The Analog Synthesizer: Applications of Fundamental Electronic Concepts and its Relevance to Education

6CCE3EEP Final Project Report

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April 11, 2024

Abstract

This report will follow an experimental approach to the design of an analog synthesizer, using an undergraduate knowledge of fundamental electronic circuits. It hopes to; demonstrate the practical application of key topics in Electronic Engineering to the field of analog music synthesis; show a deep understanding of synthesizer circuitry; and analyse their use in education.

Designs for oscillators, filters, amplifiers, and other synthesizer modules will be evaluated with consideration to their applications in undergraduate studies, and thereafter implemented in a practical breadboard project. The design process will include detailed circuit analysis, computer simulations and real-time oscilloscope feedback from the physical circuit. This project focuses purely on analog synthesis rather than its modern digital counterpart.

Originality Avowal

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Josie Chandler Massaro

April 11, 2024

Acknowledgements

Dr Naseem Ramli - Department of Engineering, King's College London

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Chapter 1

Introduction

This first chapter gives an insight into the motivation, objectives and structure for the project and report.

1.1 Project Motivation

Synthesizers are a key staple of electronic music, contributing massively to why it is such a versatile, creative, and broad music genre. The motivation behind this project is to develop a thorough level of understanding of these fascinating machines, and to secondly explore possible applications in education that may benefit undergraduates of electrical and electronic engineering.

1.2 Aims and Objectives

This project aims to showcase the large number of fundamental electronic principles that can be applied to analog synthesizer circuitry. Although the project is experimental in nature; the literary review, design process and physical implementation of the synthesizer hopes to provide a proof-of-concept so that a project of similar scope may be used in undergraduate education for Electronic Engineering students.

The main objectives of the project, in terms of physical deliverables, are contained within the essential building blocks of an analog synthesizer:

-Voltage Controlled Oscillator

-Voltage Controlled Filter

-Voltage Controlled Amplifier

-Envelope Generator

-Sequencer

-Power Supply

1.3 Report Structure

Chapter 2 of this report is a literary review exploring possible flaws in modern engineering education, and some possible alternatives. It will also provide an introduction into the analog synthesizer.

Chapter 3 is a detailed explanation of the theory behind analog synthesizers, using circuit analysis.

Chapter 4 provides circuit schematics for the analog synthesizer.

Chapter 5 shows the implementation of the synthesizer and oscilloscope plots.

Chapter 6 is a discussion on the outcomes of the project.

Chapter 7 explores professional, ethical and legal issues.

Chapter 8 concludes the report.

Chapter 2

Background

In the first half of this chapter we will explore possible flaws in modern Engineering education, reasons behind high dropout rates, lack of student motivation, and lastly examine the utilization of project-based learning in Engineering. Following this, an introduction into the analog synthesizer and its key modules.

2.1 Teaching of Electrical and Electronic Engineering

2.1.1 Attrition in Engineering Education

An alarming phenomenon in undergraduate education is the high drop out rate that occurs internationally among all fields of engineering [5], and specifically in electrical/computer engineering [6], [7]. For any university or faculty this is a major concern; there are effects on the internal finances of the faculty, economy, industry demand, and student well-being [8]. Directly solving this issue is a challenging task, and data mining techniques have been implemented in various universities to help predict and identify electrical engineering (EE) students who might be at risk of dropping out, such as in the Netherlands [9], India [10] and Brazil [11]. Factors such as academic performance (pre-undergrad and present), distance from campus, family occupation, age, sex and leave of absences were analysed in these studies [10], [11].

These individual, social and environmental factors [12] are valuable to explore in the topic of engineering attrition, and can aid in the creation of a more equal learning environment [13]. Supporting students who are struggling or at risk of dropping out should be a priority for universities, however to simultaneously thrive towards a better higher education system we must also analyse the teaching methods of the faculties/departments themselves. Evaluating how content is taught in engineering can help identify causes of student dropout relating to subject matter and methodology [6], but secondly improve the field of EE by ensuring graduates are educated to the highest standard, confident in their knowledge, and ready to transition into professional engineering [14].

2.1.2 Project Based Learning

Students who are struggling with engineering degrees often express difficulties with learning the course content, [5], [6], [7], and numerous studies have shown that EE students in particular struggle with electrical circuit modules[6], [15]. Motivation plays a key role in a students overall experience while studying any subject matter, and it is valuable to explore ways that faculties can increase engagement and retention.

Across the field of engineering, there are many theoretical concepts that students often struggle to contextualise and implement in practical applications[16], [17]. Reasons for this can include complex mathematical theory, a disconnect to real-world applications, and a lack of practical projects where these concepts can be applied in an intuitive manner. This is an significant issue to consider in all forms of education, and especially in EE where this mentioned disconnect can be the very prevalent due to the requirements for thorough understanding of theory.

Project based learning using real world applications of electronics topics can help to engage students with the course [15], [18]. We were only able to find three papers relating synthesizer modules to engineering education [19], [20], [21], however all three varied in scope, from digital synthesis using computer software to more concrete circuit analysis.

2.2 An Introduction to the Analog Synthesizer

2.3 Synthesizer Key Modules

Synthesizers can generate a plethora of different sounds, giving the user a huge amount of creative freedom compared to traditional instruments. This versatility would not be possible if not for the various modules that each play an important role in the manipulation of electrical signals.

This section will give an insight into each of these modules.

2.3.1 Voltage Controlled Oscillators

The heart of any synthesizer is the oscillator, which will typically consist of a wave generator core, followed by wave-shaper circuits to convert the signal to common geometric shapes. Otherwise known as the 'sound oscillator', this circuit provides the base periodic signal that will be passed on later to the other modules, such as filters and amplifiers. A common choice might be a sawtooth core, with wave-shapers following to convert into triangle, rectangular pulse and sine waves; which are the most common audio signal shapes used in music synthesis. Although creating a periodic signal, with its frequency controlled by a voltage, might be seen as a trivial task, the need for more complex user control and the importance of stability makes this a more complex instrument than it seems.

An ideal Voltage Controlled Oscillator (VCO) can be characterised by a number of parameters, such a tuning range, sensitivity and power consumption. However, perhaps the most important considerations for a musical VCO is the need for linear tuning and stability[22]. VCOs are commonly used in conjunction with computer software, electronic keyboards, and sequencers, i.e. controllers, which gives rise for the need of a Control Voltage (CV) input to the synthesizer, allowing the pitch to be controlled externally. A common standard for musical synthesizers is the '1 Volt per Octave', whereby a 1 Volt rise in the Control Voltage causes the pitch to rise by a single octave [22]. A musical octave is defined as the interval between two notes which have half or double the frequency of the other[23]; an exponential relationship. Later in the report we will explore how this relationship can be implemented with the use of a BJT matched pair.

2.3.2 Voltage Controlled Filters

Voltage Controlled Filters (VCFs) are used to cut out either high or low frequencies, with the cutoff frequency determining the intensity of the filtering. Often they will include resonance controls, which gives the processed signal ripples near the cut off frequency. Combining this module with an LFO to modulate the cut off frequency can improve the sound dramatically.

2.3.3 Envelope Generator

Envelope generators allow for the manipulation of the Attack, Decay, Sustain and Release of a wave-form, and can be used to modulate the VCO, VCF or VCA. Triggered by the clock oscillator, the ADSR is commonly used to modulate the amplification of the audio wave, controlling how the volume varies over the time period of the note, however can also be used to control the cutoff frequency of the VCF. Although similar to an LFO, the envelope only triggers once when the note is played, whereas an LFO oscillates continuously. Paired with an LFO, it is a powerful tool for modulation.

Chapter 3

Theory

This section will provide a concrete connection between fundamental electronic topics and synthesizer circuitry. Frequently used components and sub-circuits will be explained in context to music synthesis, and key modules in synthesizers will be explored with the aid of conceptual and mathematical circuit analysis.

3.1 Operational Amplifiers

Perhaps the most important component found in any analog synthesizer is the operational amplifier [24]. Essentially a multi stage transistor amplifier, operational amplifiers provide a large gain, high input impedance and low output impedance. These impedance characteristics make it ideal for use as a voltage buffer to prevent undesired loading effects between circuit stages, however it is the use of negative feedback that give the operational amplifier such a large variety of applications. Depending on the configuration of the feedback circuitry, mathematical functions such as add, subtract, differentiate and integrate can be applied in an electrical circuit [24]. The most commonly used configurations in analog music synthesis will be briefly explained in the next subsections.

3.1.1 Unity Gain Buffer

The unity gain buffer, or voltage follower, shown in Figure 3.1 can be found throughout analog synthesizer modules. An op amp in this configuration has the useful characteristic of replicating the input voltage at the output, while preventing any impedance loading between two parts of a circuit.

