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# Circuit Theory (SKEE 1023)

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# Operational Amplifiers

## Topics

- Operational Amplifiers, Ideal Op Amp, Inverting Amplifier, Noninverting Amplifier, Summing Amplifier, Difference Amplifier, Cascaded Op Amp Circuits.

# Operational Amplifiers

## Introduction

- The operational amplifier (op amp) is an electronic unit that behaves like a voltage-controlled voltage source.
- An op amp can sum signals, amplify a signal, integrate it or differentiate it.
- An op amp is an active circuit element designed to perform mathematical operations of addition, subtraction, multiplication, division, differentiation and integration.
- The op amp is an electronic device consisting of a complex arrangement of resistors, transistors, capacitors, and diodes.

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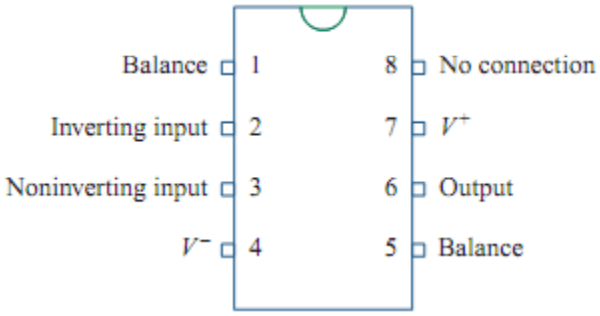
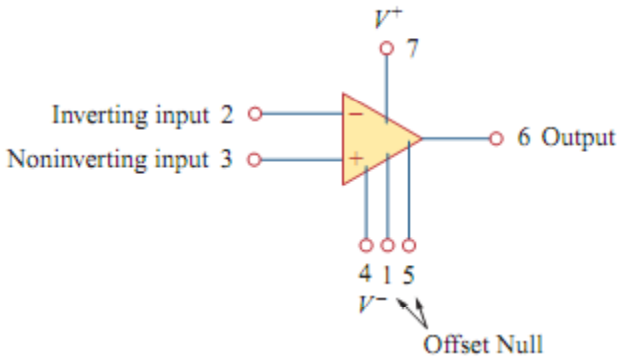
# Operational Amplifiers

## Introduction

- ✓ A typical op amp: (a) pin configuration, (b) circuit symbol.

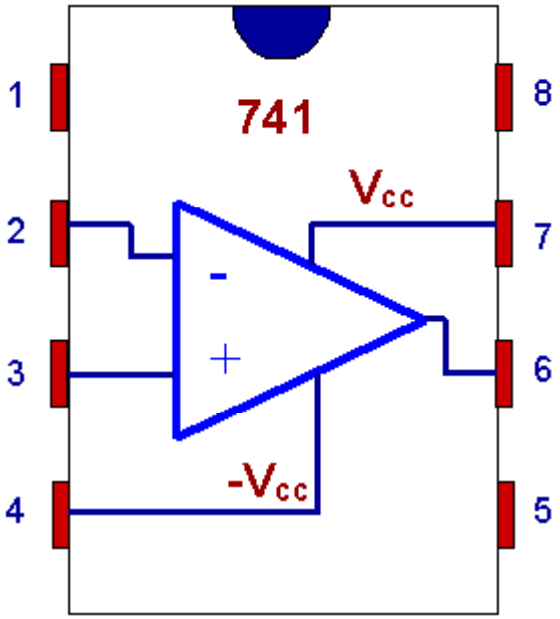



(a)

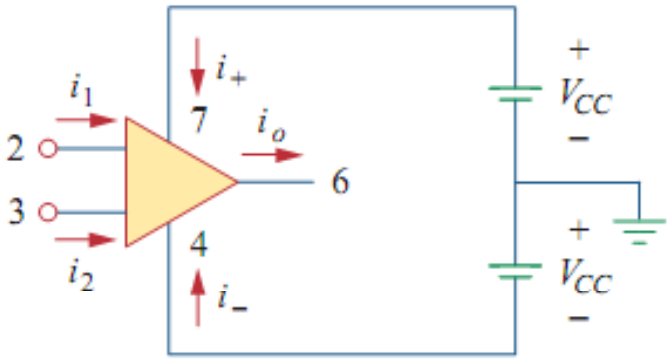



(b)

