Tuning a Fender Twin Reverb

Lee Feder
Physics 498 POM
Professor Steve Errede
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Introduction

Before the Physics 498 POM project, circuitry had always interested me. I thoroughly enjoyed Physics 112: Electricity and Magnetism . However, I faced some initial problems in choosing one project for the entire semester. My primary goal for the project was to learn about electronic circuits, vacuum tubes, and their respective effects on sound. However, choosing a specific project was easier in principle than in practice. The first difficult was a "use" constraint; I do not play electric guitar and do not use my electronic keyboard sufficiently to warrant the construction of either an external amplifier or a sound modulation device. The second and perhaps more important constraint was money; I have none. Therefore, even if I had been interested in constructing an amplifier for myself, I could not have afforded the parts.

At this point I turned to my much more musically inclined brother Aaron. Owner of at least three guitar amplifiers, several guitars, a Fender Rhodes, an electric bass, and several microphones, I imagined that he would *always* find a use for an additional amplifier. Plus, I could charge him for all the parts; this way I get the knowledge and experience, and he gets a top notch amplifier. Unfortunately, he too lacked the immediate resources to bankroll a several hundred dollar amp. His counter-offer though greatly intrigued me given both the scope of the project and the history of the class and Professor Errede. Aaron asked if I could refurbish his 1977 Fender Twin Reverb.

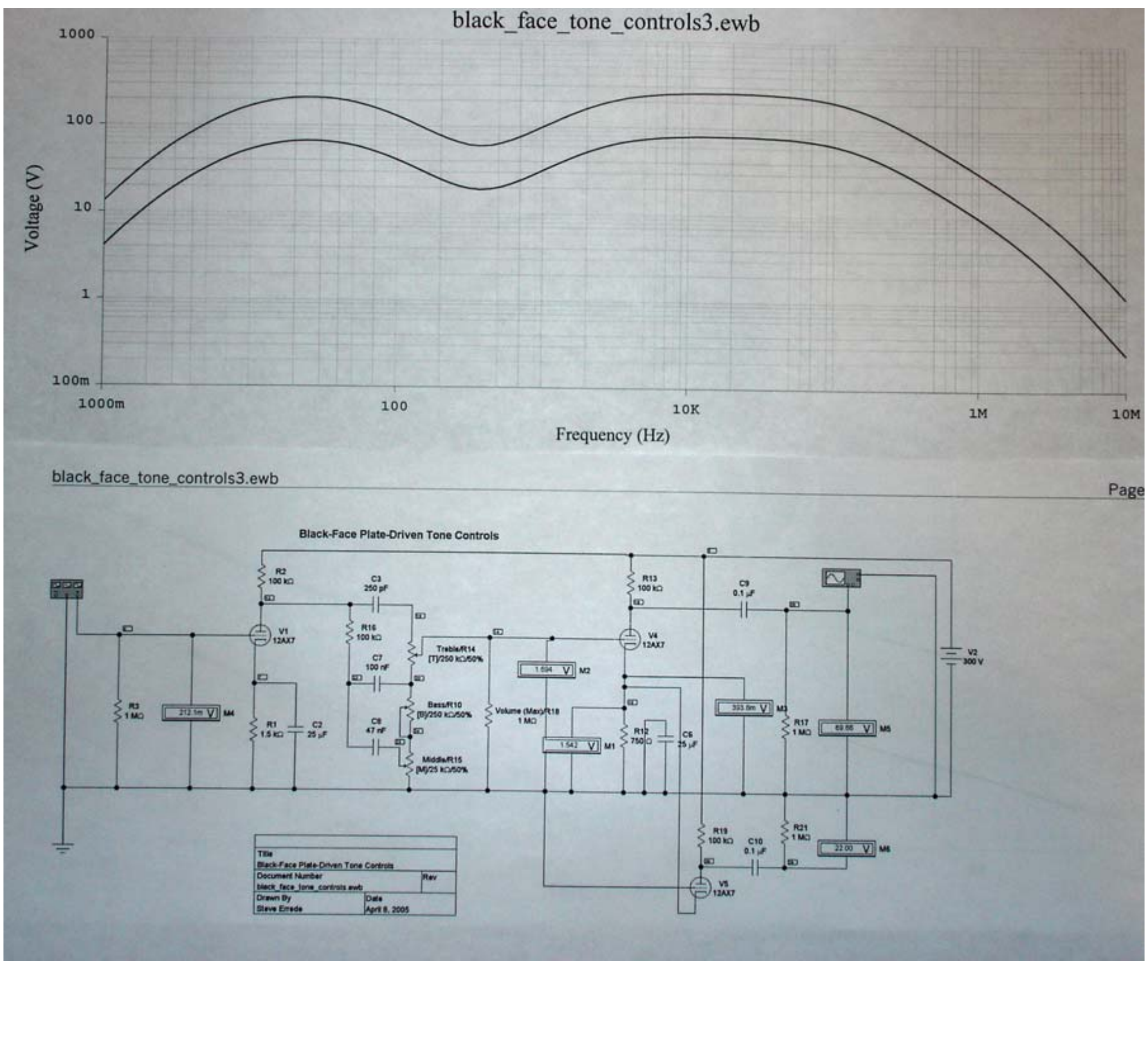
Fender Twin Reverb serial number F114553 began life as a CBS-designed recalcitrant amplifier. Upon procuring it in mid-2004, my brother had Ben Juday rebuild it to "black face" specifications, those from the Fender golden age in 1963. After the reconstruction of June 2004, the amplifier sounded fine for several months.

However, in late 2004 it began to distort heavily and, in the scientific words of my brother, it "just didn't sound *right*." He also asked that I install an overdrive circuit which would allow, with the flip of a switch, to push the regular clean "Fender sound" over the limit of the tubes and clip the signal to give a more harsh rock 'n roll tone. With really only one specific charge, the overdrive circuit, and a much more important yet vague one, I rolled the Twin into the lab to tap the knowledge of the class to clean up the sound and install the overdrive circuit.

<u>Overdrive</u>

The first and perhaps easiest of the goal I had was to install the overdrive circuit. The circuit is a relatively easy modification of the existing wiring and since my brother's amp already had an unused switch from the no-longer-functioning CBS-designed master volume control, there was not even any installation necessary. As shown in the pictures in Appendix 1, the circuit consists of shorting out the capacitor on the second gain stage of the vibrato channel. This has two positive byproducts: the first is that since the two cathodes of the second gain stages of both the normal and vibrato channels are tied together, shorting out the capacitor (switch in) allows the guitarist to use reverb on the normal channel; the second is that with the switch pulled out, there is a high gain option allowing for the amp to distort slightly on command; with the switch pushed in, the tone is softer and cleaner, but features less gain.

