The Observable Differences Between Germanium and Silicon Transistors in a Fuzz Pedal

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Introduction

My interest in effects for electric guitar started when I was fairly new to the instrument when I was a teenager. I had one of those starter cheap amp and cheap guitar kits. While for many, the first hurdle to learning guitar is the F major chord, my first hurdle was that I did not sound anything like I wanted to. I chose the electric guitar as the instrument I wanted to learn because I thought it sounded cool when rock bands like AC/DC and Green Day used it, especially when it was loud and distorted, and my equipment just sounded like a loud acoustic guitar. So, before I even really understood what distortion meant or how to get an electric guitar sound like what I always imagined an electric guitar sounded like I had to stumble across the internet to learn what an effects pedal was and how one could get me closer to the sound I was searching for.

Distortion History

The core of this project relates to effects pedals, however, it’s worth noting that the earliest examples of guitar distortion came around towards the end of the 1940s, particularly among Blues guitarists. Guitarists at the time noticed something interesting would happen if the volume levels on their amps were set very high, the sound would sound nothing like a ‘normal’ guitar and sound distorted and sound almost like static. This effect happened because of the nature of the way amplifiers were built at the time.

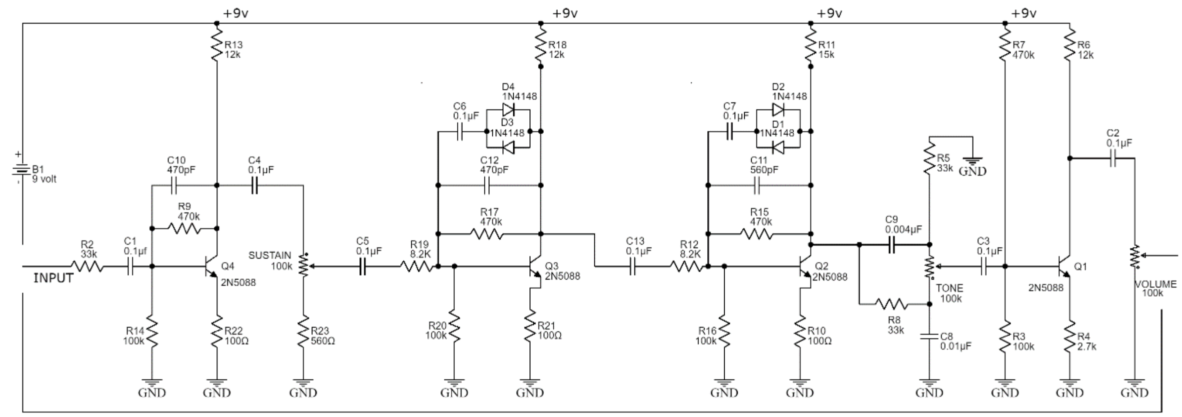
The point of an amplifier is to amplify the signal and make incoming signal louder. In contemporary times transistors are used to achieve a gain in voltage to make the signal louder, but during the early years of electric guitar transistors had not even been invented. What was used in the past to raise voltage in a circuit were vacuum tubes. Vacuum tubes are much larger than transistors are which is why vacuum tubes are seldom used in any circuits in modern times, but the larger size also means that current in a vacuum tube can be dissipated off as heat, most notably when the vacuum tube receives stronger currents that what it is built to handle. While this signal loss sounds like an undesirable trait, this feature is what causes distortion in tube amplifiers.

Guitar amplifiers weren't initially built with distortion in mind and setting the volume really high wasn't an option in every setting, so guitarists had to find different ways to distort their guitar sound. Beyond pushing the volume of their amplifiers, some guitarists would experiment with different, higher output pickups. There are also popular urban legends of guitarists damaging their equipment and cutting holes into their speakers, though a lot of this is unverifiable and there are no notable musicians that are known for doing this.

Most of the first notable instances of distorted guitar sounds happened by accident, but at some point the sound became desired enough to inspire engineers to experiment with parts to intentionally recreate the sound, specifically with germanium transistors due to their habit of outputting low-fidelity currents that had similar characteristics to the broken amplifiers it was inspired by. This discovery paved the way for many other effects pedals that would be created in the future, including the main topology that will be explored in this project.

Big Muff History

The Big Muff Pi is an effects pedal that is primarily used with electric guitars that was created by the company "Electro-Harmonix". There are many types of effects used with electric guitars, the Big Muff is considered an effect under the "distortion" umbrella. Distortion effects alter the audio signal by flattening the peaks, distorting or "clipping" the signal so much so that the produced sine wave resembles a square more than it does a rounded sine wave. Colloquially, guitarists and musicians have three subcategories to the distortion effect: overdrive, distortion, and fuzz. Overdrive is considered the weakest, or softest, distortion effect while fuzz is considered the hardest distortion effect. The Big Muff Pi is considered a fuzz effect.



The circuit was inspired by previous fuzz pedals like the Maestro Tone Bender with some changes in to make the unit more reliable and easier to build with parts that would be easy to source. Even in the present, while some specific parts (such as the FS36999) have gone out of print, they all have modern equivalents that are mass produced and easy to find.

