

DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

Spring 2019
6.101 Introductory Analog Electronics Laboratory
Laboratory No. 5 Checkoff Thu 3/14/2019

READING ASSIGNMENT

Class AB Amplifiers, Push Pull Biasing [Exercise 1]
Neamen 3rd Edition: pp. 593-596, pp. 578 [8.3.2] – 586 top

ECG Circuit [Exercise 3]

[Analysis of Salle-Key Architecture](#) [course website “Reference” tab]

[Improving Common Mode Rejection with Right Leg Drive](#) (why the penny?) [course website “Reference” tab]

Objective: Build a small audio power amp and play loud music! Build a switch mode power supply. Build an ECG amplifier on a PCB and display on any PC! **NOTE:** Your lab write-up should clearly show your circuit configurations, your element values and your calculations in addition to measurement results.

Check off: The check off for this lab is in three parts [done separately]: (1) demonstrate the audio amplifier, (2) demonstration operation of a negative buck converter and (3) demonstrate a working ECG circuit showing the heart rate in MATLAB in 38-530.

Experiment 1: SMALL POWER AMPLIFIER WITH LOCAL AND OVERALL FEEDBACK

NOTE: Do not use the variable power supply terminals on your kit for this experiment. The output current from these terminals is limited to 500 mA, and this is too low for this amplifier when driving a loudspeaker. Use the +/- 12 volt fixed terminals next to the power switch. These terminals can deliver 1 ampere before they start to current-limit. Even better, you can use the adjustable power supplies on the lab benches. There are nine of them. First, prove your circuit using the kit variable +/- 15 volt power supplies, then, hook it up to the adjustable supplies [set for +/- 15 volts], hook up a speaker, and enjoy!

NOTE: These adjustable supplies have very large filter capacitors, and they take a while to discharge after the power switch is turned off, if your circuit doesn't draw much current. You may want to monitor the supply voltages with your DMM, and you can also place a “bleeder” resistor across the power supplies' terminals to increase the speed of the capacitor discharge [time constant]. Be careful to choose a resistor with a safe power rating!

In this experiment you will build and examine the performance of the dc-coupled output stage amplifier whose schematic outline is given in Figure 1. This amplifier is intended to have a gain of 20 dB with less distortion than that found in the amplifier of experiment 5 of Lab 4.

- Note that the function of resistors R_{B1} , R_{B2} and the 1N914 diodes is to bias the output transistors *slightly* on to eliminate crossover distortion. **[Q 1.1 How does this work?]** [Use 4.7 k Ω 1/4-watt resistors for R_{B1} and R_{B2} , at least to start.] In order to ensure that the output transistors Q_1 and Q_2 are not damaged make sure that the maximum power that they will have to dissipate is limited to 1.0 watt. Note that this calculation will involve both the DC power dissipated due to static quiescent current, plus each transistor sees one-half of the output sine wave. **Q 1.2 What is the**

smallest value of load resistance R_L that can be connected to the output of the amplifier to ensure that this power dissipation limit is not exceeded?

- Note also that the requirement for relatively high input impedance may conflict with the requirement for low DC offset voltage. **Q 1.3 Explain this conflict in your write-up.** You may choose to use either the inverting or non-inverting configuration for the op-amp. You may choose to use any op-amp available in your kit or at the instrument room window or in the lab drawers.

The emitter resistors R_E is there to stabilize bias current with changes in operating temperature. The collector current is exponentially proportional to V_{be} and inversely with temperature:

$$I_C = I_o \exp\left(\frac{V_{be}}{V_t}\right) = I_o \exp\left(\frac{q \cdot V_{be}}{kT}\right)$$

Notice that we define $V_{be} = V_b - V_e$. As temperature increases, I_c decreases exponentially. However, with the R_E resistor at the emitter of the transistor, V_e will decrease with increasing T , therefore increasing V_{be} and stabilizing I_c .

Q 1.4 Explain why the output impedance of the amplifier is not at least 5.6Ω . [These resistors should be 1/2-watt size.]

1. Design your amplifier to meet the following specifications:

- Low frequency cutoff [-3dB point] ≤ 5 Hz.
[To take advantage of extended low frequency response]

