The Ideal Operational Amplifier

Op-Amp Fundamentals and Characteristics

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Outline

What is an Operational Amplifier?

The Op-Amp:

- High-gain differential amplifier
- Integrated circuit (IC) device
- Versatile building block
- Typcially used in feedback

Key Applications:

- Signal amplification
- Filtering
- Mathematical operations
- Signal conditioning
- Analog computation

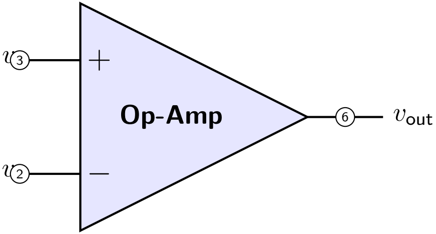


Figure 1: Op-amp circuit symbol

Black Box Approach

We treat the op-amp as a **black box** with well-defined terminal behavior

Op-Amp Terminals

Signal Terminals (3):

1. **Inverting input** $(-)$: Terminal 1
2. **Noninverting input** $(+)$: Terminal 2
3. **Output**: Terminal 3

Power Supply Terminals (2):

- Terminal 4: $+V_{CC}$ (positive supply)
- Terminal 5: $-V_{EE}$ (negative supply)

Other Terminals:

- Frequency compensation
- Offset nulling
- (Application specific)

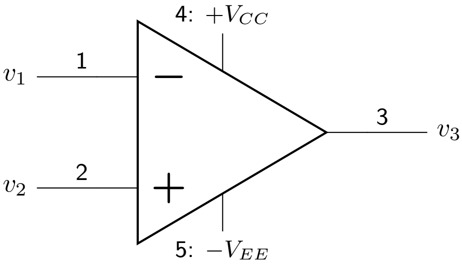


Figure 2: Op-amp with all terminals shown

The Ideal Op-Amp Small-Signal Model

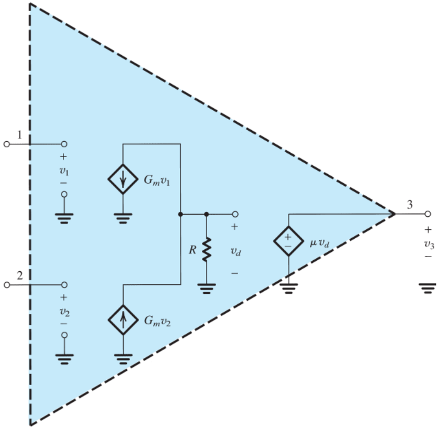


Figure 3: Small-signal op-amp model

Five Characteristics of the Ideal Op-Amp

- **Infinite input impedance** $(Z_{in} \to \infty) \to i_1 = i_2 = 0$
- **Zero output impedance** $(Z_{out} = 0) \to$ ideal voltage source at output
- **Infinite open-loop gain** $(A \to \infty) \to$ tiny $(v_2 - v_1)$ produces large v_3
- **Infinite bandwidth** $\to$ flat gain from DC to ∞
- **Zero common-mode gain** (infinite CMRR) $\to$ responds only to differential input

Important

These are idealizations; real op-amps approximate them, and designs must account for non-idealities.

Op-Amp Circuit Symbol with Ideal Assumptions

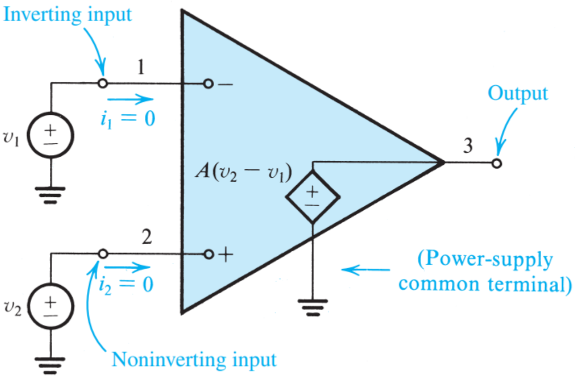


Figure 4: Equivalent Circuit for Ideal Op-Amp

Inverting vs. Noninverting Inputs

Inverting Input $(-)$:

- Output is **out of phase**
- Signal inverted (180° phase shift)

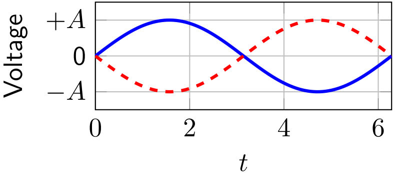


Figure 5: Inverting input response

Noninverting Input $(+)$:

- Output is **in phase**
- Signal not inverted (0° phase shift)

