Design and Assembly of PCB Electronic Self-Oscillators

Submitted in partial fulfillment of honors requirements
for the Department of Physics and Astronomy, Dickinson College,

by

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Abstract

There are many phenomena in nature in which organisms have some type of synchronization, for example heart cells all beating in unison. The purpose of this research is to model some of these phenomena using electronics. First, I started by learning how to make printed circuit boards (PCB) on a Voltera V-One machine and using the software EAGLE so that I could create an electronic model for experimentation. Then I connected operational amplifier-based oscillators in a universal coupling pattern to observe their behavior when they all could send and receive information. Experiments consisted of modifying the oscillators' natural frequencies to find regions of different types of synchronization patterns, ranging from one-to-one up to three-to-seven locking. The results have the potential to explain how different synchronization patterns can emerge in nature when systems communicate.

Acknowledgments

Thank you to Professor Lars English for taking me on for senior research. I also want to thank Professor Windsor Morgan for advising me about classes and graduate school. Thank you to Professor Hans Pfister and Professor Robert Boyle for encouraging me during my time at Dickinson! Lastly, thank you to our technician Jonathan Barrick for helping me learn to use new tools and for ordering parts. I want to acknowledge Nathan Shinkar at Voltera for the help with the drill.

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1 Introduction

It is common in Pennsylvania to look out on a summer night and see fireflies. Their abdomens flash in what appears to be a random pattern. The purpose of this paper is to study the synchronization of electronic oscillators to see if we can model systems in nature. For example when one firefly flashes then other fireflies are influenced in how they flash, or heart cells can communicate beat patterns by impulses. This is what we are going to call pulse-coupled oscillators. In general, a collection of identical oscillators, where each are connected to all the others, can manage to synchronize and then integrate-and-fire together [1]. When the oscillators are not identical, they can manage synchronization as if they are coupled strongly enough. The single firefly is an example of an integrate-and-fire oscillator in that there is the slow "integration phase" where "charge" builds up. Then there is the fast "fire phase"(it lights up), where the charge finally crosses a threshold and firing happens in an instant.

I used relaxation oscillators because they are easy to build and their frequencies are easy to control. Instead of the standard sine wave, they create a series of pulses. The duration of the pulsing is determined by the capacitor. The capacitor charges up then fires when it is full [2]. Since I have four of these oscillators, I connected them in a universal pattern, as will be described in more detail later.

Since I am experimenting with electronics, I decided to try making a printed circuit board (PCB). I used EAGLE software to layout my board and a Voltera V-One machine to build it. EAGLE is a popular electronic design automation (EDA) software used by engineers to design layouts of electronics [3]. The Voltera machine is used by engineers to build smaller designs in their lab, versus having to send them out to a manufacturer. The EAGLE software is a professionally used software while the Voltera V-One machine is used for simpler electronic circuits. So, the capabilities of EAGLE go beyond what can be accomplished by the machine.

The start of studying synchronization goes as far back as the 17th century, with Christiaan Huygens studying pendulum clocks and Lord Rayleigh studying his organ pipes [4]. The topic has expanded to cover numerous applications in nature [5], chemical systems [6], robotic systems [7] and even amongst humans [8]. The study of synchronization has even made it to the world of electronics. Studies range from general synchronization in electronic circuits [9] to synchronization without communication [10] and more topics are being explored. Each setup has a wide variety of ways of coupling different components together and the factors that they want to take into consideration. One experiment was done on two coupled oscillators paired in a unidirectional fashion to study time delay [11]. There is also an experimental study on two bidirectionally coupled Wien-bridge oscillators [12]. This research involves something even simpler, relaxation oscillators, and I am scaling it up to four couplings to better mimic nature.

The nature of this paper is structured as follows. Section 2 is the theory of why we use electronics and the details of oscillators. Section 3 is the experimentation of my research. Starting with learning about the Voltera V-One machine, learning EAGLE and then my circuit. In section 4, I list the results that I obtained in a table and explain my findings. I also suggest how to continue with this investigation. In section 5, I summarize what I have learned from using the V-One and EAGLE. Then at the end of this paper in the appendix, I have written out some detailed descriptions of how I used the equipment. Anything from the different parts of the V-One machine to an overview of EAGLE.

2 Theory

2.1 Why turn to electronics?

When studying synchronization previous investigators used mechanical systems such as pendulums [13], but switching to electronics (versus mechanical systems) has advantages. We can test different situations quicker because it will not take as long to switch a circuit, compared to adjusting a mechanical component. We also have the ability to test more, in duration and quantity. Electronics have the ability to use a wider range of frequencies, up to two orders magnitude. With electronics we can get results almost instantaneously but with a pendulum we would have to wait before we can come to an analysis. Having four oscillators on a board is fairly easy, but that is more difficult when trying to work with four pendulums. The pendulums have to be coupled all-to-all but with electronics the coupling can be varied. Hence, I switched from viewing the synchronization of pendulums on a platform to a circuit.

2.2 What is the difference between a PCB and breadboard?

On breadboard, or protoboard, you do not have to solder wires or components down. They are simply inserted into evenly spaced holes and can be removed as needed. See Figure 27 for an example of a basic breadboard. A printed circuit board (PCB), is permanent. The wires are not colored or coming out of the board but printed onto the board using a conductive ink. Then the components are soldered onto the board, either on the the surface of the board or through the board via a hole. See Figure 15 for an example of a PCB.

The advantage of the breadboard is that it allows for a quick change to the design of a circuit, but the permanence of the PCB allows for reuse over and over again. A big advantage of a PCB circuit is wire connections are much smaller, resistor leads are shorter and everything is more compact. If you have higher frequencies then the wire loops connecting various circuit components are surrounded by magnetic fields. These changing fields are picked up by other wires as noise. The compactness of the PCB reduces this noise. Plus, since the wires are printed right onto the board you do not have to worry about pulling one out or having a faulty wire.

2.3 Self-Sustaining Oscillators

When trying to model nature, what do we expect to find? In nature, it is typical to find self-sustained oscillators, or "the form of oscillation is entirely determined by the internal parameters of the system" [2]. The defining features of a self-oscillator are dissipation, stability, and nonlinearity. The dissipation is balanced by the internal energy source so that a stable amplitude of oscillation can be maintained. Without a constant energy supply, the oscillations would eventually decay. For example, fireflies maintain their flashing from chemical reactions within their bodies. Stability and nonlinearity allow for the self-oscillator to have stable oscillations. Since the oscillator neither loses nor gains energy if there was a perturbation then the oscillator would remain perturbed. Since they are nonlinear, they will go back to the unperturbed state because nonlinearity is a driver towards fixed points in a phase [2].

2.4 Relaxation Oscillators

Relaxation Oscillators, sometimes referred to as comparator-based oscillators, are created by using an operational amplifier and a capacitor as shown in Figure 1. The operational amplifier (op-amp) has two inputs and a single output. The inputs, plus and inverting (or negative), are compared. Based on the comparison the output either has a V_{++}, or V_{--}, or in case of the Figure 1 , +15V or −15V. These are called the supply voltages, or rail voltages, and are what drive the oscillations, while the input voltages change the direction. If the plus input voltage is greater than the inverting, the output will be +15V, or a V_{++}. If it is less, the output is −15V, or V_{--}. The positive input is connected to the voltage divider of the output and therefore sits at half the output voltage.

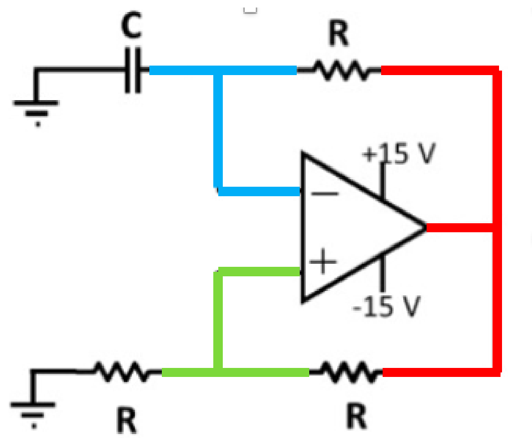

Figure 1: This is a simple relaxation oscillator. The lines in red are the output voltages, V_{out}. The blue lines are the inverting voltage, V_-. This is what monitors the capacitor charging and discharging. The green lines are the positive voltage, V_+. They are connected to the voltage divider, therefore it sits at half of the output voltage.

Voltage divider:

$$V_+ = \frac{V_{out}}{2} \tag{1}$$

The negative input monitors the capacitor. The charging and discharging of the capacitor gives the oscillation the square wave, or pulses.

Charging of capacitor:

$$\frac{V_{out} - V_-}{R} = C\frac{\partial V_-}{\partial t} \tag{2}$$

Figure 2 displays the voltages of the relaxation oscillator over a period of time. The red trace is the output switching between the rail voltages based on the comparison of the inputs. Which is governed by

The output voltage:

$$V_{out} = 15V \cdot sign(V_+ - V_-) \tag{3}$$

The green trace is the positive voltage, which is governed by Equation 1. The blue trace is the negative voltage which is governed by

Charging of the capacitor:

$$V_- = 15V(1 - e^{-\frac{t}{RC}}) \tag{4}$$

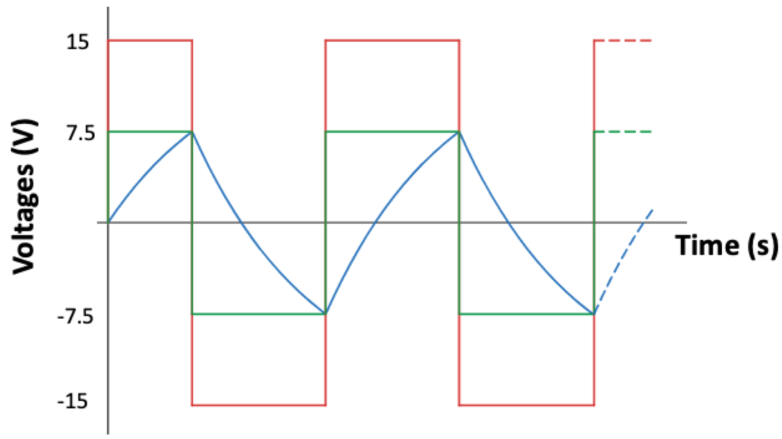

Figure 2: This is how the voltages change over time. The green trace is the positive input voltage, blue trace is the negative input voltage, and red is the rail voltages. Assuming that the capacitor starts uncharged, the rail voltage starts at +15V and the positive at +7.5V. The capacitor tries to charge to +15V but when it intersects with the positive voltage the negative input becomes larger. Thus the rail voltage is now changed to -15V. The positive input is changed to -7.5V and the capacitor starts discharging. Again it tries to discharge to -15V, but when it intersects with the positive input, the rail voltage changes again.

Discharging of the capacitor:

$$V_- = 15V(e^{-\frac{t}{RC}} - 1) \tag{5}$$

When the negative voltage and positive voltage intersect, that is when the comparator changes to its new voltage.

Multiple oscillators can be coupled unidirectional (pair-wise) or bidirectional. In unidirectional coupling, one oscillator drives the others through a coupling resistor. The output of one oscillator goes into the input of some subset of the other oscillators. The oscillators can flow from one to the other. In bidirectional coupling, an oscillator drives and is driven at the same time by another oscillator. We can therefore construct complicated oscillator networks where each edge between two nodes represents a pair-wise coupling term. Alternatively, we can consider a simpler coupling scheme called "universal coupling". The outputs of all the oscillators come together and are averaged, then go into the inputs of each oscillator including itself. See Figure 3 for a visual representation of couplings. For this research, I focused on universal coupling of four relaxation oscillators.

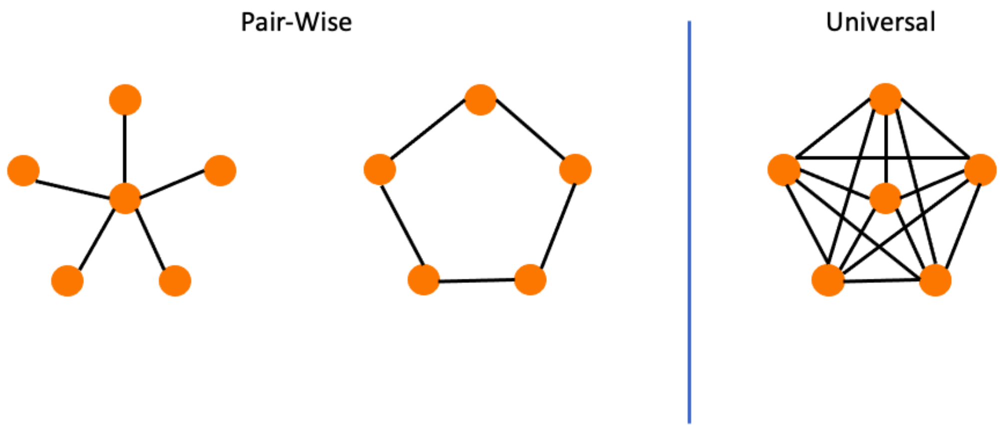

Figure 3: On the left is pair-wise coupling. Each node (orange dots) is an oscillator and the black line is a coupling. Two of various representations is displayed. The first representation has the node in the middle drive all the outer nodes, while the second has a chain where each one drives the one next to it. On the right is universal coupling. Each node is connected to all the others by a coupling. Thus, each are driving and being driven.

When coupling the oscillators back to themselves in universal coupling, a voltage adder is created, shown in Figure 4. Looking at V_o, we know that

$$I_o = I_1 + I_2 + I_3 \tag{6}$$

and

$$I_1 = \frac{V_1 - V_o}{R}. \tag{7}$$

Equation 7 is the same for the other oscillators the subscript 1 is changed to 2 and 3. Using Ohm's Law we have,

$$V_o = I_o R_o \tag{8}$$

and doing substitution using Equations 6 and 7 and solving for V_o we get

$$V_o = (I_1 + I_2 + I_3)R_o$$

$$V_o = (\frac{V_1}{R} + \frac{V_2}{R} + \frac{V_3}{R} - \frac{3V_o}{R})R_o$$

$$V_o = \frac{R_o}{R}(V_1 + V_2 + V_3) - \frac{3R_o}{R}V_o$$

$$(1 + \frac{3R_o}{R})V_o = \frac{R_o}{R}(V_1 + V_2 + V_3)$$

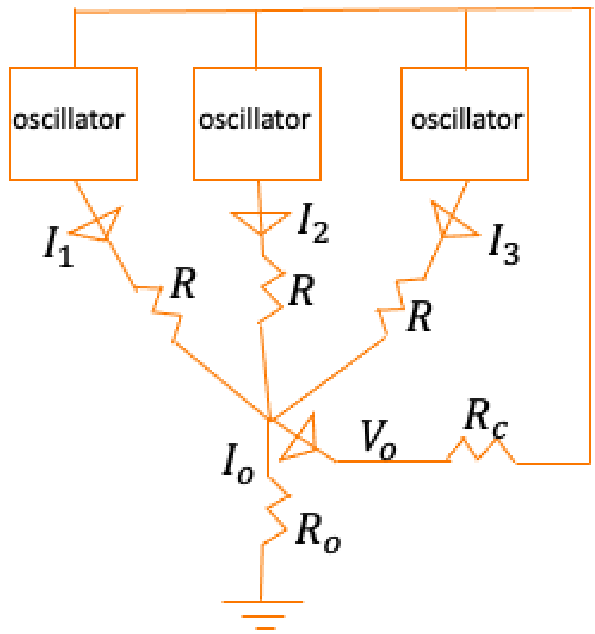

Figure 4: This is a simplified version of a voltage adder. The oscillators output's at the top come together to V_o to be averaged. Then that is fed back into the inputs of those oscillators.

$$(R + 3R_o)V_o = R_o(V_1 + V_2 + V_3)$$

$$V_o = \frac{R_o}{R + 3R_o}(V_1 + V_2 + V_3)$$

So when we normalize the last equation to apply to any number of oscillators we have,

$$V_o = \frac{R_o}{R + NR_o}\sum_{i=1}^{N} V_i \qquad (9)$$

where N is the number of oscillators. Thus this explains how the output voltages are averaged in universal coupling.

When two oscillators are operating at the same frequency and their phase difference is continuously zero, they are in-phase. The pulses are the same and they overlap, appearing as one. They can also appear out of phase, where one oscillator may lag behind the other. They are at the same frequency but in this case there are two distinct oscillators. They are considered phased-locked, because they are clearly different oscillations and their phase difference (while nonzero) remains constant over time. If the outputs shown on an oscilloscope appear as a blur or moves such that there is no distinction between one trace and the other then it is not phase-locked.

Phase-locking is important for studying nature because this means the system is still synchronized, the outputs are phase shifted. Phase shifting is when a trace is lagging or advanced by a time factor. For example, if we look at heart cells that have two groupings with a singular cell to attach them, they continue to beat on their own. The cell in the middle then beats to both of their beats. So, lets say that the two groupings are beating opposite of each other, then the one in the middle has a two to one frequency because it beats twice for each of the groupings [14].

3 Experimental Methods

To begin this project, I learned how to use a Voltera V-One machine to print out circuit boards and the software EAGLE to create the layout needed for on the board. Then I worked on coupling two and four operational amplifiers in a universal fashion, and explored the presence of phase-locked states.

3.1 First Hello World Circuit

First, I had to learn to use the printed circuit board maker, see Figure 5. Watching numerous videos on Voltera's website such as *First print survival guide* [15] and *Calibration guide* [15], helped with getting set up. I also referenced the "Getting Started (Hello World)" article while making my first circuit [16].

The machine software shows you videos, pictures, and has directions on how to make the circuit. I started with positioning the board on the bed of the machine and having the probe find it. This way when it does all the calibrations and printing it will not run off the side of the board ruining the project. Then it measures the height of the board in various spots. This is so if the board is warped then you can change out the board. For example, if the board is higher in one spot than another, while it is printing with the conductive ink the nozzle tip could break and ruin the project.

I followed the steps outlined on the software (for more details see Appendix A). While it was difficult to line up the probe with the pads, care must be taken in the alignment before soldering. Misalignment can occur frequently but has a simple solution, redoing the alignment step.

I had trouble at first getting the solder to come out and stick to the board. This was because the nozzle tip had broken off. The cylinder on top of the cone had broken off and the solder would not properly dispense because it wasn't reaching the board, see Figure 6.

