# The Ideal Operational Amplifier

## Op-Amp Fundamentals and Characteristics

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# Outline

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
- Typcially used in feedback

**Key Applications**:

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

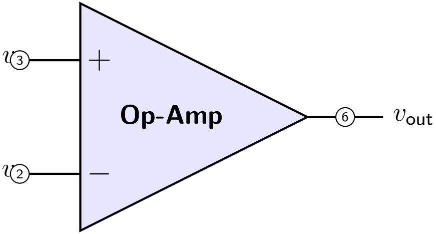



Figure 1: Op-amp circuit symbol

**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)

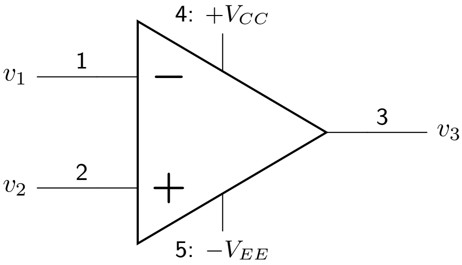



Figure 2: Op-amp with all terminals shown

# 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 $\infty$
- **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



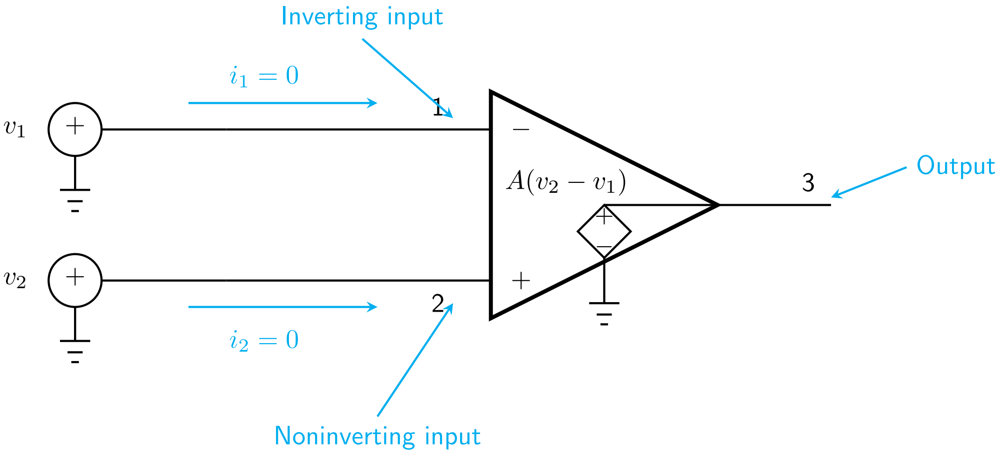



Figure 3: Equivalent Circuit for Ideal Op-Amp

# Inverting vs. Noninverting Inputs

**Inverting Input** $(-)$:

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

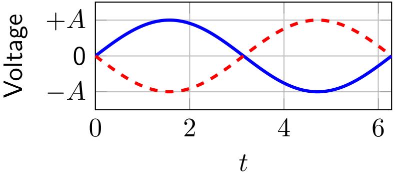



Figure 4: Inverting input response

**Noninverting Input** $(+)$:

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

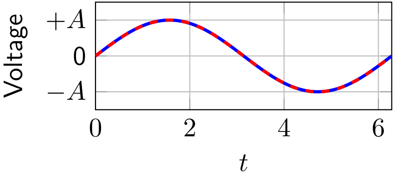



Figure 5: Noninverting input response

**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)

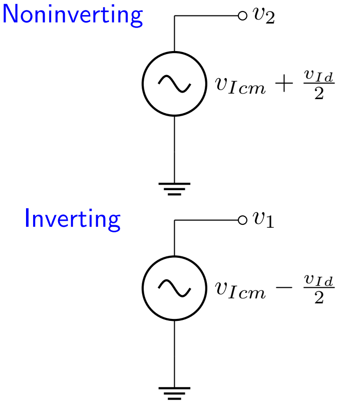



Figure 6: Signal decomposition

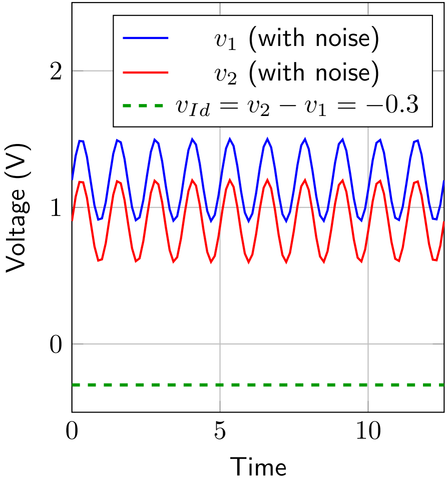