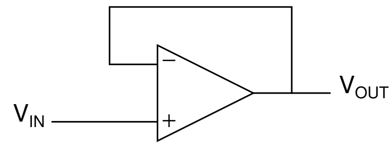

Figure 3.1: Unity gain buffer

$$V_{\text{out}} = A_{OL}(V_{\text{in+}} - V_{\text{in-}})$$
$$V_{\text{out}} = A_{OL}(V_{\text{in+}} - V_{\text{out}})$$
$$V_{\text{out}} = \frac{A_{OL}}{A_{OL}+1}V_{\text{in+}}$$
$$V_{\text{out}} = V_{\text{in+}}$$

Since the open loop gain of the ideal operational amplifier is infinite, we can approximate the output voltage as equal to the input at the non-inverting terminal. Ideal operational amplifiers also have a infinite input impedance $Z_{\text{in}} = \infty$, meaning that no current can flow into the input terminals, and an output impedance of $Z_{\text{in}} = 0$. Although in practise these values cannot be infinite, they are large enough to provide similar characteristics [24]. For example the TL07xx line of operational amplifiers has a typical input impedance of $Z_{\text{in}} = 10\text{M}\Omega$ [25].

Since very little current can flow into the input terminal, the circuit stage before the buffer will not be affected by any impedances at the next stage, keeping the currents stable and preventing signal loss and distortion, which is particularly important in audio processing. However it is important to consider the output current capabilities of the operational amplifier in use; for the TL07xx line, the maximum output current is only 50mA [25]. For general purpose this is typically large enough, but if the operational amplifier is being used within a power supply circuit, additional current sources may have to be added in series with the amplifier to provide enough current, for example with additional transistors or operational amplifiers (power booster) [24].

3.1.2 Inverting and Non-Inverting Operational Amplifiers

The inverting configuration [24] for an operational amplifier (Figure 3.2) introduces a key concept that is the presence of a virtual ground. Since the open loop gain is ideally infinite, and the non inverting terminal is at ground potential, it can be found that:

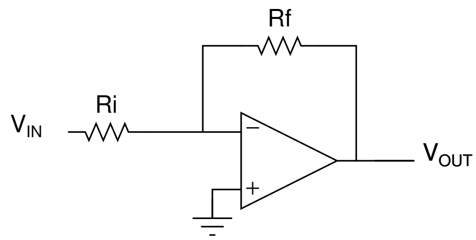

Figure 3.2: Inverting amplifier

$$
\begin{aligned}
A_{OL} = \frac{V_{\text{out}}}{V_{\text{in+}} - V_{\text{in-}}} = \infty \\
\Rightarrow V_{\text{in+}} - V_{\text{in-}} = 0 \\
\Rightarrow V_{\text{in-}} = 0
\end{aligned}
$$

The operational amplifier will output whatever current is necessary to keep the inverting terminal at a virtual ground. Pairing this concept with the large impedance at the input terminals, Ohm's law and Kirchoff's current law (KCL) can be applied easily to find the closed loop gain A_V for any circuit where one of the input terminals is grounded. In regards to the configuration in Figure 3.2, the closed loop gain A_V is:

$$
\begin{aligned}
I_{Ri} &= I_{Rf} \\
\frac{V_{\text{in}} - 0}{Ri} &= \frac{0 - V_{\text{out}}}{Rf} \\
\Rightarrow A_V &= \frac{V_{\text{out}}}{V_{\text{in}}} = -\frac{Rf}{Ri}
\end{aligned} \tag{3.1}
$$

A similar equation can be found for the non-inverting configuration [24], using the same methods.

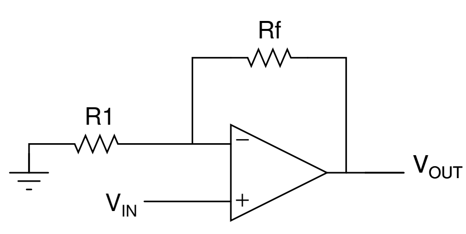

Figure 3.3: Non-inverting amplifier

$$A_V = 1 + \frac{Rf}{R1}$$

3.1.3 Summer

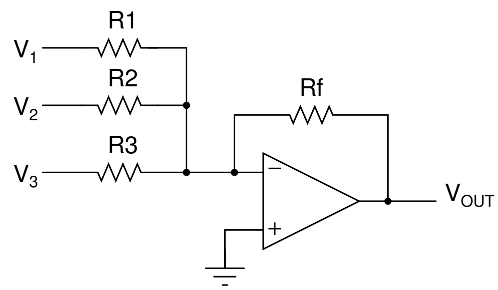

Figure 3.4: Summer amplifier

The summer configuration [24] is widely used in analog synthesis circuitry as a voltage mixer. Figure 3.4 shows a three input summer, however any number of voltages may be added. Assuming the input resistances are equal in value, $R1 = R2 = R3 = R_{in}$:

$$\begin{aligned} V_{\text{out}} &= -Rf\left(\frac{V_1}{R1} + \frac{V_2}{R2} + \frac{V_3}{R3}\right) \\ &= -\frac{Rf}{R_{in}}(V_1 + V_2 + V_3) \end{aligned}$$

To fully grasp the importance of this amplifier configuration in analog synthesizers, one must become associated with the concept of control voltages (CV).

Control Voltages

Control voltages are simply signals that alter the behaviour of a circuit, e.g. a voltage controlled oscillator, by changing certain parameters that the circuit operates upon [22]. For the example of a VCO, an obvious parameter that a user should be able to control is the frequency of oscillation. A simple implementation of this would be a DC voltage that can be varied using a potentiometer, which would then drive the VCO, or perhaps a signal from a controller such as a keyboard (how this voltage interacts with the oscillator, and other modules, will be explored further in the report). However a single control voltage input does not leave much creative freedom for the user, and is unlikely to produce a substantially interesting sound.

Ideally each module of the synthesizer should be controllable by multiple signals. For example, in addition to the 'base' DC voltage set by a keyboard controller, a second input could provide frequency modulation with the use of an external low frequency oscillator (LFO), that is added or subtracted from the base voltage. Another example could be the input from an envelope generator, which modulates the frequency over a specific time period in conjunction with a step sequencer.

To add these control voltages together algebraically, we can use the summer amplifier. Figure 3.4 is possible implementation of a control voltage mixer, although the inputs $V_{1,2,..,n}$ will often be attenuated by potentiometers so the user can vary the amplitude of each signal being fed into the mixer (scaling adder) [24], [22]. For example varying the amplitude of the LFO signal that is being superimposed onto the base voltage from the keyboard.

3.1.4 Integrator

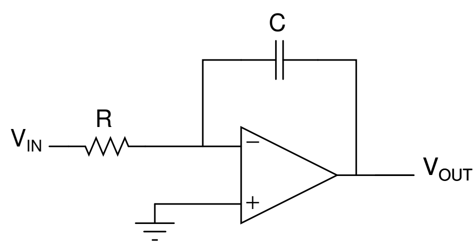

Figure 3.5: Integrator

The basic integrator configuration [24] shown in Figure 3.5 for the operational amplifier can be used to perform mathematical integration of the input voltage. Current through a capacitor is defined by $I_C = C\frac{\mathrm{d}V}{\mathrm{d}t}$, and if we assume the output voltage has a zero value at $t = 0$ we can derive the expression:

$$\begin{aligned}
\frac{V_{\text{in}}}{R} &= -C\frac{\mathrm{d}V_{\text{out}}}{\mathrm{d}t} \\
\int_0^t \frac{V_{\text{in}}}{R}dt &= -CV_{\text{out}} \\
\Rightarrow V_{out} &= -\frac{1}{RC}\int_0^t V_{\text{in}}dt
\end{aligned}$$

Integrators are used for the generation of sawtooth and triangle waveforms in VCOs, but also play a crucial role in the implementation of continuous-time (CT) filters [26], and we will explore this topic further when we discuss state variable filters.

3.2 Exponential Converters

3.2.1 Pitch

Voltage controlled oscillators are primarily characterised by their relationship between tuning voltage and frequency of the waveform. Although a linear relationship might seem desirable, designers of analog synthesizers must take into account how musical pitch is perceived by humans. Pitch is a subjective perception of a audible frequency, and similar to audible volume, this perception is measured with a logarithmic or exponential relationship. A musical octave is described as the unique distance between two notes where one note has a frequency that is double the frequency of the other [23]. To a human this corresponds to perceived pitch that has increased while still maintaining the same musical identity. If we take a base frequency of f_0, we can find the frequency that is one octave higher f_1 through the relationship:

$$f_1 = 2^n f_0$$

In its active mode, the bipolar junction transistor displays a linear voltage-current relationship, however, while in the saturation region an exponential curve is produced (Figure 3.6). This sharp rise in current is commonly utilized in digital switching and binary operations, but is particularly useful in analog synthesizers to produce exponential relationships. We can base a circuit around the BJT and use its saturation region as a conversion between linear voltage and exponential current [22]. These can be used to drive modules such as VCOs and VCAs, where a logarithmic relationship between control voltage and behaviour such as frequency and amplitude is preferable.

