# 5. Operational Amplifiers [Op-Amp)

It can perform operations on input signal
1) Addition
2) Subtraction
3) Integration
4) Differentiation
5) Log & Antilog
etc.

It amplifies both AC/DC signals.

# Outline of Presentation

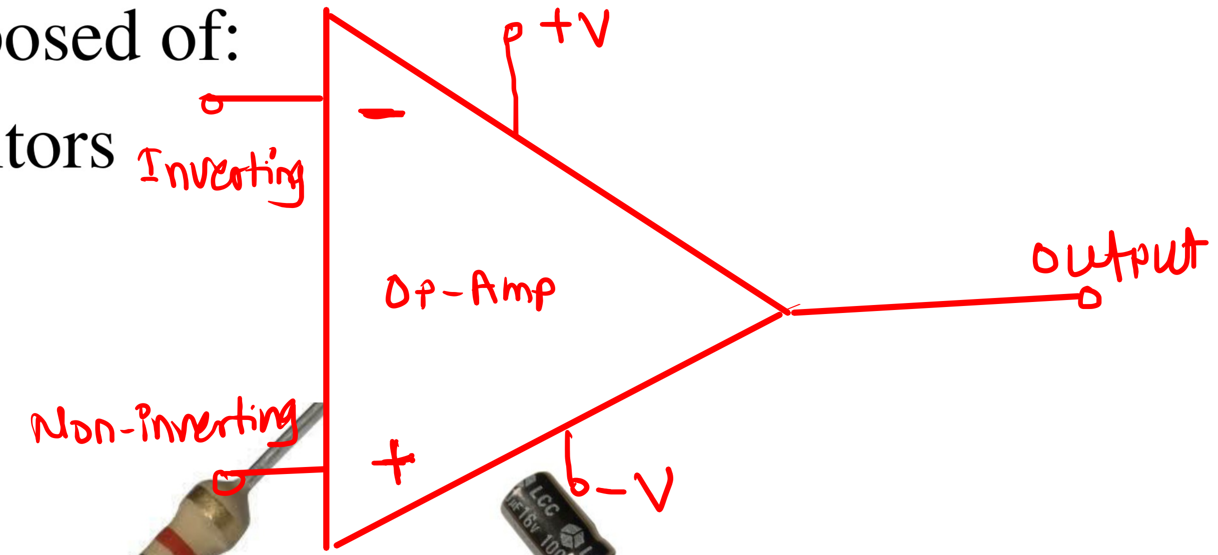
- What is an Op-Amp?
- Characteristics of Ideal and Real Op-Amps
- Common Op-Amp Circuits
- Applications of Op-Amps
- References

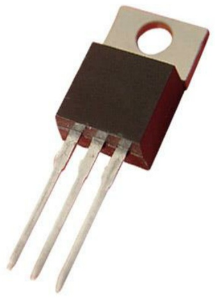
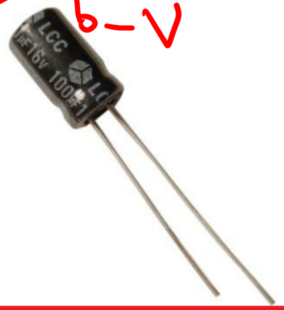
# What is an Op-Amp?

An Operational Amplifier (known as an “Op-Amp”) is a device that is used to amplify a signal using an external power source

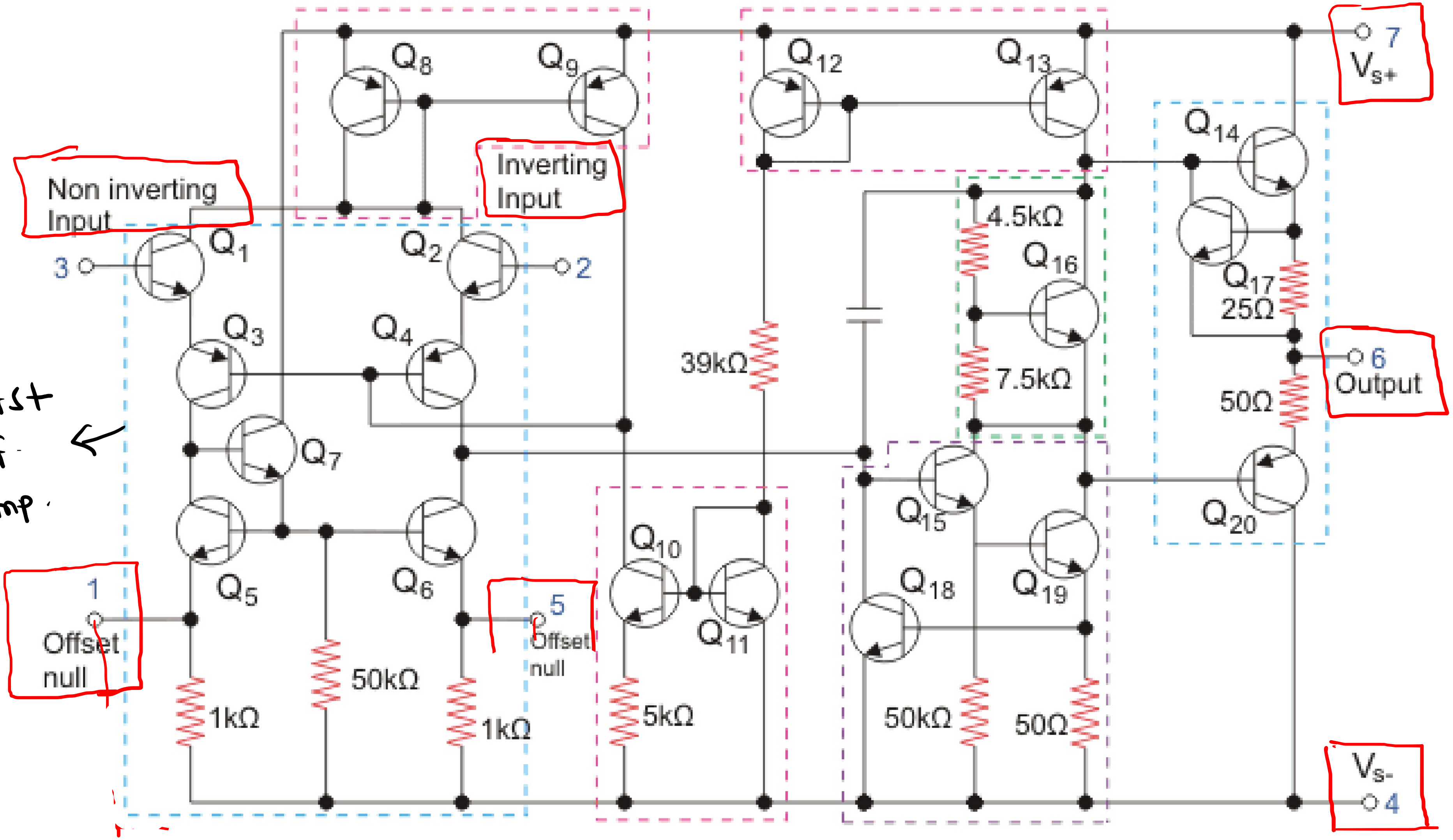
Op-Amps are generally composed of:

Transistors, Resistors, Capacitors



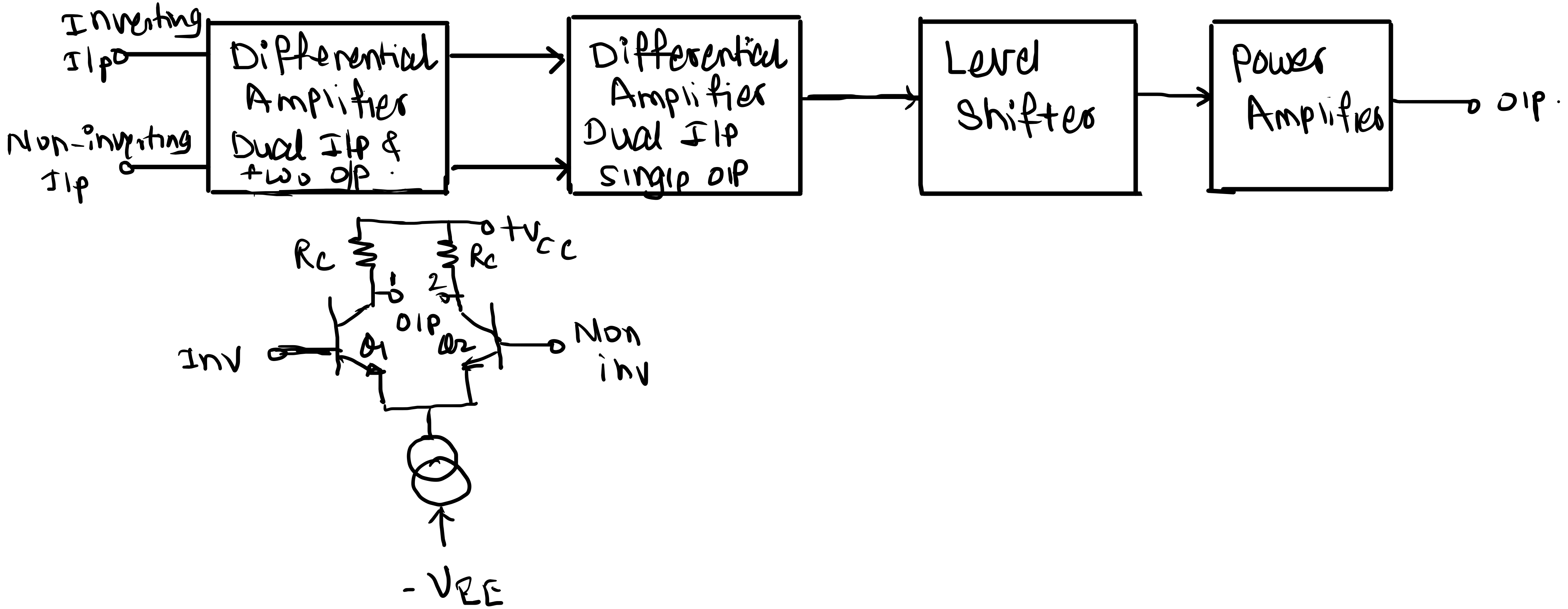

 =  +  + 

# Op-Amp internal circuit Diagram (IC 741)




First Diff. Amp.

