7 Op-Amp Basics

The operational amplifier is one of the most useful and important components of analog electronics. They are widely used in popular electronics. Their primary limitation is that they are not especially fast: The typical performance degrades rapidly for frequencies greater than about 1 MHz, although some models are designed specifically to handle higher frequencies.

The primary use of op-amps in amplifier and related circuits is closely connected to the concept of negative feedback. Feedback represents a vast and interesting topic in itself. We will discuss it in rudimentary terms a bit later. However, it is possible to get a feeling for the two primary types of amplifier circuits, inverting and non-inverting, by simply postulating a few simple rules (the "golden rules"). We will start in this way, and then go back to understand their origin in terms of feedback.

7.1 The Golden Rules

The op-amp is in essence a differential amplifer of the type we discussed in Section 5.7 with the refinements we discussed (current source load, follower output stage), plus more, all nicely debugged, characterized, and packaged for use. Examples are the 741 and 411 models which we use in lab. These two differ most significantly in that the 411 uses JFET transistors at the inputs in order to achieve a very large input impedance ($Z_{\text{in}} \sim 10^9\ \Omega$), whereas the 741 is an all-bipolar design ($Z_{\text{in}} \sim 10^6\ \Omega$).

The other important fact about op-amps is that their *open-loop gain* is huge. This is the gain that would be measured from a configuration like Fig. 38, in which there is no feedback loop from output back to input. A typical open-loop voltage gain is $\sim 10^4$–10^5. By using negative feedback, we throw most of that away! We will soon discuss why, however, this might actually be a smart thing to do.

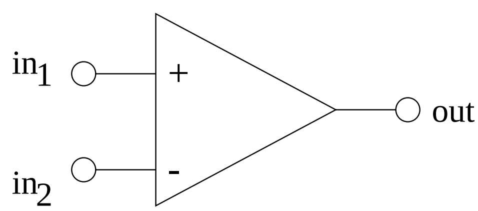

Figure 38: Operational amplifier.

The golden rules are idealizations of op-amp behavior, but are nevertheless very useful for describing overall performance. They are applicable whenever op-amps are configured with negative feedback, as in the two amplifier circuits discussed below. These rules consist of the following two statements:

1. The voltage difference between the inputs, $V_+ - V_-$, is zero.
   (Negative feedback will ensure that this is the case.)

2. The inputs draw no current.
   (This is true in the approximation that the Z_{in} of the op-amp is much larger than any other current path available to the inputs.)

When we assume ideal op-amp behavior, it means that we consider the golden rules to be exact. We now use these rules to analyze the two most common op-amp configurations.

7.2 Inverting Amplifier

The inverting amplifier configuration is shown in Fig. 39. It is "inverting" because our signal input comes to the "−" input, and therefore has the opposite sign to the output. The negative feedback is provided by the resistor R_2 connecting output to input.

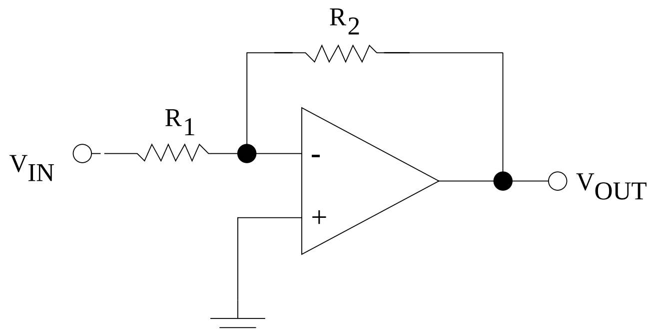

Figure 39: Inverting amplifier configuration.

We can use our rules to analyze this circuit. Since input + is connected to ground, then by rule 1, input − is also at ground. For this reason, the input − is said to be at *virtual ground*. Therefore, the voltage drop across R_1 is $v_{\text{in}} - v_- = v_{\text{in}}$, and the voltage drop across R_2 is $v_{\text{out}} - v_- = v_{\text{out}}$. So, applying Kirchoff's first law to the node at input −, we have, using golden rule 2:

$$i_- = 0 = i_{\text{in}} + i_{\text{out}} = v_{\text{in}}/R_1 + v_{\text{out}}/R_2$$

or

$$G = v_{\text{out}}/v_{\text{in}} = -R_2/R_1 \qquad (34)$$

The input impedance, as always, is the impedance to ground for an input signal. Since the − input is at (virtual) ground, then the input impedance is simply R_1:

$$Z_{\text{in}} = R_1 \qquad (35)$$

The output impedance is very small ($< 1\ \Omega$), and we will discuss this again soon.

