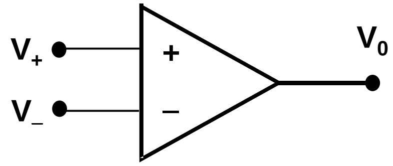
Lecture 9: Operational Amplifiers

Today, we will introduce our first **integrated circuit** element: the **operational amplifier.**



The operational amplifier, or op-amp, has three terminals*:

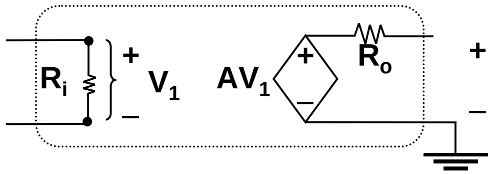
- V_+ is called the non-inverting input terminal.
- V_- is called the inverting input terminal.
- V_O is called the output terminal.

* There are actually more connections to the device that are not shown. The device connects to a power supply, which is needed for proper operation, as well as ground.

I-V Relationship

- The I-V relationship for the op-amp is complicated, since it has multiple terminals.
- The op-amp can be modeled using the following circuit:

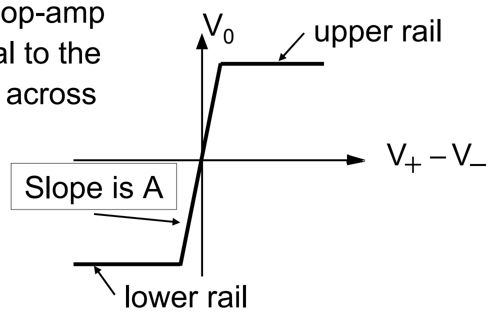
Circuit Model *in linear region*



- You can simply replace the op-amp symbol with the above circuit for analysis.
- However, the above model is only valid when V_O is within a certain range.

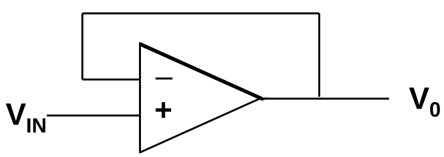
Rails and Saturation

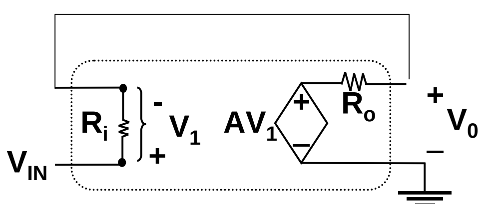
- The output V_O must lie within a range determined by the supply voltages, which are not shown.
- It will limit or "clip" if V_O attempts to exceed the boundaries. We call the limits of the output the "**rails**".
- In the **linear region**, the op-amp output voltage V_O is equal to the **gain A** times the voltage across the input terminals.
- You can "blindly" use the linear region model, and check if the output exceeds a rail. If so, the output is equal to that rail voltage.



Example: Voltage Follower

- Find the output voltage. Assume the rails are not exceeded.

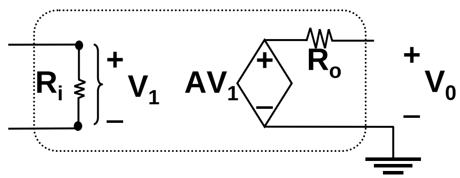




Ideal Op-Amp Assumptions

- While we can always use our circuit model for the linear region, it is complicated.
- R_i is usually very large.
- R_O is usually very small.
- A is usually very large (like 10^3 to 10^6).
- Thus, we can make the following **ideal assumptions** for easier, but still pretty accurate, analysis:
  - Assume $A = \infty$.
  - Assume $R_i = \infty$.
  - Assume $R_o = 0\ \Omega$

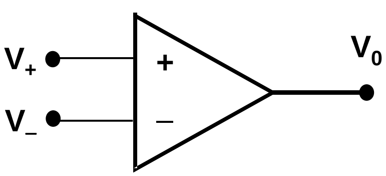
Circuit Model

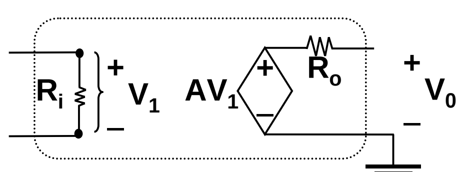


Ideal Op-Amp Model

Our idealized op-amp follows these rules within the linear region:

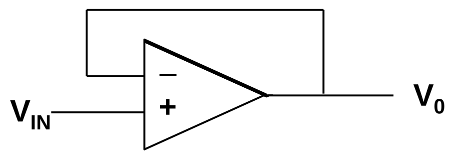
- Rule 1: $V_+ - V_- = 0$.
  - **Why? If the output voltage is limited by rails, and the gain A is very large, then $V_+ - V_-$ must be very small.**
- Rule 2: No current goes in/out of the input terminals.
  - **Why? $V_+ - V_-$ is very small and R_i is very large.**
- Remember current <u>can</u> go into/out the output terminal.
  - **Why? There are connections not shown, and the current comes from those connections.**





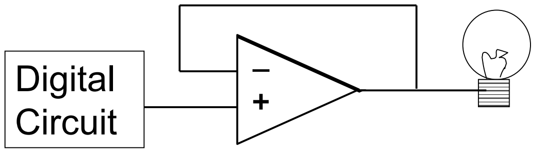
Example: Voltage Follower

- Find the output voltage. Assume the rails are not exceeded.