# Block Diagram of Op-Amp (IC 741)

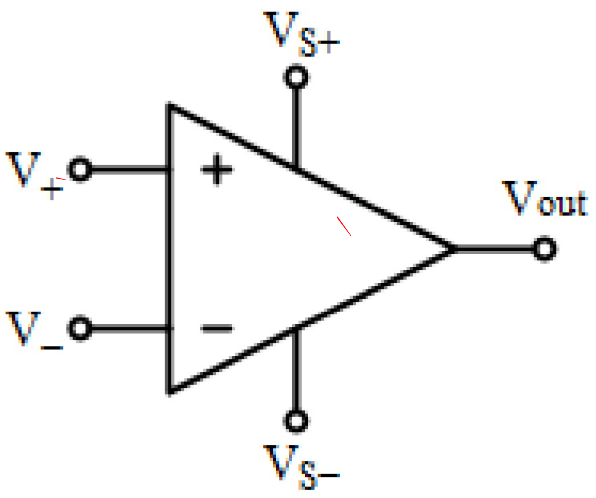


# Op-Amps and their Math

$V_{out} \propto (V_+ - V_-)$

$V_{out} = K(V_+ - V_-)$

## A traditional Op-Amp:




| | | |
|---|---|---|
| $V_+$ | : | non-inverting input |
| $V_-$ | : | inverting input |
| $V_{out}$ | : | output |
| $V_{s+}$ | : | positive power supply |
| $V_{s-}$ | : | negative power supply |

$$\boxed{V_{out} = K(V_+ - V_-)}$$

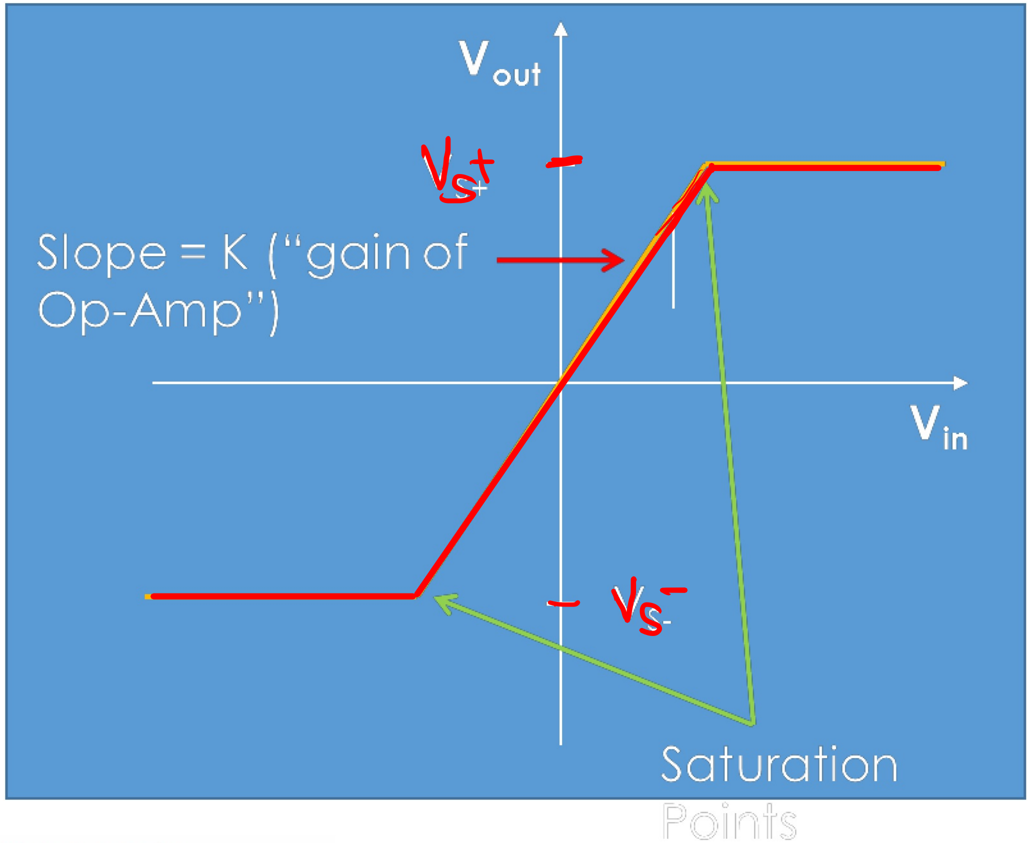
$K \rightarrow$ open loop gain

• The difference between the two inputs voltages ($V_+$ and $V_-$) multiplied by the gain (K, “amplification factor”) of the Op-Amp gives you the output voltage

• The output voltage can only be as high as the difference between the power supply ($V_{s+}$ / $V_{s-}$)and ground (0 Volts)

# Saturation

Saturation is caused by increasing/decreasing the input voltage to cause the output voltage to equal the power supply's voltage*



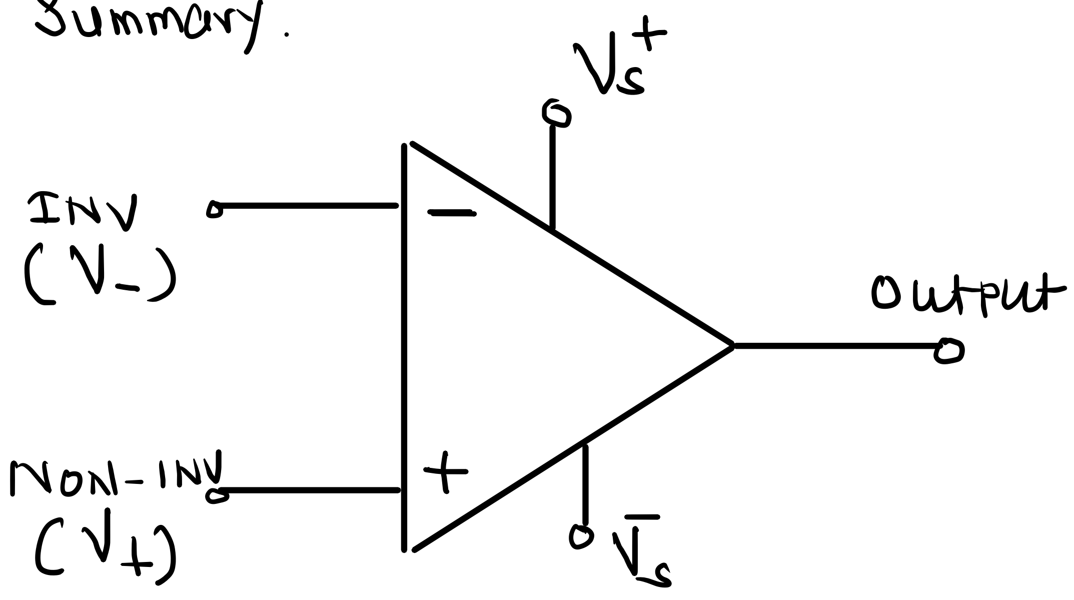

The slope is normally much steeper than it is shown here. Potentially just a few milli-volts (mV) of change in the difference between $V_+$ and $V_-$ could cause the op-amp to reach the saturation level

$$(V_+ - V_-) \Leftarrow +ve \geq (V_S^+)$$

* Note that saturation level of traditional Op-Amp is 80% of supply voltage with exception of CMOS op-amp which has a saturation at the power supply's voltage

$$(V_+ - V_-) \Leftarrow -Ve\, |\geq |-V_S^-)$$

⇒ Summary.




$$V_{out} = K(V_+ - V_-)$$

$K \Rightarrow$ open loop gain

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# CHARACTERISTICS OF OPERATIONAL AMPLIFIERS

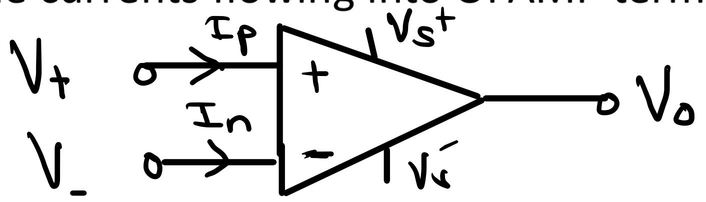
## 1. Input Bias Current and Input Offset Current:

$I_B =$

→ The input bias current is the average of the currents flowing into OPAMP terminals .(Ip+In)/2    Ideal $I_B = 0$

Input bias current in the IC741 OPAMP is 500nA

→ The input offset current is the difference between the currents flowing into OPAMP terminals (Ip-In).




## 2. Input Offset Voltage: (Ideal $V_{offset} = 0V$)

→ The OP amp are designed so that the final stage produces an output voltage of 0 Volts, when the two inputs are at the same potential level. However Internal defects can lead to a DC offset at the output.