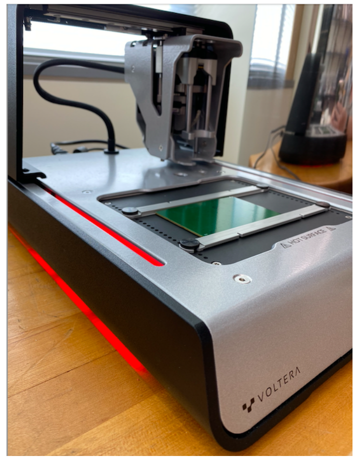

Figure 5: Voltera V-One Machine

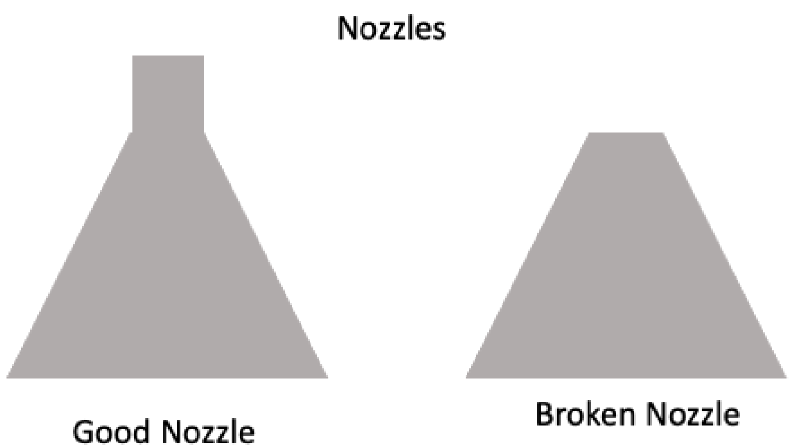

Figure 6: The good nozzle has a cylinder at the top. The cylinder is the tip and it is not broken off. In the broken nozzle image the cylinder is missing. So, the ink and solder will not dispense properly. Note the base as a diameter of about 5mm.

Replacing the nozzle fixed the problem. The rest of the board making went smoothly. Unfortunately the board did not work, see Figure 7. The LEDs on the board did not flash. I believe it was because the pads had gotten worn down from trying to solder. The ink may have been chipped off from the broken nozzle.

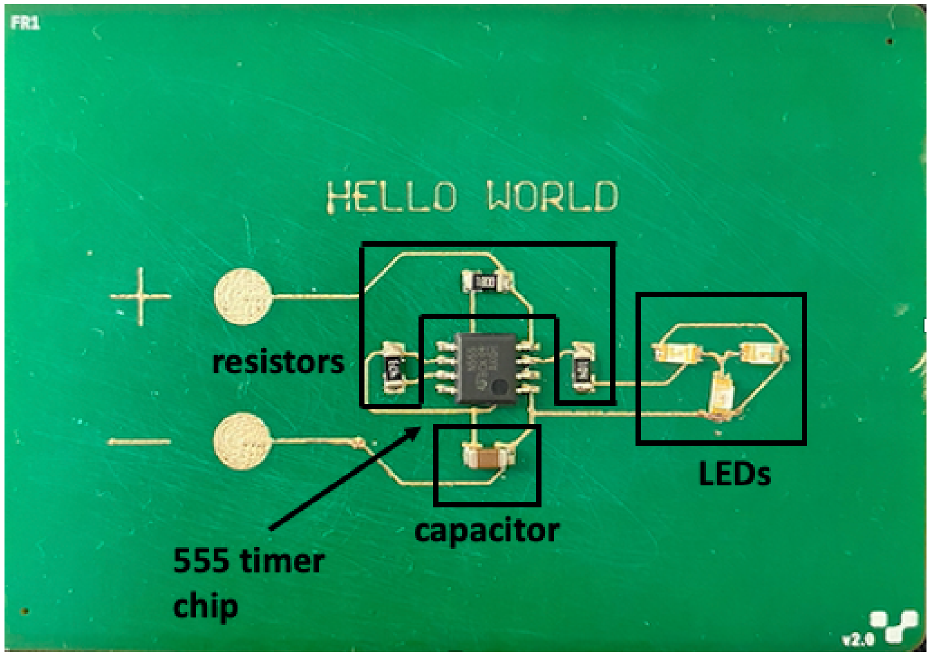

Figure 7: The first "Hello World" board that I completed with the Voltera V-One machine. The LEDs, on the right most side, did not flash as intended.

3.2 Second Hello World Circuit

To make sure an operational board could be produced from the Voltera V-One machine, I made the Hello World board again. The second time had little error occur during the building process.

When the battery was placed on the completed board, the LEDs did not flash as intended. In the initial configuration the top resistor and the right resistor were in the wrong location. Due to the high resistance values not enough current reached the LEDs. The configuration was corrected by having the reflow cycle on the machine warm the solder, which allows for the easy removal and replacement of the components in the circuit. When the heat reached its peak, the components were pulled off and switched around. Then when reflow was complete the LEDs did flash as intended, see Figure 8.

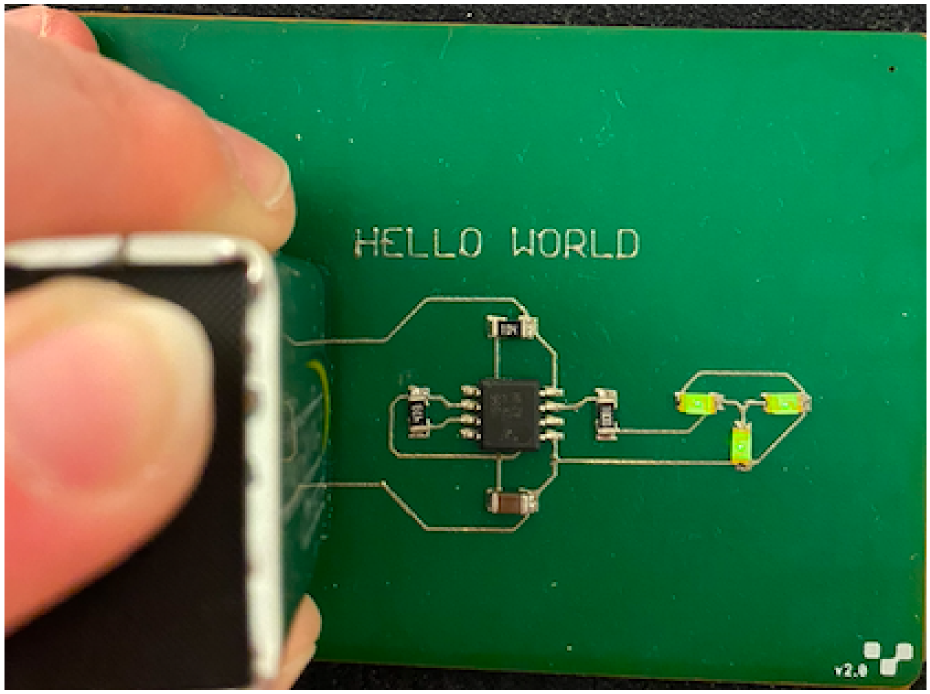

Figure 8: The second Hello World board lighting up as intended.

3.3 Learning EAGLE

EAGLE is a popular electric design automation (EDA) software used by electrical engineers to design their boards and circuits [3]. The software has two views, schematic and board. The schematic view is how one would normally draw out a circuit, by using symbols and lines to make current connections. This is the view that is generally easier to understand. The board view is what the physical circuit would look like. The components are all laid out and are connected by red or blue lines. The red lines are on top of the board and the blue lines are on the bottom of the board. There is also the possibility of adding vias to the board which are represented as green circles. Vias allow for connection on the top and bottom of the board. The board view is not as easy to understand when trying to figure out the function of the circuit.

My first project was to build a basic relation oscillator. Then, an upgraded the circuit was constructed for the research project. Figure 9 is a schematic view of a simple design that was used at the start of each experiment, it was slightly modified for each coupling. At the top of Figure 9 there are two additional op-amps. This is because the chip being used has four, thus four op-amps are displayed in the diagram. There are two relaxation oscillators, one on the left and on the right. They are each being grounded by external channel one by the top left rectangle. In Figure 10, this is what the schematic printed on the board physically looks like. I have all the external connectors labeled in the figure.

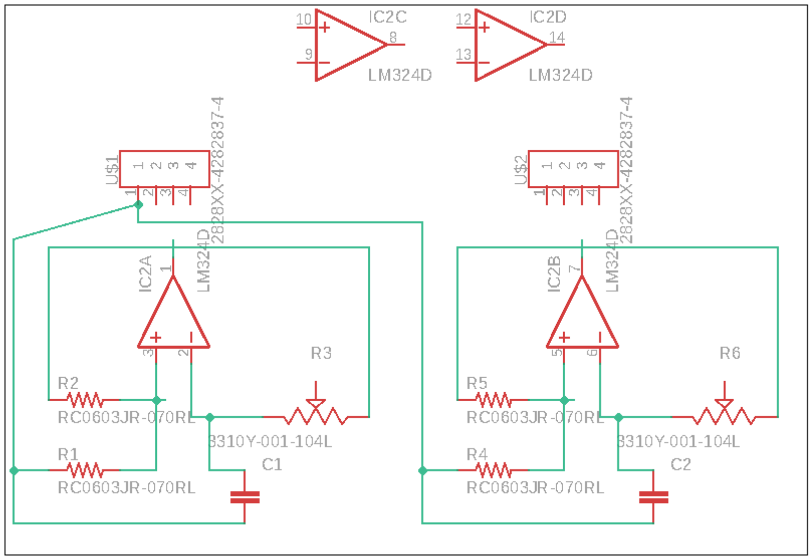

Figure 9: Two relaxation oscillators are shown uncoupled. They each are grounded by an external connector in the top left. Two additional op-amps are at the top because the chip that is being used has four on it so four are presented in the software. A second external connector has no connections but it there for future use.

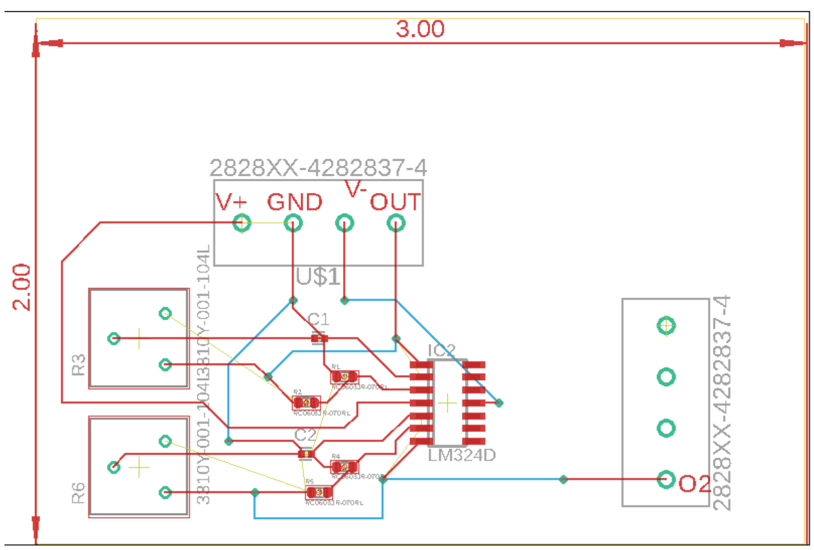

Figure 10: The board view shown is the physical layout of the schematic shown above. They are the exact same circuit. This presents how one would see it on the board that becomes printed. The external connectors are labeled with the connections that are made to them. The red lines are on the top of the board and the pads are for components. The blue lines are the bottom of the board. While the green circles are the holes that link the top and bottom of the board.

The main challenges with creating this simple design were (a) finding components within the EAGLE library and (b) wire placement. Finding the right component needed for the circuit and then trying to find it on Mouser or DigiKey was challenging. Mouser and DigiKey are websites for shopping for electronic parts for circuits. While chips are standardized, finding the exact chip needed on EAGLE took time as they have the same chip in different sizes, packages, voltages, and a variety of other differences. Secondly, on to the board itself, Figure 10, I made sure that everything is connected to the component it needed to be while not overlapping or corrected signals that went to the opposite side of the component. Also, it is generally desirable to have as few vias as possible and for the circuit to be condensed. So, the final result required several versions.

One feature that EAGLE has is "auto route", which draws automated connections onto the board. This would be helpful if the computer knew the limitations of the Voltera machine and not default to professional printing. Figure 11 shows what the computer computed as the best route for all the wires needed for the simple design. Having all the connections on a 2D board so that none cross is a hard topological problem for all but the simplest circuits. Artificial intelligence can assist with this task, but it can still go wrong. I displayed some of the fails in the magnified images of Figures 12 and 13. If you look closely at the LM324D chip you will see that the connection would be printed under the chip, as illustrated in Figure 12. Or, in another case, that there is a small enough nozzle to print a connection under the resistors that are about three millimeters wide, seen in Figure 13. Another complication with auto route is that it does not place the components for you. Where ever one has them placed is how the computer will try and make connections. For example, in Figure 11, I had placed all the surface mount components far apart manually. So the user has to figure out the best configuration for optimization of the board.

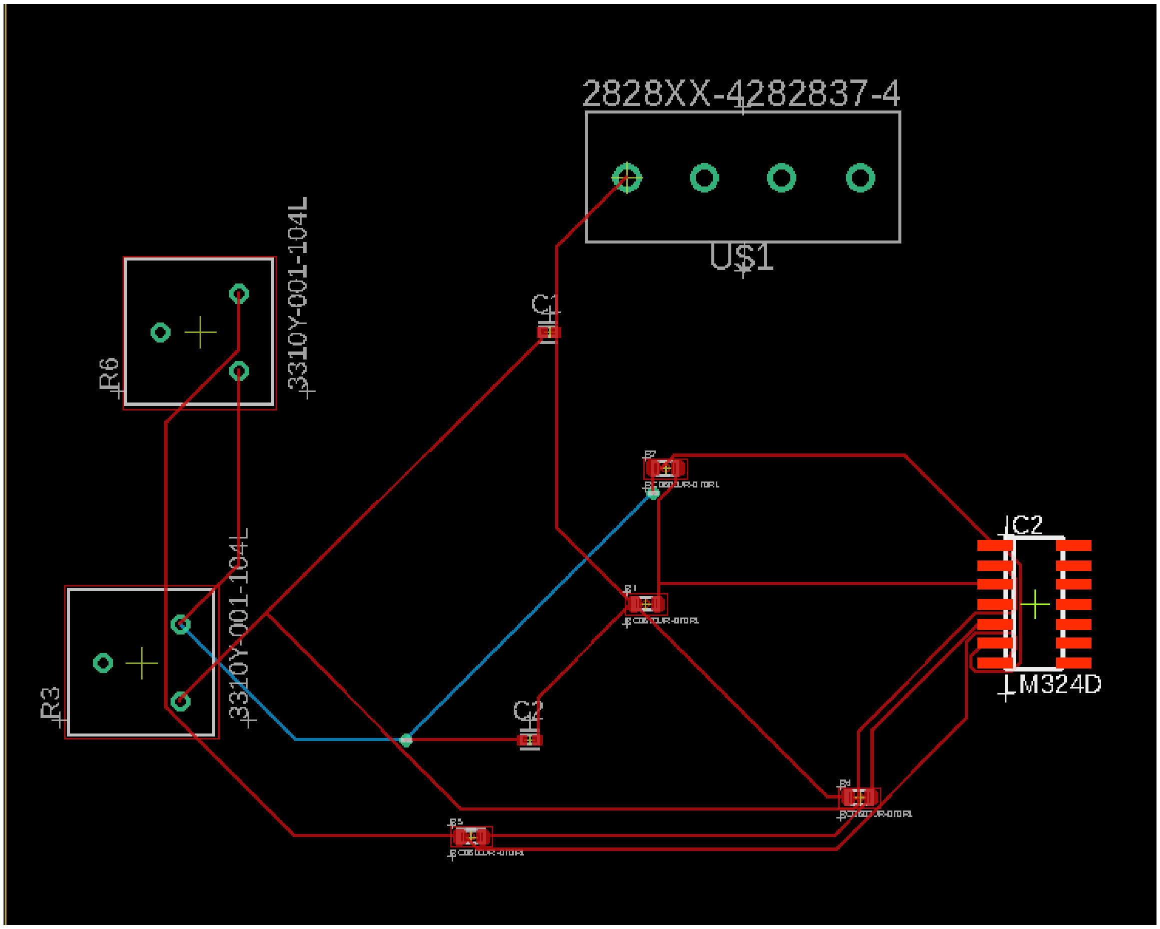

Figure 11: This is how auto route designed the board connections. The right most component is the chip which has a connection drawn underneath (zoomed in shown below, Figure 12). The right most resistor also has a connection going between the two pads it is attached to, but the Voltera does not have this capability. The user also has to place the components on the board, not using auto route. This then leads to complications as to what is the best optimization of the board.

The next important task was to change to the correct physical size and value of the resistors and capacitors needed for the circuit. Once having selected the appropriate specifications and packages for all the components, the next challenge was to order the parts. I found them all on Mouser, see Table 1 for component list. Since shipping would take time, I worked on learning the drill function. I learned how vias work and become prepared for assembly of the board.

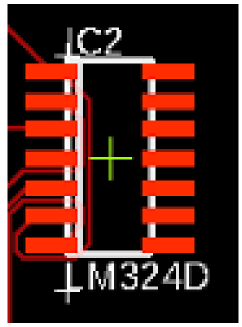

Figure 12: This is a zoomed in image of the chip from the auto route design. To the right of the left pads a connection comes down. This is not able to be done with the Voltera V-One machine.

Figure 13: This is a zoomed in image of the resistor from the auto route design. A connection is made in between the pads of the resistor. This is not able to be down with the Voltera V-One machine.

3.4 Punk Console

The punk console, as Voltera named it, is a board that produces sound. When starting, there are fewer resources on Voltera's website about how to proceed with the project. But, the software that runs the machine explains how to do most of the steps, and does not let you forget a step.

First, I downloaded the GTL and TXT files for the board from Voltera's website. The GTL file tells the printer where to put the electrical connections, pads, and solder paste. The TXT file tells the printer where to drill holes.

To begin, I selected the blank board drilling option. I mounted the drill with the .7mm head and got started. The machine is able to complete the whole process by itself, but must be monitored to check for faults. Then, when bigger holes were needed, the drill head was swapped.

