

Operational Amplifier Applications

Feedback Configurations and Mathematical Operations

Maxx Seminario

University of Nebraska-Lincoln

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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:

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

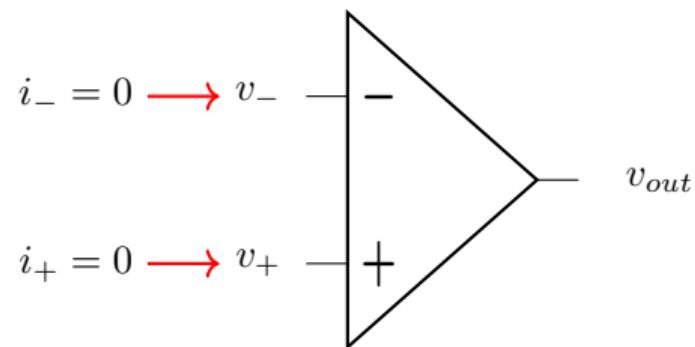


Figure 1: Ideal op-amp terminals

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:

$$v_+ = v_-$$

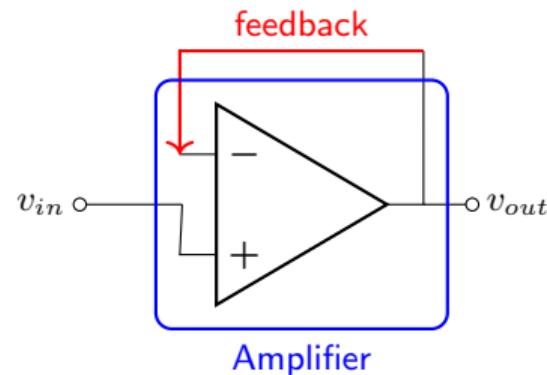


Figure 2: Negative feedback block diagram

Result:

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

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Circuit Configuration:

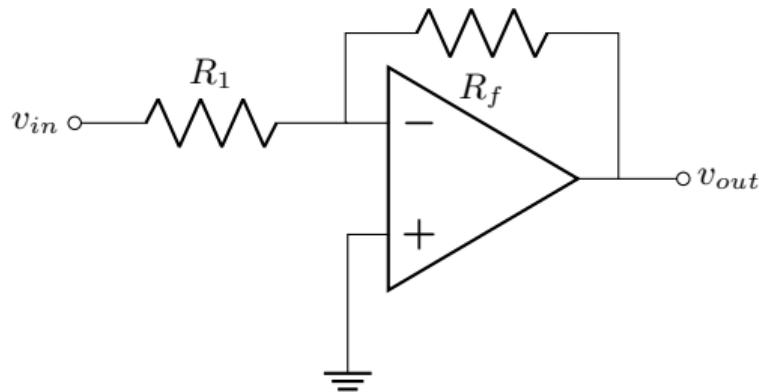


Figure 3: Inverting amplifier circuit

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!)
- $R_{in} = 20 \text{ k}\Omega$

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Circuit Configuration:

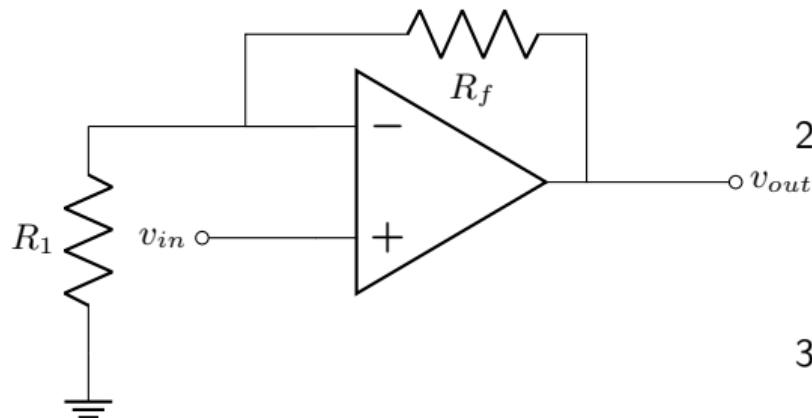


Figure 4: Noninverting amplifier circuit

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. Solve for gain:

