

# Operational Amplifier Applications

## Feedback Configurations and Mathematical Operations

Maxx Seminario

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# Outline

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# Review: The Ideal Op-Amp

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## Five Ideal OpAmp Assumptions:

- 1  $Z_{in} = \infty \Rightarrow i_+ = i_- = 0$
- 2  $Z_{out} = 0$  (ideal voltage source)
- 3  $A = \infty$  (infinite open-loop gain)
- 4 Infinite bandwidth
- 5 Infinite CMRR

## Basic Relationship:

$$v_{out} = A(v_+ - v_-)$$

With  $A \rightarrow \infty$ , for bounded output:

$$v_+ - v_- \rightarrow 0 \quad (\text{virtual short})$$

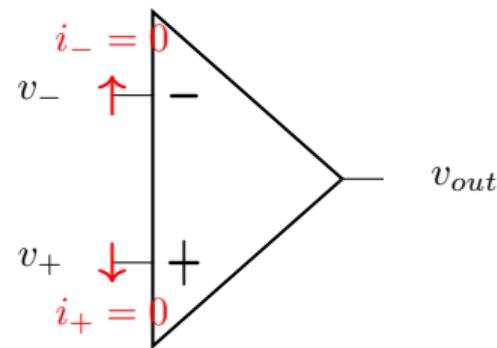


Figure 1: Ideal op-amp terminals

## Key Insight

- $v_+ = v_-$  (virtual short)
- $i_+ = i_- = 0$  (no input current)

# Negative Feedback Concept

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## What is Negative Feedback?

- Output is fed back to inverting input
- Opposes changes in output
- ☺ Makes gain predictable

## Why Use Feedback?

- ☺ Precise, stable gain
- ☺ Insensitive to  $A$  variations
- ☺ Improved linearity
- ☺ Controlled impedances

## Key Insight

With negative feedback and ideal op-amp:

$$v_+ = v_-$$

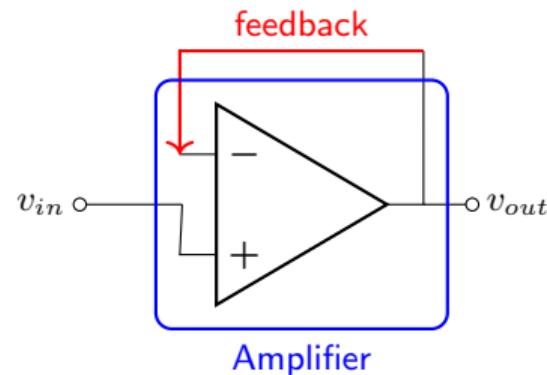


Figure 2: Negative feedback block diagram

## Result:

- Op-amp adjusts  $v_{out}$  to make  $v_- = v_+$
- ☺ Gain determined by external components

# The Inverting Amplifier

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## Circuit Configuration:

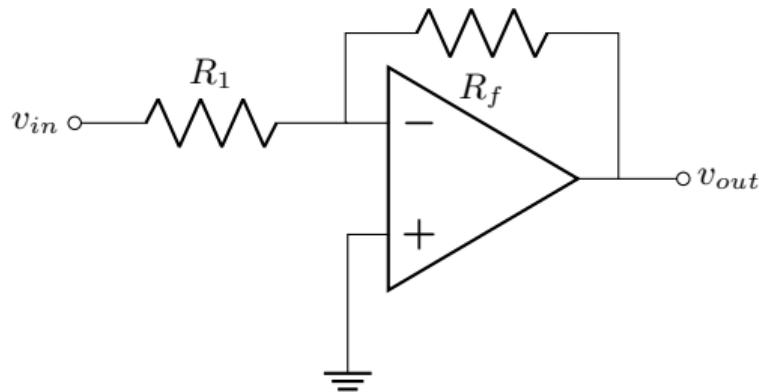


Figure 3: Inverting amplifier circuit

## Analysis:

1. Since  $v_+ = 0$  (AC Ground, be careful!):

$$v_- = v_+ = 0 \quad (\text{AC ground})$$

2. Current through  $R_1$ :

$$i_1 = \frac{v_{in} - v_-}{R_1} = \frac{v_{in}}{R_1}$$

3. Since  $i_- = 0$ , all of  $i_1$  flows through  $R_f$ :

$$i_f = i_1 = \frac{v_{in}}{R_1}$$

4. Voltage across  $R_f$ :

$$v_{out} - v_- = -i_f R_f$$

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## Voltage Gain:

$$A_v = \frac{v_{out}}{v_{in}} = -\frac{R_f}{R_1}$$

- ⌚ Negative sign: 180° phase shift
- ⌚ Magnitude set by resistor ratio
- ⌚ Independent of op-amp gain  $A$