Figure 1



The reverb, when used through the normal channel, is also affected by the volume level on the vibrato channel. As seen in Figures 1-3, the lower the volume is

Figure 2

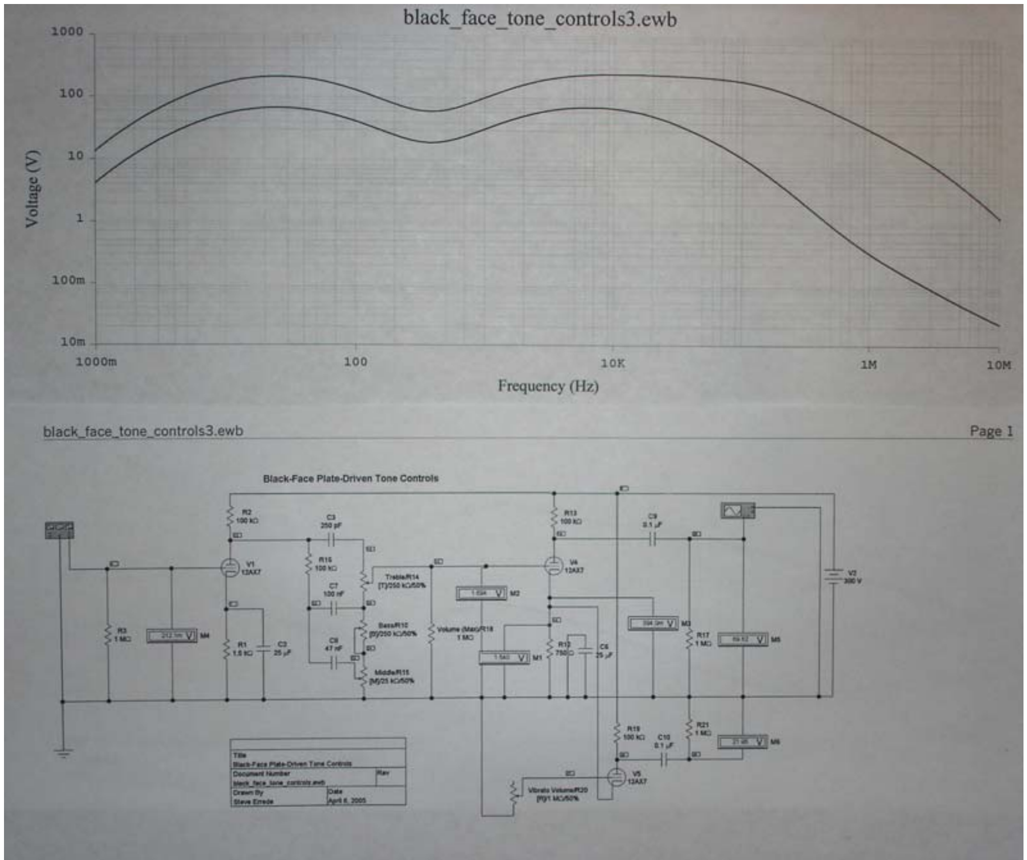
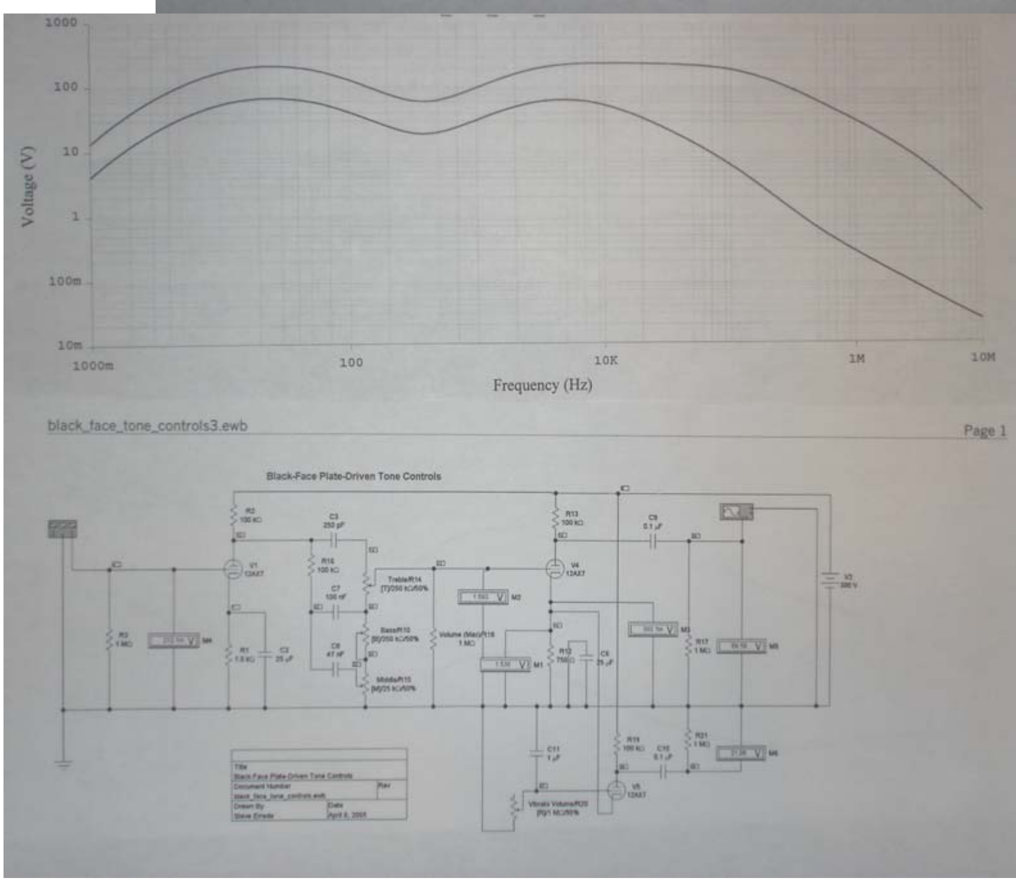


