YOUR NAME:	YOUR SID:
YOUR PARTNER'S NAME:	YOUR PARTNER'S SID:

Score: ___/100

Electroencephalograph (EEG)

Final Project Part 1: Design and Simulation

ELECTRICAL ENGINEERING 40

INTRODUCTION TO MICROELECTRONIC CIRCUITS

University Of California, Berkeley

Department of Electrical Engineering and Computer Sciences

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Lab Contents

I. Final Project Overview and Objectives

For your final project we will be building an electroencephalogram (EEG) reader on a printed circuit board (PCB). An EEG is a record of the oscillations of brain electric potential recorded from electrodes on the human scalp. The scalp EEG provides very large-scale and robust measures of neocortical dynamic function. A single electrode provides estimates of synaptic action averaged over tissue masses containing between roughly 100 million and 1 billion neurons[1]. Thus, monitoring EEG signals allow for accurate identification of, among other things: sleep stages, depth of anesthesia, seizures, and other neurological disorders. Other methods reveal robust EEG correlations with cognitive processes associated with mental calculations, working memory, and selective attention. Your project will be focused on detecting the roughly 10Hz alpha waves that are associated with the eyes-closed-waking state (detectable while blinking).

In this project we will design, simulate, layout, manufacture, and solder, a complete printed circuit board. Since this is your final project, obviously we will be using a significant portion of what you learned in previous labs about various circuit components and analysis techniques. Therefore, if you're a little rusty on some of the things we did in previous labs; it would be a good idea to brush up on what you do not feel comfortable with because you essentially built most of the modules already in previous labs. We will be working our way up to completing the PCB for the rest of the semester and it will be imperative that you do not miss critical deadlines such as fabrication.

We will be working our way up to completing the PCB for the rest of the semester and it will be imperative that you do not miss critical deadlines such as fabrication.

As with all other labs, we will start with design considerations and parameters, and simulate our circuit in Multisim. After the design process, we will prototype our design in the lab before we actually get to the manufacturing process. Once we verify that our design works in the lab, we will transfer our design to a **p**rinted **c**ircuit **b**oard (PCB) layout CAD tool that pairs with Multisim called Ultiboard (don't worry you already have this). Once we prepare our design on the PCB CAD software, we will export our design to a PCB manufacturing company and get your board manufactured. Finally, once the board arrives, we will solder the components to the PCB and we're done! This document details Part 1 of the project, which is the design and simulation of the EEG reader circuit.

This may seem a little overwhelming at first, but relax, we will try to make this as painless as possible ☺.

II. Project Deadlines

The deadlines for this project are as follows:

- Schematic Design and Simulation: **Due Nov. 7-12** (on day of your normal lab)
- Printed Circuit Board Layout: **Due Nov. 14-19** (on day of your normal lab)
- Final Soldered Board, Demonstration, and Lab Write Up: **Due December 3rd**

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[1] Nunez, P. L., & Srinivasan, R. (2006). *Electric Fields of the Brain: The Neurophysics of EEG*. *Book* (Vol. 35, p. 629). Oxford University Press. doi:10.1063/1.2915137

You must meet all deadlines for this project ON TIME. If you miss the deadline for any of these items you may not finish the project on time, and if you miss the deadline for the Printed Circuit Board Layout you may receive a zero for the project.

III. EEG Reader Circuit Design

Before we begin any sort of prototyping and PCB layout, we want to design the circuit and do a design analysis. Our EEG will either take a brainwave signal or a PWM test signal. Because the signal is so weak ($10^{-6}V$), we're going to have to amplify the signal by several orders of magnitude in order to apply appropriate signal processing. Therefore, we will first send our signal through an instrumentation amplifier. However, we might not be able to get adequate gain with just one amplification stage. In addition, having several adjustable amplification stages will allow us to have higher resolution in amplification. A block diagram of the EEG reader you will build is shown in Figure 1.