7.3 Non-inverting Amplifier

This configuration is given in Fig. 40. Again, its basic properties are easy to analyze in terms of the golden rules.

$$v_{\text{in}} = v_+ = v_- = v_{\text{out}} \left[\frac{R_1}{R_1 + R_2} \right]$$

where the last expression is from our voltage divider result. Therefore, rearranging gives

$$G = v_{\text{out}}/v_{\text{in}} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1} \qquad (36)$$

The input impedance in this case is given by the intrinsic op-amp input impedance. As mentioned above, this is very large, and is typically in the following range:

$$Z_{\mathrm{in}} \sim 10^8 \ \text{ to } \ 10^{12}\ \Omega \tag{37}$$

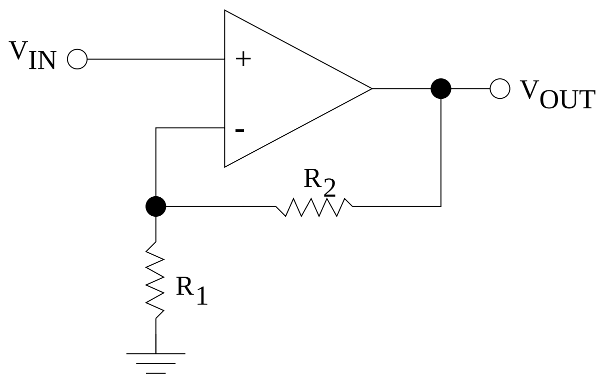

Figure 40: Non-inverting amplifier configuration.

7.4 Departures from Ideal

It is no surprise that the golden rules are not exact. On the other hand, they generally describe most, if not all, observed op-amp behavior. Here are some departures from ideal performance.

- *Offset voltage*, V_{OS}. Recall that the input of the op-amp is a differential pair. If the two transistors are not perfectly matched, an offset will show up as a non-zero DC offset at the output. As you found in Lab 4, this can be zeroed externally. This offset adjustment amounts to changing the ratio of currents coming from the emitters of the two input transistors.

- *Bias current*, I_{bias}. The transistor inputs actually do draw some current, regardless of golden rule 2. Those which use bipolar input transistors (*e.g.* the 741) draw more current than those which use FETs (*e.g.* the 411). The bias current is defined to be the average of the currents of the two inputs.

- *Offset current*, I_{OS}. This is the difference between the input bias currents. Each bias current, after passing through an input resitive network, will effectively offer a voltage to the op-amp input. Therefore, an offset of the two currents will show up as a voltage offset at the output.

Perhaps the best way to beat these efects, if they are a problem for a particular application, is to choose op-amps which have good specifications. For example, I_{OS} can be a problem for bi-polar designs, in which case choosing a design with FET inputs will usually solve the problem. However, if one has to deal with this, it is good to know what to do. Figure 41 shows how this might be accomplished. Without the 10 kΩ resistors, this represents a non-inverting amplifier with voltage gain of $1 + (10^5/10^2) \approx 1000$. The modified design in

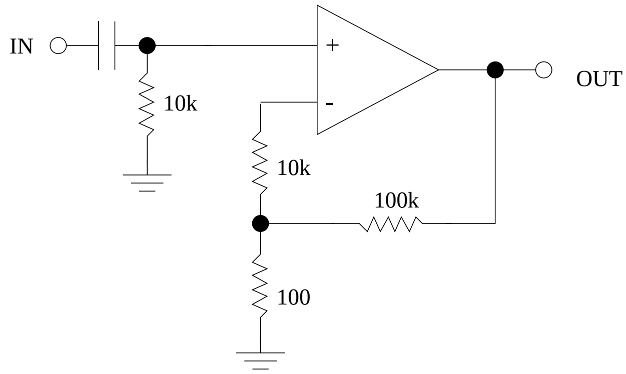

Figure 41: Non-inverting amplifier designed to minimize effect of $I_{\rm OS}$.

the figure gives a DC path from ground to the op-amp inputs which are aproximately equal in resistance (10 kΩ), while maintaining the same gain.

Similarly, the inverting amplifier configuration can be modified to mitigate offset currents. In this case one would put a resistance from the $-$ input to ground which is balanced by the R_1 and R_2 in parallel (see Fig. 39).

It is important to note that, just as we found for transistor circuits, one shpould always *provide a DC path to ground for op-amp inputs.* Otherwise, charge will build up on the effective capacitance of the inputs and the large gain will convert this voltage ($= Q/C$) into a large and uncontrolled output voltage offset.

However, our modified designs to fight $I_{\rm OS}$ have made our op-amp designs worse in a general sense. For the non-inverting design, we have turned the very large input impedance into a not very spectacular 10 kΩ. In the inverting case, we have made the virtual ground into an approximation. One way around this, if one is concerned only with AC signals, is to place a capacitor in the feedback loop. For the non-inverting amplifier, this would go in series with the resistor R_1 to ground. Therefore, as stated before, it is best, where important, to simply choose better op-amps!