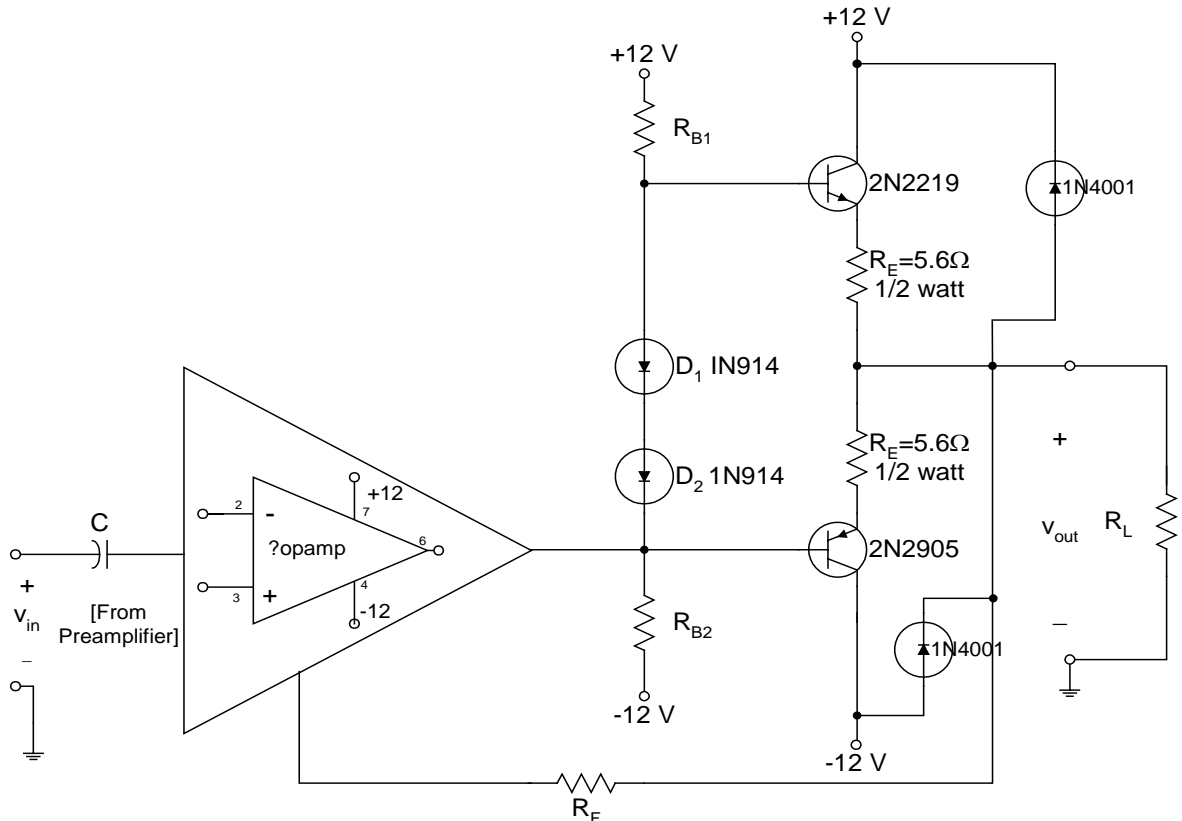


Figure 1: Amplifier circuit for experiment 1.

- Input impedance (as seen by preamplifier output) $\geq 20 \text{ k}\Omega$.
[To prevent loading down of preamps that have relatively high source impedance]
- Output stage offset voltage $< 50 \text{ mV}$.
[To keep DC from causing the speaker coil to heat and the cone to be offset from its center position between the magnet pole pieces.]
- High frequency cutoff [-3dB] point = 25 kHz **minimum**.
[To take advantage of extended high frequency response from DVD audio discs running at 48 kHz sampling rate; also some high-end sound cards.]
- Mid-frequency [1000 Hz] voltage gain of +20 dB.
- Output stage quiescent bias current between 1 and 10 mA [class AB or B operation]. [Measure the DC voltage drop across one or both emitter resistors.] Since we gave you the biasing resistor initial values, there is not much to design. However, you should measure the bias current in the output stages to make sure it is less than 10 mA. Output device β_F variations will affect the value of bias current, and it will be hard to achieve a stable bias current if the β_F 's of both output devices aren't about the same. If your output device bias current is greater than 10 mA with no signal input, turn off your +/- 12-volt supplies immediately. Increase the value of both R_{B1} and R_{B2} to the same next highest standard value and recheck the output bias. Keep increasing the value of this pair of resistors until the bias current drops to the limits given above. **Q 1.5 How does changing the value of these two resistors control the output stage bias current?** [Note: It is also possible to increase these two resistors to the point where not enough DC bias current is supplied to the base of one of the output transistors, especially if it has low β_F . It helps if your output devices have similar β_F 's. From an AC point of view, large values of these two resistors can cause clipping on one-half cycle due to the fact that not enough AC base current is supplied through these resistors on large signal swings. This is also more likely to occur when the β_F 's or β_O 's of the two output devices are not equal.] The value of DC bias current is very temperature sensitive and will be higher after you have heated the output devices by amplifying an AC signal. **Wait for the devices to cool before measuring the bias current.**

Keeping DC bias low prevents wasting power during no-signal periods and heating of output devices during no-signal periods. This design could be portable and operated by batteries if this current is low enough.

- Output stage voltage swing = 18 V_{p-p} **minimum** into a 100 Ω resistive load. [The more swing, the more power output, and the louder the music can play without clipping distortion, so choose your components wisely!] [Your kit contains a 100 Ω , 5 %, 5 watt 6.101 load resistor for all measurements on this amplifier.]
- Slew rate: No visible slewing allowable within the frequency range of 5 Hz to 20 kHz at full output into 100 Ω .

2. Construct the amplifier you have designed and verify its performance by appropriate measurements. **WARNING: The metal cans of the output devices are connected to the collector, which is connected to V_{CC} or V_{EE} . Be careful not to touch the leads of other parts to these cans!** These should include semi log frequency response [bode-amplitude only] plots to identify the low and high frequency -3dB points, offset voltage measurements, slew rate measurements. You should also measure the output resistance by measuring the open circuit v_{out}

and the loaded v_{out} ; likewise the input resistance: use a known source resistance high enough to make a voltage divider at the input when it is connected in series with the function generator. Input and output resistance measurements should be made with a 1 kHz sine wave input; frequency response measurements should always be referenced to 1 kHz in audio work, but are often referenced to 400 Hz in radio work.

To measure the input resistance, you could place a pot in series with the input, and then measure the ac signal voltage at the input while you turn the pot up until the input voltage drops from full input [start with the pot turned down = ~ 0 resistance] to -6dB . At this point the resistance of the pot will equal the input resistance.

[The output impedance is very low, so use the DMM to compare the loaded and unloaded output voltages. The DMM should be used for all measurements where its frequency response permits, as it is much more accurate than the oscilloscope, which is only good for about 5-10% accuracy.]

You will need to load the output with a very small resistance in order to see any change in output voltage between the open circuit [unloaded] and loaded output voltage. Also, to use a low load resistance, you must reduce the input signal to keep the dissipation in the output devices down. You may only be able to accommodate around 1 V RMS at the output before you start to overheat the outputs or the low value load resistance. Anyway, the idea is to measure the open-circuit and closed-circuit output voltages at 1000 Hz, and then you can calculate the source output impedance knowing the value of the load resistance. It is a very small number, although it rises at high frequencies as feedback falls off.

- Amplify 1 kHz and 10 kHz triangle waves and notice that very little distortion is evident as compared with the amplifier that you constructed in experiment 5 of Lab 4. **Q 1.6 How can you explain this?**
- Amplify 10 Hz, 1 kHz, and 10 kHz square waves and sketch the output waveforms. **Q 1.7 How do you explain any differences you see between the input and the output voltages?**

Change the feedback connection from the output of the complementary-symmetry power stage to the output of the op-amp. **[Q 1.8 What characteristic of the emitter-follower allows us to do this?]** Repeat the two test series immediately above and note any differences. **Q 1.9 Explain the differences.**

3. Q 1.10 If the amplifier had been built without the output stage, what happens to the amplifier gain and output swing if the smallest safe value of load resistor that you calculated above were connected directly to the output of the opamp? Q 1.11 What is the function of the output stage of this amplifier? Q 1.12 Is the output impedance of the output stage high or low?