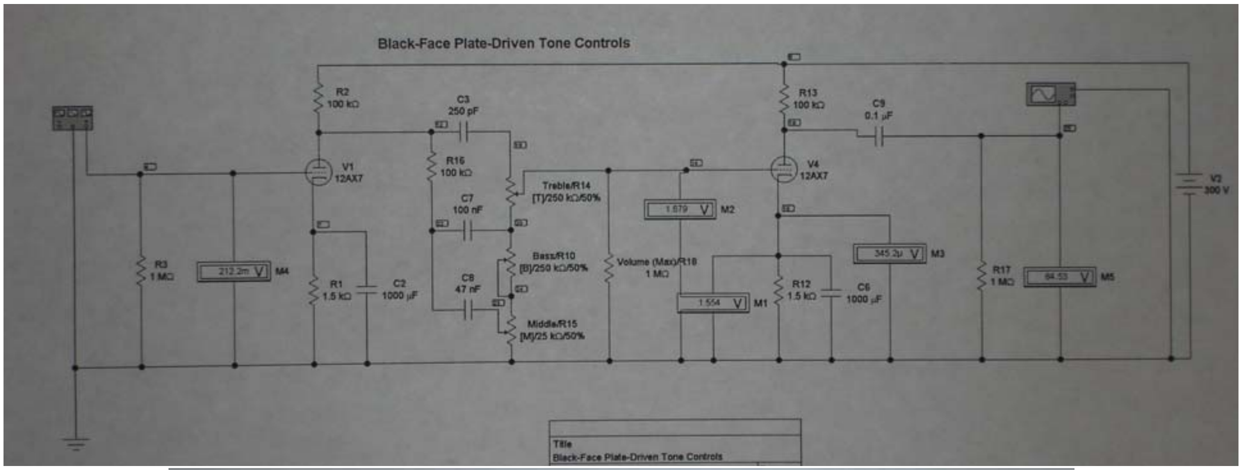
Figure 3



attenuated on the vibrato channel, the more closely the frequency response of the second channel (the bottom curve) tracks that of the normal channel. This increased tracking corresponds to a more traditional mapping of the reverb onto the normal channel. As the volume control is increased from effectively 0 (Figure 1) to near the top (Figures 2 and 3), the amp loses the high harmonics making the reverb sound darker. The graphs at the top of each picture show that the second "hump" of the bottom curve shifts further and further left as the vibrato volume increases from 50% (Figure 2) to 95% (Figure 3).

The utility of the extra gain can easily be seen in the schematics and graphs on the following pages. The first set (Figure 4) shows the functioning of the preamp stage as Leo Fender designed it: the capacitor (here it is 1000µF to enhance the effects on the graphs but on the amp is really 25 µF) is wired in parallel with the 1.5K resistor (In the amp this is 820 K because there are two preamp tubes forcing current through the resistor and since Ohm's Law V=IR is linear, if there is twice the current the resistance should decrease by a factor of 2 in order to keep the voltage drop constant; 820~1/2*1500=750. These numerical changes due not alter the effect, but only obviate it for the sake of argument and demonstration.). The gain of V4, the preamp tube in question, according to the original design is a hefty gain of 84.53/1.679=~50. The ratio compares the input voltage on the grid to the final output voltage; both are root mean square alternating current voltages (V_{AC}^{RMS}). As the Voltage v. Time graph shows, there is moderate clipping on the upper part of the sine wave. Instead of rounding off evenly or even coming to a moderate point, the top of each wave crest is chopped off and even has some visible transients. This, were we to subject it to Fourier analysis, would show the addition of harmonics not present in the original pure 1 kHz sinusoidal input wave coming off the simulate function generator. Finally, the Voltage v. Frequency graph shows a rapid drop off as frequency increases. While most of this occurs well beyond the audible range, it nonetheless happens and serves as a point of comparison.

Figure 5 shows the amp under normal operation with the volume control set at the same level, with the same input signal, but with the switch effectively pulled out. In this case the capacitor is disengaged and so has no bearing on the input signal. As a result, the gain is significantly decreased. Here the gain is 48.54/1.667=~30, using the same computation as before. As a result, there is no clipping; the first graph shows a balanced sinusoidal curve with no chopped crests or troughs and no transients.


Black-Face Plate-Driven Tone Controls
R2
100 kΩ
C3
250 pF
R16
100 kΩ
V1
12AX7
Treble/R14
[T]/250 kΩ/50%
C7
100 nF
Bass/R10
[B]/250 kΩ/50%
C8
47 nF
Middle/R15
[M]/25 kΩ/50%
Volume (Max)/R18
1 MΩ
R3
1 MΩ
212.2m V
M4
R1
1.5 kΩ
C2
1000 µF
1.679 V
M2
1.554 V
M1
R13
100 kΩ
C9
0.1 µF
V4
12AX7
345.2µ V
M3
R12
1.5 kΩ
C6
1000 µF
R17
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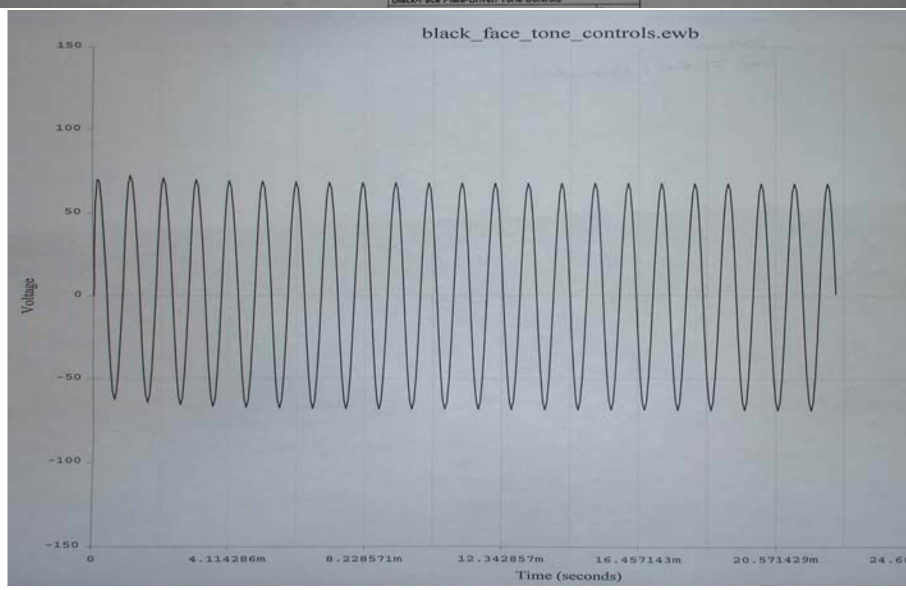
84.53 V
M5
V2
300 V
Title
Black-Face Plate-Driven Tone Controls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100
50
0
-50
-100
-150
Voltage
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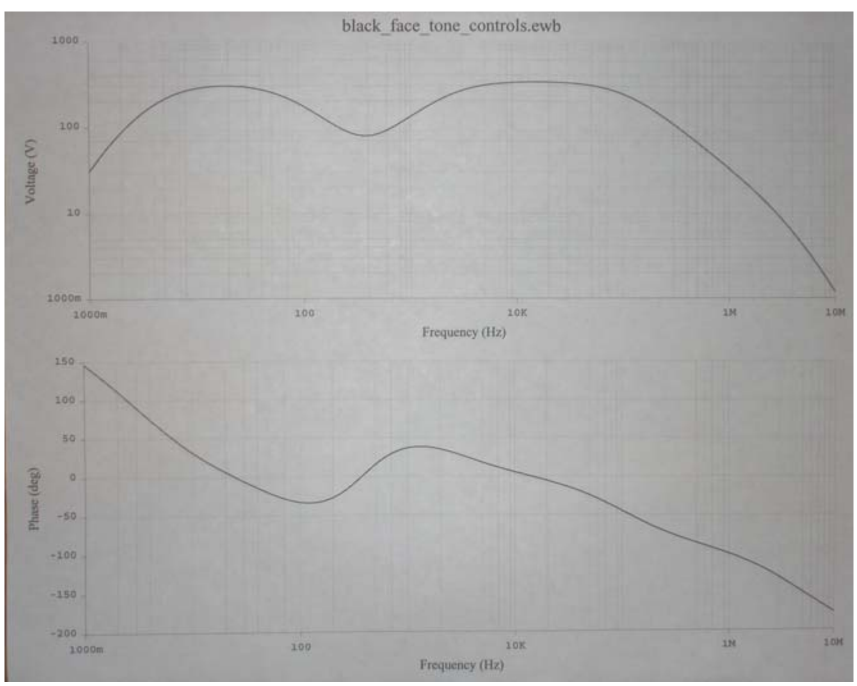
16.457143m
20.571429m
24.68
Time (seconds)

