Building a Simple Analog Synthesizer

- Carleton College -

Project Report

Alejandro Gallardo

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Taught by Barry Costanzi

Introduction

There are many, many ways an individual could produce musical notes. They can play guitar, play some keys, bang pots together, or wire up a sweet combination of circuit elements. This report focuses on the latter, specifically on the process of making an analog synthesizer. An analog synthesizer is essentially a circuit that is able to warp and modify a signal in order to produce musical sounds. Synthesizers are often presented as an interface that allows an individual to control how the circuit modifies the signal. Synthesizers make use of devices such as filters and oscillators to perform the desired tasks. Below I describe building a simple analog synthesizer based on the "Totoro-1 Synthesizer" by SyntherJack.

General Set Up

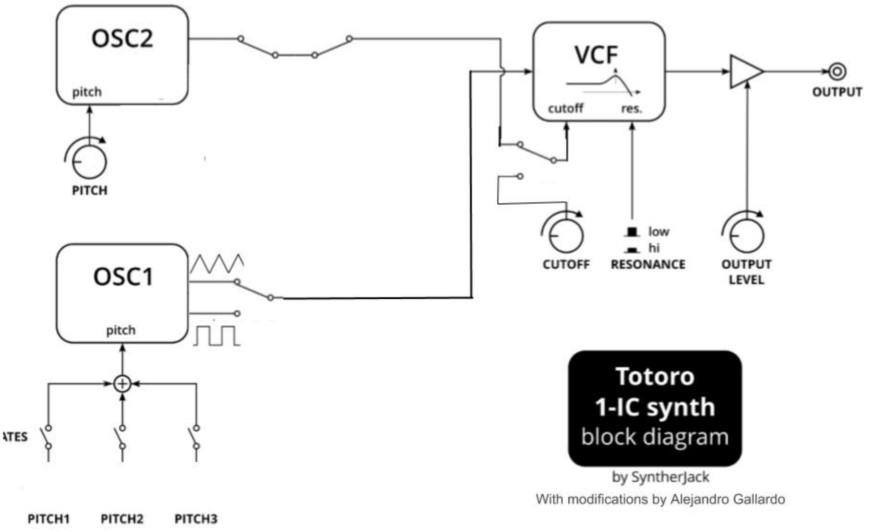

Figure (1) This is a modified block diagram of the Totoro Synthesizer by Jack. VCF stands for voltage controlled filter. OSC1 is an oscillator that controls the pitch produced by the synthesizer, and it can be switched between a square wave and a triangle wave. OSC2 is an oscillator that controls the characteristic frequency of the voltage controlled filter (producing the "wobble" effect).

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As shown in figure 1, the synthesizer I build has three main components: two oscillators and a filter. One of the oscillators (OSC1) produces the pitch that the user will hear– the note that is "played." Using switches, the user can control the frequency produced by OSC1, which in turn affects the perceived pitch produced by the synthesizer. In addition, the user can flip a switch to choose whether OSC1 produces a triangle wave or a square wave. The signal produced by OSC1 is the input of the voltage controlled filter (VCF). The VCF is a low pass filter with a characteristic frequency that can be controlled using an external applied voltage, which I'll call the cutoff voltage. Recall the characteristic frequency is the frequency at which the output voltage is attenuated by -3dB.

By changing the characteristic frequency of the filter, the user changes the perceived sound of the synthesizer. Rapid repetitive changes to the characteristic frequency will produce a "wobble" or "whoa whoa"-like effect. With a switch, this synthesizer can choose one of two ways to control the cutoff voltage. The first way is using a knob to control a DC voltage that is used as the cutoff voltage. The other more interesting way is using the AC output of OSC2 as the cutoff voltage, which would produce the 'wobble' effect.

I build the VCF, OSC1, and use a function generator for OSC2.

Voltage Controlled Filter

So the first important step, for me, was to create a working voltage controlled filter that can be used as a low pass filter. I use the filter in the Totoro 1 synth, shown in figure 2, as the basis for my filter. I simplify it, keeping only the most important elements of the original VCF. My simplified schematic is shown in figure 3.

