

Spring 5-6-2015

Project Labyrinth: Exploration of Modulating Guitar Signals

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Project Labyrinth: Exploration of Modulating Guitar Signals
By

Joseph Andrews
Andrew Patterson

Submitted in Partial Fulfillment
of the Requirements for
Graduation with Honors from the
South Carolina Honors College

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Summary

The overall objective of this project is to create a guitar pre-amplifier in the casing of an effects pedal. The pedal must be able to modulate amplitude and pitch. More specifically, the design for this pedal will include floating frequency filtering, phase shifting, and amplitude modulation. These effects are to be designed in both analog and digital domains in order to compare sound and pricing. Along with the effects, the pedal must be able to run off of 9V DC, drawing a maximum current of 100 mA from an adapter or battery. In order to get a full frequency response from the guitar signal and the best results when using this product in junction with other effects or brands, the system needs a high input impedance ($>470\text{ k}\Omega$) and a low output impedance ($<5\text{ k}\Omega$). Since some of the effects result in a perceived drop in volume, the pedal must have up to a 6dB output boost to accommodate for this. The system is required to have four variable resistance potentiometers, with two foot actuators for bypass and 1/2 speed low frequency oscillation (LFO). The circuitry for all of the effects must fit in a 1590BB Hammond enclosure, which is standard for Caroline Guitar Company, as well as have 1/4" jacks for audio input and output. Lastly, the total cost for parts should be less than \$50 and the number of parts should be minimized to allow for easy, quick assembly.

The Labyrinth Guitar Pedal is all about sound quality. Sounds may be generally characterized by pitch, loudness, and quality. Sound "quality" describes the characteristics of sound which allow the ear to distinguish sounds which have the same pitch and loudness. The primary contributors to the quality of the sound of a musical instrument are harmonic content, attack and decay, and tremolo. For sustained tones, the most important of these is the harmonic content, the number and relative intensity of the upper harmonics present in the sound. While there is some efficiency in characterizing such sources in terms of their overtones, it is always possible to characterize a periodic waveform in terms of harmonics - such an analysis is called Fourier analysis. Second, the attack and decay, attack is the extent to which the note is hit. Rhythm is communicated through attack. Decay is the time within the full duration of the note that the sound is made. Taking an example is the guitar string, the attack and decay of a plucked guitar string fig (1). The plucking action gives it a sudden attack characterized by a rapid rise to its peak amplitude. The decay is long and gradual by comparison. The ear is sensitive to these attack and decay rates and may be able to use them to identify the instrument producing the sound.



Figure 1. Attack and Decay of plucked guitar string.

The guitar pedal that we created accomplished all of the design requirements for implementation and sound quality. We were able to run the op-amps needed off the single supply, by utilizing a floating ground, or a reference voltage of 4.5V.

The majority of guitar pedals run on 9 volts, direct current. It is acceptable for typical transistor and op amp-based boosters, fuzzes, overdrives and distortions. Each pedal is going to draw a specific amount of current out of the power source, whether that source is a battery or an AC-DC adaptor. A high current draw is going to deplete the battery faster. A higher current draw is also going to require a powerful AC-DC adaptor. Analog designs based on transistors and op-amps have rather miserly requirements in the range of 3mA to 15mA. These types of pedals can last for long time with a battery, but it will require more current when it becomes more sophisticated, "Common analog transistor/op-amp designs has a current draw: 3mA-13 mA, Digital/DSP based single pedals has a current draw: 50 mA-65 mA, Multi pedal current draw: 140-200 mA." For most pedals that draw 100 mA or more, batteries are very impractical. In the user guide for the Boss DD-20 GigaDelay, it explains how to install 6 AA batteries, but then goes on to explain how these are for "testing purposes" only. Guitar pedals have a high current draw, which cannot be supplied by a battery, so the team has chosen to rely on a power adaptor. However, the pedal has the ability to work powered by a 9V battery. The labyrinth has been designed to be safe for the user that its current draw is reasonable, cased inside a box that is going to protect the pedal in case of dropping the pedal, liquid spilling, or if the pedal is exposed to high temperature.