→ The DC offset can be nulled by one of the following two ways. A DC voltage can be placed in one input terminal when the Op amp is wired as a negative feedback amplifier. The voltage placed on the input is the input offset voltage.

→ In addition, the 741 has nulling terminals where a potentiometer can be connected. The external connections pins 1 and 5 are to the emitters of some internal transistors.

$$V_o = K(V_+ - V_-)$$

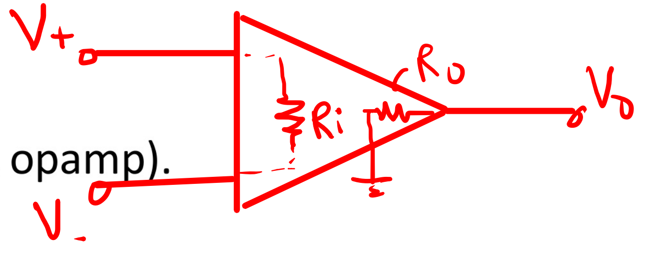
$$V_+ = V_- \qquad V_o = 0V$$

# CHARACTERISTICS OF OPERATIONAL AMPLIFIERS..

## 3. Input and Output Resistances, Rin and Ro

The input resistance looking into the two input terminals of the op-amp is ideally infinite. This means that the device draws no current.

Ideal $R_i = \infty$




→ For a real 741 op-amp, the input resistance is about 2 Mega ohms.
For FET op-amps, this resistance can be much higher $10^{12}$ ohms).

→ The output resistance on the other hand is ideally zero. (Ro=75 Ohms for 741 opamp).

Ideal: $R_o = 0\,\Omega$

## 4. Open Loop Gain

→ This is the gain of the op-amp if a signal is fed differentially into the input of the amp and no feedback loop is present. This gain is ideally infinite, but in a real op-amp the maximum gain is finite (about $10^5$ ) .

→ The gain also depends strongly on frequency. For low frequency inputs it takes on its maximum value, but the gain decreases rapidly as the input frequency goes up. For a 741, the gain decreases until it is only 1 at 1MHz.

$V_o = K(V_+ - V_-)$

$K \Rightarrow$ open loop gain

Ideal $K = \infty$

IC 741
$K \simeq 10^5$

# CHARACTERISTICS OF OPERATIONAL AMPLIFIERS..

## 5. Slew Rate

( Ideal ⇒ infinite )    IC 741. ⇒ 6mv/μsec

→ An ideal op-amp has an infinite frequency response. This means that no matter how fast the input changes, the output will be able to keep up.

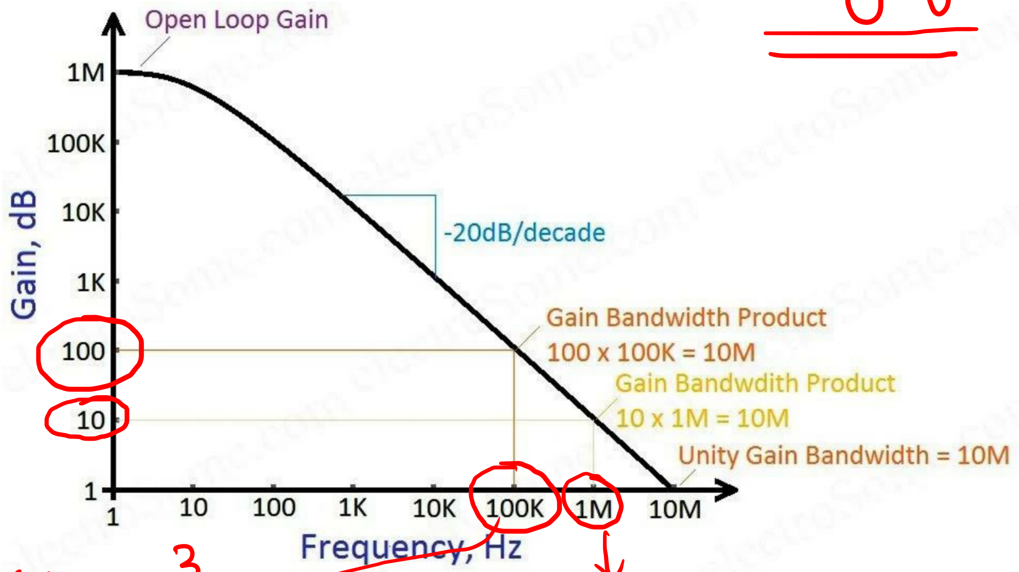
→ In practical op-amp,if the input signal changes too fast then the output will not be able to keep up. This is defined as slewing and it results in distortion of the output waveform. Slew Rate = SR = maximum dvo/dt or the maximum rate at which the output can change without distorting.

Gain in dB = 10 log (gain)

## 6. Gain - Bandwidth Product

→ The gain of the op-amp is frequency dependent. The frequency response of the open loop gain is such that the frequency decreases with gain.

→ It can be seen that the op-amp displays the property that the open-loop gain times the frequency is a constant. This constant is defined as the gain-bandwidth product and it is $1 \times 10^6$ for the 741 amplifier.




GB ⇒ $100 \times 100 \times 10^3 = 10^7$

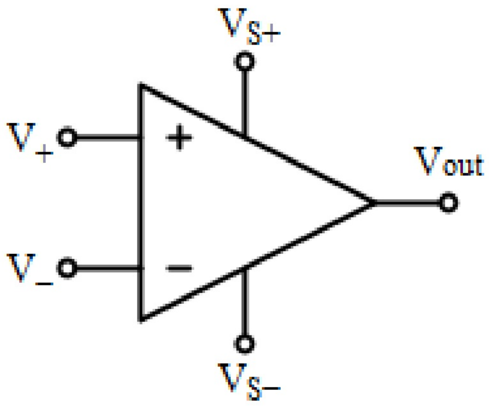
$10^6 \times 10 = 10^7$

# An Ideal Op-Amp Characteristics

- Infinite voltage gain
- Infinite input impedance
- Zero output impedance
- Infinite bandwidth
- Zero input offset voltage (i.e., exactly zero out if zero in).
- Zero input offset current
- Infinite slew rate
- Zero input bias current.

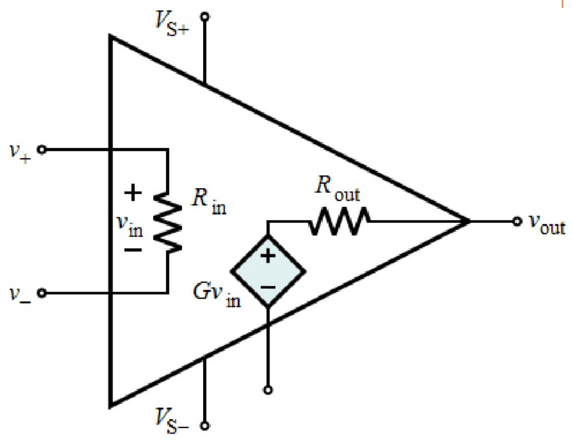
# Ideal versus Real Op-Amps

| Parameter | Ideal Op-Amp | Real Op-Amp |
|---|---|---|
| Differential Voltage Gain | ∞ | $10^5$ - $10^9$ |
| Gain Bandwidth Product (Hz) | ∞ | 1-20 MHz |
| Input Resistance (R) | ∞ | $10^6$ - $10^{12}$ Ω |
| Output Resistance (R) | 0 | 100 - 1000 Ω |




Ideal

Real



# Outline of Presentation

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# Basic Op-Amp Circuits

- An op-amp amplifies the difference of the inputs $V_+$ and $V_-$ (known as the differential input voltage)
- This is the equation for an *open loop* gain amplifier:

$$V_{out} = K(V_+ - V_-)$$

- K is typically very large – at around 10,000 or more for IC Op-Amps $(10^5 - 10^9)$
- This equation is the basis for all the types of amps we will be discussing

Example (i)

$\Rightarrow$ $K = 10^5$, $V_+ = 2V$ & $V_- = 1V$ & $V_s^+ = 10V$, $V_s^- = -10V$

$$V_O = K(V_+ - V_-)$$

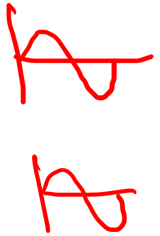
$$V_O = 10^5(2-1) = 10^5\,V$$

$$\boxed{V_o = 10^5\,V} \Longrightarrow V_O = 10V \text{ because of saturation}$$

Example (ii) How much can maximum voltage difference that can be amplified by open loop-Amp. if $K = 10^5$, $V_s^+ = 10V$, $V_s^- = -10V$

