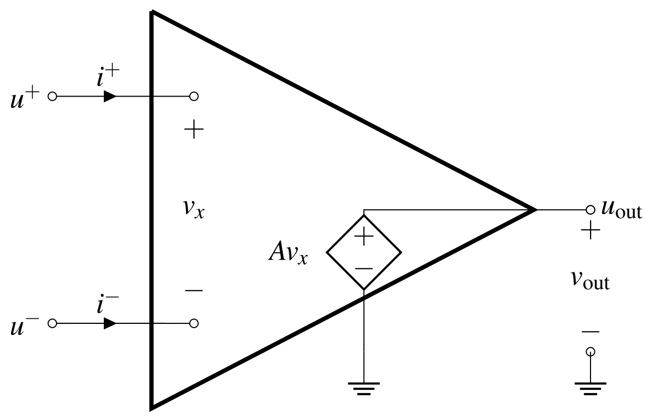
EECS 16A Designing Information Devices and Systems I
Fall 2022 Discussion 10B

1. Op-Amp 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:

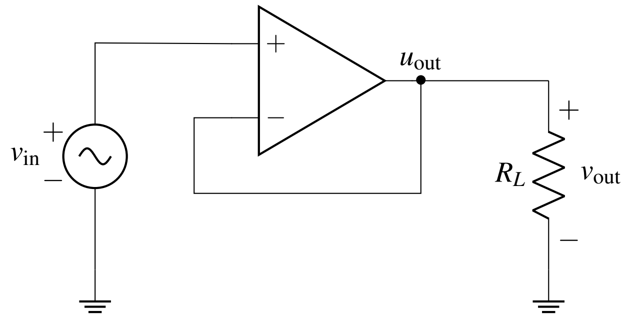
The u^+ and u^- terminals have no closed circuit connection between them, and therefore no current can flow into or out of them. This is very good because we can connect an op-amp to any other circuit, and the op-amp will not disturb that circuit in any way because it does not load the circuit (it is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



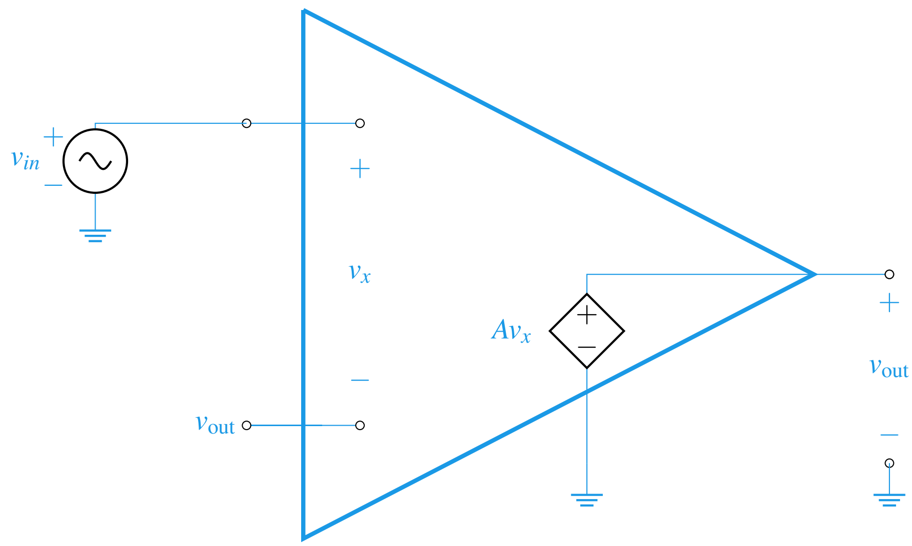
(c) Assuming that this is an ideal op-amp, what is v_{out}?

Answer:

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

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

$$
\begin{aligned}
v_{\text{out}} &= Av_x \\
v_{\text{out}} &= A \cdot (v_{in} - v_{\text{out}}) \\
v_{\text{out}} + Av_{\text{out}} &= Av_{in} \\
v_{\text{out}} &= v_{in} \frac{A}{1+A}
\end{aligned}
$$

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.

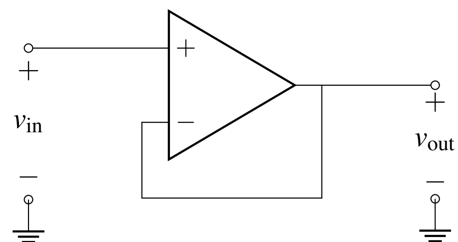
Notice that output voltage does not depend on R. Thus, this circuit acts like a voltage source that provides the same voltage read at u^+ without drawing any current from the terminal at u^+. This is why the circuit is often referred to as a "unity gain buffer," "voltage follower," or just "buffer."