3.2.2 BJT Voltage to Exponential Current Converter

The exponential relationship in the saturation region is approximated by the Ebers-Moll model,

$$I_C \approx I_S \left(e^{\frac{V_{BE}}{V_T}} - 1 \right)$$

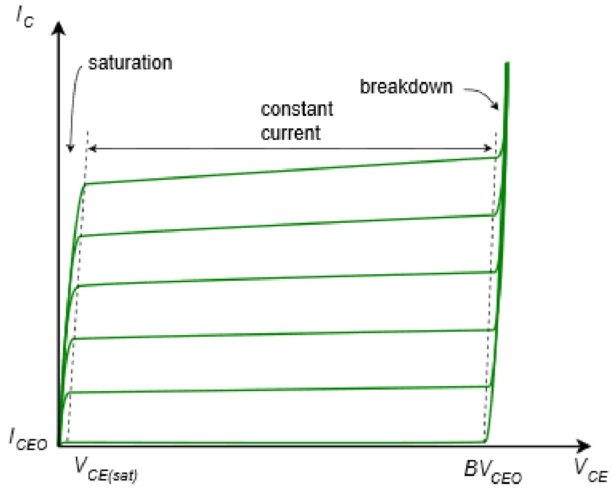

Figure 3.6: BJT collector curves [1]

where I_C is the collector current, I_S is the drift/saturation current, V_{BE} is the base-emitter voltage, and V_T is the thermal voltage. The saturation current I_S due to the drifting of minority carriers is negligible when $I_C >> I_S$, so we can approximate the model further to:

$$I_C \approx I_S \left(e^{\frac{V_{BE}}{V_T}} \right)$$

With the goal of making a stable oscillator in mind, the temperature dependency of I_C is not desirable. Furthermore I_S can vary massively with temperature [27], so a single BJT as a exponential converter will not suffice. These issues can be mitigated substantially with the application of a matched BJT pair [22], [27], [28], which will conveniently neglect I_S from the collector current gain.

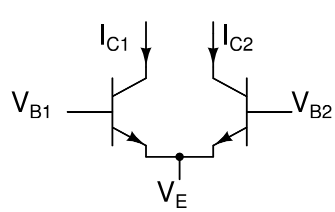

Figure 3.7: NPN BJT differential pair

The matched pair of BJTs in Figure 3.7 share an emitter node, $V_{E1} = V_{E2} = V_E$. We can formulate two equations for the emitter voltage V_E with respect to each BJT from the simplified Ebers-Moll model:

$$
\begin{aligned}
I_{S1}\left(e^{\frac{V_{BE_1}}{V_{T1}}}\right) &= I_{C1} \\
e^{\frac{V_{B1}-V_E}{V_{T1}}} &= \frac{I_{C1}}{I_{S1}} \\
\frac{V_{B1}-V_E}{V_{T1}} &= \ln(I_{C1}) - \ln(I_{S1}) \\
V_E &= V_{B1} - V_{T1}\left(\ln(I_{C1}) - \ln(I_S)\right)
\end{aligned}
$$

Assuming we have ideally matched transistors, i.e. they have identical saturation currents and are thermally coupled such that $V_{T1} = V_{T2}$, we can write:

$$V_E = V_{B1} - V_T\left(\ln(I_{C1}) - \ln(I_S)\right) \tag{3.2}$$

$$V_E = V_{B2} - V_T\left(\ln(I_{C2}) - \ln(I_S)\right) \tag{3.3}$$

$$
\begin{aligned}
\Rightarrow V_{B1} - V_T\left(\ln(I_{C1}) - \ln(I_S)\right) &= V_{B2} - V_T\left(\ln(I_{C2}) - \ln(I_S)\right) \\
V_T\left(\ln(I_{C2}) - ln(I_{C1})\right) &= V_{B2} - V_{B1} \\
\ln\left(\frac{I_{C2}}{I_{C1}}\right) &= \frac{V_{B2}-V_{B1}}{V_T} \\
\frac{I_{C2}}{I_{C1}} &= e^{\left(\frac{V_{B2}-V_{B1}}{V_T}\right)}
\end{aligned}
$$

$$\Rightarrow I_{C2} = I_{C1} \cdot e^{\left(\frac{V_{B2}-V_{B1}}{V_T}\right)} \tag{3.4}$$

Due to this ideal matching, the effect of I_S on the collector currents has been removed. To simplify the relationship between I_{C1} and I_{C2} further, we can ground one of the BJT base terminals. Although it may seem counter-intuitive to introduce a negative sign into the equation, it is convenient to ground V_{B2} to cancel out the inverting characteristic of the control voltage mixer (Figure 3.4). If we take I_{C1} to be the reference voltage, I_{REF} [22], [27], [28], and hold it at a constant value, the only changeable variable left in the equation is V_{B1}, which will be our control input for whatever the exponential converter is driving.

$$I_{C2} = I_{\text{REF}} \cdot e^{\left(\frac{-V_{B1}}{V_T}\right)}$$

A reference current may be implemented with the use of a voltage source in series with a current limiting resistor. $I_{\text{REF}} = \frac{V_{\text{REF}} - V_{C1}}{R_{\text{REF}}}$

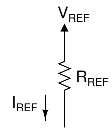

Figure 3.8: Simple reference current

To increase the stability of the reference current, an operational amplifier in an inverting configuration (Figure 3.2) can be used to hold the node V_{C1} at $0V$, due to the principle of virtual ground [27], [28]. We now have an exponential converter.

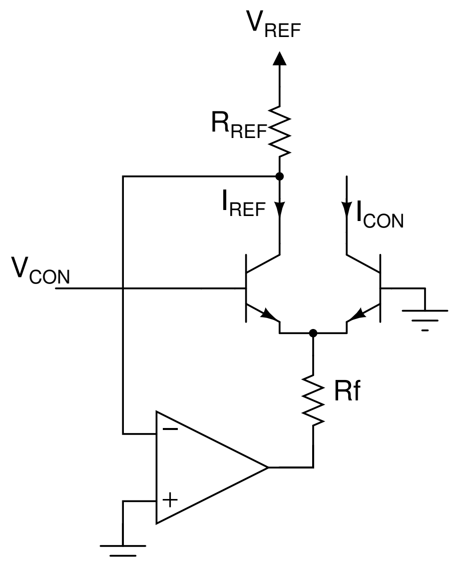

Figure 3.9: Voltage to exponential current converter

$$I_{\text{CON}} = I_{\text{REF}} \cdot e^{\left(\frac{-V_{\text{CON}}}{V_T}\right)}$$

It is important to note that the control current I_{CON} produced flows away from the module it is connected to. This is a current sink [22]. A current source can be produced in a similar fashion with PNP transistors and some polarity changes.

3.3 Voltage Controlled Oscillators

Exponential converters are most often used to control either VCOs or VCAs. This section will cover one of the possible designs for a sawtooth wave generator.

Following the exponential converter, it is common to see a operational amplifier in the integration configuration [22], [29]. As previously discussed, the integrator has a negative IO relationship, $V_{out} = -\frac{1}{RC}\int_0^t V_{\text{in}}dt$, so a current sink using NPN transistors is typically used for control. Although the integrator outputs the mathematical integral of the input voltage, Ohm's law tells us that current is proportional to voltage, $V = IR$. Therefore the control current $-I_{\text{CON}}$ flowing *into* the integrator will produce a proportional positive voltage.