At this point, our EEG should have amplified our signal enough to apply filters and various signal processing techniques. As mentioned before, the main signal components of the brainwave signal that we want to capture is around $10Hz$. In addition, we also have to eliminate any signal noise that we may have picked up. Since noise is usually a high frequency component, and we are looking for a low frequency component, we will apply a low pass filter to extract the brainwave signal. We should than be able to take the output signal and display it on an oscilloscope.

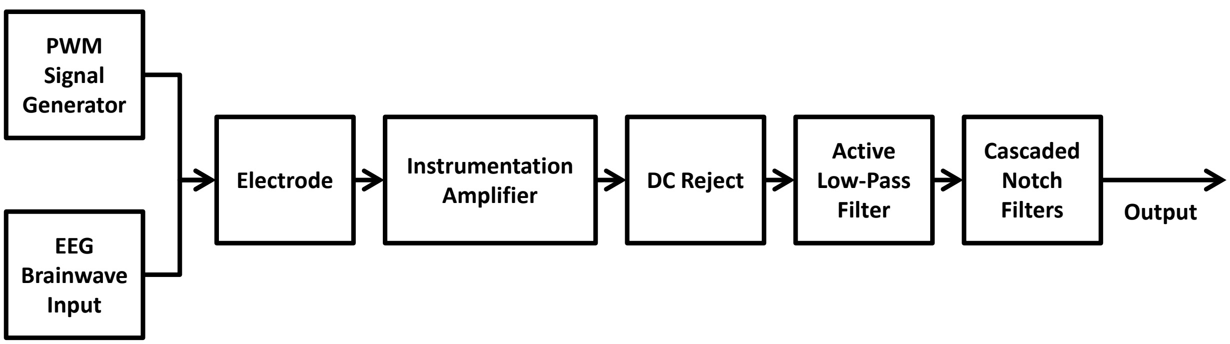


Figure 1 - Block Diagram of EEG Reader

A. The Electrode

We will be providing you the electrodes to test with after you finish the board. Every group will NOT receive an electrode; we will have a set that we will use for testing and you will return these after testing. ABSOLUTELY at any time, do not test the EEG on yourself. Use the PWM test signal generator that we build in the testing section to test your circuit.

Figure 2 - EEG Electrodes

B. The Instrumentation Amplifier Stage

Since the signal strength we are processing is on the order of $10^{-6}V$, we have to apply an incredibly high gain in order to bring it into a range that we can process the signal. Recall in lab 4, we used an instrumentation amplifier which can be configured to have high gain.

The instrumentation amplifier that you encountered is lab 4 is shown below:

