Chapter 9

Operational Amplifiers
Operational Amplifiers: (our first IC!)

Revisit Feedback: Feedback generally improves circuits.

Positive Feedback: modify circuit so that fraction $\beta$ of signal goes back to input.

New gain, $A'_v = \frac{V_o}{V_i} = \frac{A_v}{1-\beta A_v}$.

As $\beta A_v \rightarrow 1$, $A'_v \rightarrow \infty$.

$\Rightarrow$ positive feedback increases signal.

Negative Feedback: used to stabilize circuit by reducing variations in gain.

Here $\beta$ is negative $\Rightarrow A'_v < A_v$.

Ideal Op Amps:

Perfect amplifier has $Z_i \rightarrow \infty \Rightarrow$ does not affect source signal.

$Z_o \rightarrow 0 = \Rightarrow$ unlimited power by amplifier.

$A \rightarrow \infty$.

\[ \text{High gain: } A \sim 10^4 - 10^7 \]

Negative feedback to an Op Amp:

1. Improves gain stability.
2. Reduces output impedance.
3. Improves linearity.
4. Independent of IC’s internal components.
Simply stated, an OpAmp is a circuit that greatly amplifies the voltage difference between its two input terminals.

Some of the functions (or operations) that it can perform: summing voltages, summing currents, signal inversion, impedance buffering, linear amplification, integration, precision control of V or I, precision generation of waveforms, logarithmic amplification.

The OpAmp is so versatile that it is considered the key building block in analog circuits (non-passive).

It is at the heart of D-to-A and A-to-D conversions and servo systems (error correcting feedback systems).

Servo Systems
Control of a system requires measurement. If a quantity, e.g., temperature, is required to be stable to 0.5°C, then a precise measurement with resolution ±0.05°C must be made and monitored. Then, if the monitored value is measured to deviate from the 0.5°C tolerance, accurate corrective action must be applied (negative feedback).
Any system that detects a difference between actual and desired states of a controllable quantity (e.g., temperature, position, time, voltage) and then feeds the difference information back to a controlling device that causes the difference to become essentially zero is a servo system.

One type of servo system is a null detector. It incorporates a feedback system (negative) that brings the difference between the desired quantity value and the actual measured value to zero.

Op Amps have very high input impedances, hence one can generally neglect currents flowing into the Op Amp.

Inverting and Non-Inverting Amplifiers:

Inverting

\[ V_o = \frac{-V_i}{R_1} \]

Since \( I_0 = 0 \), \( I_1 \) flows through \( R_1 \) and \( R_o \) \( \Rightarrow I_1 = I_0 \)

\[ V = V_i - I_0 R_o = 0 \]

This is because open-loop (no feedback) gain is \( \infty \) and \( V = V_i = 0 \). So

\[ V_o = V_i - I_1 R_o \Rightarrow I_1 = -\frac{V_i}{R_1} \]

Also

\[ V_o = V_i - I_1 R_o \Rightarrow V_o = -\frac{R_o}{R_1} V_i \]
Hence, the closed loop gain is:

\[ A = \frac{V_{out}}{V_{in}} = -R_e \]

(Note that minus sign implies inverted output with input.)

Applying the same arguments to non-inverting amplifiers yields:

\[ A = \frac{I_R + I_{R_e}}{I_{R_i}} = 1 + \frac{R_e}{R_i} \]

Hence, choice of \( R_i \) and \( R_e \) sets the gain.
Review OpAmps: (Recall $v_o = A(v_i - V_f)$ in linear operating region)

Ideally:
- $Z_i \to \infty$
- $Z_o \to 0$
- $A \to \infty$

Allow bandwidth (frequency range of operation) $\to \infty$
Allow slow rate (rate at which $v_o$ follows $v_i$) $\to \infty$

**Golden Rules:**
1) $i_i = i_o = 0$
2) $v_o$ does whatever is necessary to minimize $(v_i - v_f)$

Reality: $i_i \neq 0$, though they are small
- if $v_i - V_f = 0$, $v_o \neq 0$
- slow rate and bandwidth $\neq \infty$

Generally, because OpAmps operate to minimize $v_i - V_f$, one takes advantage of this and uses negative feedback to create a stable circuit.
To achieve negative feedback, a circuit takes a fraction of $v_o$ and applies it to the inverted input $v_i$.

