

The Ideal Operational Amplifier

Op-Amp Fundamentals and Characteristics

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Outline

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Op-Amp

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What is an Operational Amplifier?

The Op-Amp:

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

Key Applications:

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

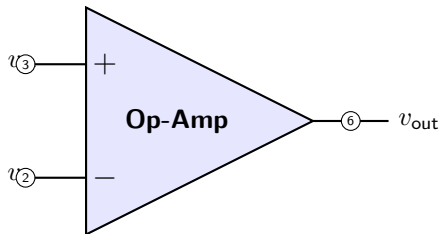


Figure 1: Op-amp circuit symbol

Black Box Approach

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

Op-Amp Terminals

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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)

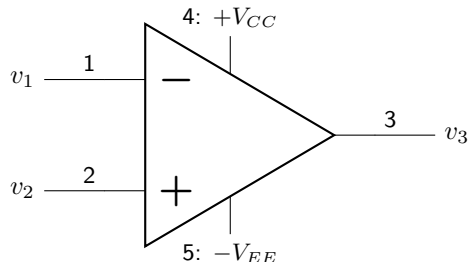


Figure 2: Op-amp with all terminals shown

The Ideal Op-Amp Small-Signal Model

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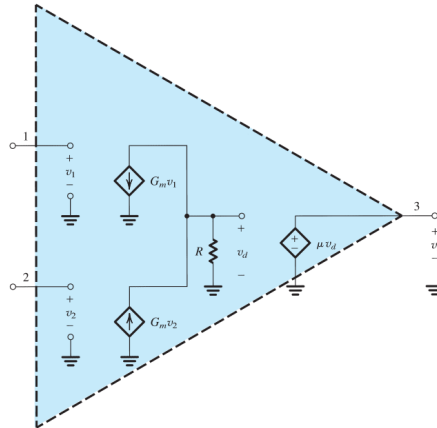


Figure 3: Small-signal op-amp model

Five Characteristics of the Ideal Op-Amp

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

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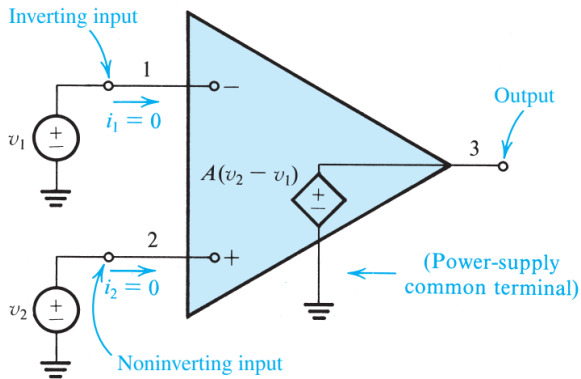


Figure 4: Equivalent Circuit for Ideal Op-Amp

Inverting vs. Noninverting Inputs

Inverting Input (−):

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

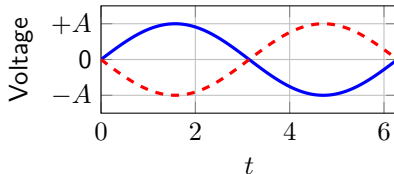


Figure 5: Inverting input response

Noninverting Input (+):

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

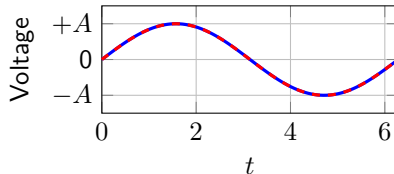


Figure 6: Noninverting input response

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)

