Guitar Effects System

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Overview

The design of the guitar pedal was motivated by the history of rock ‘n’ roll. When people first began playing electric guitar in the 1930’s, there were no specialized guitar amplifiers, so they simply hooked up the electrical signal from the guitar to an audio amplifier that would have otherwise been used for vocals. Thus, the sound that came from these speakers would be clean and accurate, which is great for vocals, but guitarists wanted to get more from their instruments. Using the early tube-style amplifiers, guitar players would turn up the volume all the way in order to force the output audio waveform beyond the limits of the amplifier, resulting in clipping of the waveform and a “crunchy” sound characteristic of rock music.

While players loved the overdriven effect they achieved by turning the amp “up to 11,” this technique posed a risk of breaking the tubes in the amp and also resulted in a lot of angry neighbors. Moreover, as guitar and amplifier technology developed throughout the 1950’s and 1960’s, many amplifiers featured additional built-in effects such as reverb, vibrato, and echo. These effects gave guitarists access to a new mode of creativity, but the technology was cumbersome to use and often lacked the quality necessary to be put in to practice in a studio or live performance setting. When the effects are built into the amplifier, the player must adjust the settings for each effect using the knobs and switches on the amplifier, which cannot be done while the guitarist is playing. Furthermore, the effects were limited to the size and scope of the amplifier within which they were confined. For these reasons, it made more sense to separate the effects from the amplifier and build them in a modular, easy to use format – the pedal.

The guitar pedal came about as a convenient and modular effect that could be connected in between the guitar and the amplifier. In the 1970’s, guitar pedals gained mass popularity as players realized how much they would add to their playing. Now, players could choose precisely the effects they wanted to use, their specific settings, and they could activate them with a simple footswitch to allow them to turn effects on or off on the fly. It became standard practice for a guitarist to activate an effect only for a specific section of a song; for instance, a musician might want to turn on the overdrive before jumping into a solo.

Nowadays, guitar pedals can be made with both digital and analog technology. While in many audio applications digital technology has taken control as a result of its ability to replicate and expand on many of the sounds desired by musicians, analog electronics remain at the core of guitar amplification and effects. Analog circuits provide elegant solutions to the acoustic needs of guitarists, and additionally they can be easily modified with different components. They also have an advantage in their signal resolution and likeness to the circuits that built the sound of electric guitar in early amplifiers.

The challenge for this project is to build a modular system of guitar effects. The pedals chosen are compression, overdrive, and equalization pedals, which together give the artist a practical and versatile set of effects for any playing setting. Each of the pedals will have an input buffer and a bypass switch so that they can be used as stand-alone units or together in any desired order. A 9V DC power supply, typical for this application, is needed to power the system, and the output of each pedal will be around 1V peak-to-peak at most, suitable for use with a standard guitar amplifier. As seen in figure 1, the guitarist can choose which of the effects to use and which order to connect them in, turning this one system into a powerful system for any electric guitarist.

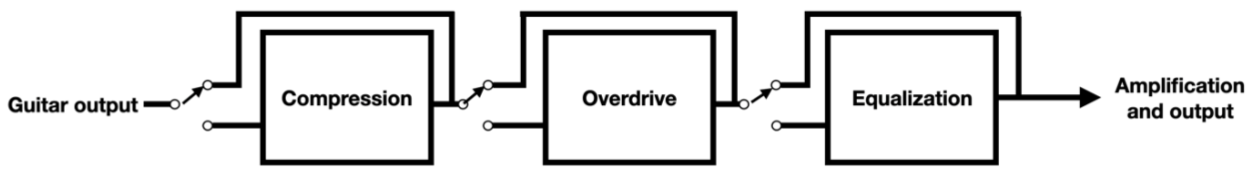

Figure 1. Pedals can be used individually or together in any order, allowing the player to combine them at his or her convenience.