Over the years there would be different versions of the circuit, built using different parts with different values to varying degrees of differences in the way the final product sounded. Most of these don't have official names or denominations and there are a lot of differences that are arbitrary; as an example, in the 1990s, Electro-Harmonix moved production of their pedals to factories in Russia and there are several "different" versions of the Russian Big Muffs that sound the same but look different (the "Civil War" Big Muff Pi and "Bubble Font Green Russian" are identical circuits that use identical components) and some that look almost the same and *sometimes* sound kind of different (the "Tall Font Green Russian" and "Bubble Font Green Russian" use slightly different components sometimes, with the "Tall Font" being the newer version). That said, one thing that makes Russian produced versions of the circuit stand out is that they have a much lower frequency response than other versions of the circuit.

The particular version being used for this project will be a version of the circuit nicknamed the "Ram's Head", which gets its name from being the first Big Muff Pi pedal to get the Electro-Harmonix logo stamped on it which is a ram. It differs from other versions of the circuit in that most Big Muff Pi circuits don't emphasize the midrange (about 1 KHz) where this version of the circuit does.

Purpose

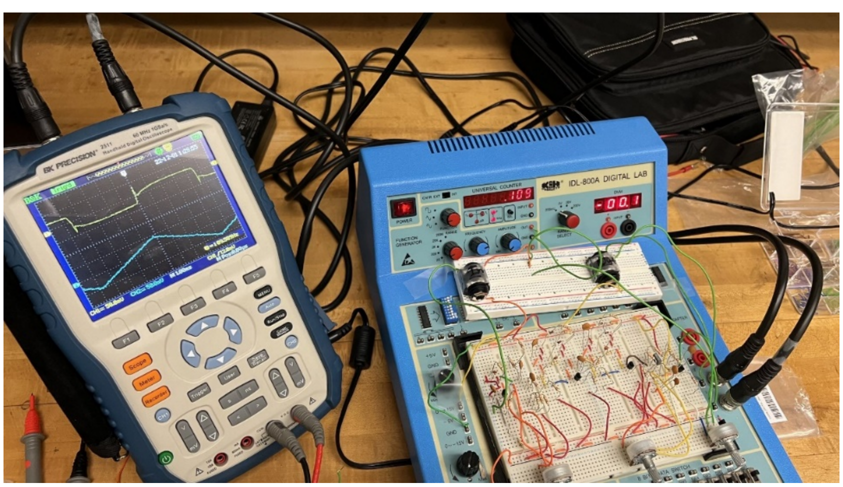
The primary purpose of this project is to investigate what differences occur when taking a transistor-based circuit and swapping out the transistors in favor of transistors with similar values and with a different semiconductor by using measuring physical and observable values.

A semiconductor is a material that has electrical conductivity somewhere between a conductor and an insulator, they are used to manage the flow of current in electronic equipment. In transistors the semiconductor material controls which direction the electrons flow (in or out). There are many kinds of semiconductors, in contemporary use the most popular semiconductor is silicon because it is considered one of the most cost-effective and stable within most temperatures. Before silicon was considered the standard, another widely used transistor semiconductor was germanium. Some early circuits built for music effects used germanium as a key part in achieving its effect, such as a distortion effect called the Fuzz Face. Germanium's prominence in early circuits of this category retains some presence in the industry, one popular mod for Big Muff pedals is to swap out a couple of the silicon transistors with germanium transistors (typically the 2N1308), some manufacturers even mass produce some units with this design inspiration, specifically Earthquaker Device's effect pedal called the "Cloven Hoof", which swaps out two silicon transistors in favor of two germanium transistors among some other parts. Much of the conversation centers around differences that are seemingly inherent to the germanium semi-conductor over other things in the circuit, which inspired the curiosity to see if there is a measurable difference between the two.

Equipment

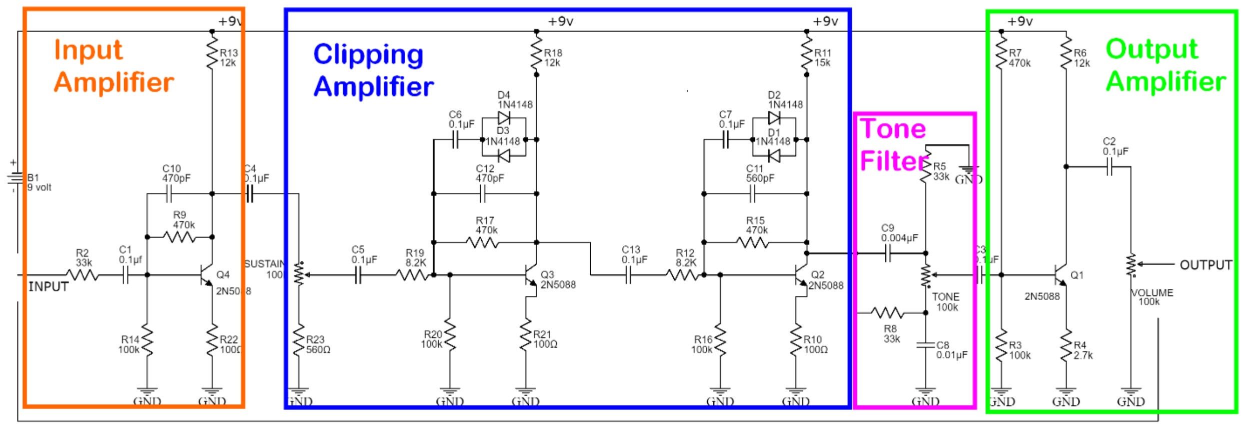
- IDL-800A Digital Lab: a device created to build and test electronic circuits. The main functions used on the device were the onboard power supply (set to about 9 volts), the coaxial output adapters, and the wave function generator, which can be tuned down to frequency, amplitude, and shape (square, triangle, round). For the project, triangle waves were primarily used as they are the most similar to the output of an electric guitar.
- BK Precision 2511: a digital oscilloscope that was used as an oscilloscope to observe and record waves as they were altered by the Big Muff Pi circuit. The device is digital and is able to record data in formats compatible with Microsoft Excel.