$V_+$

$V^-$



$$V_{O\,(max)} = \pm 10V$$

$$\pm 10V = 10^5(V_D)$$

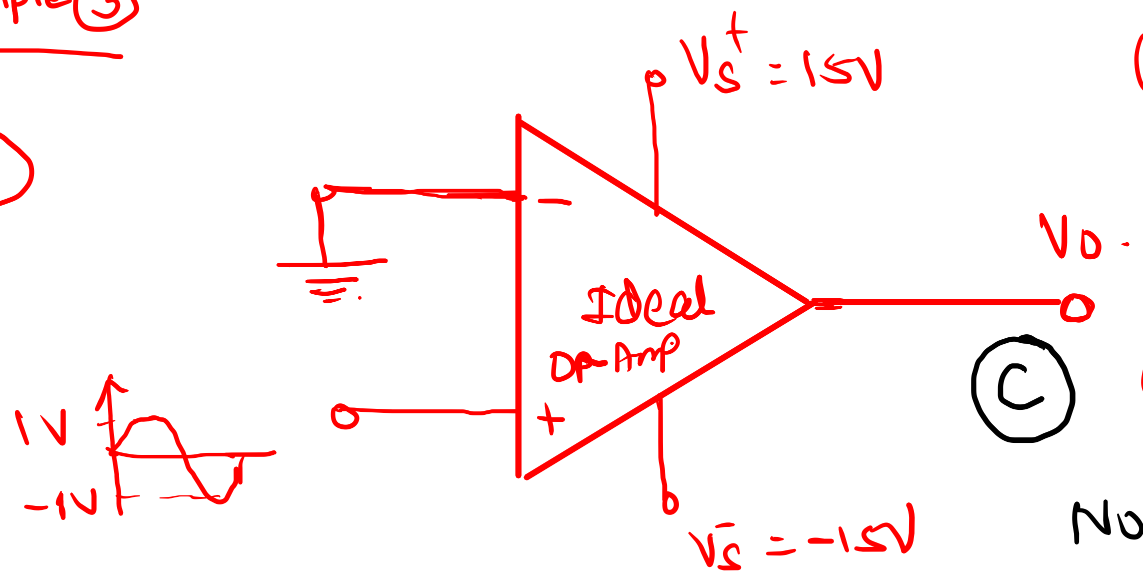
$$V^+ - V^- = V_D = \pm 10/10^5 = \pm 10 \times 10^{-5} = \pm 10^{-4}\,V$$

$$= \pm 0.1\,mV.$$

⇒ Open-loop OpAmp.

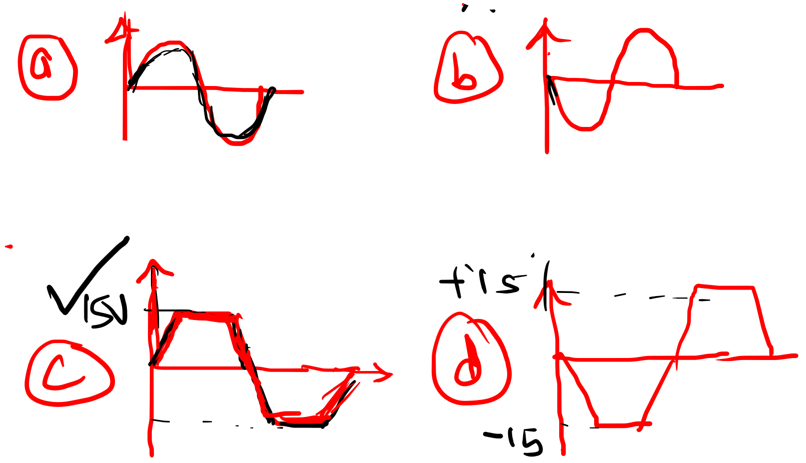
## Example (3)

(1)



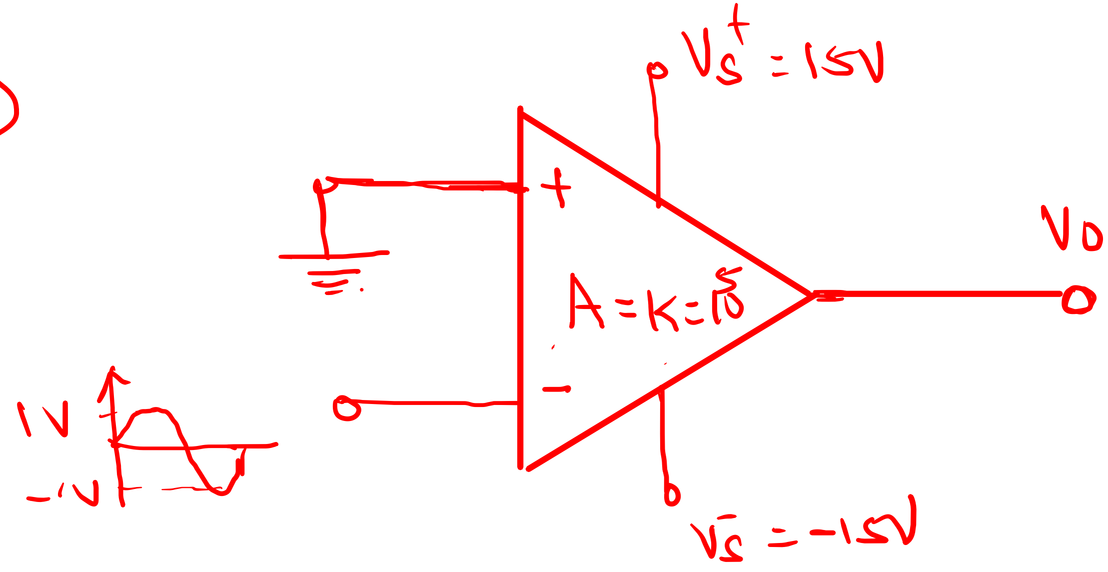

C

Options




Non-inverting & saturated.

(2)

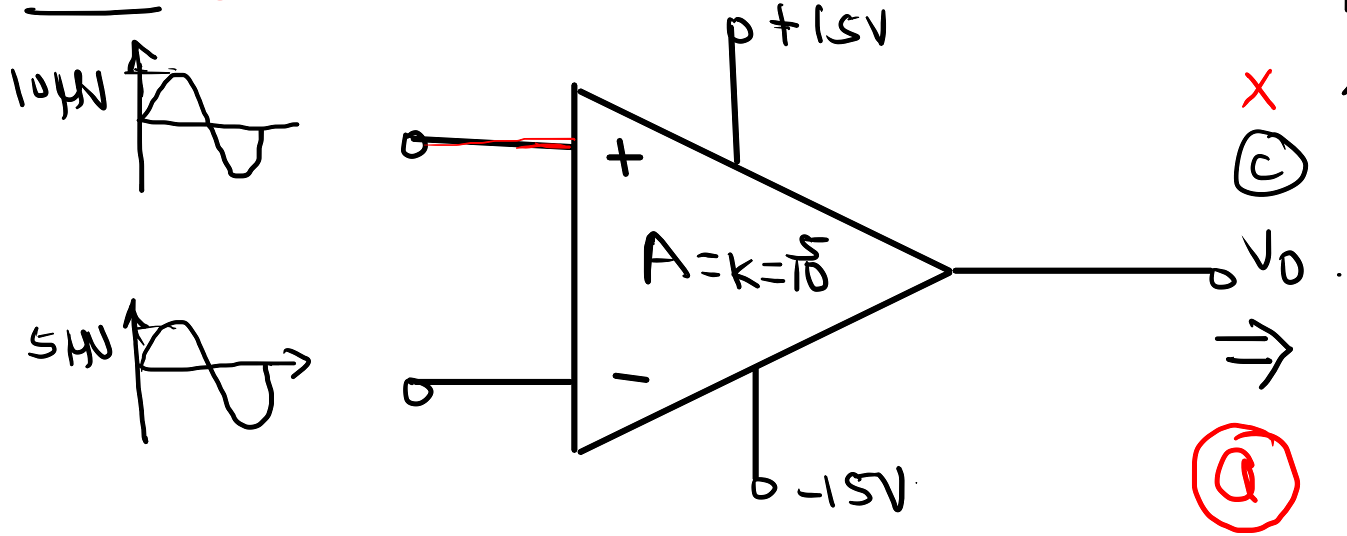


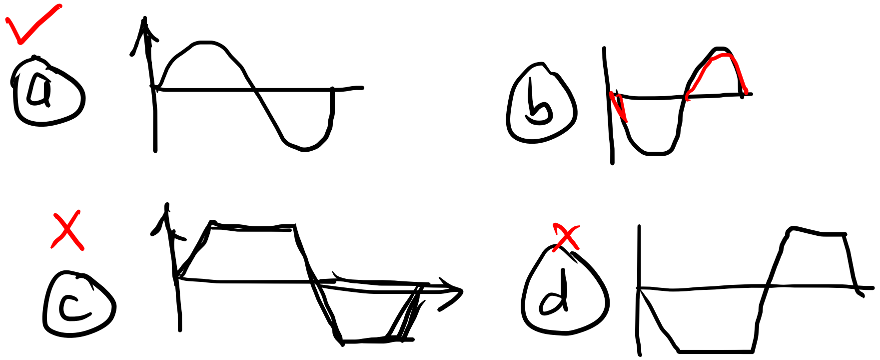

⇒ Correct

D

Inverting & saturated

## Example 4




$$\Rightarrow \quad V_o = k(V_+ - V_-)$$

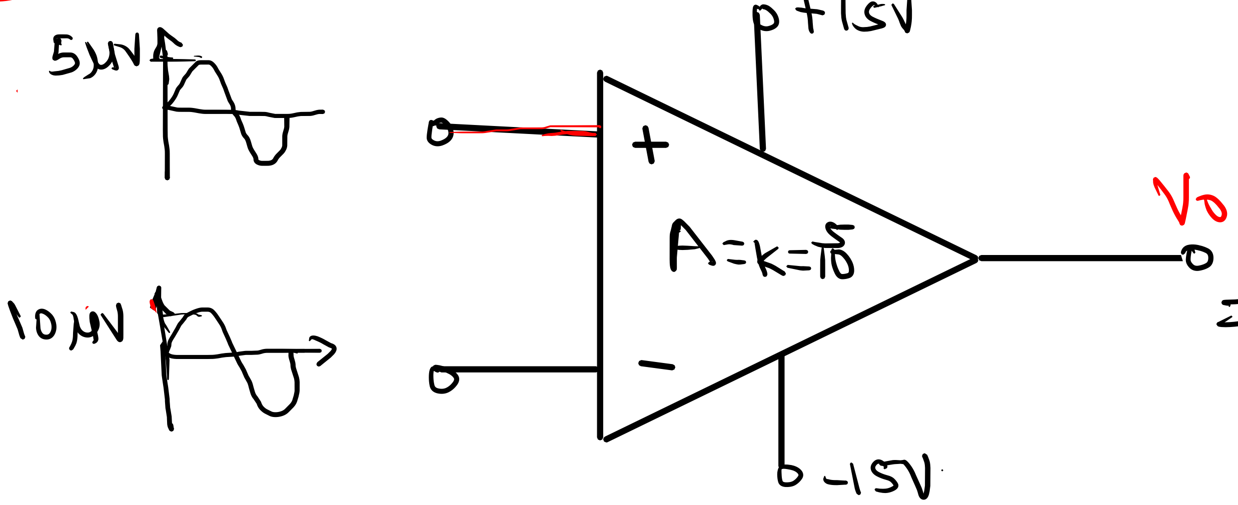
(a)