Compression Pedal

Typically used early in the signal chain from guitar to amplifier, the compression pedal reduces the dynamic range of the instrument signal. Although a subtle effect, this can be used to smooth out the differences between the peaks and valleys of a signal, which can make a big difference in a recording situation. Additionally, the use of compression adds sustain to the sound, allowing a player to hold a chord or a note for longer. The pedal achieves this effect by amplifying the lower volume sounds more than the louder sounds. In order to do this, the circuit must contain an envelope detector to detect the magnitude of the incoming signal, and then use that magnitude to control the gain of the circuit as needed.

The envelope detector from the MXR Dyna Comp pedal was used as the envelope detector along with a JFET as a voltage-controlled resistor in order to moderate the gain of the circuit appropriately. While many implementations seemed to use an operational transconductance amplifier (OTA) as a mode of gain control, this would have required a voltage-controlled current source to move from the envelope detector to the gain control. Moreover, OTA's have fallen out of fashion as time has passed, and it would be easier to source parts for production using a standard op-amp construction.

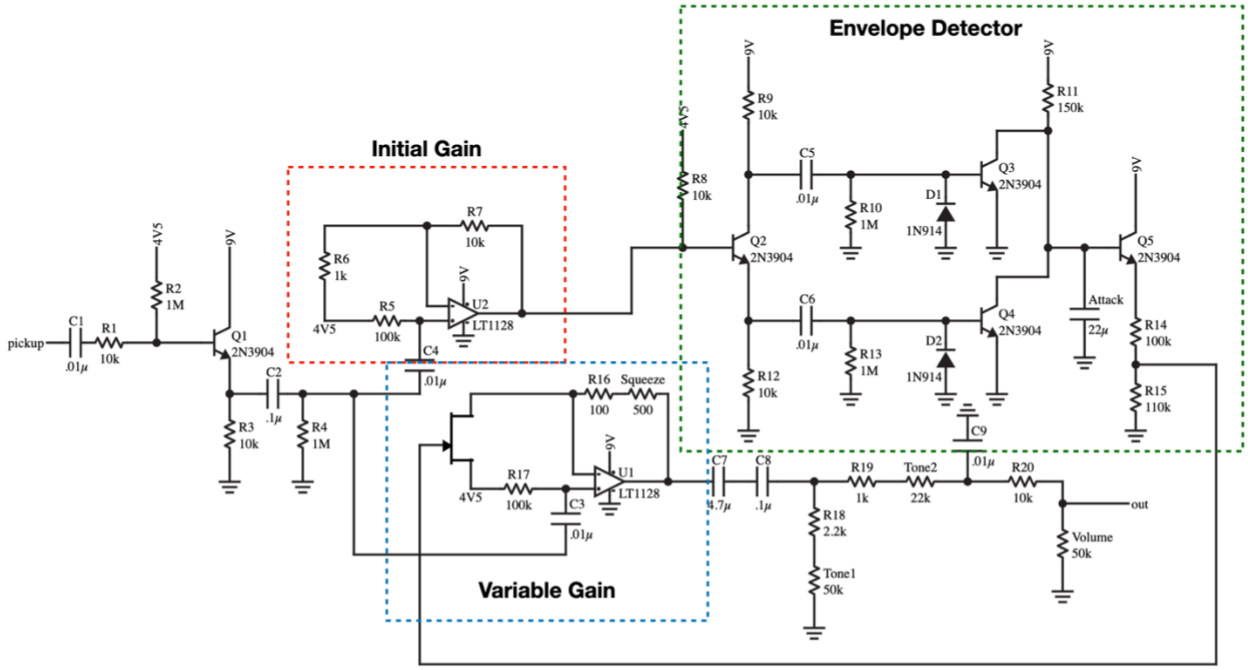

Figure 2. The initial gain block prepares the signal for the envelope detector, which ultimately controls the gain of the system.

The input first passes through a buffer constructed using an emitter-follower transistor configuration in order to isolate the signal and avoid "tone sucking" as the signal is processed. The input stage has a sufficiently high input impedance and low source impedance to preserve the integrity of the instrument signal. Next, after filtering out the DC offset, the signal proceeds to the initial gain stage highlighted in red above. The op-amp U2 is connected in a non-inverting configuration centered around the virtual ground of 4.5 V, and the gain of 11 in this circuit boosts the instrument signal to a suitable level before it passes into the envelope detector stage.