The next task was to ink the board with the conductive ink. It was nearly identical to doing the "Hello World" board. Once the board was inked and dried, there was an additional step of adding rivets. These are copper pieces that go in the drilled holes to make a connection from the top to the bottom side of the board. To put them in, I carefully flipped the board over, then used a hammer and rivet tools to make the rivets flush with the bottom of the board. In Figure 14, you can see the completed inking and the copper rivets in place. Once all the copper was in then I moved on to soldering the components on. I learned how to solder those onto the board, using a hand iron.

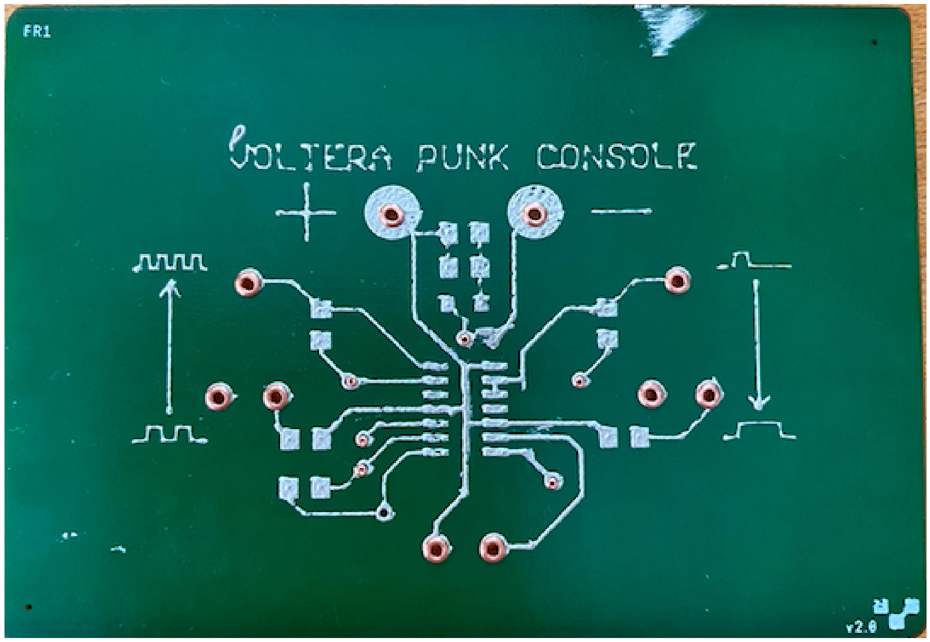

Figure 14: Completed inking and inserted rivets which are the copper colored rings.

The finished board, Figure 15, mostly worked. The LED had lit up as intended but no sound was produced. All the connections had been solid based on the multimeter readings. I concluded that it was chip failure as that was the only component that could not be tested properly. Since everything else worked as intended it was decided to move onto the main project.

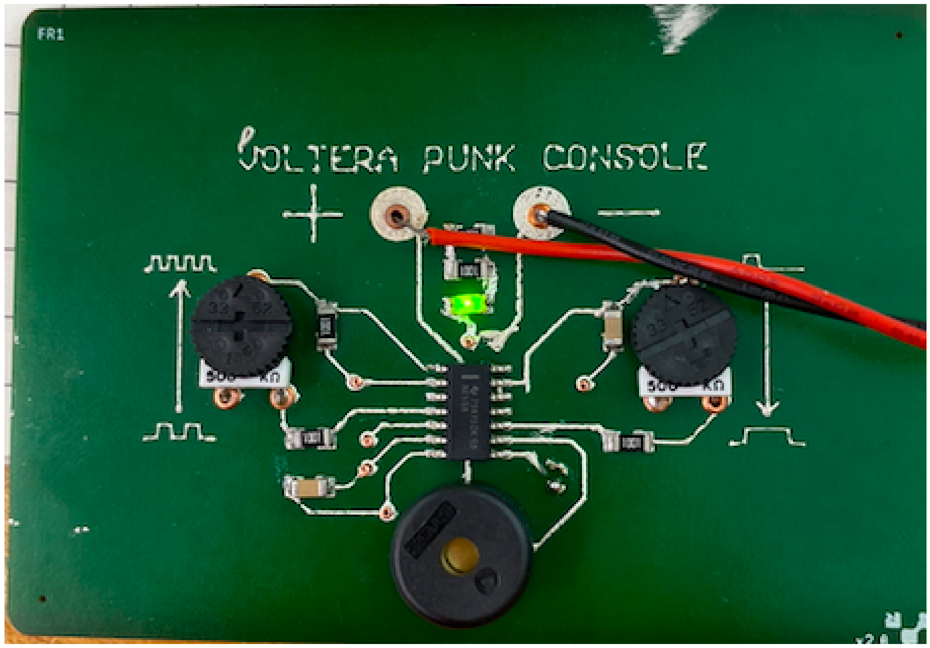

Figure 15: The completed Punk console is shown. The LED which is below the red and black wires is lit up. The chip in the center above the bottom round component (speaker) is what was determined as the failure.

3.5 From Pairwise to Universal Coupling

Once I had practice with making the provided boards, I was able to launch into designing the system. Already having determined the values for the circuit components, they were ordered in advance of starting the project. I went with LM324DR (oscillator), 10k resistors, 50k potentiometers, and .1μF capacitors.

I had found everything in Mouser, and ordered the components. Refer to Table 1 for order.

Component	Quantity	Application
LM324DR	30	Oscillator/Op-Amp chip
10k resistors	150	
50k potentiometers	30	To change the frequency
.1μF capacitors	100	Required for a pulse
4282837 wire connectors	30	External wires can be connected to the board

Table 1: Component Order

The next step was designing the circuit. I re-purposed the simple oscillator design from Figure 9 to include coupling. In Figure 16, the schematic was modified by adding in a wire connection. The green wire coming out to the right above R3 and to the left of R6 is the pair-wise connection. The connection is from the output of the left op-amp to the negative input of the right op-amp.

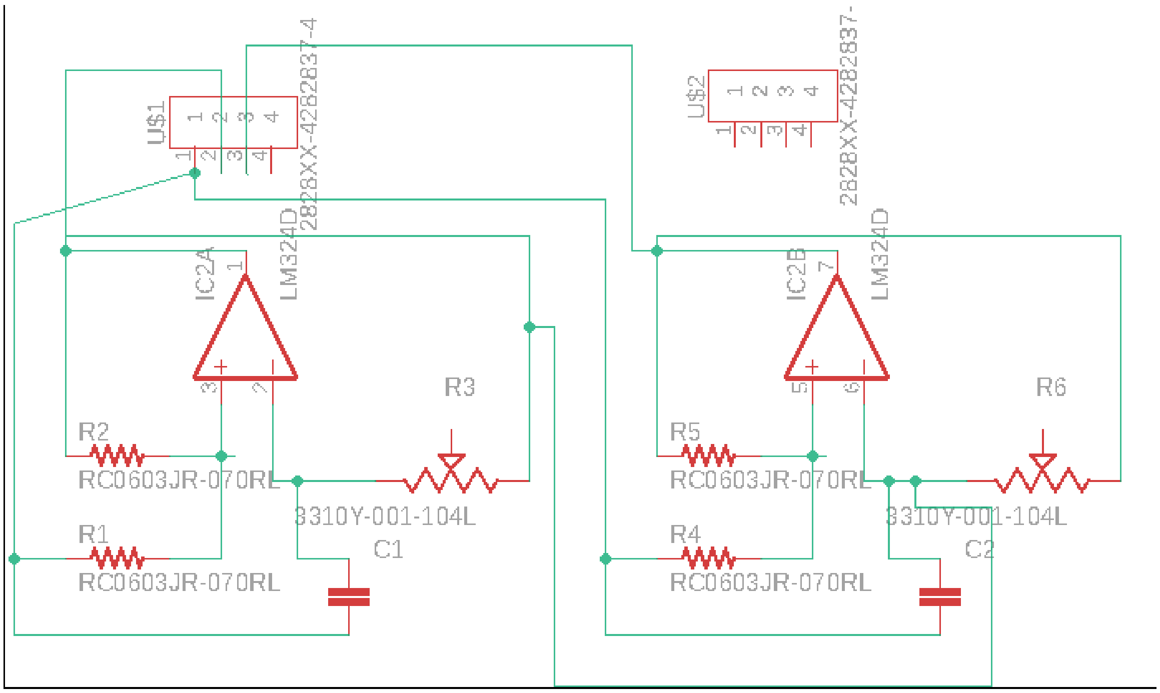

Figure 16: This is the schematic of the out to minus connection. The connection from the left of R5 to above R3 is the coupling connection.

In Figure 17, the board connections of the schematic in Figure 16 is presented. This is how it would have looked if it was printed out onto a PCB. But, it was in this design that it was realized that the output of the first oscillator went directly into the negative input of the second oscillator. For this to work, another resistor - the coupling resistor - would have to be added between the output and the inverting input. In fact, a variable resistor, a potentiometer, would allow us variable control over the coupling strength. This is implemented in the next design iteration in Figure 18.

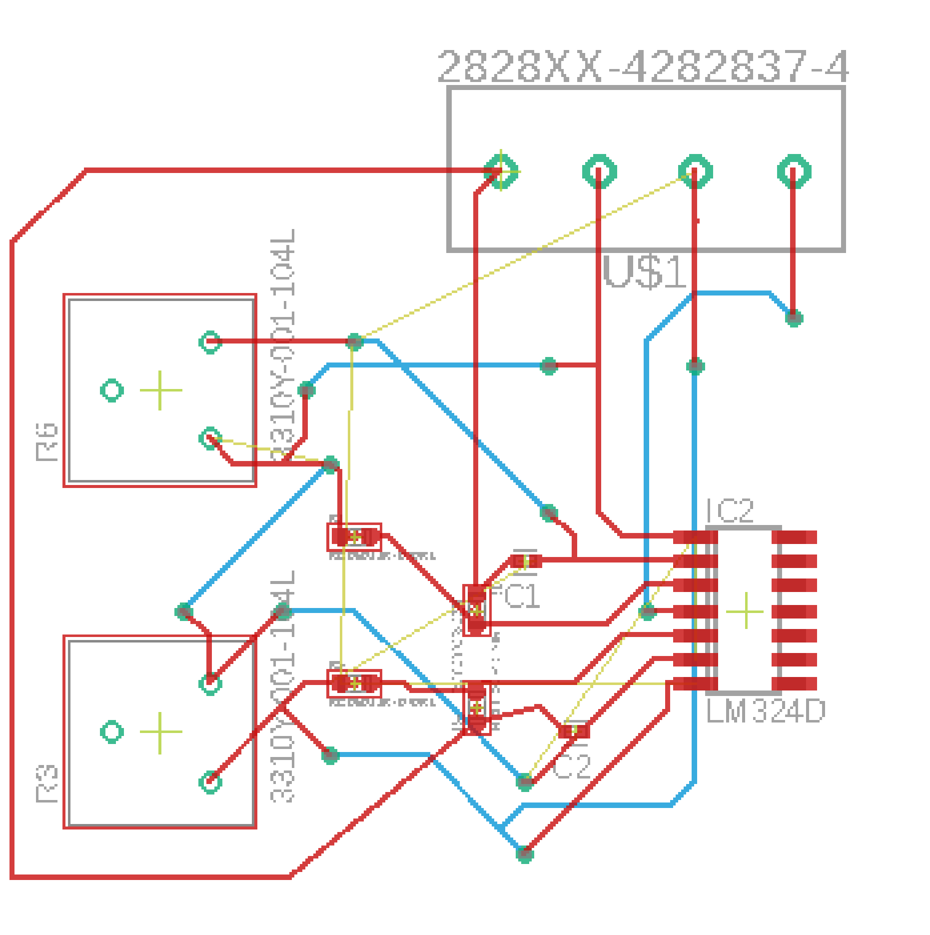

Figure 17: This is the board view of the out to minus connection. In this design it was realized that a direct connection was made between the oscillators. So, the circuit was modified.

It was decided to change from the pair-wise connections and switch to universal couplings. So, Figure 16 was modified. The significant change was the direct connection from the output of the first oscillator to the minus of the second oscillator was removed and a voltage divider was inserted. The divider starts at the outputs of each of the oscillators goes into the divider and then flows into each of the minus connections. The basic idea here is to take the individual outputs, average these voltages, and then feed the average back into each input.

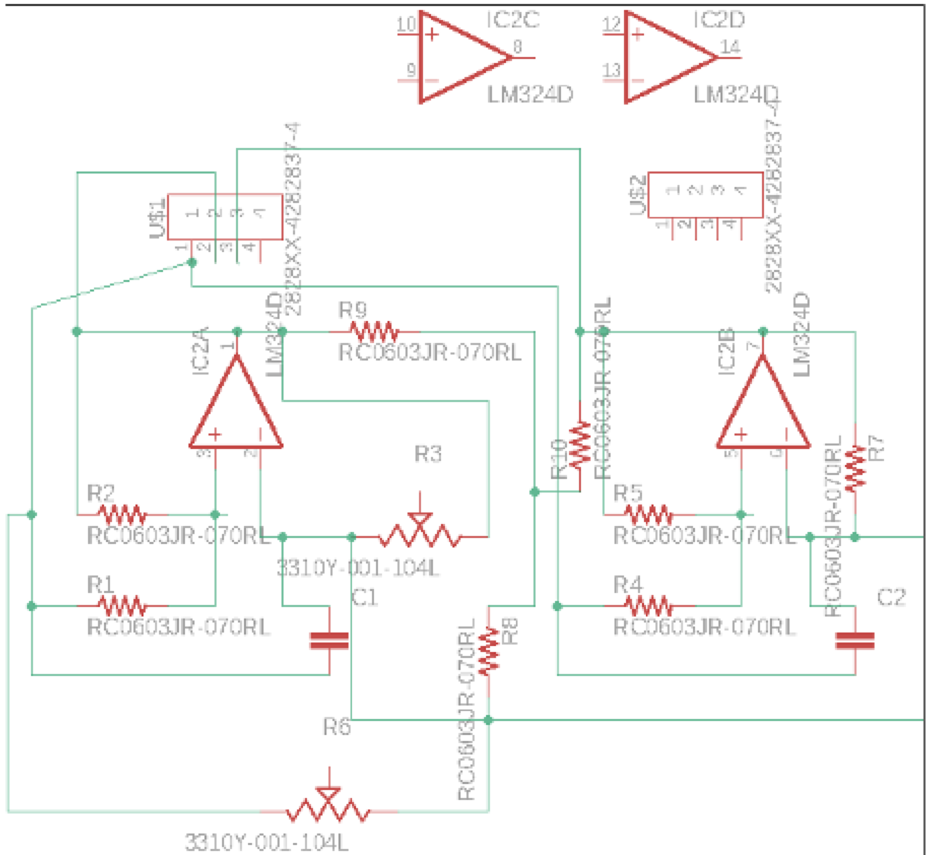

Figure 18: This is the first universal coupling design produced. It is difficult to understand as the connections seem to cross and it is not clear were everything leads. Thus, this was simplified.

The resulting schematic was somewhat difficult to interpret. I redid the schematic to get Figure 19. This looks much cleaner and easier to read. The board design was then created by using the auto route feature in EAGLE. I had to modify the design so that it would be more appropriate to be made by the Voltera machine.

I was not satisfied with the final design in Figure 20. It did not seem as if all the connections were correct. I decided to modify the design yet again. There were a number of changes that happened besides the layout of components in Figure 21. I changed the connection on the potentiometers because originally they were connected so they would have been resistors. Another external wire connector was added and each one was labeled. This way it would be less complicated as to what each of the connections where. Two resistors were removed and an external wire replaced them so the resistance could be varied externally. They are labeled SUM on the external connector.

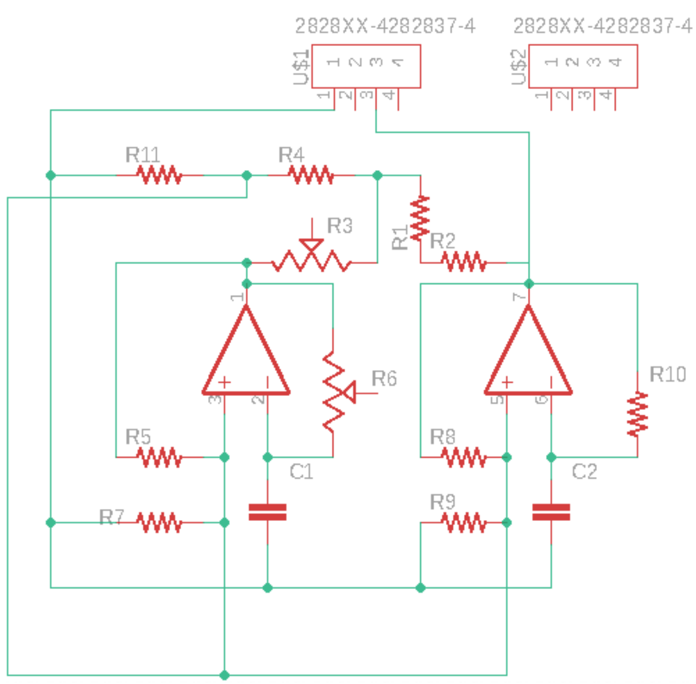

Figure 19: This is the same idea as the first universal coupling but simplified for ease of reading. Thus becoming the second universal design. The voltage divider is at the top, above all the other components and below the external connectors. The oscillator on the right is the basic relaxation oscillator while the one on the left has variable resistors to experiment how the coupling will change.

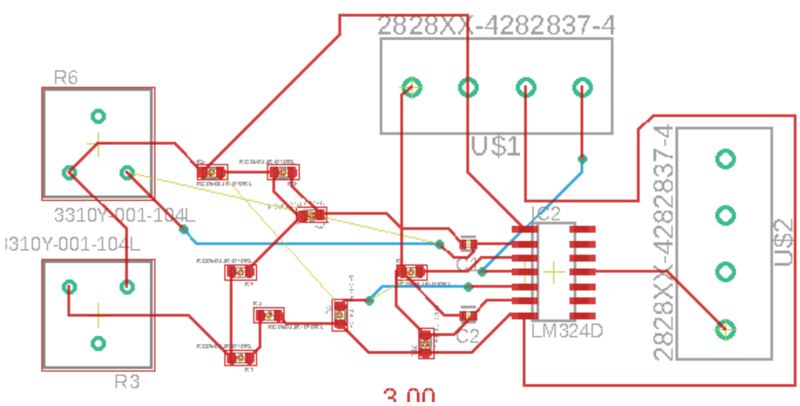

Figure 20: This is the board view of the second universal circuit. In this design all the connections were not placed in the proper position, so another was produced.