$$= 10^5(10\times10^{-6} - 5\times10^{-6})$$

$$= 10^5(10^{-5} - 0.5\times10^{-5})$$

$$V_o = 0.5\,V$$

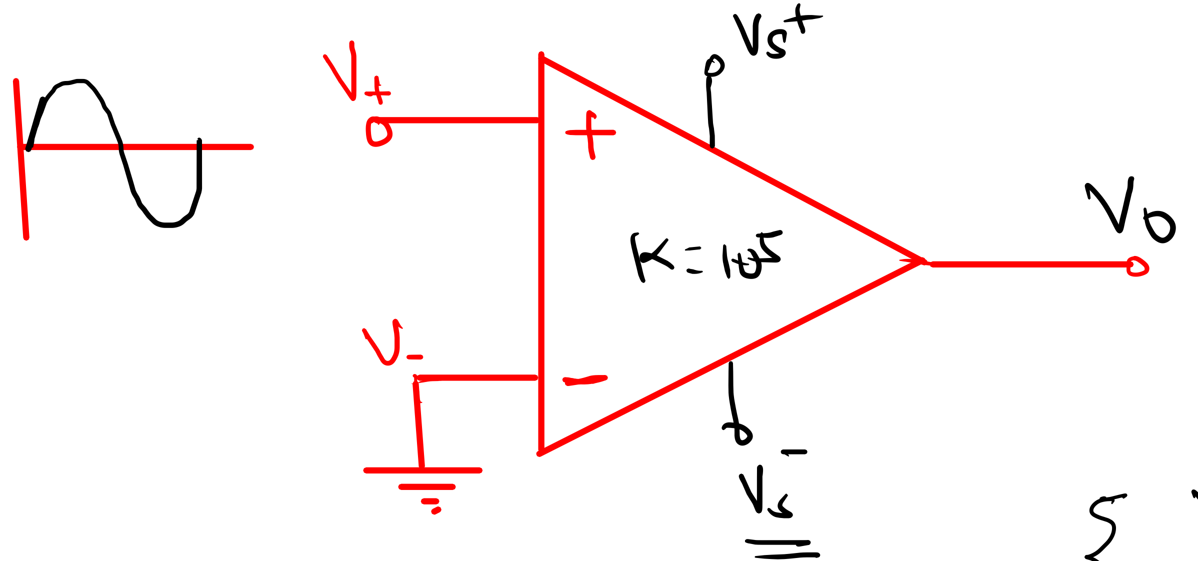
5




$\Rightarrow$ (b)

⇒ Application of op-Amp in open-loop Configuration

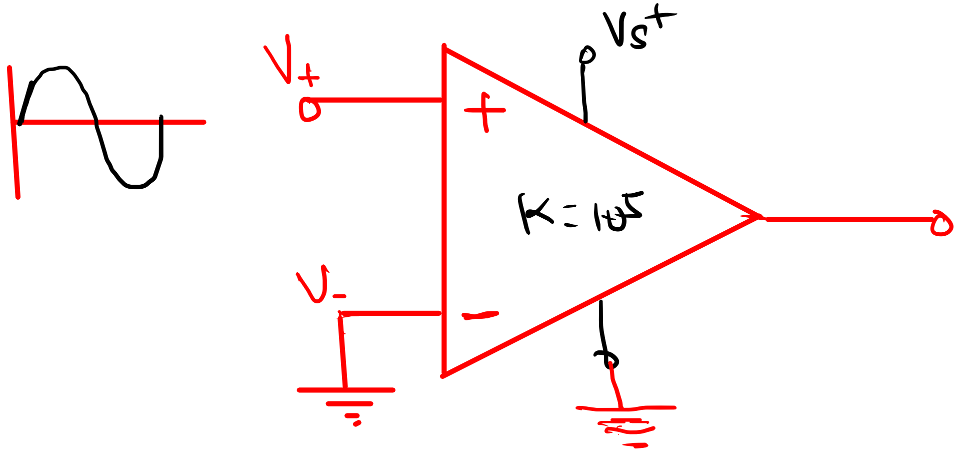
⇒ Op-Amp operation as Comparator

① 


$$V_o = K(V_+ - V_-)$$
$$= 10^5 (V_+)$$

$V_- = 0V$

$$\begin{cases} V_+ > 0, & V_o = +V_{sat} \\ V_+ < 0, & V_o = -V_{sat} \end{cases}$$

② 

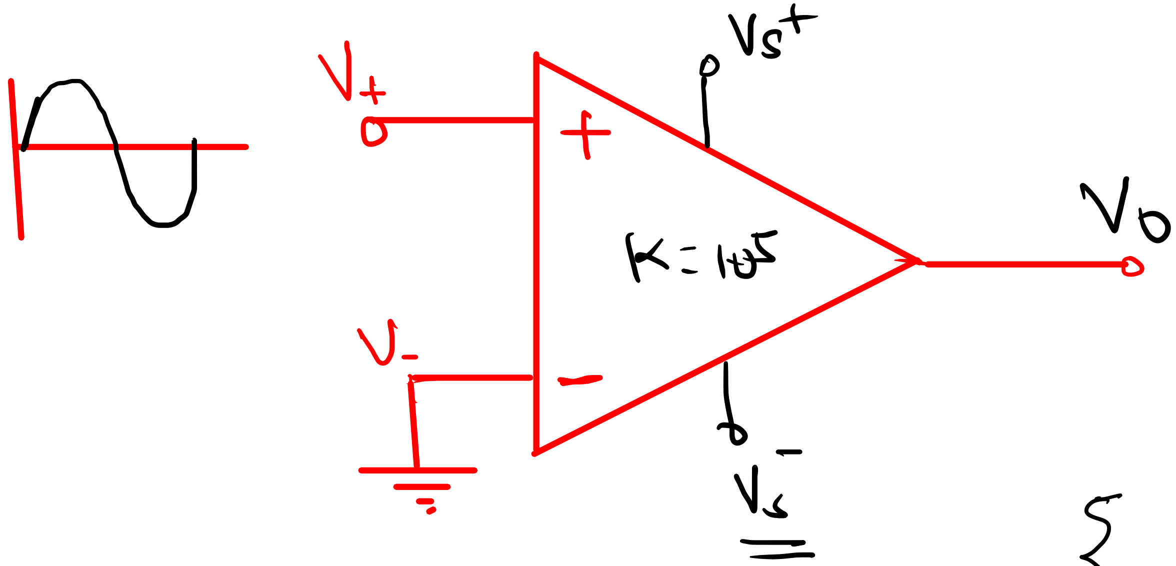

$V_+ > 0$ , $V_o = +V_{sat}$

$V_- < 0$ , $V_o = 0V$

## ⇒ Application of op-Amp in open-loop Configuration

### ⇒ Op-Amp operation as Comparator

1



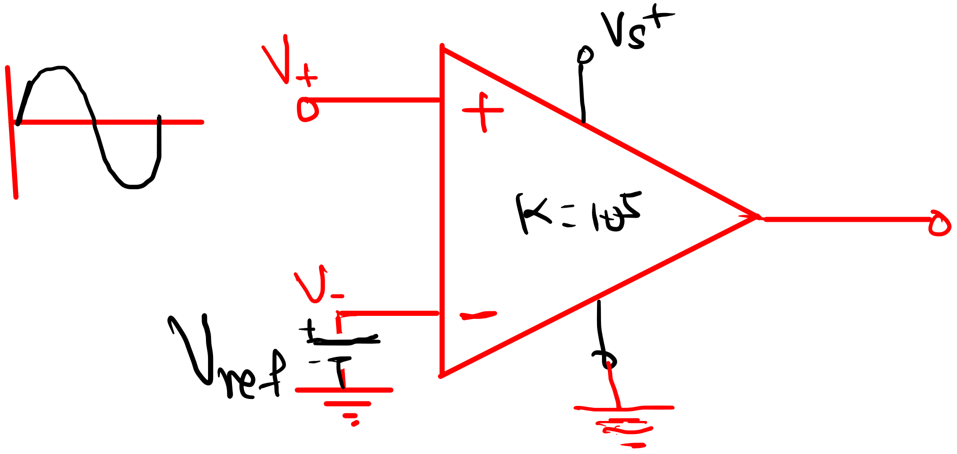

$$V_o = K(V_+ - V_-)$$

$$= 10^5 (V_+)$$

$V_- = 0V$

$$\begin{cases} V_+ > 0, & V_o = +V_{sat} \\ V_+ < 0, & V_o = -V_{sat} \end{cases}$$