## Input Impedance:

$$R_{in} = \frac{v_{in}}{i_1} = R_1$$

- ⌚ Not infinite!
- ⌚ Determined by  $R_1$

## Design Examples:

### Example 1: Unity gain inverter

- $R_1 = R_f = 10 \text{ k}\Omega$
- $A_v = -1$
- $R_{in} = 10 \text{ k}\Omega$

### Example 2: Gain of -10

- $R_1 = 10 \text{ k}\Omega, R_f = 100 \text{ k}\Omega$
- $A_v = -10$
- $R_{in} = 10 \text{ k}\Omega$

### Example 3: Gain of -0.5

- $R_1 = 20 \text{ k}\Omega, R_f = 10 \text{ k}\Omega$
- $A_v = -0.5$  (attenuation!)
- $R_{in} = 20 \text{ k}\Omega$

# The Noninverting Amplifier

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## Circuit Configuration:

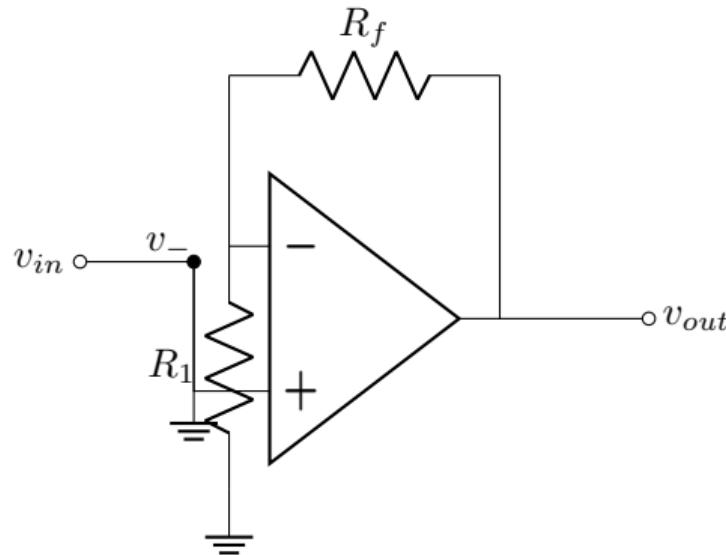


Figure 4: Noninverting amplifier circuit

## Analysis:

1. Since  $v_+ = v_{in}$ :

$$v_- = v_+ = v_{in}$$

2. Voltage divider at inverting input:

$$v_- = v_{out} \frac{R_1}{R_1 + R_f}$$

3. Equating the two expressions:

$$v_{in} = v_{out} \frac{R_1}{R_1 + R_f}$$

4. Solving for gain:

$$\frac{v_{out}}{v_{in}} = \frac{R_1 + R_f}{R_1}$$

# Noninverting Amplifier: Key Results

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## Voltage Gain:

$$A_v = 1 + \frac{R_f}{R_1}$$

- Always positive (no inversion)
- Minimum gain is 1
- Set by resistor ratio

## Input Impedance:

$$R_{in} = \infty$$

- Infinite (ideally)
- Input goes to op-amp + terminal

## Design Examples:

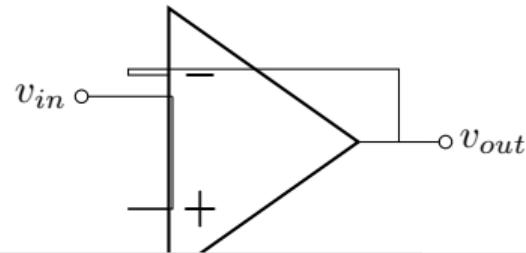
### Example 1: Gain of 2

- $R_1 = R_f = 10 \text{ k}\Omega$
- $A_v = 1 + 1 = 2$

### Example 2: Gain of 11

- $R_1 = 10 \text{ k}\Omega, R_f = 100 \text{ k}\Omega$
- $A_v = 1 + 10 = 11$

## Voltage Follower:



# The Summing Amplifier

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## Circuit Configuration:

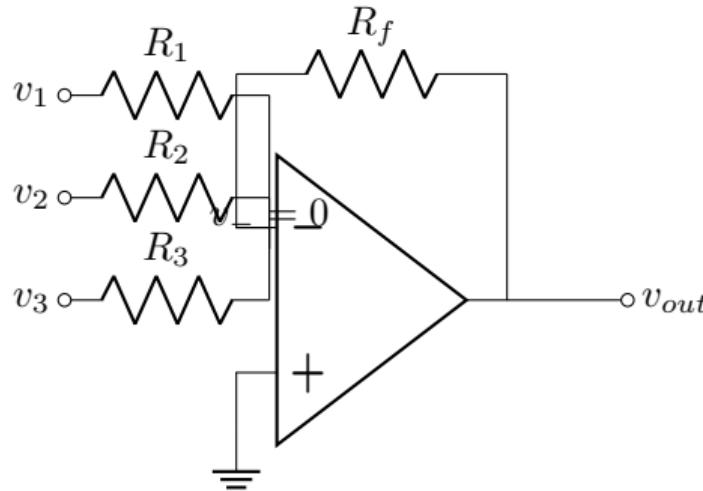


Figure 6: Summing amplifier (3 inputs)