The envelope detector is a circuit found on electrosmash.com in their analysis of the MXR Dyna Comp pedal. In this block, the transistor Q2 functions as a phase splitter, outputting two waves with opposite phase to each branch of the circuit. Then each branch averages out the signal, and the "Attack" capacitor works as a low pass filter to slow the voltage change and allow the output voltage between R14 and R15 to more closely follow the envelope of the signal. Implementing this capacitor as a trimmer allows the user to adjust how quickly this voltage responds to changes in the signal, and thus to modify the speed of attack in the compression. The output voltage divider composed of R14 and R15 ensures that the output voltage falls between 0 and 4.5 V to properly connect to the variable gain block.

Using this voltage from the envelope detector, it is possible to adjust the gain of the circuit as desired. The variable gain stage uses a JFET in a voltage-controlled resistor configuration as detailed in “FETS As Voltage-Controlled Resistors” (Vishay.com) to provide an appropriate feedback resistance to the op-amp. The “Squeeze” resistor shown in the diagram is a potentiometer that gives the user control of the level of compression. By increasing the resistance here, the dynamic range is decreased as weaker signals are amplified with more gain.

Finally, the signal passes through capacitor C7, which removes the DC offset voltage and then through an adjustable high pass filter and low pass filter. “Tone1” is a potentiometer that allows the user to control the cutoff point of the high pass filter and “Tone2” is a potentiometer that gives the user control of the low pass cutoff point. The “Volume” resistor shown is another potentiometer giving the user control over the output signal level.

Overdrive Pedal

The overdrive pedal is the foundation of rock ‘n’ roll guitar. This pedal allowed guitarists to sound like they were about to blow out their amps without actually blowing them out. Instead of clipping the tops of the waveform off in the amplifier, guitarists could distort the sound beforehand, giving them more control over the distortion level and additionally leaving them free to adjust the volume as needed for practice, recording, or performing.

Overdrive is a type of signal clipping and is seen as the least aggressive of the lot. There are also distortion and fuzz pedals that provide more aggressive signal clipping and can be heard more commonly in metal and hard rock as opposed to blues and R&B. The focus of this design will be soft clipping and gain control in order to build a versatile overdrive pedal that can be used for many styles of music.

While there are many subtle differences that contribute to the sound of an overdrive pedal, the most important difference lies in the clipping method used. Some pedals use overdriven transistors to clip the signal while others use op-amps with clipping in the feedback loop. An op-amp is chosen here for the ease of gain adjustment, use of soft clipping, and ability to filter the clipping stage. The clipping design is loosely based on the famous Ibanez Tube Screamer pedal, designed to mimic the sound of an overdriven tube amp in the late 1970’s (electrosmash.com).

As with the compressor, an input buffer isolates the input signal and allows the pedal to be used equally well on its own or as part of a string of pedals. After passing through the buffer, the signal moves on to the clipping and gain stage in the form of a non-inverting op-amp. The two diodes in parallel in the feedback each soft clip one half of the waveform. When the waveform’s voltage magnitude exceeds the forward diode voltage, the top of the wave will be clipped off. Therefore, the amount of the wave that is clipped off depends on the magnitude of the signal and can be controlled by adjusting the “Drive” potentiometer. This adjustment should not significantly change the output level since the waveform is being clipped, but it will determine the distortion level, as with more gain, increasingly more of the waveform is chopped off by the diodes in the feedback loop.

