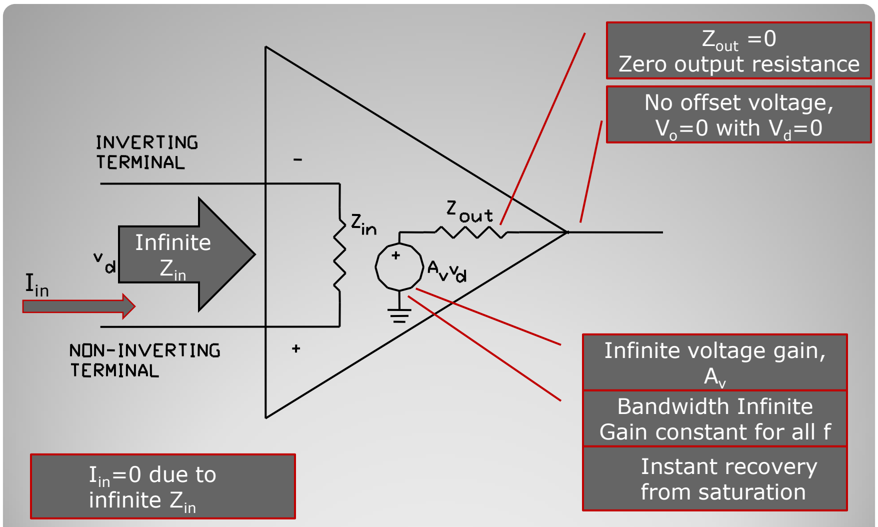
Lesson 3: Operational Amplifier Circuits in Analog Control

ET 438a
Automatic Control Systems Technology

Learning Objectives

After this presentation you will be able to:

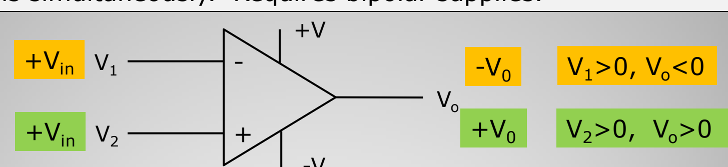
- List the characteristics of an ideal Operational Amplifier (OP AMP) circuit.
- Identify and utilize fundamental OP AMP circuits to amplify and signals.
- Use OP AMP circuits to reduce inter-stage loading effects in sensor circuits.
- Average sensor signals using OP AMP circuits.



Ideal OP AMP Characteristics

OP AMPs are voltage amplifiers designed originally for use in analog computers

OP AMPs are direct coupled (dc) amplifiers that amplify both ac and dc signals simultaneously. Requires bipolar supplies.

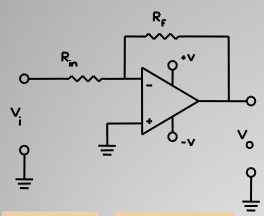


Schematic symbol for non-ideal OP AMP

Two inputs: V_1 = inverting input
V_2 = non inverting input

Non-Ideal OP AMPs

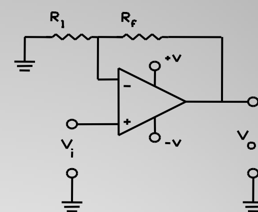
Inverting Voltage Amplifier



$$A_V = \frac{-R_f}{R_{in}} \qquad V_o = V_i\left(\frac{-R_f}{R_{in}}\right)$$

V_o Limited by saturation
Large A_v causes $V_o = \pm V$

Non-Inverting Voltage Amplifier



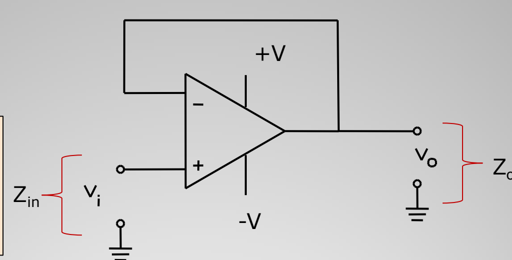
$$A_V = \left(1 + \frac{R_f}{R_{in}}\right) \qquad V_o = V_i\left(1 + \frac{R_f}{R_{in}}\right)$$