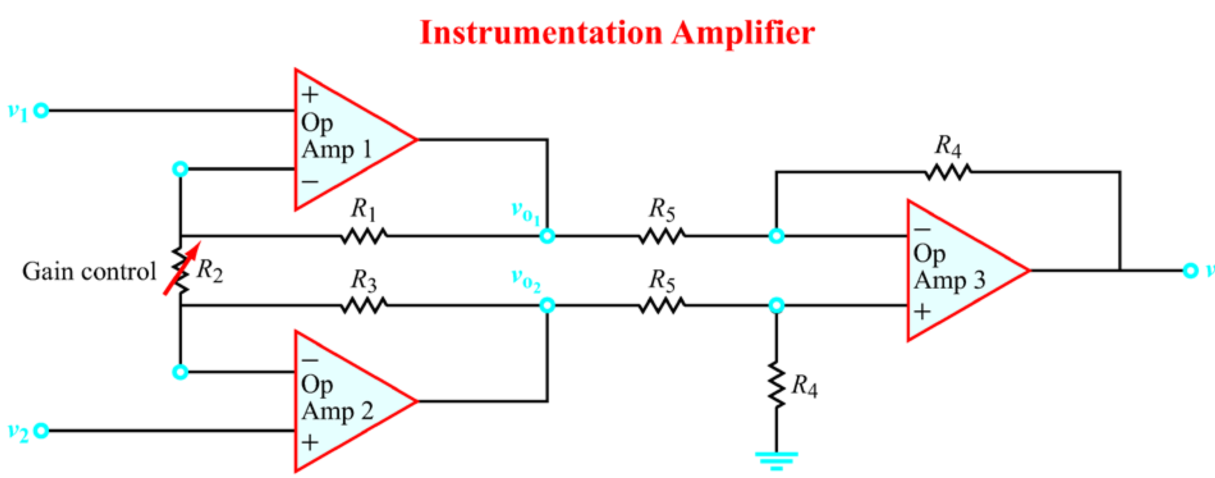


Figure 3 - Instrumentation Amplifier

Recall that in lab 4, you proved that the gain of the instrumentation amplifier is given by:

$$v_o = \left(\frac{R_4}{R_5}\right)\left(\frac{R_1 + R_2 + R_3}{R_2}\right)(v_2 - v_1)$$

Choose reasonable values such that the instrumentation amplifier has a gain of ~1000 using a $10k\Omega$potentiometer. Provide all relevant calculations that prove your values satisfy the specifications. Show the Multisim simulations and measure the gain in the simulation. (Set V_1 to ground, and V_2 a ~10 Hz AC signal with the voltage amplitude in the order of $10^{-6}V \sim 10^{-5}V$. The supply voltage of OpAmp is $\pm 5V$.)

Score:__/10

C. DC Reject

Following the voltage follower, we will need to put in a DC reject element. Remember, the signal that we are processing is being amplifier from a microvolt signal strength and the brain wave signal component that we want to read is around $10Hz$. Thus, to clean things up a little bit, we can apply a high pass filter with a very low cutoff frequency which can easily be done by a resistor and capacitor shown below.

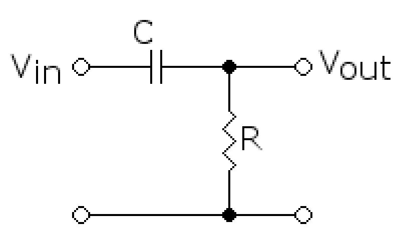


Figure 4- High Pass Filter DC Block[2]

For our circuit we will be using the DC block with a cut off frequency of $\sim .16Hz$. For this we will be using a $1\mu F$ capacitor and $1M\Omega$ resistor.

D. The Non-Inverting Active Low Pass Filter

So at this point, we've done quite a bit of amplification and signal fluffing, but haven't really amplified the signal enough nor filtered out all of its undesired components. As discussed earlier, the frequency that we want to see from our EEG lies around the $\sim 10Hz$ range so we have to extract that from our amplified signal. So let's stop piddling around and do that.

[2] http://en.wikiversity.org/wiki/RL_Circuit

First, we're going to throw a low pass filter at our signal. For our application, we're going to use a non-inverting active low pass filter which is shown below:

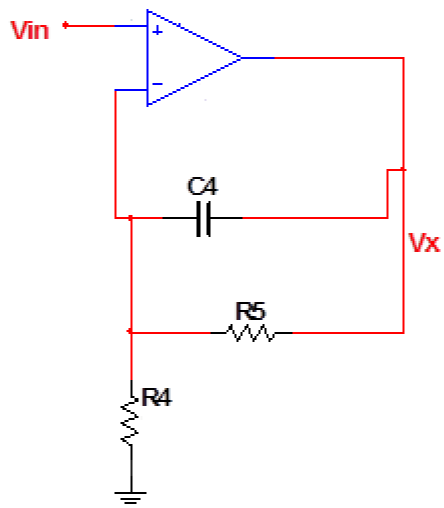


Figure 5 - Active low-pass filter

In the space provided below, show that the gain of the non-inverting active low pass filter and cutoff frequency is given by the following:

$$\text{Gain} = 1 + \frac{Z_2}{R4} \text{ and } \omega_c = 1000 \text{ rad/sec}$$

Z_2 is the impedance of C4 and R5 in parallel. Before you begin a mathematical derivation of the gain, think about the circuit above. What is the capacitor's impedance at low frequency (DC?) and high frequencies ($\omega_c \rightarrow$ infinity)? This should give you an idea of why the circuit is a low-pass filter. Plugging in values for different angular frequencies and computing the change in gain will also help you understand the circuit more. Remember that the cutoff frequency above is in rad/sec, not Hertz!