Figure 4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100
10
1000m
Voltage (V)
1000m
100
10K
1M
10M
Frequency (Hz)
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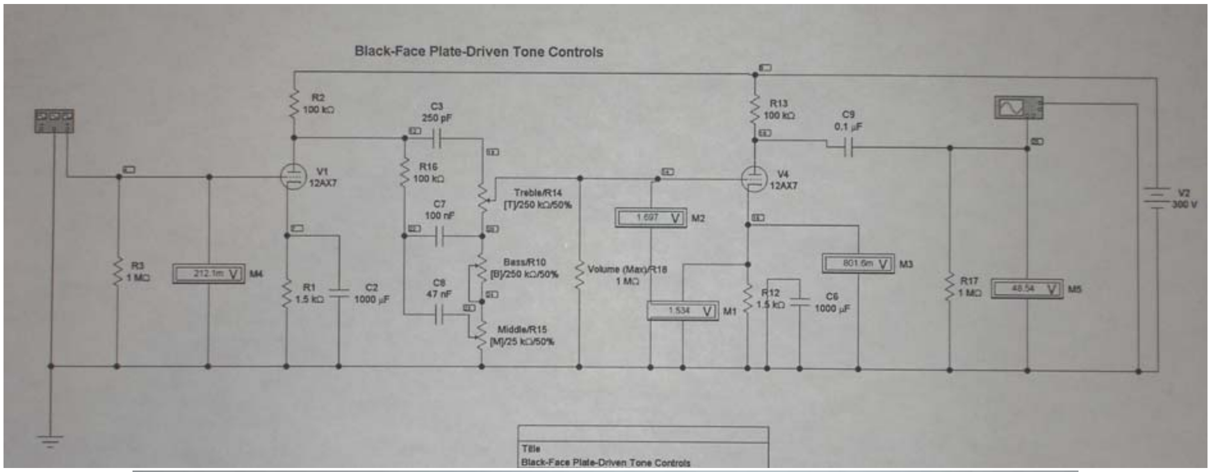
-50
-100
-150
-200
Phase (deg)
1000m
100
10K
1M
10M
Frequency (Hz)


Black-Face Plate-Driven Tone Controls
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M4
R1
1.5 kΩ
C2
1000 µF
Bass/R10
[B]/250 kΩ/50%
C8
47 nF
Middle/R15
[M]/25 kΩ/50%
Volume (Max)/R18
1 MΩ
1.697 V
M2
1.534 V
M1
R13
100 kΩ
C9
0.1 µF
V4
12AX7
R12
1.5 kΩ
C6
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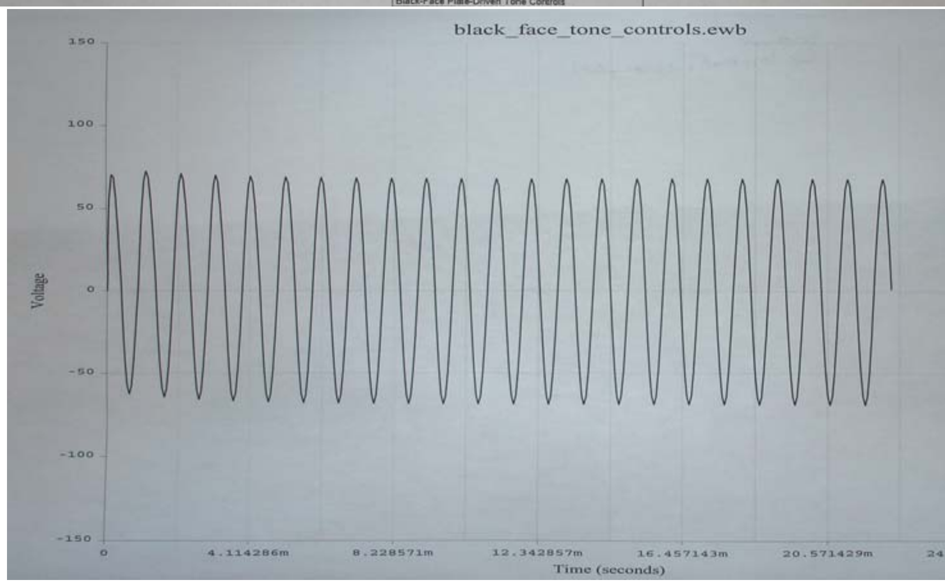
M5
V2
300 V
Title
Black-Face Plate-Driven Tone Controls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100
50
0
-50
-100
-150
Voltage
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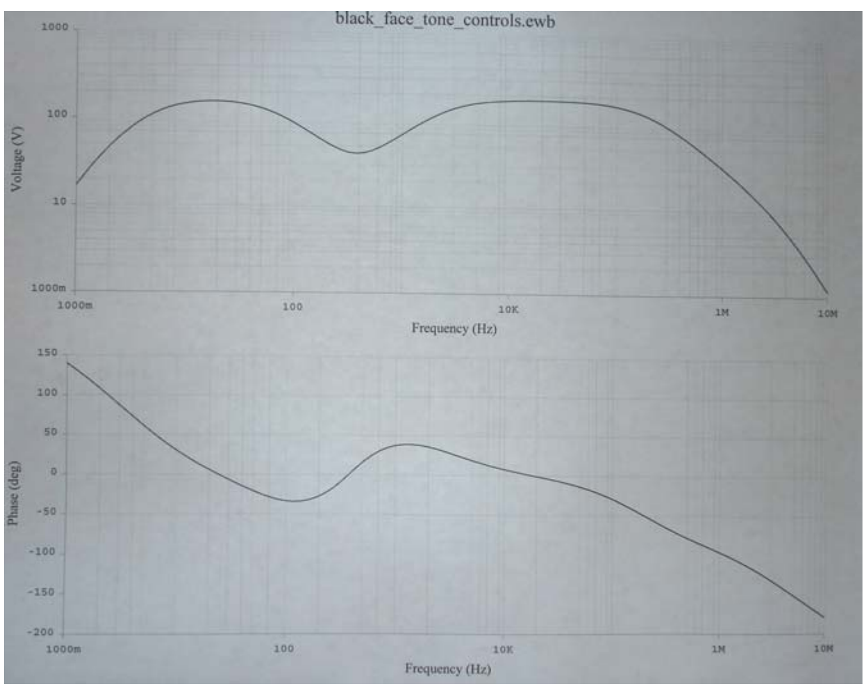
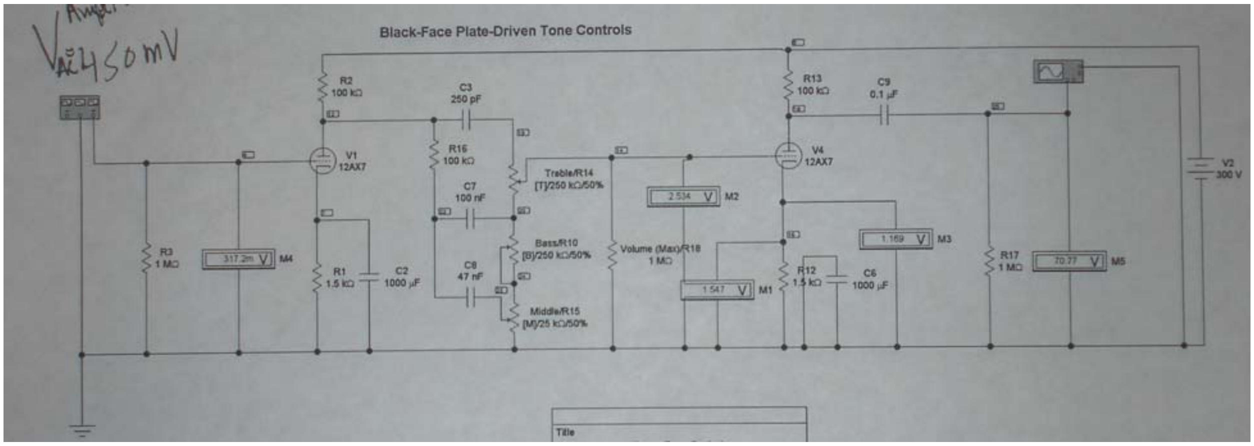
20.571429m
24.
Time (seconds)