3

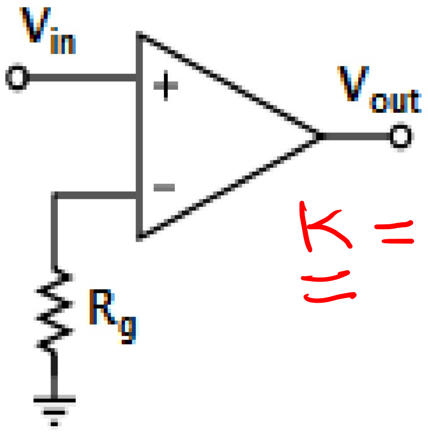



$V_+ > V_{ref}$, $V_o = +V_{sat}$

$V_- < V_{ref}$, $V_o = 0V$

# Open Loop vs Closed Loop Circuit

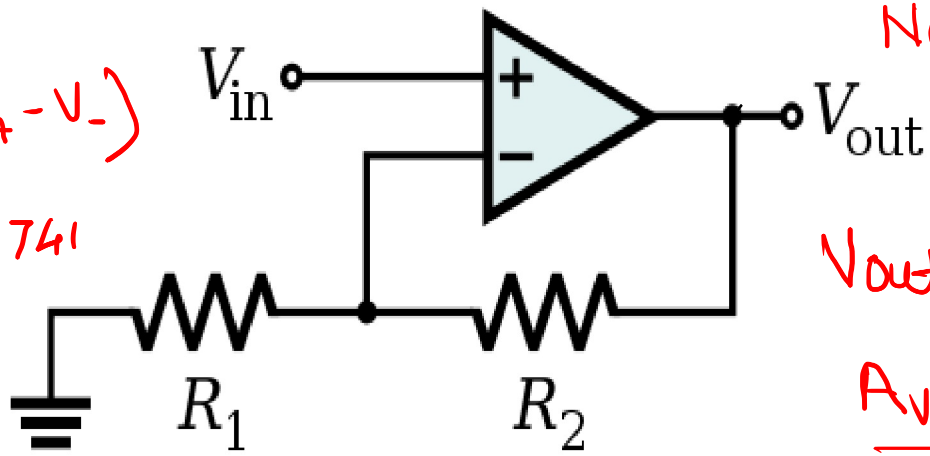
- A closed loop op-amp has feedback from the output to the input, an open loop op-amp does not




$= \underline{\underline{K}}(V_+ - V_-)$

$\underline{\underline{K}} = 10^5$ for 741

Open Loop




Negative feedback

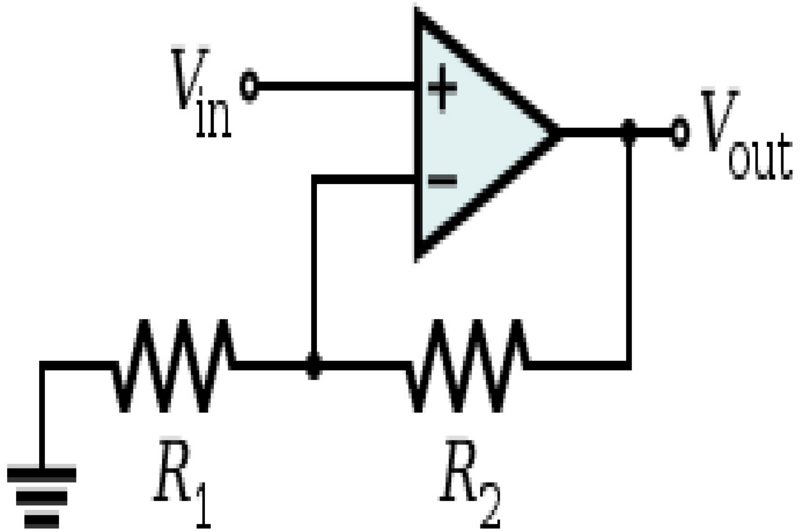
$V_{out} = \underline{\underline{A_v}} (V_{in})$

$A_v \Rightarrow$ finite

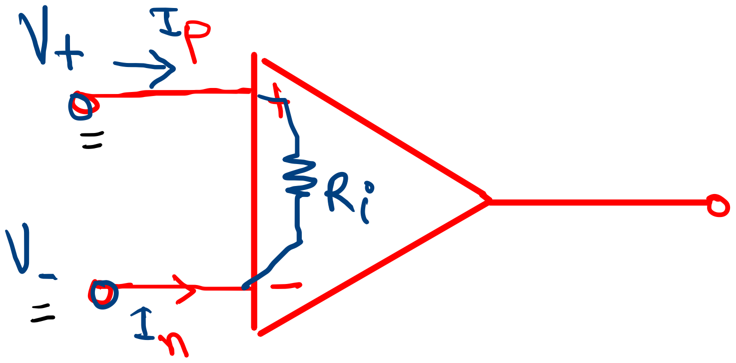
Closed Loop

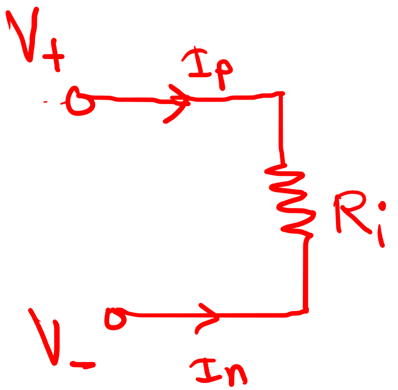
# Op-Amp as Non-Inverting Amplifier

- Amplifies the input voltage by a constant
- Closed loop op-amp
- Voltage input connected to non-inverting input
- Voltage output connected to inverting input through a feedback resistor
- Inverting input is also connected to ground
- Non-inverting input is only determined by voltage output



⇒ Concept of Virtual ground in OP-Amp.




$I_B$ = Input Bias current $= \dfrac{I_p + I_n}{2}$

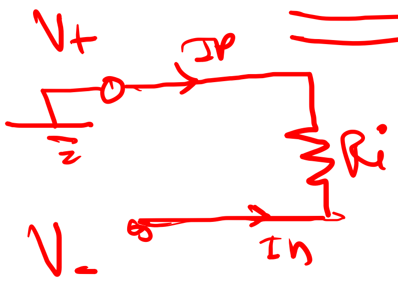
For Ideal Op-Amp $= I_B = 0$

$R_i = \infty$

$I_n = I_p = 0$

✓Case ① ⇒ $R_i = \infty$ So Open Circuit

✓Case-Ⅱ $\underline{\underline{V_+ = V_-}}$ then $I_n = I_p = 0$



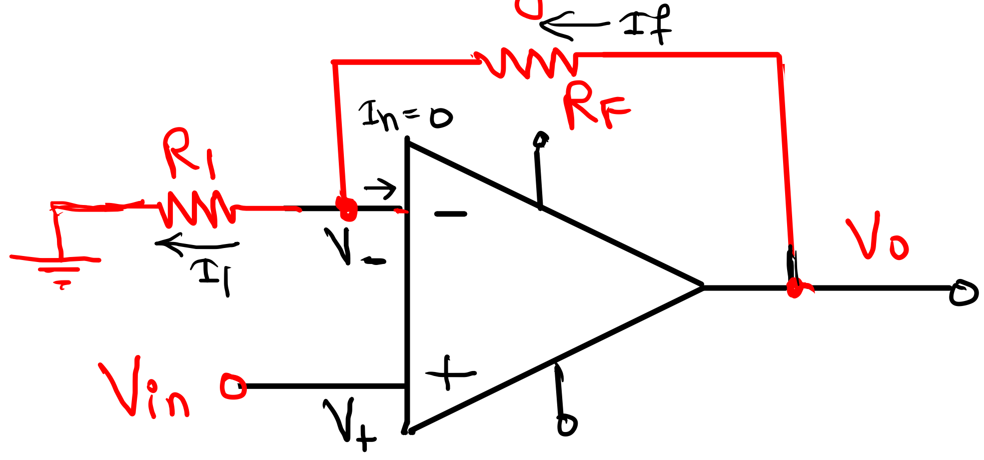

$V_+ = V_-$

$V_+ = 0V$ (ground)

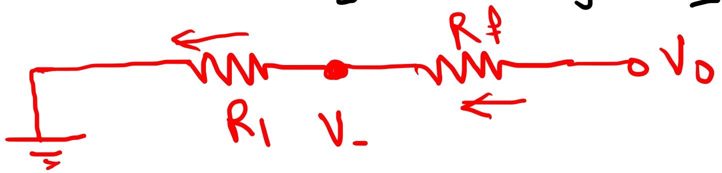
$V_- = 0V$ [Virtual ground]

# ⇒ Closed Loop Configuration of Op-Amp.

## ⇒ Non-Inverting Amplifier




$\Rightarrow V_+ = V_- = V_{in}$ [ Virtual ground]