## Introduction



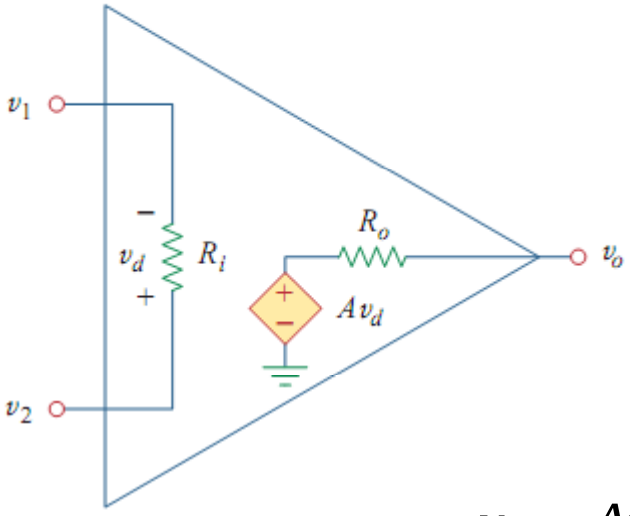

- ✓ Powering the op amp




$$i_o = i_1 + i_2 + i_+ + i_-$$

# Introduction

- ✓ Equivalent circuit of the non-ideal op amp




The differential input voltage, $v_d$ ;

$$v_d = v_2 - v_1$$

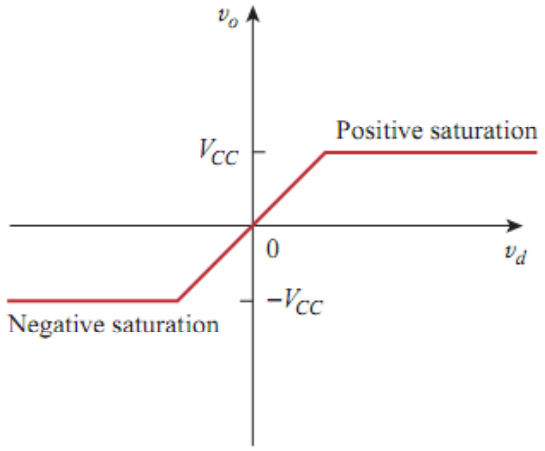
- ✓ Op amp senses the difference between the two inputs, multiplies it by the gain *A*, and causes the resulting output.

$$v_o = Av_d = A(v_2 - v_1)$$

$A$ : open - loop voltage gain

# Introduction

- The concept of feedback is crucial to understanding of op amp circuits.
- Negative feedback is achieved when the output is fed back to the inverting terminal of the op amp.
- The ratio of the output voltage to the input voltage is called the closed-loop gain, $\Rightarrow$ $(v_o / v_s)$
- A practical limitation of the op amp is that the magnitude of its output voltage cannot exceed |Vcc |.



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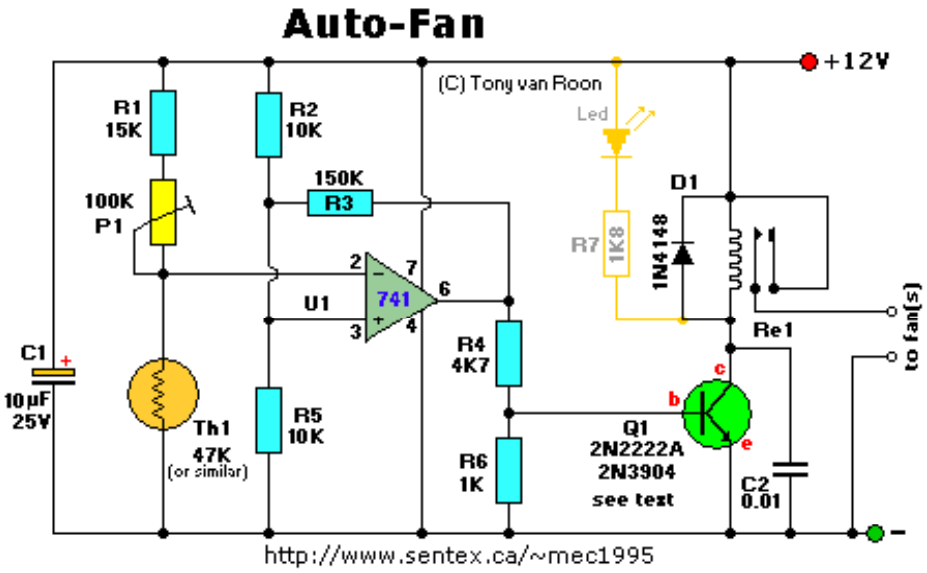
# Operational Amplifiers