The Big Muff Pi circuit was put together on a breadboard using the available parts and transistors specific to the circuit (2N5088 silicon transistors and 2N1308 germanium transistors). The diodes chosen were comparable to what was used in the original circuit (most modern releases also use 1N4148 diodes), ceramic capacitors, and carbon film resistors. It is often said that using capacitors of different materials can also change the sound of the circuit, but that is not what is being explored in this project.

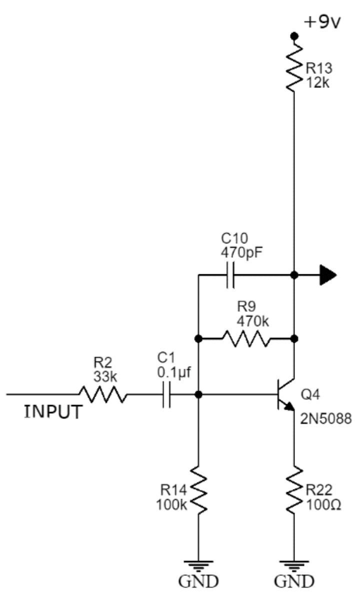


Circuit Breakdown

The Big Muff Pi circuit is made up of 46 components that ultimately contribute to five stages: an input stage, two clipping stages, a filter stage, and an output stage

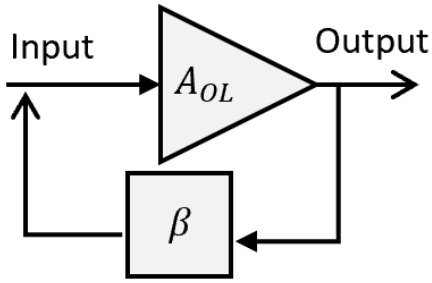


While all of the stages are built to accomplish different things there is a strong commonality to how they are constructed.



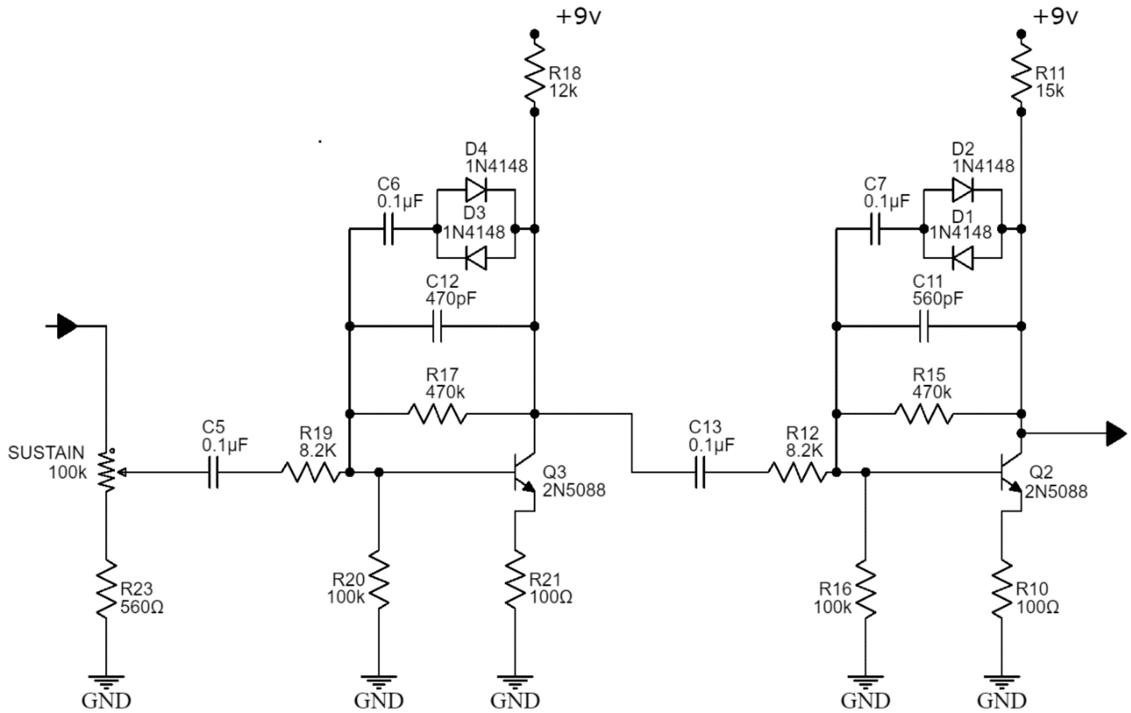
The input stage is based around a simple electronic junction referred to as a common emitter amplifier.

This amplifier uses the natural characteristics of a transistor, where the *B* base serves as the input, the *C* collector serves as the output, and the *E* emitter is connected to the ground reference. The junction then incorporates a resistor into the collector and another resistor to the emitter which will both contribute to the overall voltage gain in the circuit. The voltage gain of the current in an emitter amplifier is roughly equivalent to $-\frac{R_C}{R_E}$.