Figure 5


black_face_tone_controls.ewb
1000
100
10
1000m
Voltage (V)
1000m
100
10K
1M
10M
Frequency (Hz)
150
100
50
0
-50
-100
-150
-200
Phase (deg)
1000m
100
10K
1M
10M
Frequency (Hz)


Black-Face Plate-Driven Tone Controls
R2 100 kΩ
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Treble/R14 [T]/250 kΩ/50%
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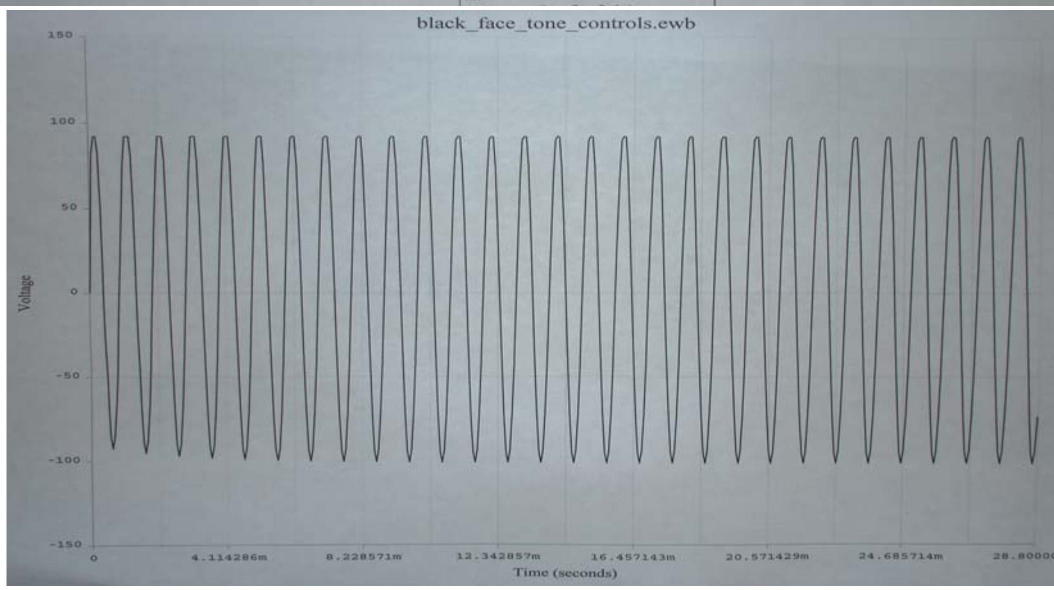
C8 47 nF
Middle/R15 [M]/25 kΩ/50%
R3 1 MΩ
317.2m V M4
R1 1.5 kΩ
C2 1000 µF
Volume (Max)/R18 1 MΩ
2.534 V M2
1.547 V M1
R13 100 kΩ
C9 0.1 µF
V4 12AX7
1.169 V M3
R12 1.5 kΩ
C6 1000 µF
R17 1 MΩ
70.77 V M5
V2 300 V
Title

black_face_tone_controls.ewb
Voltage
Time (seconds)
150
100
50
0
-50
-100
-150
0
4.114286m
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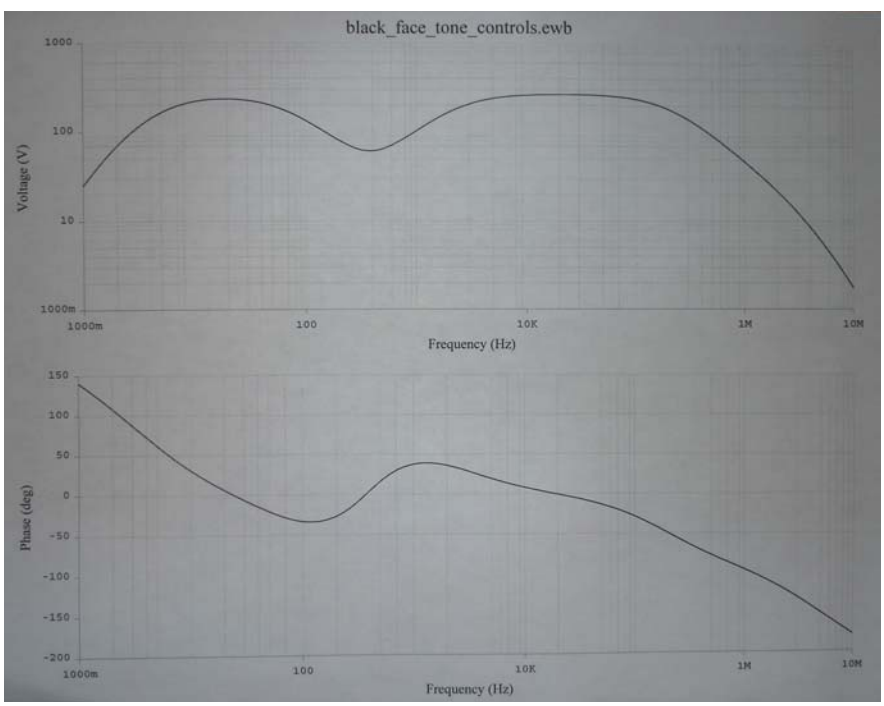
24.685714m
28.80000

black_face_tone_controls.ewb
Voltage (V)
1000
100
10
1000m
1000m
100
10K
1M
10M
Frequency (Hz)
Phase (deg)
150
100
50
0
-50
-100
-150
-200
Frequency (Hz)