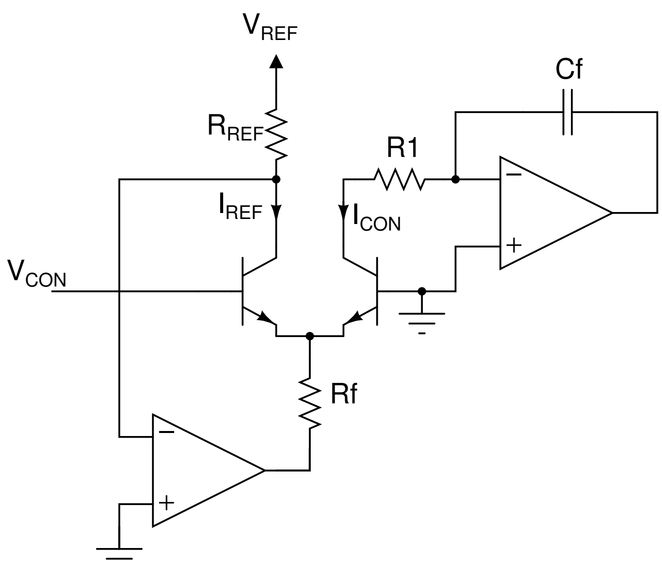

Figure 3.10: Exponential converter driving an integrator

Assuming we have a constant control current, the integrator will output a rising linear voltage over time, with its slope proportional to the time constant RC. To achieve a sawtooth wave, which has a rising edge and sharp decrease (Figure 3.11), the integrator needs to be reset when the desired maximum voltage has been reached. The frequency is determined by the time constant RC, so it is up to the circuit designer to choose a capacitor value Cf that will produce appropriate frequencies with respect to the control current I_{CON}.

In this configuration, it is typical to see designers use a JFET to reset the integrator [22], [29],

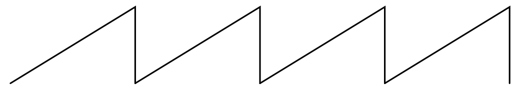

Figure 3.11: Sawtooth wave

however it is also possible to use schmitt triggers [30], [31] as a reset.

A schmitt trigger is a comparator [24] with hysteresis, which compares the signal at its input terminal with two threshold voltages, V_{T+} and V_{T-}. In comparison to a regular comparator, a schmitt trigger switches the current threshold voltage depending on the current state of the output. This helps to oppose noise and small fluctuations in the input signal around the thresholds, so are often used in digital logic circuits to reduce errors [30].

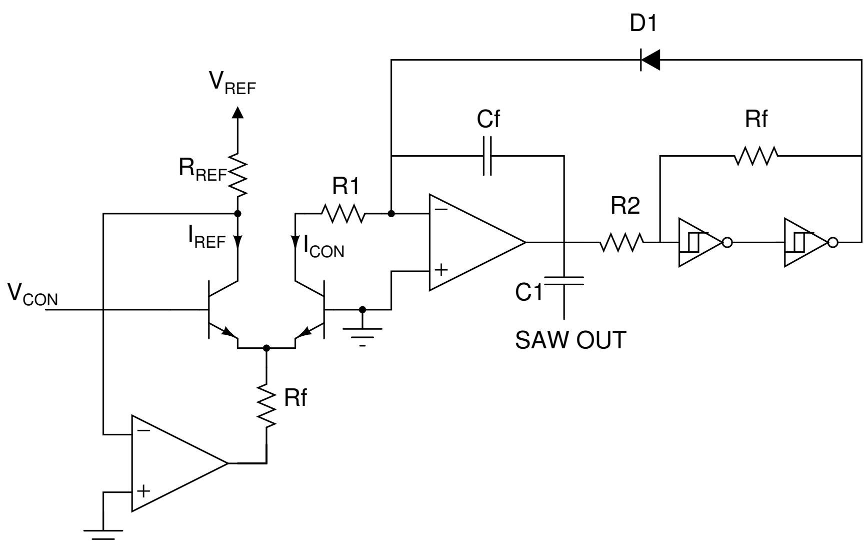

Figure 3.12: Sawtooth generator

Figure 3.12 shows an integrator with a schmitt trigger reset [31]. The feedback resistor network $R2, Rf$ set the threshold voltages of the schmitt triggers, and the diode is used to reset the integrator.

While the output of the integrator is below the threshold voltage V_{T+}, the first inverter will be HIGH, setting the second LOW. The diode will see a $0V$ at its anode, so will be reverse biased and no current can flow back into the inverting terminal of the operational amplifier, continuing the integration. Once the output surpasses the threshold voltage, inverter 1 will go LOW, settings inverter 2 HIGH. This forward biases the diode, increasing the voltage momentarily at the inverting input of the integrator. Due to the virtual ground at the inverting terminal, the integrator will respond to the increased voltage by decreasing its output voltage, resetting the integrator. The output falls below the lower threshold voltage V_{T-}, the diode falls back into reverse bias mode, and the integration can continue once more.

The selection of resistor values $R2, Rf$ in the feedback loop will determine the peak voltage of the integrator, and therefore the amplitude of the sawtooth wave. Capacitor C1 acts as a coupler to demove the DC bias and centre the wave around zero volts, which is preferable for an audio waveform [22].

Figure 3.13 shows the full schematic of a sawtooth wave VCO with multiple control voltage inputs.

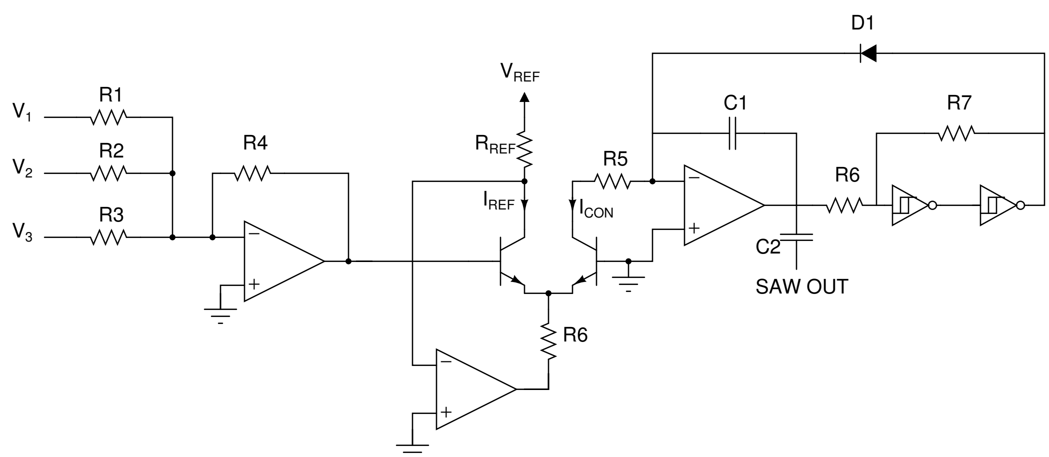

Figure 3.13: Sawtooth VCO

3.4 Operational Transconductance Amplifiers

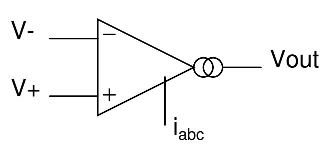

Figure 3.14: Operational transconductance amplifier

An operational transconductance amplifier (OTA) can be interpreted as a voltage controlled current source [32], [33]. It has a similar characteristics to a standard operational amplifier, with high input impedances and a differential input voltage, however it has an additional input terminal for a bias current I_{abc} (amplifier bias current), giving the output as a current [22]. The relationship between output current and differential input voltage is given by [33], [34]

$$I_{\text{out}} = g_m(V_{\text{in+}} - V_{\text{in-}})$$

where g_m is the transconductance gain of the amplifier, and is proportional to the bias current I_{abc} and the thermal voltage V_T [34], $g_m = \frac{i_{abc}}{2V_T}$. Assuming a thermal voltage of $V_T \approx 26mV$ (room temperature), and that V_{in-} is grounded, the IO characteristic of the OTA can be simplified to:

$$\begin{aligned} I_{\text{out}} &= \frac{i_{abc}}{2V_T}(V_{in+-0}) \\ &= \frac{i_{abc}}{2 \cdot 26\text{mV}}(V_{in+}) \\ &= 19.2 \cdot i_{abc} \cdot V_{in+} \qquad [22] \end{aligned}$$

3.5 Voltage Controlled Amplifiers

A straightforward application of the operational transconductance amplifier is as a voltage controlled amplifier. Since the output current of an OTA is proportional bias current I_{abc}, it can be used as a control current. A single resistor at the output of the OTA can convert the current back into a voltage [22]. OTAs are primarily built with BJTs [34], so the small signal condition for BJT differential amplifiers must be taken into account. If the inverting terminal is grounded, the input signal must be attenuated to a low enough voltage to keep the OTA in its linear region of operation.

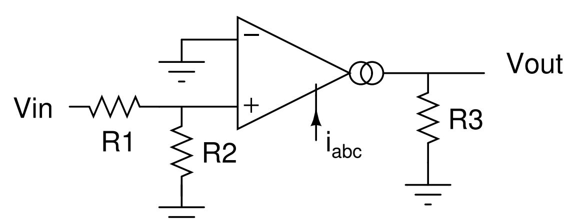

Figure 3.15: OTA as a current controlled voltage amplifier

In practise it is useful to add a voltage buffer after the amplification to prevent impedance loading. Therefore the resistor is often placed in the feedback loop of a buffer circuit.

