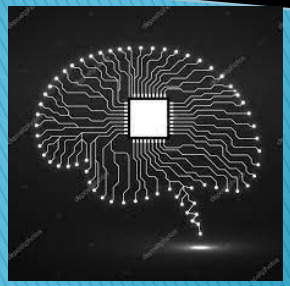
AYDIN
ADNAN MENDERES UNIVERSITY
FACULTY OF ENGINEERING
Department of Electrical and Electronics Engineering

EE201 – Circuit Theory I

Prof. Dr. Yılmaz KALKAN

circuit theory





1. **Basic Concepts (Chapter 1 of Nilsson – Week 1)**

   Introduction, Current and Voltage, Power and Energy

2. **Basic Laws (Chapter 2&3 of Nilsson – Week 2)**

   Voltage and Current Sources, Ohm's Law,

   Kirchhoff's Laws, Resistors in parallel and in series, Voltage and Current Division

3. **Techniques of Circuit Analysis (Chapter 4 of Nilsson – Weeks 3-6)**

   Node Analysis, Node-Voltage Method and Dependent Sources, Mesh Analysis, Mesh-Current Method and Dependent Sources, Source Transformations, Thevenin and Norton Equivalents, Maximum Power Transfer, Superposition Theorem

4. **Operational Amplifier (Chapter 5 of Nilsson – Weeks 9-10)**

   Op-Amp Terminals & Ideal Op-Amp, Basic Op-Amp Circuits, Buffer circuit, Inverting and Non-inverting Amplifiers, Summing Inverter, Difference Amplifier, Cascade Op-Amp Circuits

5. **Capacitors and Inductors (Chapter 6 of Nilsson – Weeks 11)**

   Inductors, Capacitors, Series and Parallel Combinations of them

6. **First Order Circuits (Chapter 7 of Nilsson – Weeks 12 & 13)**

   The Natural Response of an RL & RC Circuits, The Step Response of RL and RC Circuits, A General Solution for Step and Natural Responses, Integrating Amplifier Circuit

7. **Second Order Circuits (Chapter 8 of Nilsson – Weeks 14 & 15)**

   The Natural Response of a Parallel RLC Circuit, The Forms of Natural Response of a Parallel RLC Circuit, The Step Response of a Parallel RLC Circuit, Natural and Step Responses of a Series RLC Circuit

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Ch4: Operational Amplifiers (Op-Amp's)

❑ Having learned the basic laws and theorems for circuit analysis, we are now ready to study **an active circuit element** of paramount importance: the *operational amplifier, or* ***op-amp*** *for short.*

❑ *The op-amp is a versatile* circuit building block.

❑ The op-amp is an electronic unit that **behaves like a voltage-controlled voltage source.**

❑ It can also be used in making a voltage- or current-controlled current source. **An op amp can sum signals, amplify a signal, integrate it, or differentiate it.** The ability of the op amp to perform these mathematical operations is the reason it is called an operational amplifier. It is also the reason for the widespread use of op amps in analog design.

❑ Op-amps are popular in practical circuit designs because they are **versatile**, **inexpensive**, **easy to use**, and **fun to work with**.

Ch4: Operational Amplifiers (Op-Amp's)

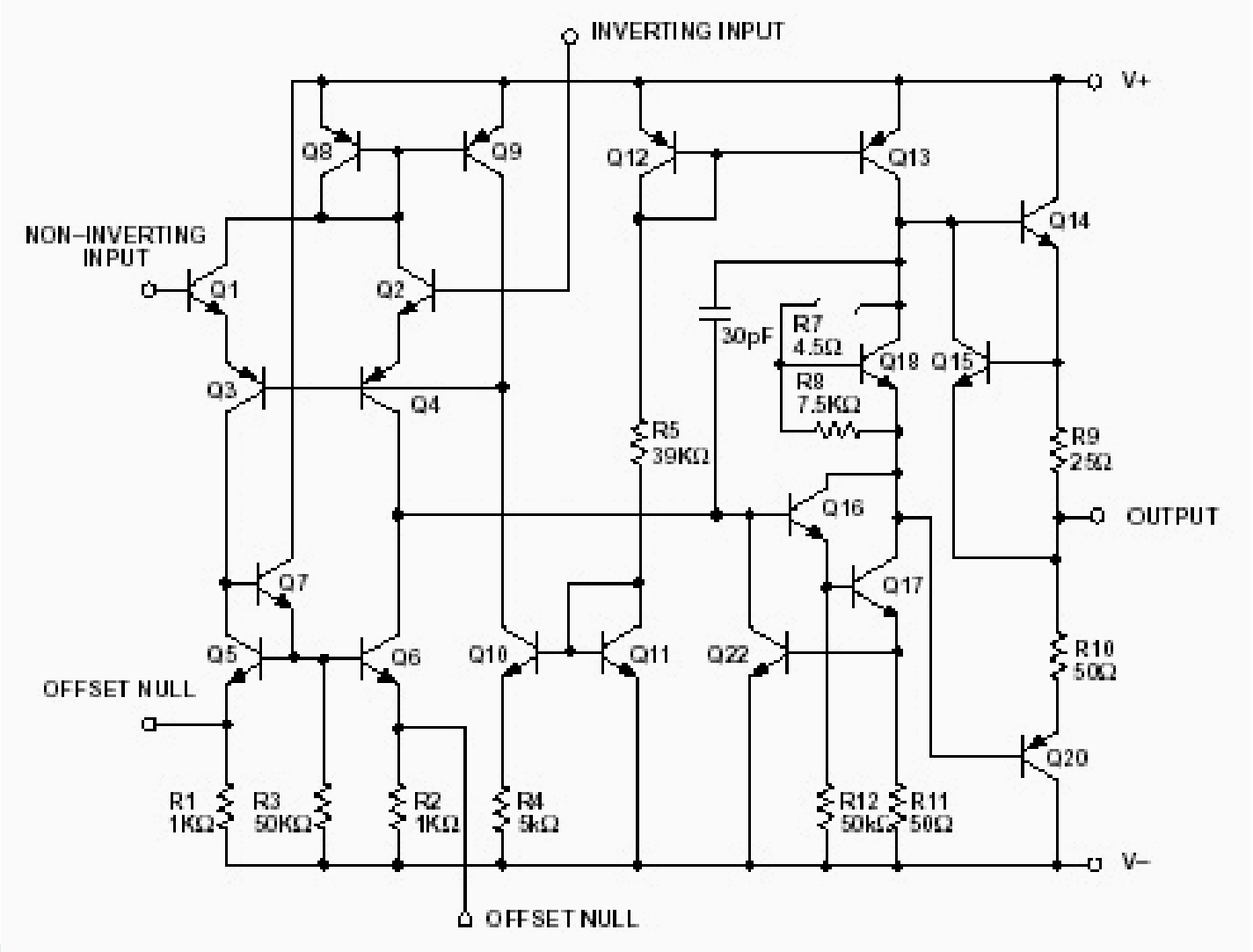
- An operational amplifier is **designed so that it performs some mathematical operations** when external components, such as resistors and capacitors, are connected to its terminals.

- An op-amp is an active circuit element **designed to perform mathematical operations** of addition, subtraction, multiplication, division, differentiation, and integration.

