A Simple, Educational Microphone Preamplifier Design ("EMP") to Support the Teaching of Introductory Electronics to Students of Audio

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This paper describes an educational microphone preamplifier design (the "EMP") intended to teach the basic concepts of electrical engineering that may be useful to students in undergraduate audio engineering and sound recording programs. The design is broken up into simple sub-circuit modules that can be built and tested as part of a laboratory section of a larger course when supported by a series of lectures on basic DC and AC circuit theory. In laboratory exercises, students may swap components within the included design to learn about the function of each sub-circuit. The combined sub-circuits provide students with a low-cost yet high quality microphone preamplifier.

INTRODUCTION

Audio programs require specially designed electronics courses that present the concepts most relevant to the discipline in a succinct way appropriate to the students' level of understanding. Providing laboratory work and project-based assignments to students of electronics within university audio programs can help students put some of these abstract electronic concepts into context and make learning more engaging. In the author's experience teaching electronics, audio students are more likely to learn when they can see the immediate relevance of the information presented to their day-to-day work. A course designed around a single, semester-long build project that includes basic circuits relevant to the field of study can keep students involved and motivated to not fall behind. This paper describes a simple, low-cost, modular microphone preamplifier design which steps through the basic concepts of electrical engineering that are most significant to audio engineers. Recommendations for designing laboratory assignments related to each module are made as well as overall recommendations for the design and pace of a university level course in audio electronics. The preamp design can be used to create a course of varying levels of difficulty depending on the goals of the coarse and the experience of the students. At the end of the recommended course, for less than the cost of a typical textbook, each student should have a working microphone preamplifier that would be at home in a professional recording session.

1 PROJECT OVERVIEW

The educational microphone preamplifier design (EMP) described in this paper includes a linear power supply, AC coupled balanced input and output, an input pad, high-pass filter, variable gain, a "clip" light, ESD protection and RF filtering. A course can easily be designed around the basic progression of concepts outlined within this paper in a logical order typical of an introductory class in audio electronics. Different aspects of the design teach core concepts of voltage, current, resistance, power, gain, frequency response, decibels, input and output impedance, dynamic range, and common mode rejection. Students completing these laboratory exercises and the final microphone preamplifier project will also learn how to use breadboards, multi-meters, DC power supplies, oscilloscopes, and function generators. Students will develop soldering skills, and basic electronics trouble-shooting skills.

Schematics for each module are provided within this paper as well as recommendations for bread-boarding, associated laboratory measurements. The project uses an inexpensive AC "wall wart" transformer before the recommended linear power supply to protect inexperienced students from dangerous line voltages.

1.1 EMP Design

A full schematic of the EMP can be found at the end of this paper. The design is based around an instrumentation amplifier style microphone preamplifier IC such as the Texas Instruments INA217, the THAT Corp. 1510 or the Analog Devices SSM2017. The use of this type of device keeps the design simple and ensures good noise performance for standard professional microphone output impedances. Because instrumentation amplifiers are an advanced concept for an introductory electronics course, in the EMP circuit it is used with a fixed 20dB gain. Before the input to the instrumentation amplifier, the EMP has basic filtering, load resistors, an -18dB pad, and clamp diodes for protection.

The variable gain stage is a two-transistor shunt-feedback amplifier for voltage gain. This stage can be replaced with other topologies, as better noise and distortion performance is possible with more complicated or integrated circuit designs. The two transistor design is simple enough to build, demonstrates basic transistor operation, and is easy for beginning students. This stage provides a 40dB gain range using a 100kΩ log taper potentiometer.

The EMP's output is signal balanced using both inverting and non-inverting op amp configurations. This provides an additional +6dB of output level when feeding a balanced input. Because the class-A stage is inverting, the output stage also restores the proper polarity. The output is AC coupled with 33uF capacitors and 22kΩ resistors and the op amps are isolated from shorts with 50Ω resistors.

A clip light is included in the EMP design using an LED driven by an IC comparator prior to the balanced output stage. The EMP is powered by a simple half-wave rectified linear regulated power supply. A full-wave rectified supply based on a centre-tapped power transformer can be substituted, however, the presented design allows for the use of a low cost AC/AC "wall-wart" transformer which protects students from having to work with potentially dangerous line voltages. The wall wart transformer should be at least 250mA and provide between 12V and 16V on its secondary.

1.2 Required Equipment

This project requires students to have access to a basic multi-meter, DC power supply, proto-board, function generator, and oscilloscope. An audio measurement system is also recommended but not necessary. A stock of various resistor and capacitor values is also useful for students to experiment with prior to assembling the circuit as per the schematic. Alternatively, software applications such as the free TINA-TI package from Texas Instruments may be used to simulate substitution of component values.

2 LAB ORGANIZATION

This project is organized into nine labs corresponding to an eleven- week semester with time off for mid-term and final exam preparation. It may be necessary to adapt the pace of the project depending on the level of the students and how the academic year is divided at other institutions. For each lab, students may run experiments to verify the electronic behaviour of different circuits and come to a deeper understanding of various electronic concepts. It may be helpful for students to generate lab reports for their findings with graphs and tables of relevant measurements. For each lab, after experimenting with the circuit part, the circuit as it is used within the EMP may be assembled. The nine labs are:

1. Ohm's law
2. Voltage dividers
3. Kirchhoff's law and Wheatstone bridge
4. Capacitors and RC filters
5. Transformers and Inductors
6. Diodes and Rectifiers
7. Transistors and Amplifiers
8. Operational Amplifiers and Comparators
9. Final Assembly and Test:
   Dynamic Range and CMR

2.1 Ohms Law, Series and Parallel Resistors

Safety First!!! The first lab is an opportunity to familiarize the students with the laboratory equipment and to test Ohm's law and Thevenin equivalence. It will be important in future labs to be able to safely use a DC power supply, breadboard and multi-meter properly. The instructor may also choose to introduce function generators and soldering irons, though these will not be used until later labs. The measurements made can be simple and not overly time consuming allowing time for the introduction of the equipment and lab practices.

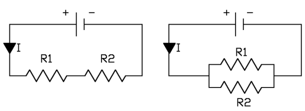


Figure 1: Series and Parallel Resistor Test Circuits

The recommended test circuits are simple series and parallel combinations of resistors. Students should make sweeps across several different input voltages measuring the current(s) and voltage(s) in the circuit and then calculating the power dissipated by each resistor. This also presents a good opportunity to go over resistor colour code, power ratings and tolerance

2.2 Voltage Dividers and Unbalanced Interconnects

Students will first test the voltage divider rule, then experiment with potentiometers, and finally, assemble and test the mic pre's "Input Pad" section.