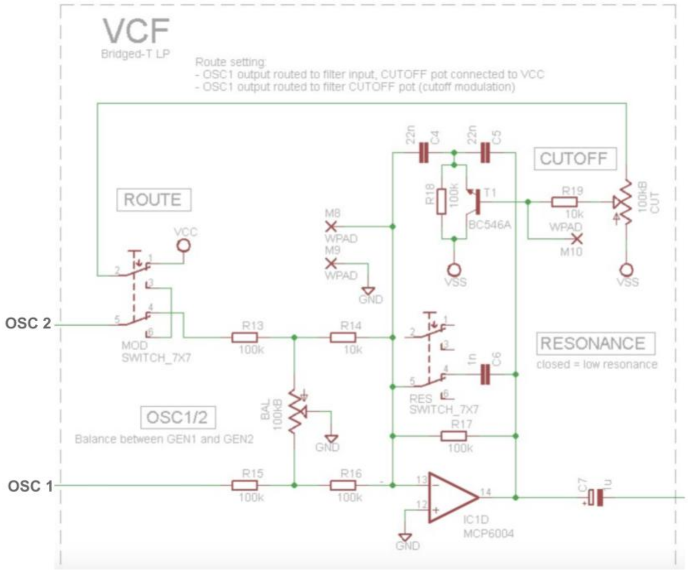

Figure (2) This is the circuit schematic for the voltage controlled filter in the Totoro 1 Synthesizer, which can be found online. The voltage controlled filter I build is based on this schematic.

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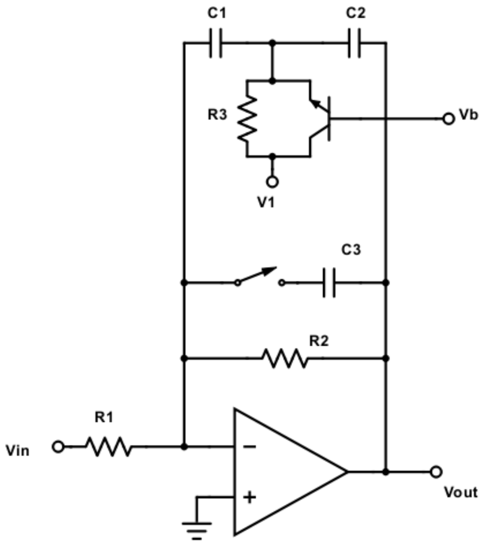

Figure (3) This is a simplified version of the voltage controlled filter presented in figure 2. Vb is the transistor's base voltage, and it can be used to control the characteristic frequency. I use an LF411 for the operational amplifier. This circuit acts as a low pass filter.

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VCF Theory

How does the voltage at the base of the transistor in figure 3 control the characteristic frequency of our synthesizer's voltage controlled filter? We can get a mathematical intuition for what is happening here using complex impedances. Let's base our mathematical solution on a simplified schematic, shown in figure 4. Let's have V1 go to zero (it becomes ground). In addition, let's mathematically model the transistor and R3 as having a total effective resistance (R_{eff}). We expect the transistor's base voltage (V_b) to change the value of the effective resistance. High values in V_b correspond to high current values. If there are high currents passing through the effective resistor, then the effective resistance must be low, using Ohm's law. Conversely, low values in Vb correspond to high values in R_{eff}.

Using complex impedances, we find that the frequency at which the output voltage is a maximum is:

$$w_0 = \sqrt{\frac{1}{Z_1 R_{eff}} C^2} \tag{1}$$

where the variables are in figure 4. Although the frequency w_0 is not the characteristic frequency (the -3db point), we can use it to determine the movement of the -3dB point. Equation 1 shows a clear dependence between w_0 and the effective resistance. As we increase the effective resistance, we can expect the characteristic

