Massachusetts Institute of Technology
Department of Electrical Engineering and Computer Science

Lab 2: Intermediate circuits and nonlinear components

6.117 Introduction to Electrical Engineering Lab Skills (IAP 2020)

Introduction

In this lab, you will become familiar with two common methods of **amplification**. Amplification is the process of increasing the level of a signal, typically by multiplying by a constant. This constant is referred to as **gain**. The first method of amplification you will encounter in this lab is the **operational amplifier**. Operational amplifiers, or "op-amps," are used to perform mathematical operations such as addition, subtraction, and amplification.

While op-amps are versatile, they often generate significant **noise** components that can negatively impact the quality of the output signal. For applications where low noise is required, such as audio amplification, **discrete amplifiers** are often used. Discrete amplifiers use **transistors** to provide voltage and current gain while preserving signal quality better than op-amp amplifiers.

Throughout this lab, the following conventions will be used for wires in breadboard diagrams:

Table 1: Breadboard wire color conventions

Black	Ground (GND)
Orange	+15V power supply
Red	-15V power supply
Yellow	Inputs and outputs
Blue	Other signals

Unless otherwise specified, the negative or ground connection of all instruments should be connected to the breadboard ground. This includes the "LO" terminal of the DMM, the ground lead of the oscilloscope and the ground lead of the function generator.

Exercise 1: Op-amps

In this exercise, you will become familiar with the use of op-amps. The LM741 is one of the oldest and most widely used op-amps. Released in the late 1960s, the LM741 is a **bipolar** device, as it is implemented using only BJTs. The pins of the LM741 are assigned as shown in Figure 1.

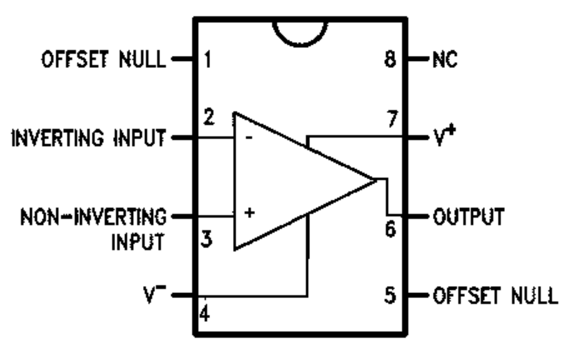

Figure 1: LM741 pinout diagram

It is important to note the Pin 1 marking on the LM741. The small "U" shape on the IC indicates the side on which Pin 1 is located. This convention is followed for all through-hole ICs.

Non-inverting amplifier

The simplest application of an op-amp is an amplifier. Generally, there are two types of op-amp amplifier circuits: **non-inverting** and **inverting** amplifiers. The polarity of the output of a non-inverting amplifier is the same as the polarity (sign) of the input, while the output of an inverting amplifier is opposite in polarity to its input. In this exercise, you will construct a non-inverting amplifier.

The non-inverting amplifier is useful for amplifying or **buffering** small signals. Occasionally, a circuit incapable of sourcing high currents may be required to drive an input that demands a high current. A buffer provides a voltage gain of 1 and is capable of sourcing high currents. The schematic of a non-inverting amplifier is shown in Figure 2.

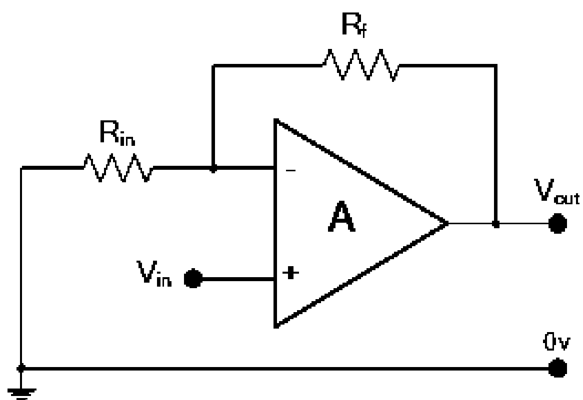

Figure 2: Non-inverting amplifier schematic

In deriving the gain of the non-inverting amplifier, we assume that the open-loop gain[1] of the op-amp (*A*) is infinite. In terms of the *feedback resistor* R_F and the *input resistor* R_{IN}, the gain of the non-inverting amplifier (A_V) is given by:

$$A_V = 1 + \frac{R_F}{R_{IN}}$$

A buffer may be created using this circuit by setting R_F to 0. R_{IN} is omitted in the buffer configuration. The breadboard layout for this exercise is shown in Figure 3.