Figure 6

Additionally, because the capacitor is no longer connected, the high frequencies have a greater presence, brightening up the sound. The bottom graph in Figure 5 shows that not only do the ultra high frequencies not drop off as quickly as in Figure 4's graph, but the lower frequencies have less gain as well. In the real amplifier, this effect would migrate down to the more audible range. Since the resistor and capacitor basically form a high pass filter to ground, the capacitor in Figure 4 permits all the high frequencies to escape from the signal path while retaining the lower ones. Since the capacitor modeled here is 40 times that of the real one, the RC constant for the filter will be 40 times what it is in the real amplifier.

The difference between Figures 5 and 6 has to do with the input signal strength. In both 4 and 5 the input signal was 300 mV whereas in 6 the input signal is 50% more, 450 mV. In both 5 and 6, the capacitor is effectively removed; since this reduces the gain of the stage, the tube effectively has more "head room" to accommodate a stronger signal. As shown in the V vs. T graph, there is moderate clipping with this stronger input despite the disconnected capacitor. While the gain is still less than with the capacitor (70.77/2.534=~27), the amp can still distort. This fact emphasizes that, for instance, a guitar player could suddenly switch from a mellow to hard playing style and, if the switch is pushed in, the amp would not distort terribly, but rather would accommodate the increased signal strength (i.e. turning up the volume on a guitar). There would only be the limited distortion manifest in a lower strength signal in Figure 4. Additionally, this configuration features the stronger top end, giving the amp a brighter sound.

The extra headroom of the modification results not only from disconnecting the capacitor, but also from liberating the cathode from a fixed potential and allowing it to track the input signal. Because the grid is biased negative with respect to the cathode, it affects the flow of electrons from it. This allows not only the modulation necessary in an amplification circuit, but also, if the cathode is not held fixed to one potential, a flexible "window" of amplification. As the signal on the grid rises and falls, the cathode's potential rises and falls as well. While the two do not move in a 1:1 ratio, the movement of the cathode increases the range in which the grid can travel from its steady state potential before clipping occurs. As seen in Figures 4 and 6, slight clipping occurs. Since the voltage into the grid as well as the voltage across the capacitor are AC and therefore RMS measurements, they must be converted by multiplying by a factor of $\sqrt{2}$. Thus, the threshold for the cathode in Figure 4 is $\sqrt{2}$*345.2 μV+1.554 V=1.554 V. Since this voltage is below the grid voltage of 1.679*$\sqrt{2}$=2.37 V the signal is cut off because the grid potential exceeds that of the cathode, that of the resistor plus that of the AC voltage drop across the capacitor, at the top of each signal crest. At this point the grid effectively turns around the electrons escaping from the cathode, thus preventing the signal from reaching the plate and continuing. In Figure 6, the numbers are similar, but as the graph of voltage versus time shows the clipping is barely present: $\sqrt{2}$*1.169+1.55= 2.63 V. The grid voltage is 1.857 *$\sqrt{2}$=2.63. This comparison manifests one of the most appreciated property of tubes: instead of cutting off sharply as transistors do, the peak more "softly." Figure 6 shows that even though the grid at best matches the cathode voltage, there is still a tiny bit of clipping, which may be desirable, depending on the listener. Both of these calculations contrast sharply with those from Figure 5. The total cathode voltage is $\sqrt{2}$*.8016+1.534=2.67 V while the total grid voltage is $\sqrt{2}$*1.697=2.40 V. Here the grid is safely below the cathode at all times and so the tube does not clip or distort significantly enough to show up on the graph.

While in theory the effect is rather pronounced and obvious, the difference in gain is hardly a case of 30 vs. 50 in the real amp. For some undiscoverable reason, the Fender Twin does not distort quite as much as other amps with this modification nor is there a significant drop in gain when pushing in the switch. Although the effect should be stronger both according to theory and the numbers from Electronics Workbench, this project, if nothing else, has been an exercise in differentiating between theory and reality. However, the reverb works beautifully through the normal channel, as it theoretically should. Overall, though, the overdrive circuit seems successful, albeit as an alternative reverb option circuit instead a true overdrive one.

Cleaning Up the Sound

Once the overdrive circuit was installed, I turned to cleaning up the overall sound of the amplifier. According to the theory of tube operation, a filament drawing 6.3 volts off an alternative secondary winding on the power transformer heats the cathode in the tube. Due to the property of thermionic emission of electrons, electrons escape from the cathode. In vacuum tubes, the positive potential plate attracts the negative electrons, creating a current that, by confounding convention, flows from the plate to the cathode. Between the two is the grid, which modulates the electron flow and inputs the signal to be amplified. By modulating the flow of electrons, the grid allows the plate to transmit an amplified signal to the output of the circuit. In beam tetrode power tubes, like the 6LBGC's in the Fender Twin Reverb, there is a fourth filament in the tube that increases the gain (or amplification power) of the tube as well as decreases the capacitance between the positive plate and negative cathode. This fourth element is called the screen and is held fixed slightly below the steady state voltage of the plate. There are also "guides" that help prevent secondary emission of electrons by the grid and focus the electron flow from the cathode to the plate.

As a natural consequence of design and implementation limits, when tubes are forced to draw too much current because the grid signal is too strong, the tubes "clip." This clipping results from the tube trying to pull too much current off the cathode. Since the cathode cannot supply enough power, the input signal loses the peaks and valleys of the sinusoidal signal, resulting in the addition of harmonics not present in the original signal. This property not only provides the warm sound so adored by users of tube amplifiers when at low and moderate gain, but also results in distortion when at high gain. This clipping is like that theoretically supplied by the overdrive circuit and creates a "dirty" tone. This was exactly one of the problems during normal use cited by my brother.

In order to limit the amount of current drawn by the power tubes, some amplifiers, including this Twin, feature adjustable biasing. When properly biased, 6L6GC tubes should be driven with around 20 mA of current. Adjusting the bias is obtained by turning a potentiometer, or "pot;" rotation in one direction increases the resistance of the pot and thereby decrease current while turning it in the opposite direction decreases resistance and increases current. This tendency follows Ohm's Law: V=IR. Although in practice the input voltage is not perfectly constant as shown in Table 2 (all Tables found in Appendix 2), the change in bias voltage was not sufficient to make impossible proper biasing of the tubes.