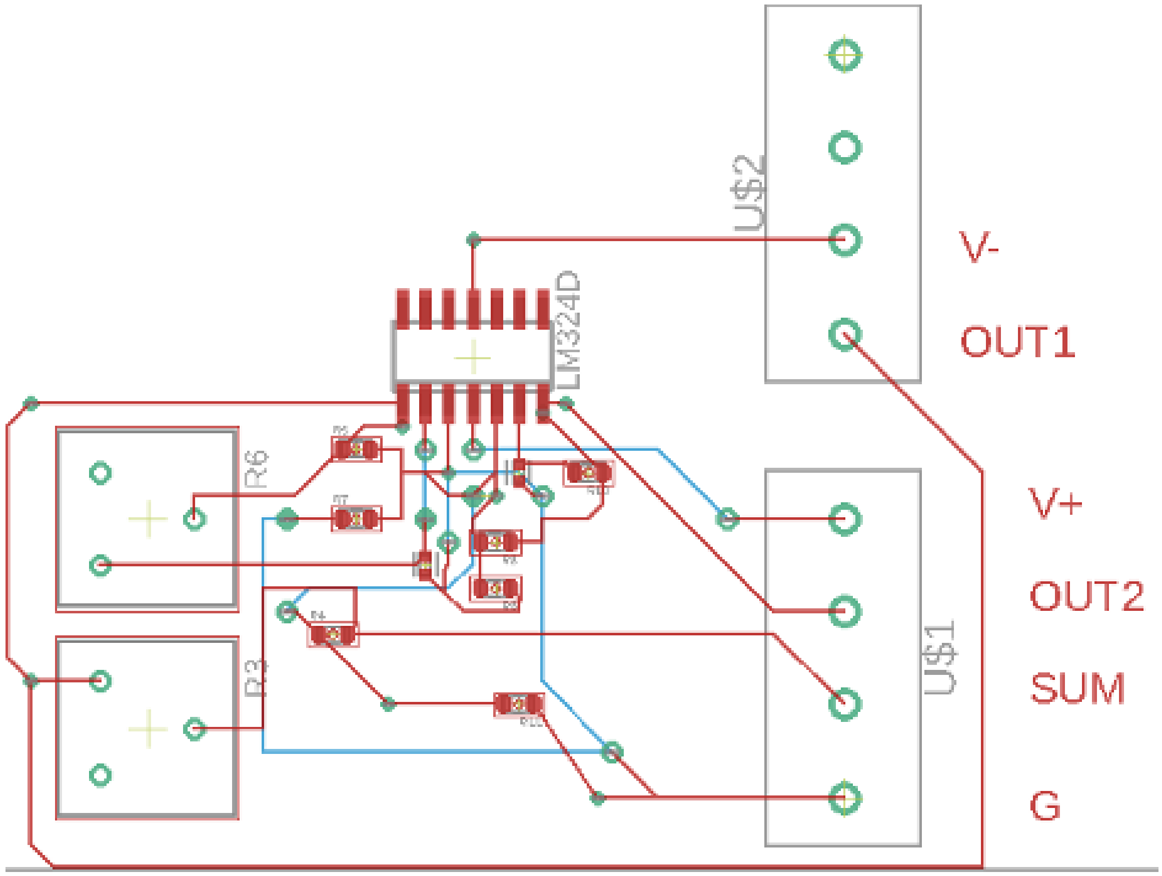

Figure 21: This is the third universal connection board design. The components were rearranged to have fewer holes, and the external connectors were labeled for clarity. In addition the potentiometer connections were altered to allow for variable resistance.

The printing process of this board took an extra step. I had to download the files that I created from EAGLE to put them into the Voltera software. In order to do that, in the board view I clicked the CAM Processor. Then there is a button to save all the files to your computer. It will create a folder called CAMOutput to the location that you chose. I learned later that EAGLE does not automatically flip the back of your board. So, to get around having to pay for the full software, to accomplish this I went back into the CAM Processor and selected the copper bottom file. There was an advanced option then selected the mirror option: to save the new folder of files as CAMOutput Mirror. Mirroring is essential to make sure the top and the bottom of the board line up correctly. Note that with this new folder all of the files will be mirrored not only the copper bottom. There is a way to save only one file or change only one file but you do need to pay for the full version.

Next the files were uploaded to Voltera. Beginning with the top of the board, I downloaded copper-top.gbr and drill.xln from the CAMOutput folder. The ".gbr" is the file name for GTL files, while ".xln" are similar to TXT files refered to in 3.4. Then proceeded to follow the steps outlined on the software. I had a problem when I went to drill .35mm holes. There is not a drill bit that size, so corrections needed to be made in EAGLE. This led me to find out that when you change the size of one via it does not make all the other vias that same size. They were manually changed. This was a quick and easy fix. Then I re-downloaded all the CAMOutput files and CAMOutput Mirror files.

No problems occurred while drilling or inking the board. However rivets fell out of the holes after I had soldered the surface mount pieces. Uncertain as to what caused them to fall out, I believe that if they were not flush with the bottom of the board, then the heat caused them to melt inward and come back out of the hole. In Figure 22 the copper circles are the rivets that stayed while the ones near the chip fell out. Since the rivets in the vias are essential to having a working board, another attempt was made.

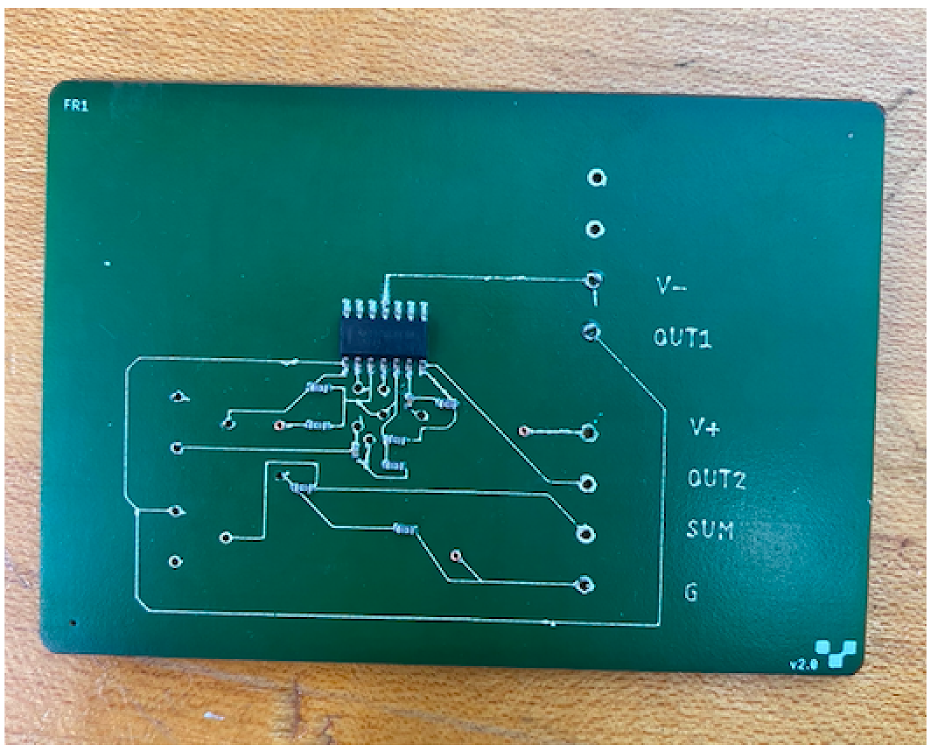

Figure 22: The copper rivets, which provide connections to the top and bottom of the board, fell out after soldering the surface mount pieces. The ones missing are near the chip, but some of the other ones did stay and are still visible.

The second attempt went much smoother. The ink did cover up some of the holes but taking a drill bit that is the same size and poking it through the hole corrects the issue. Once the board was completed, Figure 23, I inspected it and noticed that a capacitor had fallen off. I hand soldered it back on and waited for it to dry and harden over the weekend. Then it was tested, but the chip did not oscillate.

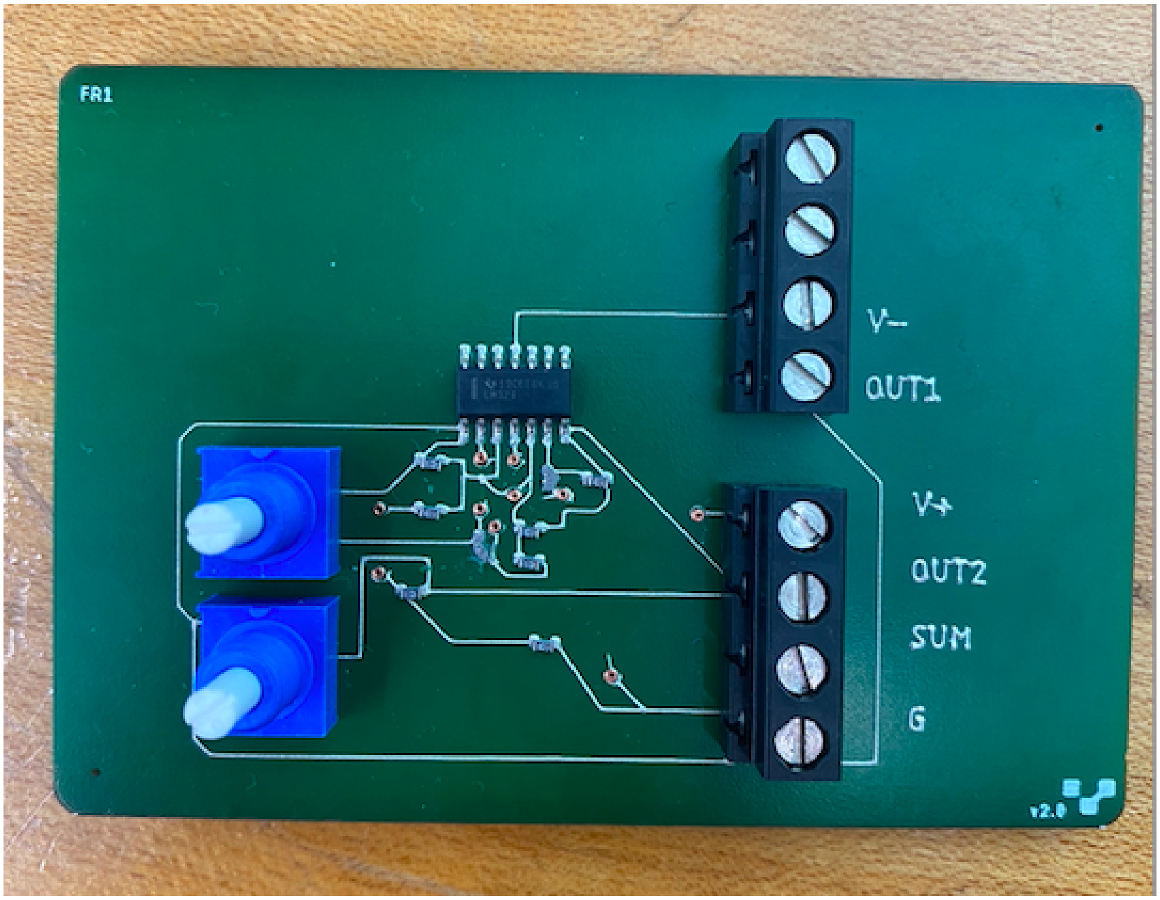

Figure 23: Board with missing capacitors and external connectors

I had to figure out why this PCB had failed. The most obvious reason was that a capacitor had fallen off and another was sticking up from the board. Also, the external connectors have ridges on the bottom of them in between each of the pins. Thus they were not making a solid connection with the conductive ink that was on the board. Hence the circuit was not receiving power and not oscillating on the oscilloscope.

Using a physically larger capacitor eliminated the problem of having it potentially lift off the board. I used the extra 4.7μF capacitors that came with the Hello World circuits. The external connectors were removed from the design and were replaced with holes. Then wires were soldered directly to the board. This eliminated the plastic ridges that prevented the connection. Having a direct wire connection, the board would receive the power that it needs. The result is Figure 24.

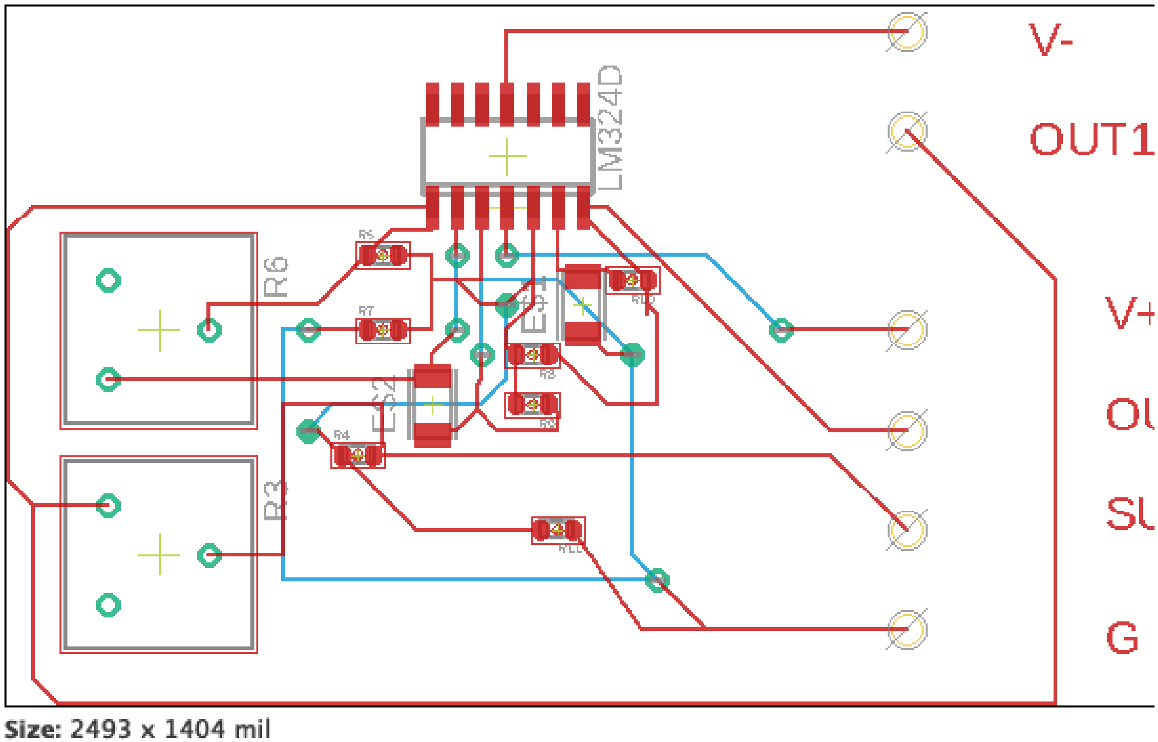

Figure 24: Design with larger capacitors and no external connectors

When it came time to work with the V-One machine, the machine indicated that the hole sizes were yet again all different. I thought I could get away with having the software select the holes that I wanted to drill and manually changing the sizes myself. This was a bad idea, as it caused the probe to crash into the side of a hole. Thus, corrections were made in EAGLE. In EAGLE the largest hole size you can select from the drop down menu is 0.039 inches, but I needed 0.069 inches so I manually typed this in.

In Figure 24, there are no pads for the rivets around the wire entries, so they were inked in by hand. I cut five long pieces of wire from a spool for the board. They were not measured, I approximated how long they were then measured the remaining four pieces off the first one. The final result is Figure 25.

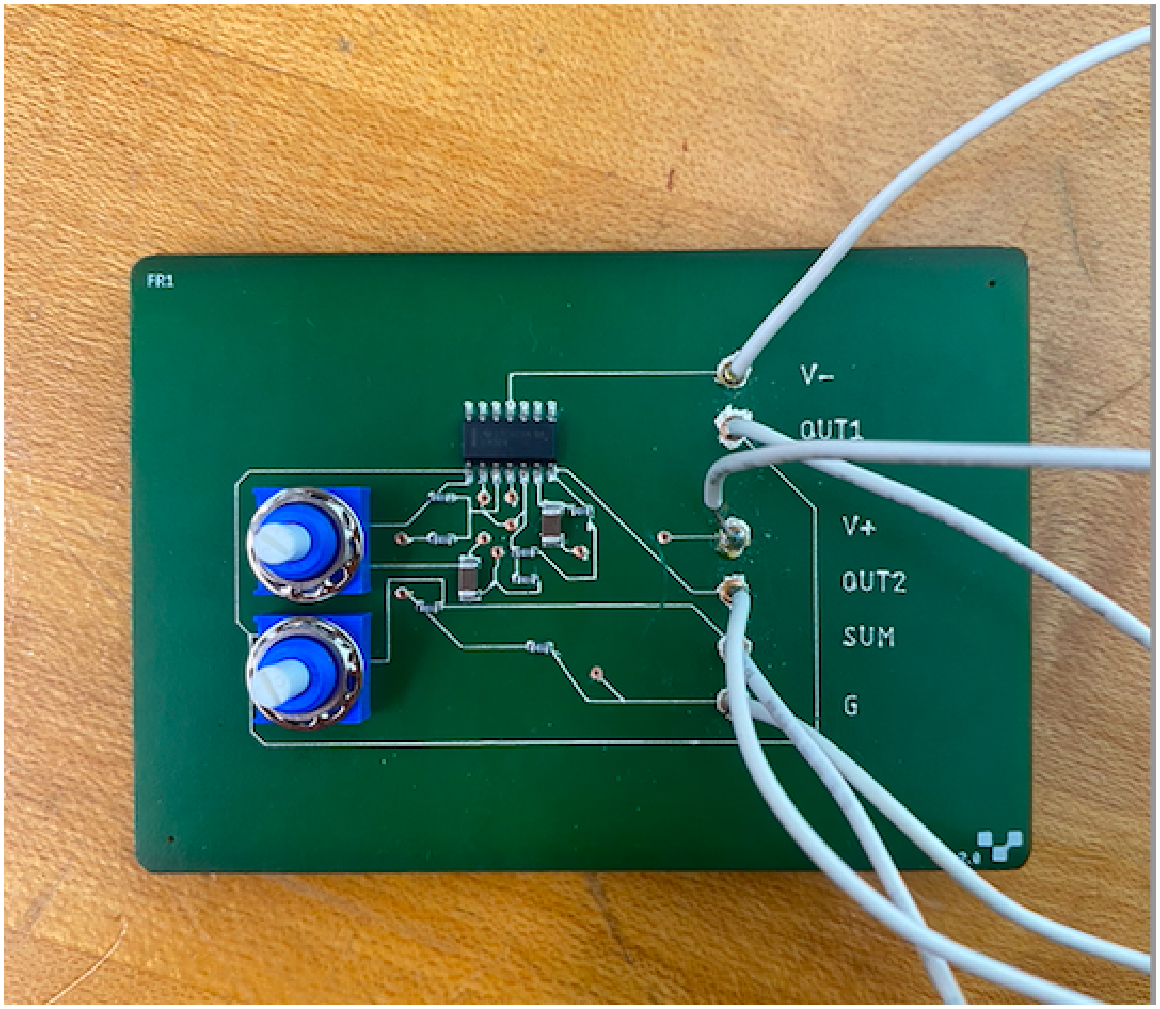

Figure 25: Board with larger capacitors and no external connectors

The board was then tested. It failed. After testing various areas on the board, the wires were re-soldered to the board to see if a better connection could be made. When that had not worked, I flattened the rivets down to the board better. This did not fix the problem either. While I moved to a breadboard to finish the project, ultimately a solution will have to be found to reliably create a PCB; then many oscillators can be integrated. Also, it is easier to collect data from them by adding ribbon cable connectors for mass observation on an oscilloscope.