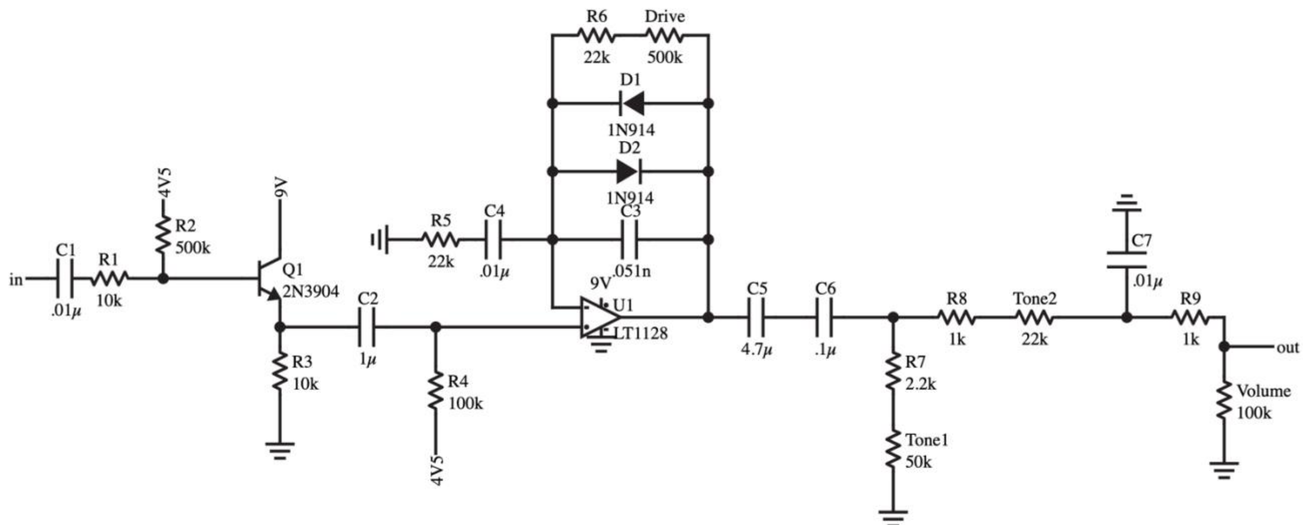

Figure 3. Overdrive pedal shows two diodes connected across the feedback loop to clip both sides of the waveform.

Additionally, there are a couple of filters in the feedback loop that determine the frequency response of the clipping stage. R5 and C4 together form a high pass filter with a cutoff frequency of 723 Hz, ensuring that higher harmonics receive the full clipping while lower fundamental tones retain more of the original signal. This can improve the sound of the pedal by preventing lower tones from sounding muddy and mellowing out the harshness of the high end by clipping these frequencies fully for a more “fat” and “crunchy” sound, so to speak. Furthermore, the drive potentiometer and capacitor C5 form a low pass filter which softens the edges of the clipped waveform and brings the sound closer to that of an old-fashioned tube amp.

Following the gain and clipping stage, we see a similar output stage as for the compression pedal. The user is able to control a low pass filter and high pass filter to filter out any unwanted lows or highs in the output. The user can also control the output volume with a 100k potentiometer.

4-Band Equalization Pedal

An audio equalizer is used to increase or decrease the level of specific frequency ranges in a signal. Sometimes they are used to reduce the level of an input signal as well, which can be particularly useful when the magnitude of the input signal is too high to be processed without undesired clipping. Another useful feature is an output boost, which simply allows the user to increase the volume of the signal before sending it out to the main amplifier in order to provide more gain than can be achieved through the main amplifier alone.

