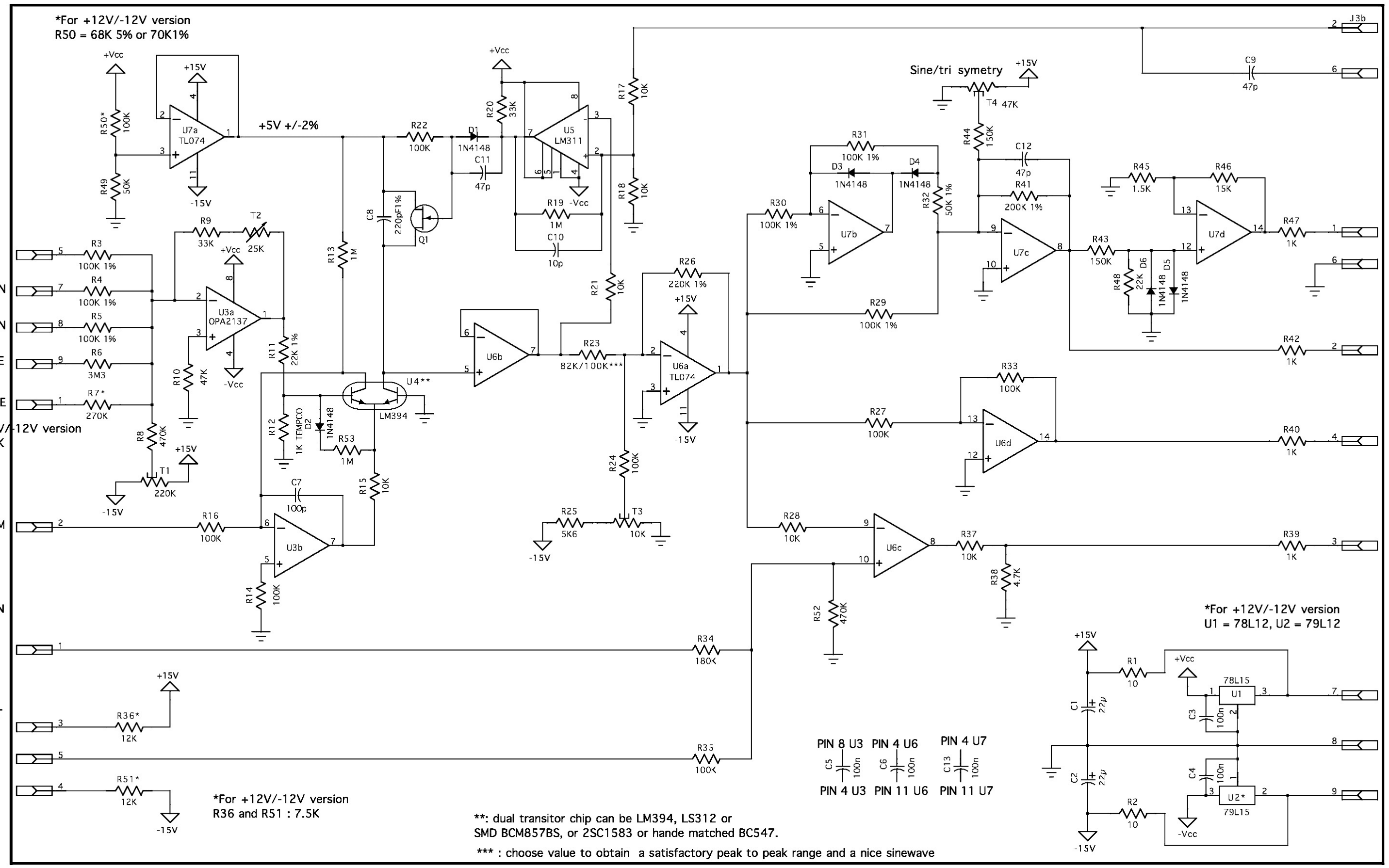

Figure 7: VCO of Yves Usson (YuSynth)