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

$$\frac{v_{out}}{v_{in}} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}$$

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)
- ☺ No loading of source

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

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

Example 3: Gain of 1

- $R_1 = \infty, R_f = 0$
- $A_v = 1 + 0 = 1$

Noninverting Amplifier: Voltage Follower (Unity-Gain Buffer)

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Special Case - Voltage Follower:

- $R_f = 0$ (short circuit)
- $R_1 = \infty$ (open circuit)
- $A_v = 1$ (unity gain buffer)

Key Features:

- ☺ Output tracks the input: $v_{out} \approx v_{in}$
- ☺ High input impedance, allows it to sense the input without loading it
- ☺ Low output impedance allows it to drive heavy loads
- ☺ Used to isolate stages, prevent loading effects

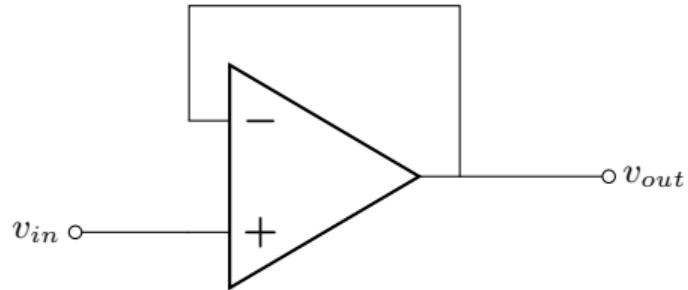


Figure 5: Unity Gain Buffer

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Circuit Configuration:

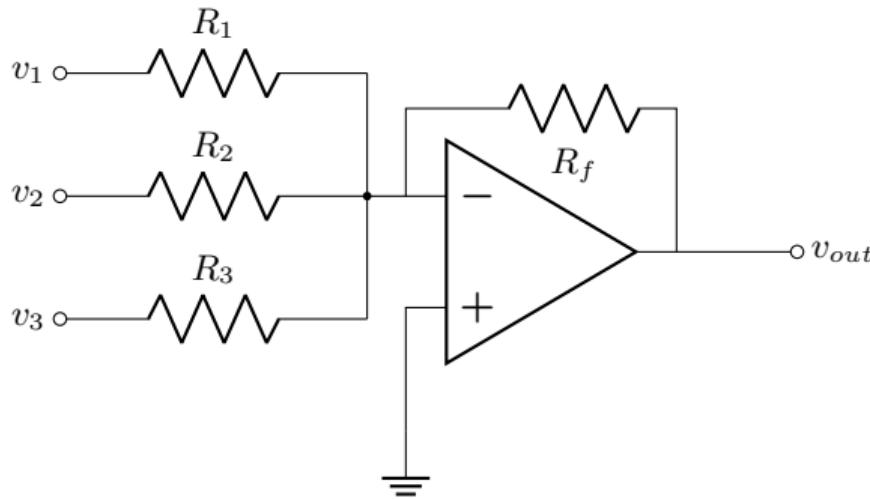


Figure 6: Summing amplifier (3 inputs)

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:

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

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

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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)
- Signal averaging

Example: 3-bit DAC:

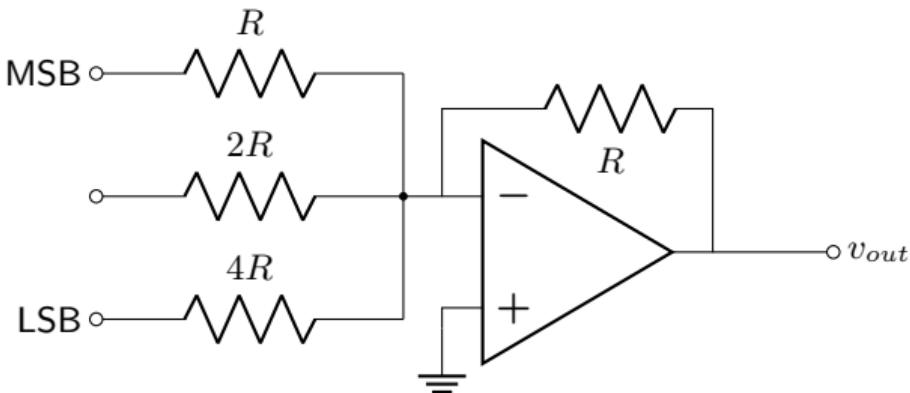


Figure 7: Binary-weighted 3-bit DAC

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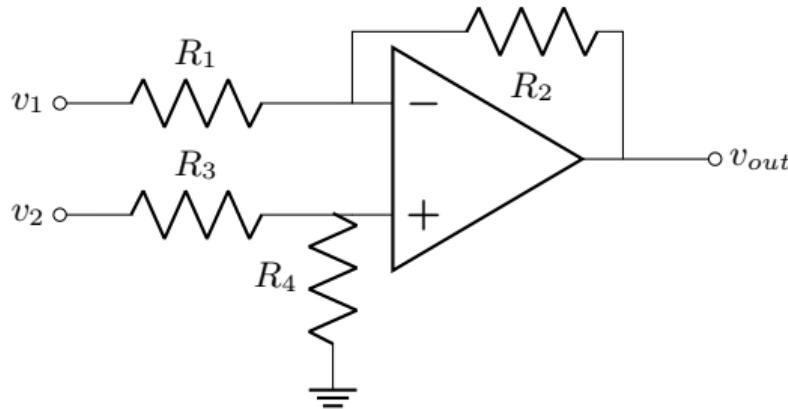


Figure 8: Difference amplifier

Analysis:

Voltage at noninverting input:

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

Current through R_1 :

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

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

$$v_{out} = \frac{R_2}{R_1} (v_2 - v_1)$$

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

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
- Noise rejection (common-mode)
- Biomedical amplifiers (ECG, EEG)

Advantages:

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

Limitations:

- 😢 Requires precision resistor matching
- 😢 Finite input impedance at both inputs
- 😢 Limited CMRR (compared to instrumentation amp)

The Integrator

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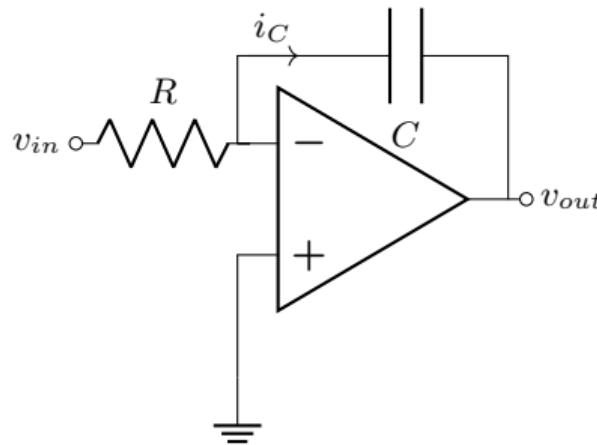


Figure 9: Inverting integrator

Analysis:

1. Virtual ground: $v_- = 0$
2. Current through R :

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

4. Capacitor voltage-current relation:

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

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

$$\frac{v_{in}}{R} = C \frac{d(-v_{out})}{dt}$$

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Transfer Function:

From:

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

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

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

Interpretation:

- Output is (inverted) integral of input
- Time constant: $\tau = RC$
- Initial condition: $v_{out}(0)$ (capacitor voltage)

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!)

Integrator: Waveform Examples

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Example 1: Step Input

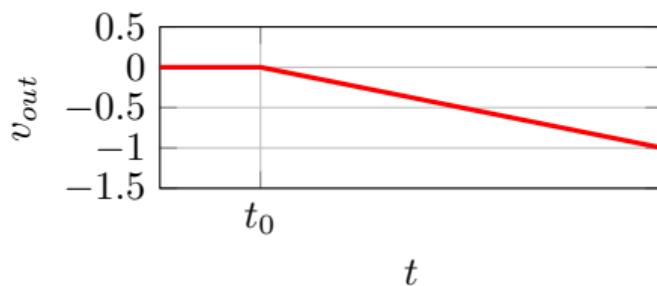
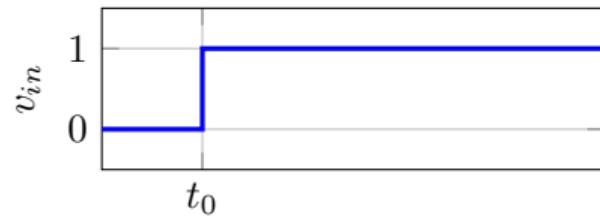