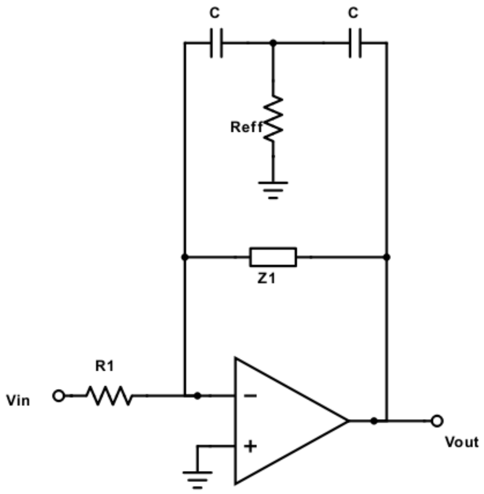

Figure (4) Simplified version of the synthesizer schematic. It is used to obtain an analytic solution to describe the characteristic frequency as a function of the effective resistance.

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frequency to decrease, which will increase the attenuation of a sufficiently high signal. In other words, as the transistor's base voltage decreases and the effective resistance consequently increases, we can expect greater attenuation in a signal that is sufficiently large.

In theory we should be able to show how Vb affects the effective resistance by measuring the resistance across both the transistor and R3 shown in figure 3. In addition, we could show how Vb affects the characteristic frequency by plotting attenuation as a function of frequency when Vb is high and when Vb is low. Comparing these plots should yield the predictions produced from our mathematical model. I show this in the section titled 'Testing Theory.'

Oscillator 1

The next important step is to create an oscillator that can produce musical pitches. The schematic for the simple oscillator I build is shown in figure 5.

Oscillator 1 Theory

The goal is to create an oscillator that we can use to effectively change the musical note produced by the synthesizer. If we examine the schematic in figure 5, we see that the op amp on the left of the schematic can be identified as an integrator circuit, where the output V1 will be an integral of the input signal. In addition, we can identify the op amp on the right as a comparator with positive feedback where

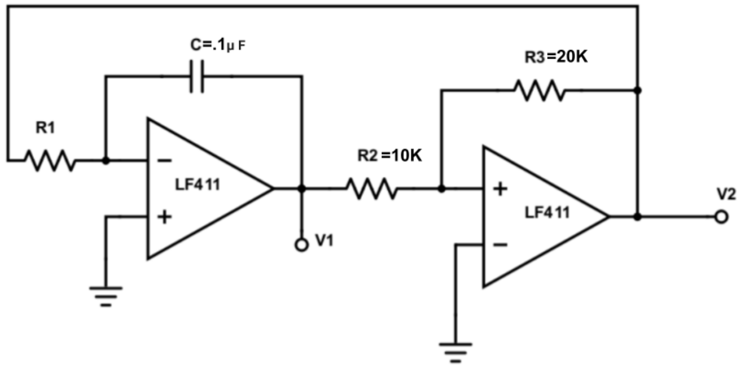

Figure (5) Schematic for an oscillator. This oscillator is how the synthesizer will produce notes. The oscillator corresponds to OSC1 in the block diagram shown in figure 1. The signal will be fed into the voltage controlled filter.

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the inverting terminal (the input voltage) is grounded. In other words, it acts as a Schmitt trigger where the reference voltage is supplied by the left op amp, and where the output at V2 is either ± Vs depending on when the input signal crosses the reference voltage. V_s is the rail voltage powering the op amps.

Let's examine the left op amp. We can derive an equation that describes the voltage at V1 from figure 5:

$$V_1(t, V_2, R_1) = \frac{-V_2 t}{R_1 C} + \frac{R_2 V_2}{R_3} \tag{2}$$

Since the right most op amp is a schmitt trigger, we know that V2 will either be ± Vs, and since Vs is a constant, V1 is really a piece wise function that depends on the sign of Vs and time:

$$V_1(t, V_2, R_1) = \begin{cases} \frac{-V_s t}{R_1 C} + \frac{R_2 V_s}{R_3} & \text{if } V_2 = V_s \\ \\ \frac{V_s t}{R_1 C} - \frac{R_2 V_s}{R_3} & \text{if } V_2 = -V_s \end{cases}$$