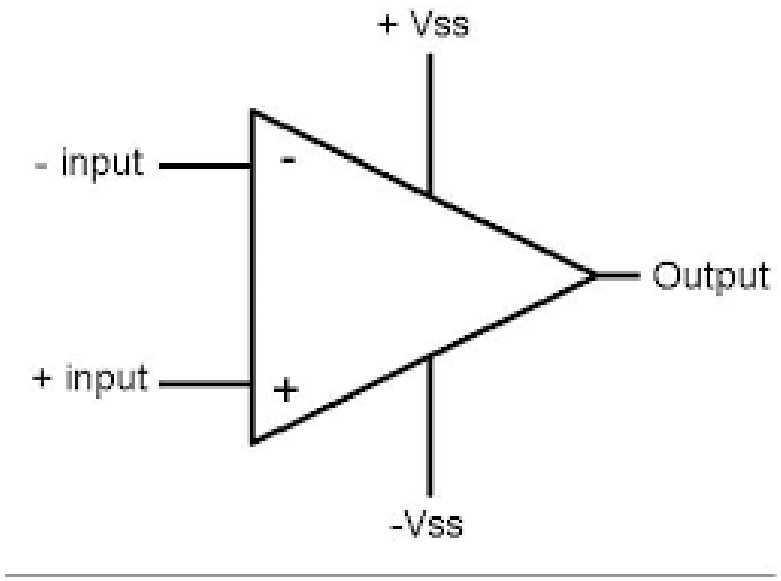
- The op-amp is an electronic device consisting of a **complex arrangement** of resistors, transistors, capacitors, and diodes.

- A full discussion of what is inside the op amp is **beyond the scope** of this book. It will suffice to treat the op amp as a circuit building block and simply study **what takes place at its terminals**.

Ch4: Operational Amplifiers (Op-Amp's)



Ch4: Operational Amplifiers (Op-Amp's)



❑ Op amps are commercially available in integrated circuit packages in several forms.

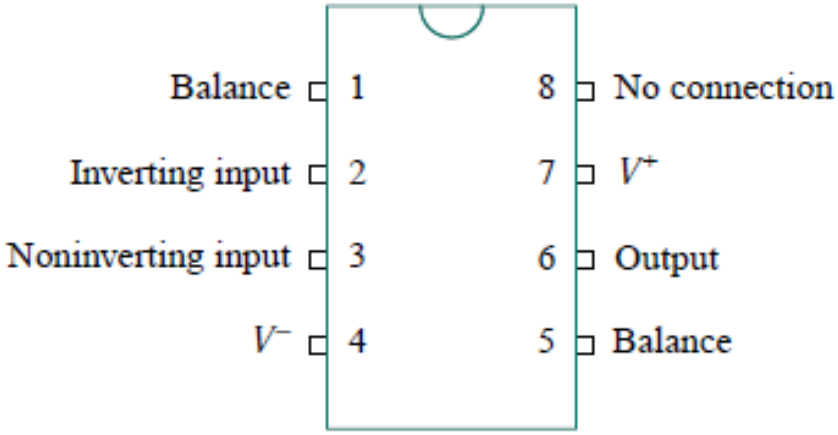


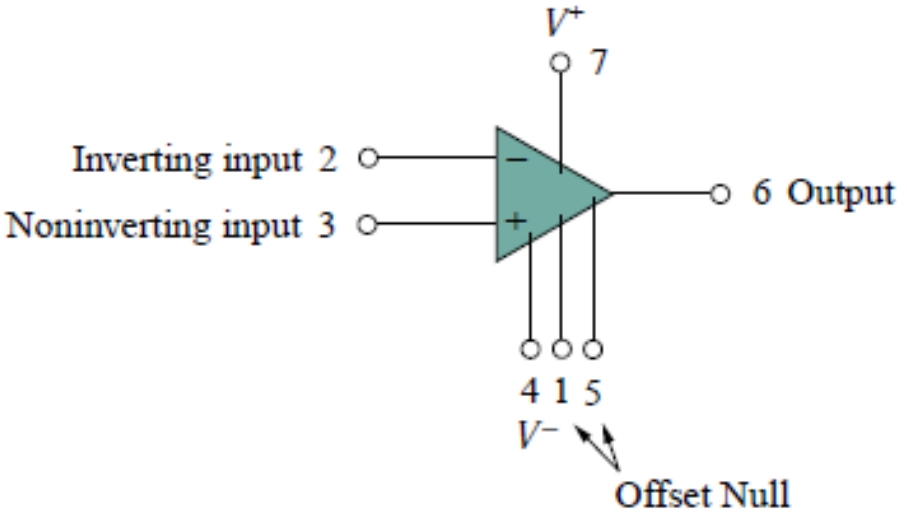




Ch4: Operational Amplifiers (Op-Amp's)

- A typical one is the eight-pin dual in-line package (or DIP).





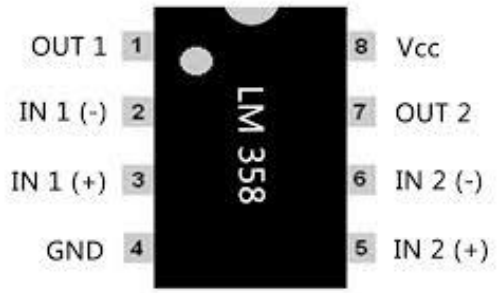
- Pin or terminal 8 is unused, and terminals 1 and 5 are of little concern to us. The five important terminals are:

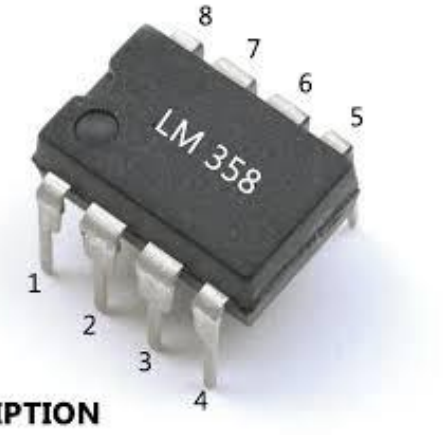
1. The inverting input, pin 2.
2. The non-inverting input, pin 3.
3. The output, pin 6.
4. The positive power supply V+, pin 7.
5. The negative power supply V−, pin 4.

Ch4: Operational Amplifiers (Op-Amp's)

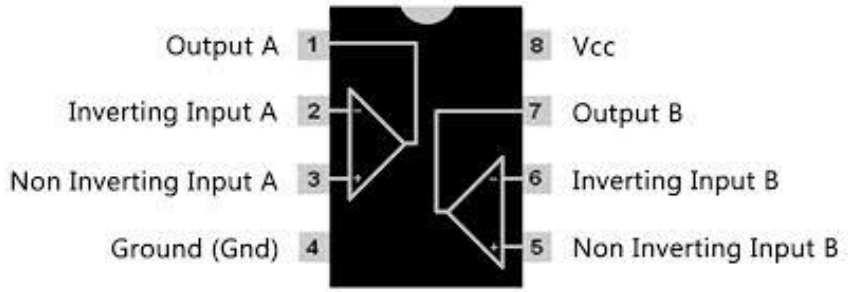
- In Laboratory we will use LM358 IC which includes 2 Op-Amps inside !!

LM358 IC Pinout





LM358 DETAILED PIN DESCRIPTION



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Electronics Components Uses, Features, Pinouts, Equivalents, Applications & More...

- Common Supply ;
  $+V_{cc}$, pin 8.
  $-V_{cc}$, pin 4.

- For the first Op-Amp;
  V_- (inv. input), pin 2.
  V_+ (noninv. input), pin 3.
  V_o (output), pin 1.