3.6 Breadboard Usage

The focus was shifted to making the circuit on the breadboard. I decided to scale up the number of oscillators that I had from two to four, illustrated in Figure 26. The black ink is the original op-amp design, but I turned the board into a voltage adder, which is what you see in blue. The pink is where the oscilloscope connections were placed.

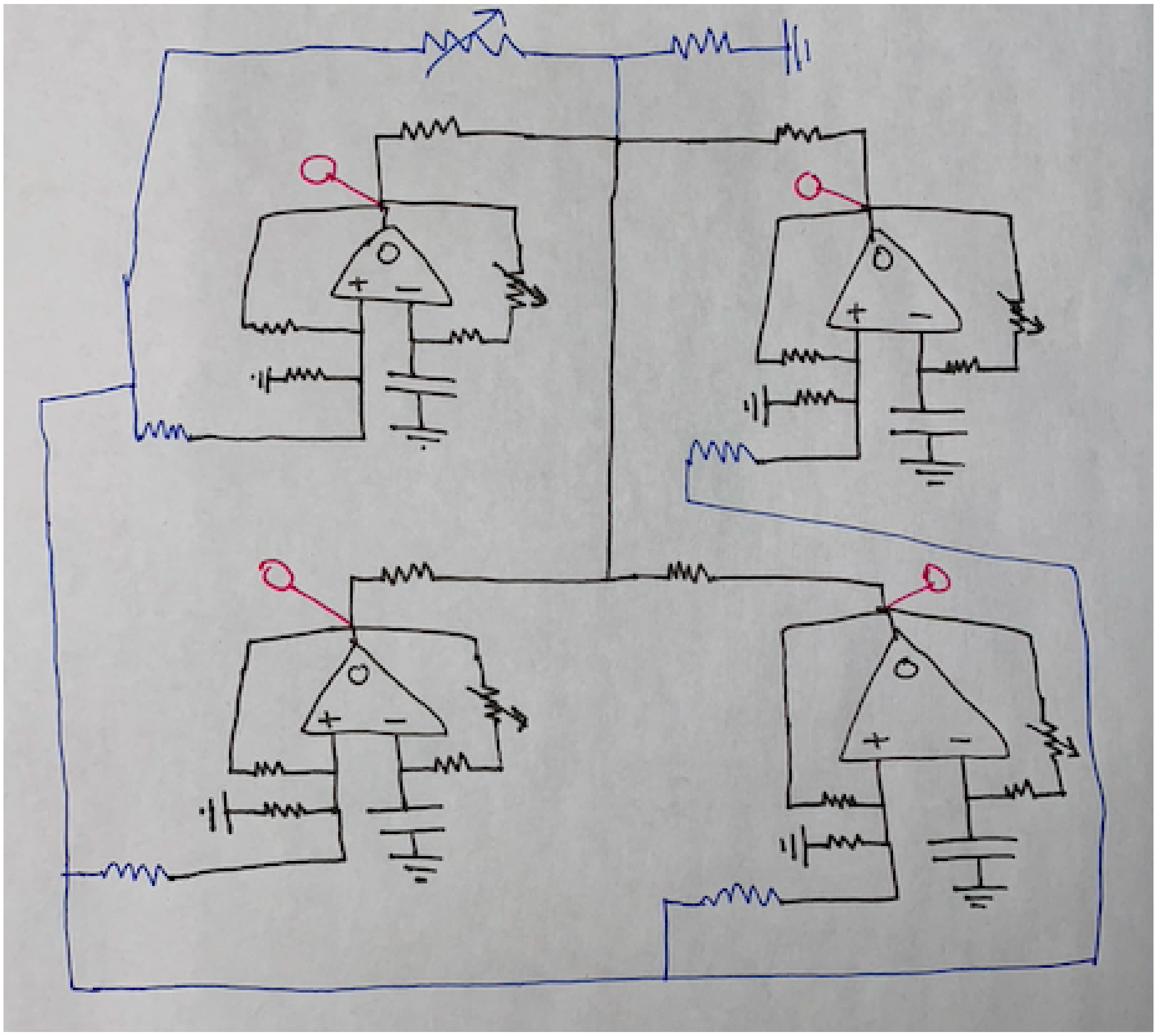

Figure 26: This is the schematic for the breadboard circuit. The black is the original design. The blue is the newly added voltage adder while the pink is where the oscilloscope connections were placed.

Creating the breadboard design was simple, and was completed within two hours. Figure 27 has the finished board that was tested for results.

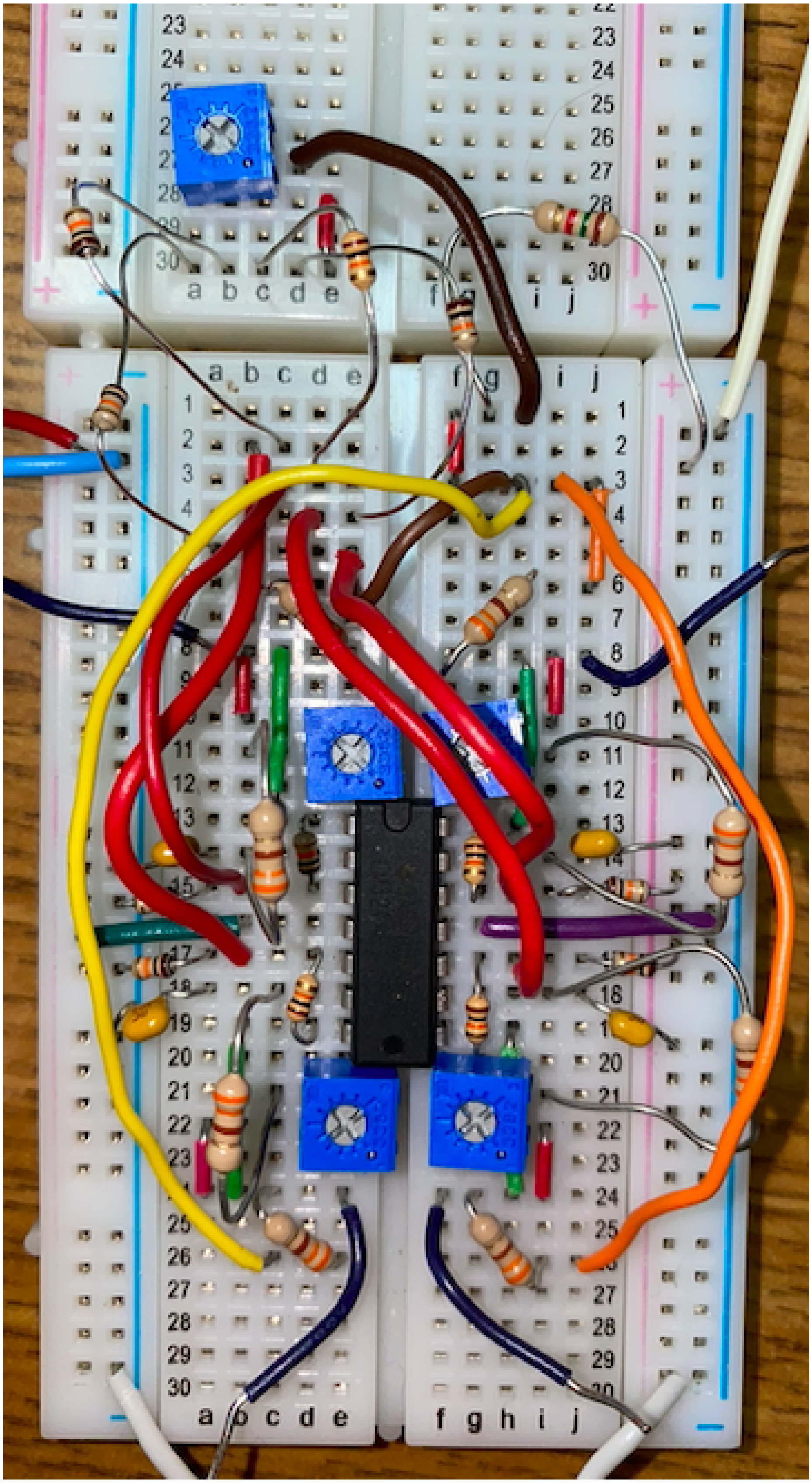

Figure 27: Board of four oscillator design

4 Discussion

4.1 Results

The first column of the Tables 2-4 enumerate the various experimental conditions that were examined. Columns two through five are the coupled frequency of each of the oscillators. Columns six through nine are the natural frequency of each oscillator and these represent the experimental parameters that were selected in each run via the potentiometer settings (note that these are averaged). In tests one through five, I changed the natural frequency of the first oscillator. In tests six through ten, I changed the natural frequency of the second oscillator. In tests eleven through fourteen, I changed the natural frequency of the third oscillator. In tests fifteen through eighteen, I changed the frequency of the fourth oscillator.

Then I tried changing two oscillators at a time. I turned the first oscillator frequency to where I saw a stable phase-locking, then I turned the second oscillator frequency until I saw another stable phase-locking. Once the second oscillator would reach its maximum, I reset it to the base test and then turned the first oscillator up to the next frequency in which I saw a different phase-locking. Then I started again by turning the second oscillator frequency. I got through all of the frequencies with two oscillators. I repeated a similar process with three oscillators and started to work on four.

	Coupled Frequency (Hz)				Natural Frequency (Hz)			
Test	1	2	3	4	1	2	3	4
Base	882.1	882.1	882.1	882.1	1221	1213	1168	1183
1	1175	1174	1175	1175	1807	1213	1168	1183
2	1780	1028	1026	1029	2456	1213	1168	1183
3	2136	935.9	935.1	935.7	3117	1213	1168	1183
4	3338	1157	1155	1156	2456	1213	1168	1183
5	7596	972.6	972.5	972.2	6175	1213	1168	1183
6	1194	1301	1198	1201	1221	1967	1168	1183
7	1042	2882	1042	1042	1221	2281	1168	1183
8	972.1	1894	971.8	971.6	1221	3117	1168	1183
9	1171	4765	1162	1164	1221	4065	1168	1183
10	976.0	1787	975.5	975.6	1221	6218	1168	1183
11	1197	1198	1199	1198	1221	1213	1256	1183
12	1033	1033	3052	1033	1221	1213	1344	1183
13	867.5	867.0	2422	867.6	1221	1213	1585	1183
14	972.9	973.0	1788	973.3	1221	1213	6199	1183
15	1198	1198	1199	1199	1221	1213	1168	1270
16	1041	1041	1041	2757	1221	1213	1168	1452
17	979.0	978.6	978.2	3490	1221	1213	1168	1664
18	961.9	962.2	962.2	2393	1221	1213	1168	6160
19	1473	1473	1473	1473	1807	2110	1168	1183
20	1786	1788	1786	1788	1807	2784	1168	1183
21	1771	5236	1781	1779	1807	3591	1168	1183
22	1331	3625	1331	1331	1807	4065	1168	1183
23	1648	10790	1523	1523	1807	6218	1168	1183
24	2485	1310	1316	1311	2900	1748	1168	1183
25	1955	1954	1953	1955	2900	2110	1168	1183
26	2950	3044	1048	1048	2900	3591	1168	1183
27	2471	7608	962.9	962.9	2900	6218	1168	1183
28	4454	1231	1230	1230	3805	1825	1168	1183
29	3693	3748	1051	1051	3805	2784	1168	1183

Table 2: Board Observations Part 1

	Coupled Frequency (Hz)				Natural Frequency (Hz)			
Test	1	2	3	4	1	2	3	4
30	4292	5979	1303	1303	3805	6218	1168	1183
31	2388	1309	1308	1309	6175	1748	1168	1183
32	6720	2062	1306	1306	6175	2784	1168	1183
33	4786	4941	1137	1137	6175	4065	1168	1183
34	6975	6842	1207	1207	6175	6218	1168	1183
35	1994	1993	1994	1995	1807	2110	3437	1183
36	1752	1751	7369	1751	1807	2110	6199	1183
37	2208	2208	2208	2206	1807	3117	3437	1183
38	2685	2681	2681	2682	1807	3117	3897	1183
39	2178	2468	3633	2171	1807	3117	6199	1183
40	1731	4996	1729	1729	1807	4065	2296	1183
41	2673	2676	2676	2676	1807	4065	3897	1183
42	2137	3875	6933	2124	1807	4065	6199	1183
43	1622	7515	1622	1621	1807	6218	1344	1183
44	2087	2888	2087	2087	1807	6218	3437	1183
45	1928	5022	5029	1927	1807	6218	6199	1183
46	1868	1868	1870	1869	3591	3437	1927	1183
47	2227	2228	2227	2229	3591	1672	3437	1183
48	2425	2424	3890	2422	3591	1672	5278	1183
49	2276	2275	2275	2275	3591	3117	2977	1183
50	2488	2490	3874	2491	3591	3117	5278	1183
51	2288	3561	2130	2139	3591	6218	1780	1183
52	2241	6061	2239	2278	3591	6218	2517	1183
53	2995	7092	2994	2995	3591	6218	4358	1183
54	3415	1763	1764	1763	4397	1967	2296	1183
55	6431	2187	2188	2188	4397	1967	2517	1183
56	2974	2975	2974	2976	4397	1967	4358	1183
57	3150	2319	2389	2476	4397	2452	1927	1183
58	3081	3082	3083	3085	4397	2452	4358	1183
59	7593	2048	2045	2047	6175	1825	2977	1183

Table 3: Board Observations Part 2

	Coupled Frequency (Hz)				Natural Frequency (Hz)			
Test	1	2	3	4	1	2	3	4
60	2806	2052	2050	2052	6175	1682	2075	1183
61	6714	5245	1384	1383	6175	4065	1464	1183
62	6178	3735	1973	1972	6175	4065	1927	1183
63	8484	3098	3100	3100	6175	4065	3897	1183
64	5723	5685	5595	1723	6175	4065	6199	1183
65	2318	2321	2322	2317	1807	2110	3437	3334
66	2477	2477	2477	4766	1807	2110	3437	5218
67	1941	1942	5247	6386	1807	2110	6199	6160
68	3002	3003	3001	3003	1807	3117	3437	5218
69	3423	3420	5831	3426	1807	3117	6199	4276
70	3075	3077	6821	6859	1807	3117	6199	6160

Table 4: Board Observations Part 3

4.2 Analysis

I started the testing by creating a base case. For the base case all the potentiometers were all set to their highest resistance values yielding the lowest oscillation frequencies (see Figure 30). In Figure 29, we see that all the oscillators are in phase. All four oscillators create nice square waves. This is what I call my base test to which I compared my subsequent data. Note that in the figures oscillator one is yellow, two is blue, three is purple, four is green, and that their coupled frequencies are listed on the right side of the screen.

First, an interesting note is that coupling lowers the frequency when in the base case. I believe that it is because the resistor that is feeding the coupling back into the plus input is a voltage adder. Normally, $V_+ = \frac{V_{out}}{2}$. Where normally the resistance is R, but we have an extra resistor, R_{couple}, which can be represented by $R_{couple} < R$. R_{couple} is not much smaller than R, but is enough to notice a difference. This changes our V_+ to, $V_+ = \frac{R}{R_{couple}+R}V_{out}$. Thus now $V_+ > \frac{V_{out}}{2}$. This lowers the frequency of the synchronized oscillators relative to their uncoupled frequency.

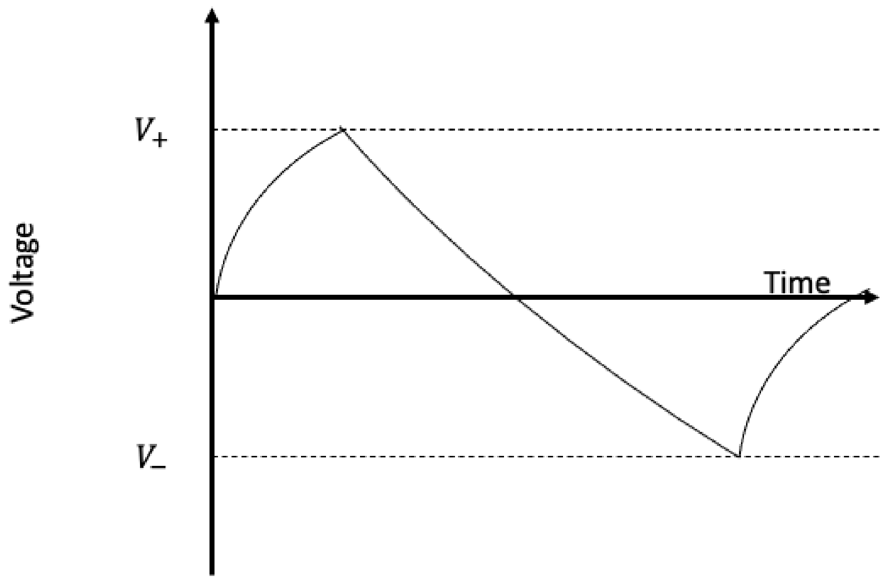

Figure 28: Voltage over time

In Figure 28, we see how the frequency will change with this new relationship. When V_+ is shifted up (as it is in this case) or V_- is shifted down, it takes longer to reach those voltages, which in turn lowers the frequency.