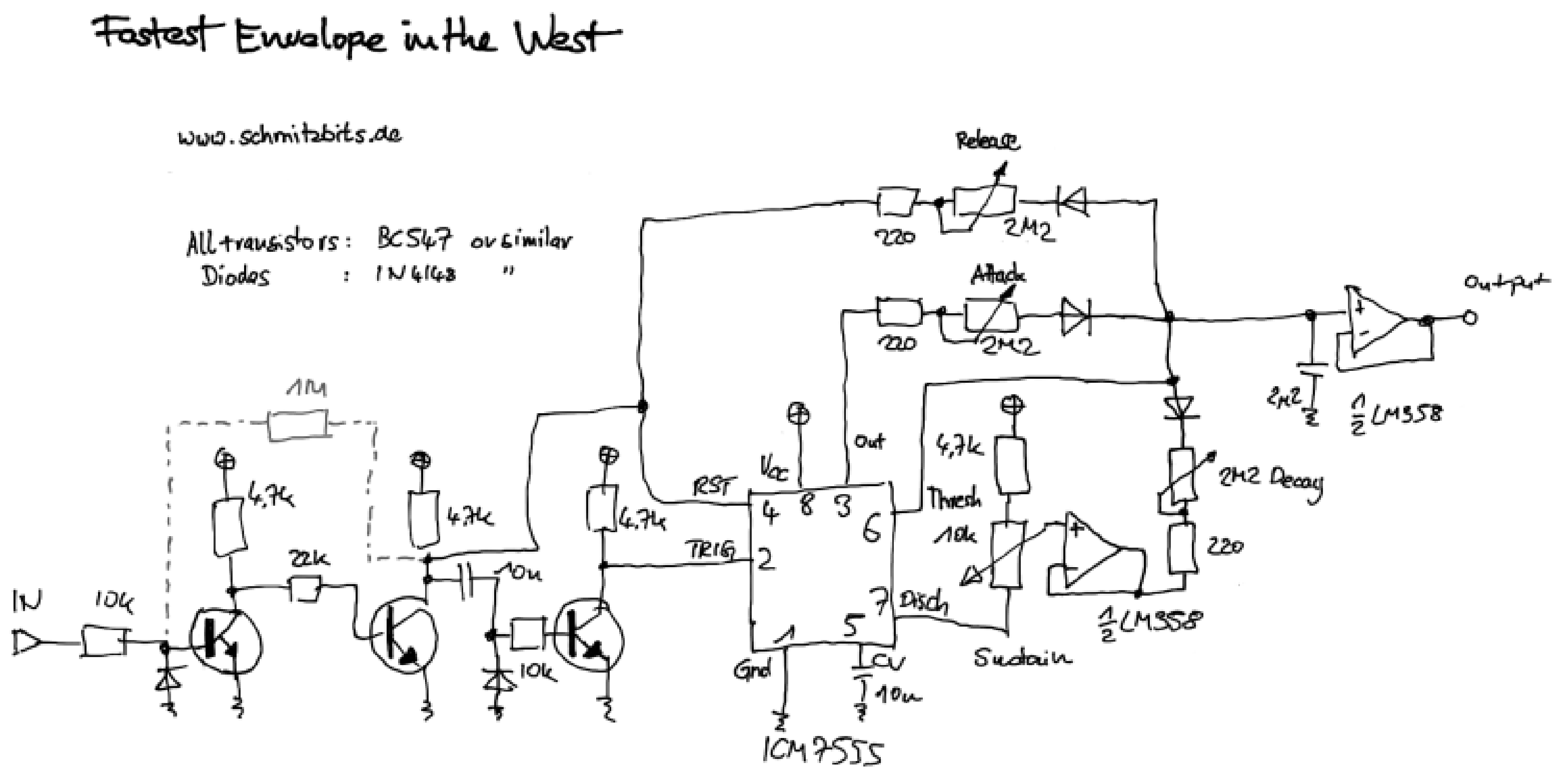

Figure 8: ADSR Envelope of René Schmitz (SchmitzBitz)