4. Reconnect the output stage to your amplifier and remove the diode biasing circuitry from the output stage and observe the increase in crossover distortion when the resistor you calculated above loads the amplifier. Note that you will have to connect the output of the opamp directly to the bases of transistors Q_1 and Q_2 . [Tie the bases together.] Keep the signal level low at first to hear the maximum crossover distortion, then turn up the level, and the distortion seems to disappear. **[Q 1.13 Why?]**

5. Reconnect the amplifier as originally shown in Figure 1. Observe the maximum clean peak-peak output voltage swing into the $100\ \Omega$ load at 1000 Hz. Now connect the output of the op-amp to the junction between diodes D_1 and D_2 instead of to the base of the PNP transistor. What difference does this change make in the output voltage swing? **[Q 1.14 Why?]**

Checkoff 1: Demonstrate your circuit to the TA for check off. Your circuit must be working properly before the check off time. The staff will question you to determine your understanding of the circuit, ask you to demonstrate some measurements, and will test your circuit with an mp3 player and loudspeaker. [1 point]

Experiment 2: Switch Mode Power Supply

To charge a cell phone in your car, you need to drop the 15V (the 12 volt car battery is really ~15 volts) from the car to 5V. Using a 7805 linear regulator, with a 1A charging current, 10 watts would be dissipated (wasted) across the regulator. This regulator has an efficiency of 33%, very poor.

A switch mode power supply design, in this example a buck converter, is more efficient than the 7805 with efficiency over 90%. Let's explore the concepts behind a switch mode power supply.

As show in figure 2a, using MOSFET as a switch to charge up a capacitor would work for very small currents only, such as the flying capacitor charge pump. For higher power, the surge current during the on cycle would eventually fry the MOSFET. Adding an inductor in series, figure 2b, would limit the current spike but results in voltage spike due to $\frac{di}{dt}$. Finally adding a free wheeling diode solves the problem resulting in a buck converter.

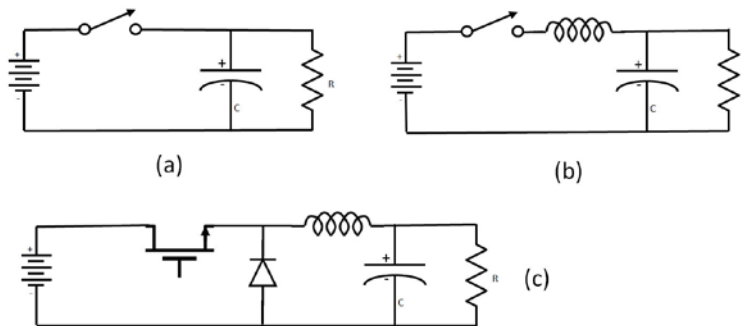


Figure 2

In this exercise, you will explore some interesting issues working with a switch mode power supply. To match the topology of the circuit, we will use a p-channel power MOSFET (IRFD9110) driven by a npn BJT 2N3904. A function generator is used to provide a square wave input with varying duty cycle.

Because of the extremely fast rise and fall times at the MOSFET, component placement and lead length is extremely important. Place the components as close as possible. Trim the components leads as short as possible. Otherwise ringing will result. **Checkoff with long “flying wires” will not be accepted.**

Construct the buck converter, as shown. Q2 is a p channel MOSFET (IRFD9110) with a gate threshold voltage of -2 to -4v. D1 is a fast recovery diode (MUR120). R3 is two 150 ohm resistor in parallel.

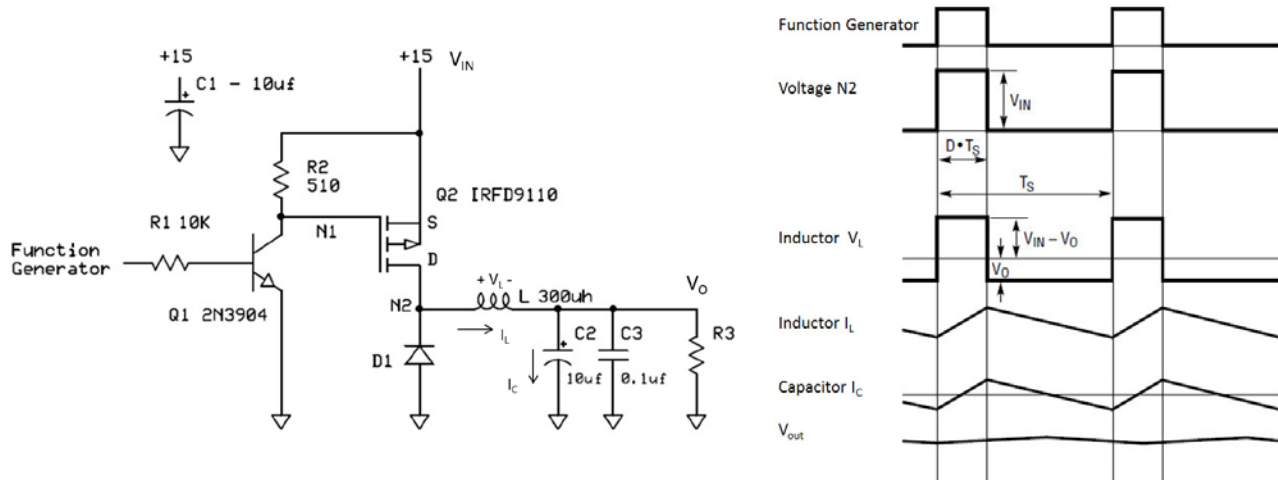


Figure 3

Set the function generator for 100Khz square wave 0-10v peak to peak with a 50% duty cycle. Let's look at this circuit in the steady state. When the MOSFET is on, node N2 is at supply voltage minus the IR drop across the MOSFET. When the MOSFET is off, the freewheeling diode D1 conducts. (An inductor does not like a discontinuous current). Diode, MUR120, is a fast recovery diode, but ideally should be a Schottky diode. (why?)