Complete this exercise according to the steps below:

1. Construct the non-inverting amplifier as shown in the breadboard layout, making sure the LM741 is inserted **in the correct orientation** (with Pin 1 facing to the left).
2. Set the function generator to output a 1 kHz sine wave at 100 mV peak-to-peak (V_{pp}). Connect the output of the function generator to the non-inverting input of the LM741 (pin 3).
3. Using the oscilloscope, measure the output of the function generator. Notice that the amplitude of the signal is extremely low. Depending on your oscilloscope, the signal may be “blurred” by noise.
4. Adjust the vertical scale of the oscilloscope to 2V per division.
5. Measure the output of the op-amp. What is the ratio of the amplitude of the output to the input? Is this what you expected?
6. Set the function generator to output a square wave at the same amplitude as before, but increase the frequency to 5 kHz.
7. Observe the shape of the signal at the output compared to the input. Why does the amplifier behave this way?

[1] The **open-loop gain** of an op-amp is the voltage gain of the op-amp when no external components are connected. This value is typically at least 100,000.

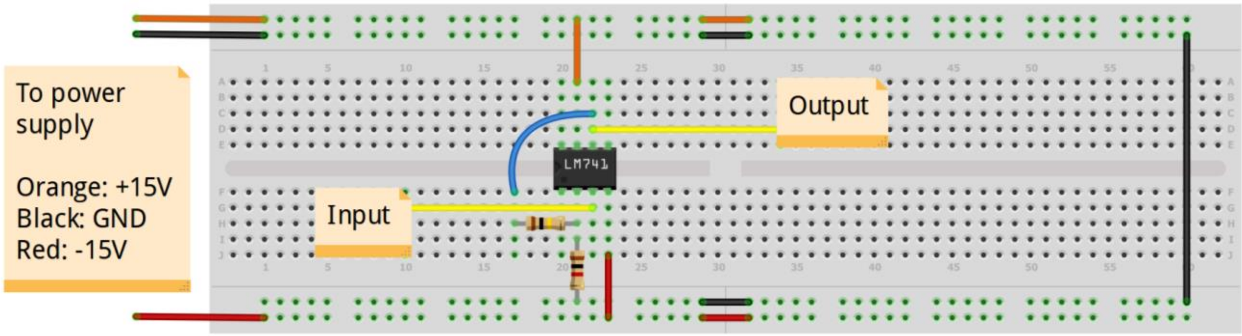

Figure 3: Non-inverting amplifier breadboard layout

Filters

In this exercise, you will construct a Sallen-Key low-pass filter (LPF). The Sallen-Key filter was developed by R.P. Sallen and E.L. Key of the MIT Lincoln Laboratory in 1955. You will compare the behavior of this circuit with the RC LPF you built at the end of Lab 1. The breadboard layout for this exercise is shown in Figure 4.

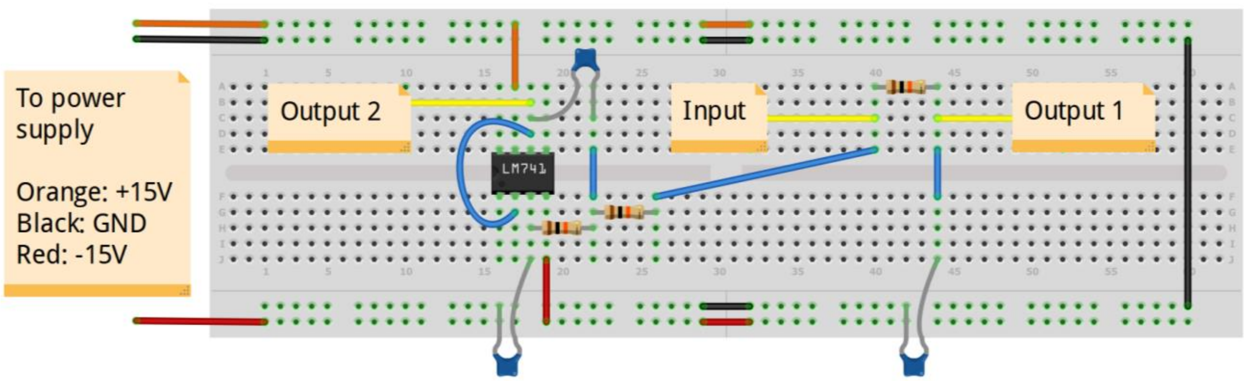

Figure 4: Filters breadboard layout

All resistors used in this exercise are 10kΩ, and all capacitors used in this exercise are 10nF (marked as “103”). Both can be found on the table near the entrance of the lab space. Complete this exercise according to the steps below:

1. Construct the simple LPF from last lab with R = 10kΩ and C = 10nF. This circuit is located on the right side of the breadboard layout above. The schematic for this circuit is shown in Figure 5.