In addition, draw the Bode plot and label any relevant points in terms of the given variables. Finally, choose values for your passive components such that the cutoff frequency ω_c is 1000 rad/sec and the DC gain is 100. Show the MultiSim simulation to confirm your results. The supply voltage of the op-amp is $\pm 5V$.

Score:__/15

E. The Notch Filter

So the low pass filtering was nice, but it doesn't really give us exactly what we want. Remember that EEG signals are on the order of $\sim 10^{-6} V$ which means that the amount of noise we have to deal with is fairly annoying. Our active low pass filter did attenuate many of the higher frequencies but it is limited to a $-20dB/decade$ dropoff.

In order to fine tune our signal, we are going to apply a cascade of notch filters to eliminate some $60Hz$ noise.[3] The 60Hz noise is due to the electrical power lines. Once again, since our circuit is dealing with such low voltage signal, we need to consider this electrical interference.

For those of you who don't know what a notch filter is, don't panic. Basically a notch filter passes all frequencies except for a narrow range and is called a notch filter because its frequency response looks like it has a "notch" in it. As you can see from the magnitude plot below, a notch filter is ideal for killing any particular undesired frequency such as the $60Hz$ component we wish to eliminate. The same notch filter magnitude plot is shown below in MultiSim.

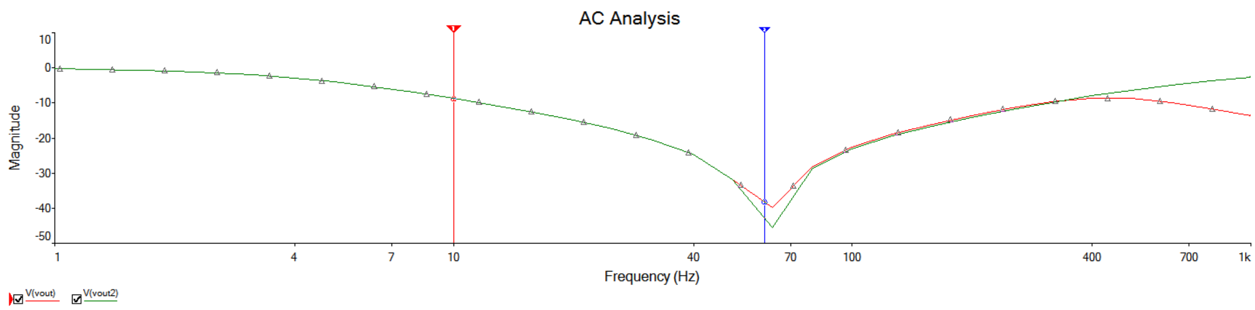


Figure 6 - Magnitude plot showing transfer function of a notch filter. Green trace shows circuit in Figure 6. Red trace shows circuit in Figure 8.

Notice in MultiSim we have *two* magnitude plots. The reason is that one of the magnitude plots belongs to the notch filter realization shown below.

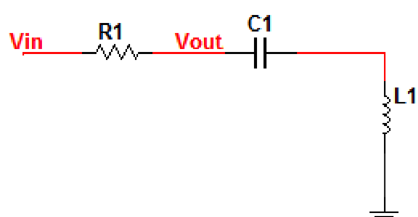


Figure 7 - Notch filter implemented with only passive components

In order to get such a low frequency for the notch (60 Hz) we needed to use an impractically large inductor size of 26.5 H! So, how did we get a practical circuit close to our theoretical performance? The answer is the gyrator, a circuit that "inverts" impedances. Consider the circuit shown below (from Wikipedia).