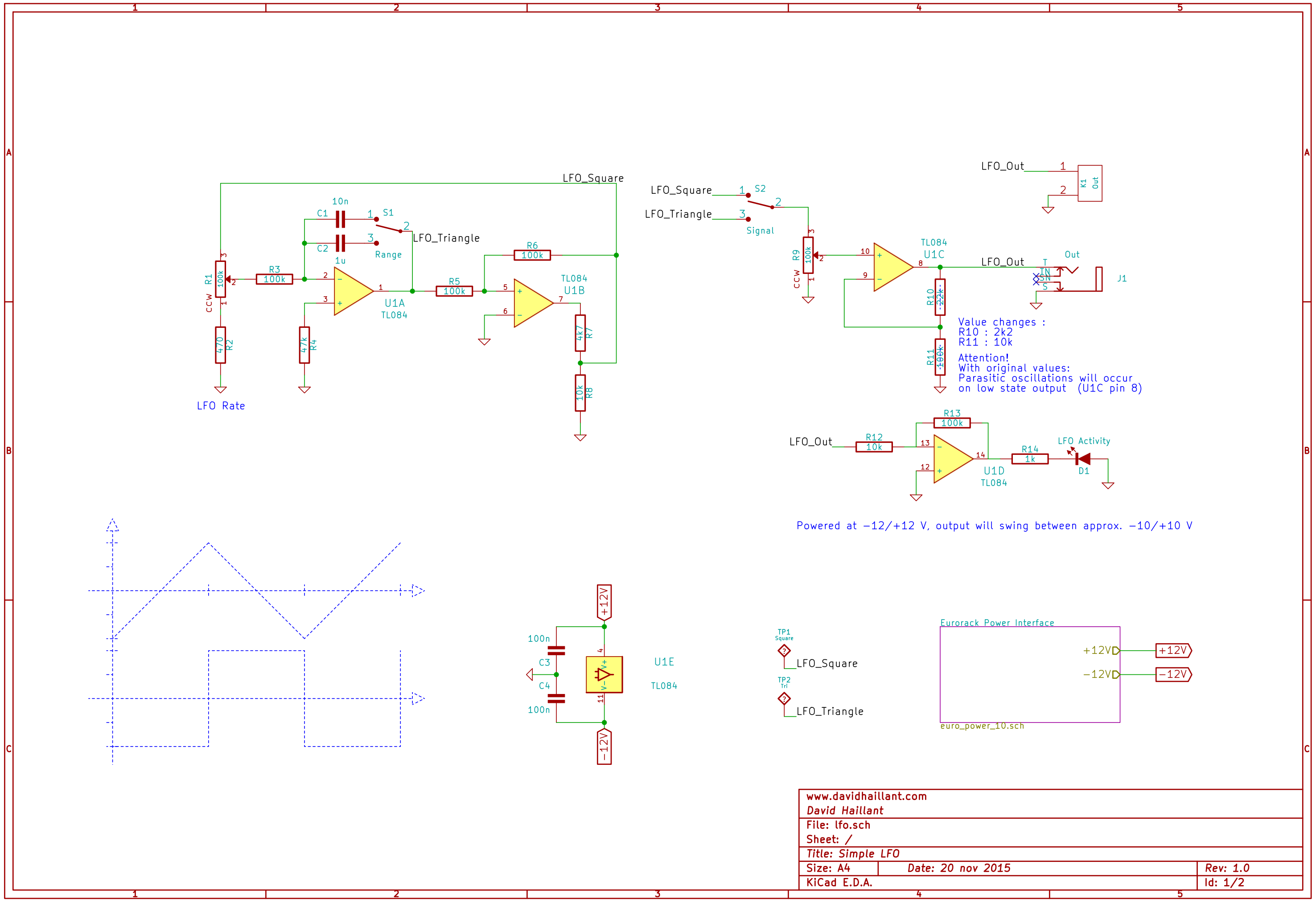

Figure 9: LFO of David Haillant

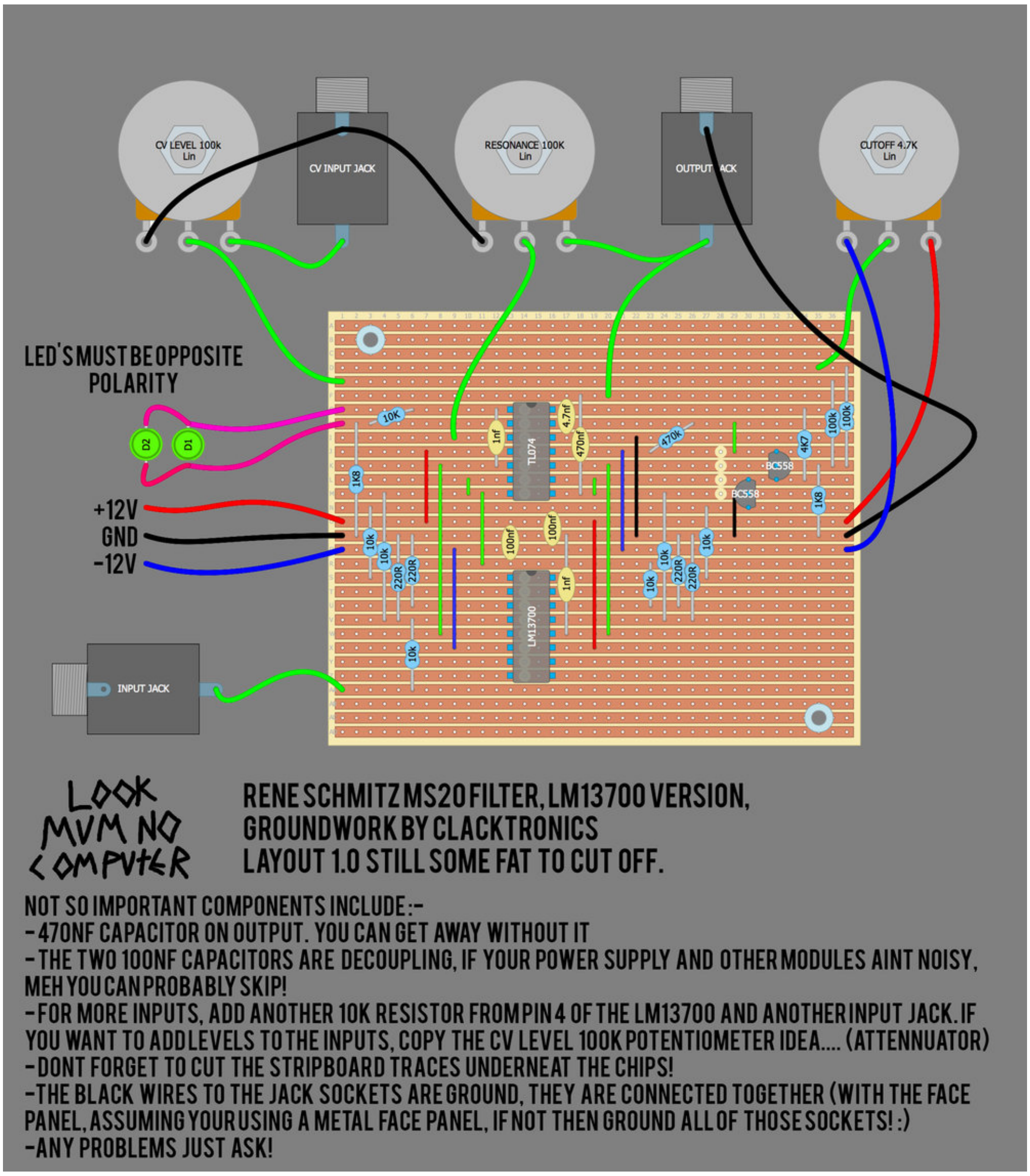

Figure 10: Low Pass VCF of Sam Battle (Look Mum No Computer)

