Pre-lab 9: Operational Amplifiers, Part I

Today we enter the promised land: the operational amplifier ("op-amp") is the Swiss Army Knife of analog electronics; it will change your life. In this first day, we'll see what an op-amp is, and what it can do. For entertainment, and for education, we'll see how you can make a very good amplifier and a clever cure for the push-pull crossover distortion we saw in the last lab. In later classes, we'll also see some limitations of these devices — stability, bandwidth, and deviations from perfection.

The op-amp

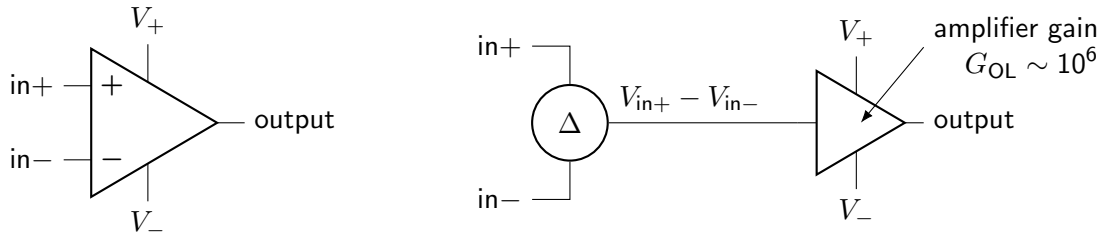


Figure 1: Op-amp symbol (left) and what it does (right).

It's simple: an op-amp (Fig. 1) is just a device with a pair of inputs (labeled "in+" and "in−"), an output (labeled "output"), and a pair of power supply connections (V_+ and V_-). Its job is to amplify the voltage difference between the inputs by a very large amplification factor G_{OL} (called the *open-loop gain*).

$$V_{out} = G_{OL}(V_{in+} - V_{in-}). \tag{1}$$

A typical op-amp runs from a pair of power supply voltages such as $\pm 15\,V$, and has an open-loop gain of 10^5–10^7(!). It also has nice characteristics such as very high input impedance (no current flows in the inputs) and very low output impedance; that is, it presents a benign load to the signals it receives, and it outputs a signal able to drive even rather unkind (low impedance) loads.

The "open-loop" voltage gain G_{OL} is way too large to be of use as an amplifier without some moderation. That moderation takes the form of *negative feedback*, a deliberate reduction of the gain by way of the circuit you wrap around the op-amp. Think of an op-amp as fodder for feedback; this mysterious statement will become less mysterious presently.

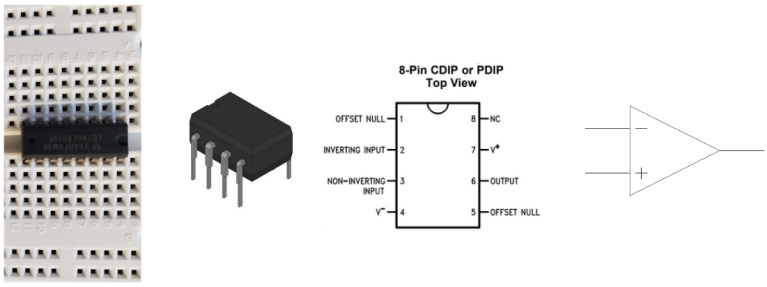
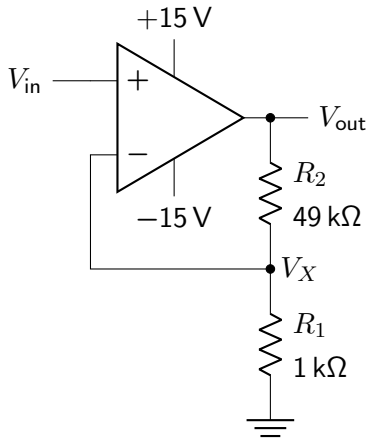


Figure 2: From left to right: 1) A dual-in-line (DIP) integrated circuit plugged into the breadboard so that each of its pins is on a different column. 2) The shape of the op-amps we'll work with today. 3) The pinout of the op-amps we will be using.