To control the VCA, a current source is required. Although an logarithmic converter similar to the exponential converter would be ideal, a simple solution is a linear voltage to current source using an operational amplifier as a voltage mixer and a BJT for the output current.

3.6 Active Filters

3.6.1 Single Pole Filters

A low pass RC filter consists of a single resistor and capacitor in series. This essentially forms a voltage divider with the reactance of the capacitor, given by $X_C = \frac{1}{2\pi Cf}$. This implies that as the input frequency increases, the capacitive reactance decreases, decreasing the voltage seen across the capacitor, attenuating high frequency signals.

The transfer function of a first order filter is given as $H(s) = \frac{w_c}{s+w_c}$ [35]. This filter has a single pole, which is where the transfer function tends to infinity. Filters with a single pole have poor roll off curves, and lack interesting qualities such as resonance [36], so they are not commonly used in analog synthesizer filters.

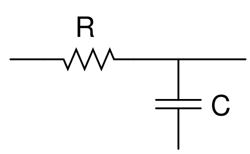

Figure 3.16: Single pole RC filter

An active low pass filter can be built using an active component such as an operational amplifier [35]. The RC network can be connected in the feedback loop of an operational amplifier, increasing its gain and attenuation.

3.6.2 Characteristics of Second Order Active Filters

A second order low pass filter is built using a cascade of two first order filters. The general form transfer function of a second order filter is:

$$H(s) = \frac{1}{s^2 + (\frac{w_n}{Q})s + w_n^2} \qquad [36]$$

where w_n is the natural frequency, and Q is the quality factor associated with the filter.

To understand the behaviour of second order active low pass filters, it is valuable to explore how the poles and quality factor of the network interact with the frequency response [36]. Although the quality factor Q is most often used to quantify the attenuation roll off over a specific bandwidth for a bandpass filter, it also has an impact on the characteristics of a low pass filter.

The poles of an active filter provide a strong indication of its behaviour [36]. In the context of analog synthesizer filters, the condition for complex poles is by far the most interesting. Applying the quadratic formula to the denominator of $H(s)$, we can find the condition for complex poles.

$$s = \frac{w_n}{2}\left(-\frac{1}{Q} \pm \sqrt{\left(\frac{1}{Q}\right)^2 - 4}\right)$$

$$\left(\frac{1}{Q}\right)^2 - 4 < 0$$

$$\Rightarrow \text{For complex poles:} \quad Q > \frac{1}{2}$$

Although a detailed explanation of the full impact of pole locations is beyond the scope of this report, we should take note of the filters response in the context of complex poles. If the Q factor is increased beyond $\frac{1}{2}$ and the poles enter the imaginary plane, the filter is under-damped and we will see oscillations in the time domain [37], [38]. Furthermore, if the Q factor is increased beyond $\frac{1}{\sqrt{2}}$ (butterworth filter), resonant peaks start to appear in the frequency domain [37], [38], [36], with the distance of the peak relative to the cut off frequency decreasing as Q is increased further.

In typical applications, increasing the quality factor Q is a tradeoff between better roll-off attenuation, and increased distortion closer to the cut off frequency. However, in the context of analog synthesizer filters, resonance and self oscillations are desired effects, and is one of the key staples of the acid house and techno. Thus, designing a filter with resonance controls is a common practise in music synthesis.

3.6.3 State Variable Filters

A state variable filter is built using a cascade of second order filters, and allows for the implementation of all three filter types, low-pass, high-pass and bandpass [39]. It can be formulated from the general form of a second order filter.

$$\frac{Y(s)}{X(s)} = H(s) = \frac{1}{s^2 + (\frac{w_n}{Q})s + w_n^2}$$
$$\Rightarrow \ddot{y(t)} = x(t) - \frac{w_n}{Q}\dot{y(t)} - w_n^2 y(t) \qquad [2]$$

The second derivative $\ddot{y(t)}$ corresponds to the transfer function of a high pass filter, $H_{HP}(s) = \frac{s^2}{s^2+(\frac{w_n}{Q})s+w_n^2}$. The first derivative $\frac{w_n}{Q}\dot{y(t)}$ corresponds to a bandpass filter, $H_{BP}(s) = \frac{\frac{w_n}{Q}s}{s^2+(\frac{w_n}{Q})s+w_n^2}$, and the last term, $w_n^2 y(t)$ to a low pass filter, $H_{LP}(s) = \frac{w_n^2}{s^2+(\frac{w_n}{Q})s+w_n^2}$.

A cascade of integrators can be used to represent this second order transfer function [2], [39]. Starting with the second derivative $\ddot{y(t)}$, an integrator block can be used to calculate the first derivative, and so on. The gains w_n^2 and $\frac{w_n}{Q}$ can be implemented using amplifiers, and lastly the subtraction will be achieved with a summer amplifier. Each filter type can be taken as the output signal at the corresponding stage of the cascade. [2]

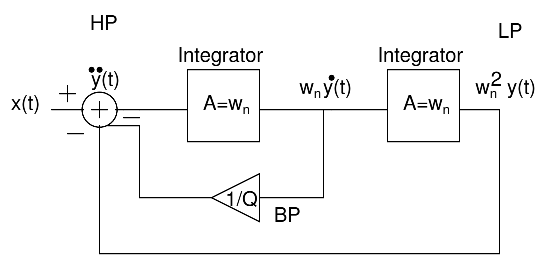

Figure 3.17: Mathematical representation of a state variable filter [2]

Chapter 4

Circuit Schematics

4.1 Voltage Controlled Oscillator

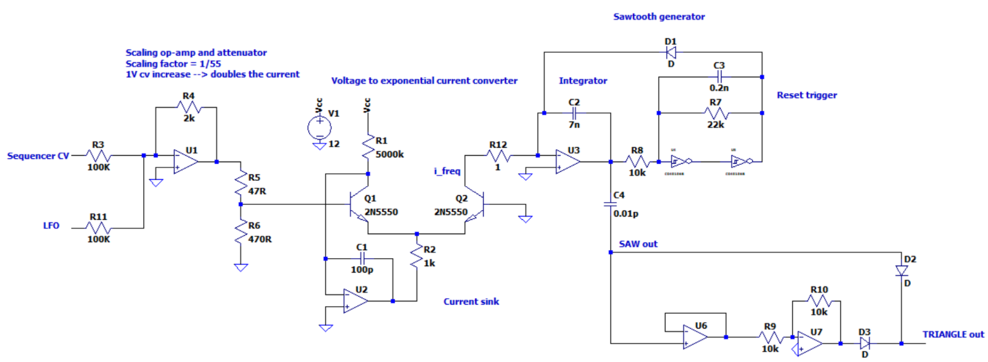

Figure 4.1: VCO schematic

Figure 4.1 shows the complete schematic for the VCO module, with two CV inputs and a sawtooth and triangle wave output. Operational amplifiers used were the TL074 [25].

Referring back to Figure 3.13, we must first calculate the change in base voltage V_{B1} that will cause a doubling of the control current, with respect to a 1 Volt per octave standard. This has been widely covered in existing literative [22], [27], [28], concluding that an 18mV increase in base voltage causes the control current to double, so a scaling factor of $\frac{1}{55}$ is required to convert the control voltage into a useable voltage.

To attenuate the control voltages at a scale of $\frac{1}{55}$, input resistors were chosen at $R = 100\text{k}\Omega$, with a feedback resistor of $Rf = 2\text{k}\Omega$. Therefore the gain of the summing amplifier is $A = \frac{2k}{100k} = \frac{1}{50}$.

The following voltage divider further attenuates the signal to $\frac{1}{55}$.

The capacitor values and feedback resistors in the integrator sub section were chosen to achieve a frequency of middle C at half the control voltage (6V), and to have a maximum peak voltage of 5V before AC coupling.