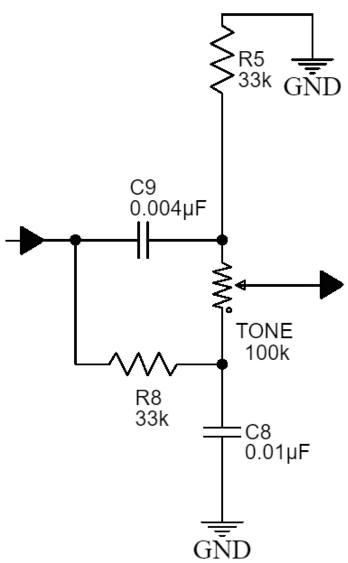
This junction is also a negative-feedback amplifier, connecting the collector node back into the base, with a resistor to create the negative feedback.

This technique is used to improve performance and stability of the amplifier but also attributes to a smaller change in voltage gain. With this loop gain is $A_{FB} = \frac{v_{out}}{v_{in}} = \frac{A_{OL}}{1+\beta A_{OL}}$ and the feedback coefficient, $\beta = \frac{v_f}{v_{out}}$. The remaining parts are primarily for the sake of maintenance on the circuit. R2, R14, are used to set a limit on how loud the input current can be, and C10 is used as part of a filter in the circuit. The arrangement in this amplifier is a low pass filter. Low doesn't necessarily refer to a direct value, but rather which relative frequencies are affected. For example, in this amplifier, the low pass filter cutoff frequency can be calculated with the equation $f_C = \frac{1}{2\pi RC}$, when resistance is 470k ohms and 470 pico-farads, the measured cut off is about 720 Hz, meaning that the filter emphasizes frequencies under 720 Hz. In a high pass filter (arranged with a capacitor before a resistor) the calculated frequency cutoff would mean that frequencies over 720 Hz are emphasized. Cutoff frequency is kind of a misnomer: the frequencies aren't necessarily removed from the circuit but are damped/silenced, while the frequencies within the range are emphasized. Most of the remaining stages in the circuit use the same concepts, the transistors in the clipping stages are built almost exactly the same with a couple new additions



There are two clipping stages that are basically identical and stacked because one clipping stage isn't enough to achieve the desired effect. Before the input current reaches the clipping stages, however, it passes a few important parts. The current that leaves the amplifier stage first interacts with a capacitor. This part is there specifically to ensure that the circuit is primarily working with alternating currents rather than direct currents, seeing as the output of the emitter amplifier is connected directly to a DC 9 volt power supply, and capacitors block direct currents because the plates of a capacitor are separated by an insulator. Another interesting component is the R23 resistor, it exists to prevent the circuit from going silent when the "Sustain" potentiometer has its resistance turned all the way up. The sustain potentiometer controls how strong the clipping is in the clipping stages, with minimum resistance allowing a louder signal into the clipping stages and creating a stronger "clip", and maximum resistance creating a softer clipping of the waves.

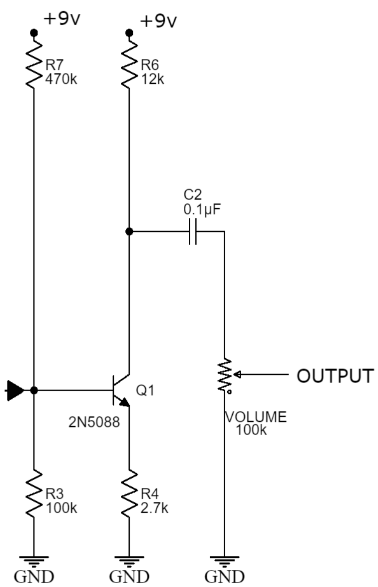
The clipping stages are built off an emitter circuit with the negative feedback loop, much like the input amplifier. A unique feature of this stage is that it incorporates anti-parallel diodes, anti-parallel meaning that they are wired in parallel to each other while facing opposite directions. A diode is a electronic component that conducts current in one direction. It has two parts, the cathode and anode and its path is from the cathode to the anode. When used to clip waves in an circuit, the diodes are limiting the voltage of the wave, which is to say the wave is being bottle-necked and compressed by the diodes. This is typically done with two diodes facing opposite directions, but it can be done with an odd number of diodes.



Both stages start off with high pass filters where the capacitors double as couplers to block direct currents while the resistors also attribute to some of the voltage gain in the transistors. The rest of the stage is the same as the input amplifier with the addition of clipping diodes and a capacitor to prevent direct current from interacting with the diodes and filter what frequencies get clipped. The filter stage is simple and different compared to similar circuits for distortion. Where most distortion circuits have a simple low-pass filter (a filter that filters out high range frequencies that can be introduced into the signal by lowering the resistance of the potentiometer associated with the filter), the Big Muff Pi combines a low-pass and high-pass filter (a filter that filters out low range frequencies).

