PRELAB FOR FIRST OP-AMP LAB

Electrical circuits are CIRCUITS. Every element must have at least two wires and the wiring must eventually come back to the power supply. Circuit diagrams are symbolic pictures of circuits. Typical circuit diagram might look like this:

In general, all branches of the circuit must eventually come back to the negative side of the power source. The negative side of the power supply is often called ground ("G"). Common symbols for circuit diagrams include:

- **Resistor**
- **Battery (or power supply)**
- **Capacitor**
- **Inductor**
- **Oscillating voltage source**
- **Operational Amplifier**

A In complex circuits, putting in all the ground wires only makes the diagram harder to read. So a new symbol is introduced.

- **Ground**
Using this symbol, the example diagram above could be redrawn as follows.

In general, it is assumed that all the grounds are hooked together. If you want to change the input supply, you can leave it out. In fact, it is usually just assumed that the input voltage is measured with respect to ground, so the simplified diagram becomes:

Some circuit elements have several inputs and require their own power supply (all of our op-amp circuits, for example). A common op amp circuit is:

(pins 1, 5, and 8 on the op-amp are not used by us).
All op amps require power, so there is really no need to show it. Using the ground symbol and leaving out the power supplies to the op amp will simplify things considerably. In addition, if we then assume that the input and output are both measured with respect to ground, we get a very simple, easy to read diagram:

Compare this to the first diagram of this circuit. The advantages of the simplified diagram are obvious. However, YOU are responsible for knowing that the op amp requires power and that the input and output devices must be hooked to ground. In fact, the input device, the output device, the power supplies to the op amp, and the side of the op amp must ALL BE HOOKED TOGETHER, TO A COMMON GROUND.

In practice, to build a circuit, it is most important to understand how to unsimplify a schematic diagram. Try it: unsimplify this diagram.
RESISTOR COLOR CODES

Many times we use resistors with particular values to tune the properties of our circuits. The resistor values are often not shown as numbers but instead using a color code consisting of four colored bands.

<table>
<thead>
<tr>
<th>Significant figures</th>
<th>Color</th>
<th>Multiplier (Ohm)</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>black</td>
<td>1</td>
<td>silver • 10%</td>
</tr>
<tr>
<td>1</td>
<td>brown</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>red</td>
<td>100</td>
<td>gold • 5%</td>
</tr>
<tr>
<td>3</td>
<td>orange</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>yellow</td>
<td>10,000</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>green</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>blue</td>
<td>1,000,000</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>violet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>gray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>white</td>
<td>gold</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>silver</td>
<td>0.01</td>
</tr>
</tbody>
</table>

For example, a 20 kOhm resistor with 5% tolerance would be red-black-orange-gold (20 x 1000 Ohm ±5%).

Try it: what is the color code for the following resistors (all 5% tolerance)?

a: 10 Ohm   b. 100 Ohm   c. 1 kOhm   d. 10 kOhm   e. 220 kOhm   f. 450 Ohm

What is the value of a resistor that has bands colored orange-red-green-silver?
PREFACE TO OP-AMP LAB #1

Circuit Connections in the Laboratory

From now on you will construct electrical circuits and test them. The usual way of constructing circuits would be to solder each electrical connection to assure good electrical contact. Since each circuit has to be changed quite often during the lab period and also be dismantled at the end of the lab, soldering is impractical.

Thus you will be provided a compact “bread-board” box which allows quick and good electrical connections without soldering. A copy of this breadboard box is shown on the next page. This box is made of aluminum and contains a variety of plug-in sockets with which circuit connections can be made. On the periphery of the box are “banana-plug” and “BNC-type” sockets, which have wire sockets connected to them. The central region of the box consists of two floating socket boards each of which contains a matrix of small sockets which are connected to each other in various ways.

With this useful box, you will be able to construct electrical circuits simply by inserting the terminal wires of the components into the appropriate sockets. By the way, this is the manner in which many circuit designers “mock-up” their circuits before connecting them permanently.
OP-AMP LAB #1

I. Introduction
Amplifiers play an important part at all stages of sound recording and reproduction and in PA systems. It probably will never be necessary for any of you to design and build your own amplifier; however, it is helpful to understand some of the limitations of amplifiers, and how high quality in one area can be traded for high quality in another.