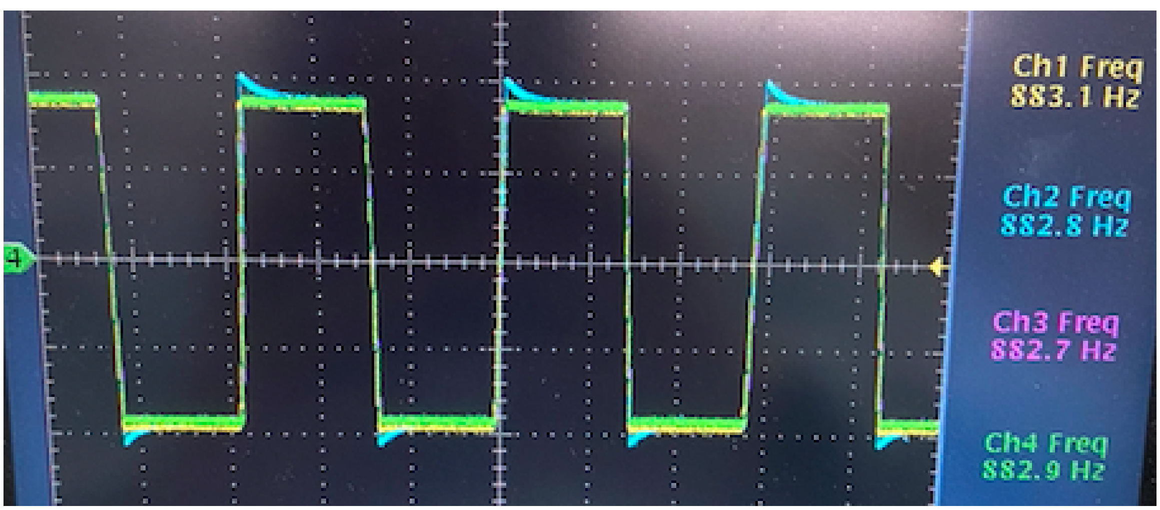

Figure 29: This is the base test traces. On the right Ch1 Freq: 883.1 Hz, Ch2 Freq: 882.8 Hz, Ch3 Freq: 882.7 Hz, Ch4 Freq: 882.9 Hz. The purple trace is underneath the other traces.

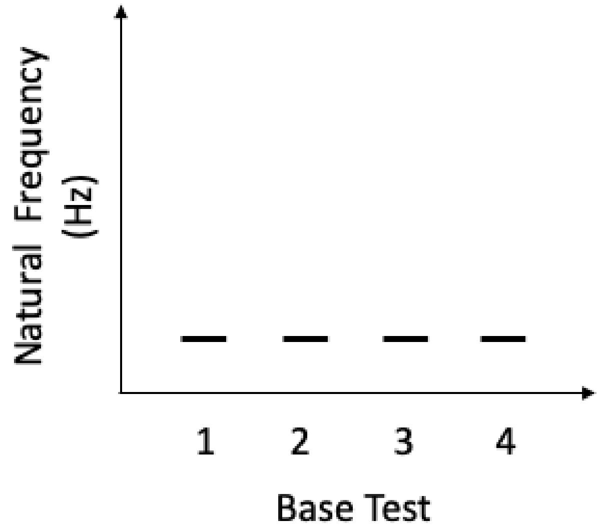

Figure 30: The natural frequencies of the oscillators during base test were all at the lowest point.

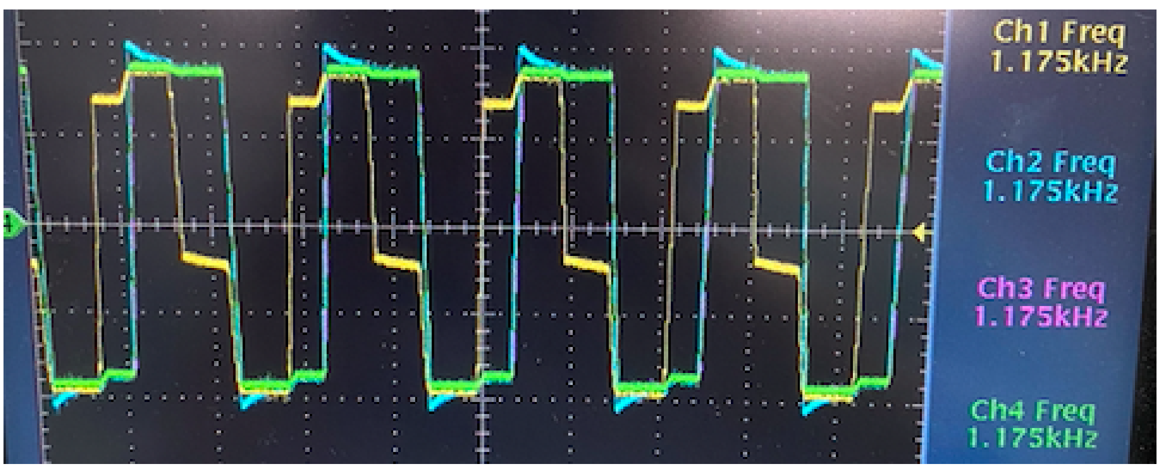

Figure 31: This is test 1. On the right Ch1 Freq: 1.175 kHz, Ch2 Freq: 1.175 kHz, Ch3 Freq: 1.175 kHz, Ch4 Freq: 1.175 kHz. The yellow trace is leading the others but there is a delay which is causing a step-like pattern.

In Figure 31, we see that the yellow oscillator tends to be a little faster than the rest of the oscillators. But the average of all the oscillators does not allow it to do so, hence it stays at the same frequency but starts leading "the pack" in phase. Due to the influence of coupling, this lead in phase creates the steps that you see in the traces. When all the oscillators are negative (at the bottom) and then yellow flips to be positive, you see that the rest of the oscillators are also brought up slightly. You also notice that the yellow oscillator is not able to make it to the rail voltage in the positive because the rest of the oscillators are still in the negative, hence bringing down the average. A similar effect happens when the yellow drops down again before the rest can follow. The yellow does not become a negative voltage but there is a slight shift down in the others because the average has changed. This is producing an one-to-one phase-locked relationship. The change from the base test is that the first oscillator's frequency was raised slightly, Figure 32.

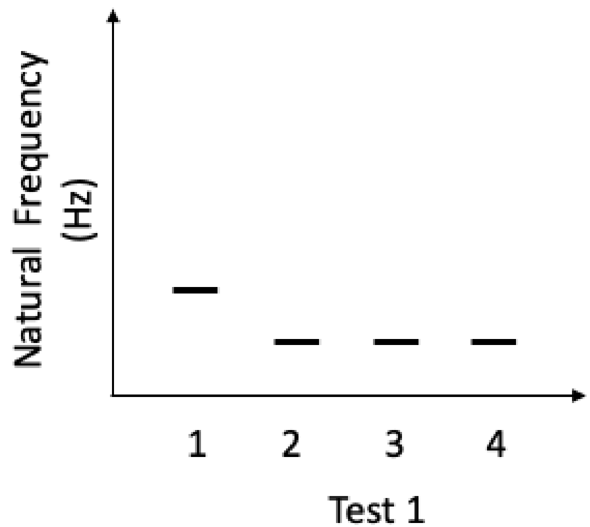

Figure 32: The natural frequencies of the oscillators during test 1 where the first oscillator's frequency was slightly raised.

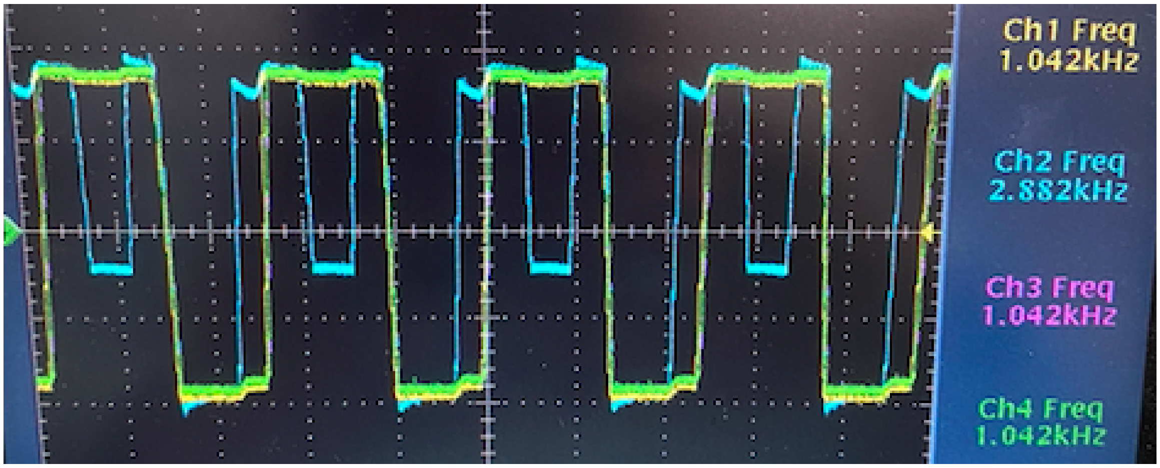

Figure 33: This is test 7. On the right Ch1 Freq: 1.042 kHz, Ch2 Freq: 2.882 kHz, Ch3 Freq: 1.042 kHz, Ch4 Freq: 1.042 kHz. The blue trace is in a two-to-one pattern with the other oscillators.

In Figure 33, a two-to-one phase-locked relationship is displayed. Here the blue oscillator peaks twice for every one peak that the rest of the oscillators complete. The change from the base test is the second oscillator's frequency was raised, Figure 34.

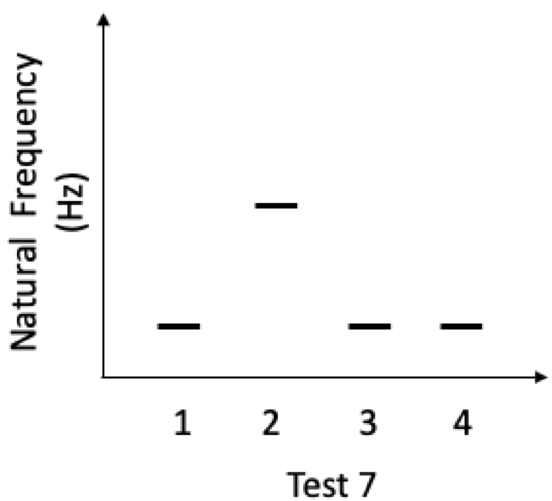

Figure 34: The natural frequencies of the oscillators during test 7 where the second oscillator's frequency was raised. The numbering of the oscillators is arbitrary, what matters is how they differ from the base test.

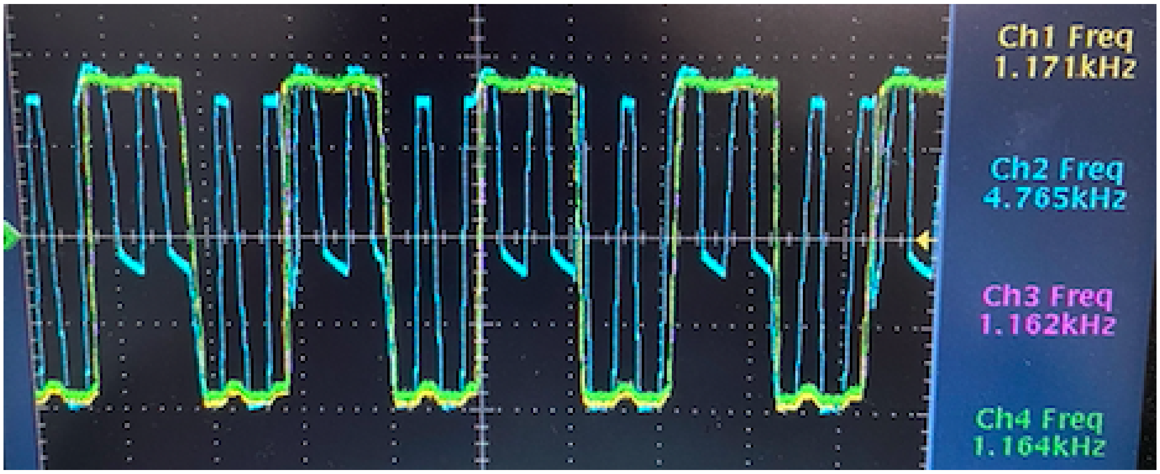

Figure 35: This is test 9. On the right Ch1 Freq: 1.171 kHz, Ch2 Freq: 4.765 kHz, Ch3 Freq: 1.162 kHz, Ch4 Freq: 1.164 kHz. The blue trace is in a three-to-one pattern with the other oscillators.

In Figure 35, a three-to-one phase-locked relationship is displayed. Here the blue oscillator peaks three times for every one peak that the rest of the oscillators complete. The change from the base test is that the second oscillator's frequency is nearly at its maximum value, Figure 36.

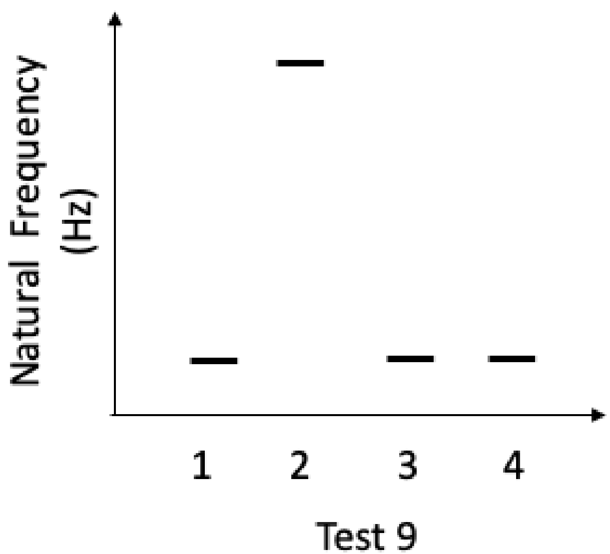

Figure 36: The natural frequencies of the oscillators during test 9 where the second oscillator's frequency was nearly maxed out.

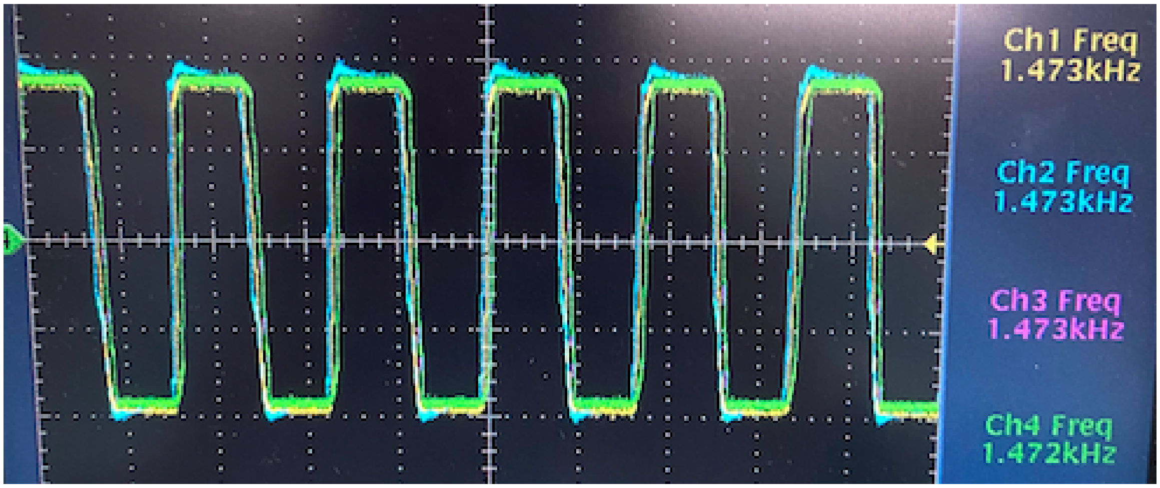

Figure 37: This is test 19. On the right Ch1 Freq: 1.473 kHz, Ch2 Freq: 1.473 kHz, Ch3 Freq: 1.473 kHz, Ch4 Freq: 1.472 kHz. All the traces are in sync and phased-locked with each other creating new square waves similar to the base test.

In Figure 37, a one-to-one, in sync, phase-locked relationship (they are in phase) is displayed. Here all the oscillators peak at the same time. The relationship looks nearly identical to the base test but oscillator one's frequency is high and oscillator two also has a different frequency, Figure 38. Oscillator two acts like a middle ground for all the frequencies to work together. This is very similar to when a person is trying to jump to a higher platform, but it is too high to physically jump up. Then they use a platform about half way to jump up to the higher platform without a problem, Figure 39. With the presence of frequencies, the middle "platform" draws oscillator one down and oscillators three and four up, even though their frequencies were not raised. Thus, making all the frequencies level.

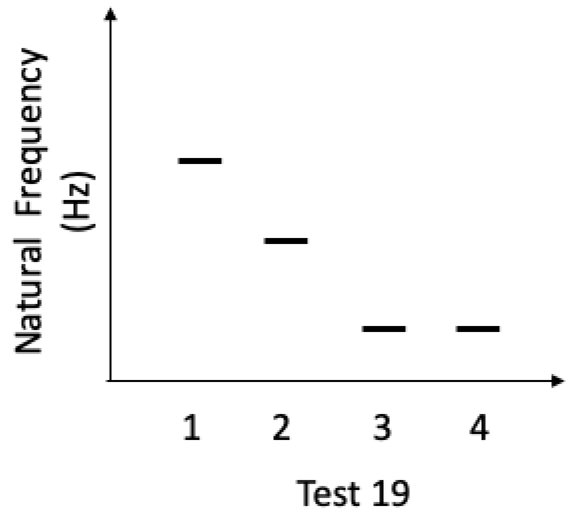

Figure 38: The natural frequencies of the oscillators during test 19 where the first oscillator's frequency was is raised above half way and the second oscillator's frequency is raised below half way. The other two are the same as the base test.