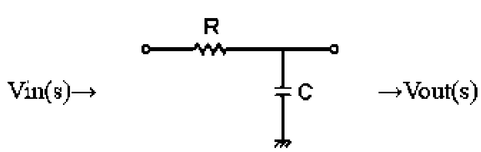

Figure 5: RC low-pass filter (LPF)

2. Construct the Sallen-Key LPF, with R1 = R2 = 10kΩ and C1 = C2 = 10nF. This circuit is located on the left side of the breadboard layout above. The schematic for this circuit is shown in Figure 6. By convention, **the power pins are hidden** in op-amp circuits. This does not mean they should not be connected; you must still connect the power pins as shown in Figure 4.

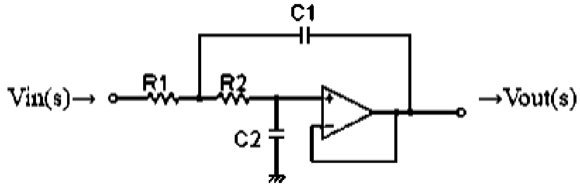

Figure 6: Sallen-Key low-pass filter

3. Set the function generator to output a 500 Hz sine wave at $1V_{pp}$. Connect the output of the function generator to the input of the circuit (located near the middle of the breadboard diagram).
4. Set the scope to 200 mV per division and attach one probe to Output 1 and one probe to Output 2. The signal at both points should be approximately the same.
5. Slowly increase the frequency of the function generator to 5 kHz. Which one of the outputs decreases in amplitude more quickly?
6. Increase the frequency to 10 kHz. What do you observe?

The Sallen-Key filter is a "second-order" filter, which means that it rejects frequencies over the cutoff frequency (f_c) more sharply than the simple RC LPF. The cutoff frequency for the RC LPF, $f_c(RC)$, and the cutoff frequency for the Sallen-Key LPF, $f_c(SK)$, are shown below:

$$f_c(RC) = \frac{1}{2\pi RC}$$

$$\mathrm{f_c(SK)} = \frac{1}{2\pi\sqrt{\mathrm{R_1 R_2 C_1 C_2}}}$$

As constructed here, $f_c \approx 1.6$ kHz for both filters. Since 5 kHz is well in excess of the cutoff frequency, we expect that the output of the Sallen-Key filter will be lower in amplitude than the output of the RC filter.

Exercise 2: LED driver

As discussed in lecture, the bipolar junction transistor (BJT) is a current-driven amplifier. In this exercise, we will use a BJT to blink a light-emitting diode (LED). An LED is a type of diode that emits light when forward biased. LEDs are identical to other diodes with the exception that they typically have a higher forward voltage (~2.0V compared to 0.7V). The breadboard layout for this exercise is shown in Figure 7.