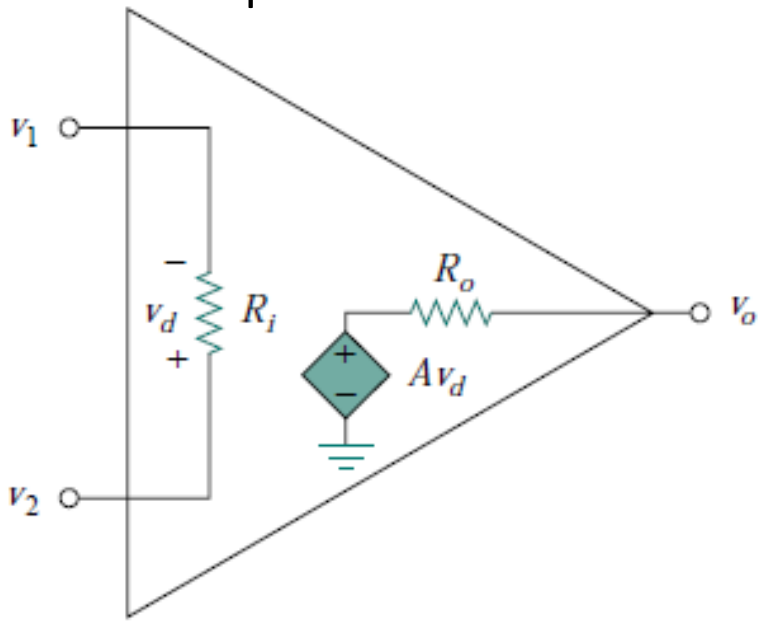
- For the second Op-Amp;
  V_- (inv. input), pin 6.
  V_+ (noninv. input), pin 5.
  V_o (output), pin 7.

Ch4: Operational Amplifiers (Op-Amp's)

- The equivalent circuit model of an op amp is shown in Figure below.

- The output section consists of a voltage-controlled source in series with the output resistance Ro.

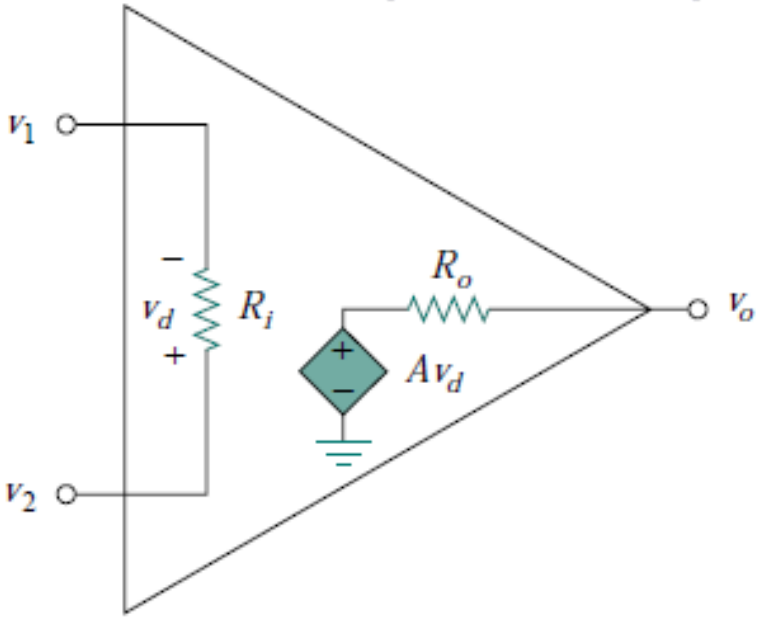
- The input resistance Ri is the Thevenin equivalent resistance seen at the input terminals, while the output resistance Ro is the Thevenin equivalent resistance seen at the output.



- The differential input voltage is given by;

$$v_d = v_2 - v_1$$
$$= v_+ - v_-$$
$$= v_p - v_n$$

Ch4: Operational Amplifiers (Op-Amp's)



$$v_d = v_2 - v_1$$
$$= v_+ - v_-$$
$$= v_p - v_n$$

$$v_0 = Av_d = A(v_+ - v_-)$$

- A is called the open-loop voltage gain because it is the gain of the op-amp without any external feedback from output to input.

Ch4: Operational Amplifiers (Op-Amp's)

Typical ranges for op amp parameters.

Parameter	Typical range	Ideal values
Open-loop gain, A	10^5 to 10^8	∞
Input resistance, R_i	10^6 to 10^{13} Ω	∞ Ω
Output resistance, R_o	10 to 100 Ω	0 Ω
Supply voltage, V_{cc}	5 to 24 V	

$$v_0 = Av_d = A(v_+ - v_-)$$

$$v_+ = 2V, v_- = 1V \Rightarrow v_d = 1V, A = 10^5$$

$$v_0 = Av_d = 10^5 V$$

Actually NO !!!!

❑ A practical limitation of the op-amp is that the magnitude of its **output voltage cannot exceed |Vcc|**. In other words, the output voltage is dependent on and is limited by the power supply voltage.

Ch4: Operational Amplifiers (Op-Amp's)

- The concept of feedback is crucial to our understanding of op-amp circuits.

- When there is a feedback path **from output to input**, the ratio of the output voltage to the input voltage is called the **closed-loop gain**.

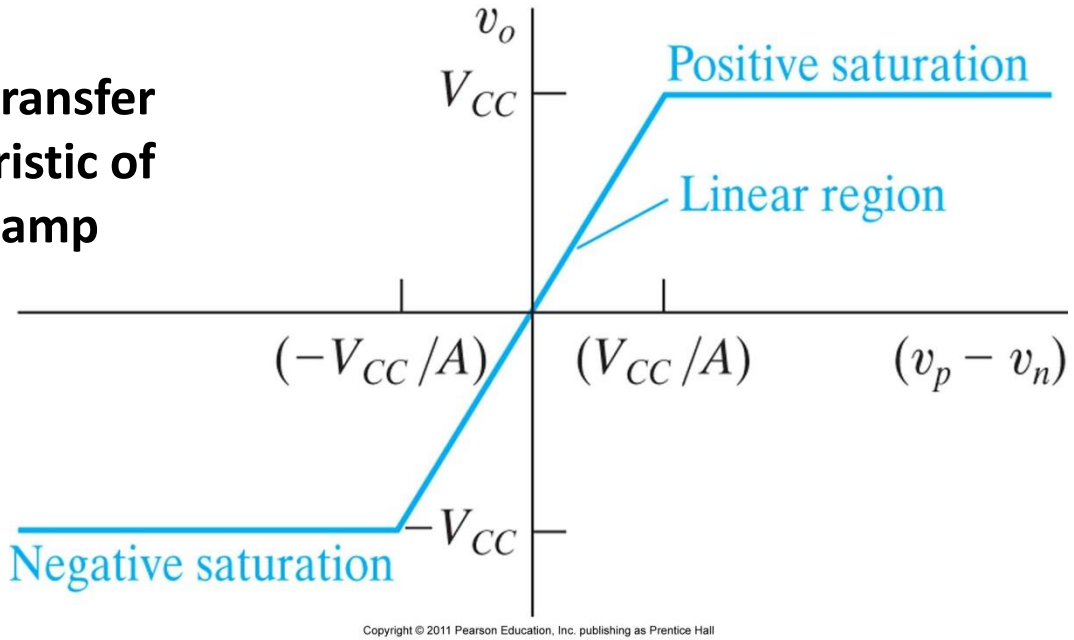
- A ***negative feedback*** is achieved when the output is fed back to the inverting terminal of the op amp.

- As a result of the negative feedback, it can be shown that the closed-loop gain is **almost insensitive to the open-loop gain A** of the op-amp.

- For this reason, **op-amps are used in circuits with feedback paths**.

Ch4: Operational Amplifiers (Op-Amp's)

Voltage transfer characteristic of an op-amp



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1. Positive saturation, $v_o = V_{CC}$.
2. Linear region, $-V_{CC} \le v_o = Av_d \le V_{CC}$.
3. Negative saturation, $v_o = -V_{CC}$.