## Analysis:

- Virtual ground:  $v_- = 0$
- Currents from each input:

$$i_1 = \frac{v_1}{R_1}, \quad i_2 = \frac{v_2}{R_2}, \quad i_3 = \frac{v_3}{R_3}$$

- KCL at inverting node:

$$i_f = i_1 + i_2 + i_3$$

- Output voltage:

$$v_{out} = -i_f R_f$$

$$v_{out} = -R_f \left( \frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} \right)$$

# Summing Amplifier: Applications

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## Special Cases:

### Case 1: Equal resistors

- $R_1 = R_2 = R_3 = R, R_f = R$
- $v_{out} = -(v_1 + v_2 + v_3)$
- Simple inverting summer

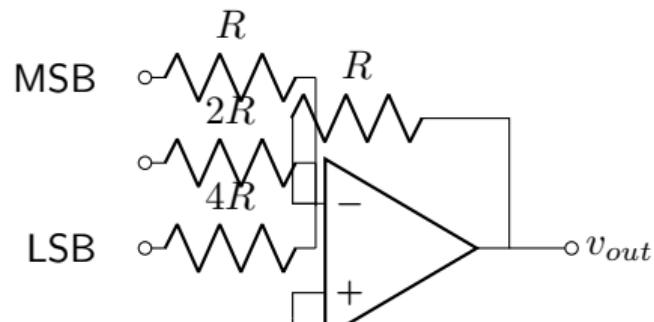
### Case 2: Weighted summer

- Different resistor values
- Each input has different weight
- Example:  $R_f = 10 \text{ k}\Omega$ 
  - $R_1 = 10 \text{ k}\Omega \Rightarrow \text{weight} = 1$
  - $R_2 = 5 \text{ k}\Omega \Rightarrow \text{weight} = 2$
  - $R_3 = 20 \text{ k}\Omega \Rightarrow \text{weight} = 0.5$
- $v_{out} = -(v_1 + 2v_2 + 0.5v_3)$

## Applications:

- Audio mixing consoles
- Digital-to-analog conversion (DAC)
- Analog computation
- Signal averaging
- Multi-input control systems

## Example: 3-bit DAC:



# The Difference Amplifier

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## Circuit Configuration:

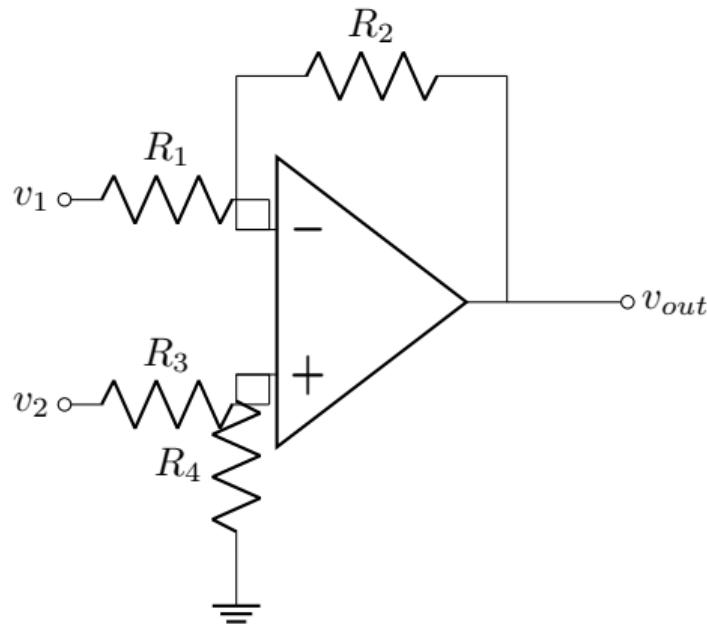


Figure 8: Difference (differential) amplifier

## Analysis:

1. Voltage at noninverting input:

$$v_+ = v_2 \frac{R_4}{R_3 + R_4}$$

2. Since  $v_- = v_+$ :

$$v_- = v_2 \frac{R_4}{R_3 + R_4}$$

3. Current through  $R_1$ :

$$i_1 = \frac{v_1 - v_-}{R_1}$$

4. Since  $i_- = 0$ :

$$v_{out} = v_- - i_1 R_2$$

# Difference Amplifier: Key Points

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## Design Constraint:

For pure differential gain:

$$\frac{R_2}{R_1} = \frac{R_4}{R_3}$$

## Common Choice:

- $R_1 = R_3 = R$
- $R_2 = R_4 = kR$
- Differential gain:  $A_d = k$

## Example:

- $R_1 = R_3 = 10 \text{ k}\Omega$
- $R_2 = R_4 = 100 \text{ k}\Omega$
- $v_{out} = 10(v_2 - v_1)$

## Applications:

- Instrumentation
- Sensor signal conditioning
- Noise rejection (common-mode)
- Bridge circuit measurements
- Biomedical amplifiers (ECG, EEG)