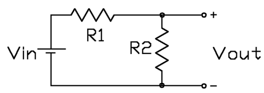


Figure 2: Voltage divider test circuit

Using the EMP’s gain potentiometer, students can breadboard and measure a variable voltage divider. By systematically adjusting the potentiometer, students may graph the logarithmic behaviour of the 100kΩ pot and relate this to the logarithmic nature of human hearing.

This may also be a good opportunity to introduce unbalanced signal interconnections as well as the concepts of output and input resistance.

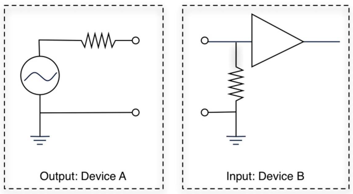


Figure 3: Unbalanced Interconnection

The input pad from the EMP is designed to allow students to easily understand it as a voltage divider at this early stage of the course.

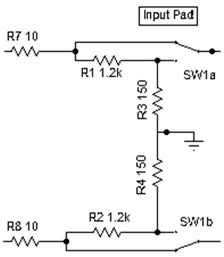


Figure 4: Input pad from EMP

During this lab, students may populate R1, R2, R3, R4, R7, R8, and SW1 of the EMP circuit.

2.3 Kirchhoff’s Laws

While the maths related to Kirchhoff’s laws are best presented in the classroom, a Wheatstone bridge provides a good example of how Kirchhoff’s voltage and current laws may be used to solve complex circuits. Wheatstone bridges also form the foundation of balanced line interconnections and are therefore important to students of audio.

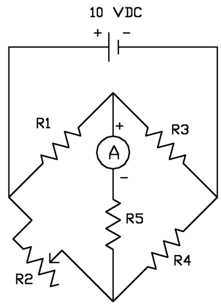


Figure 5: Wheatstone bridge test circuit

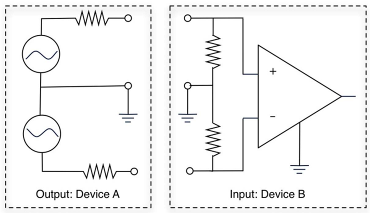
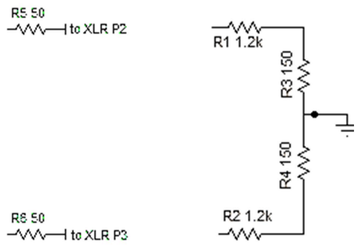


Figure 6: Balanced interconnection



A: output resistors B: input load

Figure 7: Output (A) resistance and input (B) resistance for the EMP

The input resistors for the EMP should have been assembled in Lab 2 as the input load also functions as the input pad circuitry. Students should stuff R5 and R6 of the output pad during Lab 3.

2.4 Capacitors and RC Filters

In Lab 4, students will learn about capacitor behaviour, capacitive reactance and filtering. Before working with EMP circuit, simple high-pass and low-pass filters can be bread-boarded and tested. Capacitor and resistor values can be substituted during the lab to show the relationship between filter frequency, capacitance and resistance. Measurements of frequency response and phase shift can also be made with an oscilloscope or audio measurement system.

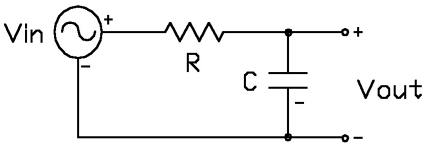


Figure 8: LPF test circuit (C and R can be swapped to create the HPF test circuit)

The EMP is AC coupled at its input and output via 33uF capacitors. At the input, these capacitors are in parallel with 2.2uF capacitors. These capacitors will function to remove any DC offset and to block +48V phantom power if ever inadvertently applied. They should therefore be rated at 50V or higher. For simplicity's sake, phantom powering is omitted in the current design. The HPF switch removes the 33uF capacitors at the input leaving only 2.2uFs, raising the filter frequency. The high pass filter of the EMP is set to approximately 54Hz when the 33uF capacitors are switched out. When the 33uF capacitors are engaged, the filter frequency is sub-sonic at approximately 3.5Hz.

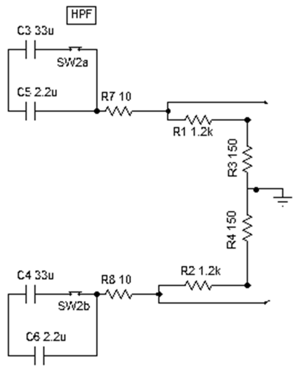
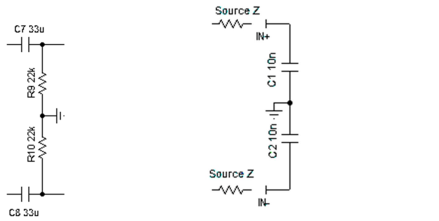


Figure 9: Switchable HPF

There are LPF capacitors for RF filtering at the input of the pre-amp, this filter frequency will be dependent on the source impedance from the microphone. The LPF of the input will vary with source impedance. The LPF is set to just over 100kHz for a 150Ω source impedance. This helps to significantly attenuate AM radio signals that begin around 500kHz.



A: Input RF filter B: Output DC decoupling

Figure 10: Input LPF (A) and Output Decoupling (B)

In this lab students will solder C1-C8, and R7-R10 into the final EMP circuit. It is recommended that R7 and R8 as well as R9 and R10 are closely matched to ensure the best possible common mode rejection.

2.5 Transformers

This lab gives students the opportunity to examine transformer behaviour. If no other transformers are available, the AC "wall wart" can be used to show how transformers shift voltage and current according to their wind ratio. A function generator and oscilloscope can be used to sweep across voltage and frequency while plotting V_{in} vs. V_{out}, I_{in} vs. I_{out}, and the transformer's frequency response.

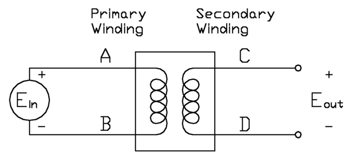


Figure 11: Transformer test circuit

The transformer should not be connected to the final EMP power-supply board until after Lab 6.

2.6 Diodes

In this lab, students will build the power supply rectifiers, filter, and diode protection for the EMP. Students will likely begin by measuring a single diode in series with a resistor to demonstrate the forward voltage drop and diode action. Adding a filter capacitor will then introduce the students to AC to DC conversion and unregulated power supplies. While the EMP uses a half-wave rectifier after the power transformer, instructors may want to have students build and test a common bridge rectifier as well.