- ✓ Some applications of op amp



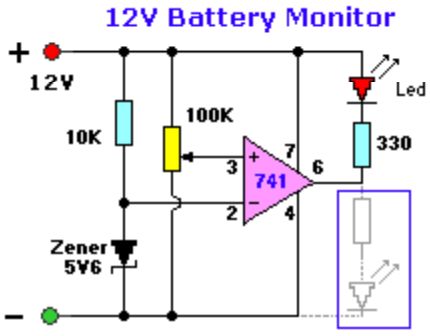




Fig. 14

## Smart Continuity Tester

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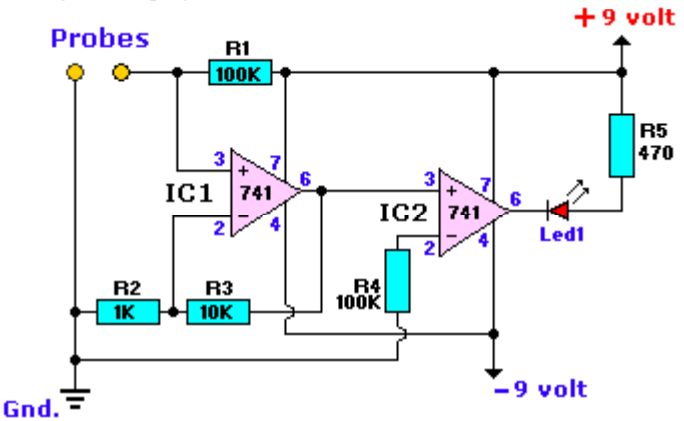
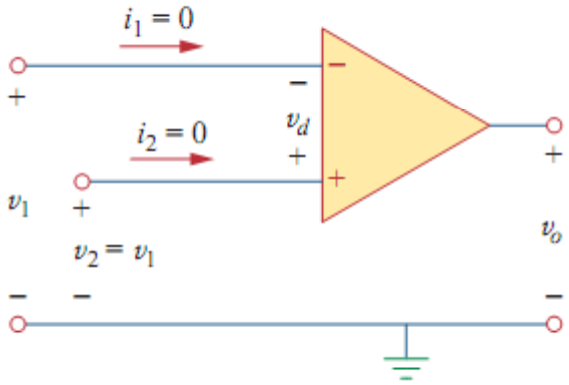



Gnd., +9V, and -9V NEEDS to be connected or the circuit will NOT work!

# Ideal Op Amp

- An ideal op amp is an amplifier with infinite open-loop gain, infinite input resistance, and zero output resistance.
- Two important characteristics of the ideal op amp are:
  - The currents into both input terminals are zero.
  - The voltage across the input terminals is equal to zero



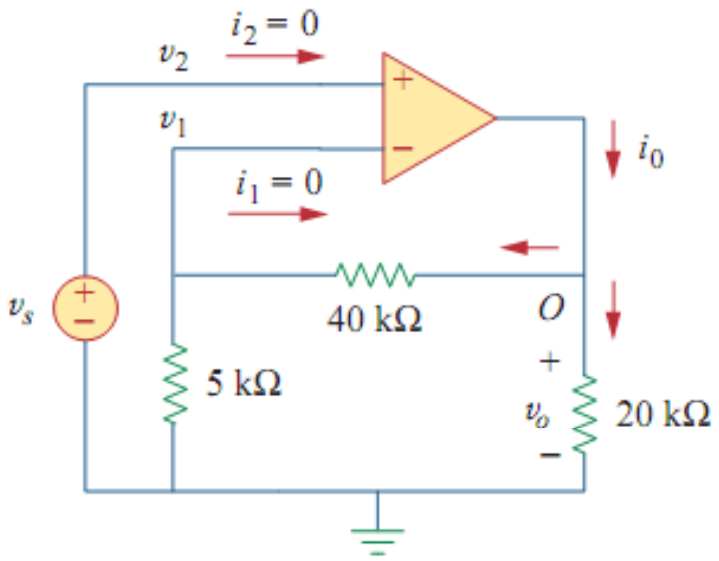

$$i_1 = 0; \quad i_2 = 0$$

$$v_d = v_2 - v_1 = 0$$

$$v_1 = v_2$$

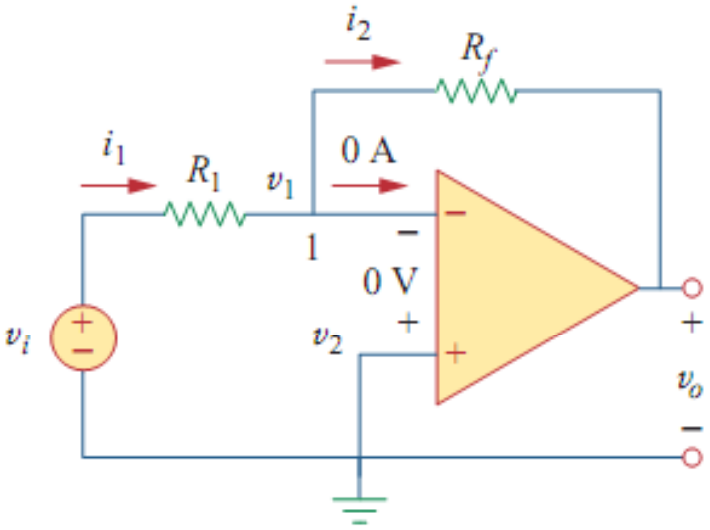
# Example 1

Calculate the closed-loop gain ($v_o$ / $v_s$). Find $i_o$ when $v_s$ = 1V.