1. $v_+ > v_-$
2. $v_+ = v_-$
3. $v_+ < v_-$

❑ **If we attempt to increase *vd beyond the linear range, the op-amp becomes* saturated and yields *Vo = Vcc or Vo = −Vcc.***

IDEAL OP-AMPS

❑ To facilitate the understanding of op amp circuits, we will assume ideal op-amps. An op-amp is ideal if it has the following characteristics:

1. Infinite open-loop gain, $A \cong \infty$
2. Infinite input resistance, $R_i \cong \infty$
3. Zero output resistance, $R_0 \cong 0$

❑ **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:

$$i_1 = 0, \qquad i_2 = 0$$

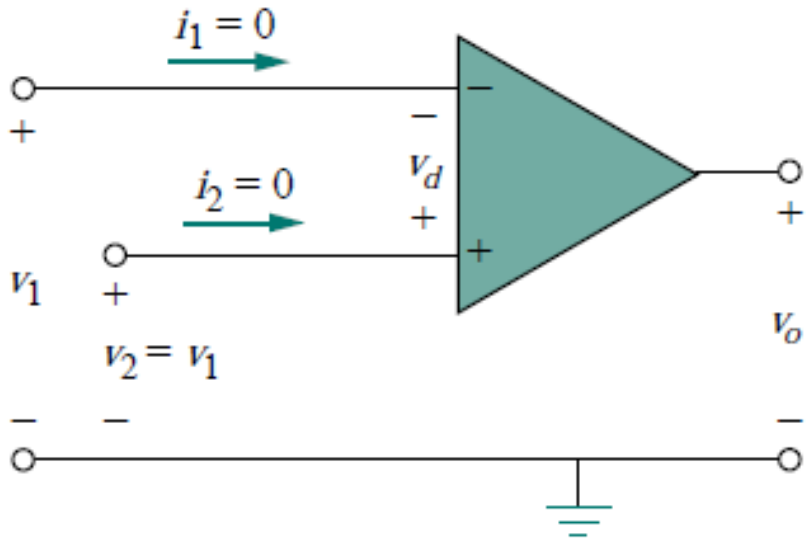
(Output current still exist!)

$$v_d = v_2 - v_1 \simeq 0$$

(Virtual short condition.)

Ch4: Operational Amplifiers (Op-Amp's)

IDEAL OP-AMPS



$$i_1 = 0, \qquad i_2 = 0$$

(Output current still exist!)

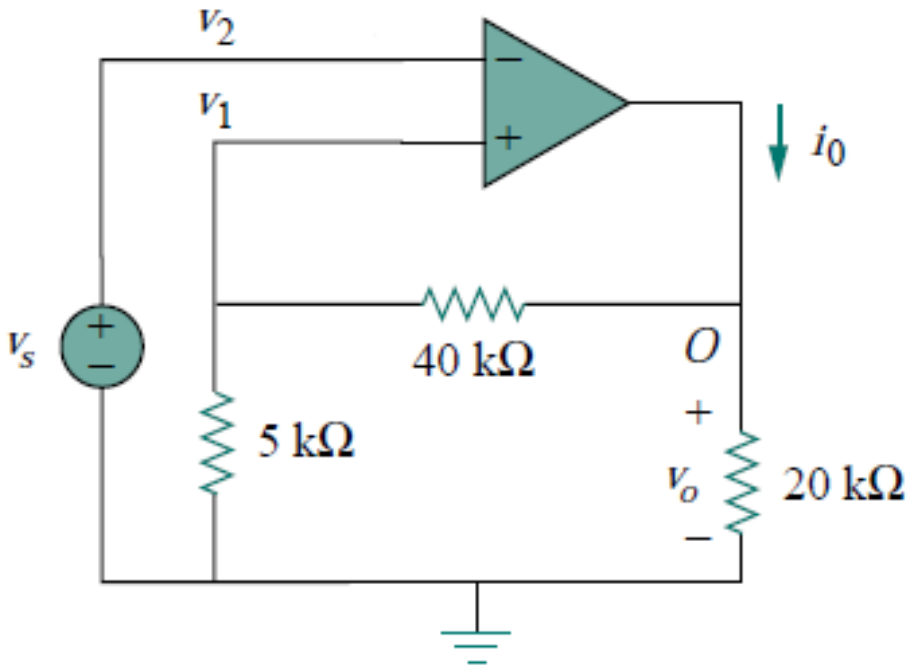
$$v_d = v_2 - v_1 \simeq 0$$

(Virtual short condition.)

- These are only valid for **LINEAR REGION**. !!!!
- Unless otherwise is stated, **OP-AMP's are IDEAL** in this course.

Analyzing the OP-AMP Circuits

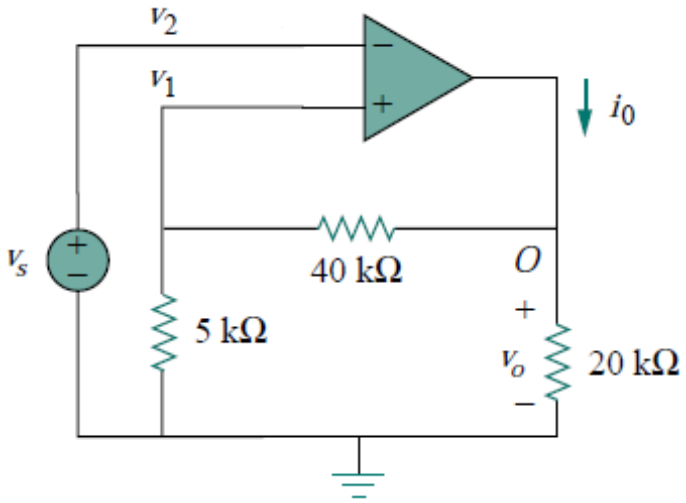
Example : Find i_0 and v_0 ? (Op-amp is ideal)



Ch4: Operational Amplifiers (Op-Amp's)

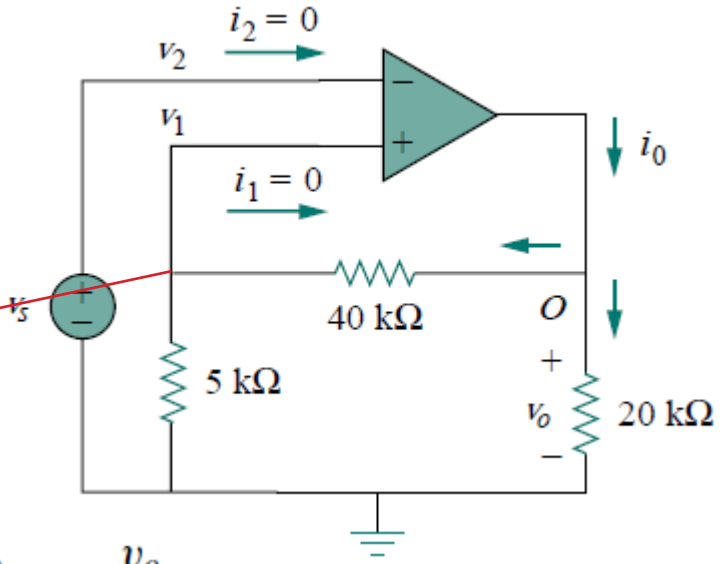
Analyzing the OP-AMP Circuits

Example : Find i_0 and v_0 ? (Op-amp is ideal)