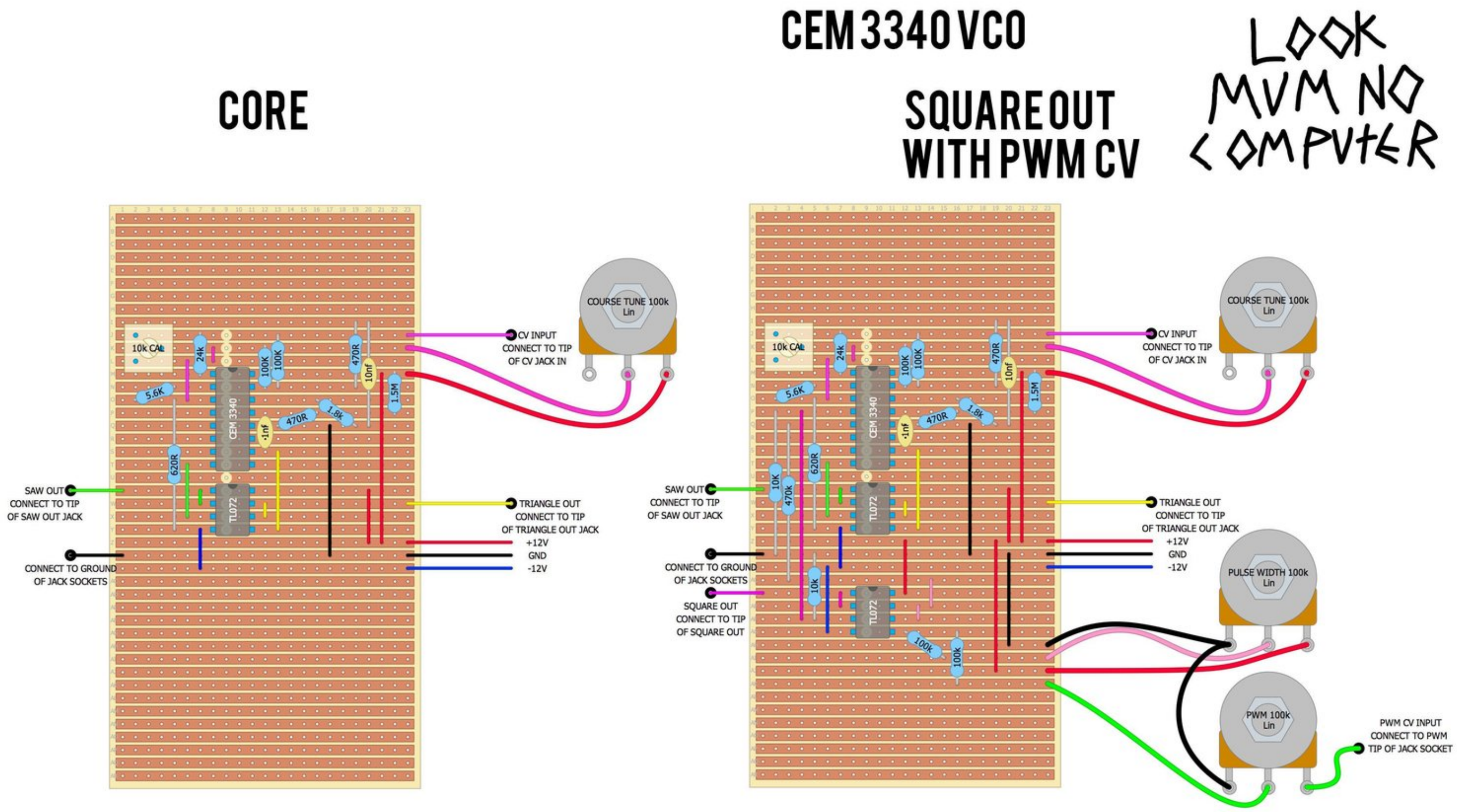

Figure 11: VCO of Sam Battle (Look Mum No Computer)