# Inverting Op Amp

- ✓ $v_i$ is connected to the inverting input through $R_1$, and the feedback resistor $R_f$ is connected between the inverting input and output




$$i_1 = i_2 \Rightarrow \frac{v_i - v_1}{R_1} = \frac{v_1 - v_o}{R_f}$$

$v_1 = v_2 = 0$ for an ideal op amp.

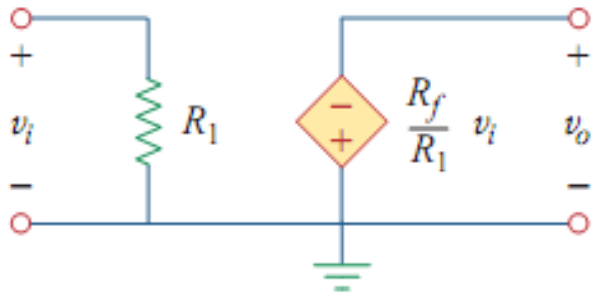
Noninverting terminal is grounded, hence

$$\frac{v_i}{R_1} = -\frac{v_o}{R_f}$$

## Inverting Op Amp

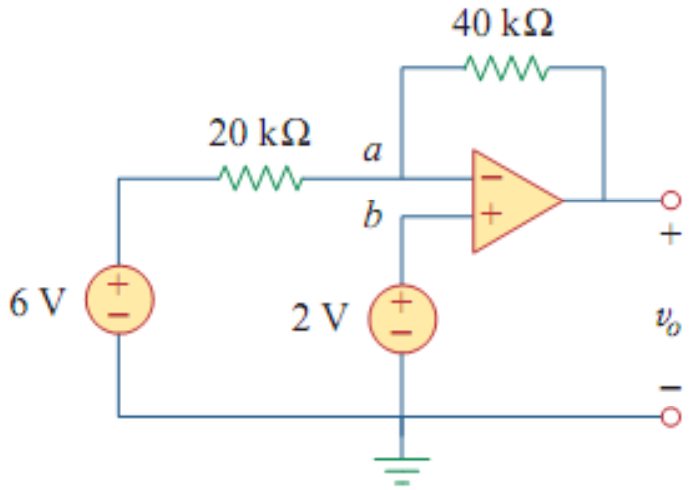
$$\text{Voltage gain, } A_v = \frac{v_o}{v_i} = -\frac{R_f}{R_1}$$

- An inverting amplifier reverses the polarity of the input signal while amplifying it.
- The gain depends only on the external elements connected to the op amp.
- Equivalent circuit for the inverting amplifier;



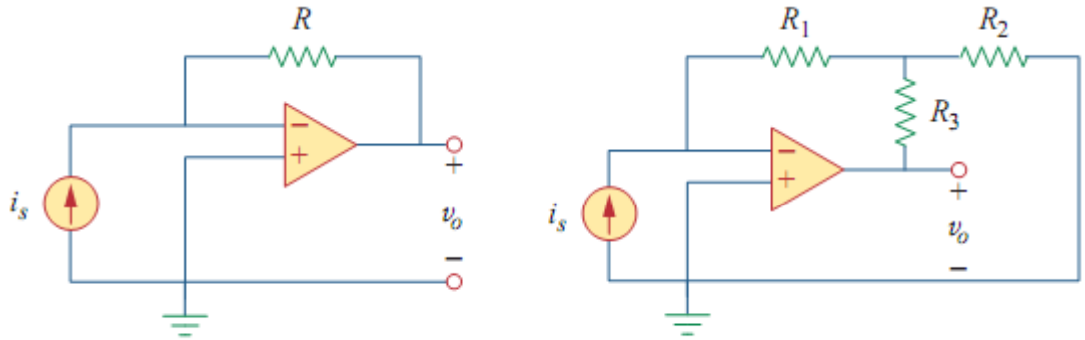
## Example 2

Determine $v_o$ in the op amp circuit below.