## Advantages:

- Rejects common-mode signals
- Amplifies differential signal
- Single op-amp solution

## Limitations:

- Requires precision resistor matching

# The Integrator

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## Circuit Configuration:

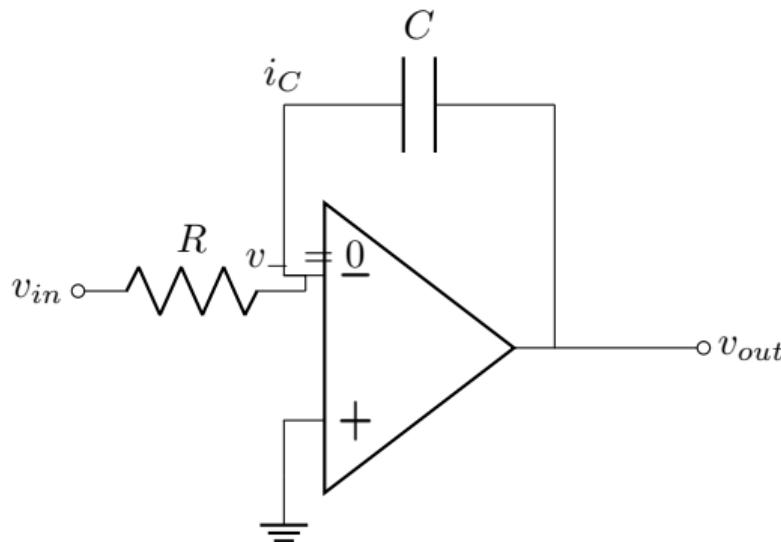


Figure 9: Inverting integrator

## Analysis:

- Virtual ground:  $v_- = 0$
- Current through  $R$ :

$$i_R = \frac{v_{in} - 0}{R} = \frac{v_{in}}{R}$$

- Since  $i_- = 0$ , all current flows through  $C$ :

$$i_C = i_R = \frac{v_{in}}{R}$$

- Capacitor voltage-current relation:

$$i_C = C \frac{dv_C}{dt}$$

- Since  $v_C = 0 - v_{out} = -v_{out}$ :

$$v_{in} = -d(-v_{out})$$

# Integrator: Time-Domain Analysis

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## Transfer Function:

From:

$$\frac{v_{in}}{R} = -C \frac{dv_{out}}{dt}$$

Rearranging:

$$\frac{dv_{out}}{dt} = -\frac{1}{RC} v_{in}$$

Integrating both sides:

$$v_{out}(t) = -\frac{1}{RC} \int_0^t v_{in}(\tau) d\tau + v_{out}(0)$$

## Interpretation:

- Output is (inverted) integral of input
- Time constant:  $\tau = RC$

## Frequency Response:

In frequency domain (assuming  $v_{out}(0) = 0$ ):

$$\frac{V_{out}(j\omega)}{V_{in}(j\omega)} = -\frac{1}{j\omega RC}$$

Magnitude:

$$|H(j\omega)| = \frac{1}{\omega RC}$$

- Gain decreases with frequency
- -20 dB/decade slope
- Infinite gain at DC (impractical!)

## Practical Issue:

# Integrator: Waveform Examples

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## Example 1: Step Input

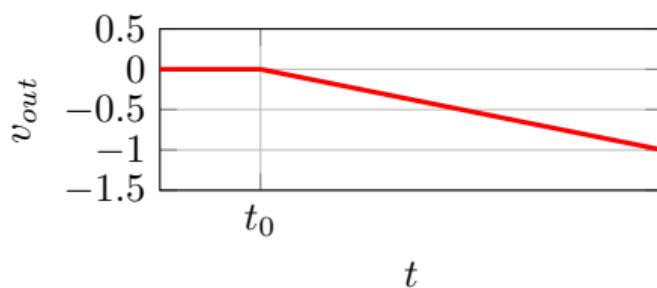
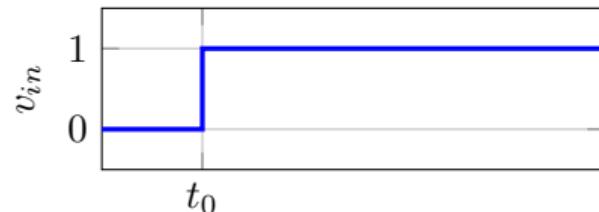