Basic op-amp circuits

It's easiest to learn about these things by looking at real circuits. Here goes...

Non-inverting amplifier



$$G_{\text{CL}} = \frac{V_{\text{out}}}{V_{\text{in}}} = 1 + \frac{R_2}{R_1}$$

Figure 3: Non-inverting amplifier.

Look at Figure 3. This is called a "non-inverting voltage amplifier." Let's pretend we are an op-amp, and our job is to amplify the voltage difference at the inputs by a million. Put another way, the only way the output can be at a reasonable voltage (i.e., between the power-supply voltages, here $\pm 15\,\text{V}$) is for the inputs to be within a few *micro*volts of each other. For all practical purposes we can say that they have to be at the *same* voltage. How can that be achieved?

We then note that the inverting input (the one with a $-$ sign) is taken from a voltage divider made of R_2 and R_1, which divides the output voltage V_{out} by

$$V_X = V_{\text{out}} \frac{R_1}{R_1 + R_2}. \tag{2}$$

If this must be (almost) the same as V_{in} then the output voltage must satisfy

$$V_{\text{out}} = V_{\text{in}} \frac{R_1 + R_2}{R_1} = V_{\text{in}} \left(1 + \frac{R_2}{R_1}\right). \tag{3}$$

For our circuit in Figure 3, the voltage gain $V_{\text{out}}/V_{\text{in}}$ is

$$G_{\text{CL}} = \frac{V_{\text{out}}}{V_{\text{in}}} = 1 + \frac{R_2}{R_1} = 50, \tag{4}$$

where "CL" denotes the "closed-loop" gain. The "loop" is the connection that feeds the output back to the inverting input.

This seemed too easy! But that's what's nice about op-amps — you don't have to worry about what's inside the op-amp, because the enormous open-loop gain swallows all ills.

The "Golden Rules"

AoE3 4.1.3

Let's take a pause before looking at the next circuit to state some simple principles of circuits with op-amps. Here are the "golden rules" of op-amp circuits with negative feedback:

First, the op-amp voltage gain is so high that a fraction of a millivolt between the input terminals will swing the output over its full range, so we ignore that small voltage and state

> **Golden Rule I** The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.

Second, op-amps draw very little input current (about 50 pA for the inexpensive JFET-input LF411, and often less than a picoamp for MOSFET-input types); we round this off, stating

> **Golden Rule II** The inputs draw no current.

One important note of explanation: Golden rule I doesn't mean that the op-amp actually changes the voltage at its *inputs*. It can't do that. (How could it, and be consistent with golden rule II?) What it does is "look" at its input terminals and swing its output terminal around so that the external feedback network brings the input differential to zero (if possible).

Inverting amplifier

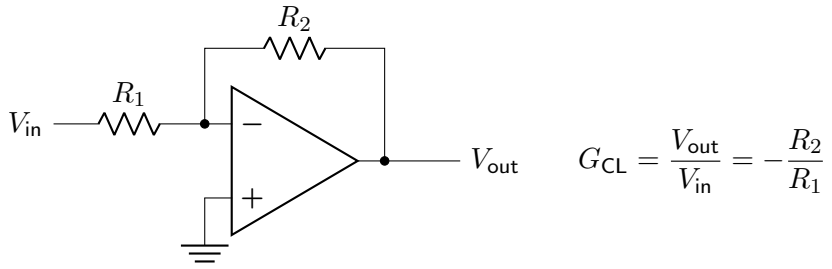


Figure 4: The inverting amplifier.

Figure 4 shows an "inverting amplifier." (Engineers aren't highly creative with nomenclature: an inverting amplifier is an amplifer whose output is inverted, relative to its input.) As with the non-inverting amplifier, the analysis is simple:

(i) The non-inverting input (marked "+") is at ground, so Golden Rule I implies that the inverting input is also at ground.

(ii) This means that (a) the voltage across R_1 is V_{in} and (b) the voltage across R_2 is V_{out}.