Figure 10: Step input produces ramp output

Example 2: Square Wave Input

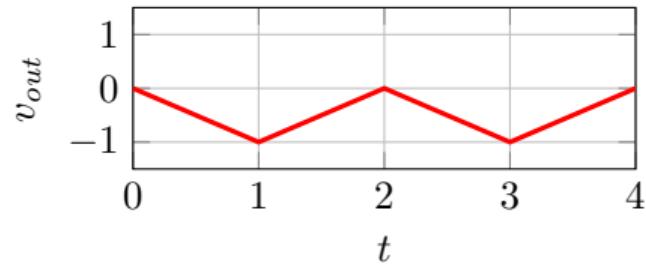
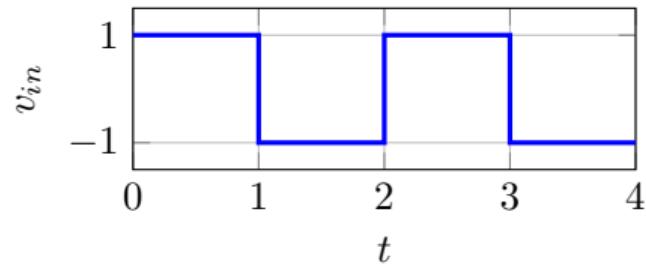


Figure 11: Square wave produces triangle wave

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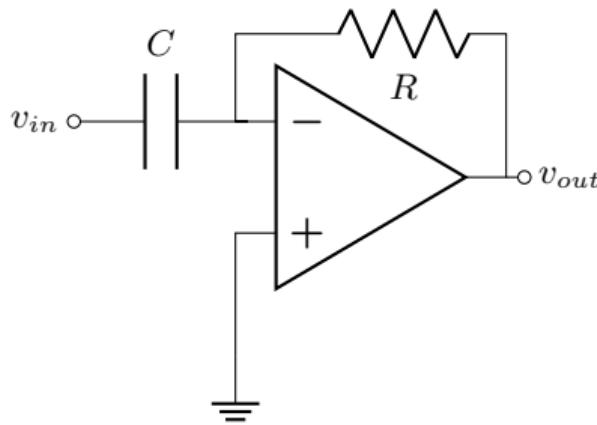


Figure 12: Inverting differentiator

Note: Integrator with R and C swapped

Analysis:

1. Virtual ground: $v_- = 0$
2. Capacitor current:

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

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

3. Output voltage:

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

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

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
- $R_s \ll R$ (typically $R_s \approx R/10$)

Practical Note

Differentiators are rarely used in practice due to noise sensitivity

Differentiator: Waveform Examples

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Example 1: Ramp Input

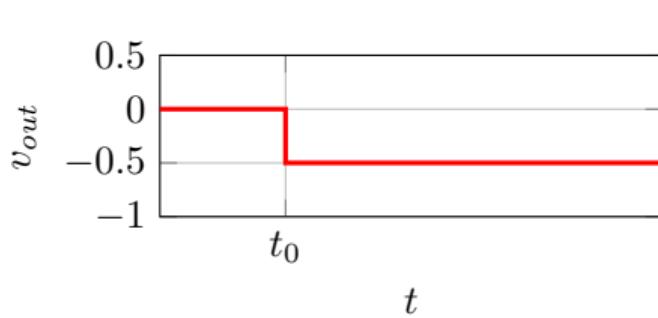
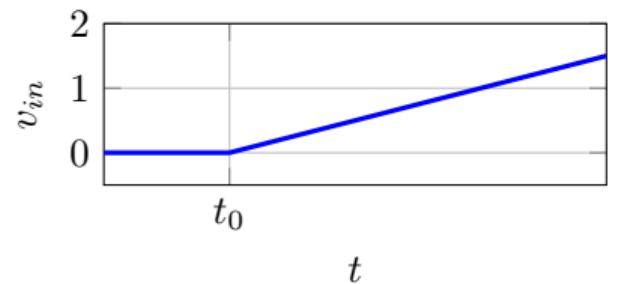