According to equation 2, if R1 is held constant, then V1 will be a linear equation that depends on time for either value of V2. From background algebra, we know that the Schmitt trigger will switch states when V1 reaches ± $\frac{R2*V2}{R3}$, which is when both terminals will have equivalent voltages. This value corresponds to the second term of our piecewise equations! This means that V1 will be a triangle wave, oscillating between the values that make the Schmitt Trigger switch states. This in turn means that the right most op amp will produce a square wave, which is the input of the leftmost op amp. Furthermore, the function describing V1 indicates that the slope at which V1 rises or falls changes depending on the value of R1, impacting the time it takes to reach the value to switch states. Therefore, we can

Musical Note	Note Frequency (Hz)	R1 Resistance (kΩ)
C4(Middle C)	261.63	19.1
D4	293.66	17
E4	329.63	15.1
F4	349.23	14.3
G4	392	12.8
A4	440	11.36
B4	493.88	10.1
C5	523.25	9.55

Table (1) The columns of this table are: musical notes, fundamental frequency of the musical note, oscillator's R1 resistance value that corresponds with the musical note.

change the frequency of the signal at V1 and V2 by changing the resistance value of R1! This is crucial– we can now map resistance values for R1 that will correspond to musical notes!

In order to do this, we need to know exactly how the resistance of R1 will impact the frequency of the wave. From the theory we have built so far, we can find that the expected frequency of both V1 and V2 behave as following:

$$SignalFrequency = \frac{R_3}{4R_1CR_2} \tag{3}$$

Higher resistance values of R1 correspond to low musical pitches, and conversely low resistance values will produce high musical pitches. Table 1 creates a map between R_1 resistance values and corresponding notes in the C major scale.

Testing Theory

We ultimately want to understand and believe in how the transistor's base voltage V_b can impact the characteristic frequency of our low pass filter. In order to get to this point I pursue the following. First I show the relationship between the transistor base voltage and the effective resistance R_{eff}. I vary the transistor base voltage, and measure the output voltage as well as the effective resistance R_{eff}, which I measure across R_3 and the transistor using a digital multimeter. I graph effective resistance as a function of V_b, shown in figure 6. It shows that V_b and R_{eff} are approximately inversely related, which is what we expect. As V_b increases, the current increases, which means that the effective resistance should decrease. This becomes more intuitively clear if one applies ohm's law across the theoretical effective resistor.

The next step is to show that the relationship between characteristic frequency and effective resistance is what we expect. I show this by measuring the output voltage as a function of frequency when R_{eff} is high and low, shown in figure

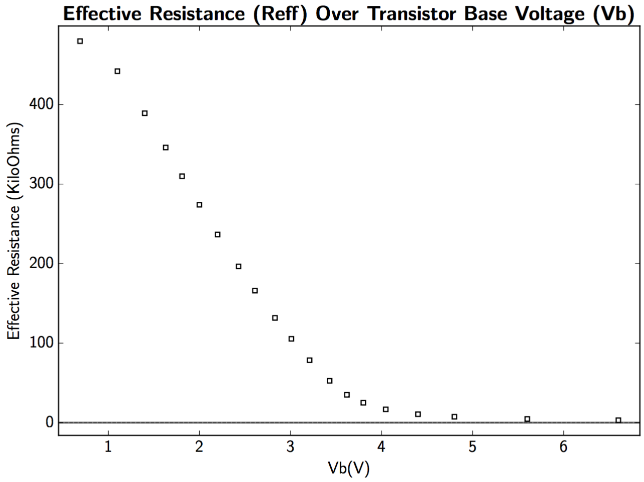

Figure (6) The y axis is the effective resistance measured across the resistor and transistor section shown in figure 3. The x axis is the transistor's base voltage. This shows that R_eff generally decreases as V_b increases, as we expect.