Solution: As Op-amp is ideal; $i_- = i_+ = 0$

In linear Region; $v_- = v_+$



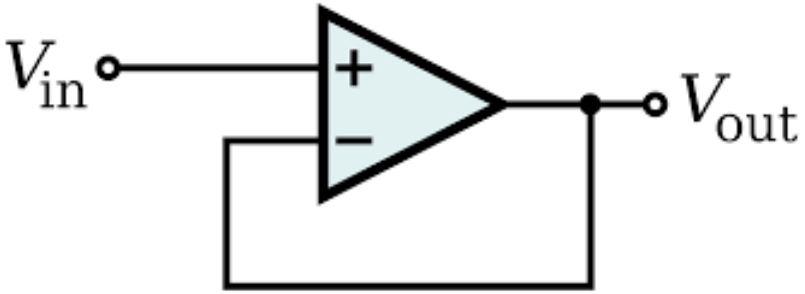
$$v_- = v_+ = v_s = v_1 = v_2$$

$$v_1 = \frac{5}{5+40} v_o = \frac{v_o}{9}$$

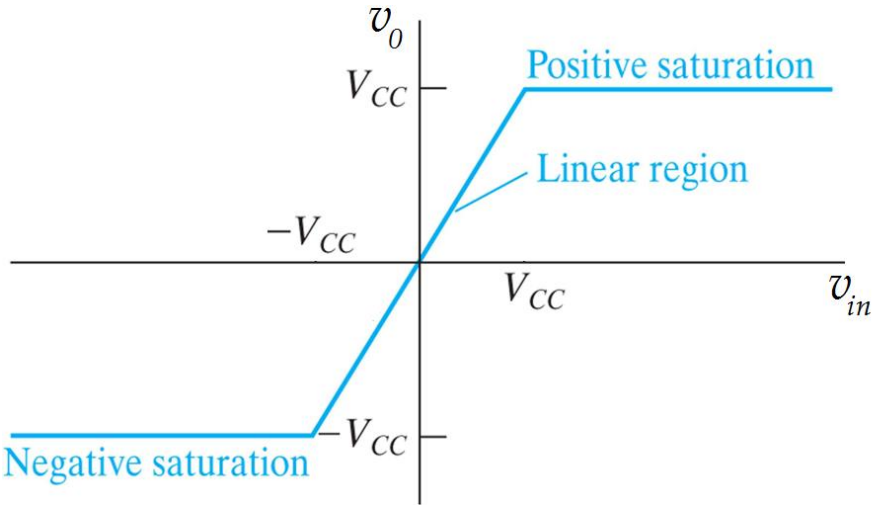
$$v_s = \frac{v_o}{9} \quad \Longrightarrow \quad \frac{v_o}{v_s} = 9 \qquad i_o = \frac{v_o}{40+5} + \frac{v_o}{20} \text{ mA}$$

$$if\ V_s = 1V \Rightarrow i_0 = 0.65mA,\ v_0 = 9V$$

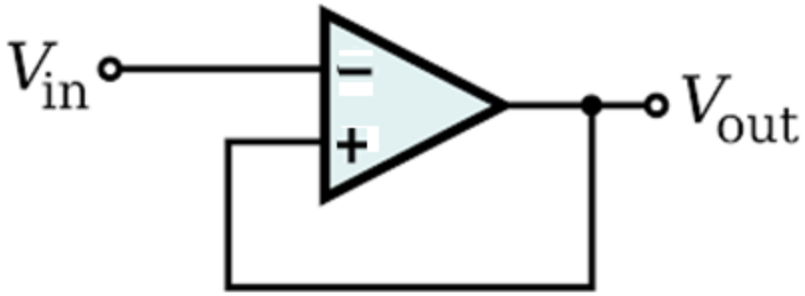
Basic OP-AMP Circuits – Buffer (Voltage Follower)



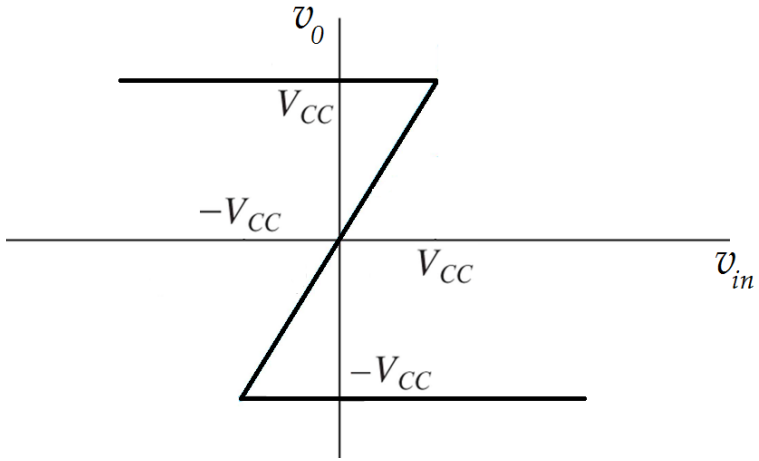
$$v_0 = \begin{cases} v_{in} \;\; ; -V_{CC} \le v_{in} \le V_{CC} \\ -V_{cc} \;\; ; v_{in} < -V_{CC} \\ V_{CC} \;\; ; v_{in} > V_{CC} \end{cases}$$



Basic OP-AMP Circuits – Buffer (Voltage Follower) with positive feedback

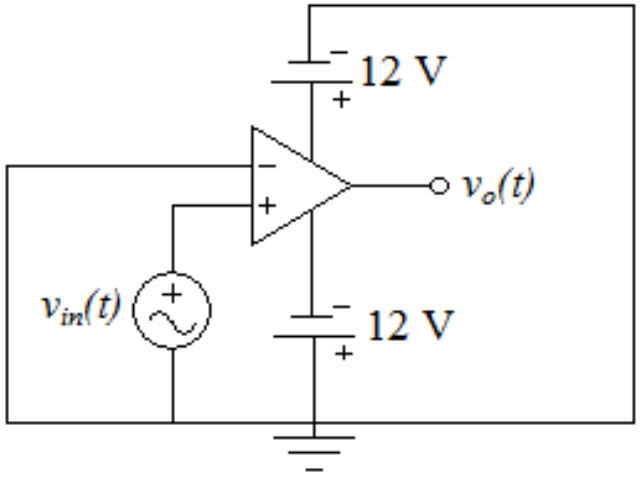


$$v_0 = \begin{cases} v_{in} & ; \quad -V_{cc} \leq v_{in} \leq V_{cc} \\ V_{cc} & ; \quad v_{in} < V_{cc} \\ -V_{cc} & ; \quad v_{in} > -V_{cc} \end{cases}$$



❑ This structure is unstable. Hence, op-amp can not stay in linear region, it is either in positive saturation or in negative saturation.

❑ Operational Amplifiers (Op-Amps)



$v_- = 0 \quad v_+ = v_{in(t)} \qquad v_- \neq v_+$

NOT In linear Region

❑ Steps to analyze op-amp circuits:

1) Assume op-amp is ideal;

2) In linear region;

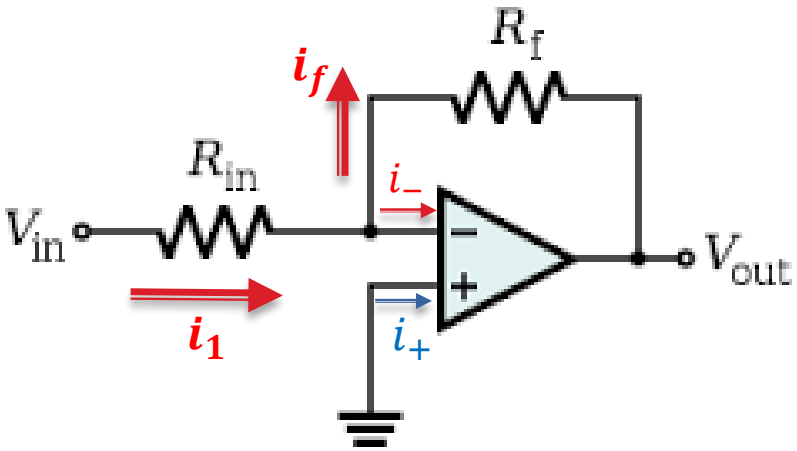
$$i_- = i_+ = 0 \qquad v_- = v_+$$

3) Analyze circuit using any circuit analyze methods (KCL, KVL,, Node analysşs, mesh analysis, etc.) to find $v_0(t)$ wrt $v_{in}(t)$