## Practice Problem 1

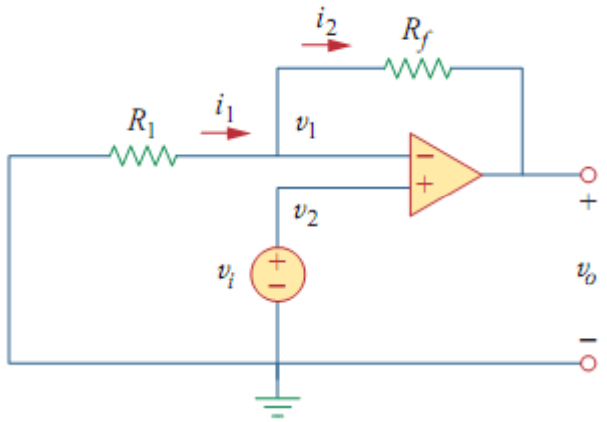
Find $v_o$ / $i_s$ for the current-to-voltage converter circuits as shown below.




*Answers:* (a) $\frac{v_o}{i_s} = -R$; (b) $\frac{v_o}{i_s} = -R_1\left(1 + \frac{R_3}{R_1} + \frac{R_3}{R_2}\right)$

## Noninverting Op Amp

- Input voltage $v_i$ is applied directly at the noninverting input terminal, and $R_1$ is connected between the ground and the inverting terminal.



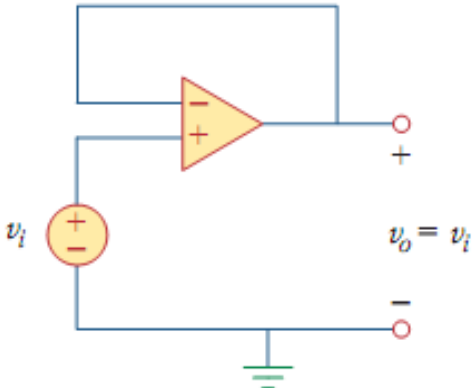

$$\text{Voltage gain, } A_v = \frac{v_o}{v_i} = \left(1 + \frac{R_f}{R_1}\right)$$

## Noninverting Op Amp

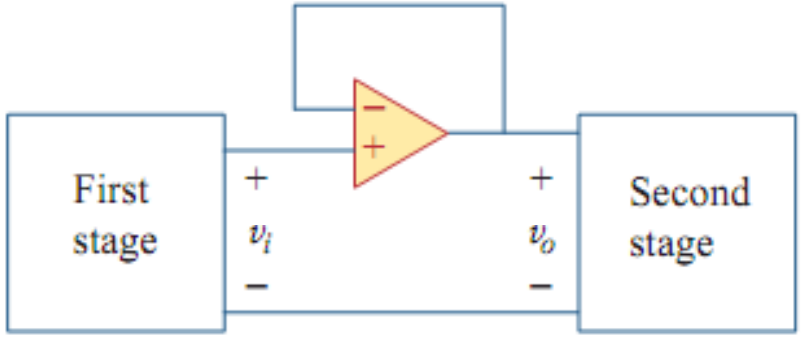
- A noninverting amplifier is an op amp circuit designed to provide a positive voltage gain.
- Gain depends only on the external resistors.
- If $R_f = 0$ (short-circuit) or $R_1 = \infty$ (open-circuit) or both, the gain becomes 1; $\Rightarrow$ called a voltage follower (or unity gain amplifier).
- This voltage follower circuit has a very high input impedance and is therefore useful as an intermediate-stage (or buffer) amplifier to isolate one circuit from another.

# Operational Amplifiers

## Noninverting Op Amp




The voltage follower




A voltage follower used to isolate two cascaded stages of a circuit

## Example 3

For the op amp circuit in Fig E3, calculate the output voltage $v_o$ .