Table 1 shows that the initial bias of the four Sovtek 6L6GC power tubes was slightly high. These measurement were carried out across the 1Ω resistors connected to the tubes. Once again, according to Ohm's Law this resistance makes the voltage equal to the current, facilitating measurement using a digital multimeter. After some minor adjustment to the biasing pot, we achieved proper biasing current. Although ideally the four power tubes would run at the same current, this is an unrealistic expectation of four used power tubes, especially since we do not know their origin or age. The maximum variation of 1.7 mA, however, was well within the acceptable range according to Professor Errede.

As the bias currents show, vacuum tubes are not all exactly the same in their internal resistance. For example, Tube 1 decreased in current by 4.5 mA while Tube 4 decreased by 4.3 mA. This would violate Ohm's Law if internal resistance were constant. It also manifests some of the inherent non-linearity of tubes: Tube one decreased in current by 18.3% while Tube 4 decreased by only 16.5%. Table 2 also shows that the relatively significant changes in biasing current barely affect other relevant voltages within the amplifier. Specifically, the voltage off the main secondary winding of the input transformer, which distributes the bulk of the voltage to the power supply and therefore the circuit of the amplifier, changed by less than 1/6 of 1%. The changes in the bias voltage ($-V_{bias}$) and the B+ voltage (V_{B+}), measured after the power supply, were similarly negligible.

After ensuring that the tubes were not running "hot", drawing too much current, we examined the voltages around the choke transformer. The choke, combined with the diodes in the power supply, are used to smooth out the current flow and convert the alternating current wall power into the direct current necessary for most of the amplification circuitry. As Tables 3 and 4 show, the choke voltage, along with the plate and screen voltages are all 439 V. According to the original schematic, the plates should have the same voltage as the choke since they draw from the same power source with no interruptions. The screen, used to decrease the capacitance between the grid and the plate as well as increase the gain of the tube, should have a slightly lower potential, but as shown in Table 4 the drop due to the 470Ω resistors was too small to affect a 400+ voltage. Both the screen and plate voltage, though, are well within 20% of the specified potentials on the schematic of 458 V and 460 V, respectively.

Besides examining the voltages on the power tubes, we measured the plate, grid, and cathode potential of the auxiliary tubes. While the power tubes, which amplify the final signal, would clearly have a greater effect on the sound of the amp, a damaged, worn out, or misbehaving preamp tube could easily provide distortion. This fact became even more manifest at the end of the project when, for comparison purposes, we switched out one of the Sovtek preamp tubes and replaced it with a new Groove Tubes 12AX7-M; the increase in clarity throughout the range of the guitar was incredible, especially given the relatively easy fix. Comparing the values in Table 5 with the limits on the schematic, all except for the tremolo are well within the specified potential. Since the tremolo only acts as an oscillator, the slightly high values on the plate should have no effect on the final sound unless tremolo is applied.

After all the measurements, the final conclusions were that there was no serious internal damage to the amplifier. Any remaining distortion would come from a myriad of sources, including issues internal to the tubes. First, the tubes could be worn and most likely were at least to some degree. The swapping of one of the preamp tubes for the recommended Groove Tubes showed that new tubes would definitely clean up the sound. This improvement would either result from replacing the worn existing tubes or improving the inherent quality of the installed tubes. This second point becomes increasingly important with respect to the power tubes. Since my brother had no information on the prior use of either set of power tubes he owns, we had no way of knowing either the wear on them or their rating. Power tubes are rated on a scale from

1-10 with the rating being an inherent quality in the production. A 10 tube produces an extremely clean sound while a 1 creates a very distorted tone.

Once we took all the measurements, we reassembled the amp to make a qualitative analysis. At low volumes, the amp sounded nice, with a clear, clean tone throughout the frequency range. However, at high volumes it distorted terribly and the bass was entirely muddy. Because the distortion was so bad, we had to investigate non-ciurcuit causes of distortion.

Other Factors

The first conclusion Professor Errede made was that the speakers in the cabinet were of "low quality," to put it nicely. After investigating, it turned out that the speakers were some of, if not the, worst Fender ever shipped with an amp. As soon as possible we pulled the speakers from the cabinet and replaced them with a pair of Eminence speakers from the Professor. While not top-of-the-line speakers, these still represented a major improvement. Installing them proved easy, once the old speakers, the glue attaching the gasket to the baffle board, and the torn gasket were all scraped clean and made level. Without this painstaking attention to detail, the speakers will not seat properly on the baffle board and could be damaged during playing. Once installed, we retested the amp and found major improvements in the high and low end clarity. While some distortion at maximum volume remained in the bass region, the tone sounded much more clean and listeners could finally hear the "clean Fender tone" that my brother felt had disappeared from the amp. The new speakers, which featured a large voice coil and magnet to improve frequency response, combined with soldered connections between the plug and two sets of speaker terminals, replaced what had clearly been the weakest link in the chain (see pictures, Appendix 1).

After resolving the speaker issues, we turned to a myriad of issues that arise whenever working with vintage equipment. First, all the tone and volume pots were so dirty that adjusting them with the amp on resulted in crackling and noise from the amp. In order to remove that crackling, Professor Errede simply sprayed them heavily with pot cleaner. While this does little to remove constant distortion, it fundamentally improves the real world operation of the amp. Second, both the power and standby switches had as much lateral movement as vertical travel. While also not necessarily a major cause of distortion, dirt on the contacts or infirm soldering can create distortion, according to Professor Errede's experience, and the lateral movement could pose a major safety risk.

Perhaps the most important change we made involved the tube sockets. At the end of the semester we were preparing to compare the backup set of Svetlana 6L6GC power tubes with the already-installed Sovteks. However, as soon as we switched the tubes, there was a moderately loud hum. The hum remained even when we replaced the tubes with the original Sovteks. It seemed to be 60 Hz noise, so we switched off the amp to investigate for blown capacitors or resistors. Were one of the electrolytic capacitors to pop, the amount of ripple traveling throughout the amplifier circuit would greatly increase. The capacitors, combined with the diodes and choke, work to limit the oscillations of the wall power, so this was a logical first step. However, no resistors, capacitors, or tubes appeared to have burned out. After several frantic measurements, Professor Errede discovered that the pin sockets on the power tubes were unconscionably corroded (see pictures, Appendix 1). While one of the tube sockets had clearly been replaced last June by Ben Juday, the others were still original and looked as though someone had kept the amp in a high-humidity environment. Despite over an hour of cleaning, it became obvious that for both safety and performance reasons, the sockets would have to be replaced. Unfortunately, this was not something I could do since it required several intricate solders in tight space. Many thanks to Professor Errede for performing this painful fix. With new tube sockets and the Sovtek 6L6GC's rebiased, the amp sounded slightly cleaner, with no hum, and performed much louder as well. The final biasing data are shown in Table 6.