(iii) Because of Golden Rule II, the current flowing through R_1 and R_2 must be the same, and can be expressed as

$$I = \frac{V_{\text{in}}}{R_1} = \frac{V_{\text{out}}}{R_2}.$$

The closed-loop voltage gain is therefore

$$G_{\text{CL}} = \frac{V_{\text{out}}}{V_{\text{in}}} = -\frac{R_2}{R_1}. \tag{5}$$

Pre-lab 9 Hand-in

Name: _____

Pre-lab 9.1 What are the input impedances of (a) the non-inverting amplifier of Figure 3, and (b) the inverting amplifier of Figure 4?

Hint: Consider how much current I_{in} flows into the input of each circuit for a given value of V_{in}. The input impedance is the ratio $Z_{\text{in}} = V_{\text{in}}/I_{\text{in}}$. You should assume the op-amp is ideal, and the Golden Rules hold.

(a) non-inverting amplifier The input is connected directly to the non-inverting input of the op-amp, which does not draw any current (Golden Rule II). That means $I_{\text{in}} = 0$ for any value of V_{in}. The input impedance is therefore infinity.

(b) inverting amplifier The input is connected through R_1 to the inverting input of the op-amp, which, by Golden Rule I, is at 0 V. The input current is therefore

$$I_{\text{in}} = \frac{V_{\text{in}}}{R_1}$$

for the input voltage V_{in}. The input impedance is therefore simply R_1.

From the last lab:

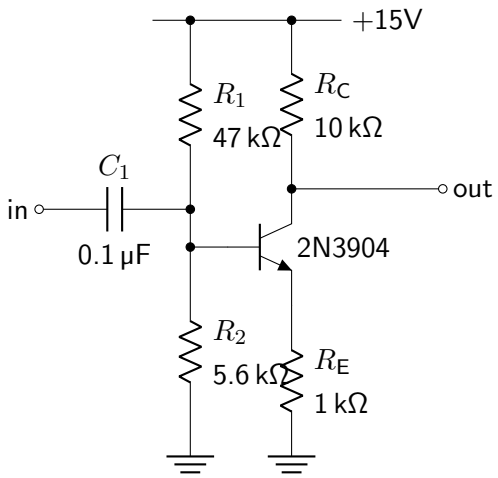


Figure 5: The common-emitter amplifier from Lab 6.

Pre-lab 9.2 When you use an amplifier like the one you built in Lab 6 (schematic in Figure 6), you need to know what input impedance it presents to the signal source that is driving it, to make sure the signal is not significantly reduced. This problem helps you figure that out.

The input part of the circuit in Figure 6 is made of

- a capacitor C_1,
- a voltage divider made of R_1 and R_2,
- an emitter follower made of 2N3904.

We will figure out the impedance of each, and combine them.

(a) Recall from Lecture 6 that the impedance looking into the base of the emitter follower is βR_E, where $\beta \approx 100$. What is the input impedance of this emitter follower?

R_E is 1 kΩ, so the input impedance is 100 kΩ.

(b) What is the impedance of the voltage divider alone (i.e., ignore the transistor)? We are interested in the impedance at the connection between R_1 and R_2, which is the "output" of the voltage divider.

We found in Lab 2 that the Thévenin resistance of the output of a voltage divider was the two resistors in parallel. Thus, the input impedance of this divider is $R_1 \cdot R_2/(R_1 + R_2) \approx 5\,\mathrm{k\Omega}$.

(c) What is the combined impedance of the emitter follower and the voltage divider. (Are they in series or in parallel?)

The two are in parallel, yielding a total input impedance of about 4.76 kΩ.

(d) Now you can figure out what the effect of C_1 in front of what you have found in (c). What is the corner frequency (−3 dB frequency) of this amplifier input?

It is just an RC high-pass filter. The corner frequency is

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi \cdot 4.76\,\mathrm{k\Omega} \cdot 0.1\,\mu\mathrm{F}} = 334\,\mathrm{Hz}.$$