$In + saturation\ Region \Rightarrow v_+ > v_- \Rightarrow v_{in(t)} > 0 \Rightarrow v_{out} = +V_{cc} = 12V$

$In - saturation\ Region \Rightarrow v_+ < v_- \Rightarrow v_{in(t)} < 0 \Rightarrow v_{out} = -V_{cc} = -12V$

Inverting Amplifier



❑ Steps to analyze op-amp circuits:

1) Assume op-amp is ideal;

2) In linear region; $i_- = i_+ = 0$, $v_- = v_+$

KCL @ $inverting\ terminal\ node$

$$i_1 = i_f + i_-$$

$$\frac{v_{in} - v_-}{R_{in}} = \frac{v_- - v_{out}}{R_f}$$

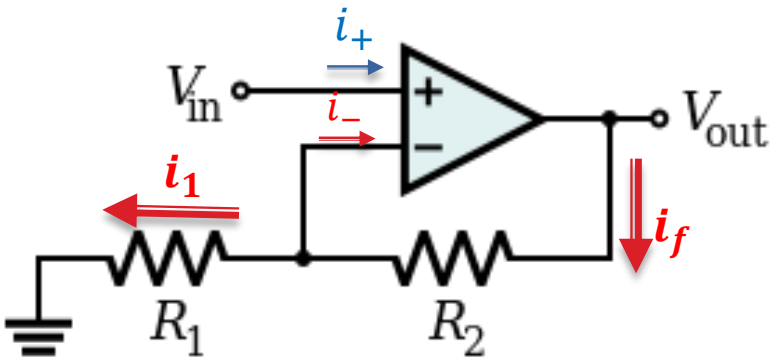
$$v_- = v_+ = 0$$

$$\frac{v_{in}}{R_{in}} = \frac{-v_{out}}{R_f}$$

$$v_{out} = -\frac{R_f}{R_{in}} v_{in}$$

Closed loop gain.

Non-Inverting Amplifier



❑ Steps to analyze op-amp circuits:

1) Assume op-amp is ideal;

2) In linear region; $i_- = i_+ = 0$, $v_- = v_+$

$$v_{out} = \left(1 + \frac{R_2}{R_1}\right) v_{in}$$

Closed loop gain.
(Always >1, hence an attenuator can not be built!!!!)

KCL @ inverting terminal node

$$i_1 + i_- = i_f$$

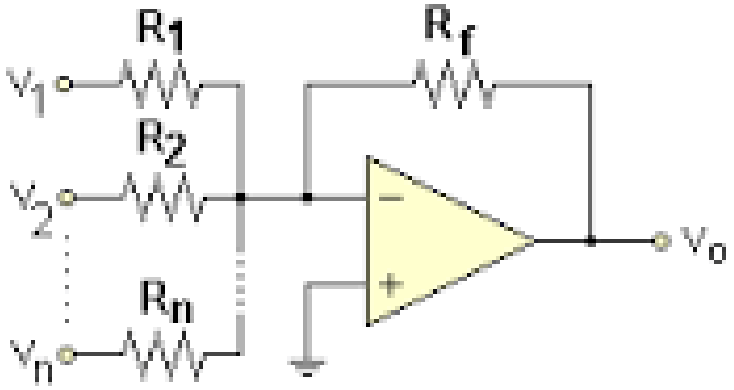
$$\frac{v_- - 0}{R_1} = \frac{V_{out} - v_-}{R_2}$$

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

$$\frac{V_{in}}{R_1} = \frac{V_{out} - V_{in}}{R_2}$$

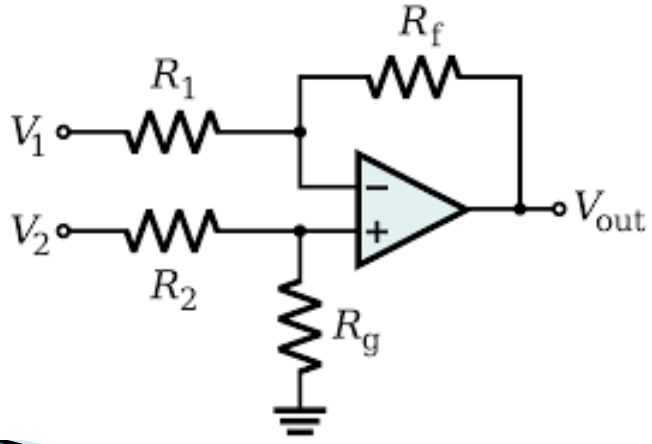
Ch4: Operational Amplifiers (Op-Amp's)

Summing Amplifier



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

Difference Amplifier



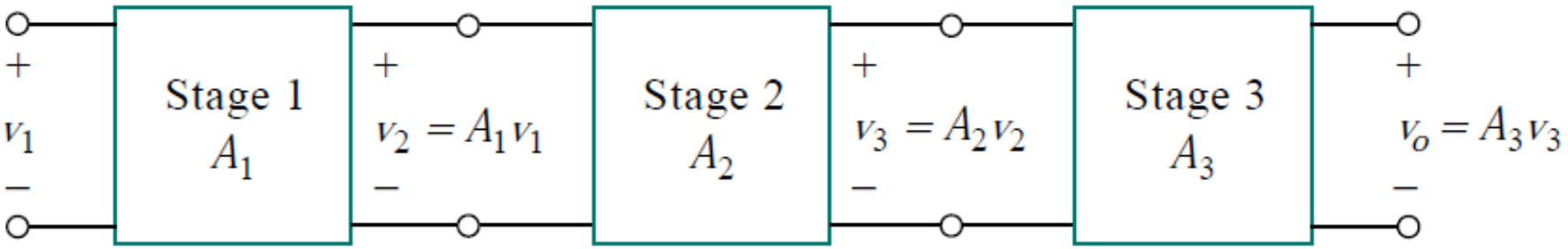
$$v_{out} = \frac{R_1 + R_f}{R_1}\left[\frac{R_g}{R_2 + R_g}V_2 - \frac{R_f}{R_1 + R_f}V_1\right]$$

$$if\ \frac{R_1}{R_f} = \frac{R_2}{R_g} \Rightarrow v_{out} = \frac{R_f}{R_1}(V_2 - V_1)$$

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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.



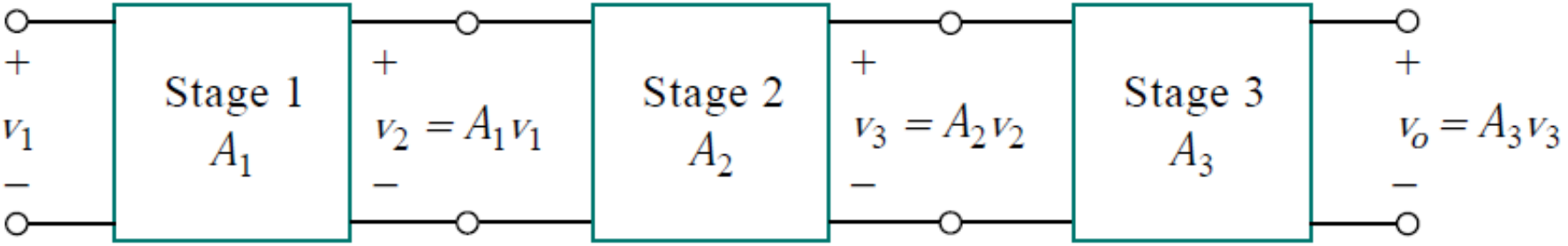
A three-stage cascaded connection.