Figure 13: Ramp input produces constant

Example 2: Triangle Wave Input

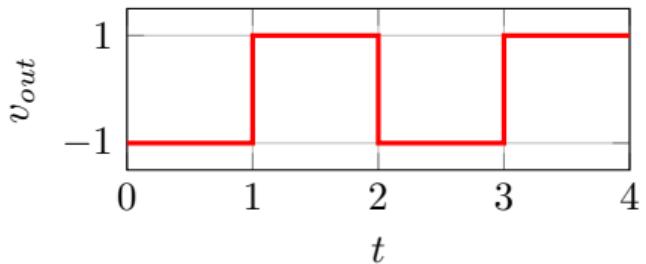
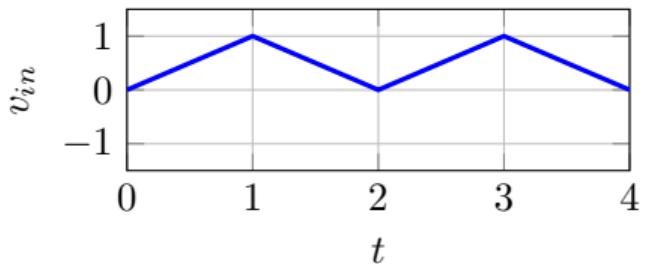


Figure 14: Triangle wave produces square wave

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Configuration	Gain	R_{in}	Application
Inverting	$-\frac{R_f}{R_1}$	R_1	Amplification with inversion
Noninverting	$1 + \frac{R_f}{R_1}$	∞	Amplification, no inversion
Voltage Follower	1	∞	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	$-\frac{1}{RC} \int v_{in} dt$	∞ (AC)	Analog computation, filters
Differentiator	$-RC \frac{dv_{in}}{dt}$	$\rightarrow 0$ (HF)	Rarely used (noise!)

Table 1: Summary of op-amp configurations

Standard Analysis Steps

- 1 Apply virtual short: $v_+ = v_-$ (with negative feedback)
- 2 Apply zero input current: $i_+ = i_- = 0$
- 3 Use KCL at input nodes
- 4 Solve for output voltage

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 $R_{in} = R_1$

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

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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 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 5

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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 $v_{out} = A_d(v_2 - v_1)$

Advanced Application: Instrumentation Amplifier

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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

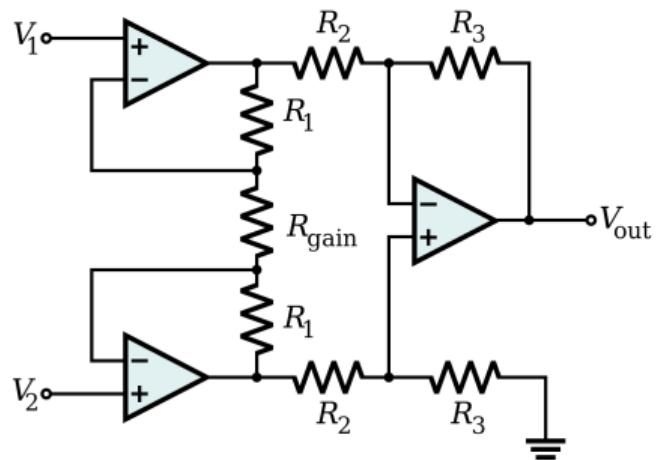


Figure 15: Instrumentation amplifier schematic

$$A_v = \left(1 + \frac{2R}{R_G}\right)$$

Comparison of Configurations

Op-Amp
Applications

Maxx Seminario

Review and
Negative
Feedback

Inverting
Amplifier

Noninverting
Amplifier

Summing
Amplifier

Difference
Amplifier

Integrator

Differentiator

Summary and
Practice

Feature	Inverting	Noninverting	Difference
Phase shift	180°	0°	0° (for $v_2 - v_1$)
Input impedance	R_1	∞	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
- Use **integrator** for: low-pass filtering, waveform generation