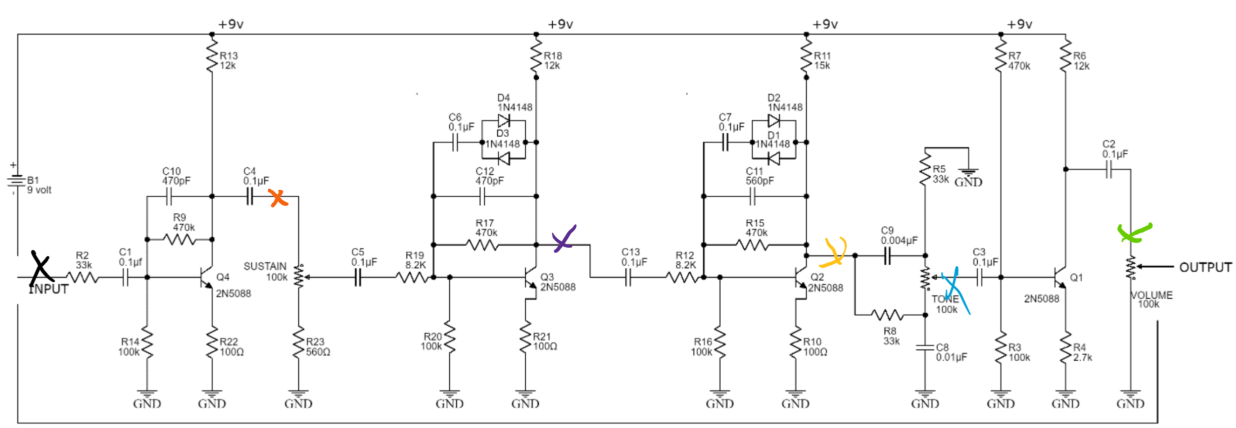
Both filters are connected to a potentiometer that blends the two currents together, so turning the filter potentiometer will introduce the current of one of the filters while blocking out the other (turning the potentiometer to minimum resistance will block out the low-pass filter while using the high pass filter).

The output amplifier is another simple emitter amplifier where the transistor recovers any volume loss that occurred in the clipping stage and the tone filter with a capacitor that blocks direct current from becoming a part of the output. The volume potentiometer controls how much of the current is allowed to go out into the output.

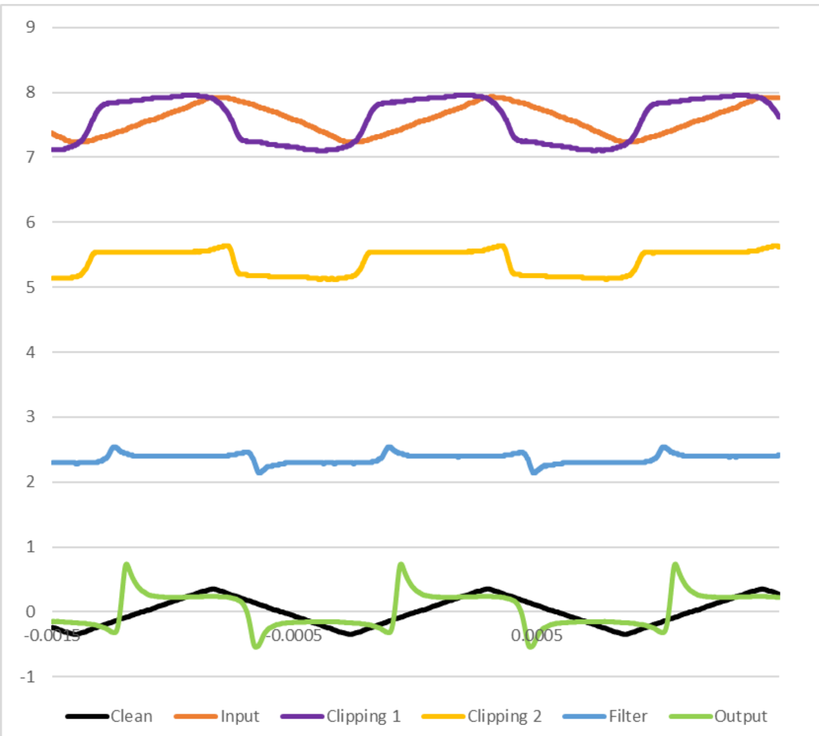


Circuit Analysis

To better grasp how the stages alter the signal, readings were taken on a BK 2511 oscilloscope at the ends of each stage as marked.