The high input impedance was accomplished through inputting the circuit into a MOSFET at the gate, which would control the signal, which would be input into the main circuit. The high impedance output was instituted by taking the output of an op-amp, the final stage of our circuit. We obtained two, quarter-inch plugs and soldered on the positive and negative wires to allow for quarter inch input and output jacks. The final cost of our circuit was \$16.50, lower than the \$20 parts allotment desired by Caroline Guitar Company. Finally, the output knobs we created were consistent with the requirements. We implemented three knobs in order to control the frequency of oscillation in the low frequency oscillator, the depth of the effect, and the output volume coming from the pedal. The one objective that was not met was the true bypass circuit. This was a trivial part of the project, given that our sponsor already has the circuitry to accomplish this in a simple single pole double throw switch. In conclusion, all the significant hard objectives for the guitar pedal were met.

The more ambiguous objective we had was related to the sound of the effect. Our goal was to create a "swirly" effect. We implemented this through both amplitude and frequency modulation, with the addition of a nonlinear, saturation influenced attenuation of the signal. Subjectively, this creates a swirly tone, in which the frequency of the "swirl" can be changed by adjusting the frequency of the low frequency oscillator. Overall, the guitar effect meets all objectives. It is well under the desired price and implements the desired sound effect. It would be a boost to any musician's arsenal on stage, and give them a musical advantage over their competition.

Initial Design Concept

The Labyrinth Pedal must modulate the input signal from a guitar. This modulation must include both amplitude modulation as well as frequency modulation. To accomplish this task, the system has been split into four subsystems as outlined in the block diagram below. The system is fully linear so no interface between the subsystems are needed, with the exception of signal amplification or attenuation at the beginning and end of the signal path.

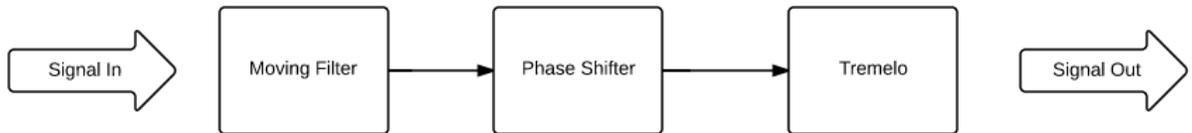


Figure 2. System block diagram.

Moving Filter Design Concept

The frequency of the output signal of the average guitar varies from 82.4 Hz (Low E) to approximately 1318.510 Hz (Highest note on average guitars). The signal from an electric guitar is often a combination of many different frequencies and can be a very complex signal, particularly when the player is playing many notes at the same time (Chords). The purpose of the auto-“wah” pedal would be to smoothly roll a band pass filter across the frequencies of the guitar signal at a specific frequency. This will be accomplished using both digital and analog methods. This filter will be a wide bandpass filter that allows a range of 300 Hz to pass through, while only attenuating those outside the pass band at approximately -5 to -8 dB. The sweeping frequency must be able to be set by the user and will range from .25 to 10 Hz.

For this application one needs a wide band pass filter in order to ensure that the other frequencies from the guitar signal are not completely attenuated. A design for a wide band gap filter was found through Texas Instruments and is shown in the figure below.

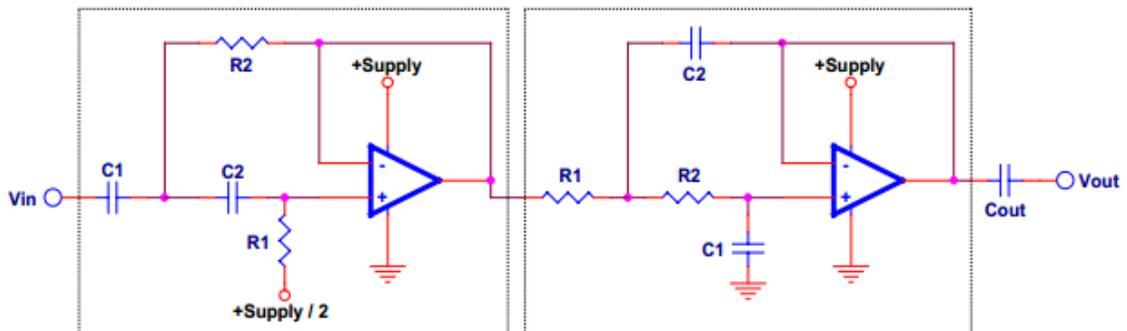


Figure 3. Wide bandpass filter schematic

For choosing the values one will need to harp back to the range of frequencies one wishes to operate in. From let's say 60Hz to 1350 Hz (A little lower in case the user is using a 7 String guitar). Therefore we need the low end of the band to move between 80 and 270 Hz and the High end to move between 420 and 1350 Hz).

