Section E2: Ideal Op-Amps

As mentioned in the introductory comments, the op-amp is our first practical example of an integrated circuit. As ICs go, common op-amps are generally on the smallish side, with several tens of elements on the chip. For our purposes in this section, we will consider the op-amp to be a “black box” with input and output terminals and treat it similarly to basic circuit elements (R, L, C) in the creation of more complicated circuits. Don’t worry though – next semester we will get into the op-amp innards and study the function and contribution of the individual electronic devices that make up the IC.

The symbol for the operational amplifier is given in Figure 2.2a of your text and is reproduced to the right. In this figure,

\[ +V \] indicates the positive dc supply
\[ -V \] indicates the negative dc supply
\[ v_o \] is the op-amp output, defined with respect to signal ground
\[ v_- \] is the inverting input, defined with respect to signal ground
\[ v_+ \] is the non-inverting input, defined with respect to signal ground

As shown above, both positive and negative supplies power an op-amp. This allows the output voltage to swing both above and below ground potential while providing a bound on the output voltage (since \(+V\) and \(-V\) are the most positive and negative voltages in the circuit). Note that it is common practice (and one we will follow) to omit the power supply connections from op-amp circuits. Even though the supplies are not explicitly shown in the schematic drawings, it is understood that the sources are present – in practice, the op-amp won’t turn on and do anything unless they are!

The equivalent circuit for the op-amp is Figure 2.2b of your text and is given to the right. In this figure, the **differential input voltage** is defined as the difference between the voltage of the non-inverting and inverting terminals, or \( v_d = v_+ - v_- \). The output side of the op-amp circuit is related to the input side through the dependent voltage source \( Gv_d \), where \( G \) is the **open loop gain** of the op-amp.
amp. The input and output resistances of the op-amp are shown in the figure as \( R_{\text{in}} \) and \( R_{\text{o}} \) respectively. Keep in mind that here, as in our discussions with BJTs, we are showing the circuit components as pure resistances but they are probably complex impedances.

In this section, we are also restricting ourselves to the case of the ideal op-amp. **Ideal op-amps** are characterized by:

- **Infinite gain** \((G \to \infty)\)
- **Infinite input impedance** \((R_{\text{in}} \to \infty)\)
- **Zero output impedance** \((R_{\text{o}} = 0)\)

Combining the two parts of Figure 2.2 and including the information above, a composite representation for an ideal op amp is presented to the right. Notice that the dc supplies are understood but not explicitly shown, \( R_{\text{in}} \) has been replaced by an open circuit, \( R_{\text{o}} \) by a short, and that the inverting input \((v_-)\), the non-inverting input \((v_+)\) and the output \((v_o)\) are implicitly referenced to signal ground. Therefore, for the ideal op amp (or looking at the strictly open loop case for any op-amp),

\[
v_o = Gv_d = G(v_+ - v_-). \quad \text{(Equation 2.8)}
\]

But, wait a minute...we said that the gain was infinite for an ideal op-amp. Rearranging Equation 2.8 and letting \( G \) go to infinity, we get

\[
v_d = v_+ - v_- = \frac{v_o}{G} \to 0 \text{ as } G \to \infty \quad \text{(Equations 2.9 & 2.10)}
\]

since \( v_o \) is limited by the dc supplies (+V and −V) and must be finite.

This result is actually very important and makes our life much easier in the design and analysis of op-amp circuits. Since \( v_+ - v_- = 0 \) for \( G \) very large (ideally infinite), the voltages at the two input terminals must be the same, or

\[
v_+ = v_- \quad \text{(Equation 2.11)}
\]
Also, since the input resistance is infinite, the current into each input terminal is zero, or
\[ i_+ = i_- = 0. \]

Before we get too far into this and (hopefully) realize what a wonderful thing the ideal op-amp is, I would like to reiterate a caution in your text. The model derived for the ideal op-amp is a very good approximation, even for practical devices, as long as they are operating in linear amplification mode. If the device is operating in a nonlinear mode (which happens quite frequently), all bets are off and these approximations are no longer valid. Also, we haven’t even started talking about frequency dependencies! The configuration shown in the figures above is known as open loop since there is no association between the output and the input. The more common configuration, especially for linear applications, is closed-loop with feedback. We’ve talked about this briefly before, but will get into it hot and heavy again next semester. Essentially the goal is the same, to remove the behavioral dependencies on device characteristics and make the output dependent only on external circuit elements.

OK – I just had to say that. Now let’s get into the method for analyzing op-amp circuits using the voltage and current relationships of the inverting and non-inverting terminals.

\textit{Ta-Da! It’s circuits all over again!}

\textbf{Procedure for analyzing any ideal op-amp circuit:}

Write the KCL equation at the inverting terminal, \( v_+ \), using \( i_-=0 \).
Write the KCL equation at the non-inverting terminal, \( v_+ \), using \( i_+=0 \).
Set \( v_-=v_+ \) and solve for the desired closed-loop gains (or resistor values or whatever the problem is asking for).

\textit{Pretty sweet, huh?}