❑ 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.

$$v_o = Av_1 \Rightarrow A = A_1 A_2 A_3$$

Ch4: Operational Amplifiers (Op-Amp's)

Cascaded Op-Amp Circuits



❑Op-amp circuits have the advantage that they can be cascaded **without changing their input-output relationships.**

❑ This is due to the fact that each **(ideal) op-amp circuit has infinite input resistance and zero output resistance.**

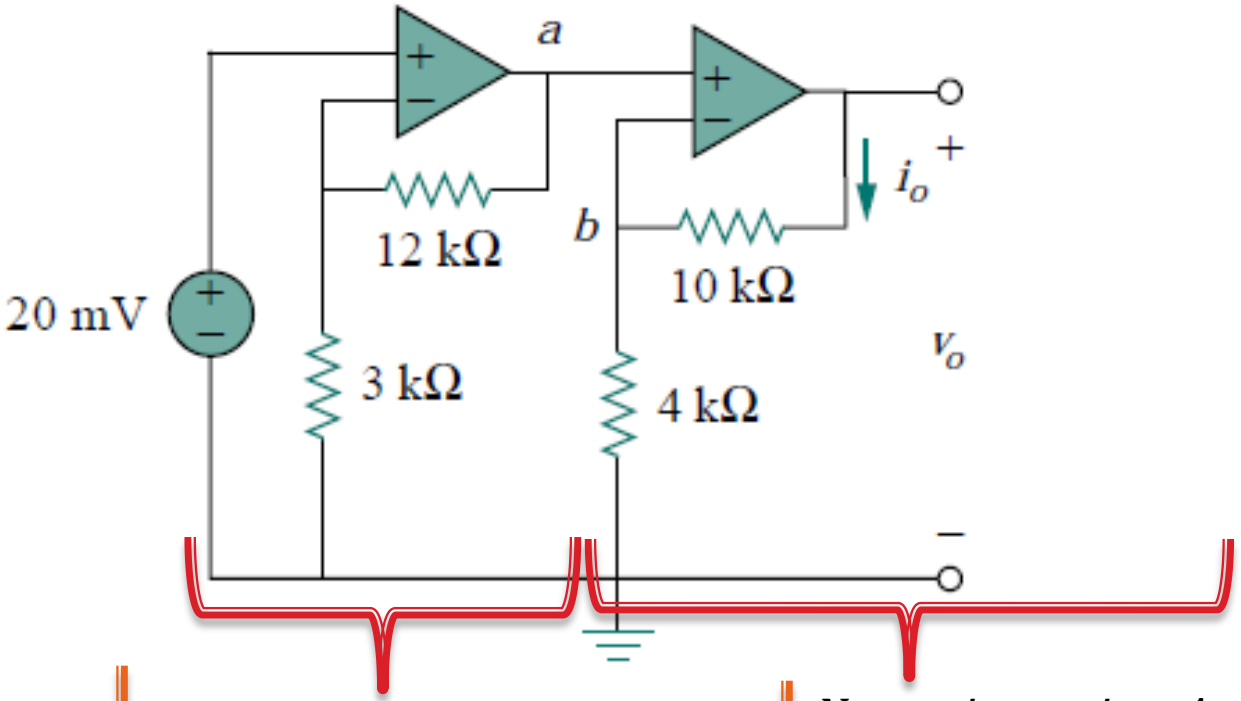
❑ Although the cascade connection does not affect the op-amp input-output relationships, care must be exercised in the design of **an actual op-amp circuit** to ensure that the load due to the next stage in the cascade **does not saturate** the op-amp.

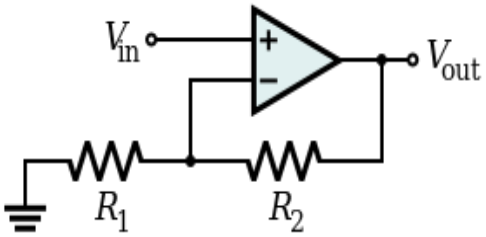
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Ch4: Operational Amplifiers (Op-Amp's)

Example:

Find v_0 & i_0 ?





$$v_{out} = \left(1 + \frac{R_2}{R_1}\right) v_{in}$$

Non − inverting Amplifier

$V_{in} = 20mV \quad V_{out} = V_a$

$R_2 = 12k\Omega, R_1 = 3k\Omega,$

$V_{out} = V_a = 5 * V_{in}$

$V_a = 100mV$

Non − inverting Amplifier

$V_{in} = V_a \qquad V_{out} = V_o$

$R_2 = 10k\Omega, R_1 = 4k\Omega,$

$V_{out} = V_o = 3{,}5 * V_a$

$V_o = 350mV$

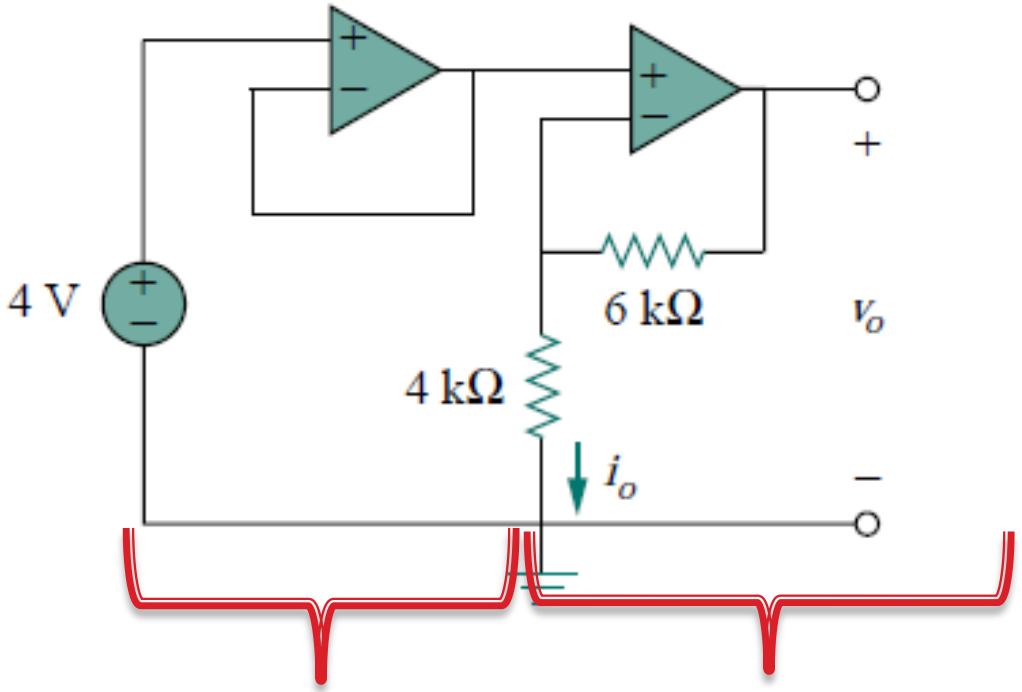
$i_o = \frac{V_0}{14k\Omega} = 25\mu A$

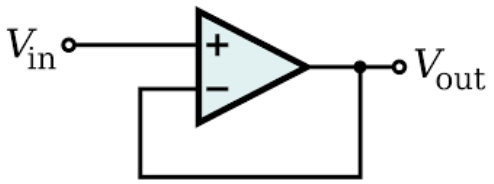
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Ch4: Operational Amplifiers (Op-Amp's)

Example:

Find v_0 & i_0 ?





