Lab 3:

Op-Amps: Comparators and Sound Amplifiers

Op Amps are REALLY useful components and widely used in electronics. 'Op Amps' are short for 'Operational Amplifiers', and they formed the heart of early analog computers because they could be used to carry out all mathematical operations, simply by reconfiguring the way they were wired. Understanding them will enable you to design and build useful and interesting circuits including those covered in this lab.

The op amp is in an integrated circuit (IC) chip which can be placed directly on your breadboard. There are many different types of op amps, but perhaps the most popular one, and the one that we will be using in the first part of the lab, is called the "LM741 General Purpose Op Amp", or "741" for short.

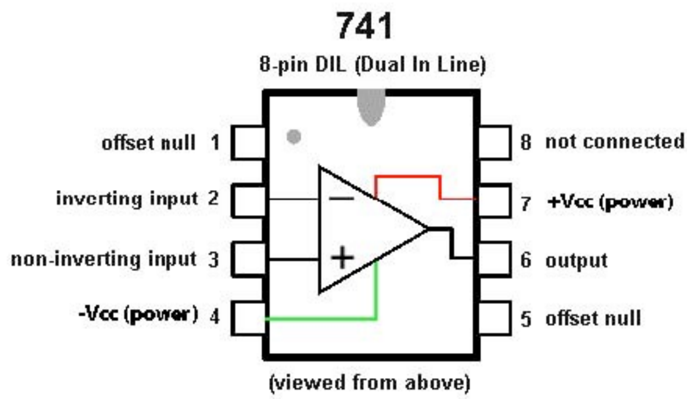

Figure 1. LM 741 Pinout.

1. Objective:

a. To understand how op-amps work and use them to construct comparators and amplifiers with controlled gain. Specifically, you will synthesize an audio amplifier with gain in the range 10-100, and use it to amplify an audio signal from your portable music player or lab computer ☺.

b. To understand the non-ideal behavior and the limitations of simple op amps.

c. If you have time, you will have the chance to build: i) a two-stage amplifier-and-transistor (Section 7) and/or ii) the *real-deal*, serious, 3 Watt amplifier (Section 8).

2. Pre-Lab Questions:

a. *Read Lab 3 handout* prior to coming to the lab. Write "READ" in your pre-lab when done.

b. *Look through* at a data sheet (provided on the course website) for the 741 Op Amp to familiarize yourself with the meaning of the various pins, limitations, etc. The 'pin-out' for this integrated circuit is also shown in Figure 1. Write "READ" when done.

c. *Draw* a simple schematic of a non-inverting op amp (you can use lecture notes), which will include two external resistors. On your schematic, please indicate all relevant pins (inputs, output, bias, etc.) and label them according to the pin-out scheme shown in Figure 1.

d. On your schematic, indicate where you would hook up your load – e.g. speaker or headphones.

e. Using spec sheet of 741, find the maximum current that can be delivered by the op amp. If the output voltage has a maximum value of 10V, what constraints are there on R_L, the resistance of the load? That is, what are the maximum and minimum values of R_L?

3. Theoretical Overview:

As you heard in lectures, the Op Amp is an active element and needs to be powered in order to operate. When solving Op Amp circuits, we often omit these bias connections but it is ALWAYS understood that the power is supplied to the Op Amp (via pins 4 and 7 in the case of LM 741). REMEMBER: the Op Amp will not work without the power supplied to it! You will use power supplies (Agilent E3631A) at your workbench to deliver voltages of both positive and negative polarity. To achieve this, you will use ± 25 V output:

- Positive bias voltage will be provided between "+" and "COM" ports: hook up "+" terminal to $+V_{cc}$ pin (pin 7) of the Op Amp. To set the positive bias properly, push "+25 V" button and set the voltage to +10 V.
- Negative bias voltage will be provided between "-" and "COM" ports: hook up "-" terminal to $-V_{cc}$ pin (pin 4) of the Op Amp. To set the negative bias properly, push "-25 V" button and set the voltage to -10 V.
- Finally, **make sure** that you connect "COM" to the ground node in your circuit. To simplify things, you can use one of the "blue" lines on the board to create a 'ground node'. Later in the lab, you'll have to connect one terminal of the function generator to this node, and one to the op-amp input, in order to use the amplifier.

As a final reminder, before we do something useful, remember that the output voltage (V_{out}) of the Op Amp (pin 6) can have values in the range $-V_{cc} < V_{out} < +V_{cc}$ only!