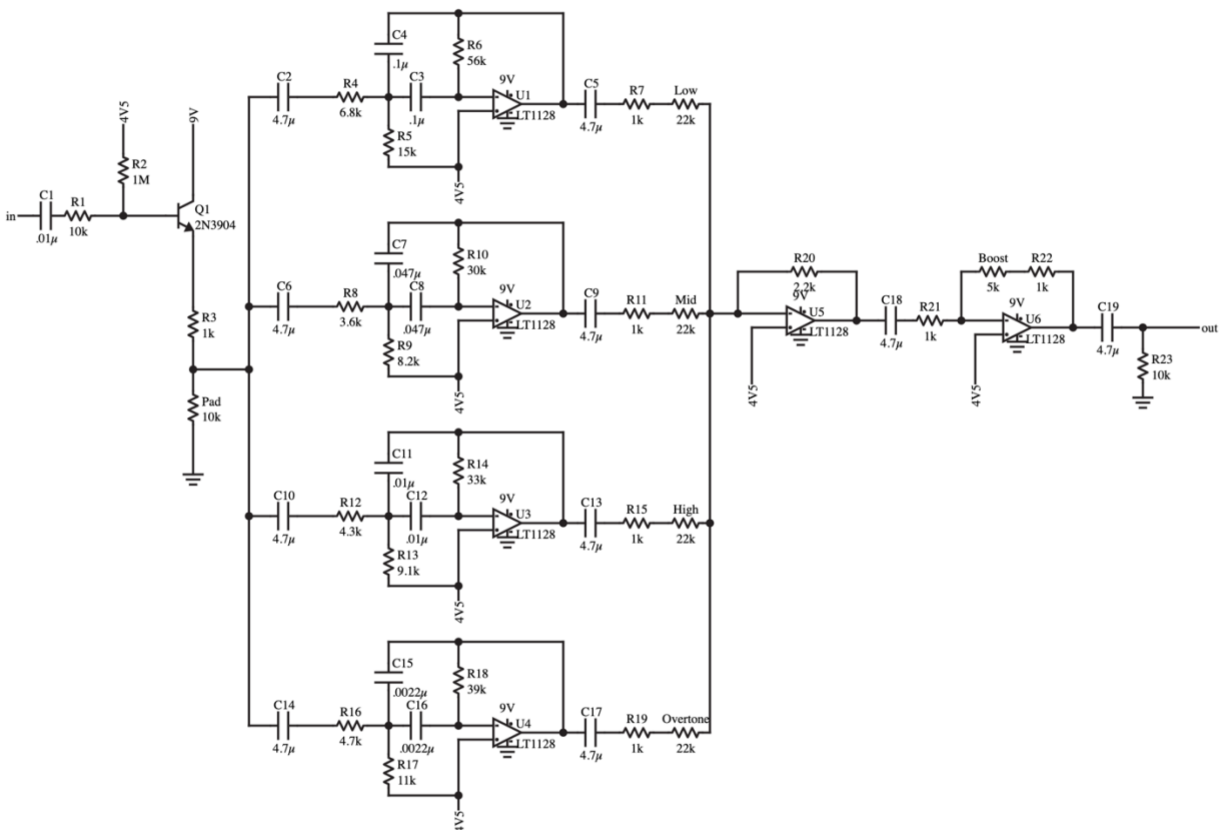

Figure 4. Signal passes through 4 bandpass filters in parallel before coming back together and passing through a boost stage.

The main difference between equalizers is the number of bands they have and their center frequencies, as well as the range of gains for each of these bands. Four bands is sufficient here, as the range of a guitar is relatively confined, and there is more than room enough with this design to devote one band each to the low-end, mid-range, and high-end frequencies of the instrument. An additional band for the higher harmonics should be sufficient considering the drop off in magnitude of higher order harmonics. Considering the lowest note on a guitar is 82 Hz, the lowest band was centered at 100 Hz and successive bands proceeded upward in multiples of 4, resulting in bands centered at 100 Hz, 400 Hz, 1.6kHz, and 6.4kHz. Each band provides the user with at least +/- 12dB of volume control in order to accommodate any desired adjustments to the tone.

The input signal is buffered as in the previous two pedals, but this buffer also features a "Pad" potentiometer that allows the user to attenuate the input signal using a voltage divider. After passing through this voltage divider, the signal proceeds to the bandpass filters, which are constructed using multiple feedback bandpass filters, allowing for precise tuning of the center frequency, gain, and bandwidth all in one unit. This efficient circuit block was inspired by a five-band equalizer project from the University of Evansville. Using a gain of 4 and a quality factor of 1.7, the resistance values for each filter were calculated after choosing reasonable capacitance values.

The outputs of each of the bandpass filtered are then added together with the op-amp U5, and the level of each band in this addition is controlled by potentiometers "Low," "Mid," "High," and "Overtone." This sum then passes through op-amp U6, which allows the user to boost the signal using the "Boost" potentiometer before the signal proceeds to the output.