R_{in} = R_{in} of OP AMP
A_v has minimum value of 1

Fundamental OP AMP Circuits

Voltage follower (Impedance buffer) circuit used to reduce circuit loading. (Has a high Z_{in} and low Z_{out})

Circuit causes minimum loading on previous stage



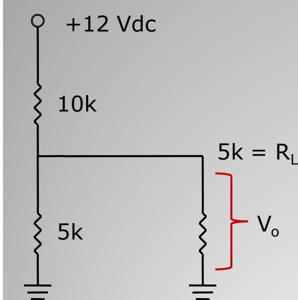
Characteristics

Practical Circuit (LM741)
A_v = 1
Z_{in} = 1 MΩ
Z_o = 10 Ω

Ideal
A_v = 1
Z_{in} = infinite
Z_o = 0

Voltage Follower Circuit

Voltage divider formula only valid for infinite load resistance



Find V_o under load

No load V_o

$$V_o = \left(\frac{5\ \text{k}\Omega}{5\ \text{k}\Omega + 10\ \text{k}\Omega}\right) \cdot 12\ \text{V}$$

$$V_0 = 4.0\ \text{V}$$

With load resistor

$$R_L \parallel 5\ \text{k}\Omega = 5\ \text{k}\Omega \parallel 5\ \text{k}\Omega = 2.5\ \text{k}\Omega$$

$$V_{oL} = \left(\frac{2.5\ \text{k}\Omega}{2.5\ \text{k}\Omega + 10\ \text{k}\Omega}\right) \cdot 12\ \text{V} = 2.4\ \text{V}$$

ANS

Example 3-1 Buffered Voltage Divider Circuit

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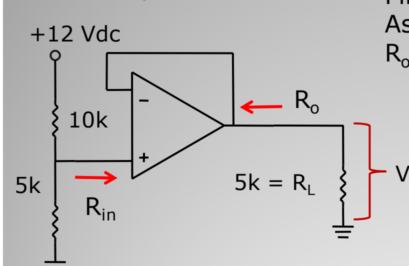
Add impedance buffer



Find V_o with load and OP AMP buffer
Assume LM741 with R_i=1 MΩ and R_o =10 Ω A_V= 1 so V_{in} = V_o

With load resistor

$$R_L \parallel 1\ \text{M}\Omega = 5\ \text{k}\Omega \parallel 1\ \text{M}\Omega = R_{eq}$$

$$R_{eq} = \frac{1\ \text{M}\Omega \cdot 5\ \text{k}\Omega}{1\ \text{M}\Omega + 5\ \text{k}\Omega} = 4975\ \Omega$$

$$V_{in} = \left(\frac{4975\ \Omega}{4975\ \Omega + 10\ \text{k}\Omega}\right) \cdot 12\ \text{V} = 3.987\ \text{V}$$

$$V_{in} = V_o = 3.987\ \text{V}$$

ANS

Example 3-1 Buffered Voltage Divider Circuit (1)

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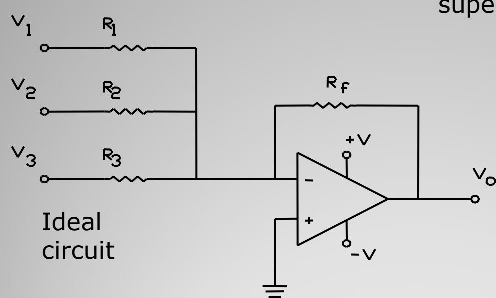
Inverting Summing Amplifier