The steady state voltage across an ideal inductor must be zero. A steady state voltage would imply a constant, nonzero $\frac{di}{dt}$ which results in infinite current. In equilibrium, the voltage across an ideal inductor is zero. (Real inductors, however, have resistance, which will lead to an IR drop.)

$$v_L(t) = L \frac{di_L(t)}{dt} \quad i_L(t) = i_L(T_o) + \frac{1}{L} \int_{T_o}^{T_s} v_L(t) dt$$

At steady state, the current are the same at every T_s or

$$i_L(T_o + T_s) = i_L(T_o) \quad \text{or} \quad i_L(T_o + T_s) - i_L(T_o) = 0 = \frac{1}{L} \int_{T_o}^{T_s} v_L(t) dt$$

Therefore: the average voltage across an inductor must be zero

$$v_{L(average)} = T_{ON} \cdot (v_{IN} - v_o) + (T_s - T_{ON}) \cdot (-v_o) = 0$$

$$\therefore v_o = \frac{T_{ON}}{T_s} v_{IN} \quad D = \frac{T_{ON}}{T_s} \text{ (duty cycle)}$$

Note that the output voltage is constant and independent of the load.

Question 2.1: A sharp (or may not so sharp) engineer, trying to saving costs, replaces Q1 and Q2 with a n-channel MOSFET (figure 4) with a gate to source threshold of 3v and driven by a 10v peak to peak signal. Will this circuit work? Explain mathematically why the solution will work or not work.

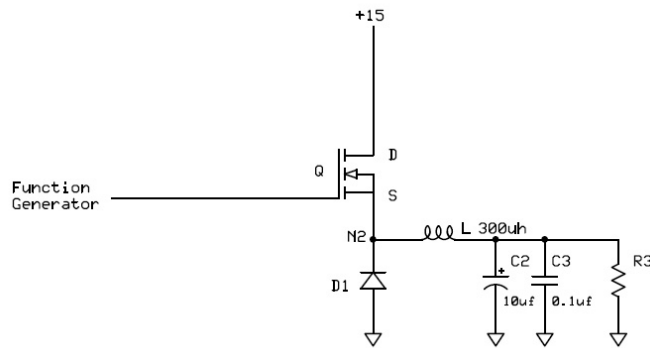


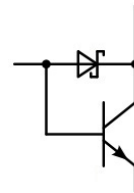
Figure 4

Now back to the circuit in figure 3. Measure supply voltage, V_{IN} and the output, V_O . You will see that the voltage is slightly more than half of the input voltage, higher than predicted. Now compare the duty cycle of the signal from the function generator and node n2. Also look at the duty cycle of node n1.

Question 2.2: Explain the cause of the differences in duty cycle between nodes N1 and N2 and the underlying cause in figure 3.

Now adjust the duty cycle of the function generator so node N2 is at 50%. Measure the output voltage. Now the output voltage should be closer to predicted.

One way to speed up the turn off time of Q1 is use a Schottky diode between the base and collector, a Baker clamp. Since the voltage drop a forward biased Schottky diode is less than the base emitter voltage, base drive to Q1 is diverted away through the Schottky diode thus limiting saturation and the stored charge in the pn junction.



Turn off the power and carefully add a 1N5911 Schottky diode to the base collector junction. Note the polarity of the diode. Now compare the output voltage to with and without the Schottky diode.

Question 2.3: What is the change in output voltage change when the Schottky diode is added and in what direction?

Another way is to speed up the turn off time for Q1 is to add a speed up capacitor in the base drive. Add a 10nf in parallel with R1. Note the improvement in transition time resulting in a lower output voltage.

Now increase the load by adding a few more resistors in parallel. Notice that the voltage constant but the ripple has increased.

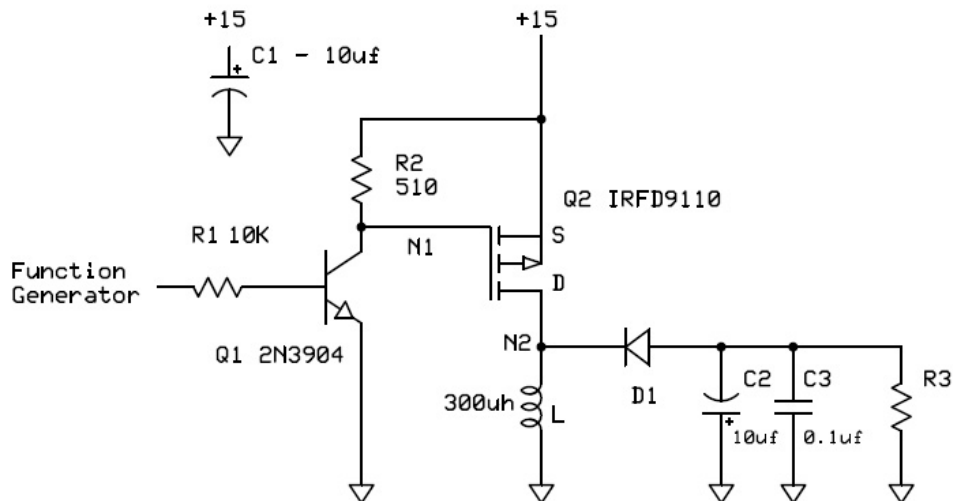
Up to now, the buck converter has been operating in continuous conduction mode, i.e. there is always currently flowing through the inductor, a much easier analysis. When the load is light or the frequency is low, the inductor current eventually will go to zero during the off time. When this occurs the diode and MOSFET, in their off state acts as capacitors creating a RLC circuit thus producing oscillations. At this point, the output voltage is no longer stable at a fixed duty cycle. Reduce the frequency until discontinuous conduction occurs. You should see this waveform at node N2.