Conclusion

Given the inauspicious beginnings of this project, the indecision, the lack of funds, the lack of overt problems initially, it turned out to be a fascinating and very difficult endeavor. Drawing on the lecture materials and the supplemental readings in class, I learned not only about the functioning of my brother's amplifier, but also the fundamental principles of vacuum tubes, thermionic emission of electrons, amplification circuits, transformers, capacitors, RC circuits, and countless other specific facets of electronics that can only be learned during a hands-on project such as this. Although the lack of overdrive distortion remains a mild disappointment, my brother seems very satisfied with the sound of his amp. He currently is considering upgrading the speakers to an even higher fidelity pair that can better handle the amps newfound power. Additionally, replacing the preamp and power tubes with new or new old stock ones would greatly improve clarity and perhaps even power.

Perhaps the single most important thing I learned from this project was that "everything affects everything else." While clearly replacing the preamp tubes would have cleaned up the tone at the beginning, the speakers would have remained a weak point, limiting clarity, as would the corroded pins. The power and standby switches would have been at least a safety issue and the pots would have created noise with every adjustment. There is no one part of an electric circuit that can be said to "not matter at all." This reinforces the principle set forth at the inception of the class in January. The class was to be not merely another physics or electronics class, but one that helped bridge the chasm between the theory and reality, that taught how to distinguish "between the forest and the trees." Music is perhaps the best medium for manifesting that for all science can predict, there are some parts of humanity and nature that defy theory and remain either too complex or too vague to analyze piecemeal. Music and sound are both very real concepts that have very quantitative aspects, but there has yet to be a definitive or overarching theory that explains why certain people perceive a sound one way or find one type of music pleasing. Once again, thanks to Professor Errede for his patience, knowledge, and much needed help and counsel.

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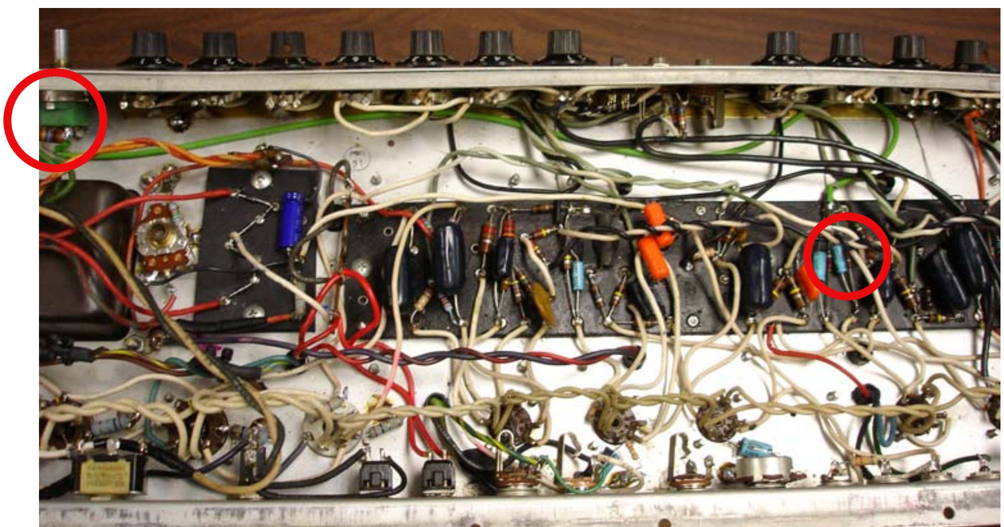
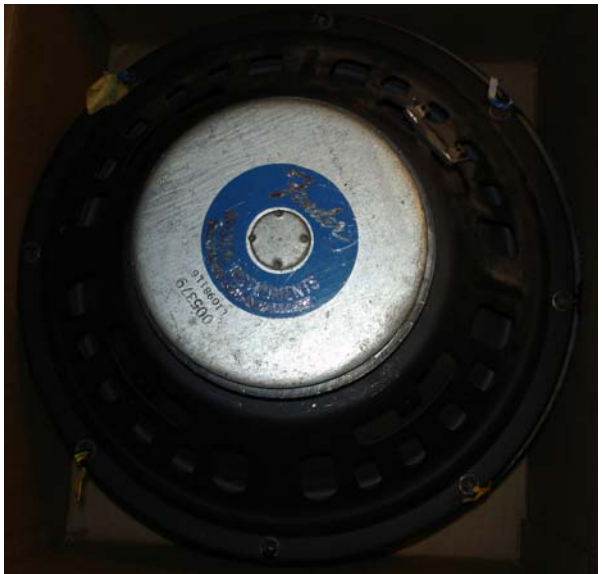
Schematic Heaven. (Fender schematics).

Appendix 1: Pictures

Above: The amp on its custom-built amp stand.



Left: The old master volume switch and the capacitor, both used for overdrive circuit are circled in red in this picture of the wiring of the amp.
Below: Pictures of the replacement 1997 Eminence speakers. Compare the magnet and voice coil with those



Counter-clockwise from top right: Notice the smaller voice coil in the original speakers; the smaller magnet on the original Fender speakers; the biasing pot; the damaged pins on one of the old power tube sockets–look closely for corrosion and signs of abuse; a curious fellow performs an investigation of his own.

Appendix 2: Tables/Data

Table 1

	Initial Bias (mA)	Final Bias (mA)
Tube 1	24.6	20.1
Tube 2	25.9	21.2
Tube 3	25.1	20.7
Tube 4	26.1	21.8

Table 6

Tube 1	20 mA
Tube 2	21 mA
Tube 3	20 mA
Tube 4	20 mA
V_{B+}	441 V_{DC}
$-V_{Bias}$	-49.5 V_{DC}

Table 2

	Screen (V_{DC})	Plate (V_{DC})	470Ω Res. (V_{DC})
Tube 1	439	439	.26
Tube 2	439	439	.25
Tube 3	439	439	.29
Tube 4	439	439	.24

Table 3

	Initial Voltages	Final Voltages
$V_{main\ secondary}$	658 V_{AC}^{RMS}	659 V_{AC}^{RMS}
V_{B+} (Operating)	438 V_{DC}	440 V_{DC}
$-V_{Bias}$ (Operating)	-46.9 V_{DC}	-48.9 V_{DC}

Table 4

Choke (B in Schematic)	439 V_{DC}
1KΩ Res. (C)	427 V_{DC}
4.7KΩ Res. (D)	392.5 V_{DC}

Table 5

	Tube A/B	Plate (V_{DC})	Grid (V_{DC})	Cathode (V_{DC})
Normal	A	262.5	0	1.88
	B	273.0	0	2.086
Vibrato	A	271.2	0	1.867
	B	261.5	0	2.091
Reverb Driver	A	433	.015	8.24
	B-Tied to A	N/A	N/A	N/A
Mixer Preamp	A	278.5	0	1.905
Reverb Recovery	B	270.5	0	1.905
Tremolo	A	428	-53.4	0
	B	378.8	-53.5	.006
Phase Inverter	A	236.2	100	101.9
	B	227.6	100	101.9

Above: The original schematic from CBS. Below: The much simpler and much more relevant 1963 "Black Face" schematic. The area circled contains the components

Appendix 3: Schematics