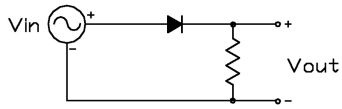


Figure 12: Single diode test circuit

Students should measure the power supply at different stages of completion to show how AC is converted into DC. It is recommended that students test the circuit with diodes D5 and D6 in place prior to adding the 5600uF filter capacitors C11 and C12. Once these capacitors have been added, students can measure the filtering that they provide. Finally, the voltage regulators and their associated circuitry can be assembled.

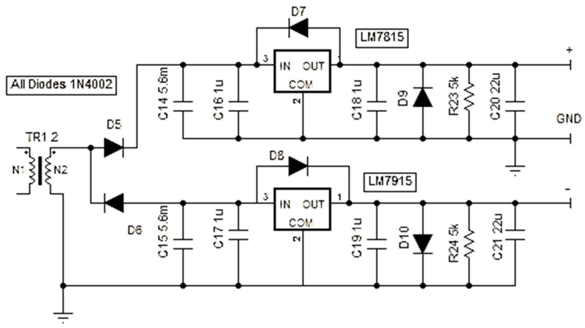


Figure 13: EMP power supply

The EMP uses diodes for protection on its input as well. For more information see reference [2]. This basic implementation helps to prevent the instrumentation amplifier from seeing voltages greater the power rails.

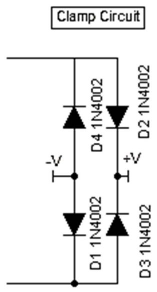


Figure 14: Diode clamp circuit

In Lab 6 students will build and test the full power supply for the EMP as well as populating D1-D4 on the main board.

2.7 Transistors and Amplifiers

The transistor amplifier module is designed to teach students the basics of BJT operation and the fundamentals of common emitter and emitter follower amplifiers. The two-transistor shunt feedback class-A amplifier used in the EMP combines both these implementations. To gain a basic understanding students should measure the DC characteristics of each style of amplifier on a breadboard before assembling the complete circuit on the EMP board.

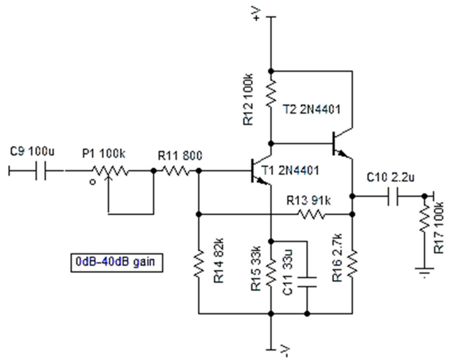


Figure 15: Shunt-feedback Class-A amplifier

In this lab students will assemble R11-17, C9-11, T1 and T2 of the final EMP circuit.

2.8 Operational Amplifiers

The output section of the EMP uses the basic behaviour of inverting and non-inverting op amp configurations in order to produce a balanced output. Students can be asked to find the pin-out of the 5532 to familiarize themselves with the information provided by manufacturer data sheets. Students should build both amplifiers on a breadboard initially and measure the gain behaviour of both amplifier topologies using discrete resistors and compare this with the gain equations.

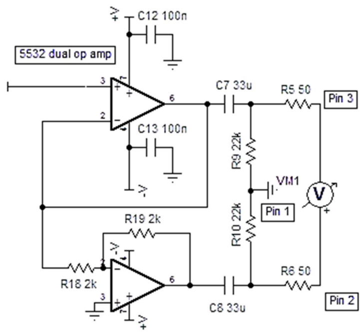


Figure 16: Two op amp balanced output stage

At this point, students may also be introduced to the comparator circuit that detects clipping and turns on the LED. During this lab students will stuff the 5532 dual op amp, R18, R19, C12 and C13. When assembling the output stage students should be made aware of the difference between this output stage and a transformer balanced output stage. When driving an unbalanced input like their oscilloscope, students should take care not to ground pin 3.

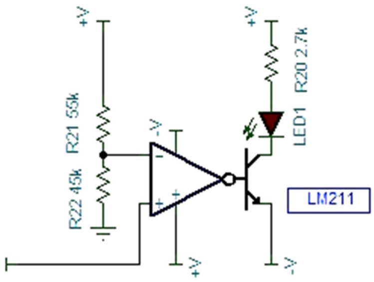


Figure 17: Comparator based clip indicator

2.9 Final Assembly and Test

In the final lab section, students will solder the instrumentation amplifier IC and its gain resistor. The power supply unit can then be connected to the audio circuit. When the power supply is connected, the protection diodes at the input to the audio circuit will produce a voltage drop of approximately 0.6V. The DC power rails within the audio circuit should therefore be +/-15.4V. These power rails should be checked immediately after connecting the power supply to confirm there are no shorts in the circuit.

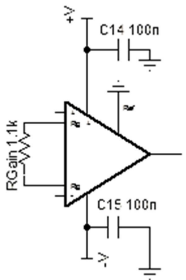


Figure 18: Instrumentation amplifier - fixed 20dB gain

At this point the full EMP design should be complete and ready for testing. In order to evaluate the performance of their circuit it is recommended that students measure the gain range, equivalent input noise, common-mode rejection, input impedance, output impedance, and frequency response. Students can be asked to generate data for their mic pre in the same format commonly found in microphone preamplifier manufacturer's product data sheets.

3 EVALUATION OF THE EMP DESIGN

3.1 Physical Measurements

The EMP design has been fully built and tested using an Audio Precision System II analyser. Its specifications are reasonable although limited by the simplicity of the class-A stage. At 60dB of gain, the EMP's equivalent input noise (EIN) is -104dB, 22Hz-22kHz. At +4dBu output with minimum gain, THD+N @ 1kHz is 0.07%. For maximum gain, at +4dBu output, the THD+N is 0.7% @ 1kHz. The clipping point is +22dBu when run off of a +/-15.4V supply.

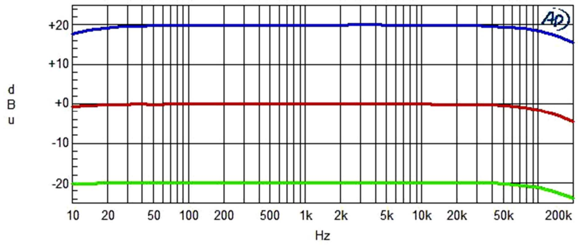


Figure 19: Frequency response at minimum gain, middle gain, and maximum gain for a -46dBu input, 150Ω source impedance.