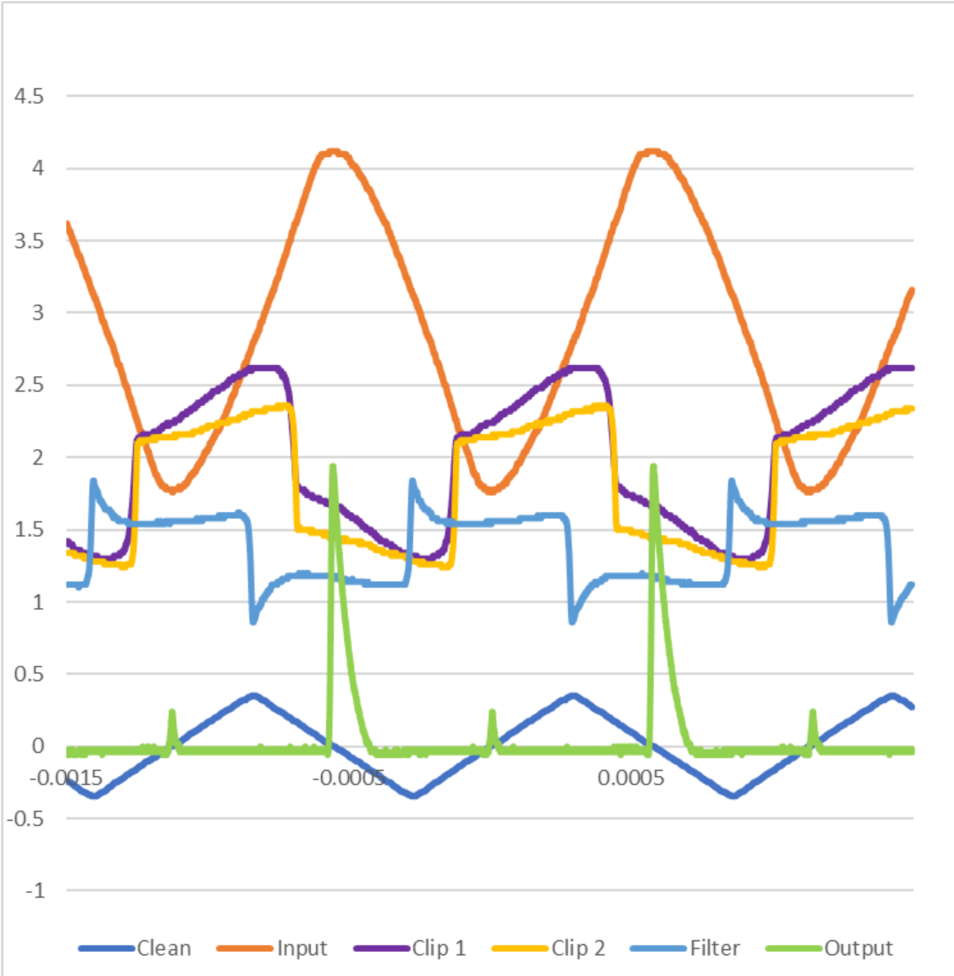
The first readings were taken on the circuit based on the original specs, with 2N5088 silicon transistors. The source signal was generated from the IDL-800A wave generator at the triangle setting and set to about 880 Hz with an amplitude of about 340 mV (approximating an output close to what an electric guitar would output at a frequency comparable to an A6 note), sampling 250 microseconds at a time, and all the potentiometers were set to contribute no additional resistance to the circuit.



It's demonstrated that the clipping stages do clip the signal, and the tone filter has its volume restored by the output amplifier, and the output overall is louder than the input.

It's also worth noting that the notches at the beginning of the peaks of the waves increase when the frequency of the signal increases, whether it be the source signal is of a higher frequency or the filter stage is set to emphasize the higher frequencies.

The primary question asked is what affect would swapping germanium transistors have on the circuit. There are many transistors available, the 2N5088 was chosen because it's equivalent to what was used in the first version of the circuit. The germanium transistor chosen was a 2N1308 because its specifications are similar to the 2N5088 and are commonly used for similar modifications.



The second circuit being analyzed is one where all the parts are the same but all four silicon 2N5088 silicon transistors are swapped with 2N1308 germanium transistors. Upon recording data, it became apparent that while swapping 2N5088 transistors with 2N1308 can complete the circuit and produce an output, the output isn't a desirable output. When charted along with the outputs of each stage.

While the stages accomplish similar changes (input amplifier greatly increases voltage of the signal, clipping stages clip the waves, and the filter stage puts notches into the waves), the overall changes are noticeably different. The input amplifier boosts the voltage of the current far less (compare roughly 7.5 volts compared to a peak of about 4 volts). With how small the voltages among the stages are relative to the original read with the 2N5088 transistors, it's obvious why the output looks the way it does: it appears that these parts alone aren't capable of producing a comparable output as the circuit is.

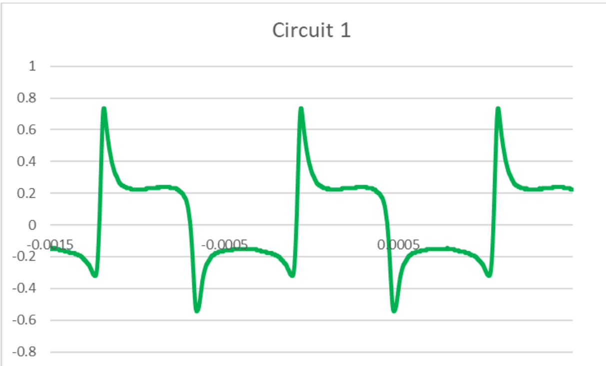
This isn't a net negative, it does provide answers as to what changes with a part swap. As noted prior, the notches at the beginning of the peaks of the waves are sharper and larger with relatively higher frequencies, meaning that there is something that is more represented in this circuit within the 880 Hz frequency than there was in the first circuit, considering how much louder the peaks are compared to the rest of the waves, unless it's just noise.

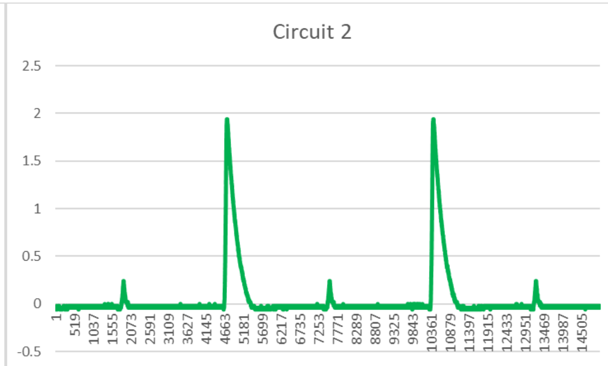
To test the circuits for different frequencies to compare the response to different frequencies, the Bode plot technique will be employed to chart what frequencies do in the circuit.