4.2 Voltage Controlled Filter

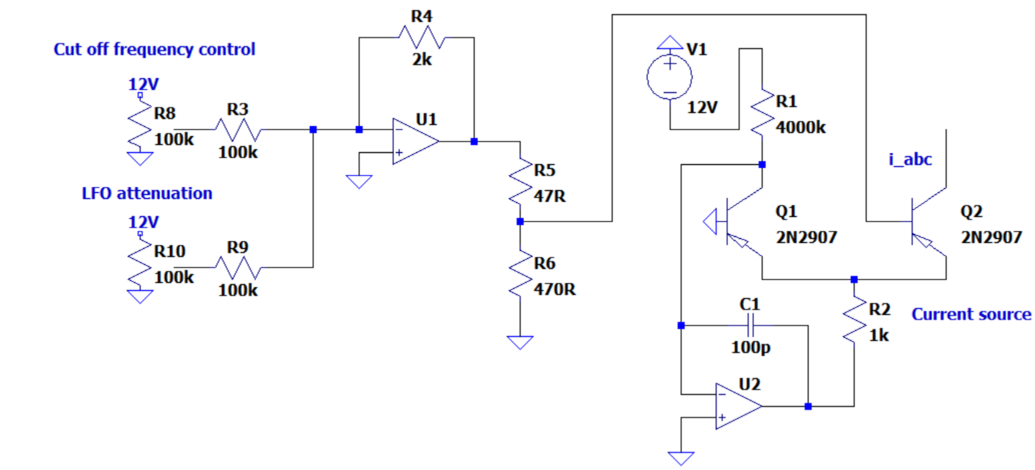

Figure 4.2: VCF exponential converter schematic

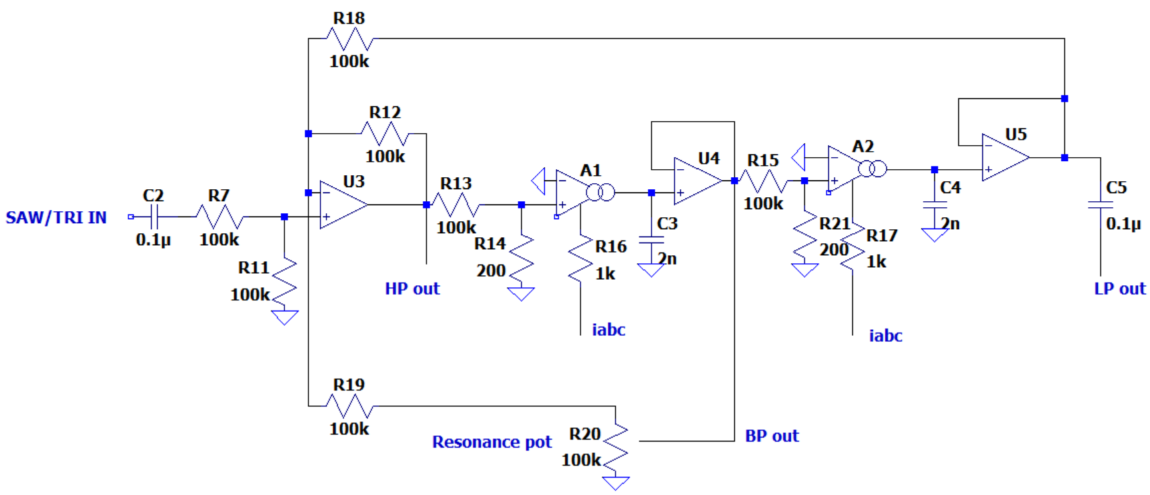

Figure 4.3: State variable VCF schematic [3]

4.3 Sequencer

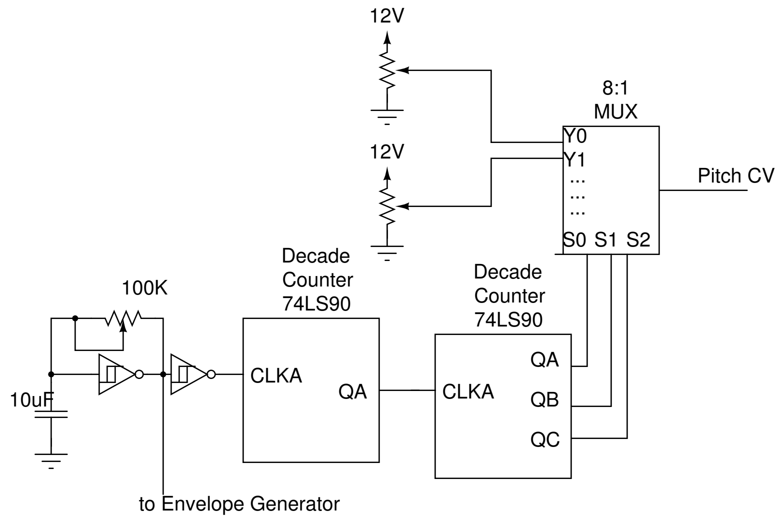

Figure 4.4: Sequencer schematic

Figure 4.4 shows the design of the sequencer. A relaxation oscillator produces a square wave with variable tempo from a potentionmeter. It is then passed through an inverter and into a decade counter in a divide by two configuration. Once again the signal is fed into a decade counter, and the outputs QA,QB,QC count up in binary at each step. The binary outputs are used to control a multiplexer, the 4051, which acts as an analog switch. Control voltages, set by potentiometers, are sequentially passed through the multiplexer depending on the step time. For simplicity only two potentiometers have been shown on the schematic.

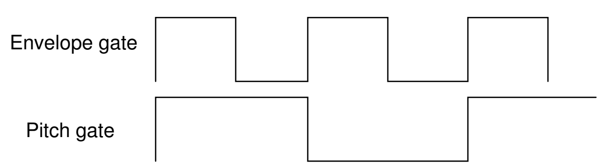

Figure 4.5: Sequencer clock vs envelope gate

The signal is initially passed through a divide by two decade counter so that the step time is double the signal sent to the envelope generator. We want to trigger the envelope at the start of each note, and begin the release while the note is still playing. This gives the envelope generator time to complete its cycle.

4.4 Envelope Generator

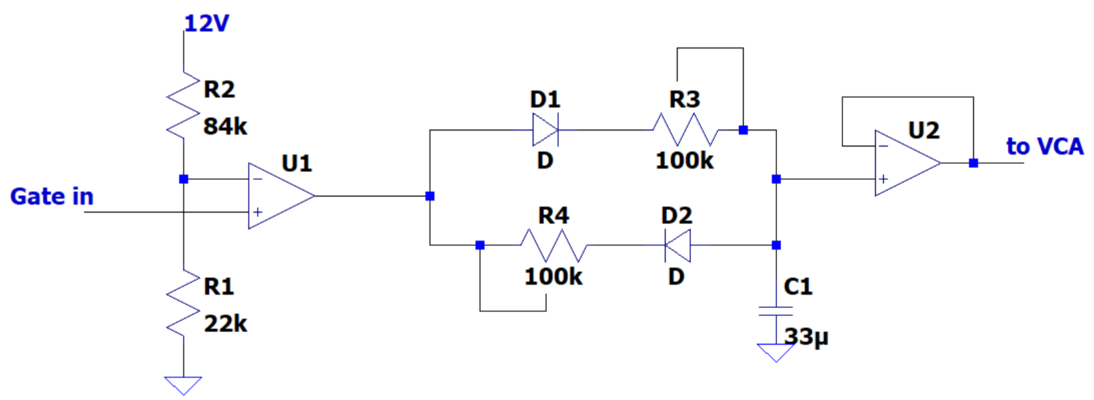

Figure 4.6: Envelope Generator schematic [4]

The comparator U1 compares the gate signal to its negative terminal. The threshold has been set at approximately half the amplitude of the gate to avoid switching due to noise. Once the comparator is triggered, the diode D1 conducts and charges up the capacitor C1 through the 'Attack' potentiometer R3. This will cause a rise in control voltage. Once the gate goes LOW, the comparator will output a LOW signal, causing the capacitor to discharge through D2 and the 'Release potentiometer'. This control signal will then get sent to the VCA.