Figure 10: Step input produces ramp output

## Example 2: Square Wave Input

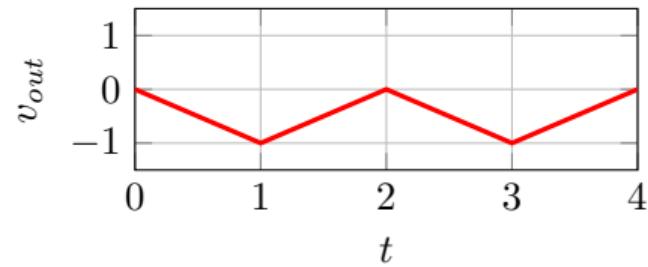
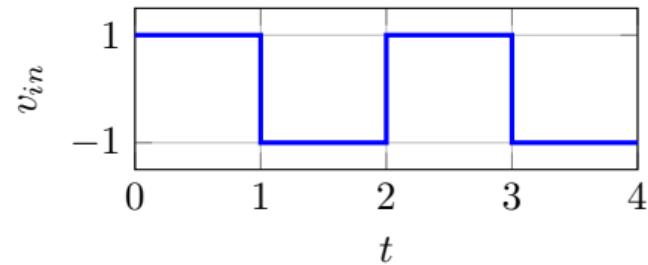


Figure 11: Square wave produces triangle wave

# The Differentiator

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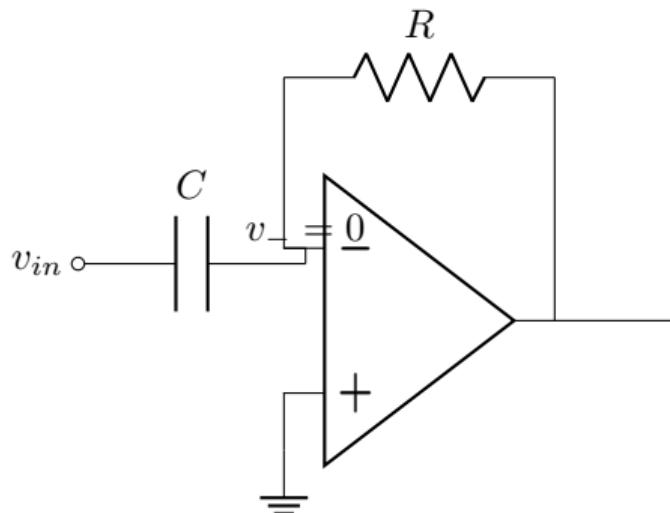
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## Circuit Configuration:



## Analysis:

- Virtual ground:  $v_- = 0$
- Capacitor current:

$$i_C = C \frac{dv_C}{dt} = C \frac{d(v_{in} - 0)}{dt}$$

$$i_C = C \frac{dv_{in}}{dt}$$

- Since  $i_- = 0$ ,  $i_C$  flows through  $R$ :

$$i_R = i_C = C \frac{dv_{in}}{dt}$$

- Output voltage:

$$v_{out} = 0 - i_R R = -RC \frac{dv_{in}}{dt}$$

Figure 12: Inverting differentiator

Note: Integrator with  $R$  and  $C$  swapped!

# Differentiator: Characteristics and Issues

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## Transfer Function:

Time domain:

$$v_{out} = -RC \frac{dv_{in}}{dt}$$

Frequency domain:

$$\boxed{\frac{V_{out}(j\omega)}{V_{in}(j\omega)} = -j\omega RC}$$

Magnitude:

$$|H(j\omega)| = \omega RC$$

- Gain increases with frequency
- +20 dB/decade slope

## Practical Problems:

### 1 Noise amplification

- High-frequency noise magnified
- Can saturate output

### 2 Stability issues

- Phase shift can cause oscillation
- Needs compensation

## Practical Solution:

Add small resistor  $R_s$  in series with  $C$ :

- Limits high-frequency gain
- Improves stability
- $R_s \ll R$  (typically  $R_s \approx R/10$ )

Warning

# Differentiator: Waveform Examples

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## Example 1: Ramp Input

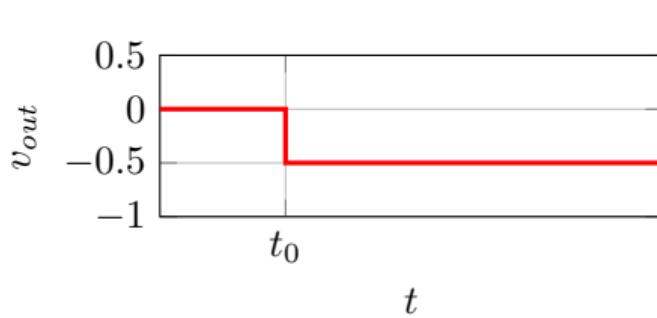
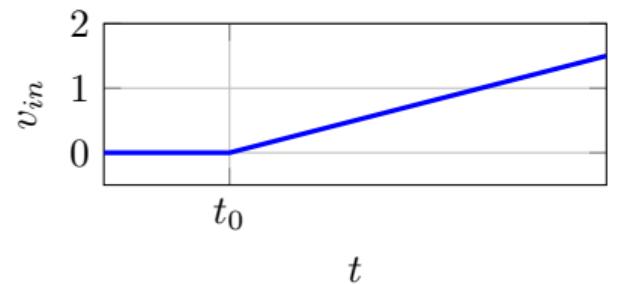