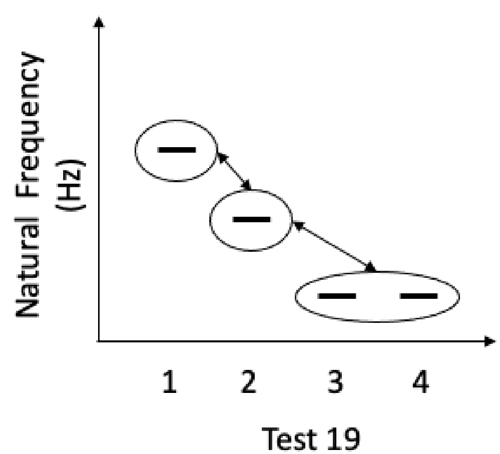

Figure 39: The frequency levels are similar to jumping up platforms. When the top is to high to physically jump, a middle platform is added to make it possible. In the case of the oscillators, the middle frequency pull the first down and the others up.

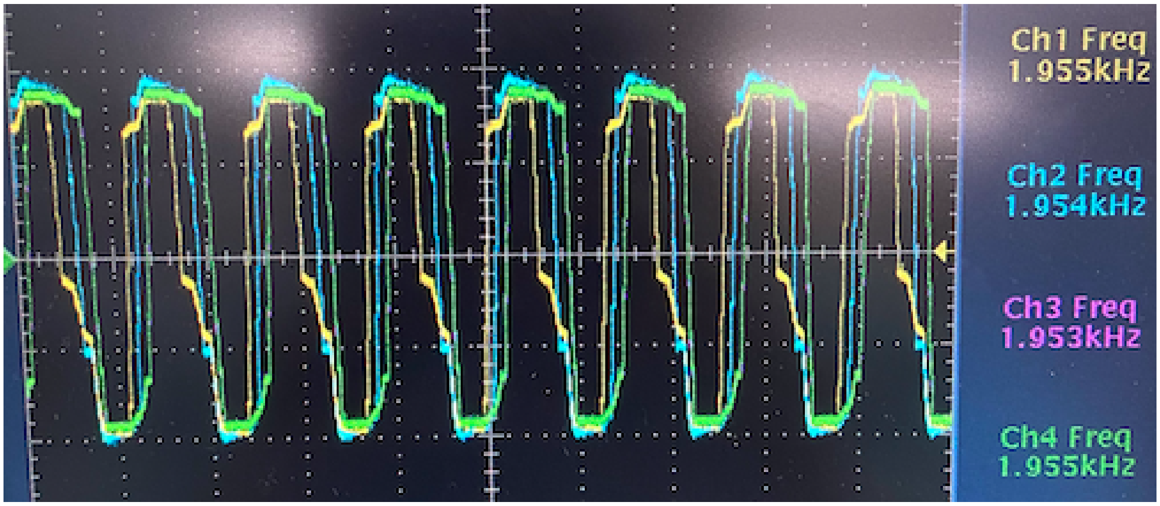

Figure 40: This is test 25. On the right Ch1 Freq: 1.955 kHz, Ch2 Freq: 1.954 kHz, Ch3 Freq: 1.953 kHz, Ch4 Freq: 1.955 kHz. This is similar to test 1 where the first oscillator is leading the others but they lag slightly behind creating the step.

In Figure 40, a one-to-one, phase-locked relationship is displayed. This particular test is very interesting because oscillator three and four have doubled their frequencies and their natural frequencies have not changed from the base test, Figure 41. This test represents the upper limit to which oscillators three and four can be stretched.

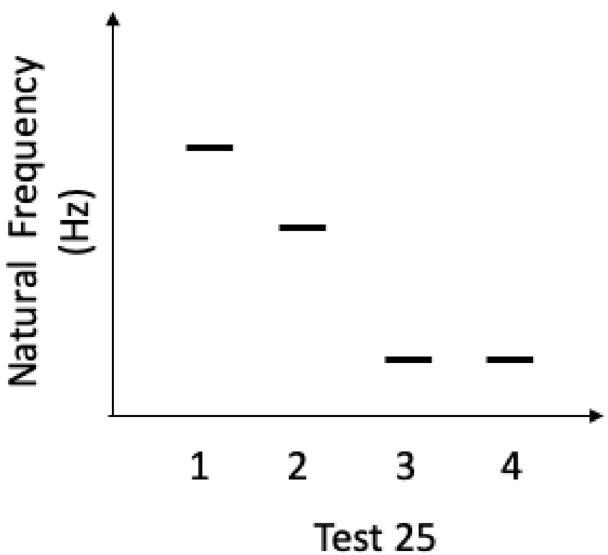

Figure 41: The natural frequencies of the oscillators during test 25 where the frequencies of one and two are slightly higher than they were in test 19. This creates the step-like pattern.

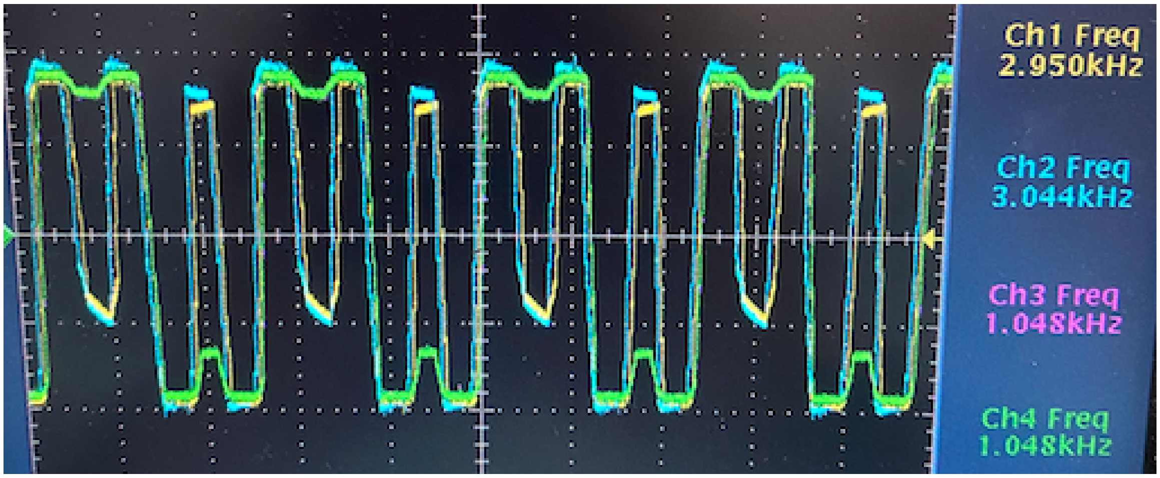

Figure 42: This is test 26. On the right Ch1 Freq: 2.950 kHz, Ch2 Freq: 3.044 kHz, Ch3 Freq: 1.048 kHz, Ch4 Freq: 1.048 kHz. Here the oscillators broke off into two groups. The yellow trace and blue trace are together, creating a three-to-one pattern.

In Figure 42, you see that the oscillators break off into two groups. Oscillators one and two peak three times to oscillators three and four's one peak. This happens because one and two's natural frequencies are much higher than three and four compared to the base test, Figure 43

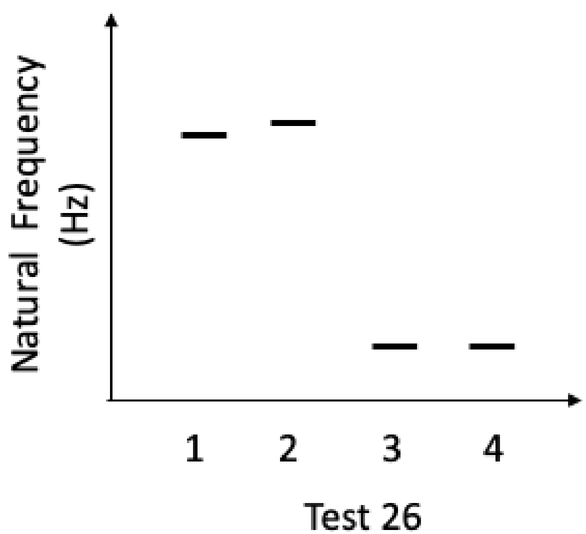

Figure 43: The natural frequencies of the oscillators during test 26 where the frequencies of one and two are significantly higher than the others. Thus, creating the two groupings.

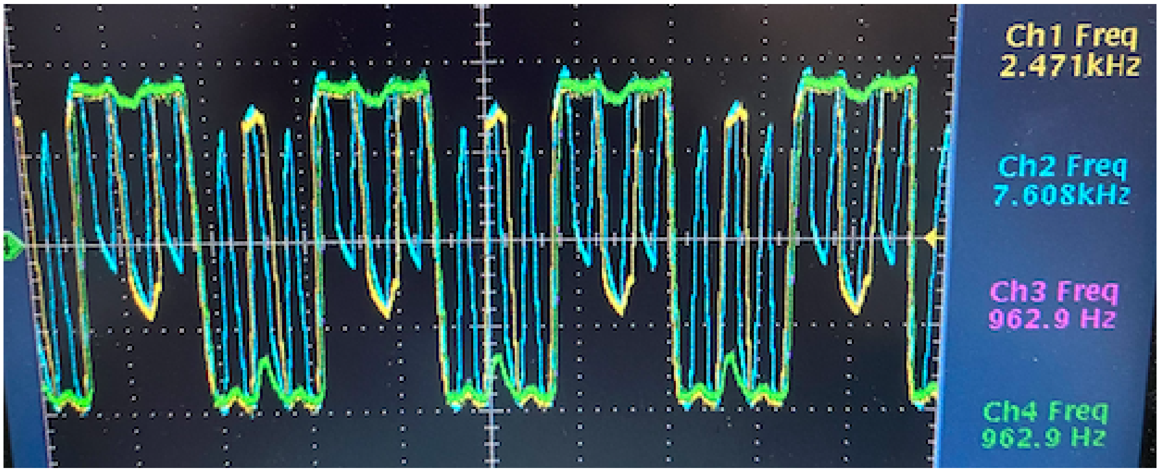

Figure 44: This is test 27. On the right Ch1 Freq: 2.471 kHz, Ch2 Freq: 7.608 kHz, Ch3 Freq: 962.9 Hz, Ch4 Freq: 962.9 Hz. Here oscillators one and two are now separated from each other. The yellow trace is in a three-to-one pattern with the purple and green traces, while the blue trace is in a seven-to-one pattern with the purple and green traces.

In Figure 44 we see three different relationships happening at the same time. Oscillator one compared to three and four is three-to-one, two compared to three and four is seven-to-one, and one compared to two is three-to-seven. This is because the natural frequencies are so far from each other that they want to be phase-locked and this is how they manage to compromise, Figure 45.

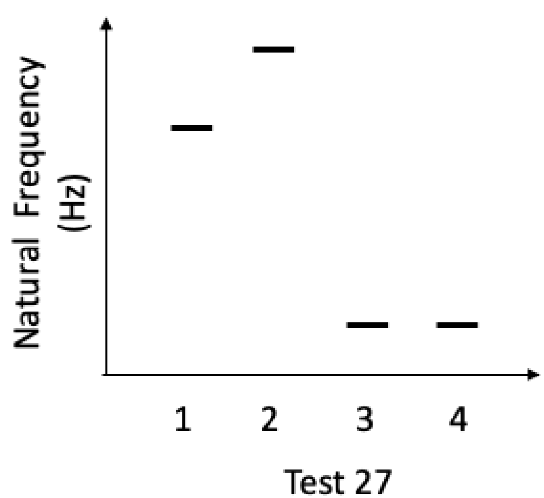

Figure 45: The natural frequencies of the oscillators during test 27 where oscillator two's frequency is at maximum and oscillator one's is much higher than three and four. Oscillators three and four are the same as the base test.

4.3 Suggestions for Further Research

The circuit that I was able to build only had four relaxation oscillators paired in a universal coupling. I would recommend scaling that up to have ten to twenty different oscillators. Then you would be able to see a smoother average acting back on the individual oscillators, akin to a 'mean-field' in condensed matter physics. It would also be interesting to study the effects of varying the universal coupling strength.

I would also suggest trying different couplings. For example, have everything universally connected but take one oscillator out from sending a signal. If you have a large scale you could remove two or three from sending a signal and see how that affects the rest of the system.

Another suggestion is to bring in an external factor. In nature, systems are not in isolation, but have other systems that could change what is happening. Add in a signal dampener or an external driving signal that would change the frequencies of the oscillators. Even self-oscillators can be synced to an external driver given enough coupling to the driver, but this should also depend on the internal dynamics of the oscillators network.

5 Conclusion

5.1 Learned from Voltera and EAGLE

Working with EAGLE takes time, as it can be a complicated software to learn. But, once you can start designing your own circuit, it is a fairly efficient process. You can streamline the work by searching, copy and paste, and use auto route. It even provides all the files that you need to print your board for free.

While I enjoyed working with the Voltera V-One machine, I have concluded that it is not effective to use if you are making a double-sided board. The second Hello World board was the only board that was operational, as every other one had failed. The perfect rivet connection to the board is difficult to make as the whole surface wants to touch the electrical connection. So, if a part of that surface is grounded for any reason then the whole hole becomes grounded. Plus, trying to solder the wires to the board was a challenge as well. The wires do not want to stay touching the metal when the solder comes near, the wires wiggled so that solder would come between the metal connections.

Another downside to the machine is that there are many ways it can fail. There is the possibility of accidentally shifting the board, the ink not drying correctly, the ink may make the board uneven so you have to figure out how to sand it down without ruining the rest of the board, and more. While it is fun to learn the process of making a PCB, I would say it would be simpler to send it to a professional manufacture.

5.2 Oscillations

The breadboard of four oscillator design produced results. I saw that the system tended to be in some type of phase-lock pattern. There were different one-to-one patterns, two-to-one, three-to-one, even a three-to-seven pattern. This tells me that in a biological system, it is likely that many frequencies that would be found. Each frequency would relay different information.

A Operating Equipment and Software

A.1 Basics of EAGLE

I highly recommend that anyone go on to YouTube and watch the large number of videos that have been posted on how to use EAGLE.

When you open EAGLE to create a project you will either start with a schematic view or a board view. Starting with the schematic you will see a screen similar to Figure 46.

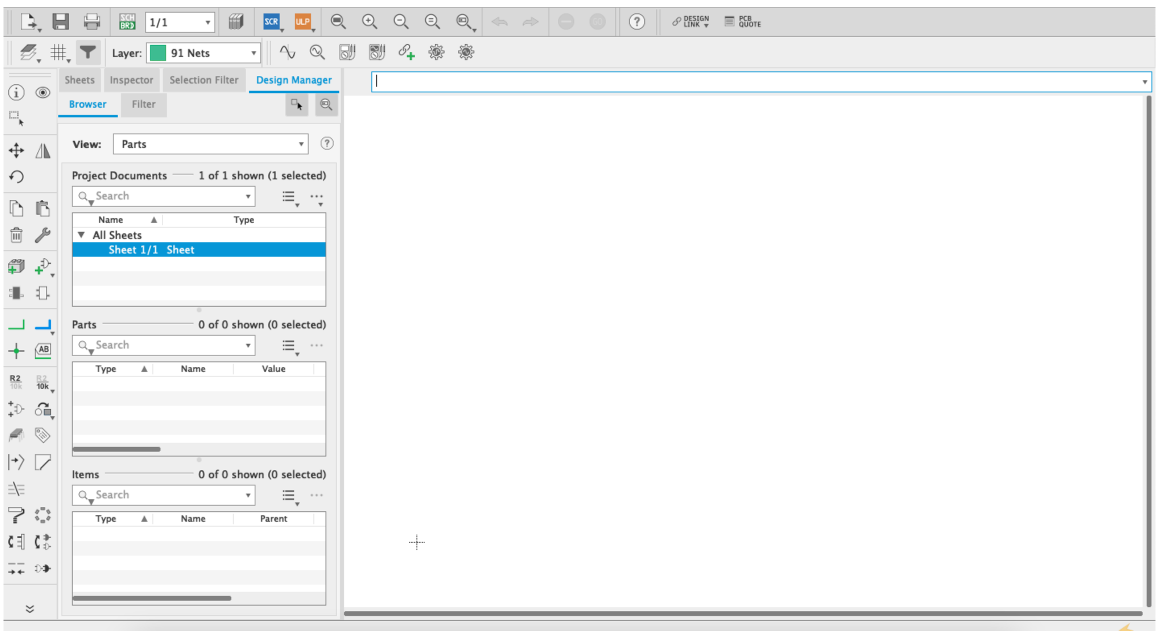

Figure 46: The Schematic View that will pop up once you open this for a project.

You see that on the left side several options and an area for information to go. On the right is a large white area. This area is where you will build the schematic. The built-in library has components like resistors, capacitors and chips. With over a thousand options to choose from, it allows for all types of circuits to be made.

In Figure 47, you can see I made a simple oscillator using parts from EAGLE's library. The parts are now listed on the left side. The connections were made by adding green connection wires to the parts.

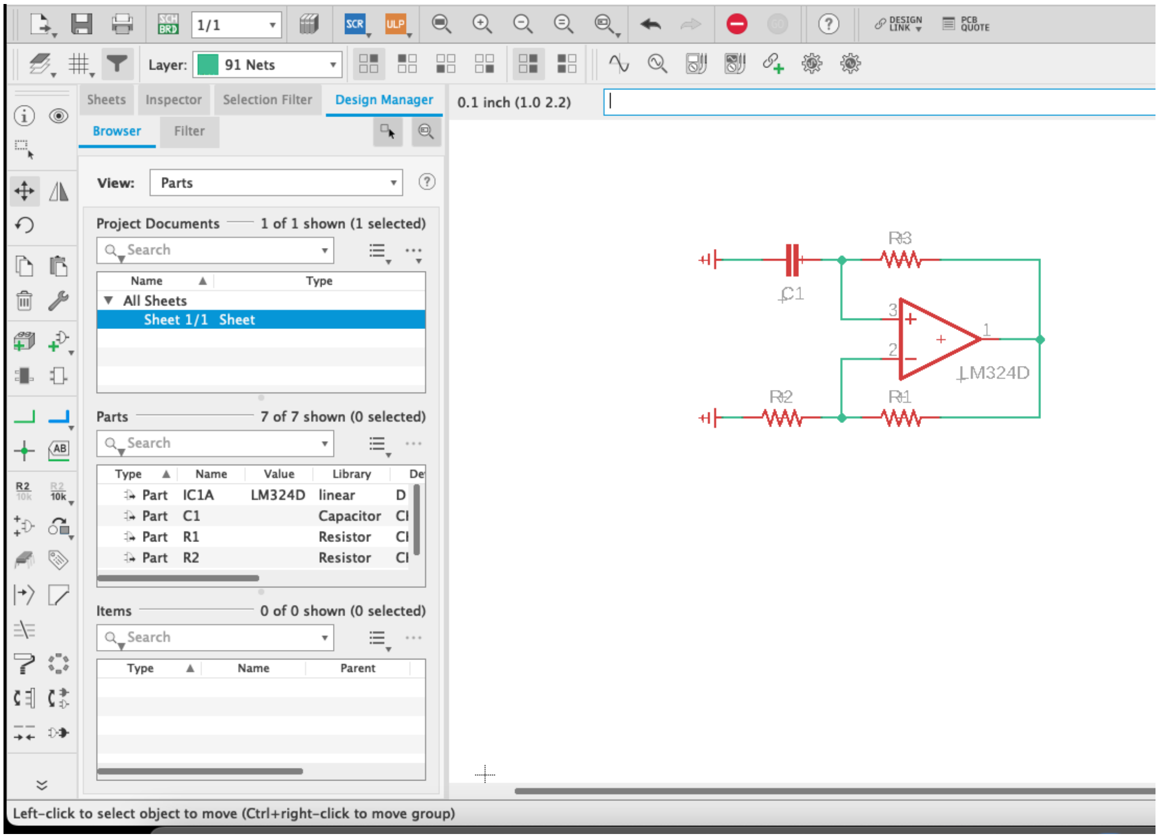

Figure 47: I created a simple relaxation oscillator using components from the EAGLE library

In Figure 48, I converted the schematic I had made and turned it into a board. I did this with a click of a button. You see yellow lines that connect all the components and seem to cross. These are air wires, they are telling you where you need to connect components based on the schematic. The yellow box outline that the components are in, is a part of your board. You can adjust the box to the size of your board to make sure that everything fits. Another option is to use the measurement tool. This will show you the actual size you are using, similar to a ruler.