Using voltage division formula

$$V_- = \left(\frac{R_1}{R_1 + R_f}\right) V_o$$

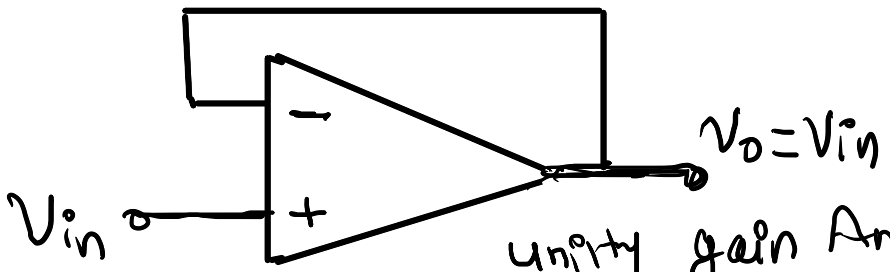
But $V_- = V_{in}$

$$V_{in} = \left(\frac{R_1}{R_1 + R_F}\right) V_o$$

$$\frac{V_o}{V_{in}} = \text{gain} = \frac{R_1 + R_F}{R_1}$$

$$\boxed{\text{gain} = 1 + \frac{R_F}{R_1}}$$

if $R_F = 0$ & $R_1 = \infty$ ∴ gain $= 1 + 0 = 1$

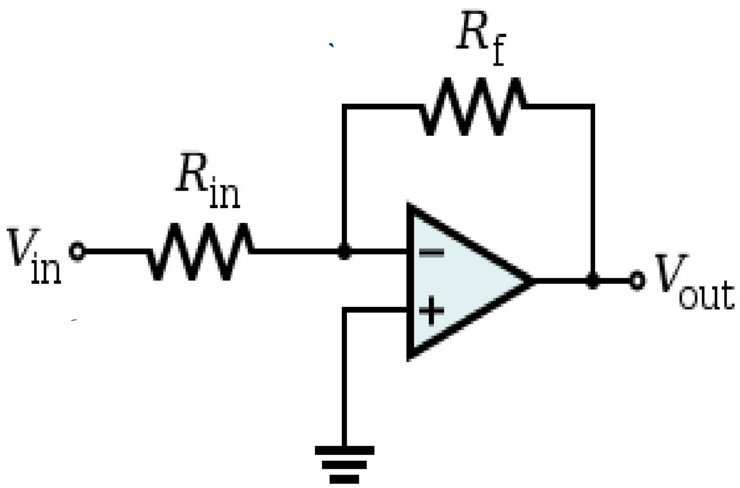



unity gain Amp.

Voltage follower.

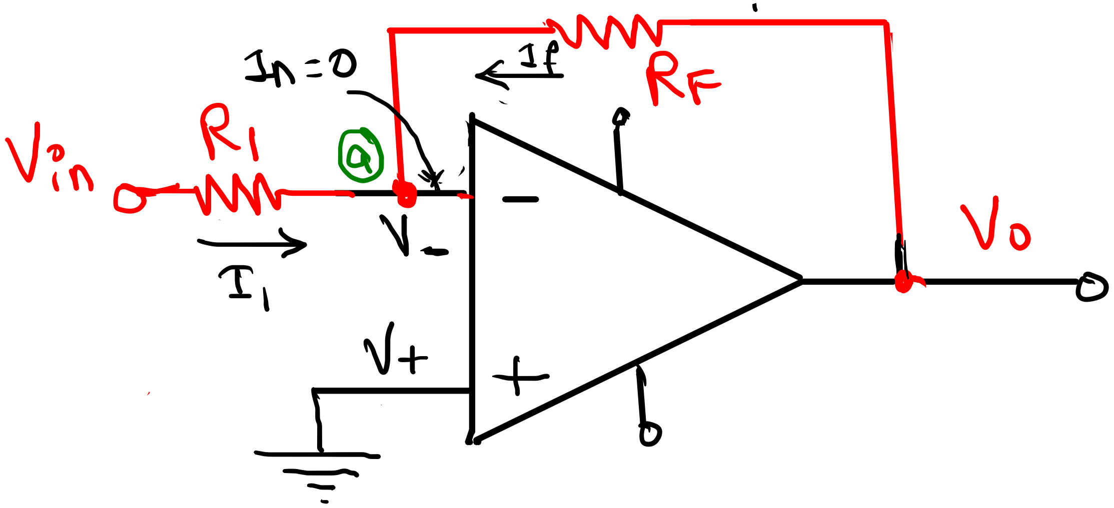
# Op-Amp as Inverting Amplifier

- Amplifies and inverts the input voltage
- Closed loop op-amp
- Non-inverting input is determined by *both* voltage input and output
- The polarity of the output voltage is opposite to that of the input voltage
- Input Voltage is connected to inverting terminal
- Output Voltage is fedback to inverting input through a feedback resistor
- Non-inverting input is grounded



# ⇒ Closed Loop Configuration of Op-Amp.

## ⇒ Inverting Amplifier




⇒ $V_- = V_+ = 0V$ [Virtual ground]

KCL at node a

$$I_1 + I_F = 0$$

$$I_1 = \frac{V_{in} - 0}{R_1} = \frac{V_{in}}{R_1}$$

$$I_f = \frac{V_o - 0}{R_F} = \frac{V_o}{R_F}$$

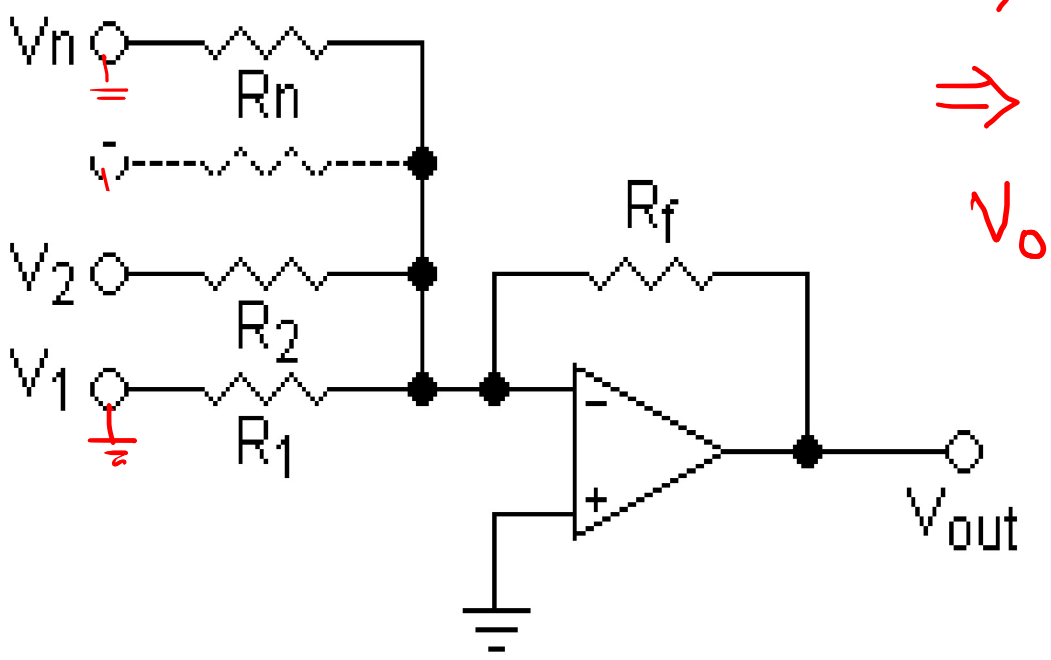
$$I_1 + I_F = 0$$

$$I_1 = -I_F$$

$$\frac{V_{in}}{R_1} = -\frac{V_o}{R_F}$$

$$\boxed{\text{gain} = \frac{V_o}{V_{in}} = -\frac{R_F}{R_1}}$$

# Op-Amp as Adder/Summing Amplifier




⇒ Inverting Configuration

⇒ Superposition principle.

$V_{o1} = -\frac{R_F}{R_1} \cdot V_1$ , $V_{o2} = -\frac{R_F}{R_2} \cdot V_2$ ... $V_{on} = -\frac{R_F}{R_n}$

$V_{out} = V_{o1} + V_{o2} + \cdots + V_{on}$

$$V_{out} = -R_f \left( \frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n} \right)$$

$R_1 = R_2 = \cdots = R_n$

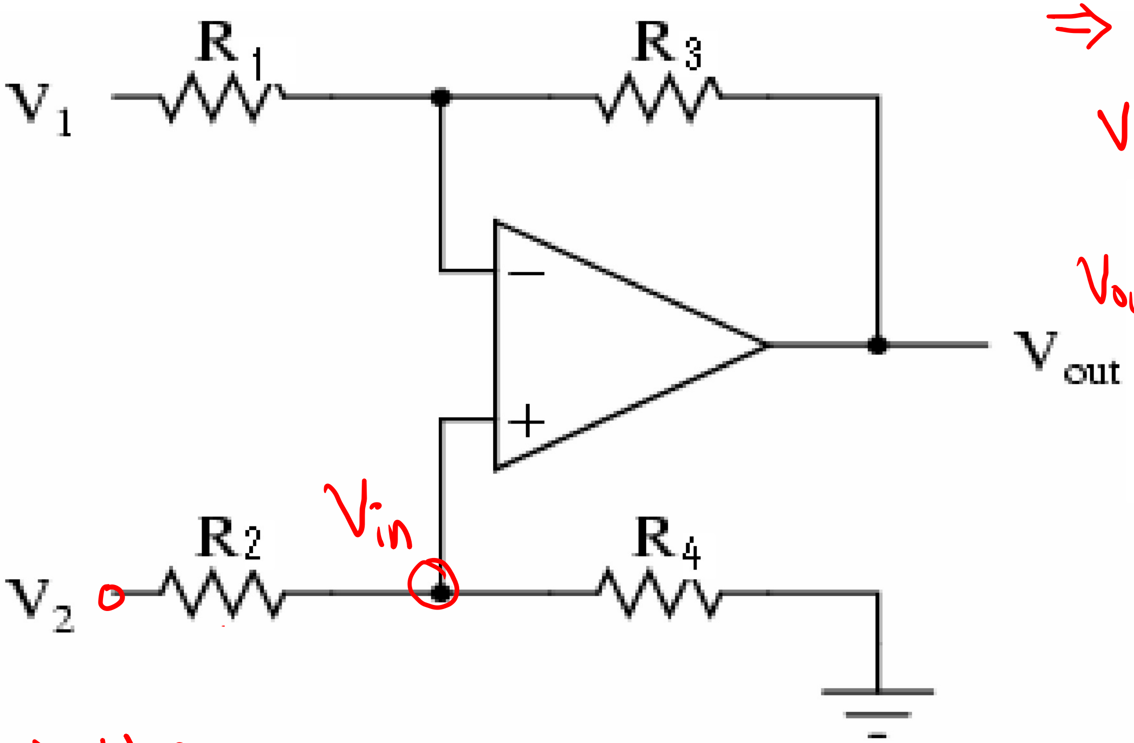
$V_{out} = -\frac{R_F}{R_n} [V_1 + V_2 + \cdots + V_n]$