Figure 13: Ramp input produces constant

## Example 2: Triangle Wave Input

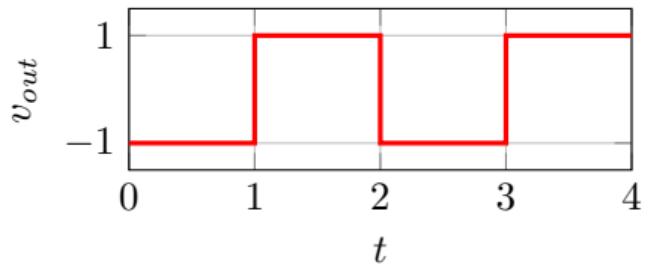
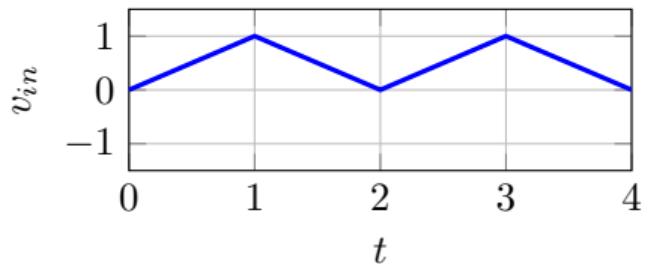


Figure 14: Triangle wave produces square wave

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Configuration	Gain	$R_{in}$	Application
Inverting	$-\frac{R_f}{R_1}$	$R_1$	Amplification with inversion
Noninverting	$1 + \frac{R_f}{R_1}$	$\infty$	Amplification, no inversion
Voltage Follower	1	$\infty$	Buffering, impedance matching
Summing	$-\sum \frac{R_f}{R_i} v_i$	$R_i$	Audio mixing, DAC
Difference	$\frac{R_2}{R_1} (v_2 - v_1)$	finite	Instrumentation
Integrator	$-\frac{1}{RC} \int v_{in} dt$	$\infty$ (AC)	Analog computation, filters
Differentiator	$-RC \frac{dv_{in}}{dt}$	$\rightarrow 0$ (HF)	Rarely used (noise!)

Table 1: Summary of op-amp configurations

## Key Analysis Steps

- 1 Identify configuration
- 2 Apply virtual short:  $v_+ = v_-$  (with negative feedback)

# Practice Problem 1

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**Given:** An inverting amplifier with  $R_1 = 4.7 \text{ k}\Omega$  and  $R_f = 47 \text{ k}\Omega$

**Find:**

- (a) The voltage gain  $A_v$
- (b) The input impedance  $R_{in}$
- (c) If  $v_{in} = 0.5 \text{ V}$ , what is  $v_{out}$ ?
- (d) What resistor value should  $R_f$  be to achieve  $A_v = -15$ ?

**Hint:** Use  $A_v = -\frac{R_f}{R_1}$  and  $R_{in} = R_1$

# Practice Problem 1 Solution

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**Given:**  $R_1 = 4.7 \text{ k}\Omega$ ,  $R_f = 47 \text{ k}\Omega$

**Solutions:**

(a) Voltage gain:

$$A_v = -\frac{R_f}{R_1} = -\frac{47 \text{ k}\Omega}{4.7 \text{ k}\Omega} = \boxed{-10 \text{ V/V}}$$

(b) Input impedance:

$$R_{in} = R_1 = \boxed{4.7 \text{ k}\Omega}$$

(c) Output voltage:

$$v_{out} = A_v \cdot v_{in} = (-10)(0.5 \text{ V}) = \boxed{-5 \text{ V}}$$

(d) For  $A_v = -15$ :

$$-15 = -\frac{R_f}{4.7 \text{ k}\Omega} \Rightarrow R_f = 15 \times 4.7 \text{ k}\Omega = \boxed{70.5 \text{ k}\Omega}$$

(Use standard value 68 kΩ or 75 kΩ in practice)

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**Given:** A noninverting amplifier with the following requirements:

- Voltage gain:  $A_v = 5$
- Input voltage:  $v_{in} = 0.2 \text{ V}$
- Choose  $R_1 = 10 \text{ k}\Omega$

**Find:**

- (a) The required value of  $R_f$
- (b) The output voltage  $v_{out}$
- (c) The input impedance
- (d) If you need  $A_v = 1$  (unity gain buffer), what should the circuit look like?