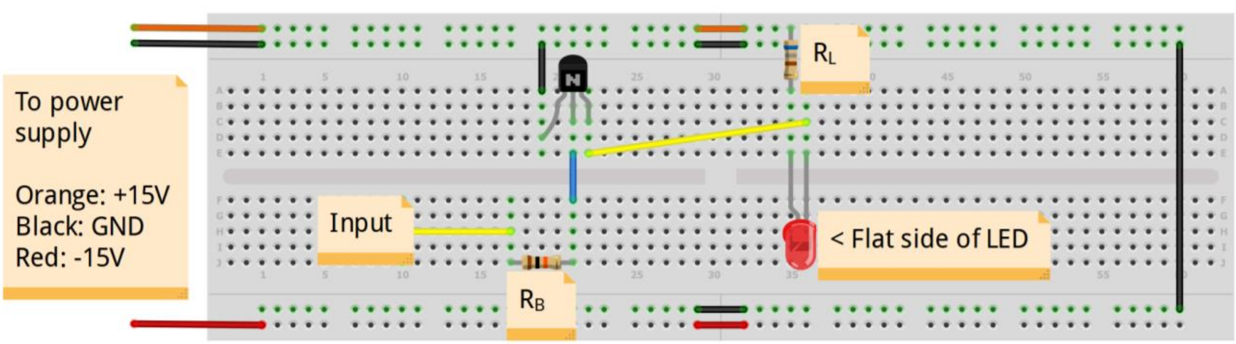

Figure 7: LED driver breadboard layout

When constructing this circuit, you must pay attention to the orientation of the LED. The flange near the leads of a through-hole LED is commonly flattened on one side and rounded on the other side. The **flat side corresponds to the cathode** of the LED, which is connected to the collector of the BJT in this circuit.

Complete this exercise according to the steps below:

1. Construct the LED driver. The BJT used in this exercise is the **2N3904**, which is available on the table near the entrance of the lab space.
2. Set the function generator to output a 1 Hz (not kHz) square wave at $5V_{pp}$. Adjust the **DC offset** of the output to 2.5V.[2]
3. Construct the circuit shown in the breadboard diagram with R_B = 10kΩ and R_L = 680Ω.
4. Connect the function generator and activate the output. Using the DC voltage measurement function of the DMM, measure the voltage across R_B.[3]
5. Using Ohm's Law, calculate the current through the resistor when the function generator output is on (at the peak of the square wave).
6. Using the DC voltage measurement function of the DMM, measure the voltage across R_L. Using Ohm's Law, calculate the current through the resistor when the function generator output is on (at the peak of the square wave).
7. Notice that the current through R_L is much higher than the current through R_B. Why?
8. Now change R_B to 100k. What happens to the brightness of the LED? Why?

Exercise 3: Audio amplifier

In this exercise, you will construct a 3-transistor Class AB audio amplifier. As discussed in lecture, there are three main classes of BJT amplifiers: Class A, Class B and Class AB. The characteristics of the three classes are summarized below:

Table 2: Summary of amplifier characteristics

Characteristic	Class A	Class B	Class AB
Signal quality	High	Low	High
Efficiency	Low	High	Medium
Conduction angle	360º	180º	180º – 360º
Output impedance	High	Medium	Low

The breadboard layout for this exercise is shown in Figure 8.

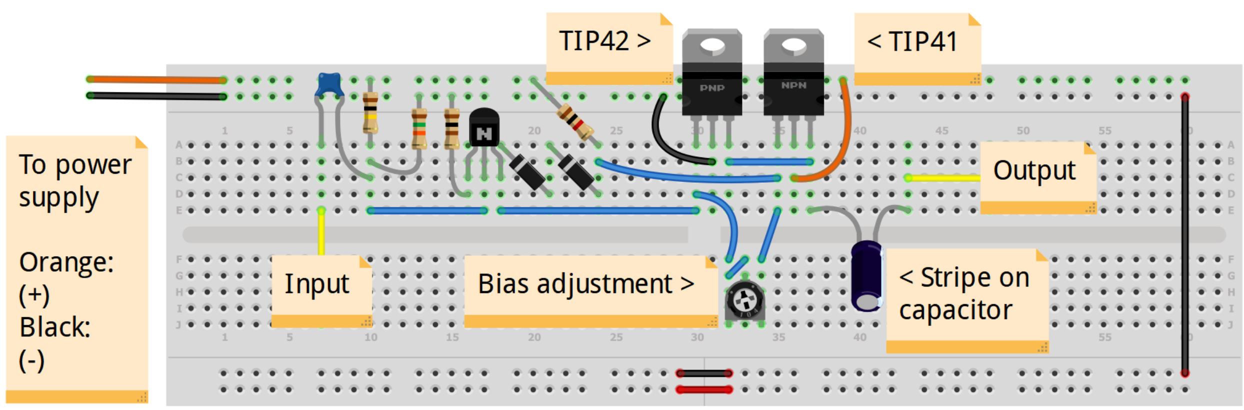

Figure 8: Audio amplifier breadboard layout

Figure 9 shows the schematic diagram of the amplifier used in this exercise, along with annotations describing the purpose of each component in the amplifier.

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[2] This results in a waveform that alternates between 0V and 5V every 500 milliseconds (ms).
[3] If this measurement is difficult to make, set the function generator to output a lower frequency.