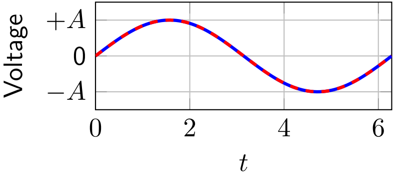


Figure 6: Noninverting input response

Remember

Output: $v_3 = A(v_2 - v_1)$ — noninverting term $(+v_2)$, inverting term $(-v_1)$

Differential-Input, Single-Ended Output

Differential Input:

$$v_{Id} = v_2 - v_1$$

- The **difference** between inputs
- What the op-amp amplifies

Common-Mode Input:

$$v_{Icm} = \frac{1}{2}(v_1 + v_2)$$

- The **average** of inputs
- Ideally **rejected** by op-amp
- Noise component (often)

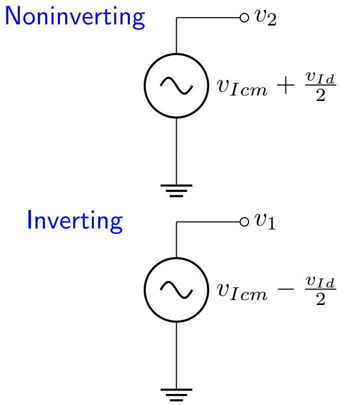


Figure 7: Signal decomposition

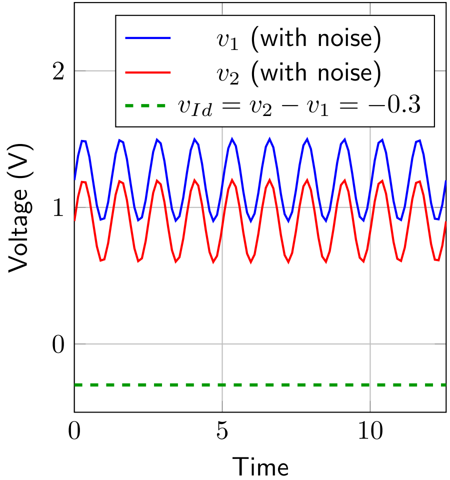
Common-Mode Rejection

Why Common-Mode Rejection?

- Noise often appears equally on both inputs
- Power line interference
- Environmental pickup
- Ground potential differences

Ideal Op-Amp:

- Common-mode gain $= 0$
- CMRR $= \infty$ dB
- Perfectly rejects v_{Icm}



Open-Loop Gain: Why Infinite?

Open-Loop Configuration:

- No feedback from output to input
- Gain $A = \infty$ (ideal)
- **Not practical**

Why $A = \infty$?

- With feedback, gain becomes predictable
- Allows precise closed-loop gain
- Makes circuits insensitive to A variations

Practical Note

Real op-amps: $A \approx 10^3$ to 10^6 (60 dB to 120 dB)

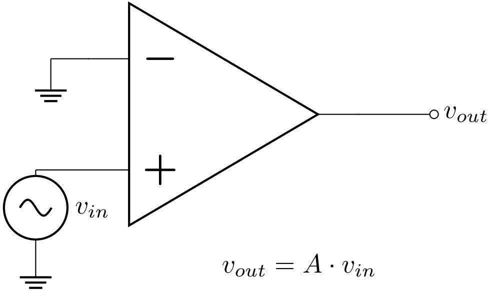


Figure 9: Open-loop configuration (impractical)

Problem with Open-Loop:

- Unstable and unpredictable
- Sensitive to temperature, supply, etc.

DC Amplification and Bandwidth

Direct-Coupled (DC) Amplifier:

- Amplifies down to **0 Hz** (DC)
- No coupling capacitors needed
- Preserves DC level of signals

Advantages:

- Measure slow-varying signals
- Sensor interfaces
- Precision applications

Disadvantages:

- DC offsets can be problematic
- Drift with temperature

Infinite Bandwidth (Ideal):

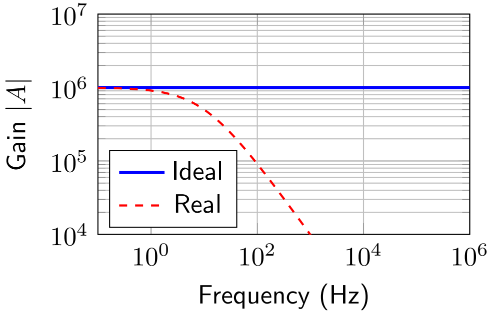
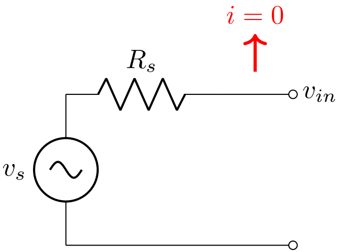


Figure 10: Ideal vs. real frequency response

- Ideal: constant gain at all frequencies
- Real: gain decreases at high frequency

Input and Output Impedances

Infinite Input Impedance:

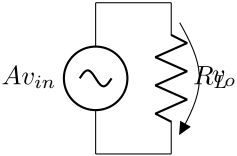


$$v_{in} = v_s \text{ (no drop!)}$$

Figure 11: Input: no loading effect

Benefit:

Zero Output Impedance:



$$v_o = Av_{in} \text{ (any } R_L\text{!)}$$

Figure 12: Output: ideal voltage source

Benefit:

- Output voltage independent of load
- Can drive any R_L

Summary: The Ideal Op-Amp

Five Golden Rules:

1. $Z_{in} = \infty$ (no input current)
2. $Z_{out} = 0$ (ideal voltage source)
3. $A = \infty$ (infinite gain)
4. Infinite bandwidth (DC to ∞)
5. Infinite CMRR (rejects common-mode)

Key Relationships:

- $v_3 = A(v_2 - v_1)$
- $i_1 = i_2 = 0$
- $v_{Id} = v_2 - v_1$
- $v_{Icm} = \frac{1}{2}(v_1 + v_2)$

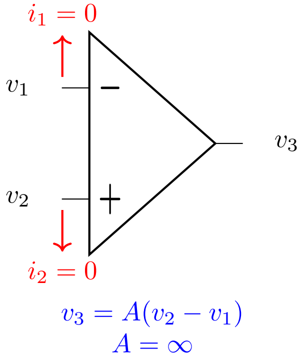


Figure 13: Ideal op-amp summary

Next Lecture

Practice Problem 1

Measurements:

(a) $v_2 = 0$ V and $v_3 = 2$ V
(b) $v_2 = +5$ V and $v_3 = -10$ V
(c) $v_1 = 1.002$ V and $v_2 = 0.998$ V

Find: The missing terminal voltage, v_{Id}, and v_{Icm} for each case.

Hints:

- Use $v_3 = A(v_2 - v_1)$
- $v_{Id} = v_2 - v_1$
- $v_{Icm} = \frac{v_1+v_2}{2}$

Practice Problem 1 Solution

(a) $v_2 = 0$, $v_3 = 2$:

$$v_2 - v_1 = \frac{v_3}{A} = \frac{2}{1000} = 2 \text{ mV} \Rightarrow v_1 = v_2 - 2 \text{ mV} = -0.002 \text{ V}$$

$$v_{Id} = v_2 - v_1 = 2 \text{ mV}, \qquad v_{Icm} = \frac{v_1 + v_2}{2} = \frac{-0.002 + 0}{2} = -1 \text{ mV}$$

(b) $v_2 = +5$, $v_3 = -10$:

$$v_2 - v_1 = \frac{-10}{1000} = -10 \text{ mV} \Rightarrow v_1 = v_2 + 10 \text{ mV} = 5.01 \text{ V}$$

$$v_{Id} = -10 \text{ mV}, \qquad v_{Icm} = \frac{5 + 5.01}{2} = 5.005 \text{ V} \approx 5 \text{ V}$$

(c) $v_1 = 1.002$, $v_2 = 0.998$:

$$v_{Id} = v_2 - v_1 = -4 \text{ mV}, \qquad v_3 = A(v_2 - v_1) = 1000(-4 \text{ mV}) = -4 \text{ V}$$

$$v_{Icm} = \frac{1.002 + 0.998}{2} = 1.000 \text{ V}$$

Practice Problem 2

Given: An op-amp with the internal model shown below

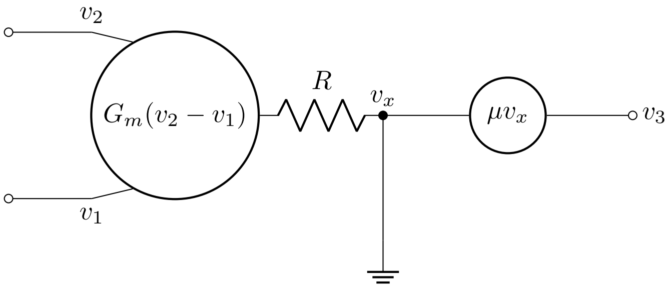


Figure 14: Internal op-amp model: $G_m = 10$ mA/V, $R = 10$ kΩ, $\mu = 100$

Find: Express v_3 as a function of v_1 and v_2, then find the open-loop gain A.

Practice Problem 2 Solution

- $v_x = R \cdot G_m(v_2 - v_1)$
- Numerically:

$$v_x = (10\,\text{k}\Omega)(10\,\text{mA/V})(v_2 - v_1) = 100(v_2 - v_1)$$

- $v_3 = \mu v_x = 100 \cdot 100(v_2 - v_1) = 10{,}000(v_2 - v_1)$
- Therefore,

$$\boxed{A = 10{,}000\ \text{V/V} = 80\ \text{dB}}$$