**Hint:** Use  $A_v = 1 + \frac{R_f}{R_1}$

# Practice Problem 2 Solution

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**Given:**  $A_v = 5$ ,  $R_1 = 10 \text{ k}\Omega$ ,  $v_{in} = 0.2 \text{ V}$

**Solutions:**

(a) Required  $R_f$ :

$$5 = 1 + \frac{R_f}{10 \text{ k}\Omega}$$

$$\frac{R_f}{10 \text{ k}\Omega} = 4 \Rightarrow R_f = \boxed{40 \text{ k}\Omega}$$

(b) Output voltage:

$$v_{out} = A_v \cdot v_{in} = 5 \times 0.2 \text{ V} = \boxed{1.0 \text{ V}}$$

(c) Input impedance:

$$R_{in} = \boxed{\infty} \text{ (ideally)}$$

(d) For unity gain buffer ( $A_v = 1$ ):

- Connect output directly to inverting input (direct feedback)
- Remove  $R_1$  and  $R_f$
- Input to noninverting terminal

# Practice Problem 3

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**Given:** A summing amplifier with three inputs

- $R_1 = 10 \text{ k}\Omega$ ,  $R_2 = 20 \text{ k}\Omega$ ,  $R_3 = 5 \text{ k}\Omega$
- $R_f = 20 \text{ k}\Omega$
- Input voltages:  $v_1 = 1 \text{ V}$ ,  $v_2 = 0.5 \text{ V}$ ,  $v_3 = -0.25 \text{ V}$

**Find:**

- (a) The weight (coefficient) for each input
- (b) The output voltage  $v_{out}$
- (c) If you want equal weights for all inputs, what should the resistor values be?

**Hint:** Use  $v_{out} = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$

# Practice Problem 3 Solution

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Summary and  
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**Given:**  $R_f = 20 \text{ k}\Omega$ ,  $R_1 = 10 \text{ k}\Omega$ ,  $R_2 = 20 \text{ k}\Omega$ ,  $R_3 = 5 \text{ k}\Omega$

**Inputs:**  $v_1 = 1 \text{ V}$ ,  $v_2 = 0.5 \text{ V}$ ,  $v_3 = -0.25 \text{ V}$

**Solutions:**

(a) Weights:

$$w_1 = \frac{R_f}{R_1} = \frac{20}{10} = \boxed{2}$$

$$w_2 = \frac{R_f}{R_2} = \frac{20}{20} = \boxed{1}$$

$$w_3 = \frac{R_f}{R_3} = \frac{20}{5} = \boxed{4}$$

(b) Output voltage:

$$v_{out} = -(2 \times 1 + 1 \times 0.5 + 4 \times (-0.25))$$

$$v_{out} = -(2 + 0.5 - 1) = \boxed{-1.5 \text{ V}}$$

(c) For equal weights:  $R_1 = R_2 = R_3 = R$  (any equal value, e.g.,  $10 \text{ k}\Omega$ )

# Practice Problem 4

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Summary and  
Practice

**Given:** An integrator circuit with  $R = 100 \text{ k}\Omega$  and  $C = 1 \mu\text{F}$

**Find:**

- (a) The time constant  $\tau = RC$
- (b) If a constant input  $v_{in} = 2 \text{ V}$  is applied starting at  $t = 0$  (with  $v_{out}(0) = 0$ ), find  $v_{out}$  at  $t = 0.1 \text{ s}$
- (c) At what time will the output reach  $-5 \text{ V}$ ?
- (d) What is the magnitude of the transfer function at  $f = 10 \text{ Hz}$ ?

**Hint:**  $v_{out}(t) = -\frac{1}{RC} \int_0^t v_{in}(\tau) d\tau$ , and  $|H(f)| = \frac{1}{2\pi f RC}$

# Practice Problem 4 Solution

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**Given:**  $R = 100 \text{ k}\Omega$ ,  $C = 1 \mu\text{F}$ ,  $v_{in} = 2 \text{ V}$  (constant)

**Solutions:**

(a) Time constant:

$$\tau = RC = (100 \times 10^3)(1 \times 10^{-6}) = \boxed{0.1 \text{ s}}$$

(b) At  $t = 0.1 \text{ s}$ :

$$v_{out}(t) = -\frac{1}{RC} \int_0^t 2 d\tau = -\frac{2}{RC} \cdot t$$

$$v_{out}(0.1) = -\frac{2}{0.1} \times 0.1 = \boxed{-2 \text{ V}}$$

(c) For  $v_{out} = -5 \text{ V}$ :

$$-5 = -\frac{2}{0.1} \cdot t \Rightarrow t = \frac{5 \times 0.1}{2} = \boxed{0.25 \text{ s}}$$

(d) At  $f = 10 \text{ Hz}$ :

$$|H(f)| = \frac{1}{\omega_{-f} RC} = \frac{1}{\omega_{-(10)(0.1)}} = \frac{1}{\omega_-} \approx \boxed{0.159}$$

# Practice Problem 5

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Summary and  
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**Given:** A difference amplifier with the following components:

- $R_1 = R_3 = 10 \text{ k}\Omega$
- $R_2 = R_4 = 50 \text{ k}\Omega$
- Input voltages:  $v_1 = 2.5 \text{ V}$ ,  $v_2 = 3.0 \text{ V}$

**Find:**

- (a) Verify that the resistor matching condition is satisfied
- (b) The differential gain  $A_d$
- (c) The output voltage  $v_{out}$
- (d) If  $v_1 = v_2 = 2.5 \text{ V}$  (common-mode), what is  $v_{out}$  (ideally)?

