1. Op-Amp Rules and Negative Feedback Rules

Here is an equivalent circuit of an op-amp (where we are assuming that \( V_{SS} = -V_{DD} \)) for reference:

(a) What are the currents flowing into the positive and negative terminals of the op-amp (i.e., what are \( I^+ \) and \( I^- \))? Based on this answer, what are some of the advantages of using an op-amp in your circuit designs?

**Answer:**

The \( u^+ \) and \( u^- \) terminals have no closed circuit connection between them, and therefore no current can flow into or out of them. This is very good because we can connect an op-amp to any other circuit, and the op-amp will not disturb that circuit in any way because it does not load the circuit (it is an open circuit).

(b) Suppose we add a resistor of value \( R_L \) between \( u_{out} \) and ground. What is the value of \( v_{out} \)? Does your answer depend on \( R_L \)? In other words, how does \( R_L \) affect \( Av_C \)? What are the implications of this with respect to using op-amps in circuit design?

**Answer:**

Notice that \( u_{out} \) is connected directly to a controlled/dependent voltage source, and therefore \( v_{out} \) will always have to be equal to \( Av_C \) regardless of what \( R_L \) is connected to the op-amp. This is very advantageous because it means that the output of the op-amp can be connected to any other circuit (except a voltage source), and we will always get the desired/expected voltage out of the op-amp.

For the rest of the problem, consider the following op-amp circuit in negative feedback:
(c) Assuming that this is an ideal op-amp, what is $v_{\text{out}}$?

**Answer:**
Recall for an ideal op-amp in negative feedback, we know from the negative feedback rule that $u^+ = u^-$. In this case, $u^- = v_{\text{out}} = u^+$.

(d) Draw the equivalent circuit for this op-amp and calculate $v_{\text{out}}$ in terms of $A$, $v_{\text{in}}$, and $R_L$ for the circuit in negative feedback. Does $v_{\text{out}}$ depend on $R_L$? What is $v_{\text{out}}$ in the limit as $A \to \infty$?

**Answer:**
Notice that the op-amp can be modeled as a voltage-controlled voltage source. Thus, we have the following equation:

$$v_{\text{out}} = A(v_{\text{in}} - v_{\text{out}})$$

$$v_{\text{out}} + Av_{\text{out}} = Av_{\text{in}}$$

$$v_{\text{out}} = v_{\text{in}} \frac{A}{1 + A}$$

Thus, as $A \to \infty$, $v_{\text{out}} \to v_{\text{in}}$. This is the same as what we get after applying the op-amp rule.

Notice that output voltage does not depend on $R$. Thus, this circuit acts like a voltage source that provides the same voltage read at $u^+$ without drawing any current from the terminal at $u^+$. This is why the circuit is often referred to as a “unity gain buffer,” “voltage follower,” or just “buffer.”
2. Comparators

For each of the circuits shown below, plot $V_{\text{out}}$ for $V_{\text{in}}$ ranging from $-10\,\text{V}$ to $10\,\text{V}$ for part (a) and from $0\,\text{V}$ to $10\,\text{V}$ for part (b).

(a)

![Comparator Circuit Diagram](image)

**Answer:**

When the positive terminal’s voltage, $V_+$, is greater than the negative terminal’s voltage, $V_-$, the value at the positive supply rail, $V_{\text{DD}}$, will be output. Likewise, if the negative terminal’s voltage, $V_-$, has a higher voltage then the value at the negative supply rail, $V_{\text{SS}}$, will be output. Since $V_-$ is just the output of a voltage divider with the source $V_{\text{in}} = V_+$, it will always have lower absolute value and same polarity as the positive terminal. Thus, the comparator’s output will depend only on the sign of the source $V_{\text{in}}$.

![Voltage Plot](image)
Answer:

\[ V_+ = \frac{2 \text{k}\Omega}{1 \text{k}\Omega + 2 \text{k}\Omega} V_{\text{in}} = \frac{2}{3} V_{\text{in}} \]

\[ V_- = 2 \text{V} \]

The comparator will output positive 5V when the voltage divider’s output \( V_+ > 2 \text{V} \) and thus when \( V_{\text{in}} > 3 \text{V} \). Otherwise, it will output -5V.