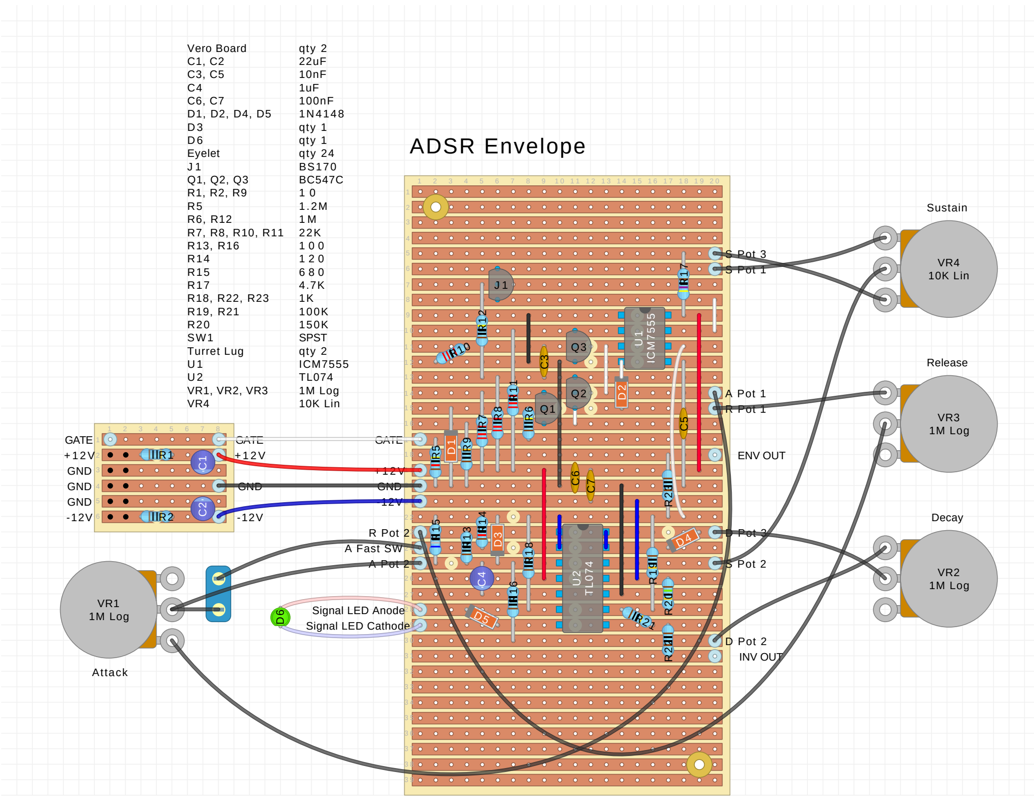

Figure 12: Self-made stripboard layout of the Yusynth-ADSR

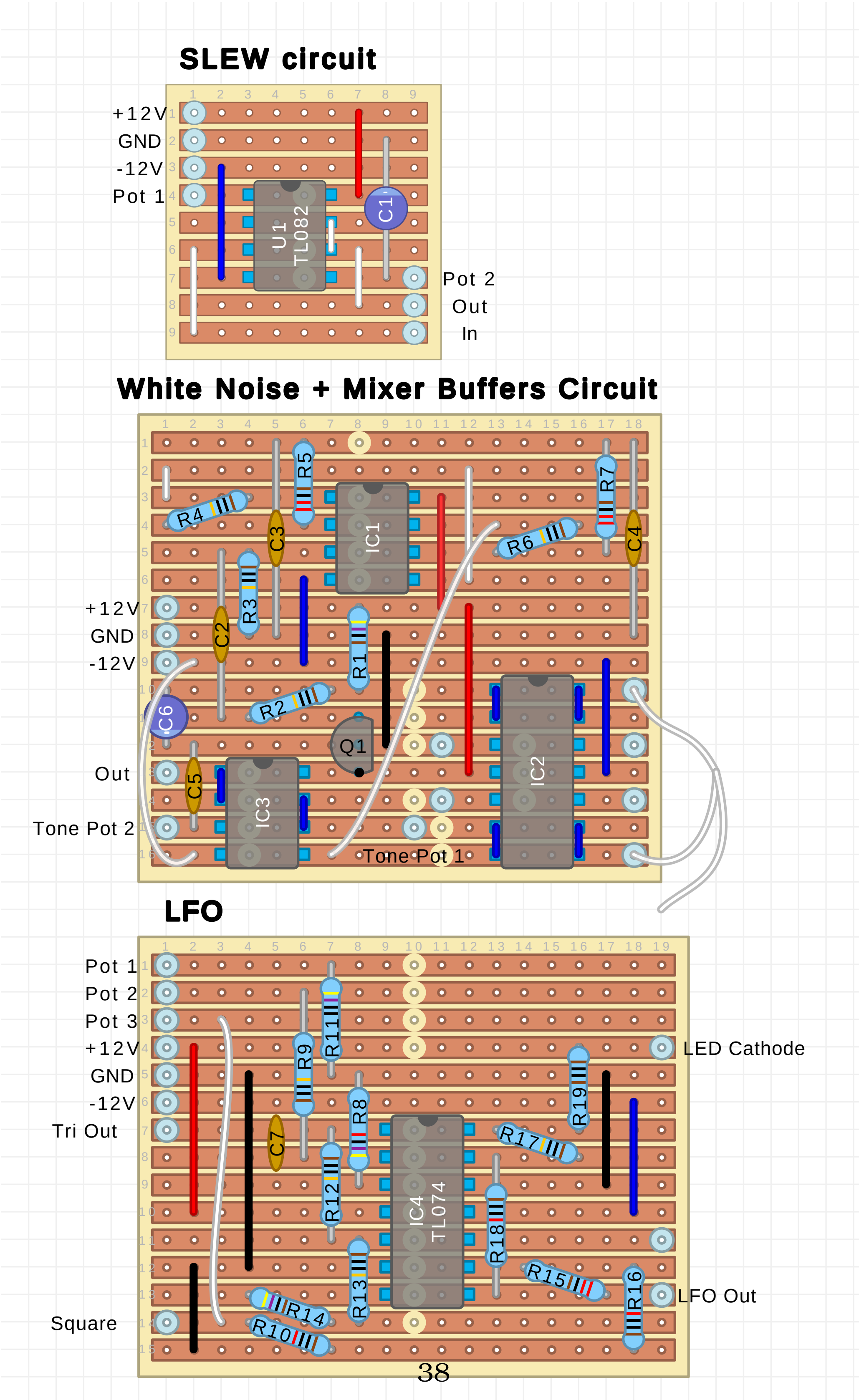