[3] Yes, notch filters are actually used outside of EECS20/120

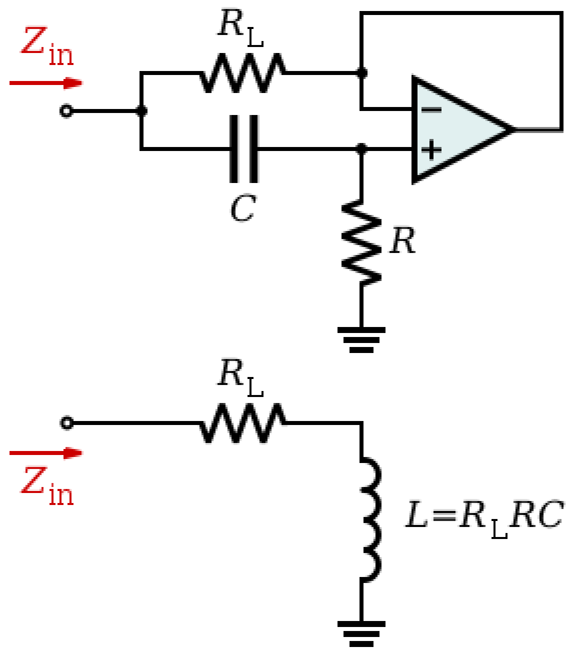


Figure 8 – Gyrator Circuit

First, prove below that the op-amp gyrator circuit above has $Z_{in} = R_L + j\omega R_L RC$, assuming that R is chosen so that $R >> R_L$.

Score:__/15

Using this gyrator circuit, the notch filter will appear as the circuit shown below in Figure 8.

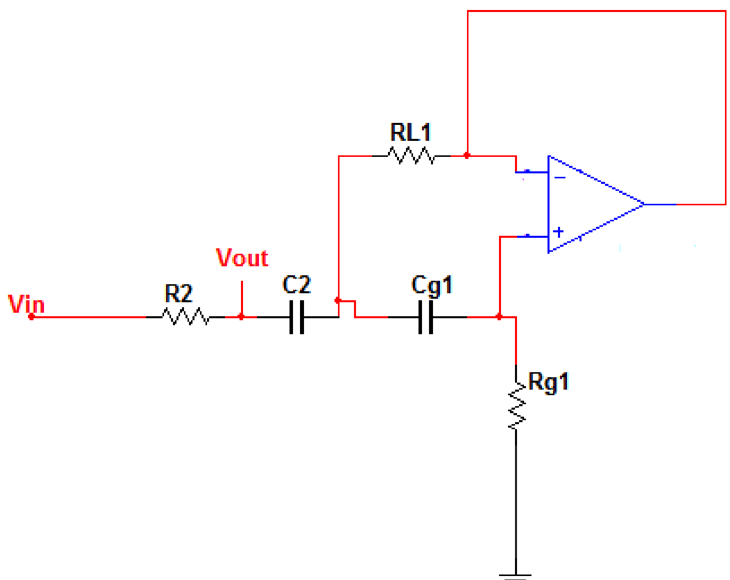
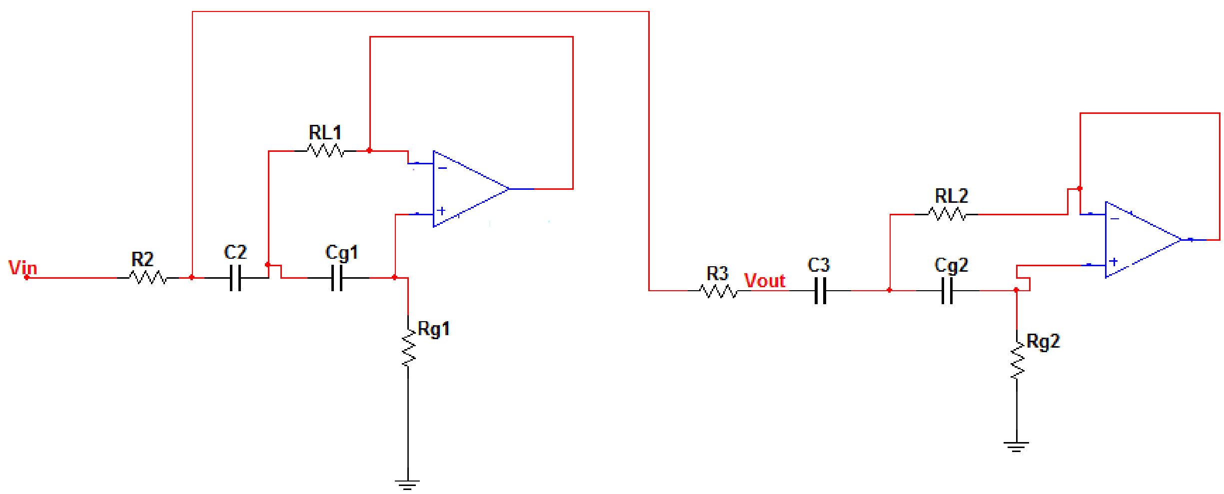