Find total output using superposition



Ideal circuit

Gain v_1 $\frac{-R_f}{R_1}$

Gain v_2 $\frac{-R_f}{R_2}$

Gain v_3 $\frac{-R_f}{R_3}$

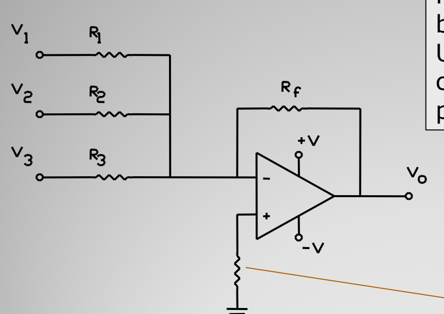
Total output $$v_o = -R_f\left(\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3}\right)$$

Output is inverted sum of v_1, v_2, and v_3

Electronic Addition and Subtraction

Improved circuit (non-ideal OP AMP)

Practical OP AMP chips require bias currents to operate. Unequal R values at each input cause voltage differences that produce output errors.

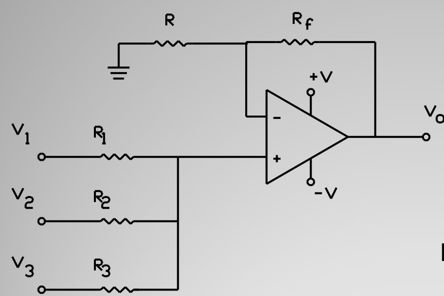


Bias compensation R

$$R_c = R_1 \,||\, R_2 \,||\, R_3 \,||\, R_f$$

Electronic Addition and Subtraction

Non-inverting Summing Amp



Assuming $R_1 = R_2 = R_3$

$$v_0 = \left(1 + \frac{R_f}{R}\right)\left(\frac{v_1 + v_2 + v_3}{3}\right)$$

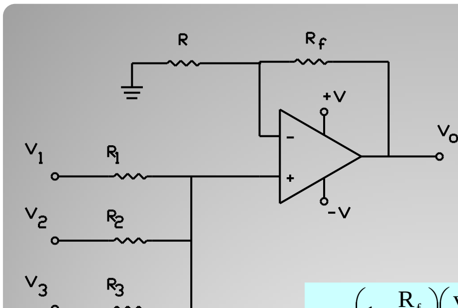
For any number, n, inputs.

$$v_0 = \left(1 + \frac{R_f}{R}\right)\left(\frac{v_1 + v_2 + \ldots\ldots + v_n}{n}\right)$$

n input average

Assuming $R_1 = R_2 = R_3 = \ldots R_n$

Electronic Addition and Subtraction



For circuit shown n=3
$R_1 = R_2 = R_3 = 56k$
$R_f = 9k \quad R = 1k$
$V_1 = 0.5$ Vdc
$V_2 = 0.37$ Vdc
$V_3 = 0.8$ Vdc Find V_o

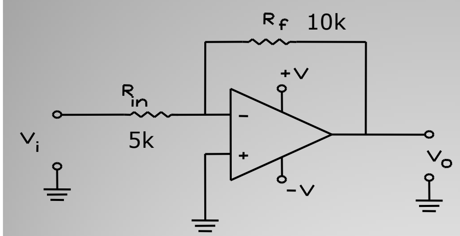
$$v_0 = \left(1 + \frac{R_f}{R}\right)\left(\frac{v_1 + v_2 + v_3}{3}\right)$$

$$v_0 = \left(1 + \frac{9k}{1k}\right)\left(\frac{0.5 + 0.37 + 0.8}{3}\right) = 5.5667$$

ANS

Example 3-2 Non-inverting Averager

For the circuit shown find V_o with V_{in} = 2 Vdc



$$V_o = \frac{-R_f}{R_{in}} V_i$$

$$V_o = \frac{-10k\Omega}{5k\Omega} V_i$$

$V_o = -2V_i \quad V_i = 2.0$

$V_o = -2(2.0V) = \boxed{-4\ Vdc}$

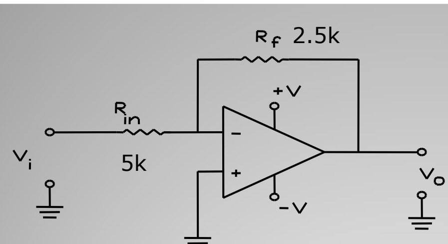
LET $R_f = 5k\Omega$ Find A_v and V_o for $V_i = 2.0$