Figure 13: Self-made stripboard layout of the LFO, Slew and Noise

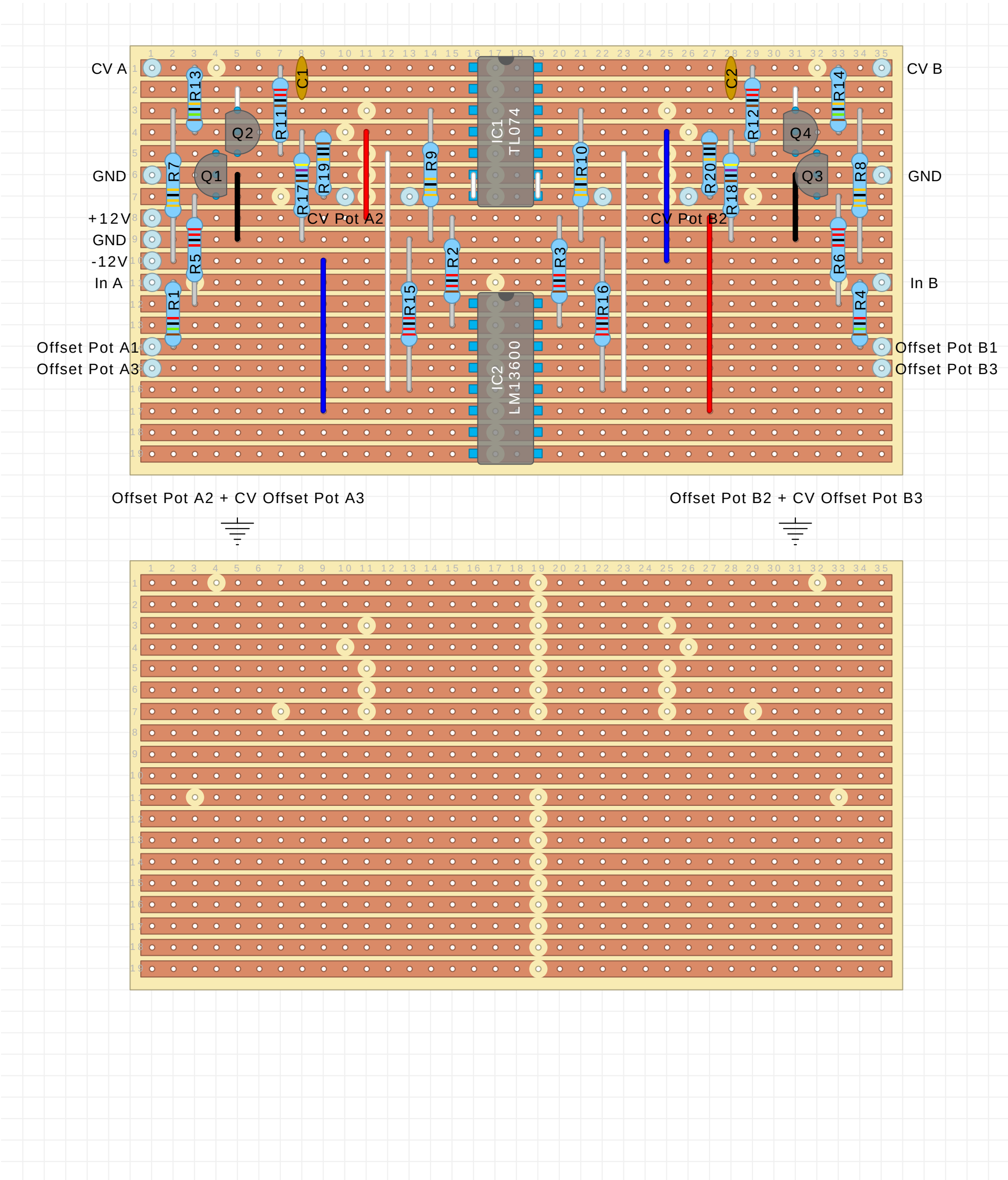