In the next few labs you will start with a working amplifier. You will then modify the amplifier in various ways which will change its capabilities.

The major purpose of this first lab is to introduce you to an integrated-circuit (IC) amplifier and the equipment needed to get it to work and to study it; “bread-boards”, power supplies, resistors, capacitors, and, of course, the oscilloscope.

You will also learn some of the characteristics of amplifiers and how they are measured.

II. The 741 Op-Amp
You will be using an “operational amplifier”, or op-amp, which comes in an 8-lead IC package. The op-amp diagram is:

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1: not used              8: not used
2: inverting input      7: +V supply
3: noninverting input   6: output
4: -V supply            5: not used
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+V and –V are the places where the power supply is connected to the op-amp, and need to be at +15V and –15V respectively. Pins 1, 5, and 8 are not used.

Use the oscilloscope to check the voltages coming out of the power supply on the breadboard.

\[ V_+ = \text{__________} \quad V_- = \text{__________} \]

Your instructor will show you how to mount your chip on the bread-board and how to power it. You can also look at the sample set-up for help.
The first circuit we want to try is:

Use the 2002 Function Generator to put a 1000 Hz “sine wave” with a 1 Volt amplitude into the inverting input of the op-amp. Use the dual trace feature of the oscilloscope to display both the unamplified and the amplified signals on the screen. **What is the gain (the ratio between the output voltage and the input voltage)?**

Increase the amplitude of the input to find **what is the maximum peak-to-peak voltage output** the op-amp can produce without clipping (clipping is when the peaks and/or valleys of the signal are “clipped-off” because they have surpassed the maximum voltage which can be produced by the amplifier)?

**What is the phase of the output compared to the input?**

Observe the effect of changing the DC offset on the function generator (this is produced by pulling out the DC OFFSET knob and turning it). **What is the largest positive voltage the op-amp can produce? The most negative voltage?**

Congratulations! You have made your first amplifier. This amplifier employs "negative feedback" (notice that the output is connected back to the input), which reduces the gain of the amplifier, but greatly reduces distortion and gives a flat response from dc to well above 1 kHz. To see why negative feedback is a good idea, we next measure the amplifier response without it.
III. Pure, Unadulterated Op-amp

Op amps without negative feedback (operating "open loop") have a very high gain for low frequency signals. To see this, we need an input signal of no more than 10 mV. In order to produce a clean voltage signal this small from your 2002 Function Generator you will need to make a "voltage divider" (on the bread board, to one side of your amplifier):

![Voltage Divider Diagram]

The amplitude of the voltage difference across the small resistor, R1, is $V_1 = V \cdot \frac{R1}{R1+R2}$, where V is the voltage amplitude from the function generator. Since $R1=10$ Ohm here and $R2$ is $10$ kOhm, the amplitude $V1$ is about 1000 times smaller than V (which is less than 20 Volts peak-to-peak).

The complete circuit will now be the same as your first circuit, but with the "feedback" resistor (10 k?) removed and the input coming from the "output" of your voltage divider instead of directly from the function generator. Note that the output signal is saturated (either clipping or pegged at its maximum output) for almost any frequency, even with very small or zero input voltage. That is, without feedback there is so much gain that the amplifier saturates. For higher frequencies (100 kHz range), you may see that there is an unsaturated signal if you play with the DC OFFSET setting of the generator (pull the knob out and turn it).

IV. Frequency Response with Negative Feedback

Your op-amp, as you have noticed, has an extremely large gain (which falls off rapidly with increasing frequency). You can trade away some of the low frequency gain for a flat frequency response by using negative feedback.

Recall that the original signal was fed into the inverting input of the op-amp. You can feed some of the inverted output back into the input. When the output is very large, the (negative) feedback is large. This kind of feedback decreases the gain the most at exactly those frequencies where the gain of the op-amp is largest. The result is to make the gain constant over a wide range of frequencies. A graph of the gain as a function of frequency is a straight line, and so is called a “flat” response.

