

# The Ideal Operational Amplifier

## Op-Amp Fundamentals and Characteristics

Maxx Seminario

University of Nebraska-Lincoln

Spring 2026

# Outline

The Ideal  
Op-Amp

Maxx Seminario

Introduction to  
the Op-Amp

Ideal Op-Amp  
Characteristics

Differential and  
Common-Mode  
Signals

Key Properties

Summary and  
Examples

- 1 Introduction to the Op-Amp
- 2 Ideal Op-Amp Characteristics
- 3 Differential and Common-Mode Signals
- 4 Key Properties
- 5 Summary and Examples

# 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

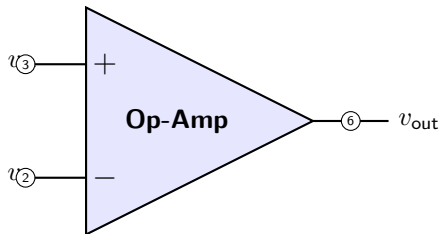


Figure 1: Op-amp circuit symbol

## Black Box Approach

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

# Op-Amp Terminals

The Ideal  
Op-Amp

Maxx Seminario

## 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)

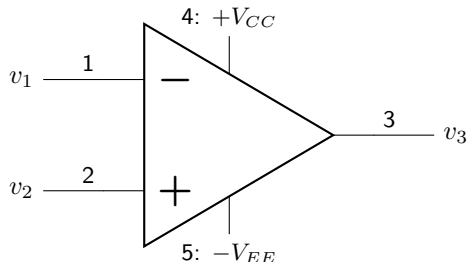


Figure 2: Op-amp with all terminals shown

# 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  $\infty$
- **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

The Ideal  
Op-Amp

Maxx Seminario

Introduction to  
the Op-Amp

Ideal Op-Amp  
Characteristics

Differential and  
Common-Mode  
Signals

Key Properties

Summary and  
Examples

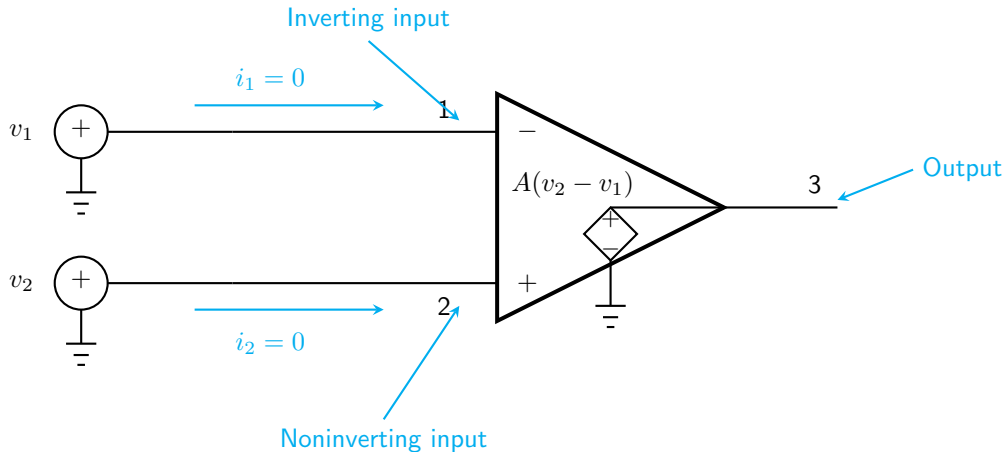


Figure 3: Equivalent Circuit for Ideal Op-Amp

# Inverting vs. Noninverting Inputs

## Inverting Input (−):

- Output is **out of phase**
- Signal inverted ( $180^\circ$  phase shift)

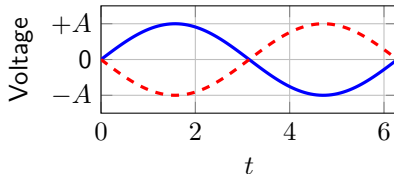


Figure 4: Inverting input response

## Noninverting Input (+):

- Output is **in phase**
- Signal not inverted ( $0^\circ$  phase shift)