One needs automated variable resistors for these filters to be floating at the same rate (i.e. all resistors moving in same direction in unison). For this application Voltage Controlled Resistors will be used. JFET transistors can act as a variable resistor with the resistance between the drain and source being controlled by the gate voltage. The gate voltage will be controlled by a low frequency oscillator outputting a sign wave. Therefore all resistances will be varying at the same rate with respect to time as long as all the gates of the variable resistors are controlled by the same LFO. There are many choices for the correct JFET but specific ones which allow for a controllable resistance between 4-8kOhm and 100-600Ohm are the PN4119A and 2N5486 respectively.

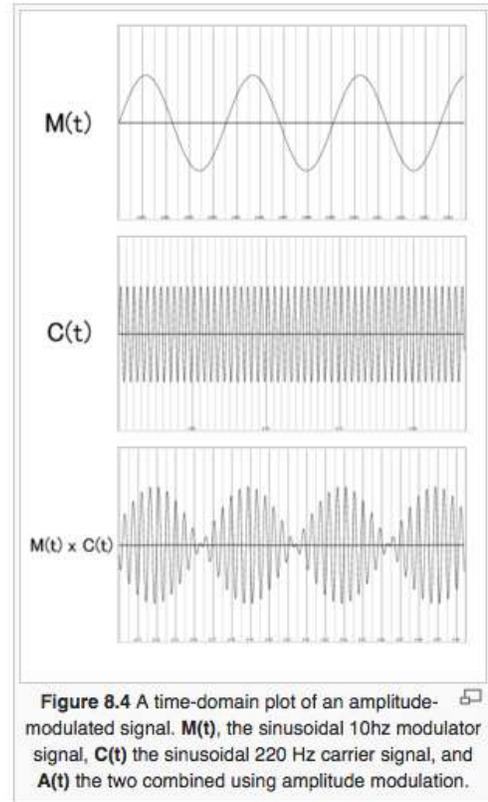


Figure 4. A time-domain plot pf an amplitude-modulated signal.

Amplitude Modulation Design Concept

Amplitude Modulation Synthesis is a type of sound synthesis where the gain of one signal is controlled, or modulated, by the gain of another signal. The signal whose gain is being modulated is called the "carrier", and the signal responsible for the modulation is called the "modulator". In classical Amplitude Modulation, or AM Synthesis, both the modulator and the carrier are oscillators. However, the carrier can also be another kind of signal, such as an instrument or vocal input. Tremolo is a form of amplitude modulation where the gain of an audio signal is changed at a very slow rate, often at a frequency below the range of hearing (approximately 20 Hz). This effect is commonly used to alter the sound of organs or electric guitar. The tremolo main component and the most important one, the unipolar Low-Frequency Oscillator or what is called "LFO". Its function is controlling the amplitude of modulator. The oscillator, as known, is just an amplifier with a positive feed-back loop. There are two signals in the tremolo, one is the carrier signal "the modulated signal". The second signal is the one responsible for the modulation "the modulator". They are both oscillators. So, accomplishing the amplitude modulation is reached by multiplying the carrier signal (sine wave) of frequency and the unipolar modulator;

$$A(t) = C(t) \times M(t)$$

Where C is the carrier signal and M is the unipolar modulator and they both in the time domain. The result of that is an amplitude modulated, shown in Figure 4. In the LFO “an electronic signal which is usually below 20 Hz and creates a rhythmic pulse or sweep, this pulse or sweep is often used to modulate synthesizers in order to create effects used in the production of electronic music” the output signal is fed back in-phase then the amplifier starts to oscillate or produce a signal of specific frequency as the input and the output feed each other with a constant signal. The determination of the frequency is determined by outer resistors and capacitors as well, which are implanted into the feedback loop. Another property of the tremolo is that its signal is infrasonic which is below the hearable frequencies for the human (<20Hz), to be more accurate it works in the range of 3Hz to 10Hz.