Figure 14: Self-made stripboard layout of the VCA

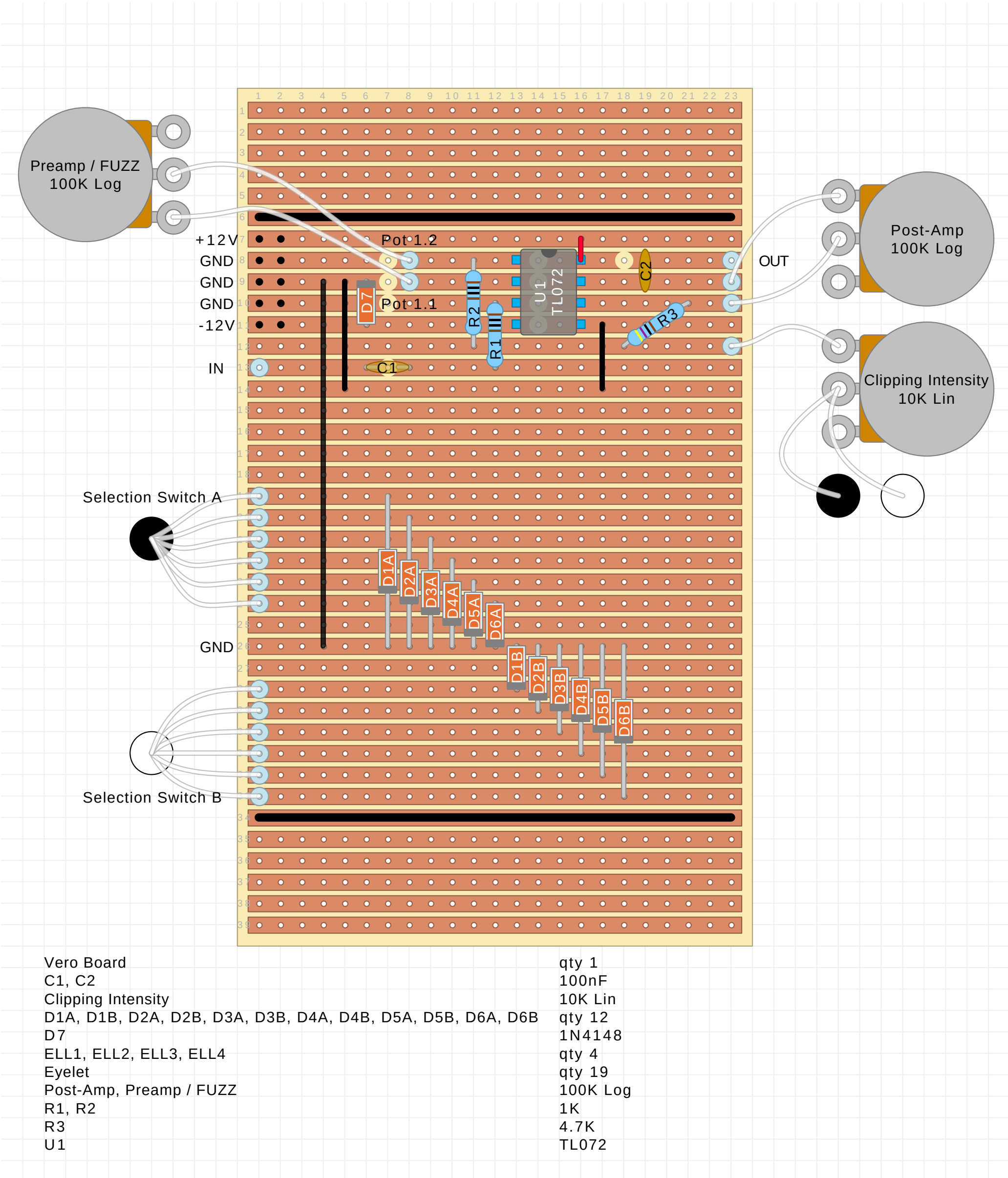

Figure 15: Self-made stripboard layout of the