Figure 9 - Notch filter implemented with gyrator

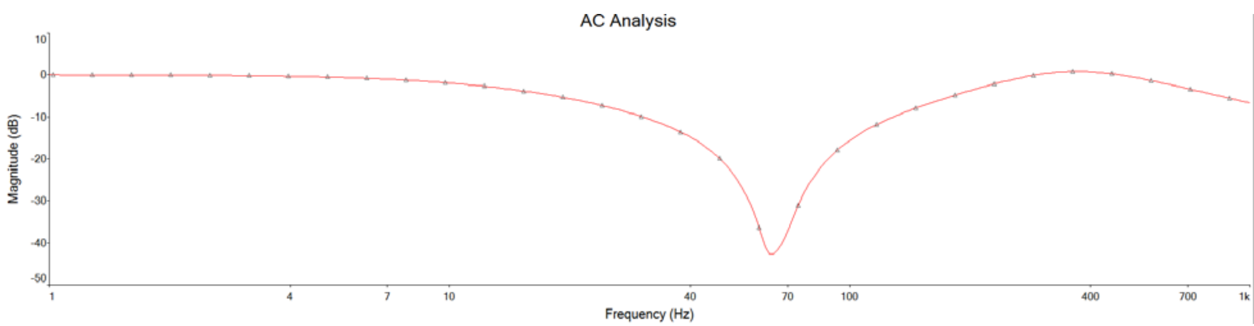
Derive the transfer function of the circuit in Figure 8. Use R_{L1} = 10 ohms, C_{g1} = 10 µF and remember that the inductor you are simulating is 26.5 H. Choose R_2 = 20k, this should help you solve for C_2 and thus you should be able to draw a magnitude Bode plot. Show YOUR OWN MultiSim simulation results to confirm your Bode plot. Make sure they agree with our previous STANDARD simulation results from MultiSim. The supply voltage of OpAmp is $\pm 5V$.

Score:__/25

Note that in our application, we are going to cascade two notch filters (we're going to kill the $60Hz$ frequency twice for good measure). The implementation for this portion of the circuit is shown below.



The bodeplot for the cascaded notch filter is shown in the following.



F. Powering Your Circuit

To power your circuit, we will be using two 9V batteries to provide $\pm 5V$ power supplies to your circuit. In order to do this, we will be using $\pm 5V$ regulators. The regulators in question are the LM7805 and LM7905 regulators. These components are available in the Multisim file made available with this project document. In the space below, look at the datasheet for these components and draw the circuit diagrams showing how to connect them. Clearly indicate where the 9V battery goes and where the $\pm 5V$ output is.