From a mathematical point of view, the tremolo effect is a kind of low-frequency amplitude modulation applied to a certain signal. It is specified by the speed (rate) of the signal change, depth and the waveform. The speed, or the rate of the tremolo, specifies how many times per second the signal changes or more specifically changes its depth. The typical values of the rate are between 0.5 Hz to 10 Hz.

The depth specifies how rapidly the signal changes. The depth is measured in dB (decibels) and shows how much the signal goes from quiet to full loudness. For simplicity the depth is measured in percent. 0% indicates silence, 100% - maximum loudness. The typical values of the depth in dB are from 3dB to 10dB. The depth potentiometer controls the depth of the modulation from 4 dB to 8 dB.

Phase Shift Design Concept

The phase shifter effect will use a series of all-pass filters to shift the signal from the floating frequency effect. An all-pass filter is designed using resistors, a capacitor, and an op-amp as shown in Figure 5. It has a transfer function of $H(s) = \frac{sRC-1}{sRC+1}$. The phase of $H(i\omega)$ is given by Equation **Error! Bookmark not defined.** for any angular frequency, ω . There is a non-linear response to the filter meaning that there will be a different phase shift for different input frequencies. A phase shift of 90° occurs when $\omega = 1/RC$. At a phase shift of 180° , the shifted signal cancels with the original signal causing a notch in the overall sound at that frequency. When a note is played on a guitar there are multiple frequencies in the signal since harmonics occur. Because there are multiple frequencies in the signal, only the frequency that is shifted by 180° will cancel with its original signal. All other frequencies will be shifted by a different amount corresponding to the specific frequency.

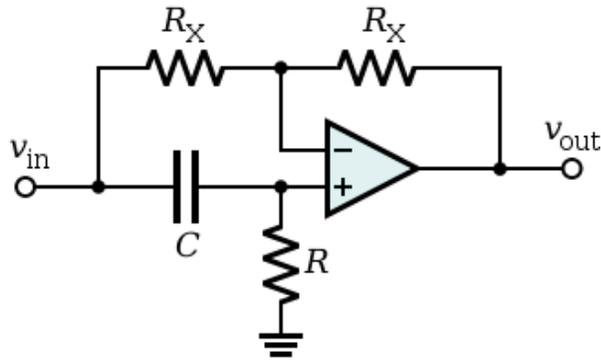


Figure 5. Schematic of an all pass filter

Figure 4 shows a block diagram of how the all-pass filters can be implemented to complete the phase shift effect. The original signal is split in two so that the shifted signal can be recombined with the original signal. Adding a feedback branch, with a variable resistor, will make the peaks of the signal sharper giving the signal a more distinct sound. The variable resistor will allow for the user to determine the desired amount of feedback. The resistor, R, in Figure 3 is a voltage controlled resistor that is controlled by the low-frequency oscillator (LFO) as shown in Figure 4. The LFO will change the value of the resistor connected to the positive input of the op-amp. In doing this, the frequency, at which the signal cancels with itself, will change with the LFO.

There can be as many filters, or stages, as desired. A system will have half as many notches (occurring at the signal canceling frequency) as it does stages. So, a four stage phaser will have two notches, an 8 stage phaser will have 4 notches, and so on. The overall phase shift must be 180° in order for the shifted signal to cancel with the original signal. The phase shift after each filter depends on the desired number of stages (i.e. a four stage system will have a phase shift of 45° after each stage).

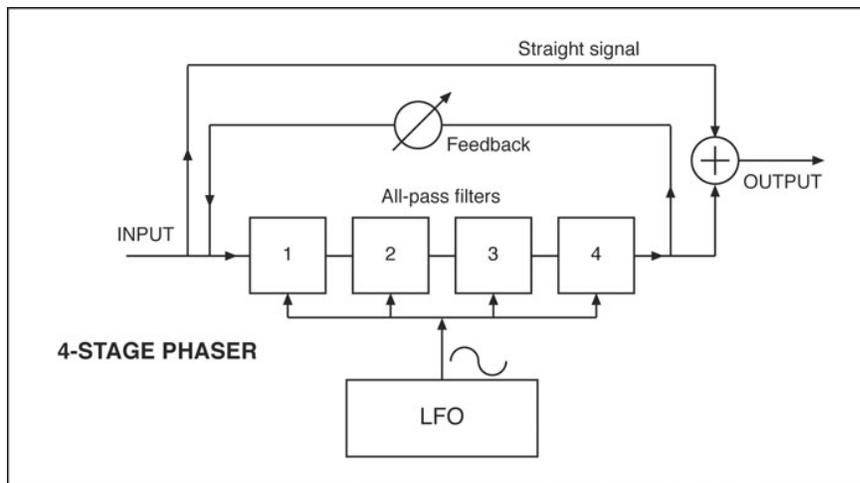


Figure 6. Block diagram of a 4-Stage Phaser

A 4 stage phaser will be used to modify the guitar signal. The specific values for the components R and C are not that important since the frequencies are always changing,