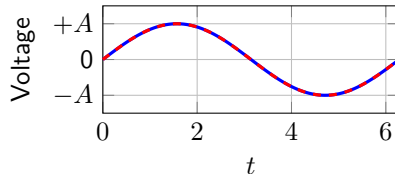


Figure 5: Noninverting input response

## 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)

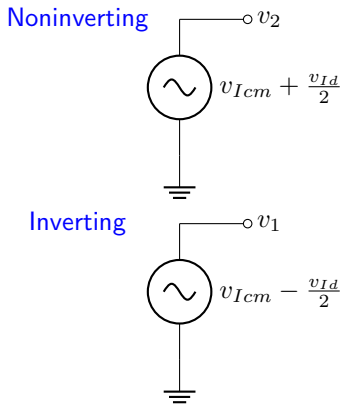


Figure 6: Signal decomposition



# Common-Mode Rejection

The Ideal  
Op-Amp

Maxx Seminario

Introduction to  
the Op-Amp

Ideal Op-Amp  
Characteristics

Differential and  
Common-Mode  
Signals

Key Properties

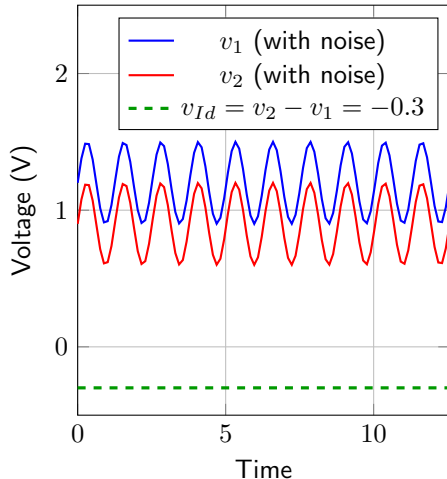
Summary and  
Examples

## 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?

The Ideal  
Op-Amp

Maxx Seminario

## 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)

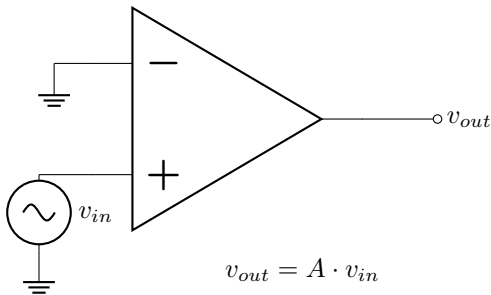


Figure 8: Open-loop configuration (impractical)

## 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):

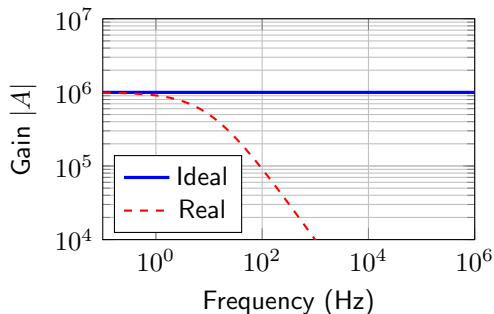


Figure 9: Ideal vs. real frequency response

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

# Input and Output Impedances

The Ideal  
Op-Amp

Maxx Seminario

Introduction to  
the Op-Amp

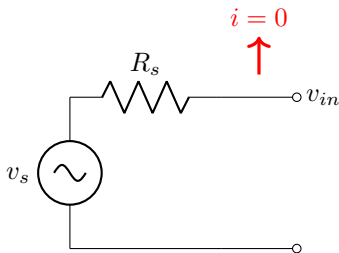
Ideal Op-Amp  
Characteristics

Differential and  
Common-Mode  
Signals

Key Properties

Summary and  
Examples

## Infinite Input Impedance:

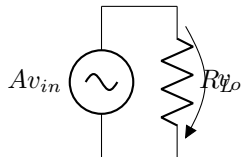


$$v_{in} = v_s \text{ (no drop!)}$$

Figure 10: Input: no loading effect

## Benefit:

## Zero Output Impedance:



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

Figure 11: Output: ideal voltage source

## Benefit:

- Output voltage independent of load
- Can drive any  $R_L$

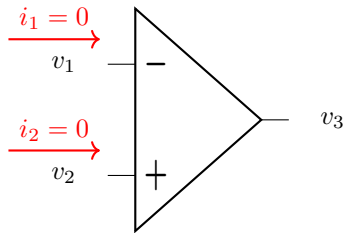
# Summary: The Ideal Op-Amp

## 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  $\infty$ )
- 5 Infinite CMRR (rejects common-mode)

## Key Relationships:

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



$$v_3 = A(v_2 - v_1)$$
$$A = \infty$$

Figure 12: 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

The Ideal  
Op-Amp

Maxx Seminario

Introduction to  
the Op-Amp

Ideal Op-Amp  
Characteristics

Differential and  
Common-Mode  
Signals

Key Properties

Summary and  
Examples

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

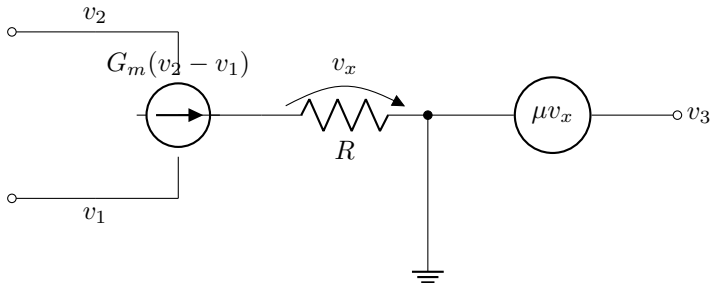


Figure 13: Internal op-amp model:  $G_m = 10 \text{ mA/V}$ ,  $R = 10 \text{ k}\Omega$ ,  $\mu = 100$

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



# Practice Problem 2 Solution

The Ideal  
Op-Amp

Maxx Seminario

Introduction to  
the Op-Amp

Ideal Op-Amp  
Characteristics

Differential and  
Common-Mode  
Signals

Key Properties

Summary and  
Examples

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

- 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,

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