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 $R_o = 0 \, \Omega$

### 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 can 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: \( V_p - V_n = 0 \)

**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.