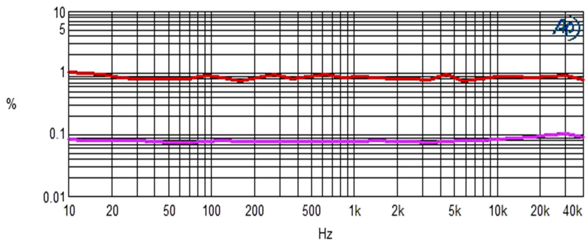


Figure 20: THD+N vs. Frequency at minimum and maximum gain. +4dBu output, 150Ω source impedance.

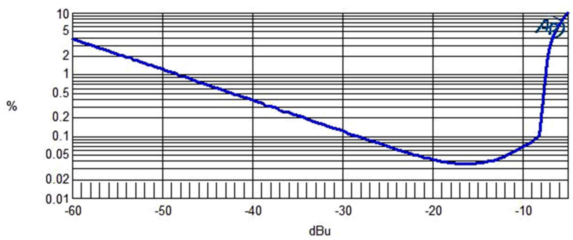


Figure 21: THD+N vs. Amplitude for 1kHz, 30dB gain, 150Ω source impedance.

3.2 Discussion

The EMP's distortion and noise are higher than many commercially available microphone preamplifiers although this gives the circuit a particular character and colour. If a very clean microphone preamplifier is desired, students can remove the class-A gain stage and add variable gain to the instrumentation amplifier stage as per the data sheet for this component. Advanced students may want to try out new intermediate gain stages such as FETs, germanium transistors, discrete op amps, etc. For a higher performance design, phantom power may be added and the half wave rectified PSU can be replaced with a centre tapped toroidal transformer with a bridge rectifier.

3.3 Future Work

The author hopes to make files and full documentation for the EMP including circuit-board layout and its corresponding Gerber files available in a standard dimension that will allow for either self etching of boards or ordering from a PCB fabricator. The layout will include test points and clearly defined circuit sections. The author will make the SPICE models available by request.

REFERENCES

[1] D. Self, "Small Signal Audio Design", Focal Press (2010).

[2] R. Bortoni and W. Kirkwood, "The 48 Volt Phantom Menace Returns," JAES (2009).

[3] P. Horowitz and W. Hill, "The Art of Electronics", Cambridge University Press (1989)

[4] THAT Corp "1510, 1512 Datasheet", THAT Corp, Document 600031 Rev 07 (2009).

[5] Texas Instruments " INA217 Datasheet", Texas Instruments, SBOS247B (2005).

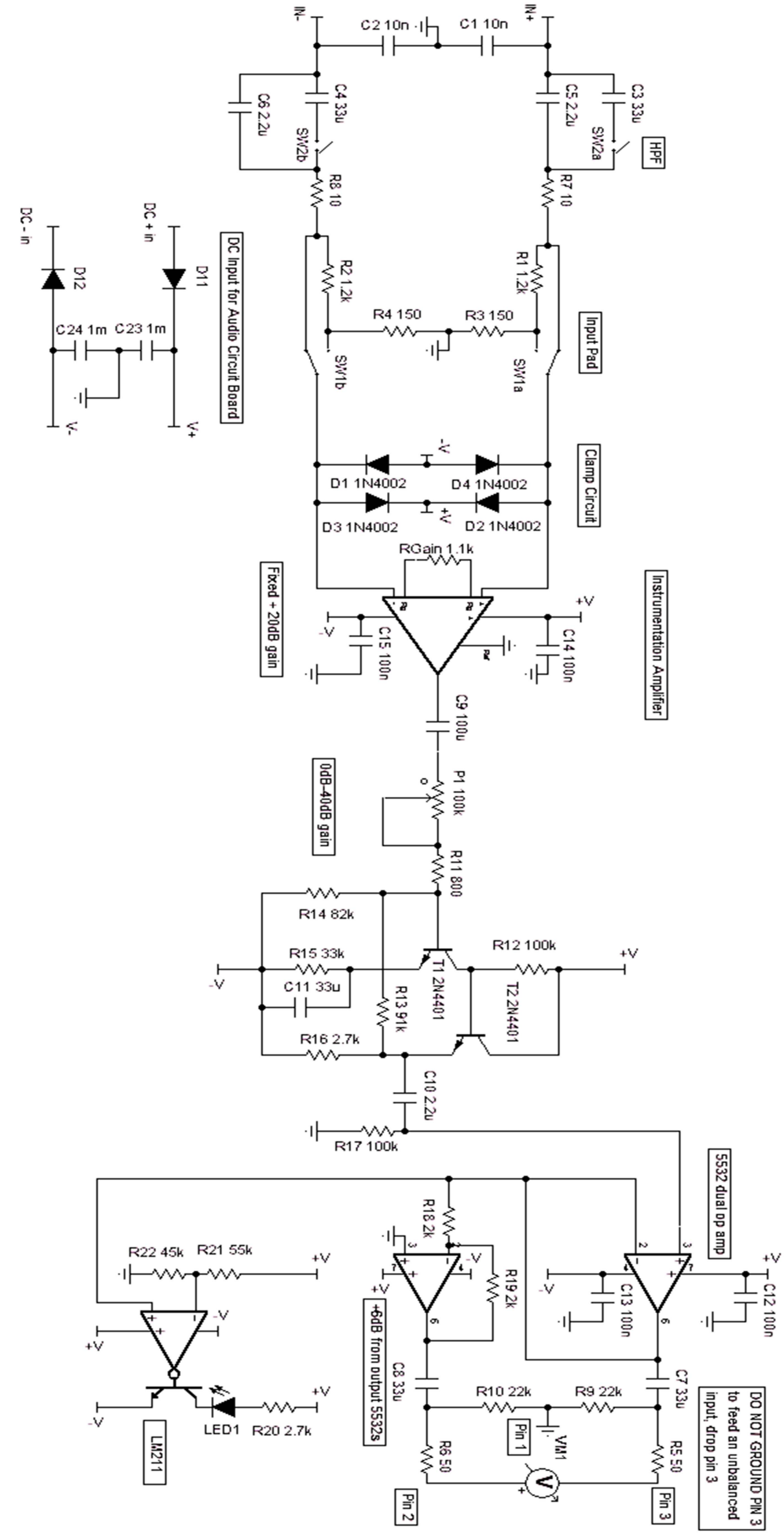
DOCUMENTATION

EMP Main Board:

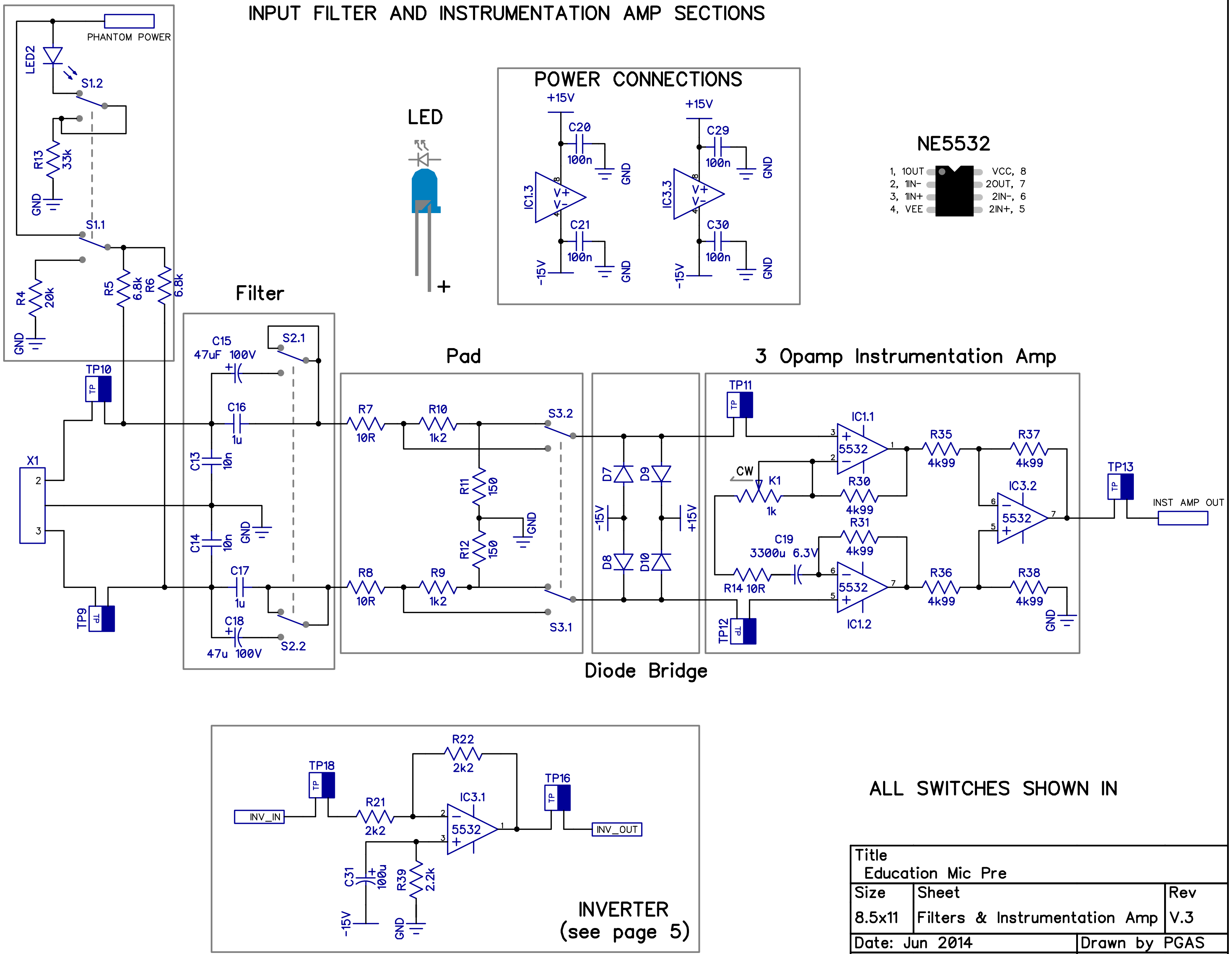
Part	Value	Description
R1	1.2kΩ	Input load+
R2	1.2kΩ	Input load-
R3	150Ω	Input pad+
R4	150Ω	Input pad-
R5	50Ω	Output +
R6	50Ω	Output -
R7	10Ω	Input +
R8	10Ω	Input -
R9	22kΩ	Out HPF
R10	22kΩ	Out HPF
R11	800Ω	Max gain
R12	100kΩ	Collector
R13	91kΩ	Feedback
R14	82kΩ	Base
R15	33kΩ	Emitter
R16	2.7kΩ	Emitter follower
R17	100kΩ	Inter-stage load
R18	2kΩ	Inverting gain 1
R19	2kΩ	Inverting gain 2
R20	2.7kΩ	Clip LED brightness
R21	55kΩ	Clip LED divider 1
R22	45kΩ	Clip LED divider 2
Rgain	1.1kΩ	Inst amp gain
C1	150pF	Input LPF
C2	150pF	Input LPF
C3	33uF	DC decouple In
C4	33uF	DC decouple In
C5	2.2uF	HPF
C6	2.2uF	HPF
C7	33uF	DC Decouple Out
C8	33uF	DC Decouple Out
C9	100uF	Class A buffer in
C10	2.2uF	Class A buffer out
C11	33uF	Class A bypass
C12	100nF	5532 PS bypass +
C13	100nF	5532 PS bypass -
C14	100nF	Inst Amp PS bypass
C15	100nF	Inst Amp PS bypass
C23	1000uF	PS Input filter +
C24	1000uF	PS Input filter -
D1-D4	1N4002	Clamp
D11	1N4002	PS Input +
D12	1N4002	PS Input -
LED1		Clip Indicator
SW1	DPDT	Pad
SW2	DPDT	HPF
P1	100k log	Var. Gain
T1	2N4401	Common Emitter
T2	2N4401	Emitter Follower
OP1	5532	Balanced Out
OP2	LM211	Comparator

EMP PSU Board:

Part	Value	Description
R23	5kΩ	PSU load +
R24	5kΩ	PSU load -
C14-C15	5600uF	PSU Filter Caps
C16-C19	1uF	Regulator bypass
C20-C21	22uF	PSU output filter
D5	1N4002	+ rectifier
D6	1N4002	- rectifier
D7-D10	1N4002	Regulator protection
Z1	LM815	+15V regulator
Z2	LM915	-15V regulator