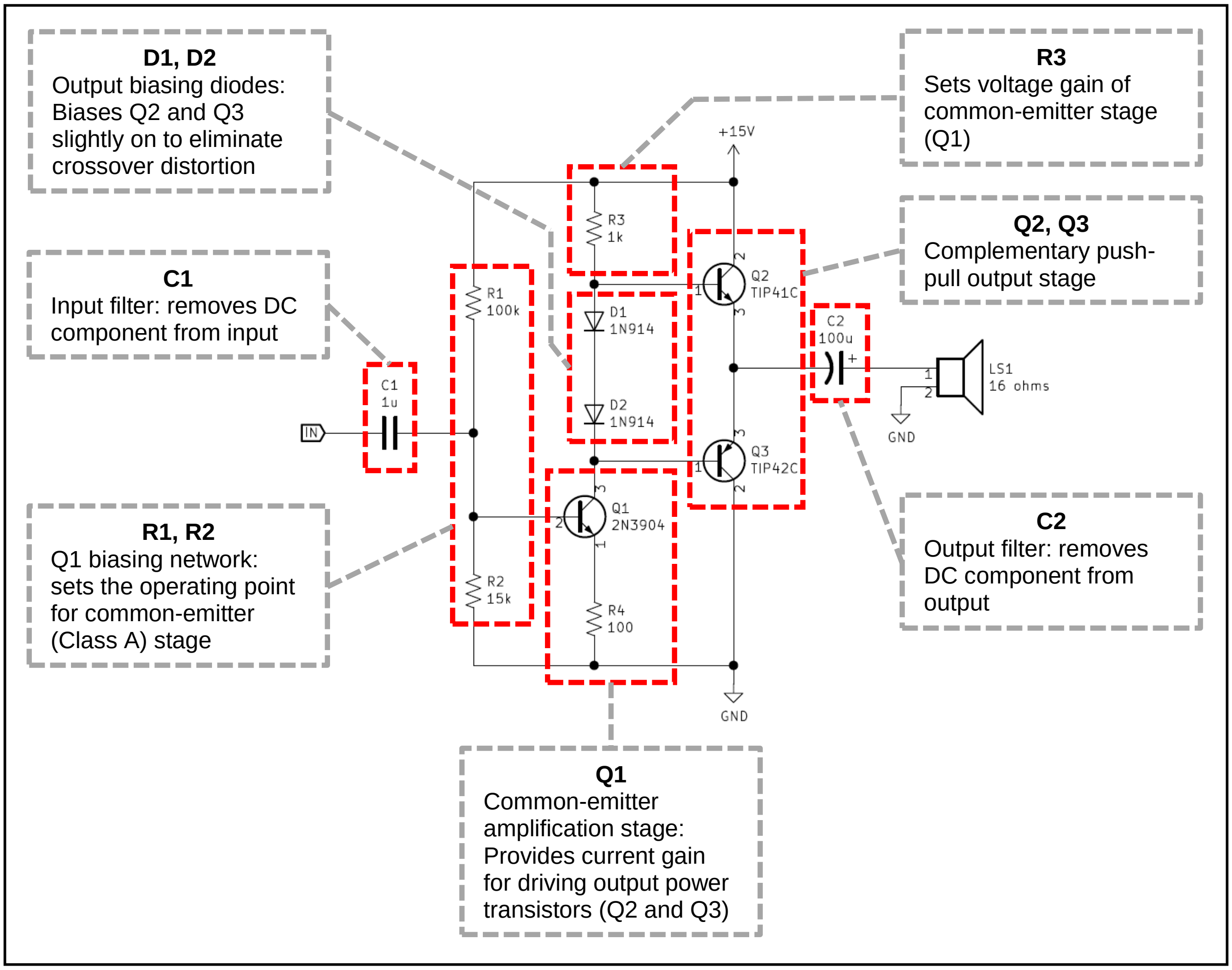

Figure 9: Audio amplifier circuit and analysis

The amplifier consists of two stages: a Class A **preamplifier** and a Class AB **power amplifier**. The preamplifier provides the current gain necessary to drive the output transistors (Q2 and Q3). In general, high-power transistors like the TIP41 and TIP42 used in this exercise have low current gain (“beta” or β). As a result, a higher current is needed to drive them than is needed to drive **small-signal** transistors like the 2N3904. Most mobile devices are not capable of providing such a high current, so a preamplifier is necessary to provide current amplification.