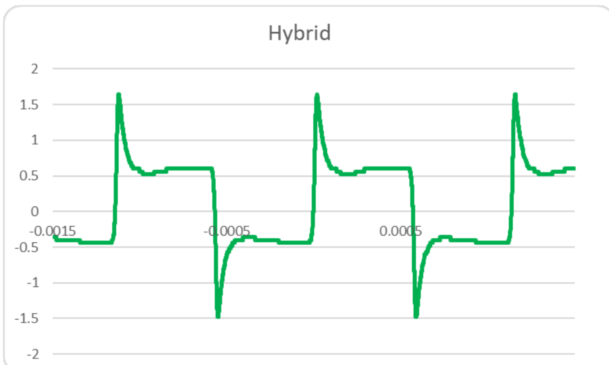
A Bode plot is a way of charting frequency response done by comparing changes in peak-to-peak voltage relative to the voltage of the source frequency at different frequencies. The logic is that circuits that emphasize certain frequencies will output those frequencies louder (with higher voltages) and will output frequencies that aren't emphasized as lower voltages. The plot is expressed in magnitudes, in this case will be decibels where zero decibels will mean the output is the same volume as the source, negative decibels will mean the output is quieter than the source, and positive decibels will mean the output is louder than the input. To obtain data that fits on a frequency response Bode plot, the following equation is used $A_{dB} = 20\,log\left(\frac{V_{out}}{v_{in}}\right)$.

Regarding the unbalanced output of the all second circuit, the circuit could be used as is to measure frequency response and can provide some insight as to what frequencies are affected by the change in transistors.

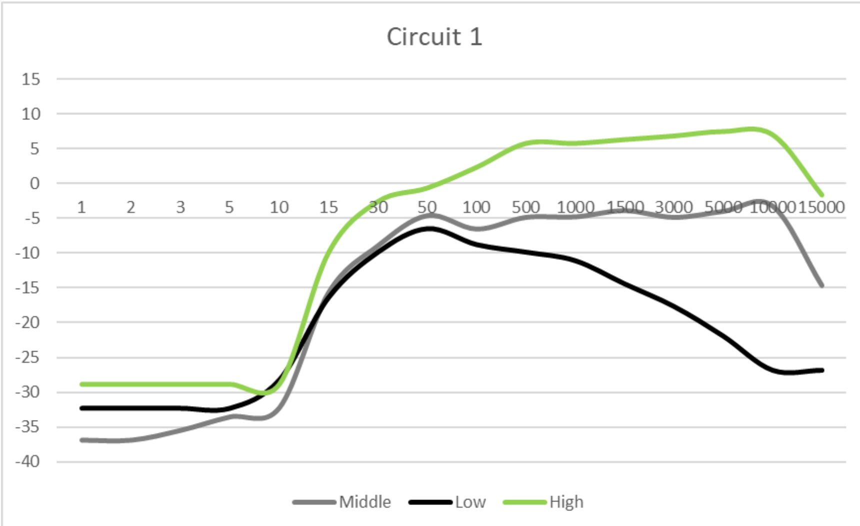
I went ahead and changed the output transistor of the second circuit (the one with 2N1308 transistors) to see if the three other transistors were enough to show if there was a difference. Despite the hybrid being louder, it can be shown that there is a difference in how the input would clip differently, meaning that the change in voltage isn't the only difference; in one way or another the germanium transistors are bottlenecking the signal in some way.