4. Comparator – An Op Amp Without Feedback

Let's see what an Op Amp does if we simply apply a voltage between its input terminals, and DO NOT use any negative feedback. To figure this out, we will use a pulse generator (sometimes called function generator, or arbitrary waveform generator) to provide input signals to the Op Amp and an oscilloscope to monitor both input and output voltages of the Op Amp.

- Connect the positive terminal of the pulse generator (red wire) to the non-inverting input of the Op Amp (pin 3).
- Connect the negative terminal of the pulse generator (black wire) to the ground (GND). Remember, the GND node is one where "COM" from power supply is

connected to.

- Connect the inverting input (pin 2) of the Op Amp to GND as well.
- Set up the pulse generator so that it produces a sine wave with frequency 1 kHz and peak-to-peak signal of 2 V ($V_{pp} = 2V$).

Now let's use the ***oscilloscope*** to see what is actually going on with our circuit. To do so, hook up Channel 1 of the oscilloscope in parallel with the input voltage of the Op Amp and Channel 2 in parallel with the output voltage of the Op Amp. Obtain both traces on the screen of the scope.[1] Study the signals obtained on the scope and answer following questions:

a. What can you say about the shapes of the input and output signal?

b. What happens to the output signal if you switch your input from sine-wave to saw-tooth/ramp wave on your function generator? Can you explain the results you've gotten?

c. Based on your observations write a few sentences on the function that the open-loop Op Amp is performing on the input signal.

5. Amplifier – An Op Amp With Feedback

In the previous section we saw that the Op Amp without any feedback can provide an output signal that looks very different from the input signal. This clearly is not desirable if one wants to achieve a high-fidelity (Hi-Fi) audio amplifier or guitar amp, for example. To fix this, as you know, we can use negative feedback.

a. Realize non-inverting amplifier using the schematic that you came up with in your pre-lab. Pick the resistor values so that the gain of your amplifier is in the range of 10-50 (or you can go to 100 if you wish ☺). For example, you can choose the resistance of the smaller resistor to be around 1 kΩ. What should the value of the other resistor be to achieve a gain of let's say 50?

   Note: if you wish to make a more fancy circuit, use a 100 kΩ potentiometer (that is, a variable resistor - remember this from earlier labs?) instead of one or even two resistors in your circuit. This will allow you to achieve tunable gain.

   Make sure that you still have $+V_{cc}$ and $-V_{cc}$ biases hooked up, as well as pulse generator (as the source), and oscilloscope to monitor the signals. This is the same as in the previous section.

b. Select the frequency of the sine-wave signal to be 1 kHz and its amplitude 50 mV (peak to peak). The offset should be zero. Display the input and output signals of your amplifier circuit on the oscilloscope.

c. Is your amplifier behaving correctly? That is, is the input signal simply an amplifier replica of the input?

[1] To do this properly, make sure that you are using "DC coupling" on the scope: you can do this by pushing first the "CH 1 MENU" button, and then the soft key associated with the "Coupling" option on the screen until "DC" shows up. Do the same for CH2. Also, please select CH1 as the trigger source ("TRIG MENU") for triggering the oscilloscope. Ask your TF about triggering and its meaning.

d. What is the gain of your amplifier based on your experimental data[2]? How does this value correspond to the calculated gain based on the measured values of the resistors used?

6. Non-idealities and Limitations of Op Amps

Frequency limitations:

First, let's see how 'fast' our amplifier is, and if it is has any frequency-related limitations – that is if it works better (or perhaps the same) at low or high frequencies of the input signal. To do so, start increasing the frequency of the input signal in increments of 1 kHz (using the dial on the pulse generator) and observe the output signal. How high can you crank up the input frequency and still have an output signal that is an amplified replica of the input signal? What does the signal look like for 20 kHz and 40 kHz inputs? Would this circuit be a good audio amplifier?

Output voltage limitations:

Let's go back to our 1 kHz signal frequency and see what other non-idealities our circuit has. Start increasing the amplitude of the input signal and observe the output on the oscilloscope. What happens to the output signal? Why?

Output current (power) limitations:

Let's go back to a 50 mV input signal. How big is your output voltage?

a. Now hook up small speaker as a load. Check the output signal on the scope. How large is the output voltage now? Is the output still an amplified replica of the input signal? Why yes or no? Can you hear the sound coming out of the speaker?

b. To understand what is going on, let's calculate how much current your speaker would like to "draw" from the Op Amp. Find out the resistance of the speaker (you can measure it or read it on its back). Now, using this value and the maximum amplitude of the output voltage (determined by biases), calculate the maximum current that your speaker would 'like' to draw from the Op Amp. What value did you get? Can the Op Amp supply that much current (remember your prelab ☺)???