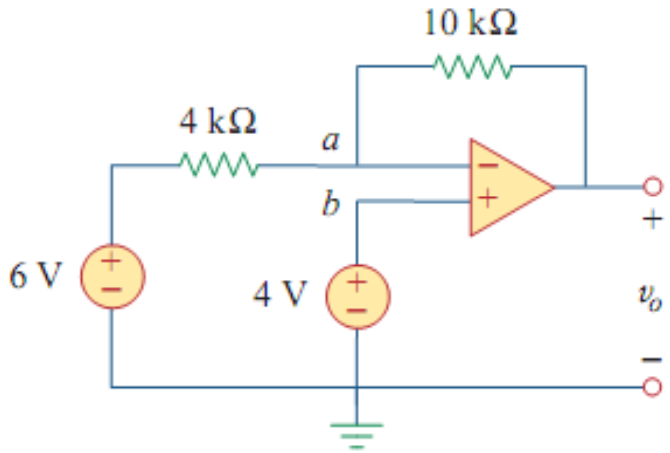
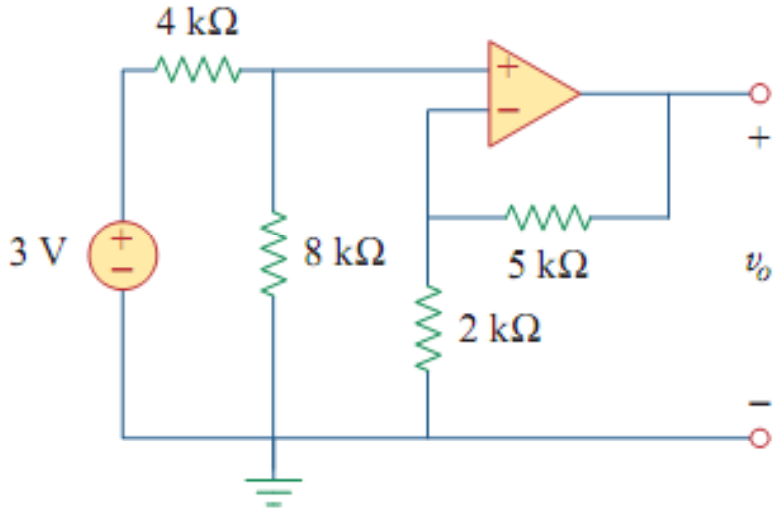



Fig E3

## Practice Problem 2

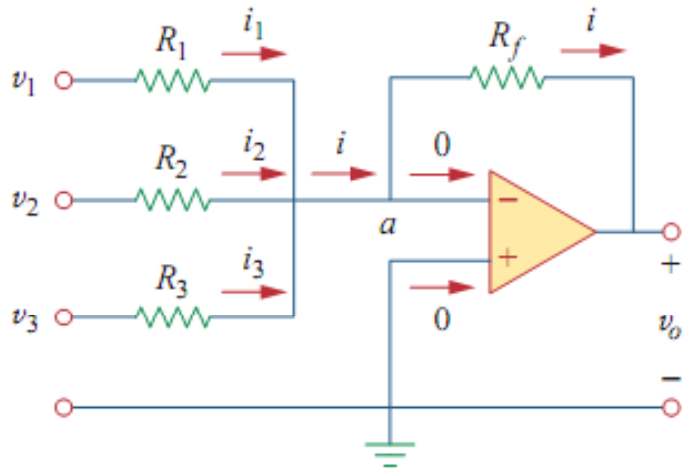
Calculate $v_o$ in the circuit of Fig. P2.




*Answers: 7V*

# Summing Amplifier

- A summing amplifier is an op amp circuit that combines several inputs and produces an output that is the weighted sum of the inputs.




Also called *summer*

$$i = i_1 + i_2 + i_3$$

$$i_1 = \frac{v_1 - v_a}{R_1}, \quad i_2 = \frac{v_2 - v_a}{R_2}$$

$$i_3 = \frac{v_3 - v_a}{R_3}, \quad i = \frac{v_a - v_o}{R_f}$$

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

## Practice Problem 3

Find $v_o$ and $i_o$ in the op amp circuit of Fig. P3.