Score:__/5

G. Output Signal and Testing

Once we have finally finished processing the signal in the lab, we are going to send it to an oscilloscope so that we can actually see the EEG signal. To test your signal, we will be using the oscilloscope to perform a fast Fourier transform to see the frequency components of the signal you processed. Everyone's signal will look different but generally you will end up with a strong DC component and weaker spike around $10Hz$.

Unfortunately, we cannot let you test the EEGs on yourself and we don't have enough electrodes to go around. However, recall that we did design a pulse width modulation square wave generator to provide a test signal (recall the relaxation oscillator from Lab 5). This will be the primary means for you to test and debug your signal when you prototype.

H. Tips on Simulation and Testing

- To test your circuit in the simulator you will have to generate an oscillating signal using an AC voltage source or something equivalent. Make sure that this source is set to a microvolt level signal ranging from around a few $\mu V - 100\ \mu V$.
- As you are building the circuit in the simulator, make sure that you build it modularly and that each part of the circuit is clearly identified. This is to help you and to help us quickly debug your schematic should there be any obvious problems. You may want to label each module on the circuit with a short description.
- When you are simulating your entire EEG circuit, you may need to set the DC Convergence Limit to 2000 and Transient Convergence Limit to 1000 if you end up getting convergence errors.
- Make liberal use of the virtual multimeters, probes, scopes, and Bode Plot analyzers that Multisim provides you. These are the primary ways you will be able to tell whether your simulation is actually working or not. Make sure to probe key points in your circuit like between critical modules and check to see if the outputs you are reading match with what you expect.
- One important consideration that we will need to observe when we use Multisim for our project schematic, is to use non-virtual components (we will see why later). So how do we know if we are using a virtual or non-virtual component? When you open the "Select a Component" window, virtual components will have a blank in the field Footprint manufacturer/type. You can still place these components but Multisim will display them as a black outline. Non-virtual components will appear with a blue outline when placed on the schematic design and the Footprint manufacturer/type field will not be empty. Don't worry about the GND and Vcc nodes appearing with a black outline. These components are not physical circuit components but node connection abstractions.

IV. Project Parameters

Below are the project specifications that your design for you PCB must meet along with any metrics of evaluation. Each module of the project is covered in detail in the next section.

A. Design Specifications

- Your PCB must contain all of the modules required for the EEG
- You must use an instrumentation amplifier built from discrete components with appropriate gain
- The instrumentation amplifier must have adjustable gain
- Any other amplifier stage must also have adjustable gain
- You must use a +/- 5 V regulators to obtain +/- 5 V from the 9 V batteries.
- You must have coupling and decoupling capacitors in appropriate parts of your circuit
- Your board must have a PWM test signal generator output for you to test your circuit
- Your test signal generator must output a test signal on the order of $\sim 10^{-6}V$ to $10^{-5}V$ and be able to adjust the frequency between $10Hz$ and at least $100Hz$
- You must have voltage followers where necessary

B. Part Specifications

The following parts are available for your design. You will be provided a kit with these parts at the beginning of the prototyping phase provided that you have a schematic ready to build. You will not receive the kit if you do not complete the schematic beforehand. Kits will be distributed one per group. It is your responsibility to figure out how these components work. Look at the datasheets. You are encouraged to sample additional components from http://www.ti.com/.

- 4 x TLC277CP Dual Operational Amplifier
- 1 x LM7805 +5V Regulator, 1x LM7905 -5 V regulator
- 1 x $10k\Omega$ potentiometer (for instrumentation amplifier gain control)
- 4 x 50k 1% tolerance resistors (for instrumentation amplifier input stage and gain stage)
- 2 x 500k 1% tolerance resistors (for instrumentation amplifier input stage and gain stage)
- 1 x 1M resistor (for filtering)
- 1 x 100k resistor (for filtering)
- 1 x $5k\Omega$ potentiometer (for gain control in active low pass filter)
- 2 x 10 ohm resistors (for notch filter)
- 2 x $\mathbf{20k\Omega}$ resistor (for notch filter)
- 2 x $247k\Omega$ resistor (for notch filter)
- 1 x 1 uF capacitor (for filtering)
- 1 x 0.01 uF capacitor (for filtering)
- 2 x 0.22 uF capacitors (for filtering)
- 2 x 10 uF capacitors (for filtering)
- Header pins for test pad connections
- 4 x 8 pin DIP sockets for each of your 8 pin chips