$V_{out} = V_{in}$

Buffer (Voltage follower)

$V_{in} = 4V \qquad V_{out} = V_{in}$

$V_{out} = 4V$

Non − inverting Amplifier

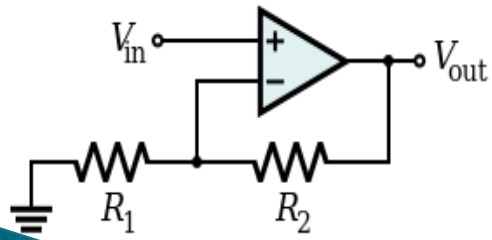
$V_{in} = 4V \qquad V_{out} = V_o$

$R_2 = 6k\Omega, \quad R_1 = 4k\Omega,$

$V_{out} = V_o = 2{,}5 * V_{in}$

$V_o = 10V$

$i_o = \dfrac{V_0}{10k\Omega} = 1mA$

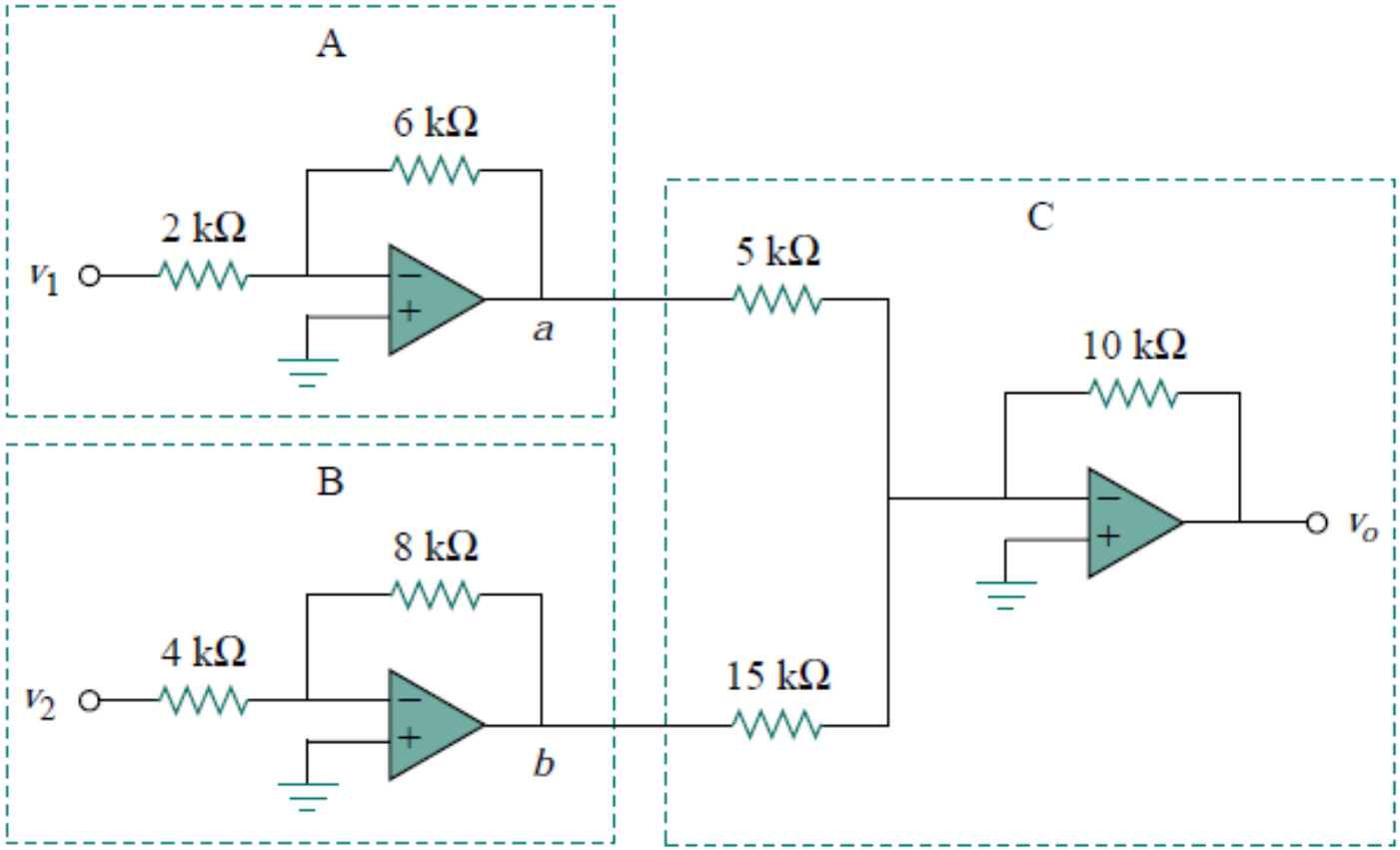


$$v_{out} = \left(1 + \frac{R_2}{R_1}\right) v_{in}$$

Exercise:

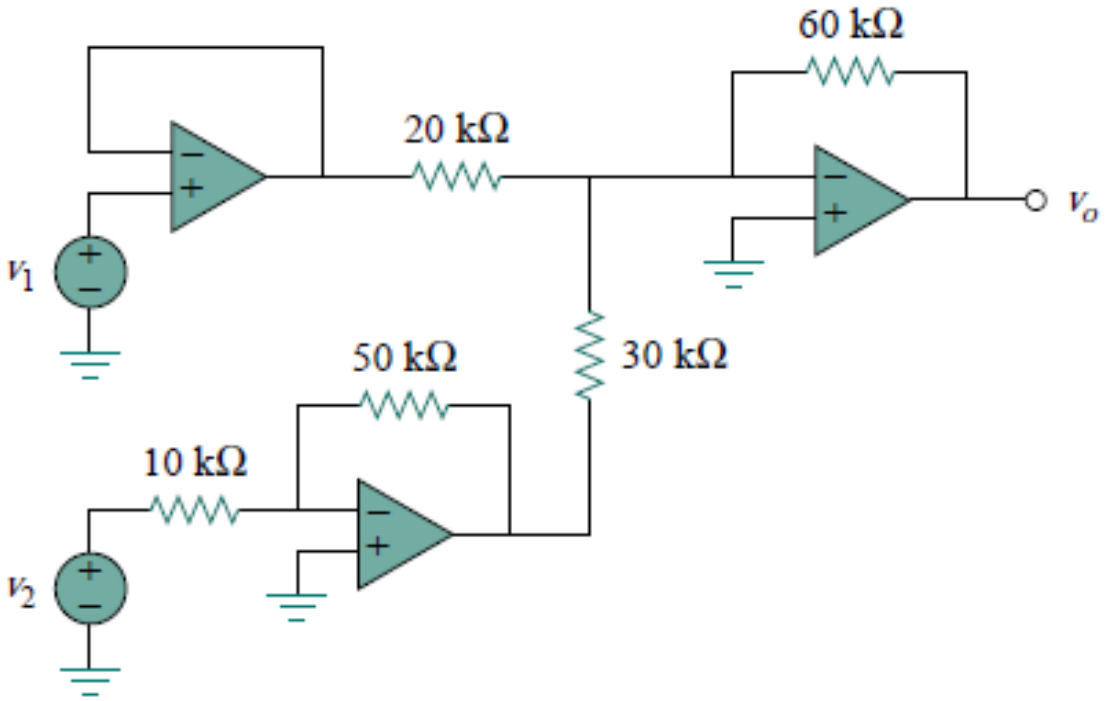
$If\ v_1 = 1V\ \&\ v_2 = 2V,\ find\ v_0\ ?$

$v_0 = 8.333\,V$



Exercise:

$If\ v_1 = 2V\ \&\ v_2 = 1.5V,\ find\ v_0\ ?$



$$v_0 = 9V$$

END OF CHAPTER 4
Op-Amp's

Dr. Yılmaz KALKAN