Open Loop = no feedback
Closed Loop = w/ feedback

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Don't forget that in lab, circuit diagrams don't show power connections for the OpAmp. I suggest that you set up OpAmp power BEFORE building your circuit.
To test the reality that \( V_0 \neq 0 \) when \( V_+ = V_- = 0 \), one can adjust \( V_+ - V_- \) by applying an adjustable dc input voltage to one of the inputs AND using an open-loop configuration. In lab, create a 1000:1 voltage divider using \( \pm 15\text{V} \) to \( V_0 \) input.

(Note that for a high gain OpAmp, may only see when circuit flips output from inverting to non-inverting)

Recall Inverting Amplifier:

\[
V_o = -\frac{R_f}{R_i} V_i
\]

To measure \( Z_i \), think of

Then, \( V_+ - V_- \) a voltage drop of the input signal over the \( 1\Omega \) resistor, so \( V_+ \) is different with and without \( 1\Omega \)

\[
\Rightarrow V_+ - V_- \text{ is different with and without } 1\Omega
\]

\[
\Rightarrow V_0 \text{ is different, } K
\]

However, the gain \( K = \frac{V_0}{V_i} \) is the same. Use those facts to infer \( Z_i \).
To test the reality that $V_o \neq 0$ when $V_+ - V_- = 0$, one can adjust $V_+ - V_-$ by applying an adjustable dc input voltage to one of the inputs AND using an open-loop configuration. In lab, create a 1000:1 voltage divider using ±15V to obtain ±15mV to $V_+$ input.

(Note that for a high gain OpAmp, may only see when circuit flips output from inverting to non-inverting)

Recall Inverting Amplifier:

$$V_o = -\frac{R_o}{R_i} V_i$$

To measure $Z_i$, think of

There is a voltage drop of the input signal over the 1MΩ resistor, so $V$ is different with and without 1MΩ

$$\Rightarrow V_+ - V_- \text{ is different with and without 1MΩ}$$

$$\Rightarrow V_o \text{ is different, } \neq 0$$

However, the gain $A = \frac{V_o}{V_i}$ is the same. Use these facts to infer $Z_i$. 
Difference Amplifier: review

If the + and - inputs have the same gain, then the output is proportional to the difference in inputs.

In the circuit:

\[
\begin{align*}
V_i &= \frac{V}{R_1} \\
V_o &= \frac{V}{R_f} \\
V_o &= \frac{V}{R_1} \\
V_o &= \frac{V}{R_2} \\
\end{align*}
\]

if \( R_1 = R_2 \), the gains are matched

\( \Rightarrow \) Good for common-mode noise rejection

\( \Rightarrow \) Common-mode noise is usually picked up in a circuit or on leads and resides on both signal AND return legs of a circuit.

\( \Rightarrow \) both signal lead and return plugged into difference amplifier \( \Rightarrow \) \( R_1 = R_2 \) will cause noise to cancel

\( \Rightarrow \) then if signal is added in one lead, it will be amplified

\( \Rightarrow \) CMRR = common-mode rejection ratio

\[ CMRR = 20 \log \left( \frac{V_{	ext{diff}}}{V_{	ext{com}}} \right) \]

In lab, recall that since OpAmp is NOT ideal

\( V_o \neq 0 \) when \( V_+ - V_- = 0 \). This is why potentiometer is required to tune the circuit.
Difference Amplifier: review

If the + and - inputs have the same gain, then the output is proportional to the difference in inputs.

In the circuit

\[ V_{i+} @ R_1 \]
\[ V_{i-} @ R_2 \]
\[ V_o \]

if \( R_1 \cdot R_e = R_2 \cdot R_e \), the gains are matched

- Good for common-mode noise rejection
- Common-mode noise is usually picked up in a circuit or on leads and resides on both signal AND return legs of a circuit.
- Both signal lead and return plugged into difference amplifier \( R_1 \cdot R_e = R_2 \cdot R_e \) will cause noise to cancel
- Then if signal is added in one lead, it will be amplified

\[ CMRR = \text{common-mode rejection ratio} \]
\[ = 20 \log \left( \frac{A_{\text{diff}}}{A_{\text{cm}}} \right) \]

In lab, recall that since OpAmp is NOT ideal
\( V_o \neq 0 \) when \( V_i = 0 \). This is why potentiometer is required to tune the circuit.