Utility of Voltage Follower

- Suppose I have a voltage coming out of a digital circuit.
- I want to apply the voltage to “turn on” some device that requires high power (the device “drains” a substantial amount of current).
- Digital circuits usually cannot provide much current; they are designed for low power consumption.
- If we put a voltage follower between the digital circuit and the load, the voltage follower replicates the desired voltage, and can also provide current through its power supply.



Op-Amp Circuits

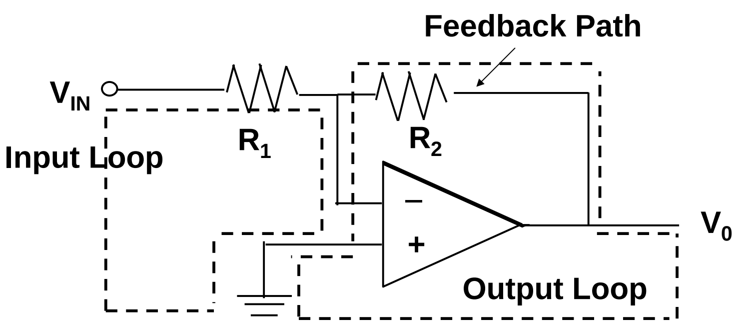
- Op-Amp circuits usually take some input voltage and perform some “operation” on it, yielding an output voltage.
- Some tips on how to find the output, given the input:

Step 1: KVL around input loop (involves V_{in} and op-amp inputs)
Use Rule 1: Vp-Vn = 0

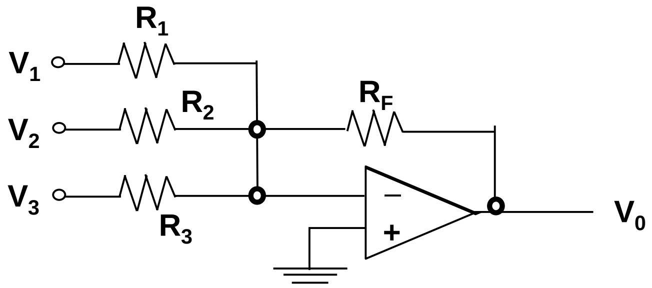
Step 2: Find the current in the feedback path
Use Rule 2: No current into/out of op-amp inputs

Step 3: KVL around output loop (involves V_o and feedback path)
Remember current can flow in/out op-amp output

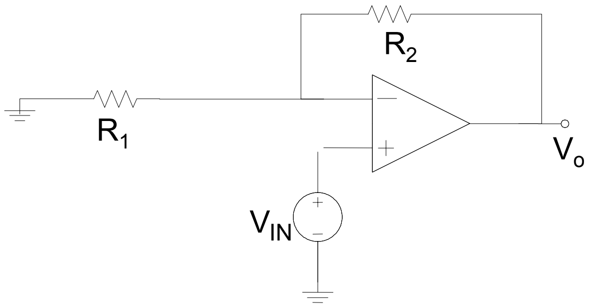
Example: Inverting Amplifier



Example: Inverting Summing Amplifier



Non-inverting Amplifier

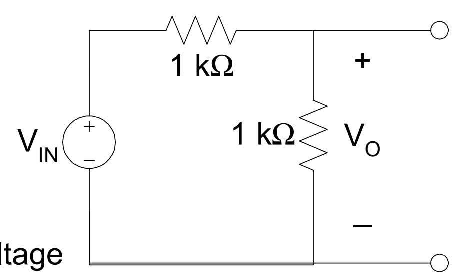


Important Points

- The amplifier output voltage does not depend on the "load" (what is attached to the output).
- The "form" of the output voltage (the signs of the scaling factors on the input voltages, for example) depends on the amplifier circuit layout.
- To change the values (magnitudes) of scaling factors, adjust resistor values.
- Input voltages which are attached to the + (non-inverting) amplifier terminal get positive scaling factors.
- Inputs attached to the – (inverting) terminal get negative scaling factors.
- You can use these principles to design amplifiers which perform a particular function on the input voltages.

Example: Voltage Divider

- Suppose I want to use the following circuit to supply a certain fraction of V_{IN} to whatever I attach.
- What is V_O if nothing is attached?
- What is V_O if a 1 kΩ resistor is attached?
- This circuit clearly does not supply the same voltage to any attached load.



What could I add to the circuit so that it will supply the same fraction of V_{IN} to any attached device?

Example

- Design a circuit whose output is the sum of two input voltages.

Example

- Design a circuit whose output is the average of two input voltages.