4.5 Voltage Controlled Amplifier

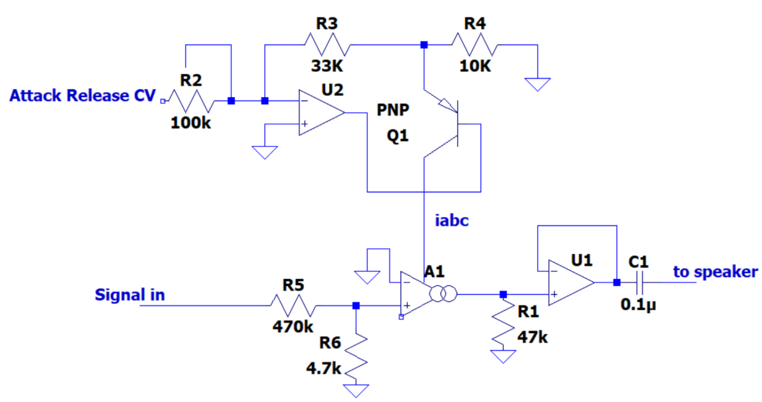

Figure 4.7: VCA schematic

4.6 LFO

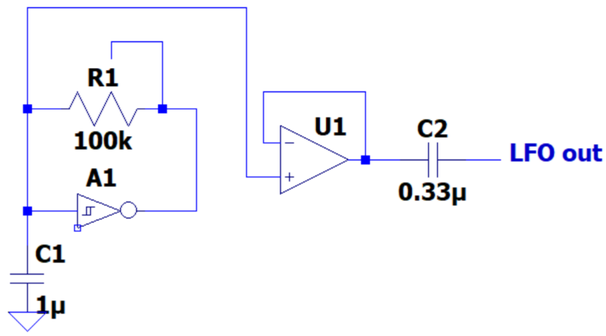

Figure 4.8: LFO (x2) schematic

Chapter 5

Implementation

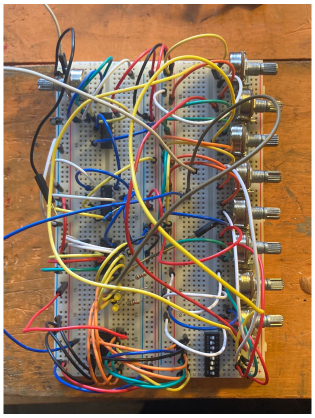

Figure 5.1: Sequencer circuit

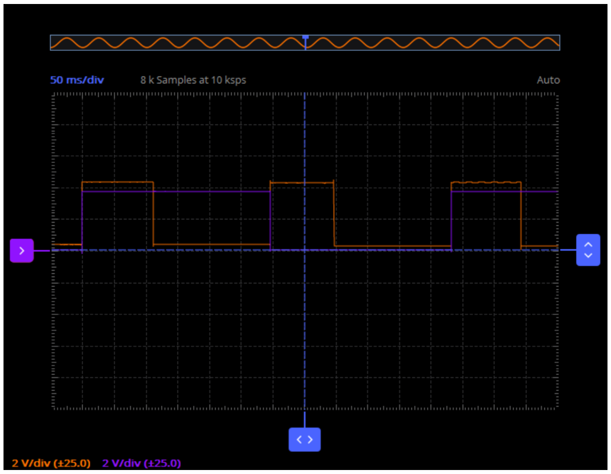

Figure 5.2: Envelope gate vs Pitch control gate

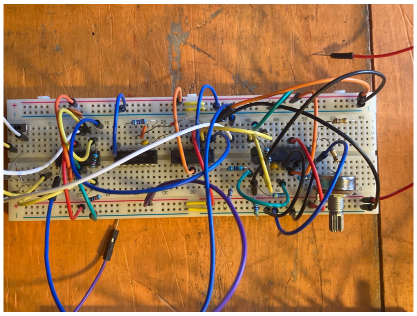

Figure 5.3: VCO circuit

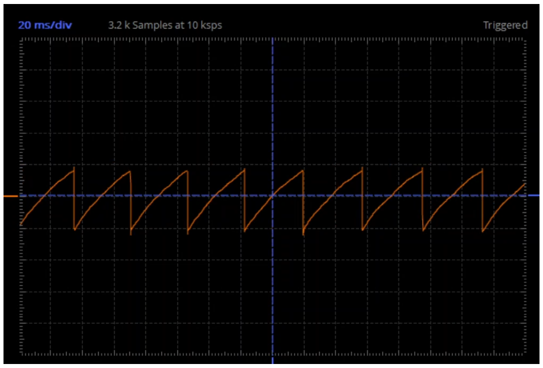

Figure 5.4: Saw wave generator

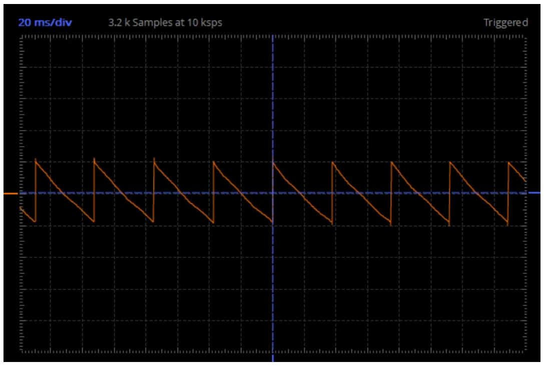

Figure 5.5: Reverse saw wave generator

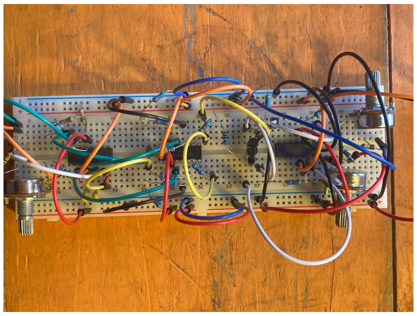

Figure 5.6: VCF circuit

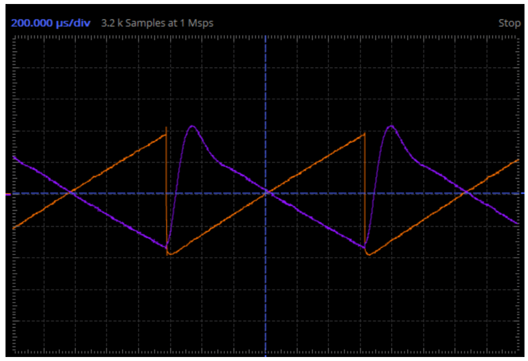

Figure 5.7: Filtering of sawtooth wave

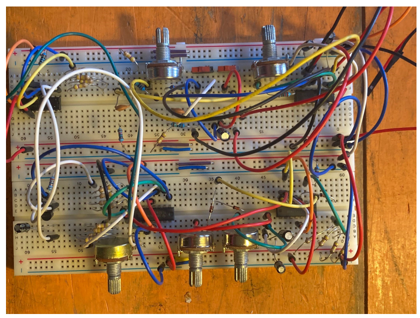

Figure 5.8: VCA, AR and LFO circuit

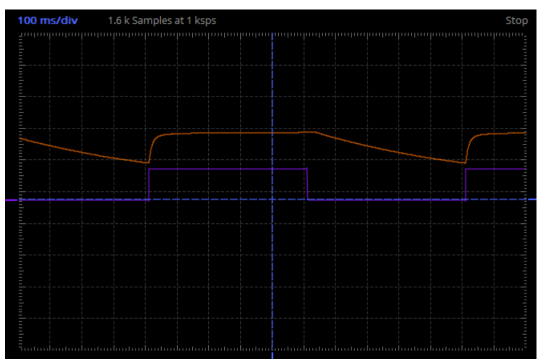

Figure 5.9: AR envelope over a step

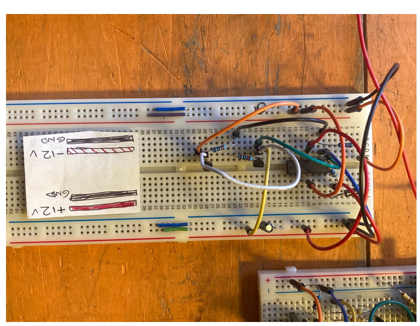

Figure 5.10: Power circuit

Chapter 6

Discussion

This report has covered the main building blocks of the analog synthesizer, namely the VCO, VCF, VCA, envelope generators and sequencers. We will briefly discuss common themes in the circuitry and relate them to key concepts in electronic engineering.

6.0.1 Operational Amplifiers

A component found in every module of the synthesizer is the operational amplifier. Different configurations are utilized throughout, such as the voltage follower, summer, subtracter and integrator. Implementing operational amplifiers effectively in the synthesizer may help to reinforce key concepts such as virtual ground, input impedances and negative feedback, and introduce intuitive and practical applications for these configurations.

6.0.2 Transistors

Creating current sources and sinks are required in analog synthesizer design. Although modules such as the VCO and VCA have control voltage inputs, in reality it is a current source that drives the modules. Synthesizer circuits such as the exponential converter require an understanding of the BJT matched differential pair, their VI characteristics, regions of operation, and small signal conditions.

6.0.3 Filter Design

This report only briefly touched upon the design of analog filters,

In contrast to filter applications in industries such as telecommunications, the analog synthesizer provides a

Chapter 7

Legal, Social, Ethical and Professional Issues

7.0.1 Intellectual Property

Throughout the research and development of this analog synthesizer, we have been careful to note down and save all references relating to intellectual property, notably circuit designs. Although the aim of this project is explore the topic of analog synthesizers and their applications in education, and not to publish or commercialise any design, it was paramount to give credit to all designers where possible. Difficult mathematical derivations have also been cited where possible, to ensure this report remains at a professional standard.

7.0.2 Environmental Impact

To reduce the environment impact of the synthesizer, each module was built and simulated on LTSpice, a circuit simulation software, before any components were ordered. This not only ensured the functionality of the synthesizer, but allowed for more careful component selection and less waste from unused electronics. Thorough simulation of each module meant that alternative designs with less components could be tested, and could be analysed with respect to their power consumption.