IN+
IN-
C1 10n
C2 10n
C3 33u
SW2a
HPF
C5 2.2u
R7 10
C4 33u
SW2b
C6 2.2u
R8 10
Input Pad
R1 1.2k
SW1a
R3 150
R4 150
R2 1.2k
SW1b
Clamp Circuit
D4 1N4002
D2 1N4002
D1 1N4002
D3 1N4002
-V
+V
Instrumentation Amplifier
C14 100n
RGain 1.1k
C15 100n
Fixed + 20dB gain
C9 100u
P1 100k
R11 800
0dB-40dB gain
R12 100k
T2 2N4401
T1 2N4401
R13 91k
R14 82k
R15 33k
C11 33u
R16 2.7k
C10 2.2u
R17 100k
5532 dual op amp
C12 100n
C13 100n
DO NOT GROUND PIN 3
to feed an unbalanced
input, drop pin 3
C7 33u
R5 50
Pin 3
R9 22k
VM1
Pin 1
R10 22k
R19 2k
R18 2k
R6 50
C8 33u
Pin 2
+6dB from output 5532s
R21 55k
R22 45k
R20 2.7k
LED1
LM211
DC Input for Audio Circuit Board
D11
V+
DC + in
C23 1m
C24 1m
D12
V-
DC - in

INPUT FILTER AND INSTRUMENTATION AMP SECTIONS



ALL SWITCHES SHOWN IN

Title Education Mic Pre		
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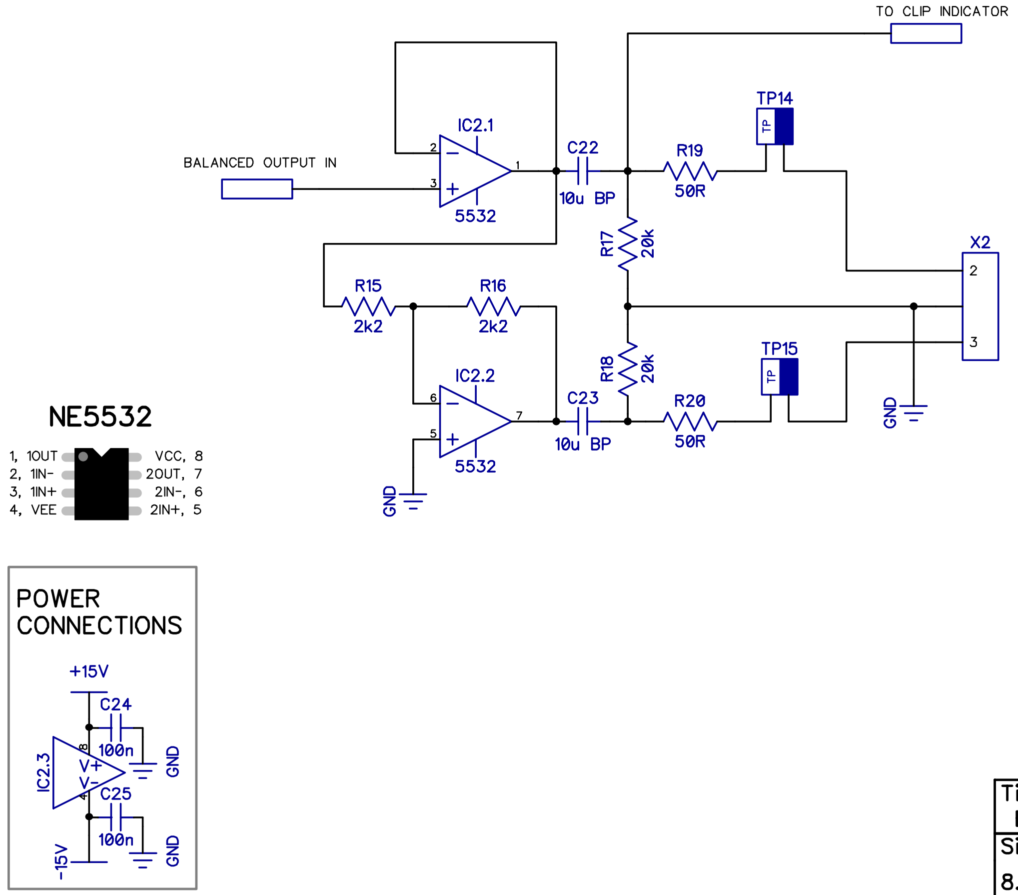
BALANCED OUTPUT SECTION



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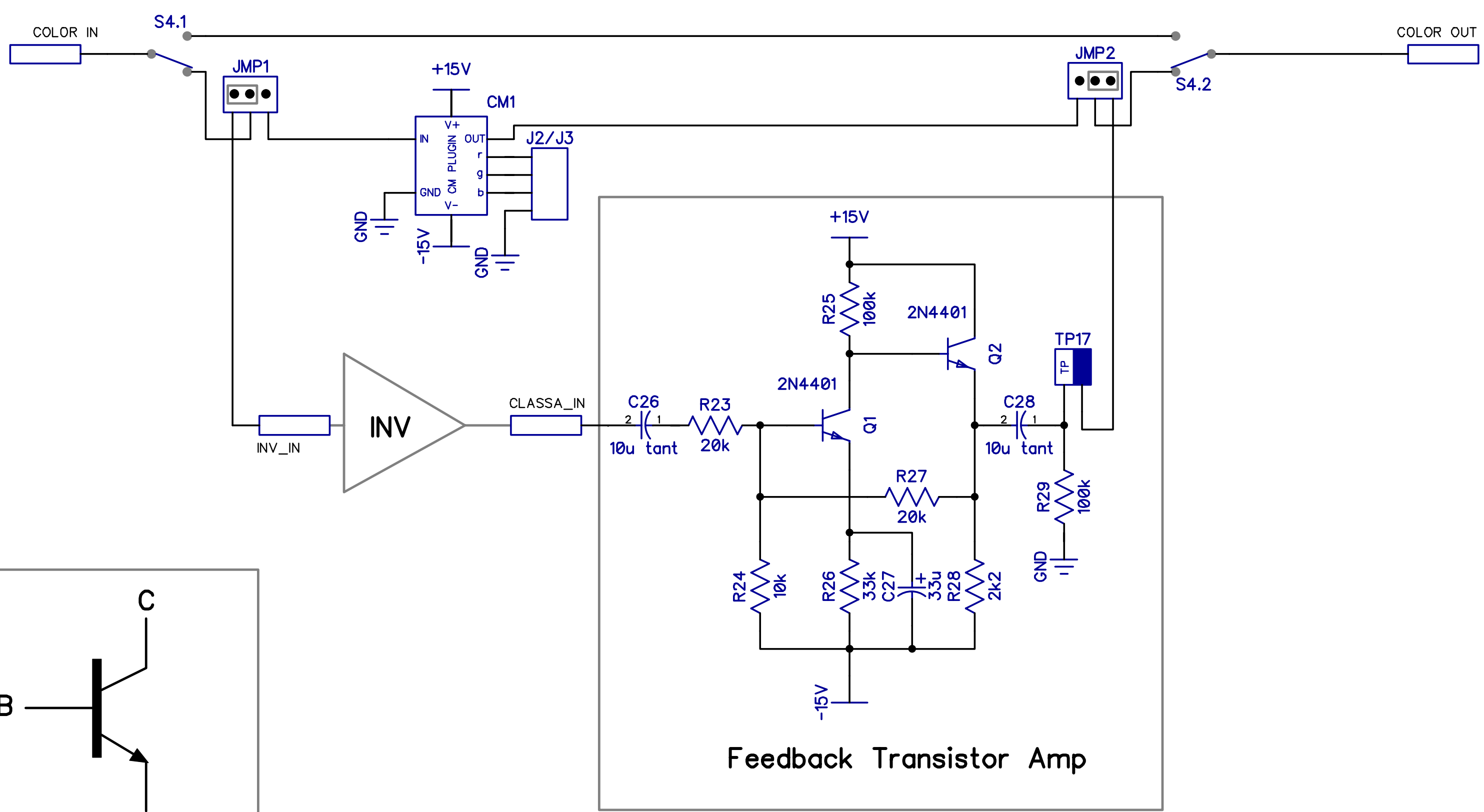
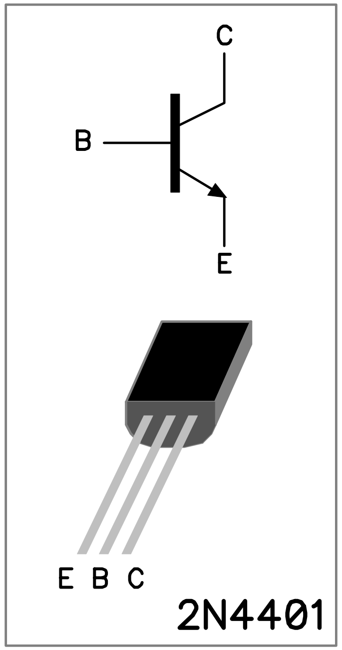
Filename EducMP.dch		Sheet 4/6