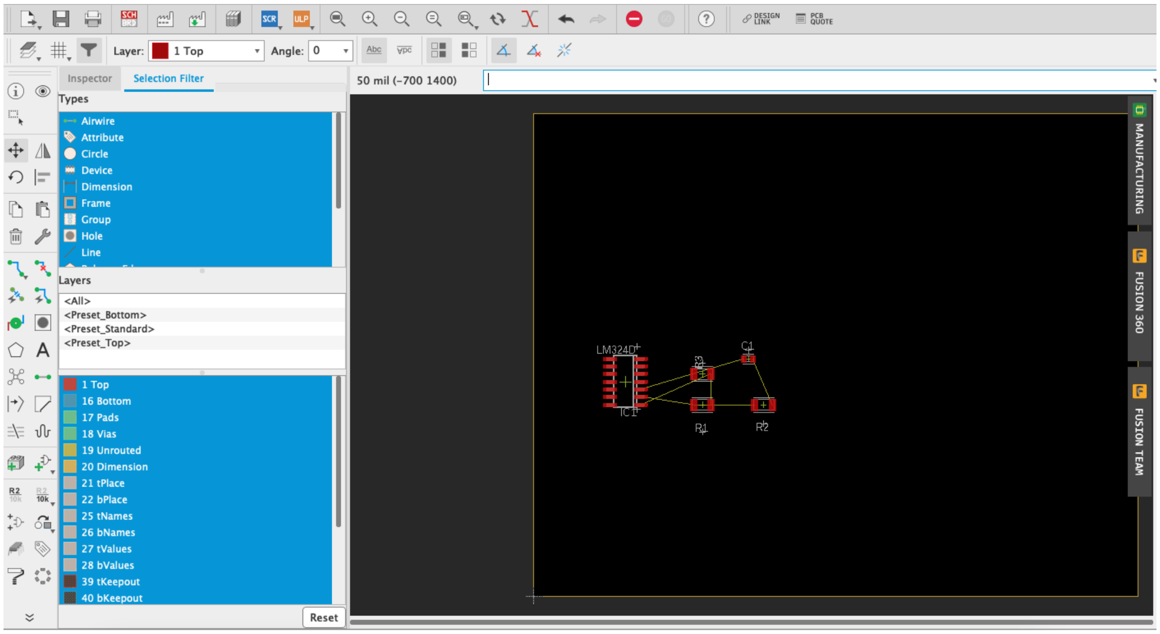

Figure 48: Conversion of the schematic view to board view

In Figure 49, you will see that there are red lines instead of yellow. These are the electrical connections that will be printed onto the board. If you were working on the bottom of the board, they would appear blue. There is also the possibility to have multiple layers, so then other colors would appear for each layer. Also note, there is an auto route feature that will make all the electrical connections for you. But, the program is not perfect and human analysis will be need to fix some of the errors. See Figure 11, in section 3.3 Learning EAGLE.

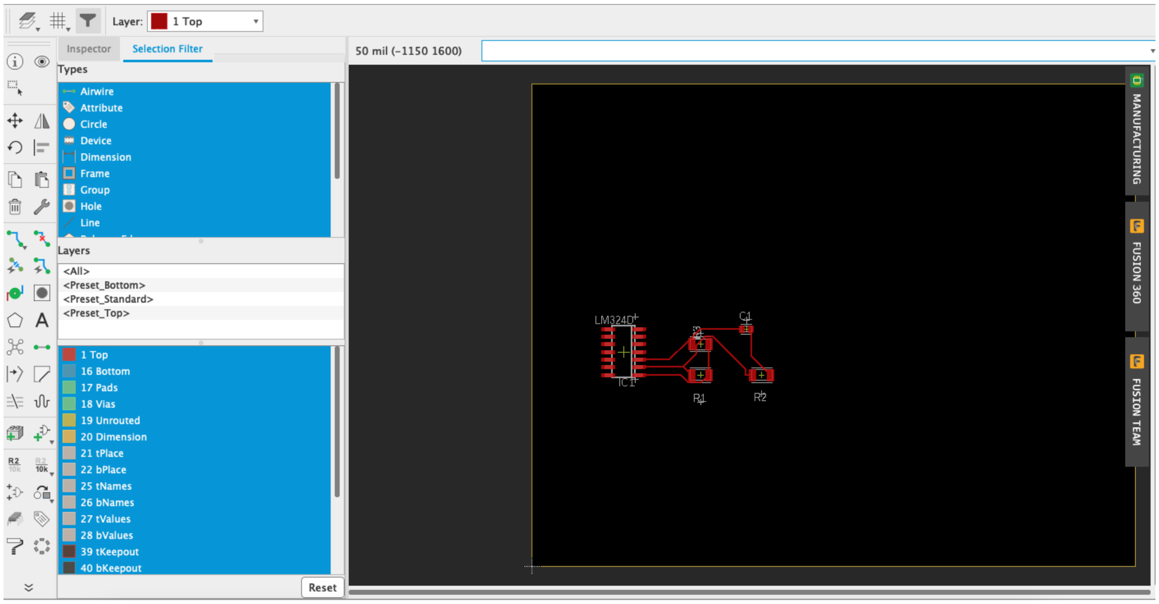

Figure 49: The red lines are the electrical connections to each of the components

The schematic view helps with the design of the board. This is the view where we see and understand all the connections. It also helps with understanding the implementation of a circuit. The board view is what the circuit is going to look like physically. It is not as easy to understand what is going on in the circuit as it is in a schematic view. Both view are helpful when it comes to creating a PCB as the board view is what you will have printed.

A.2 How to Use the Voltera V-One

A.2.1 Software

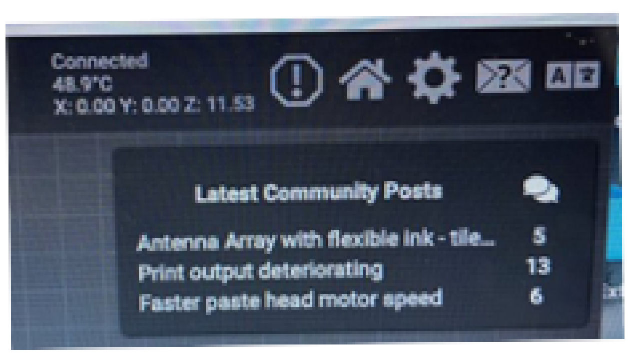

Figure 50: Software Settings

While learning to use the Voltera V-One machine may seem overwhelming at first, after one's first use it is simple. The first and foremost step is to download the free software from Voltera's website. It only takes a couple of minutes, and this is how one will run the machine. Once you open the software, you will see in the upper right corner, five symbols, and text, as seen in Figure 50. Starting on the right, the domino-looking symbol is so that one can change the language that is seen in the software. The envelope with the question mark is so one can ask questions about using the machine and get connected with support. The gear is where you can change the settings for the software, like font size. The house icon makes the probe on the machine move back to the home position. The exclamation mark symbol is an emergency stop. On the left, there are three lines of text; (1) telling you if you connected with the machine, (2) how hot the bed of the machine is, and (3) the position of the probe.

When the machine is connected to the computer, four settings pop-up; Print, Solder, Heat, Drill. The print option takes you to the very beginning process, where you start with a blank board and are going to start printing the circuit onto it. The solder option is for when you have done the drilling and printing of the circuit. Now you are ready to place the surface mount parts on and need to have the machine place the solder paste. The heat option is for when you are trying to reheat something on your board. This is the option that you will hardly use at all, as heating is incorporated into the end process for Print and Solder. The last option is the drill. When you click on the drill option it will ask if you have existing features on the board or if you are starting from a blank board. I recommend that you start with a blank board, but having printed the circuit will work as well. When you go to make your board you will select the option that best suits what you plan on making. Refer to A.1.4 for the procedure.

A.2.2 Machinery

Note when the machine is plugged in and running, everything the machine does will be translated into information within the software. The machine has lights that will change color if it is on standby (white), running (purple), hot (red) and cooled (blue). Before setting up anything to work on, clean the sensors with a cotton swab. Then when you go to clamp the board down, check to make sure that the ledge with the indents is what goes on top of your board. The thin ledge side will be used for baking. Use the provided thumbscrews to hold the clamps and board in place. You will also want to place the probe into the home carriage, make sure that the metal strip on the probe lines up with the metal strip on the carriage. Then, check to make sure that all the magnets are secured to the carriage.

If you are drilling, make sure that you remember to put the protective layer down. Otherwise, there is the possibility of damaging the machine. When not drilling the layer is not needed. Make sure that the drill cord that is attached to the machine is secured and away from the board. This ensures it is not in the way and will not affect the making of a circuit.

Occasionally the machine may go out of alignment. This happens when the machine is moved or if the probe crashes. To have the alignment reset on a Mac; hold fn + Alt + C then fn + Alt + H. A black box should have popped up in the lower right of the software, then type I2 C2, making sure there is a space between 2 and C. For a PC; Alt + C then Alt + H. A black box should have popped up in the lower right of the software, then type I2 C2, making sure there is a space between 2 and C.

A.2.3 Dispensers

When you receive a new ink or solder they will come with a cap on the bottom. Remove that cap and place the ink or solder in one of cartridges. They will fit snug inside and the plastic ridged outside fits into the cartridge. Then add a nozzle. You take the nozzle out of the plastic covering and check to make sure that it is not broken, Figure 6, or clogged from previous use. Carefully hold the tip and screw it onto the cartridge. Finally, add the dial portion of the dispenser, make sure that it clicks into place. To prime either the ink or the solder paste turn the dial counterclockwise until the product is dispensed. Then, do a quarter turn in a clockwise motion so that the product stops flowing. Carefully wipe away the product, and make sure not to break the tip of the nozzle.

When either ink or solder is not in use, use the protective cap to save the nozzle and prevent leakage. Make sure that you store it in the refrigerator when you plan on not using for a long period of time. The cartridge, nozzle, and cap protector can all go into the refrigerator as well, so no need to remove ink or solder every time. When you are ready to use the ink or solder again, take it out of the refrigerator and let warm up to room temperature (about fifteen minutes).

A.2.4 Steps

The software will walk you through all the steps every time. But in general they are:

1. Clean out the sensors with a cotton swab

2. Finding the position of the board on the machine

3. Measuring the height of the board
4. Drilling:
    (a) Attach drill with proper drill head size
    (b) Drill holes
    (c) Repeat a and b for different sizes
5. Prime the ink
6. Test the ink follow
7. Wipe away the ink
8. Ink the circuit
9. Bake the board
10. Burnish
11. Locate the pads and validate them
12. Add the solder paste
13. Add the surface mount components
14. Reflow
15. Use your board!

A.3 How to Use the Voltera Drill

The drill is a separate attachment that comes with the Voltera V-One machine. First before you hook it up with the machine you will want to add the drill head. Select the size from the case, and unscrew the holding screw from the side of the drill end. I recommend that you use the provided Allen wrench and not to unscrew the screw the whole way, but enough that you can get the head in. Make sure that you do proper placement of the head, Figure 51, other wise it may damage the board.

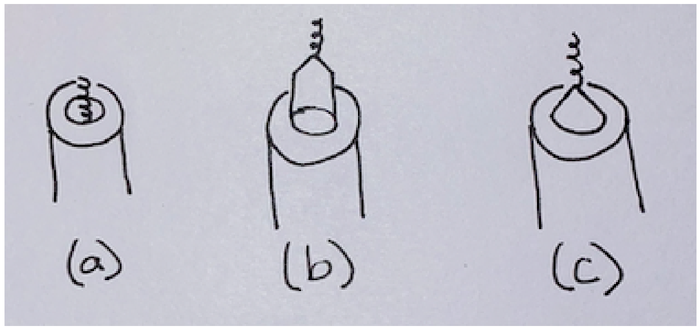

Figure 51: (a) shows the head of the drill being to far down into the chamber, (b) shows the head being to far above the chamber, (c) shows the correct positioning where the cone of the head meets the base of the chamber. Each drill head is roughly 5mm in diameter.

Now, you hook the drill attachment to the machine. First line up the magnetic strip with that on the machine. Then make sure the the drill is secure and in place. Once, that is done you can take the cord that is attached to the machine and insert it in the side of the drill. It should make a beep sound, and the lights on top should be lit up.

When you are using the drill make sure that you are wearing safety glasses, as board shavings do fly everywhere. Once you are done with drilling, make sure to clean all the shavings away. If they get stuck on the belt the arm will not move properly, or if they are left on the board they will burn. When storing the drill make sure to remove the drill head. This way if dropped it does not break off. Also, secure the cord for the drill out of the way by tucking back in on itself.

A.4 Tips for making a board

Tip 1:

When you are inking the board make sure that the ink is making a good connection. Figure 52 shows what a bad ink job is. There are cracks in the connections and the pads are not full. Figure 53 shows that you want the ink to look like before you bake. If you have bad inking, do not panic, get frustrated and wipe away the ink. You can highlight the areas that you want re-inked again on the software. For one pad or line, simply click on it and then hit start and the machine will only redo that selection. If you want an area done, click and drag your mouse over the designated area. Once highlighted click start and it will redo the area. If you have spaced out parts that need to be redone, click the first one then hold the shift button while you click on the rest. The click start once all the desired are highlighted.

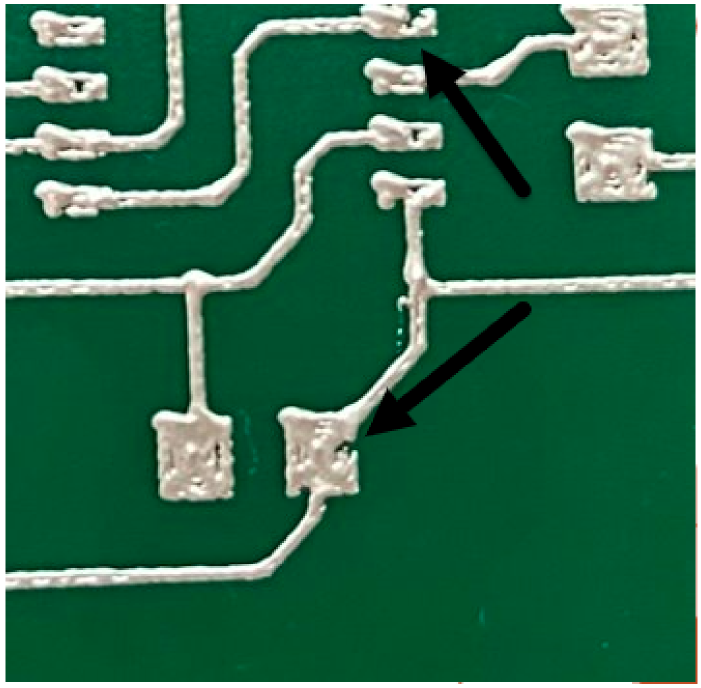

Figure 52: A bad ink job with cracks in the pads

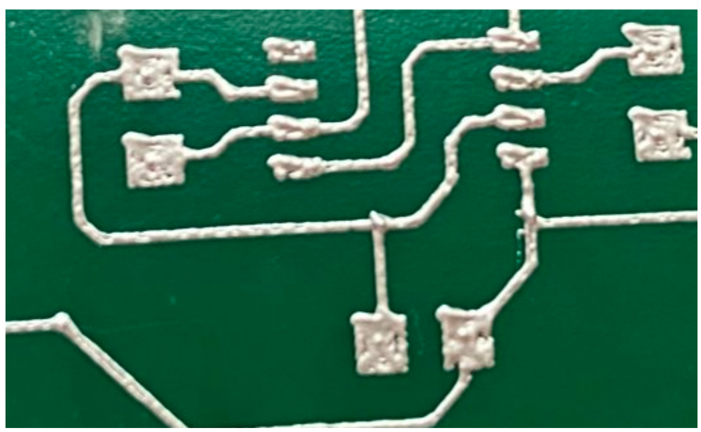

Figure 53: The ink job with solid pads

Tip 2:

When burnishing you want the ink to have a soft shine. It will look dull when it comes off from baking, so take the burnishing pad and run over it in a circular motion. The ink will get a soft silver shine. This shine will help you know you are getting a good electrical connection.

Tip 3:

If the drill stops drilling in the middle of doing holes, do not get frustrated. Let the drill finish its process of touching down on each of the hole areas and not spin. Once that is done, and it had returned to the home position, unplug it. If the drill does not return to the home position, select the emergency stop on the Voltera software, and manually send it home with the home button. If you do not send it home before proceeding you will mess up the alignment. Turn everything off, even the software. Unplug the machine from power and the drill cord from power. Plug them both back in. Make sure that the cords are not hanging down from the table or dragging. Then you can boot the software back up and start again. You can highlight the holes that you need drilled if it started on some but did not finish.

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