either from the LFO or the player. They will be used more as a starting point and will be replaced with other values until the desired sound is achieved. However, the values must allow for a 180° shift within the frequency range of a guitar. An electric guitar has a frequency range of 82Hz - 1397Hz. The starting values will be $C = 47 \text{ nF}$ and $R = 6 \text{ k}\Omega$. This will cancel the signal at a frequency of about 564Hz. The resistors, R_x , are used as voltage dividers so, their values must equal. Once the signal has passed through the phaser, it is sent to the amplitude modulator.

The figure below shows a standard comb filter which is similar to the outcome signal of the phase shifter. There are different aspects of the filter that, ideally, would be user controlled including where the notches occur, the number of notches, and the slope. Controlling the frequency of the notch can be achieved using the LFO that controls the resistor on each filter. This will essentially shift the whole spectrum of the comb filter left and right. The range of this sweep must stay inside the range of frequencies of a guitar, 82Hz - 1397Hz. Secondly, the number of notches can be adjusted by changing the number of filters in series. For every two all-pass filters, there is one notch in the signal. This will be a little trickier to implement since there will need to be outputs at multiple places along the line of all-pass filters. Thirdly, changing the slope of the signal can be achieved using a variable feedback resistor as shown in Figure 2. This will change the "sharpness" of the signal.

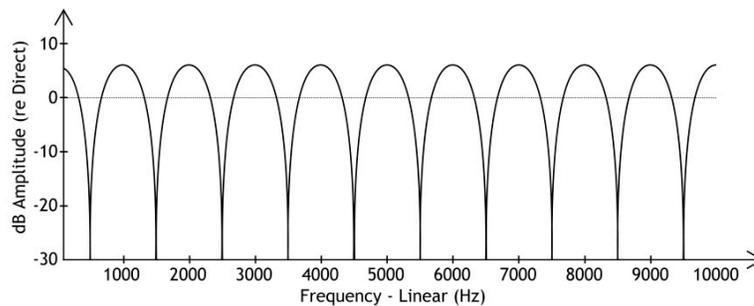


Figure 7. Frequency Responsive Phaser

Digital Design

The digital design for each part will be implemented as described below. The signal characteristic values should be similar to those stated above for the analog versions. The digital characteristics should be fast enough and accurate enough to sound like an analog signal to listeners. Since the max frequency of a guitar is around 1400 Hz, ideally the sampling rate should be more than ten times this value. The bit resolution value on the ADC and DAC should also be 8-16 bits for the best reproduction of the signal.

Moving Filter

The moving filter can either be realized with a FIR or IIR filter, where the cutoff frequency is adjusted by changing the response coefficients. This will likely be the hardest effect to implement. A formula for the coefficients of the FIR Filter is shown

below, where $M=N/2$. The IIR Filter can be created by changing the desired transfer function into the digital domain using the Tustin transform.

$$h_d[n] = \begin{cases} \frac{\sin(\omega_{c2}(n-M))}{\pi(n-M)} - \frac{\sin(\omega_{c1}(n-M))}{\pi(n-M)}; & n \neq M \\ \frac{\omega_{c2} - \omega_{c1}}{\pi}; & n = M \end{cases}$$

Tremolo

Tremolo is amplitude modulation of an input signal, meaning the input signal will be multiplied by a value that changes every time step. This value will be determined by a sine wave with a frequency determined by an input. As the input goes up, the frequency of the amplitude sine wave will be increased. The discrete time implementation of this function in MatLab and results can be seen below, where the frequency of x could be adjusted.