COLOR BUFFER SECTION

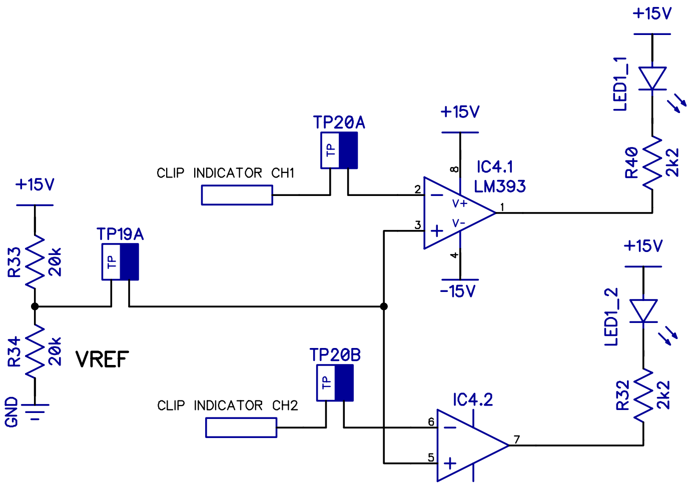


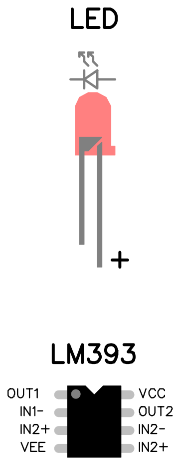


ALL SWITCHES SHOWN IN

Title		
Educational Mic Pre		
Size 8.5x11	Sheet Transistor Amp	Rev V.3
Date: Jun 2014		Drawn by PGAS
Filename EducMP.dch		Sheet 5/6

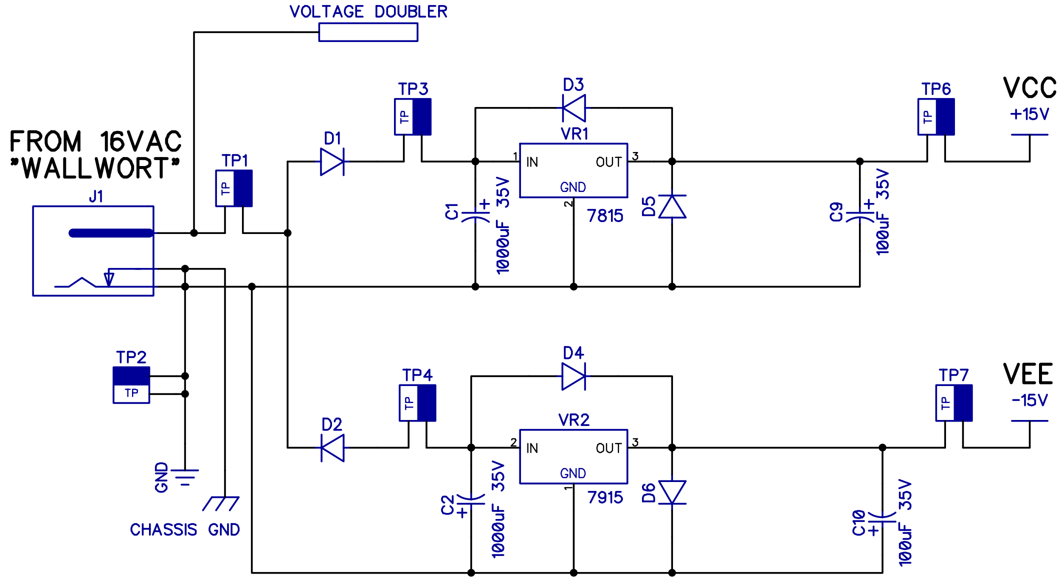
CLIPPING DETECTION SECTION





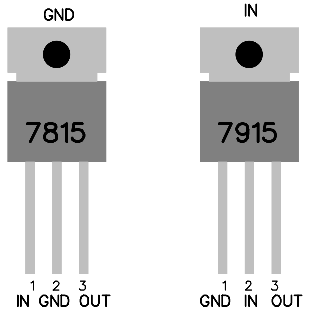
Title		
Educational Mic Pre		
Size 8.5x11	Sheet Clip Indicator	Rev V.3
Date: Jun 2014		Drawn by PGAS
Filename EducMP.dch		Sheet 6/6