The problem you encountered above is that the speaker we are using has a very low resistance. Ohm's Law can lead us to conclude that our poor op-amp has to output a lot of current to maintain the high output voltages it is producing, something the 741 isn't very good at doing. Thus, the signal gets distorted, something that ideally doesn't happen in a typical audio amplifier. This is similar to trying to start a car with an AA battery — it just doesn't work too well!

To help resolve this problem, there are several things one could do. One solution is to achieve a better match to the amplifier: instead of using a speaker with low resistance, we can use speakers that have a higher resistance (e.g. 150 Ω) or a pair of high-resistance headphones. You can try this and see what happens.

c. Using the higher-resistance speaker and/or headphones repeat the measurement from

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[2] Make sure that the gain setting on your oscilloscope probe is 1X and that it matches the setting on the scope: The "probe" should display the value "1X"

6.a. Any difference?

Note: if your amplifier has large gain (~100) you may want to try using even smaller input amplitude to get nice non-distorted output signal (~20 mV for example).

Now that we've understood the basics of the op-amp, let's amplify something interesting – an audio signal. Replace the pulse generator wires at the input of your amplifier with the wires coming from the audio cable that is plugged either into your portable music player or lab computer. Play some music… Can you hear the sound? Play with the gain control (if you used potentiometer…), too, and check if you can achieve variable gain.

Most likely, this will not sound very spectacular since, as we mentioned above, the LM 741 cannot provide enough current to drive even a small speaker, let alone the big massive speakers that you would use at your dorm party. In fact, it turns out that LM 741 can deliver fraction of 1 W of power…. And that is not a lot….

So what do we do about this? Well, if you are up for some additional challenge(s), please try section Sections 7 and/or 8.

7. OPTIONAL: Two-stage amplifier with transistor

To overcome current limitations of our 741, we will add current amplifier at its output using a transistor as shown in Figure 2.

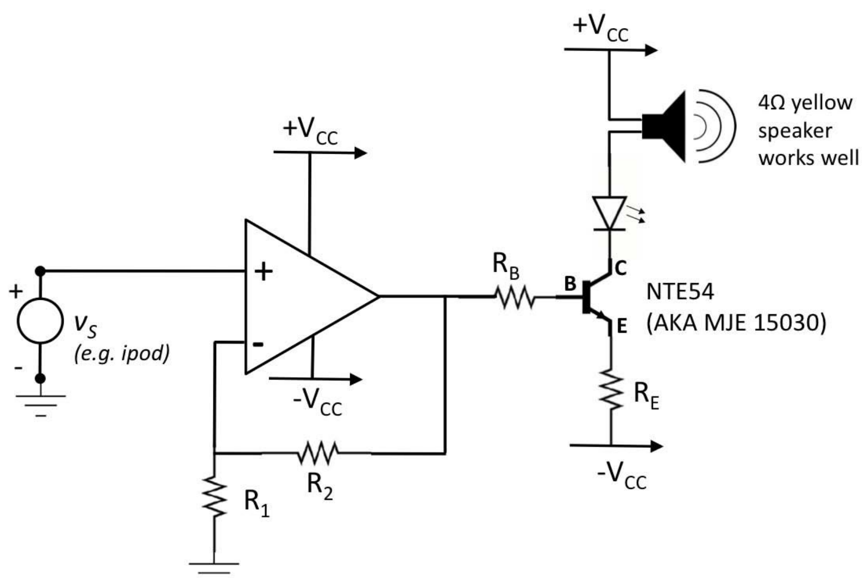

Figure 2. Two stage amplifier: Op Amp with power-transistor added to its output. Note that you can use any speaker you wish (does not have to be 4 Ω one). Notice that the speaker is hooked up to $+V_{cc}$ and R_E to $-V_{cc}$ (NOT to ground!).

We have not yet discussed transistors, but the basic idea is that it will take the small current from the Op Amp, amplify it and send it straight to the speaker. (Note that, for added fun, we have also included an LED that will now be blinking in beat with music :).) In this way, by combining the Op Amp with a power transistor, you can amplify both voltage and current, which means a lot of power!