The threshold for discontinuous conduction operation is determined the following by:

$$f > (1-D) \left(\frac{v_o}{2i_o L} \right) \quad D = \left(\frac{T_{ON}}{T_S} \right)$$

For many applications, both positive and negative voltages are required for operation. By swapping the diode and inductor, a negative voltage converter can be created. Reconfigure your circuit as show. Note the orientation of the diode. **Be sure to reverse the polarity of the electrolytic capacitor. Repeat: reverse the polarity of the electrolytic capacitor.**



Set the function generator for 100Khz square wave 0-10v peak to peak with a 50% duty cycle. **Before applying power double check and verify the polarity of capacitor C2.** Measure the output voltage.

Using a procedure similar to the first buck converter we can derive the output voltage. The current following into the inductor when the MOSFET is on is: $i_L (on) = \frac{V_{in}}{L} T_{ON}$

When the MOSFET is off, the diode is conducting the change in inductor current is

$$i_L (off) = \frac{V_O}{L} (T_S - T_{ON})$$

In equilibrium, they are equal and opposite

$$\therefore V_O = -\frac{T_{ON}}{T_S - T_{ON}} V_{IN} = \frac{T_{ON}}{T_{OFF}} V_{IN} \quad \text{with } T_{OFF} = T_S - T_{ON}$$

Checkoff 2: Demonstration operation of the inverting power supply. [1.8 points]

Question 2.4: List at least three major sources of losses that limit the efficiency of the power supply.

Experiment 3: Sallen-Key Filter and ECG

In lecture, we discussed the theory of operation of an ECG circuit. In this exercise, you will build a low pass filter, measure and plot the characteristics, determine component values for some blocks of the ECG and build/solder an ECG circuit.

Low Pass Filter (LPF)

The frequency spectrum of electrical signals picked up from the human body ranges from less than 1 Hz (the heart beat) to megahertz (electrical noise pickup). In order to view an ECG, noise must be filtered out. Much of the noise is at 60 Hz from the AC power lines. Using a low pass filter with a cutoff at 23 Hz would filter out most of that noise. (The heart, at rest, beats 40-80 times per minute, slightly less than 2 Hz.) In this exercise, you will build a low pass filter and plot the frequency response of the filter.

In 1955, R.P. Sallen and E.L. Key of MIT's Lincoln Labs presented what was then a novel approach to filter design¹. The design allowed for implementation of an elegant low pass or high pass filter without the use of inductors. Their implementation is now referred to as the Sallen-Key filter. A full analysis of the Sallen Key circuit is available on the course website.²

Ideal filters, not realizable, would completely eliminate any frequency above the cut off frequency. A first order filter, realizable, attenuates by a factor of one half for every doubling of frequency beyond the cut off frequency. A second order filter attenuates by a factor of one fourth for every doubling of frequency. The Sallen-Key filter is a second order filter. We will use a Sallen-Key low pass filter in

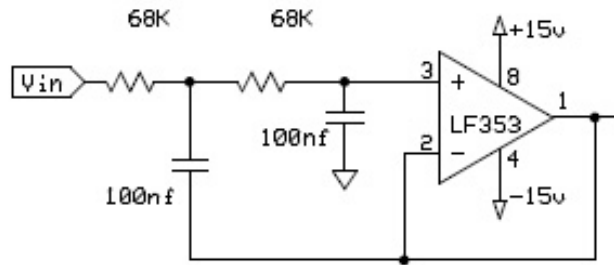
¹ Sallen, R. P.; E. L. Key (1955-03). "A Practical Method of Designing RC Active Filters". IRE Transactions on Circuit Theory 2 (1): 74-85.

² focus.ti.com.cn/cn/lit/an/sloa024b/sloa024b.pdf

our ECG circuit. The Sallen-Key implementation can also be configured as a high pass filter. In this variation frequencies below the cut off frequency are attenuated. In addition, an op-amp circuit will remove much of the common mode noise

Exercise 3.1 – Sallen-Key Low Pass Filter

The Sallen-Key filter attenuates high frequency signals starting at a cutoff frequency. Ideally the cutoff frequency for the LPF should be 40hz with a notch filter at 60hz. A cutoff of 40hz would still allow a significant amount of 60hz noise through and would require a notch (band stop filter) at 60hz. However, to achieve a notch filter at 60hz would require a variable resistor or precision components.



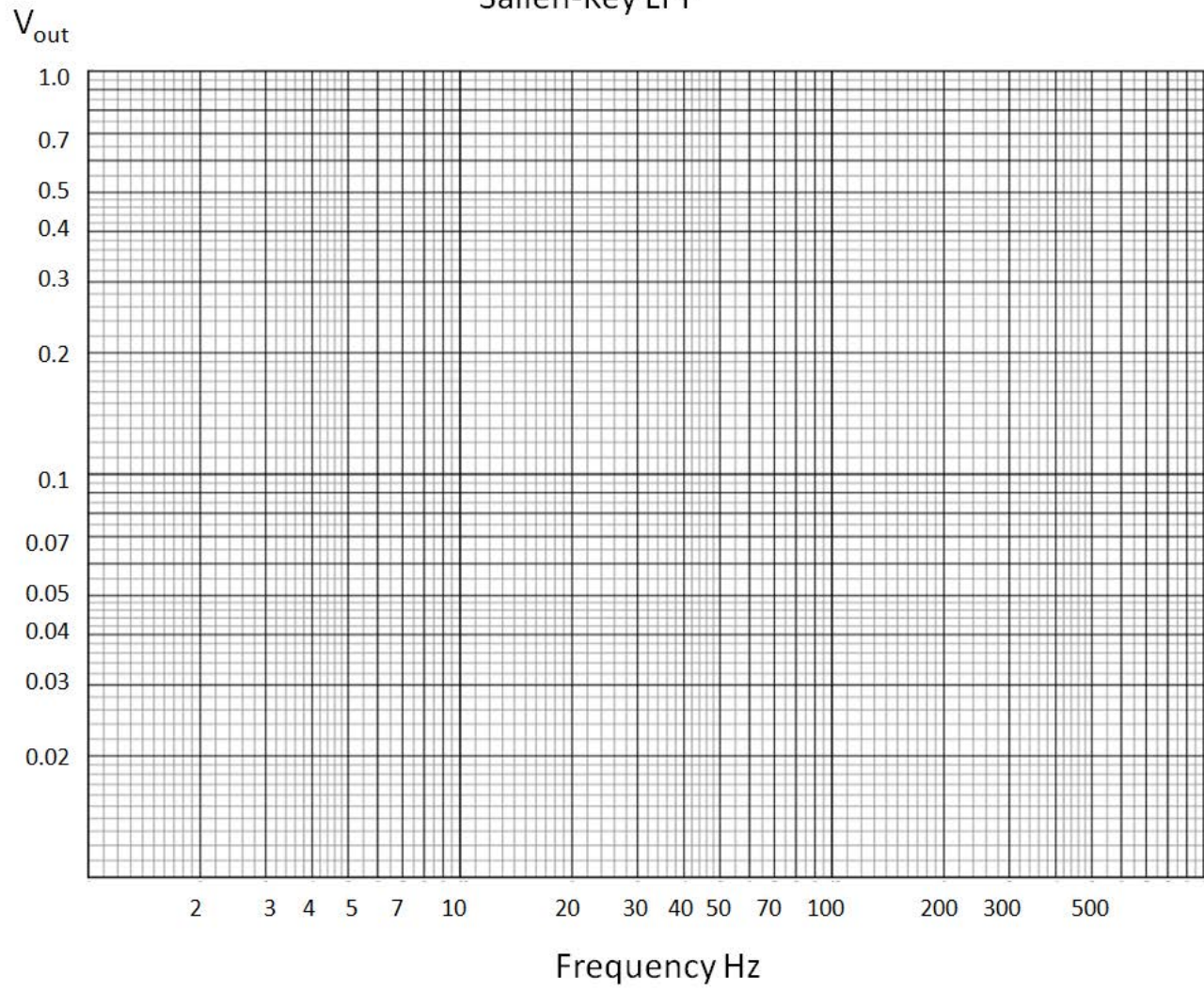
For this circuit, the cutoff frequency is $f_c = \frac{1}{2\pi\sqrt{R_4R_5C_1C_2}}$ and $Q = \frac{\sqrt{R_4R_5C_1C_2}}{R_5C_1+R_4C_1}$.