POWER SUPPLY



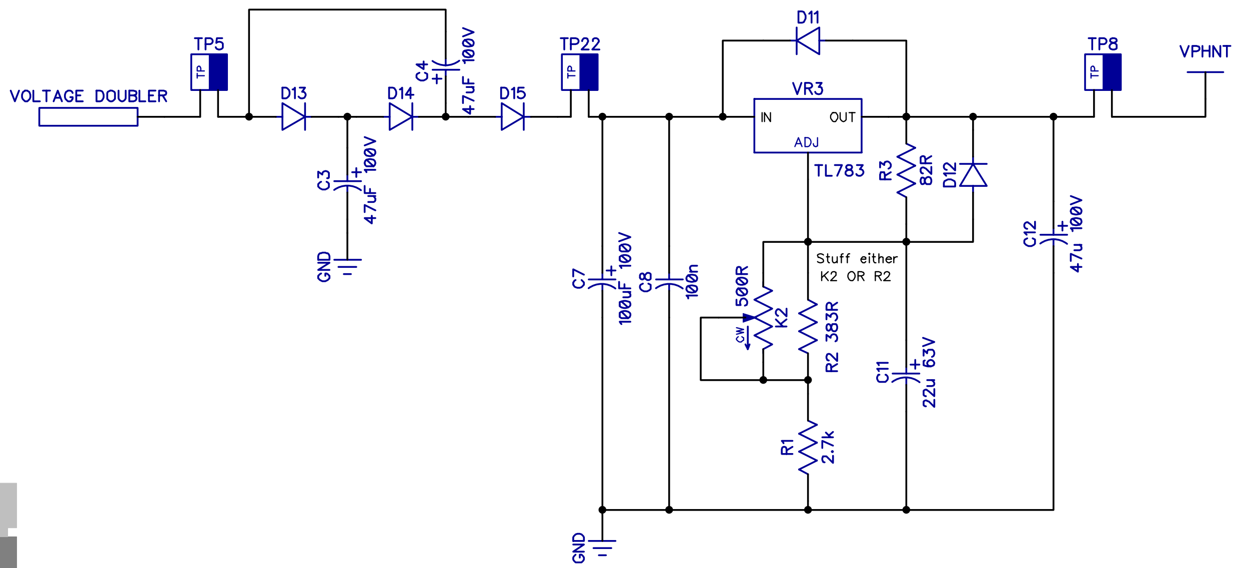
POSITIVE

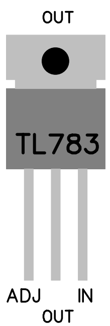
NEGATIVE



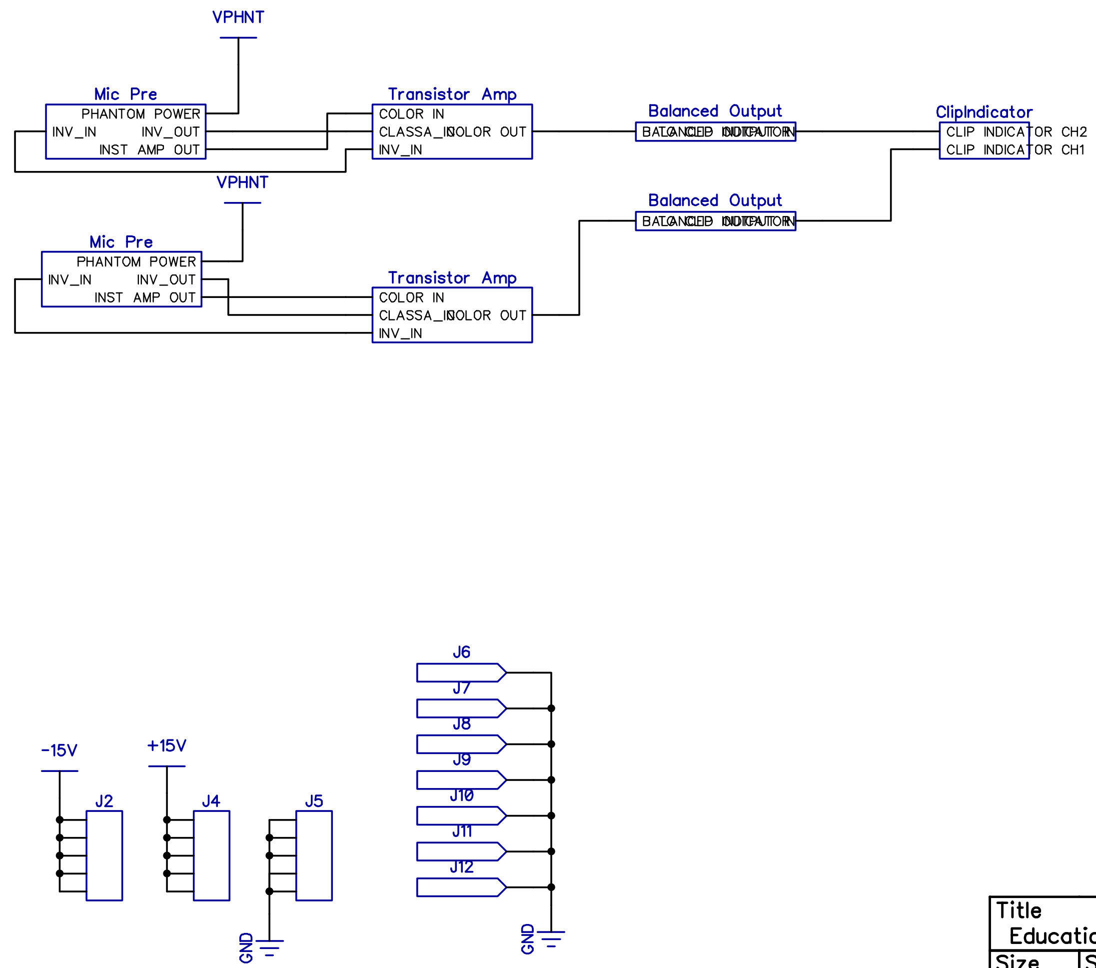
Title: Educational Mic Pre		
Size: 8.5x11	Sheet: Power Supply	Rev: V.3
Date: Jun 2014	Drawn by PGAS	
Filename EducMP.dch	Sheet 1/6	

PHANTOM POWER SUPPLY





Title Educational Mic Pre		
Size 8.5x11	Sheet Phantom Power Supply	Rev V.3
Date: Jun 2014		Drawn by PGAS
Filename EducMP.dch		Sheet 2/6



Title Educational Mic Pre		
Size 8.5x11	Sheet CHANNEL DEFINITIONS	Rev V.2
Date 17 Mar 2014		Drawn by PGAS
Filename EducMP.dch		Sheet 1/1