2. Testing for Negative Feedback

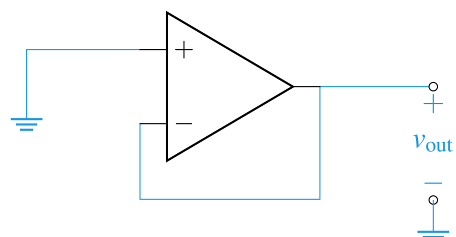
While it is tempting to say "if the feedback voltage is connected to the negative op-amp terminal, then we have negative feedback", this is not always true. Here is a two-step procedure for determining if a circuit is in negative feedback:

- **Step 1: Zero out all independent sources**, replacing voltage sources with wires and current sources with opens as we did in superposition. You do not need to zero out the voltage sources that serve as the power supplies to the op-amp, since they are not treated as signals and are not considered part of the op-amp.
- **Step 2: Wiggle the output and check the loop**. Assume that the output increases slightly. Check the direction of change of the feedback signal and the error signal from the circuit. Any change in the error signal will cause a new change in the output. This change is the feedback loop's response to the initial change.
  - If the error signal decreases, then the output must also decrease. This is the *opposite direction* we initially assumed, i.e. the loop is trying to correct for the change. So the circuit is in negative feedback.
  - If the error signal instead increased, then the output would also increase. This is the *same direction* we initially assume, i.e. the initial increase lead to further increase. We call this positive feedback.

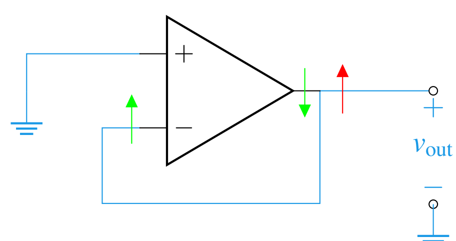
(a) Show that the voltage buffer circuit is in negative feedback. Note that here v_{in} is acting as a voltage source.



Answer: First, zero out all independent sources. For this problem, we just need to tie the input to ground.

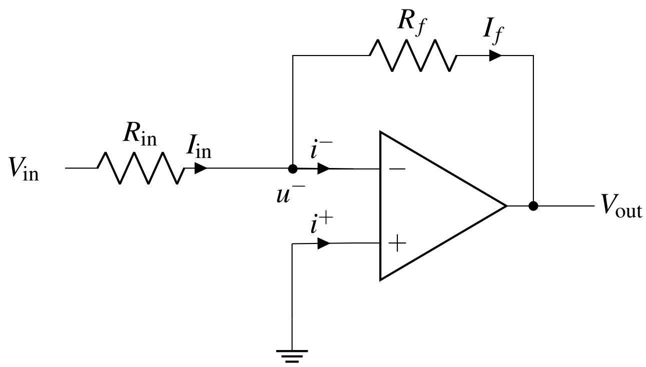


Next, wiggle the output and check the loop. Below, we label the initial change in the output in red and label subsequent changes in green:

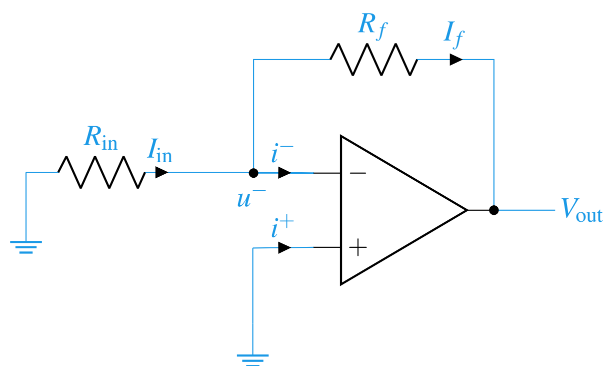


We suppose that the v_{out} increases. Output voltage v_{out} is connected to the negative terminal input u^- so u^- also increases. Our op-amp equation is $v_{\text{out}} = A \cdot (u^+ - u^-)$, so increasing u^- will cause v_{out} to decrease. This is the opposite of what initially happened, so we are in negative feedback.

(b) Show that the inverting amplifier circuit is in negative feedback.

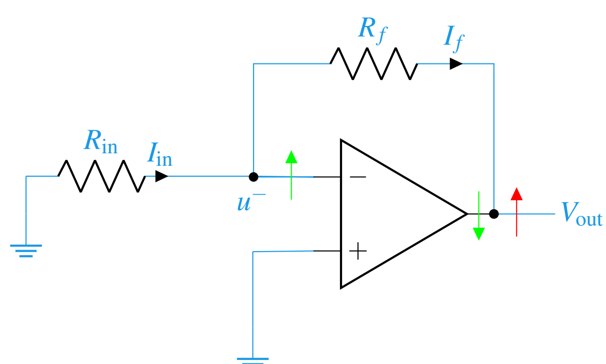


Answer: First, zero out all independent sources. For this problem, we just need to tie the input to ground.



Note that R_f and R_{in} now form a voltage divider.

Next, wiggle the output and check the loop. Below, we label the initial change in the output in red and label subsequent changes in green:



We suppose that the v_{out} increases. Output voltage v_{out} is connected to the negative terminal input u^- so u^- also increases. Our op-amp equation is $v_{\text{out}} = A \cdot (u^+ - u^-)$, so increasing u^- will cause v_{out} to decrease. This is the opposite of what initially happened, so we are in negative feedback.