**Hint:** Matching condition:  $\frac{R_2}{R_1} = \frac{R_4}{R_3}$ , and  $v_{out} = A_d(v_2 - v_1)$

# Practice Problem 5 Solution

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**Given:**  $R_1 = R_3 = 10 \text{ k}\Omega$ ,  $R_2 = R_4 = 50 \text{ k}\Omega$

**Inputs:**  $v_1 = 2.5 \text{ V}$ ,  $v_2 = 3.0 \text{ V}$

**Solutions:**

(a) Check matching condition:

$$\frac{R_2}{R_1} = \frac{50}{10} = 5, \quad \frac{R_4}{R_3} = \frac{50}{10} = 5$$

$$\boxed{\frac{R_2}{R_1} = \frac{R_4}{R_3} \checkmark} \quad (\text{condition satisfied})$$

(b) Differential gain:

$$A_d = \frac{R_2}{R_1} = \frac{50}{10} = \boxed{5}$$

(c) Output voltage:

$$v_{out} = A_d(v_2 - v_1) = 5(3.0 - 2.5) = 5(0.5) = \boxed{2.5 \text{ V}}$$

(d) Common mode input ( $v_{in+} - v_{in-}$ ):

# Advanced Application: Instrumentation Amplifier (Preview)

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## Limitations of Simple Difference Amp:

- Finite input impedance
- Limited CMRR (requires precise matching)
- Gain-impedance tradeoff

## Instrumentation Amplifier:

- Three op-amp configuration
- Very high input impedance (both inputs)
- Excellent CMRR ( $>100$  dB)
- Single resistor sets gain
- Industry standard for precision measurement

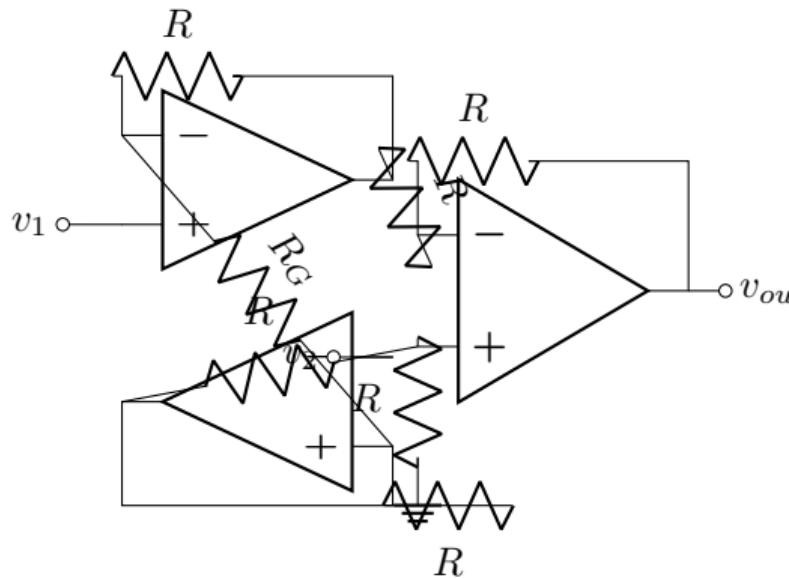


Figure 15: Three op-amp instrumentation

# Comparison of Configurations

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Feature	Inverting	Noninverting	Difference
Phase shift	$180^\circ$	$0^\circ$	$0^\circ$ (for $v_2 - v_1$ )
Input impedance	$R_1$	$\infty$	Finite at both
Minimum gain	0 (can attenuate)	1	0
Gain polarity	Negative	Positive	Positive
Complexity	Simple	Simple	Moderate
Virtual ground	Yes (at $v_-$ )	No	No
CMRR	N/A	N/A	Depends on matching

Table 2: Comparison of basic op-amp configurations

## Design Guidelines

- Use **inverting** when: phase inversion acceptable, moderate  $R_{in}$  OK
- Use **noninverting** when: high  $R_{in}$  needed, no phase inversion
- Use **difference** when: differential measurement needed, CMRR important

# Practical Considerations

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## Resistor Selection:

- Typical range:  $1\text{ k}\Omega$  to  $1\text{ M}\Omega$
- Too low: excessive current, power
- Too high: noise pickup, offset errors
- Use 1% or better for precision
- Match resistors for difference amp

## Capacitor Selection:

- Integrator: low-leakage (polypropylene, polyester)
- Avoid electrolytic for precision
- Consider temperature coefficients
- ESR affects high-frequency performance

## Common Mistakes:

- 1 Forgetting DC path (integrator saturation)
- 2 Exceeding op-amp output current limit
- 3 Ignoring bandwidth limitations
- 4 Poor layout causing oscillations
- 5 Wrong polarity on electrolytic caps

## Verification Steps:

- Check DC operating point
- Verify gain with known input
- Test frequency response
- Check for distortion/clipping
- Measure with realistic loads