Intuitively, you can see that at low frequencies, C1 and C2 appear as open circuit and the circuit operates as a voltage follower. At high frequencies, C1 and C2 appear as short circuits. Note that the gain is one for this configuration. **Q 3.1 With two resistors, you can add gain to the configuration. How?**

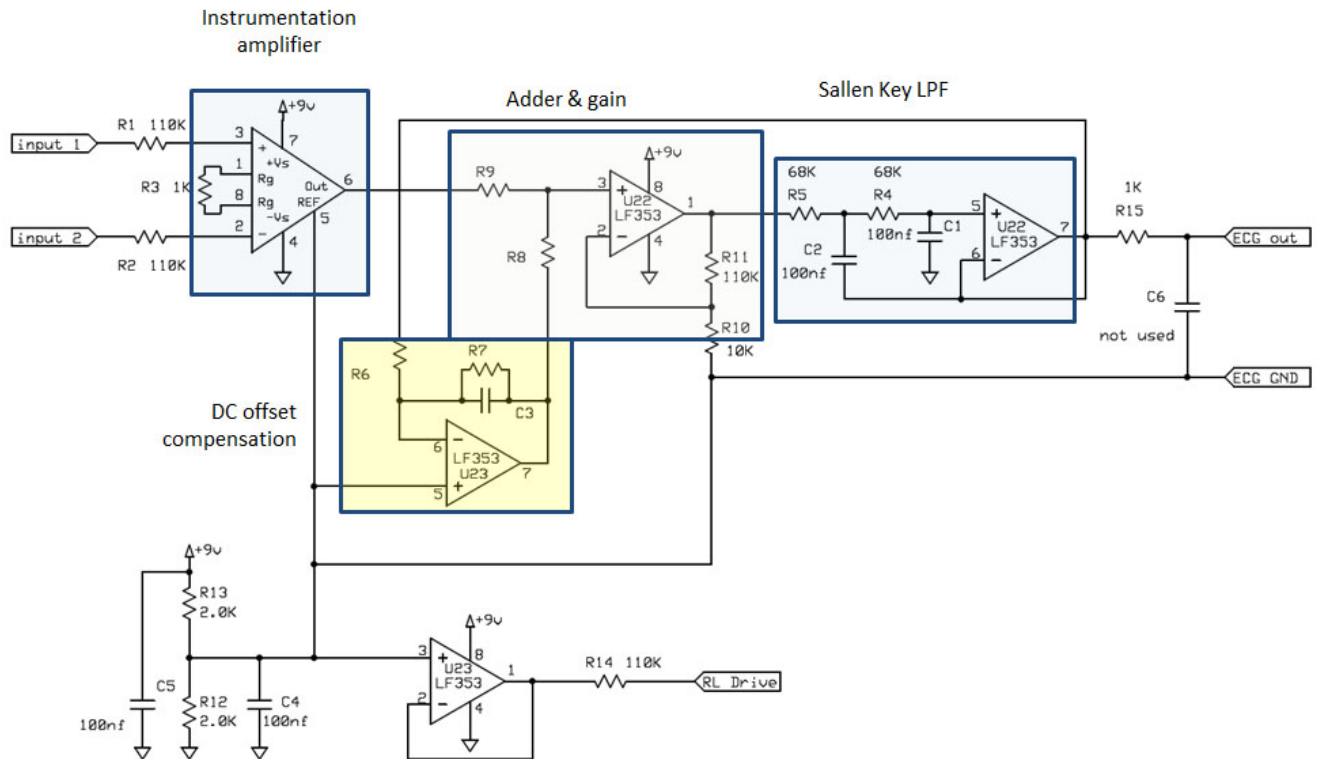
As with amplifiers, with gain, it is easy to end up with a pole in the right half plane and have oscillations. For our application we set the gain to unity and avoid this situation.