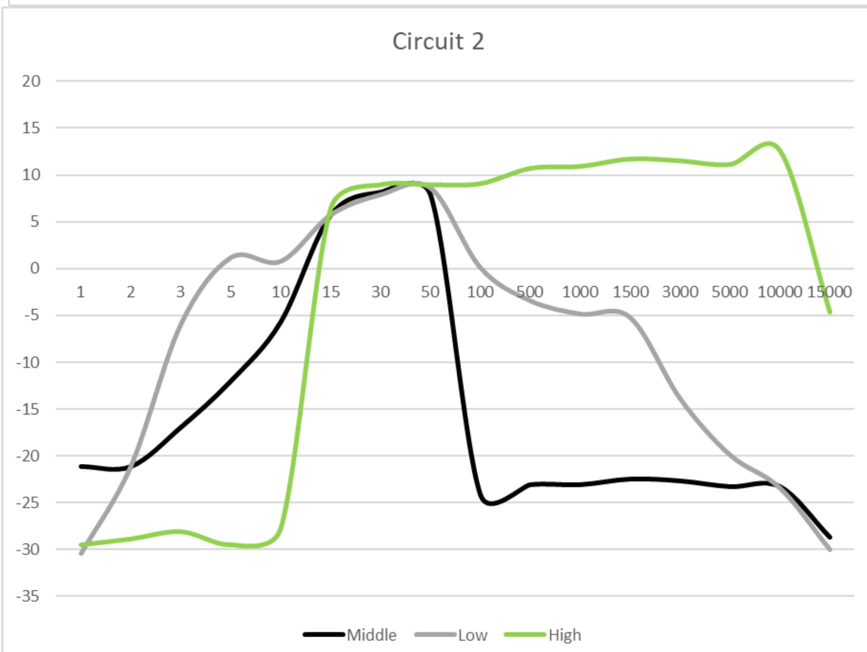






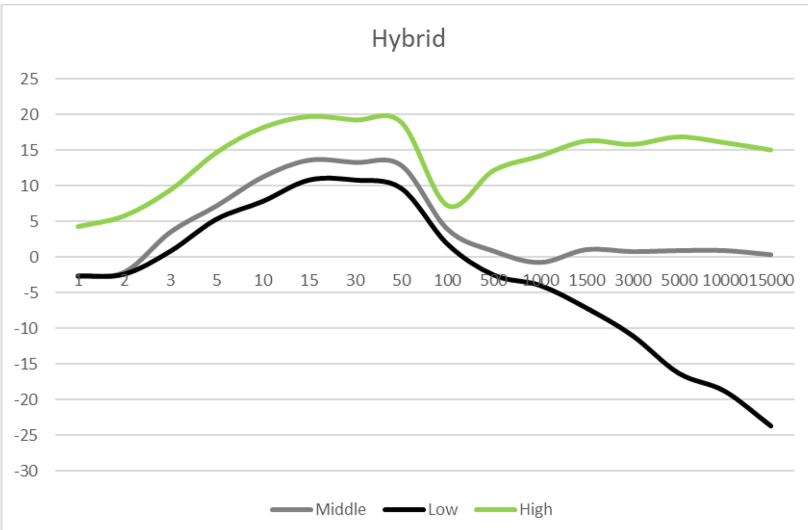
To compare the frequency response Bode plots of the two circuits investigated, the first and second circuits, frequencies between 1 Hz and 30 KHz were measured and charted at about 500 mV. In standard tuning the electric guitar typically covers the frequencies of 80 Hz – 1300 Hz (roughly between E2 – E6). The data was gathered over three different positions on the potentiometer connected to the filter stage, once with the resistance turned all the way up, all the way down, and at about the middle (about 50k ohms of resistance). The remaining potentiometers were set to zero resistance.





A couple of note-worth differences between the two charts is how much louder second chart is compared to the first chart. The second circuit seems to boost frequencies at about 15 Hz at all three readings where the first circuit's output is only really begins reaching zero (about unity amplitude relative to the input) at about 50 Hz, except for the reading at the minimum resistance. Another key observed difference is how the frequency response in the second circuit falls much earlier than it would in the first circuit. Keeping in mind that in standard tuning the lowest guitar note is about 82 Hz, even if the circuit had an output similar to the original circuit, it would likely also sound quieter at most points unless the potentiometer had very little resistance. In fact, as the circuit is now it appears it would likely be surprisingly compatible with a bass guitar, seeing as the lowest note on a bass guitar in standard tuning would be E1 at about 42 Hz, perfectly in line with the frequencies emphasized by this circuit.

In order to get a better idea of what was happening to the sound, another frequency response chart was made using the Bode plot method with the circuit having all germanium transistors except for the last transistor, the output amplifier, and it being replaced with a 2N5088.



The new chart shows that the output is significantly louder than the output of both circuits presented initially, but is also shows some interesting trends unrelated to the voltage increase. The hybrid model better retains frequencies higher than 50 Hz, where in the all germanium circuit the frequency response falls sharply rather than trailing off, and now platues around the middle and when favoring high frequencies. That aside, the circuit still favors lower frequencies (less than 100 Hz), but the stable representation in higher frequencies lends credence to the idea that germanium transistors displace high frequencies while silicon transistors are better equipped to retain them. This makes more sense when considering that the only transistor that was changed between the all germanium circuit and the hybrid model was the transistor that comes after the filter stage.

Conclusion

Overall, the differences were more dramatic than expected. I expected a small difference in frequency response and maybe a small difference in output.

What is the best explanation for the difference? While it is apparent that the circuit layout doesn’t adequately function with germainium 2N1308 transistors, without additional modifications, there are still differences that aren’t solely because of voltage gain.

The best explanation for the differences can be explained by the history of the semiconductor and its contemporary use. Nobody in the present uses any germanium as a semiconductor anymore, primarily because it has a lower operating temperature (70 degrees Celsius for germanium compared to 150 degrees Celsius for silicon) which can lead to current integrity being compromised and leaving some of the current to be dissipated as heat, meaning that germanium as a semiconductor is more likely to leak current compared to a more stable semiconductor like silicon. Another effect that used transistors in the music world long before the Big Muff Pi did was a guitar pedal called the Fuzz Face, which got a clipped signal from overloading transistors without needing the aid of diodes.

It is possible that some of the data collected doesn’t perfectly represent how the circuit would work in practice as the output of electric guitars aren’t perfectly generated waves and there’s always the possibility that the equipment could be picking up on some ‘noise’ unrelated to the materials being tested such as radio frequencies or some other electromagnetic interference. Additionally, the data collected for the frequency response charts had to be manually collected and calculated which always opens the possibility of recording/graphing information incorrectly.

The most apparent conclusion is that parts alone aren’t solely responsible for the output of the circuit. The output of the modified circuits did work but aren’t in a useable state (potentially too noisy and too loud) but could likely be easily modified to work with the parts available. As mentioned in the beginning, there are a lot of variations of the Big Muff Pi circuit because there would often be times where the parts specific to the original circuit were no longer available and modifications would need to be made to make parts that were available useable.