C. Performance Specifications

- Your test signal must output a waveform within the correct order of magnitude and appropriate frequencies
- All excess high frequency noise must be adequately attenuated
- You should have a spike at 10Hz on the frequency spectrum and a strong DC component

- You will NOT under any circumstances test this device on yourself (we're not going to supply you electrodes anyways)
- The circuit should perform completely off the 9V battery

V. Extra Credit

This semester we decided to offer extra points for circuits and board designs that go beyond the requirements outlined in this document. We hope this makes the designs more interesting and gives an opportunity for all students to be creative and do something cool that will further their learning and make demo day extra fun!

We will be giving out up to ~30 extra credit points (this may be lower or higher, just an estimate for now) for any or all of the following:

1. Smaller boards.
    a. Note that smaller designs should not sacrifice neatness or logical positioning of components.
    b. You may still use the standard 3" by 5"PCB, just limit your circuits to a smaller portion of the board (preferably a corner) and the rest you can fill with your name and optionally other things (e.g., team name / logo, favorite quote (like the midterms), bitmap pic, etc.). Make sure you measure and label the actual rectangle with the circuit components so we can quickly tell how big your circuit block is.

2. Extra or improved functionality.
    a. Potential examples:
        i. LED/LCD indicators for the EEG signal
        ii. Speakers that produce sounds that depend on the input
        iii. Digital / analog support circuits such as counters, peak detectors, rectifiers, etc. (just make sure you add a switch / jumper so we can see your standard output signal as well)
        iv. Any improvements to the original EEG circuit (just make sure you explain what they are and how they improve your circuit). More gain is not a sufficient improvement.
        v. Anything else that involves electronics and somehow augments the experience or functionality of the EEG measurement. If you are not sure whether your idea qualifies, ask a TA, but as long as it deals with electronics it's probably good to go. And be creative! We love to see cool features!
    b. Before adding extra functionality or improvements, make sure your standard EEG works and it does not depend on your extra circuits and that your additional circuits can be quickly disabled / removed in case they do not work or you run out of time
    c. You can obtain components from lab (resistors, LEDs, caps, etc.), order them through TI, or buy them yourself (they are yours so you can use them on other projects in the future).
    d. Expect Michel to spend 1-2 min per project, so if we cannot get a good idea what your extra circuits do in that time, it won't be very useful. Make sure your demonstration fits into this time frame.

Extra credit points will be given out on a heuristic basis with no particular structure, so please do not expect this substantially change your grade. We hope that you have fun designing

VI. Simulation/Design Check-off

Your task is to complete the rest of the EEG design, put everything together, and simulate it in Multisim. We recommend that you draw a rough draft on a spare sheet of paper so that you have a good idea of where you are going when you start to place components in Multisim. We also recommend that you build and test your circuit in modules. This will increase the chances that you will be able to catch errors and debug your design.

Make sure to attach a copy of your working schematic and simulation results to this lab report. Show that your simulation results meet the design specifications described above. You will need to show both an AC analysis showing the overall transfer function of your circuit from 0.1Hz to 100kHz and a 1-second transient analysis with a 10Hz input waveform. Also **use clean wiring in your schematic** because it makes it easier for us and for you to trace your circuit. **We will refuse to help groups** that do not wire their circuits cleanly. This is a fairly large circuit and if you don't wire things neatly, you will be hopelessly confused and proceed to throwing fragile objects.

In addition, you will need to get your schematic checked off below by your GSI in order to get your parts kit.

Your GSI Signs Here **(30 points)**