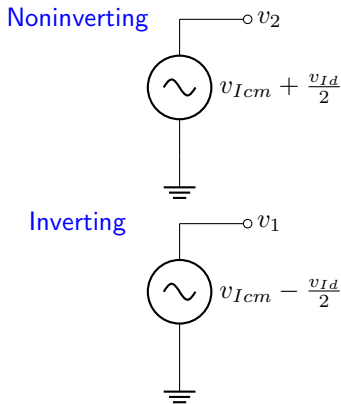


Figure 7: Signal decomposition

Common-Mode Rejection

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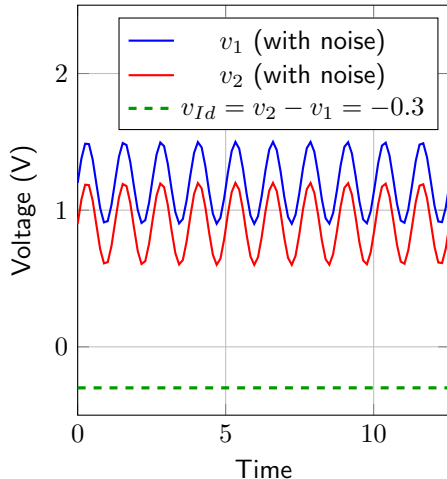
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Why Common-Mode Rejection?

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

Ideal Op-Amp:

- Common-mode gain = 0
- CMRR = ∞ 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)

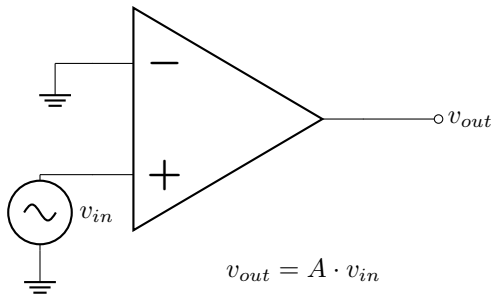


Figure 9: Open-loop configuration (impractical)

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):

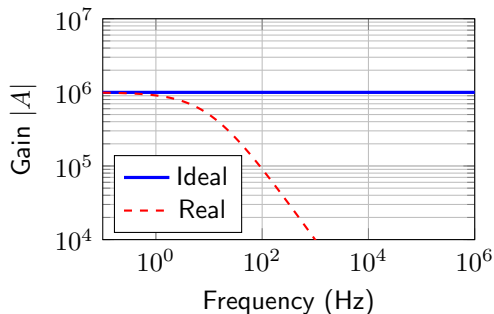


Figure 10: Ideal vs. real frequency response

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

Input and Output Impedances

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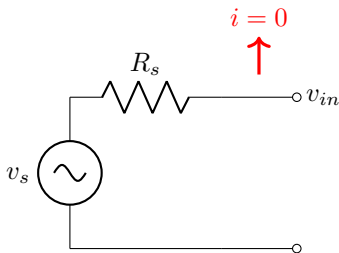
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Infinite Input Impedance:

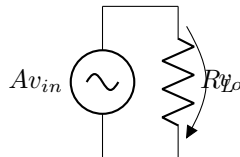


$$v_{in} = v_s \text{ (no drop!)}$$

Figure 11: Input: no loading effect

Benefit:

Zero Output Impedance:



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

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:

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

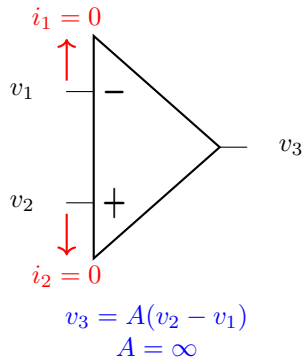


Figure 13: Ideal op-amp summary

Practice Problem 1

Measurements:

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

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) $v_2 = 0, v_3 = 2$:

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

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

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

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

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

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

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

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

Practice Problem 2

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

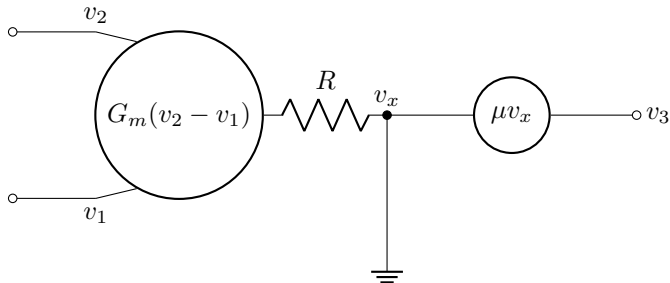


Figure 14: Internal op-amp model: $G_m = 10 \text{ mA/V}$, $R = 10 \text{ k}\Omega$, $\mu = 100$

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,

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