$A_v = \frac{-R_f}{R_i} = \frac{-5k\Omega}{5k\Omega} = \boxed{-1}$ Inverting voltage follower

$V_{in} = 2.0\,Vdc$

$V_o = (-1)(2\,Vdc) = \boxed{-2.0\,Vdc}$

Example 3-3:Inverting Amplifier



Let R_f= 2.5 kΩ and find A_v and V_o for V_i= 2.0 Vdc

$$A_v = \frac{-R_f}{R_{in}} = \frac{-2.5k\Omega}{5k\Omega} = -0.5$$

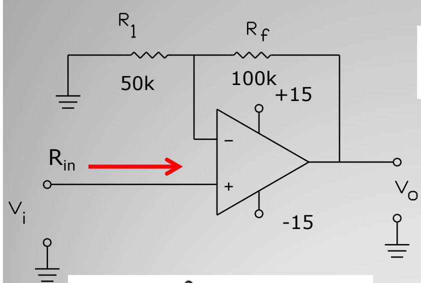
Reduces input voltage

$$V_o = A_v V_i = -0.5(2.0V) = -1\,Vdc$$

Output is smaller than input. Circuit divides input by 2 (0.5 = ½)

Example 3-3: Solution (2)

Find V_o and A_v given values of R and V_i = -1 Vdc. Assume non-ideal OP AMP with power supply values of ±15 Vdc



$$V_o = V_i\left(1+\frac{R_f}{R_1}\right) = V_i\left(1+\frac{100k\Omega}{50k\Omega}\right)$$

$$V_o = -1(3) = \boxed{-3\ Vdc}$$

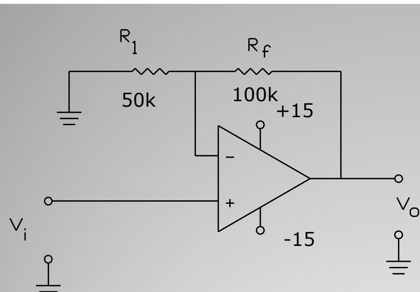
No sign change

$$A_v = \left(1+\frac{R_f}{R_1}\right) = 1+\frac{100k\Omega}{50k\Omega}$$

$$A_v = 1+2 = \boxed{3}$$

Note: R_{in} of non-inverting OP AMP is infinite (Ideally). Circuit will not load previous stage significantly

Example 3-4 Non-Inverting Amp (1)



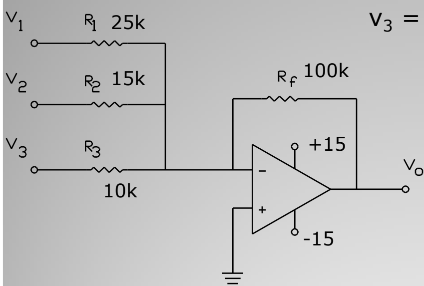
V_{in} rises to 6 Vdc. What is V_o? Assume a non-ideal OP AMP with given power supply values of ±15 Vdc

$$V_o = A_v V_i = 3(6) = 18\ Vdc$$

This value can’t be achieved since the OP AMP saturates between 13-15 Vdc. Power supplies limit output. Ac signals distorted (clipping)

Example 3-4 Solution (2)