The transistor that we will use is called NTE54 (also labeled MJE15030). Suggested values for additional resistors are $R_B \approx 1\,k\Omega$, $R_E \approx 200\,\Omega$. $V_{cc} \approx 10\,V$ and $-V_{cc} \approx -10\,V$. The resistor, R_E is important as it determines the current through the transistor, and through the speaker (and LED). Basically, the voltage across R_E will track the output voltage of the Op Amp, and via Ohm's Law, set the current through R_E. This current flow through the "emitter" of the transistor (E terminal) and is also known as the emitter current. It turns out that in a transistor, the emitter current is almost exactly the same as the current going through the "collector" terminal (C). The collector current in our circuit is the same as the current flowing through LED and speaker.

8. OPTIONAL: 3 Watt audio amplifier that you can take home :)

In this part we will use a serious audio amp circuit, called LM384, instead of LM741. LM384 is basically an Op Amp similar to the 741, but it has an integrated negative feedback that is pre-wired to have a fixed gain of 50, and more importantly has an output power stage that can put out quite a bit of power -3 Watts to be specific!

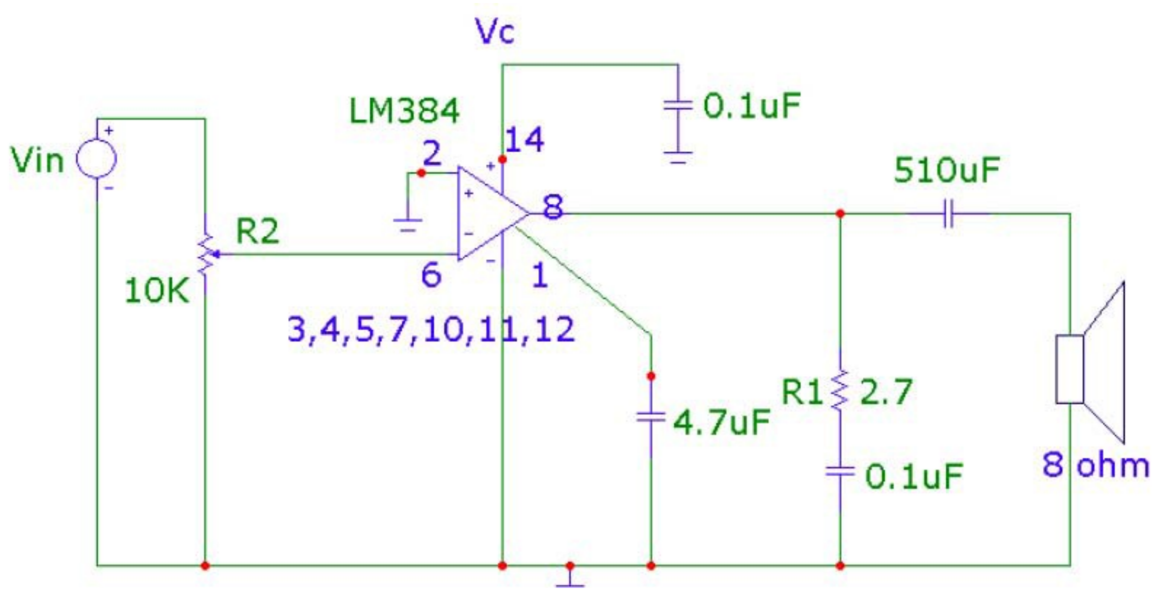

Figure 3. Fancy audio amplifier with LM384 integrated circuit.

Obtain the printed circuit board (PCB) from your TF and collect all the components needed to put together the circuit shown in Figure 3. There will be some resistors, capacitors, etc. Discuss with your TF the role that each of the components plays in the circuit (especially the capacitors). For example, the 510 μF capacitor is a so-called DC-block (or high-pass filter) that has the sole purpose of removing the DC bias signal from the output speaker.

Solder up the circuit! Pay special attention when soldering electrolytic capacitors! Also, please make sure that you DO NOT solder up the LM384 circuit directly, but instead solder the chip-carrier. You can then insert the LM384 chip into that carrier. This ensures that you do not melt the circuit when soldering :).

Once the circuit is ready, hook up the audio signal to its input and different types of speakers at its output (does not have to be 8 Ω). Be smart about choosing the speaker based on its power rating and resistance. Enjoy the music! :)

And…. if you've gotten THIS far, you are truly amazing and destined for EE-hood! As a reward, you get to keep your amplifier!