# Common-Mode Rejection

**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)

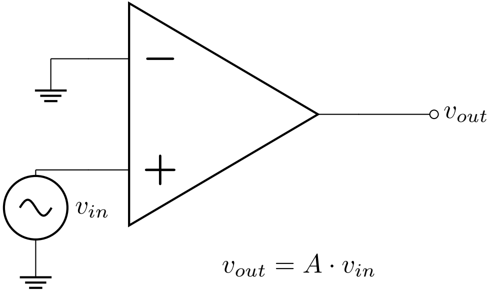



Figure 8: Open-loop configuration (impractical)

**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)**:

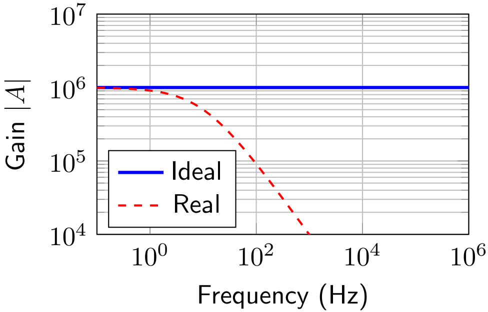
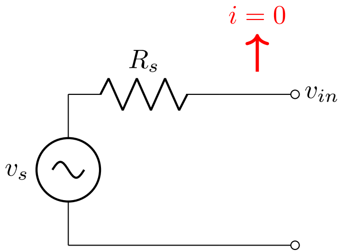



Figure 9: Ideal vs. real frequency response

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

# Input and Output Impedances

**Infinite Input Impedance**:

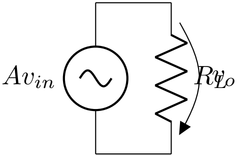



$v_{in} = v_s$ (no drop!)

Figure 10: Input: no loading effect

**Benefit**:

**Zero Output Impedance**:




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

Figure 11: Output: ideal voltage source

**Benefit**:

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

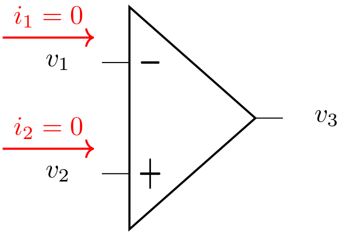
# Summary: The Ideal Op-Amp

**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) $v_2 = 0$ 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

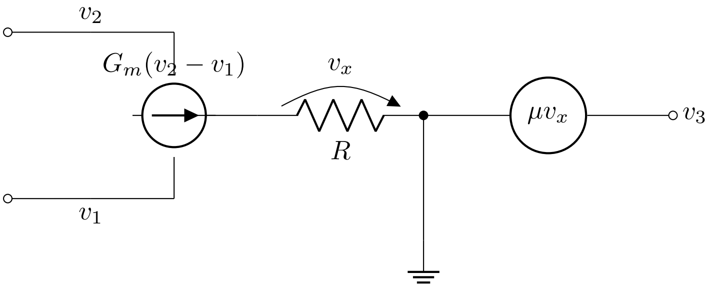



Figure 13: Internal op-amp model: $G_m = 10$ mA/V, $R = 10$ kΩ, $\mu = 100$

**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:
$$v_x = (10\,\mathrm{k\Omega})(10\,\mathrm{mA/V})(v_2 - v_1) = 100(v_2 - v_1)$$
- $v_3 = \mu v_x = 100 \cdot 100(v_2 - v_1) = 10{,}000(v_2 - v_1)$
- Therefore,
$$\boxed{A = 10{,}000 \text{ V/V} = 80 \text{ dB}}$$