7.0.3 Safety and Compliance

The rigorous testing and simulation of the circuits helped minimise risk of any safety issues that may have occurred in the building of the synthesizer. Potential short circuits could be identified in the simulations, and currents analysed to ensure there were no surges. While building, special attention was given to the power supply circuit, and the Ampere reading on the DC bench supply was always kept in full view in case of a current surge.

Chapter 8

Conclusion and Future Work

This project has successfully explored each key module of the synthesizer in detail, and has aided in the understanding of how analog synthesizers function in great detail. It has inspired a deeper passion for music and especially music production. The filter in particular was very rewarding to work on and implement.

Future work on this topic could include the implementation of an experimental module in a university where one of the key modules of the analog synthesizer is taught, and topics such as operational amplifiers and analog filters reinforced. Feedback from students on why they find circuit analysis difficult and motivating could provide further insights and help to structure a course around analog synthesizers that is engaging, motivating and inspires creativity and teamwork amongst young engineers.

References

[1] J. M. Fiore. Bjt collector curves. [Online]. Available: https://eng.libretexts.org/Bookshelves/Electrical_Engineering/Electronics/Semiconductor_Devices_-_Theory_and_Application_(Fiore)/04%3A_Bipolar_Junction_Transistors_(BJTs)/4.3%3A_BJT_Collector_Curves

[2] Ece4450 l24: State variable filters and the oberheim sem vcf (analog circuits for music synthesis). Aaron D. Lanterman, Georgia Institute of Tehnology. [Online]. Available: https://www.youtube.com/watch?v=jAokGV71MEw&list=PLOunECWxELQS5bMdWo9VhmZtsCjhjYNcV&index=29

[3] Oberheim sem s1. Oberheim. [Online]. Available: https://synthfool.com/docs/Oberheim/Oberheim_SEM1A/Oberheim_SEM_1A_Schematics.pdf

[4] Envelope circuits: a simple ar design using op amps. Synthnerd. [Online]. Available: https://synthnerd.wordpress.com/2016/04/06/envelope-circuits-a-simple-ar-design-using-op-amps/

[5] J. R. Casanova, R. Vasconcelos, A. B. Bernardo, and L. S. Almeida, "University dropout in engineering: motives and student trajectories," 2021.

[6] Q. Kabashi, I. Shabani, and N. Caka, "Analysis of the student dropout rate at the faculty of electrical and computer engineering of the university of prishtina, kosovo, from 2001 to 2015," *IEEE Access*, vol. 10, pp. 68 126–68 137, 2022.

[7] A. Tayebi, J. Gómez, and C. Delgado, "Analysis on the lack of motivation and dropout in engineering students in spain," *IEEE Access*, vol. 9, pp. 66 253–66 265, 2021.

[8] C. Stăiculescu and R. N. E. Ramona, "University dropout. causes and solution," *Mental Health: Global Challenges Journal*, vol. 1, no. 1, pp. 71–75, 2018.

[9] G. W. Dekker, M. Pechenizkiy, and J. M. Vleeshouwers, "Predicting students drop out: A case study," pp. 41–50, 2009.

[10] S. Pal, "Mining educational data to reduce dropout rates of engineering students," *International Journal of Information Engineering and Electronic Business*, vol. 4, no. 2, p. 1, 2012.

[11] R. da Fonseca Silveira, M. Holanda, M. de Carvalho Victorino, and M. Ladeira, "Educational data mining: Analysis of drop out of engineering majors at the unb-brazil," pp. 259–262, 2019.

[12] M. Meyer and S. Marx, "Engineering dropouts: A qualitative examination of why undergraduates leave engineering," *Journal of engineering education*, vol. 103, no. 4, pp. 525–548, 2014.

[13] S. Secules, A. Gupta, A. Elby, and C. Turpen, "Zooming out from the struggling individual student: An account of the cultural construction of engineering ability in an undergraduate programming class," *Journal of Engineering Education*, vol. 107, no. 1, pp. 56–86, 2018.

[14] C. S. Nair, A. Patil, and P. Mertova, *Enhancing learning and teaching through student feedback in engineering.* Elsevier, 2012.

[15] A. Gero, Y. Stav, and N. Yamin, "Increasing motivation of engineering students: Combining "real-world"examples in a basic electric circuits course," *International Journal of Engineering Education*, vol. 32, no. 6, pp. 2460–2469, 2016.

[16] E. Tempelman and A. Pilot, "Strengthening the link between theory and practice in teaching design engineering: an empirical study on a new approach," *International journal of technology and design education*, vol. 21, pp. 261–275, 2011.

[17] F. Sadikoglu and D. Ibrahim, "Teaching signals and systems at undergraduate level," *Procedia computer science*, vol. 120, pp. 812–819, 2017.

[18] Z. Zhang, C. T. Hansen, and M. A. Andersen, "Teaching power electronics with a design-oriented, project-based learning method at the technical university of denmark," *IEEE Transactions on Education*, vol. 59, no. 1, pp. 32–38, 2015.

[19] S. Billis, N. Anid, and S. Giordano, "Work in progress—music synthesizers: A tool in engineering education," pp. S3E–1, 2011.

[20] M. Tarragona, F. Davoine, and G. Eirea, “The synthesizer: a versatile active learning tool for electrical engineering,” *12th. Active Learning in Engineering, Caxias do Sul, Brasil, ALE 2014.*, 2014.

[21] J. Marpaung, L. Johnson, S. Sohoni, and S. Lakkakula, “Music synthesizer for digital logic design course,” pp. 76–79, 2011.

[22] H. Chamberlin, *Musical applications of microprocessors.* Sams, 1980.

[23] Octave. Wikipedia. [Online]. Available: https://en.wikipedia.org/wiki/Octave

[24] B. Carter, T. R. Brown *et al.*, *Handbook of operational amplifier applications.* Texas Instruments Dallas, TX, 2001, vol. 9.

[25] Tl07xx operational amplifier datasheet. Texas Instruments Dallas, TX. [Online]. Available: https://www.ti.com/lit/ds/symlink/tl074.pdf?ts=1712742464782&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FTL074%253FCMP%253Dconv-poasamples

[26] D. V. Kamath, “Overview of opamp and ota based integrators,” *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering (IJIREEICE)*, vol. 3, no. 9, pp. 74–81, 2015.

[27] Synth theory. Xonik. [Online]. Available: https://www.xonik.no/

[28] A tutorial on exponential convertors and temperature compensation. René Schmitz. [Online]. Available: https://www.schmitzbits.de/expo_tutorial/index.html

[29] Sawtooth vco. Ian Fritz. [Online]. Available: https://electro-music.com/wiki/pmwiki.php?n=Schematics.SawtoothVCOByIanFritz

[30] Understanding schmitt triggers. Texas Instruments Dallas, TX. [Online]. Available: https://www.ti.com/lit/ab/scea046a/scea046a.pdf?ts=1712806913755&ref_url=https%253A%252F%252Fduckduckgo.com%252F

[31] Cmos vco. René Schmitz. [Online]. Available: https://www.schmitzbits.de/vco4069.html

[32] Demystifying the operational transconductance amplifier. Texas Instruments Dallas, TX. [Online]. Available: https://www.ti.com/lit/an/sboa117a/sboa117a.pdf?ts=1712736740854&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FOPA861%253Futm_source%253Dgoogle%2526utm_medium%253Dcpc%2526utm_campaign%253Dasc-null-null-GPN_EN-cpc-pf-google-eu%

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[33] A. Gratz, "Operational transconductance amplifiers," *Synth stromeko*, 2005.

[34] R. L. Geiger and E. Sanchez-Sinencio, "Active filter design using operational transconductance amplifiers: A tutorial," *IEEE circuits and devices magazine*, vol. 1, no. 2, pp. 20–32, 1985.

[35] Active filter design techniques. Texas Instruments Dallas, TX. [Online]. Available: https://web.ece.ucsb.edu/~ilan/Classes/ECE2A_F2010/Tutorials/App%20notes/sloa088.pdf

[36] Analog filters. Analog Devices. [Online]. Available: https://www.analog.com/media/en/training-seminars/design-handbooks/Basic-Linear-Design/Chapter8.pdf

[37] C. Zhu and T. Hubing, "Q-factor and resonance in the time and frequency domain," *Clemson Vehicular Electronics Laboratory Technical Report: CVEL-11*, vol. 28, 2011.

[38] Second-order active filters. P.Allen. [Online]. Available: https://hasler.ece.gatech.edu/Courses/ECE6414/Unit1/Discrete_01.pdf

[39] State variable filters. Analog Devices. [Online]. Available: https://www.analog.com/media/en/training-seminars/tutorials/MT-223.pdf