Phase Shift

Phase shifting will be implemented with a simple delay. The number of samples by which to delay the output signal will be determined by the potentiometer input and be restricted to less than a half cycle to prevent an echoing sound. The discrete time implementation can be see below in Matlab where ϕ is the adjustable phase shift, changing the position of the phase shifted red, output line from the blue input.

Commercialization Plan

Novel Product Features

The Labyrinth guitar pedal is a combination effects pedal that combines phase shift, tremolo and auto-wha effects into the same package. The Labyrinth pedal provides benefits above the state of the art by providing easy setup, easy tuning and well-characterized circuitry. These effects, if needed in combination, are currently added in a daisy chain of single effect pedals and each effect requires a significant amount of tuning. The combination allows the unique sound of these pedals to be implemented with a single pedal and the tuning to be combined and restricted to produce a range of pleasant effects, decreasing the amount of effort required to hone in on the sound needed. The effect circuitry will be implemented entirely with analog circuitry which adds character to the sound that is often absent in digital implementations of cheaper pedals.

Patent Search Results

Term #	Category	Search Terms	Patent Number	License?
1	Tremolo	Tremolo circuit	US 3978421 A	0
			US 3510567 A	1
			US 3629484 A	0
2		Vibrato Circuit	US 3342924 A	0
			US 3260785 A	0
			US 3978421 A	0
3	Auto-Wah	Auto-wah Circuit	US 3812278 A	0
4		Envelope Filter Circuit	US 20050120870 A1	0
5	Phase	Phaser Circuit	US 4873491 A	0
			US 5448196 A	0
			US 4122364 A	1
6		Phase Shifter Circuit	US 4866397 A	0
			US 5148062 A	0
			US 5317288 A	0
7	Combination	Combination Effect Pedal	US 20050056142 A1	0
8		Multi-Effect Circuit	CN 103745714 A	0
9		Multi-Effect Guitar Synth	US 5105711 A	0
10		multi-type guitar effect	WO 2014077537 A1	0

Licensing Conclusion

Most of the patents found were either circuits for communications or high-level descriptions of something that may include one of the effects. As such, it is unlikely that licenses will be needed even if we use something similar because the application is different and the circuitry will have to be modified.

Even the high-level patents on multi-effects have little overlap with what we are trying to accomplish. Most of these focus on integrating certain effects into the guitar or on combining single effect pedals into a soundboard type apparatus instead of creating a combined circuit from the separate parts.

The exception to this rule is for the tremolo circuit where there are multiple different circuit designs claiming to improve the performance over the prior art. One patent that bears closer inspection is US3510567A, which uses a FET as a variable resistance to change the amplification of a circuit. Since our circuit uses a field effect transistor, it will be necessary to insure the components are implemented in different ways. A good indication that we will not need to license the patent is that our signal goes into the gate of the FET while theirs goes into the drain terminal.

The second patent marked as a possible license is US4122364A, which is a voltage-controlled phase shift circuit. Not only does it provide a description of a prior art phase

shift circuit that may be useful to implement, its claimed improvement is a phase shift circuit that scales logarithmically instead of linearly with logarithmically increasing voltage. If this circuit provides enough benefit in sound quality and ease of use, it may be worth purchasing a license.

Other than these two examples, it does not look like any licensing will be necessary for the circuits being built or any type of combination of effects.

Sales Price

Caroline Guitar Company sells single effect pedals around the \$200 price point, which is standard in the boutique pedal industry. Since this is a multi-effect pedal, a slightly higher price point may be acceptable.

Most “multi-effect processors” which provide a similar function, are designed to be large, with many different controls and cost upwards of \$400. This may indicate that a higher sales price could be chosen but because the Labyrinth pedal comes in a smaller stomp box and does not have the long list of features and memory available in the digitally implemented multi-effect processors, the sales price cannot be on the same level.

With these factors taken into account, the sales price of the Labyrinth pedal will be set at \$250 for a conservative estimate.

Profit Margin

A requirement on this pedal is that the cost of components is less than \$20 and so the profit margin will be considerable. Adding in a \$20 manufacturing cost per box, and another \$30 for incidentals such as nice knobs, pre-painted boxes and shipping the profit for a sold box is \$180.