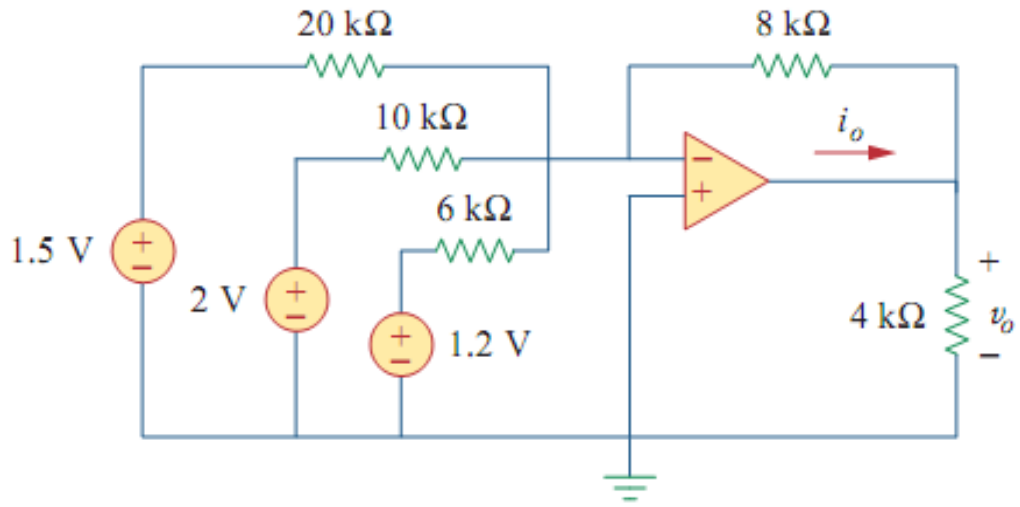
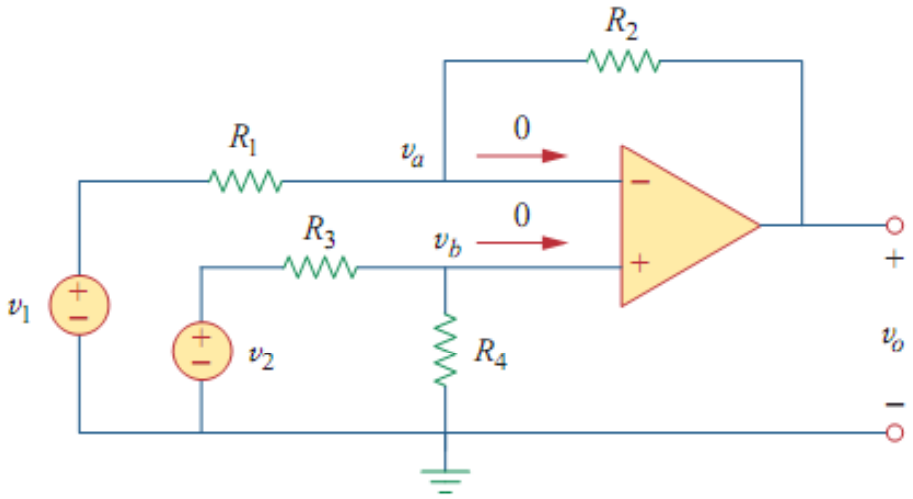



Fig. P3

*Answers: -3.8V, -1.425mA*

## Difference Amplifier

- A difference amplifier is a device that amplifies the difference between two inputs but rejects any signals common to the two inputs.




KCL at node a;

$$v_o = \left(\frac{R_2}{R_1} + 1\right) v_a - \frac{R_2}{R_1} v_1$$

KCL at node b;

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

# Operational Amplifiers

## Difference Amplifier

Since $v_a = v_b$, therefore ;

$$v_o = \frac{R_2\left(1 + R_1 / R_2\right)}{R_1\left(1 + R_3 / R_4\right)} v_2 - \frac{R_2}{R_1} v_1$$

- Since a difference amplifier must reject a signal common to the two inputs. ∴ amplifier must have the property $v_o = 0$ when $v_1 = v_2$ .

This property exists when,

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}; \quad \Rightarrow \quad v_o = \frac{R_2}{R_1}\left(v_2 - v_1\right)$$

If $R_2 = R_1$ & $R_3 = R_4$;

diff. amp becomes a *substractor*

$$\Rightarrow \quad v_o = v_2 - v_1$$

## Practice Problem 4

Obtain $i_o$ in the instrumentation amplifier circuit of Fig. P4.