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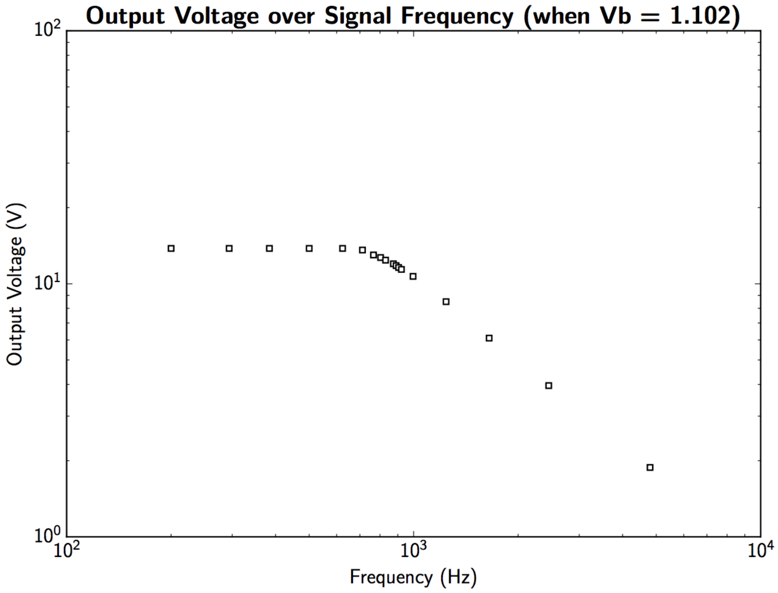
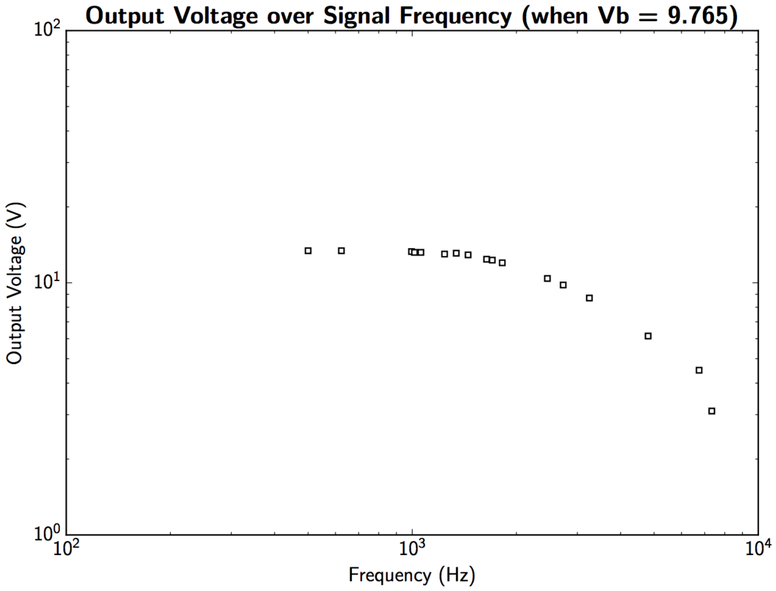
Figure 7. We indeed find the relationship between characteristic frequency and effective resistance to be defined by equation 1.

Conclusion

I end up with a synthesizer that can use either a square or triangle wave to produce a musical note. The actual pitch is adjusted using a switch resistor, used as R_1 from figure 5. This wave undergoes a filter, and the characteristic frequency of this filter can be adjusted depending on an external voltage (the cutoff voltage). I can control this voltage using a potentiometer or using the function generator. When connected to the function generator, the synthesizer produces a cool wobble effect. There are many ways that this project can be expanded. One way could be by exploring how C_3 in figure 3 affects the resonance of the circuit. Another way could be by implementing a high pass filter, which would produce different interesting sounds. Finally one could explore how to increase the range in which the characteristic frequency of the VCF can wobble. This latter alleyway of exploration could produce really cool sweeping sound effects. One could explore it by examining how to expand the range of values that R_{eff} can take.



(a) Output voltage as a function of frequency when transistor's base voltage is low ($V_b = 1.102$ V)



(b) Output voltage as a function of frequency when Vb is high ($V_b = 9.765$V)

Figure (7) Output attenuation plots. Low R_{eff} results in high characteristic frequency. Converse is true, confirming equation 1.