Of course, the more negative feedback you use, the less gain you get. The amount of feedback (and gain) is controlled by the ratio of the sizes of the input and feedback resistors. In part two, the feedback resistor was 10 k?, which gave a gain of 10. Here, we will use a 100 k? feedback resistor, which will have more gain:
Build this amplifier (just put a 100 kΩ resistor back connecting pins 2 and 6 of the op amp), measure its gain at several frequencies. Remember that it is not important to take a lot of data in the region where the gain is constant (that is, where the response is flat).

Table: 741 Op-amp gain versus frequency

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>input amplitude (volts)</th>
<th>output amplitude (volts)</th>
<th>gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
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<td></td>
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<tr>
<td>500</td>
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<tr>
<td>1000</td>
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<td>2000</td>
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<tr>
<td>5000</td>
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<td></td>
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<tr>
<td>10k</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20k</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50k</td>
<td></td>
<td></td>
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</tbody>
</table>

Plot your results on the 3 cycle • 3 cycle paper. For what range of frequencies do you get a gain close to 100?

Where does the gain "roll off" (drop to 71% of its low frequency value)?

By setting the scope mode to ALTernate and the INTernal TRIGger to CH1 you can observe the phase relationship between the input and the output. Why is this op-amp/resistor configuration called an “inverting amplifier”? 
V. Frequency response for high gain with negative feedback

Put a 1 MΩ resistor as the feedback resistor (replacing the 100 kΩ resistor).

Measure the amplitude of the small signal (point A) directly with the scope from 100 Hz to 50 kHz. Use a signal of 20 mVpp. You may need to play around with the DC offset knob on the generator to get the output to stay between the • and • 15 V limits of the op-amp.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>input amplitude (milivolts)</th>
<th>output amplitude (volts)</th>
<th>gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 Hz</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>200</td>
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<td>500</td>
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<td>10k</td>
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<td>20k</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>50k</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Plot your results on the same 3 cycle • 3 cycle log graph paper which you used before.

What is the low frequency gain for the 1 MΩ feedback resistor?

Where does the gain roll off?

Compare the frequency response for low gain and high gain.
VI. Positive Feedback

In the last circuit, some of the output was run into the inverting input (negative feedback) to reduce the gain of the amplifier. It is also possible to send some of the output to the non-inverting input, resulting in positive feedback. This feedback is often sent through circuit elements which are more resistive to some frequencies than others. In this case a combination of a capacitor and an inductor will be used. A variable resistor will allow you to control the amount of positive feedback; the less resistance, the more feedback.

Turn off the function generator and bread board and construct the following circuit:

![Circuit diagram]

Turn each of the lowest 4 dials on the variable resistor (1 kOhm, 100 Ohm, 10 Ohm, 1 Ohm) to 10 and set the remaining dial to 0. This gives a total resistance of 11,110 Ohms.

Push in the ATT 30 dB button on the function generator and set the frequency multiplier to 10k. Now turn on the function generator. Use the frequency dial to sweep through various frequencies while you watch the output on the scope. Is the response still completely flat?

Turn the 1 kOhm knob on the variable resistor down to 9. Now the output should show a definite frequency preference. Continue turning down the resistance by turning the 100 Ohm knob to 9. It may be necessary to reduce the amplitude to keep the output from clipping near the resonant frequency.
Keep turning down the variable resistor and sweeping through frequencies. **To the nearest Ohm, what is the lowest resistance you can use before the amplifier start oscillating on its own, independent of the output?**

Turn down the resistance another Ohm or two and turn off the function generator. The amplifier should oscillate on its own. You have built a fixed frequency oscillator. **By carefully measuring the period on the scope, determine the frequency of this oscillation and compare it to the natural resonant frequency of the inductor-capacitor (LC) combination we are using:**

\[
fo = \frac{1}{2\pi(LC)^{1/2}}.
\]