# Op-Amp as Subtractor

$$V_{o_1} = -\frac{R_3}{R_1} \cdot V_1 \quad \text{-----} \; (1)$$

⇒ Consider $V_2$ & ground $V_1$

$$V_{in} = \frac{R_4}{R_2+R_4} \cdot V_2 \quad , \quad V_{o2} = \left(1+\frac{R_3}{R_1}\right) \cdot V_{in}$$




$$V_{out} = V_{o1} + V_{o2} = V_{out} = \frac{V_2(R_3+R_1)R_4}{(R_4+R_2)R_1} - \frac{V_1R_3}{R_1}$$

If all resistors are equal:

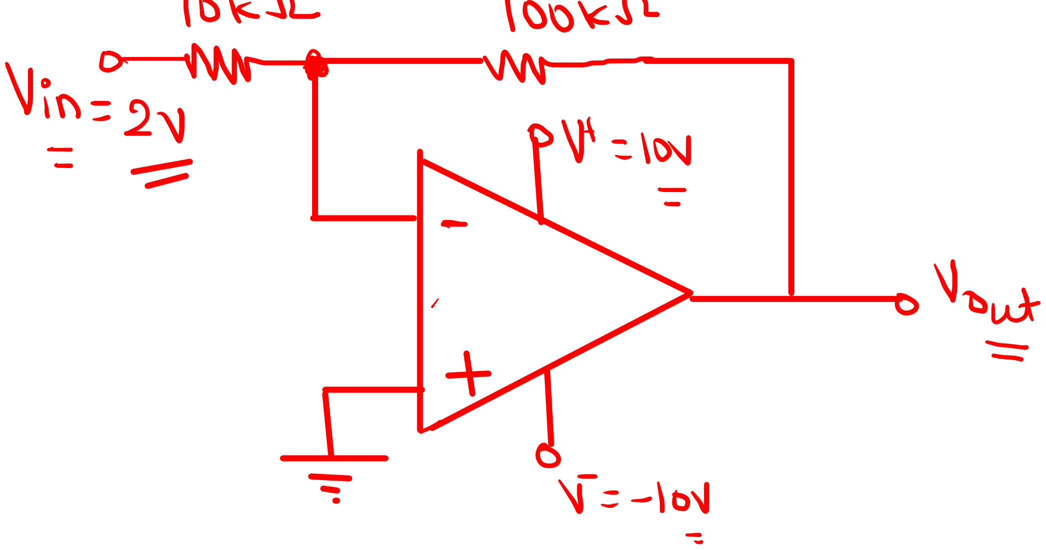
$$V_{out} = V_2 - V_1$$

⇒ Using superposition principle.

Consider $V_1$ & replace $V_2$ by its resistance

$\Rightarrow$ Inverting & Non-inverting Amplifiers.

Ex ① Find Vout




modification to get $V_{out} \le |V^+|$

Rf changed from $100k\Omega \to 50k\Omega$

$$\boxed{V_{out} = -\frac{50}{10} \times 2 = -10V}$$

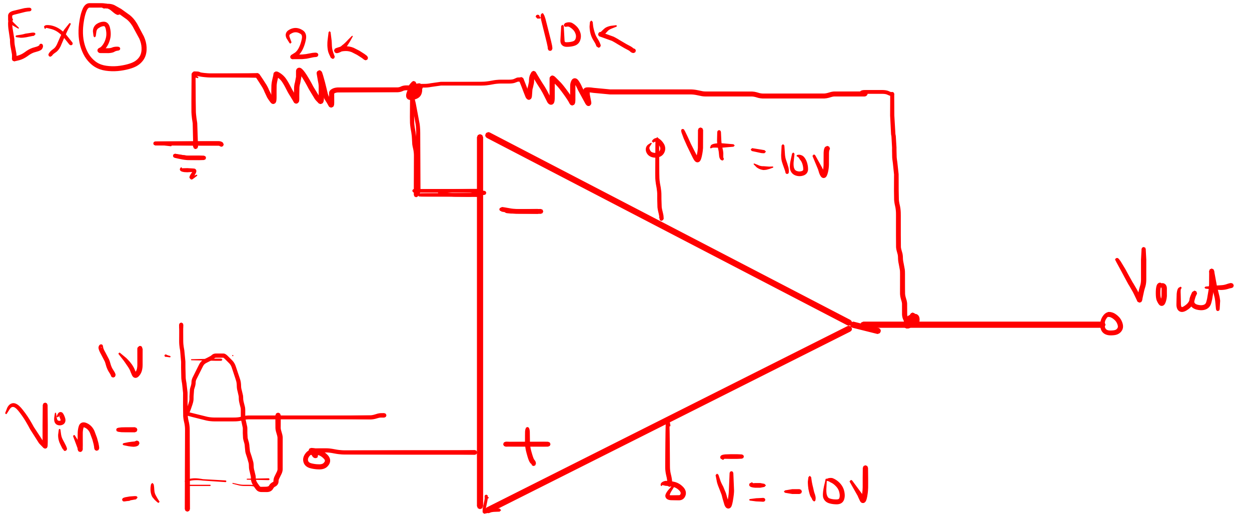
Sol$^n$ $\Rightarrow$

$$V_{out} = -\frac{100}{10} \times 2 = |-20V| \ge |V^+/V^-|$$

So $\boxed{V_{out} = -10V}$ saturation

$V_{out}(max) = |V^+/V^-|$

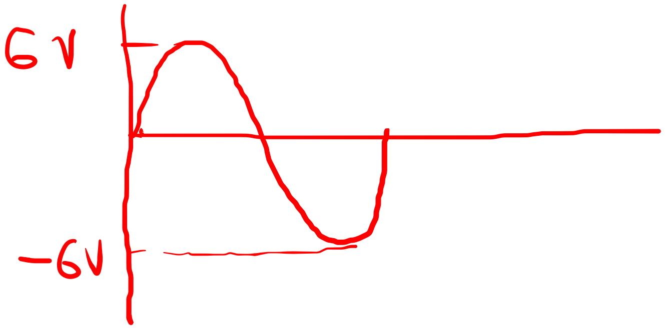
Ex (2)




$$\text{gain} = \left(1 + \frac{10K}{2K}\right) = 1 + 5 = 6$$

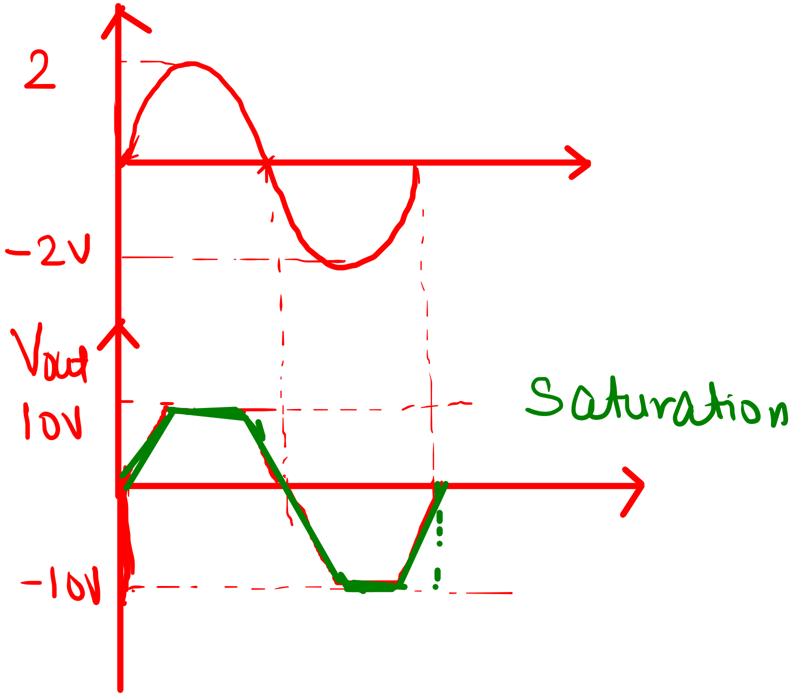
$$V_{out} = \text{gain} \times V_{in} = 6 \times 1V_p = 6V_p.$$

$V_o \Rightarrow$




If $V_{in} = 2V_p$.

$V_{out} = \text{gain} \times V_{in}$



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