Market Preparation

To complete a ready-to-sell box, the following items are needed: the pre-drilled and painted effect box, an empty PCB, all the parts for the PCB, the knobs for the outside of the box, and the mounting fasteners for the board and box. The manufacturing process is having an hourly employee on site solder the components to the PCB, place the board in the box and attach the knobs. Based on current box manufacturing times, the process should take about an hour once all the parts are in hand as stated above, the manufacturing should take about \$20 worth of time.

In order to get to the stage above, a month of design needs to be put in behind the initial prototype to make it market ready. This design time will be spent first verifying the circuit, recreating it and testing the different systems for repeatability. After this stage is complete, the designer will have to analyze the output sound to tune the effects into a pleasing range for the vision of the pedal. For example, matching the range of oscillation of the effects can lead to a harmonious sound but would preclude songs with dissonance, which have been popular during different eras. When the components have been set to their final values and the adjustable values have been selected, the designer will have to create the PCB layout for manufacture.

With the design work complete, the aforementioned manufacturing process can be completed and the product tested for shipping.

Competitors and Market Share

Based on the 2014 NAMM Global Report (page 13), the effects pedal industry is a \$60 million market and has increased from \$50 million in the past 10 years.

The market for guitar pedals can be broken up into two different types of competition, local boutique pedals and the large national companies. Though the large companies such as BOSS, MXR, Electro-Harmonix and Dunlop seem to control a large portion of the market share, the Labyrinth pedal fits in the niche of the boutique pedals that have a small chunk of the market share.

If this guitar pedal were to sell at 1 per week, a very optimistic estimate in the beginning, the yearly profit would be around \$9,000 or 0.15% of the market. More realistically, 5 will sell in the first year leading to a profit of \$900 or 0.015% of the market. This pedal is a specialty item and not ideal for starting a business. This effect pedal is the product of a very successful pedal company that can branch out now that it has a line of 6 pedals that provide the financial backbone of the company.

Human Resources

Based on the Caroline Guitar Company model the human resources will be a business manager, a product designer and several on call builders where product designer is the only full time employee. This will keep the company light during the growing pains of the company. Details of the roles can be seen below in table form.

Title	Type of Work	Salary	Hours
Designer	Full-Time	\$40,000/yr	40 hrs/week
Business Manager	Part-Time	\$20,000/yr	20 hrs/week
Builder	Part-Time	\$10-\$15/hr	As Needed

Responsibilities:

The Designer is responsible for overseeing the builders, designing pedals for sale, troubleshooting and technical support for the group and customers. The majority of the forty hours a week will be spent developing new pedals to sell and maintaining sales contacts. Salary based off an electronics technician salary.

The Business Manager is responsible for making sales connections, handling orders and monitoring the finances of the operation by making sure rent and the employees are paid and the customers pay for any shipment of pedals. Salary based off small business manager salary.

The builders are part time employees that are called in whenever a shipment of pedals is ordered. Preferably high school or college student, they will be taught how to solder components to a PCB. Since the components are through hole for small boards, the labor requires little skill. The builder's work is overseen by the designer.

Facilities

In Columbia, SC, the rates for commercial space are about \$100 per sq. ft. for purchasing office property and \$15 per sq. ft. per year for renting.

For a 300 sq. ft. office space (the size of a studio apartment), the purchase price would be \$30k and the rental price would be \$4.5k per year. This amount of space is reasonable for

one full time employee and a small number of part time employees. This space will also include benches for production where the builders will work.

Market Strategy

Selling Point: The Labyrinth pedal is a handcrafted pedal with a unique combination of effects that allows even inexperienced users to produce a good combination sound unlike anything that could be produced with a single effect pedal. The pedal should appeal to anyone lamenting the lack of innovation in the effects industry.

Broad Strategy:

Since these guitar pedals are in a niche market, diversity of sales outlets is more likely than selling a large number to one customer. As such, the marketing strategy will be to try to work out deals with all the local music shops but more importantly to sell to individuals who will be repeat companies because they are interested in the brand.

Cash-Flow and Break-Even Time

From a simple calculation over a year including no costs but the manufacturing, payroll and facilities costs, around 400 units would need to be sold before the company broke even. This many units would correspond to somewhere around 20 years if a realistic average of 15 pedals are sold a year. To finish in a single year, 32 pedals have to be sold per month. Even if the designer and business manager take no salary, 28 units have to be sold in the first year to break even. As such, starting a business off of this guitar pedal would not be fiscally responsible.