Find V_o given $v_1 = 0.2$ Vdc $v_2 = 0.1$ Vdc $v_3 = -0.1$ Vdc



$$V_o = -R_f\left(\frac{V_1}{R_1}+\frac{V_2}{R_2}+\frac{V_3}{R_3}\right)$$

$$V_o = \frac{-R_f}{R_1}V_1 + \frac{-R_f}{R_2}V_2 + \frac{-R_f}{R_3}V_3$$

$$V_o = \frac{-100k}{25k}V_1 + \frac{-100k}{15k}V_2 + \frac{-100k}{10k}V_3$$

$$V_o = -4(0.20) + -6.667(0.1) + -10(-0.1)$$

Gains

$$V_o = -0.8 - 0.6667 + 1.0 \text{ Vdc}$$

$$V_o = -0.4667 \text{ Vdc}$$

Example 3-5 Inverting Summing Amplifier

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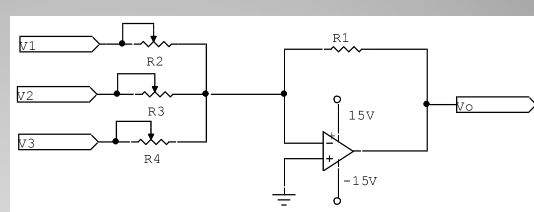
Letting R_1, R_2 and R_3 be potentiometers produces an audio mixer

When $R_1=R_2=R_3$ Output voltage is the average of the input values



Summing Amplifier Applications

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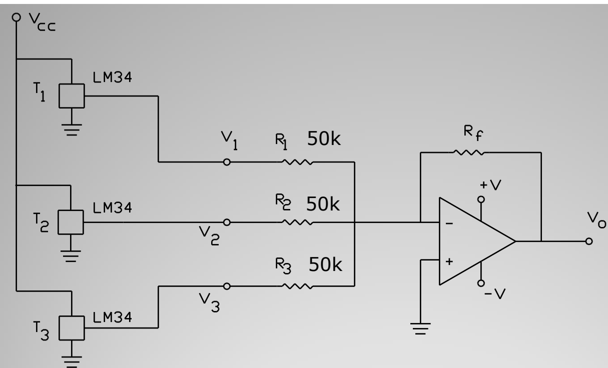


LM34 - temperature sensors. Gain = 10 mV/F
T_1 = 50 F T_2 = 45 F T_3= 40 F

Average the temperature using a gain of -1 and -5. Find the value of R_f and V_o for each gain value.

Example 3-6: Averaging Sensor Signals

To average let $R_1=R_2=R_3=50\ k\Omega$

Summing equation $V_0 = -R_f\left(\frac{v_1}{R_1}+\frac{v_2}{R_2}+\frac{v_3}{R_3}\right)$

Since $R_1=R_2=R_3$ $V_0 = -R_f\left(\frac{v_1}{R_1}+\frac{v_2}{R_1}+\frac{v_3}{R_1}\right) = -\left(\frac{R_f}{R_1}\right)(v_1+v_2+v_3)$

Find relationship for average with 3 inputs and gain of -1

$$V_{ave} = -1\cdot\left[\frac{v_1+v_2+v_3}{3}\right]$$

$$V_o = V_{ave} = -\left(\frac{R_f}{R_1}\right)(v_1+v_2+v_3) = -\left(\frac{1}{3}\right)(v_1+v_2+v_3)$$

Example 3-6 Solution (1)

Complete Algebra to find value of R_f

$$-\left(\frac{R_f}{R_1}\right) = -\left(\frac{1}{3}\right)$$

$$R_f = \frac{R_1}{3}$$

Make equation more general by letting n be the number of inputs and A_v be the desired gain factor.

$$V_0 = -R_f\left(\frac{v_1}{R_1} + \frac{v_2}{R_1} \ldots + \frac{v_n}{R_1}\right) = -\left(\frac{R_f}{R_1}\right)(v_1 + v_2 \ldots + v_n)$$

$$V_{ave} = -A_v \cdot \left[\frac{v_1 + v_2 \ldots + v_n}{n}\right]$$

Example 3-6 Solution (2)