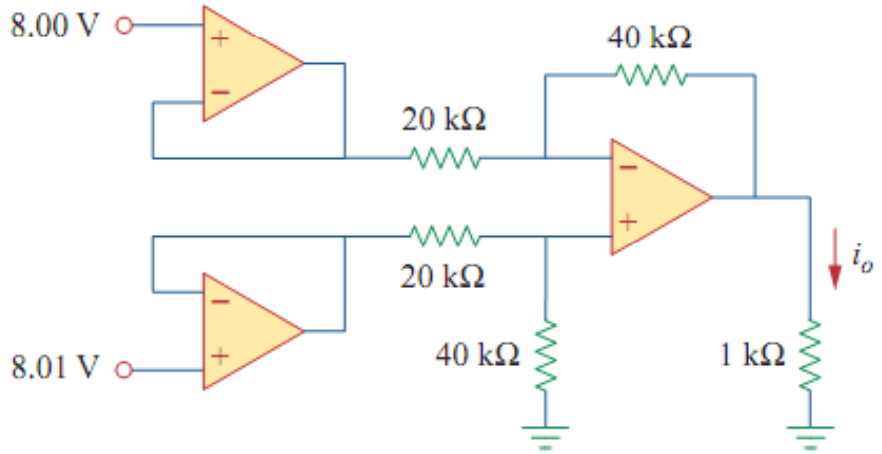



Fig. P4

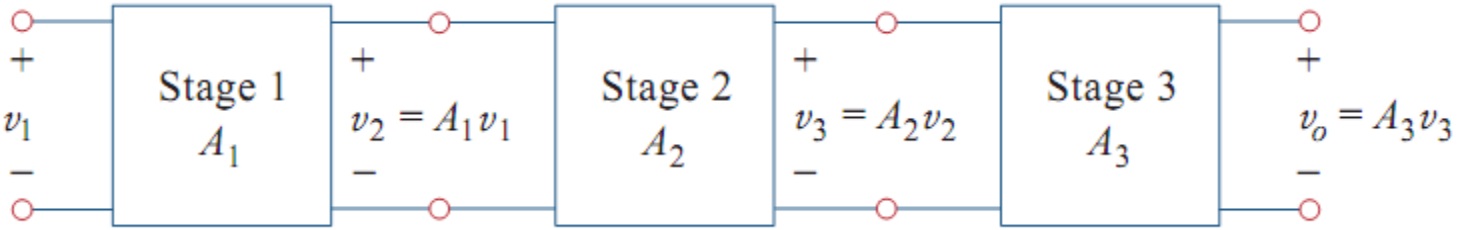
*Answers: 20 μA*

## Cascaded Op Amp Circuits

- A cascade connection is a head-to-tail arrangement of two or more op amp circuits such that the output of one is the input of the next.
- When op amp circuits are cascaded, each circuit in the string is called a stage; the original input signal is increased by the gain of the individual stage.
- Can be cascaded without changing input-output relationships.
- The overall gain of the cascaded connection is the product of the gains of the individual op amp circuits; $A = A_1 A_2 A_3$
- Care must be exercised in the design of an actual op amp circuit to ensure that the load due to the next stage in the cascade does not saturate the op amp.

## Cascaded Op Amp Circuits

A three-stage cascaded connection




$$v_2 = A_1 v_1 \; ; \quad v_3 = A_2 v_2 \; ; \quad v_o = A_3 v_3$$

$$v_o = A_3 A_2 v_2 = A_3 A_2 A_1 v_1$$

$$\therefore \quad \frac{v_o}{v_1} = A = A_1 A_2 A_3$$

## Example 4

Find $v_o$ and $i_o$ in the circuit in Fig E4.

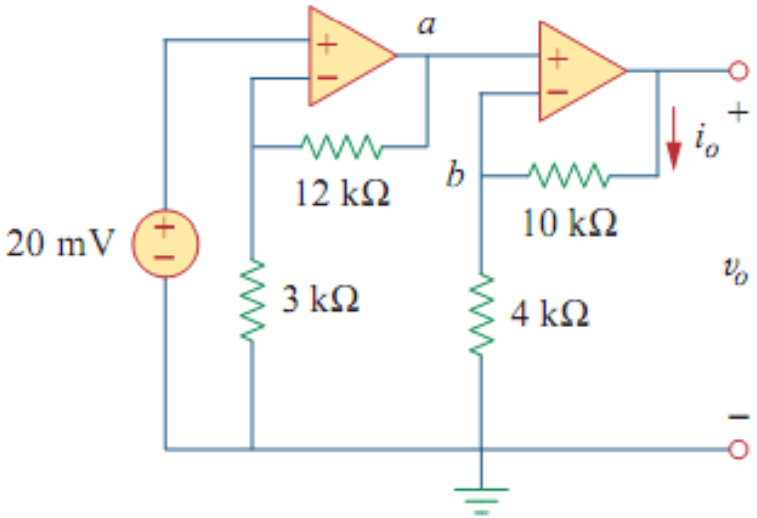



Fig E4

## Practice Problem 5

Determine $v_o$ and $i_o$ in the op amp circuit in Fig. P5.

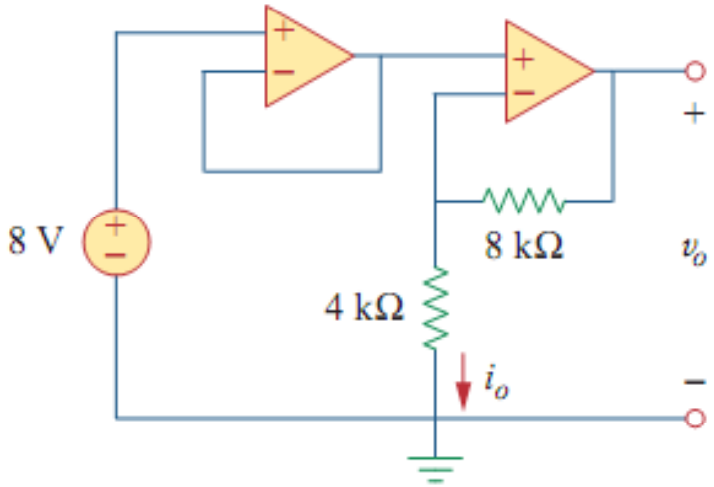



Fig. P5

*Answers: 24 V, 2 mA*