For this lab exercise, build the Sallen-Key LPF circuit. Using the function generator, apply a 1 volt 1 Hz sine wave to the input (V_{in}) and display V_{in} using channel 1 and the output (V_{out}) using channel 2 on the oscilloscope. Plot V_{out} as a function of frequency (at the 15 frequencies on the x axis) keeping V_{in} at 1 volt. The cutoff frequency is the value at which the output begins to decrease. Take a few more measurements around the cutoff frequency and see the roll off. You will need to switch the oscilloscope probes from 10X to 1X for higher frequencies. **Q 3.2 The Sallen Key filter is a second order filter. What is the slope of the filter expressed in dB/decade?**

Sallen-Key LPF



Exercise 3.2 – ECG



For safety a 9V battery is used in the ECG. To avoid using two power supplies, we use R12 and R13 and create a virtual ground at 4.5 volts. Thus the op-amps see a +4.5 volt and a -4.5 volt. A note regarding safety. A 110K resistor is in series with any leads, including the penny, being attached to the skin. This limits the current flowing to the body in the event of a single point of failure. Assuming 9V appears at the resistors because of a failure in the integrated circuit (very unlikely) and a 1 Mohm (megohm) body resistance, the maximum current is $9\text{V} / (110\text{K} + 110\text{K} + 1 \text{ Mohm}) = 7.4 \mu\text{A}$.

The ECG amplifier consists of four major blocks. An instrumentation front end, another gain stage, a DC offset compensation and a Sallen-Key LPF. The instrumentation op-amp has high differential gain but a common mode gain of one. The details are described in Operational Amplifiers.³ Rather than wire up four op-amps for implementation, we use an INA111 or AD620. The devices are already configured as instrumentation op-amps. Ideally, the gain could be set 1000 without the need for a second gain stage. Typically the ECG signal at the electrodes is riding on top a DC voltage. However any amplification would also amplify this DC voltage and could easily saturate the output voltage. For this stage, setting R3 to 1K gives a gain of 51.

The second block consists of adder/gain stage but also is used to compensation for any DC offset at the input electrodes. To compensate for the DC voltage, the ECG output signal is integrated (another way to view a LPF) and compared to the virtual ground. Any difference is then added in the adder/gain stage. The output of the second stage is then filtered by Sallen-Key filter. R15 (in conjunction with C6) is included in case additional filtering is required.

For this lab, select an integration period to compensate for any DC offset at the inputs. Choose an appropriate value for the adder resistors, R6 and R7. You want a time constant for the R6, R7, C3 that

³ James Roberge, Operational Amplifiers pages 450-451.

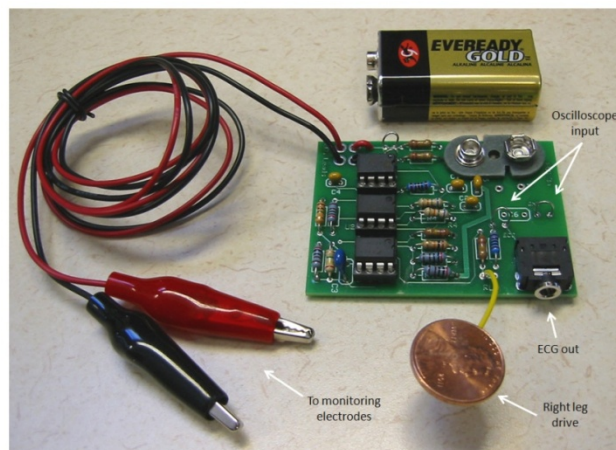
compensates for the DC offset yet long so as to not impact the ECG signal. **Q 2.3 Show the transfer function and your calculations for R6, R7 and C3 and plot the transfer function for this block. Indicate the cutoff frequency and the slope. Q2.4 What limits the maximum value for R7?**

Now build and solder the PCB. We suggest the following steps:

- a) solder resistors,
- b) solder capacitors C1, C2, C4, and C5
- c) solder IC sockets,
- d) solder capacitor C3,
- e) solder 3.5mm audio jack,
- f) solder ECG signal and ground leads

Final Steps

- Insert the 3.5mm audio jack into the PCB. Be sure the jack is flush with the board by pressing the jack against the circuit board as you solder audio jack. This will seat the tiny plastic feet into the holes in the circuit board. The plastic feet will help to anchor the audio jack as the cable is plugged and unplugged. Solder joints do not have good mechanical strength.
- Solder a 36" red and 36" black #22 stranded wire to the ECG input marked "+" and "-" respectively. Be sure to use the smallest hole. Route the wires from the top through the two larger holes in the circuit board. This will provide strain relief as the wires are flexed. Remove the red rubber insulator and the black rubber insulator from the alligator clips. **Insert the insulators into the wire.** Crimp and solder the wires to the clips. The leads will be used to connect to the ECG monitoring electrodes.
- There are two ECG outputs: one pair for the oscilloscope and one for the microphone jack. Form a small loop using the leads from a recycled resistor and solder the wires into the holes marked "ECG" and "GND". These wire loops will allow you to display the ECG on an oscilloscope.
- Solder the battery clip to the board. Note the polarity of the clip. The orientation of the battery clip is shown on the photo below. Using a large diagonal cutter, snip battery clip leads. A solder joint should not be used for mechanical strength but will probably work in this instance.
- Solder the penny to board. The signal is marked RLD (right leg drive) but will be connected to the right hand.



Before powering up the circuit, check and make sure all the components are soldered and that there are no solder shorts or bridges. A solder bridge is when two adjacent unconnected pads are inadvertently soldered together. Insert the three IC's. U21: AD620 or INA111; U22 and U23: LF353.