Equate the OP AMP output and the average formula

$$V_o = V_{ave} = -\left(\frac{R_f}{R_1}\right)(v_1 + v_2 \ldots + v_n) = -\left(\frac{A_v}{n}\right)(v_1 + v_2 \ldots + v_n)$$

$$-\left(\frac{R_f}{R_1}\right) = -\left(\frac{A_v}{n}\right)$$

$$R_f = \frac{A_v \cdot R_1}{n}$$ Use this formula

Find sensor output voltages using temperature and gain value

$$T_1 = 50^\circ\ F \quad V_1 = (10\ mV/F)(50^\circ\ F) = 0.5\ V$$

$$T_2 = 45^\circ\ F \quad V_2 = (10\ mV/F)(45^\circ\ F) = 0.45\ V$$

$$T_3 = 40^\circ\ F \quad V_3 = (10\ mV/F)(40^\circ\ F) = 0.40\ V$$

Example 3-6 Solution (3)

Find R_f and V_o for a gain of -1 and R_1=50 kΩ, n=3

$$R_f = \frac{A_v \cdot R_1}{n} = \frac{1 \cdot 50{,}000\,\Omega}{3} = 16{,}670\,\Omega$$ ANS

$$-\left(\frac{R_f}{R_1}\right)(v_1 + v_2 + v_3) = -\left(\frac{16.67k}{50k}\right)(0.50 + 0.45 + 0.40) = -0.45\text{ V}$$ ANS

Use average formula to check output

$$V_{ave} = -1 \cdot \left(\frac{(0.50 + 0.45 + 0.40)}{3}\right) = -0.45$$ Checks

Example 3-6 Solution (4)

Find R_f and V_o for a gain of -5 and R_1=50 kΩ, n=3

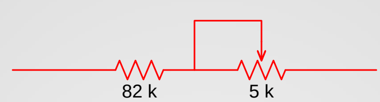
$$R_f = \frac{A_v \cdot R_1}{n} = \frac{5 \cdot 50{,}000\,\Omega}{3} = 83{,}330\,\Omega$$ ANS

$$V_o = -\left(\frac{R_f}{R_1}\right)(v_1 + v_2 + v_3) = -\left(\frac{83.33k}{50k}\right)(0.50 + 0.45 + 0.40) = -2.25\text{ V}$$ ANS

$$V_{ave} = -5 \cdot \left(\frac{(0.50 + 0.45 + 0.40)}{3}\right) = -2.25$$

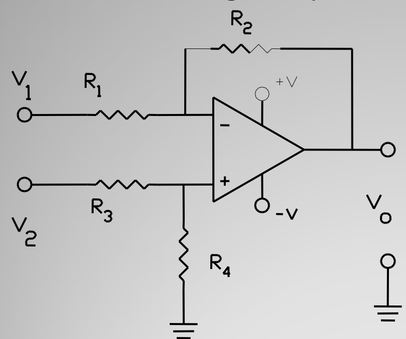
Note: both values of R_f are not standard values. Use potentiometer and closest standard value then calibrate circuit to get desired output

Practical R_f



Example 3-6 Solution (5)

Differential Voltage Amplifier Circuit



Input/output Formula

$$V_o = \left(\frac{R_2 + R_1}{R_4 + R_3}\right) \cdot \left(\frac{R_4}{R_1}\right) \cdot V_2 - \left(\frac{R_2}{R_1}\right) \cdot V_1$$

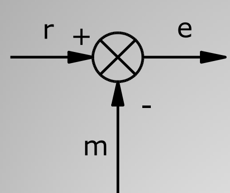
To simplify let
R1 = R3 R2 = R4

$$V_o = \left(\frac{R_2}{R_1}\right)(V_2 - V_1)$$

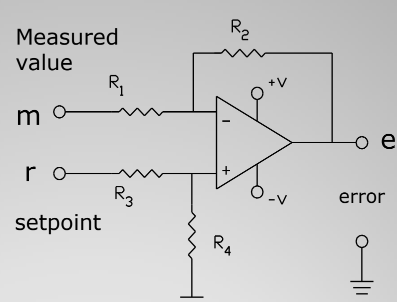
Amplifiers the difference between + - terminals

Differential Voltage Amplifier

Can use voltage differential amp to generate an error signal



Block diagram



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Differential Amplifier Applications

End Lesson 3: Operational Amplifier Circuits in Analog Control

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