PCB Layout

The main challenge of the PCB layout was to give easy access to the input and output audio jacks, the DC power supply, and the various adjustment knobs that are part of the board. After placing the jacks and potentiometers appropriately, the rest of the layout revolved around making efficient use of the space available on the board. The bottom plane was defined as ground and the top plane as + 9 V. A 3-dimensional view of the final layout can be seen in figure 5.

In order to further improve the board, time could be devoted to arranging the potentiometers in a more structured arrangement. This would make it possible to design a more aesthetic case for the PCB and eventually build a product ready for the big stage. Additionally, making more efficient use of the ground and +9 V zones would allow for streamlined connections and greater ease of arrangement of components.

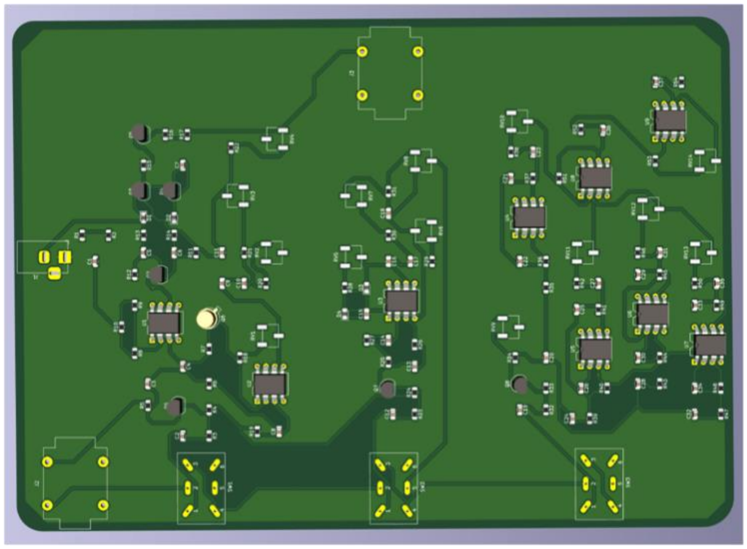

Figure 5. The push switches mounted on the bottom of the board allow for easy switching between effects during play.

Lessons Learned

The abundance of schematics available for various guitar pedals does not necessarily make it simple to design a pedal to a desired set of specifications. In fact, I think that the varied resources on the web often sent me down paths rather tangential to my goals, and in many cases I would have been better off focusing on finding a solution to the specific problem on hand rather than looking to designs of other guitar pedals. Specifically, when designing the compression pedal, I spent a lot of time trying to find a way to make OTA amplification work simply because it was a part of several compression designs I had read about. Once I turned my focus to the problem of using a voltage to control the gain of the system, I was able to find a solution quickly.

More generally, I would have been better off at the end of the project had I spent some more time up front laying out the essential components of each circuit. For example, it would have been more efficient to specify the gain of each circuit block in the initial stage of design so that I could choose component values accordingly. With my more loosely structured workflow, I was stuck spending a lot of time at the end of the project working backwards to figure out the desired characteristics of each block and finalizing component values accordingly. Additionally, it would have been helpful to have sketched out a rough schematic of some blocks before my design presentation in order to ask for more specific feedback.

The PCB layout delayed me for some time because I was worried that it would be more complicated than it really was. It may have been a bit more efficient to just jump into the software and figure things out as I went rather than spend time trying to get a solid grasp on the process beforehand. Nevertheless, my layout definitely leaves a lot of room for improvement and I would like to spend some more time practicing with PCB software in the future.

Conclusion

The design of compression, overdrive, and equalizer pedals provided insight into analog design from idea conception to PCB layout. Moreover, analog guitar pedals allow for easily modifiable, modular, and harmonically pleasing guitar effects suitable for any performance or recording application. Moving forward, it would be interesting to explore other effects such as delay that are commonly designed using both analog and digital technology for further understanding of the advantages and disadvantages of each design methodology.

Sources

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