To display the ECG:

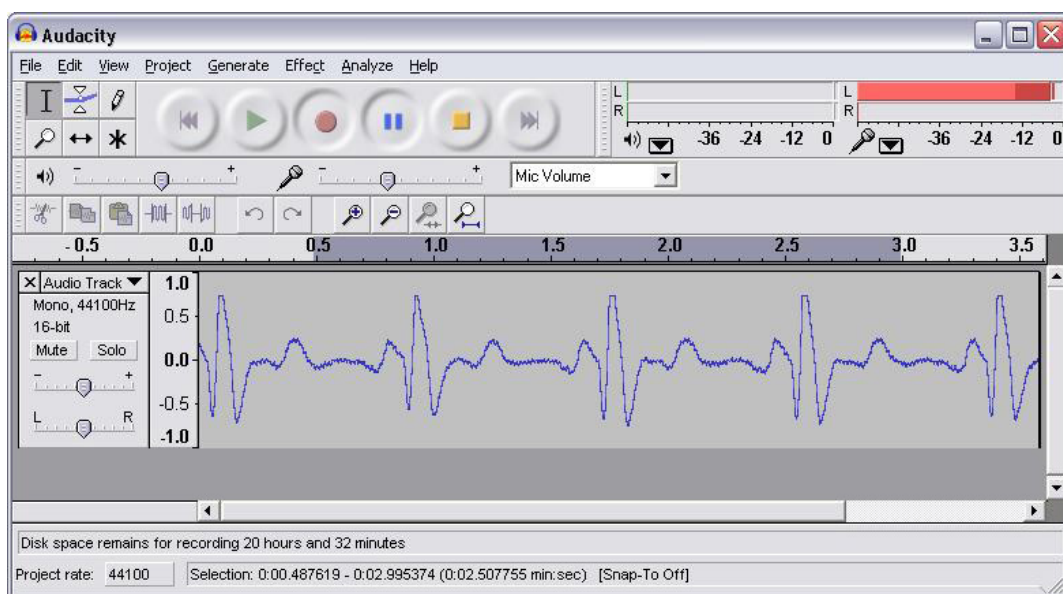
- (a) Apply the two 3M™ Red Dot™ Monitoring Electrodes to your arms. Attach the red lead to the left arm and the black lead to the right arm. The resultant waveform is referred to as LEAD I.
- (b) Using 10X oscilloscope probes, attached the scope probe to the ECG output leads.
- (c) Attached the 9v battery and grab the penny with your hand. Set the oscilloscope to 100 mv/division and 400 ms/division. You should be able to see your ECG. The penny is used in place of a “right leg drive” circuit to bias the body at 4.5 volts and improve common mode rejection. You can save the screen shot to a floppy disk in the oscilloscope by pressing the print button.

The microphone input into a laptop contains a 20 bit analog to digital converter. This can be used to view your ECG in place of an oscilloscope.

For safety, use a laptop that is powered only by battery. Make sure the laptop is not plugged into the wall. The AC adapter will add significant noise to the ECG .

The output of the ECG circuit, set at approximately 100 mv, is designed to be compatible with microphone voltage levels. Attach the output of the ECG unit to the microphone input. (If your laptop does not have a microphone input, use a USB adapter from the lab.) You should be able to view your ECG on the PC using an audio recording program such as Audacity. The display shows voltage on the y axis and time on the x axis just like an oscilloscope. Use the slider to control amplitude and the magnifier to zoom in. In the screen shot below, the heart rate is approximately 60 beats per minute. If you are using an older MacBook with a mic jack, your signal will be very small and must be software amplified (use “Effects” “Amplify”).

If your ECG output is noisy, you can perform additional filtering using Audacity. After recording, select “Effect”, Low Pass Filter”. Experiment with various cut off frequencies to reduce the noise.



Now use MATLAB to display your ECG waveform. Use your laptop with a microphone to USB adapter or use a MAC in 38-530 running Windows 7. If you are using a MAC:

1. Login using Username: admin
Password: \$rf2@CDE*8
2. Connect the ECG board to the audio input jack on the back of the MAC using a 3.5mm cable. Be sure to use the audio input jack and not the headphone jack.



Download `ecg6101v1.m` from mit.edu/6.101/www/matlab. (Right click "Save as".) Using the MATLAB program, you will be able to record a 5 second clip of your ECG. This verifies correct operation of the settings on the computer.

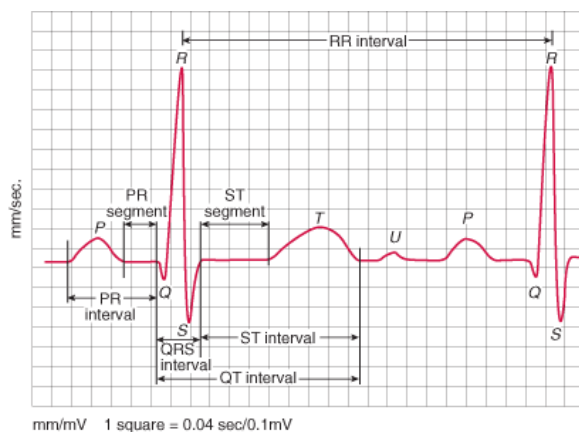
There are two parts to the script. First part samples the ECG and displays it as a graph. It uses the audio input and samples the data at 1kHz. The second part saves the data to a file named "mydata". You may change the name if you wish.

The MATLAB script is written such that you can execute each section of the MATLAB script by "CTRL-ENTER". You can now analyze your ECG signal in MATLAB.

In the MATLAB command window, load and plot the saved data

```
>> load('mydata')  
>> plot(t,myECG); shg;
```

Your ECG (expanded) should be similar this waveform.



The waveform consisting of the peak is referred to as the QRS complex and occurs during ventricular depolarization which triggers the contraction of the ventricles. The large signal corresponds to the larger tissue mass of the ventricle.

Compute your average heart rate using MATLAB. To do this you will need to write a program that will allow you to identify the positions of peaks, the R wave. This is called segmentation. Use the built-in Matlab function "findpeaks".

`[pks,locs]= FINDPEAKS(X)` returns the indices "locs" at which the peaks occur as well as the value of the peaks "pks"

Findpeaks also allows the user to specify the minimum peak height and the minimum peak distance. For example:

```
[peaks,locs] =findpeaks(myECG,'MinPeakHeight',MPH,MinPeakDistance,MPD)
```

```
%enter a value for MPH and/or MPD
```

By observing your ECG, you can set a threshold for MINPEAKHEIGHT so that small peaks are not counted. Calculate the average heart rate by counting the number of peaks. The number of peaks is shown in the MATLAB workspace. You can also use the command

`length(X)` returns the length of vector X.

You will need the total elapsed time between the first and last peak to calculate the beats/minute. The total elapse time is location of the last peak - the location of the first peak. Since the sample rate is 1000hz, elapsed time is in milliseconds. Note that the number of heart beats is `length(X) -1`. Why?

Checkoff 3: Display your ECG waveform and your heart rate in beats/minute [2.2 points]