Diode and Fuzz Distortion Module

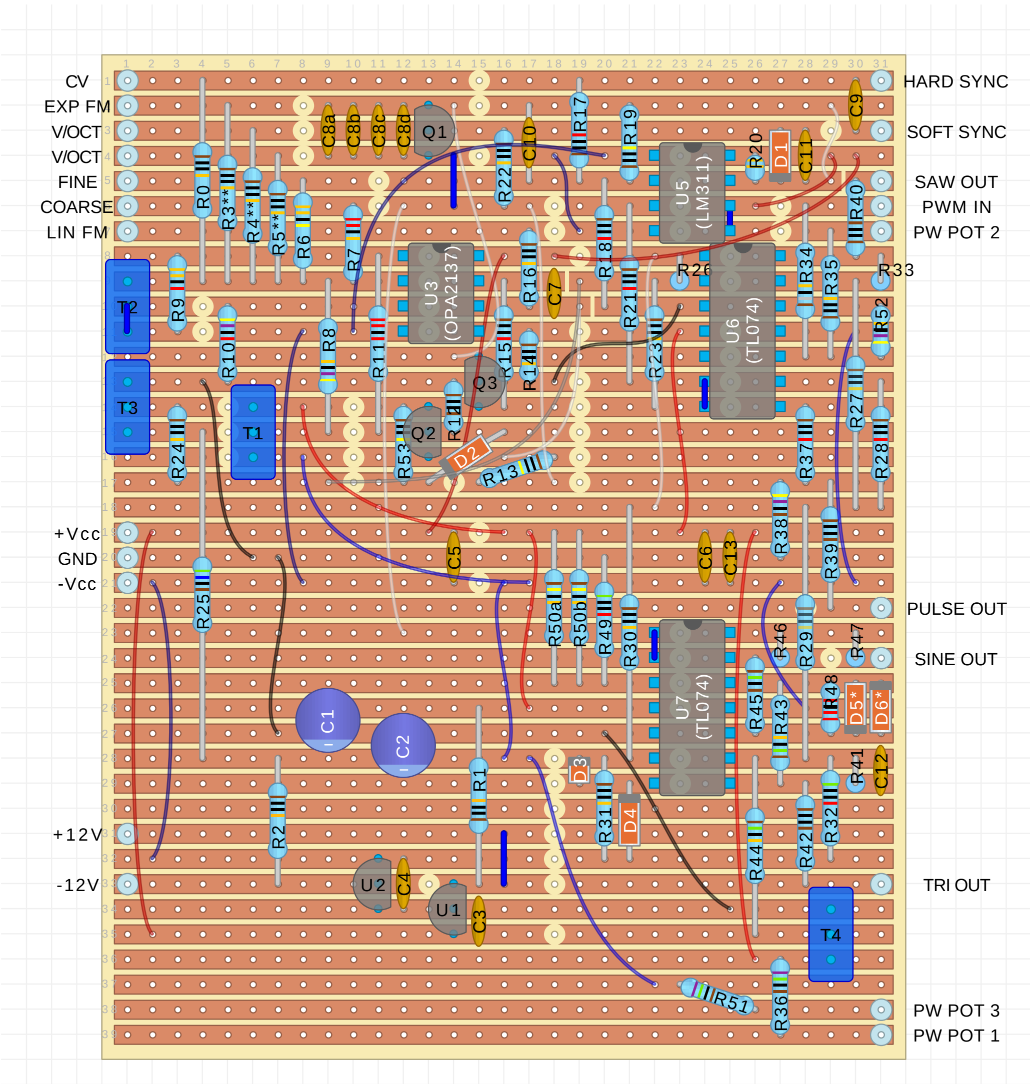

Figure 16: Self-made stripboard layout of the failed VCO