Additionally, the preamplifier provides a small voltage gain (on the order of 10). Importantly, this voltage gain cannot always be realized in practice. For example, if the input to the amplifier is $10V_{pp}$, the preamplifier will try to produce an output voltage of $100V_{pp}$. However, the supply voltage used in this exercise is only 12V. This causes a type of distortion known as **clipping**, as discussed in lecture.

Complete this exercise according to the steps below:

1. Obtain the required parts to build the amplifier. Resistors are located in the supply cabinets outside the lab space, and all other components are located on the table near the entrance of the lab. You will need the following:

Table 3: Parts required for audio amplifier

Component	Values needed
Resistors	100kΩ, 15kΩ, 1kΩ, 100Ω
Capacitors	1uF, 100uF
Diodes	1N914 (x2)
Transistors	2N3904, TIP41, TIP42
Potentiometers	1kΩ

2. Construct the circuit, ensuring you follow all of the following instructions:
    a. Do not connect the breadboard to its built-in power supply (±15V). This experiment will only use the **variable power supply**.
    b. Make sure to **connect all power rails with jumpers** near the center of the breadboard if your breadboard requires it. Note that the bottom power rail is not used in this experiment.
    c. **Make sure you insert the power transistors in correct positions**. The TIP41 and TIP42 look very similar, but switching them around or using two of either part will ruin them.
    d. **Align the pins of the power transistors** with the holes of the breadboard **before** inserting them. Simply forcing the pins into the breadboard will bend the breadboard contacts and make it difficult to insert other components in the future.
    e. **The metal tabs on the power transistors must not touch**. They are internally connected to the collector pins of the power transistors, and touching them will short-circuit the variable power supply.
    f. **Pay attention to the stripes on the biasing diodes** (D1 and D2). The amplifier will not operate correctly if they are reversed.
3. Ask a member of the course staff to check your circuit. **Do not power on the amplifier**.

In the next steps we will adjust the bias of the output stage. As discussed in lecture, crossover distortion results when neither of the transistors in a Class B output stage is turned on. For a sinusoidal input, this results in a waveform similar to the one shown in Figure 10.

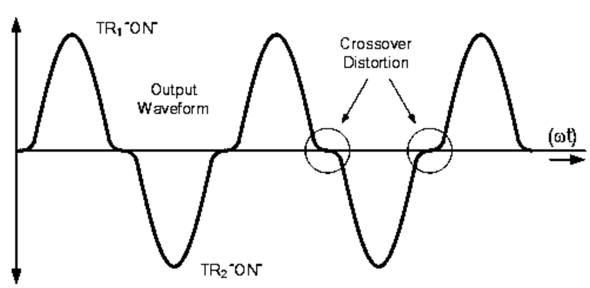

Figure 10: Crossover distortion

In this circuit, biasing is accomplished with two rectifier diodes, D1 and D2. The thermal characteristics of these diodes are similar to the thermal characteristics of the output transistors, so their forward voltage will closely track the base-emitter voltage of the output transistors as a function of temperature.

However, as the biasing diodes are small-signal devices, their forward voltage will be slightly higher than the base-emitter voltage of the output transistors for a given current. To correct this difference, a 1kΩ potentiometer is used as a variable resistor in parallel with both diodes. As the resistance is decreased, the biasing voltage of the output stage decreases proportionally. Adjust the bias point according to the steps below:

4. Set the function generator to output a 1 kHz sine wave at 100mV_{pp}. With the output turned off, connect the positive lead to the input terminal of the amplifier and the negative lead to the breadboard ground.
5. Connect the oscilloscope to the output of the amplifier.
6. With the variable power supply **turned off**, set the voltage control on the variable power supply to 0 (counterclockwise) and set the current control to about 25% of its maximum value. Turn on the variable power supply and set its voltage to 12V.
7. Adjust the biasing potentiometer until the current reading on the power supply is at a minimum. **You must do this adjustment quickly** (within 30 seconds) **or else the output transistors will get dangerously hot**.
8. Activate the output of the function generator and measure the output of the amplifier with the oscilloscope.
9. Slowly adjust the potentiometer until the crossover distortion appears to be gone. **Stop as soon as the crossover is gone**.
10. Turn off the output of the function generator. Obtain a speaker from the back of the lab, connect its positive terminal to the output of the amplifier and connect its negative terminal to the breadboard ground.
11. Turn on the output of the function generator. Is the sound what you expect?
12. *(optional)* Obtain a 3.5mm cable from the back of the lab. Use it to play music through your amplifier.