23/02/24

# Operational Amplifier

→ Gets its name from Operational (performs addition, subtraction, integration, differentiation,..) + Amplifier.

→ Shortly called OpAmp.

## Applications:

(1) Mathematical operations

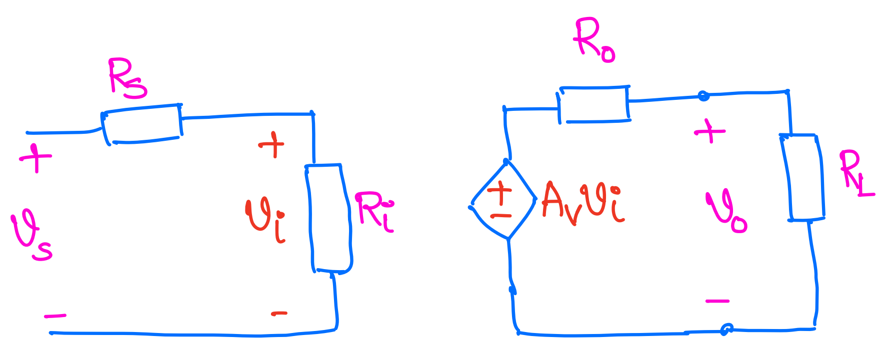
Addition, subtraction, integration, differentiation,.

(2) Filtering applications

(3) Sensing voltage, current, pressure, temperature,...

## Ideal chara. of Amplifier:

Consider structure of amplifier given below.




$v_s$ : Source voltage

$v_o$ : Load voltage

$A_v$ : Voltage gain

$R_s$ : Source resistance

$R_i$ : Input resistance

$R_o$ : Output resistance

$R_L$ : Load resistance

$$v_o = \frac{R_o}{R_o+R_L} \cdot A_v v_i$$

$$\Rightarrow v_o = A_v \cdot \frac{R_o}{R_o+R_L} \cdot \frac{R_i}{R_i+R_s} \cdot v_s$$

For $\frac{v_o}{v_s}$ to be $A_v$ $\Rightarrow$ $R_o << R_L$ (Low o/p impedance)

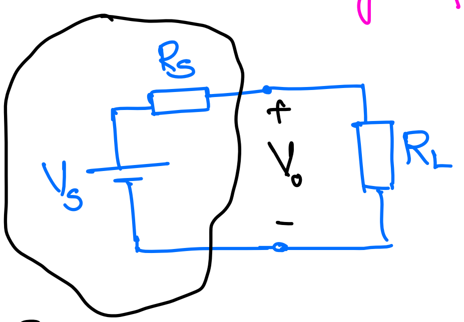
$R_i >> R_s$ (High o/p impedance)

$\rightarrow$ Ideal amplifier: $R_i \rightarrow \infty$ $\quad R_o \rightarrow 0$

$\Downarrow$

Otherwise loading effects take place.

What is loading effect?




$\Rightarrow$ As you load this circuit ($I \uparrow$) $\Rightarrow$ o/p voltage dips!!

Source ($V_s$) with internal resistance ($R_s$)

$$V_o = \frac{R_L}{R_L+R_s} \cdot V_s$$

$R_L = 1k\Omega$

$R_s = 500\Omega$

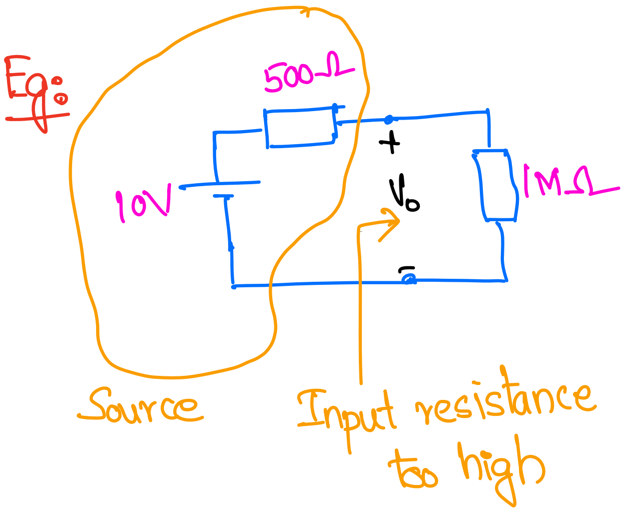
$V_s = 10V$

$\Downarrow$

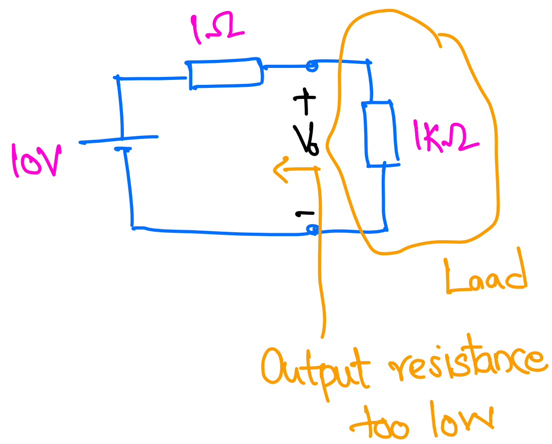
$V_o$ is only 6.67V (Not 10V).

→ For loading effect to be not much seen, Input resistance has to be very high and output resistance has to be too low.

Eg:

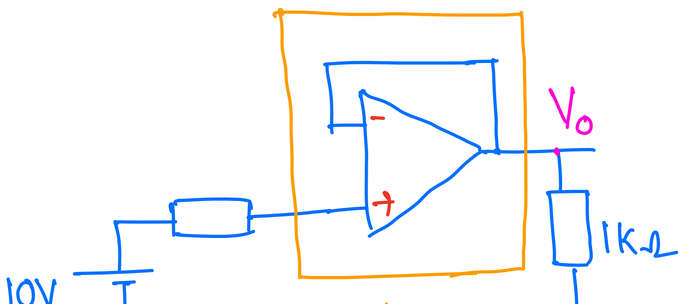



$V_o \approx 10V$




$V_o \approx 10V$.

→ Suppose that $R_s = 500\Omega$ and $R_L = 1k\Omega$? How to take care of loading effect?



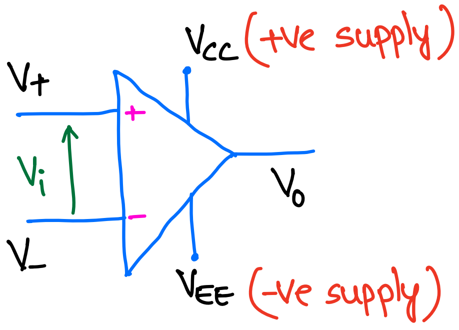

⇓

Put an OpAmp buffer here (since $R_i$ is very high and $R_o$ is very low for OpAmp).

⇓

We will understand how this works, in a few slides from here, after getting introduced to OpAmps.

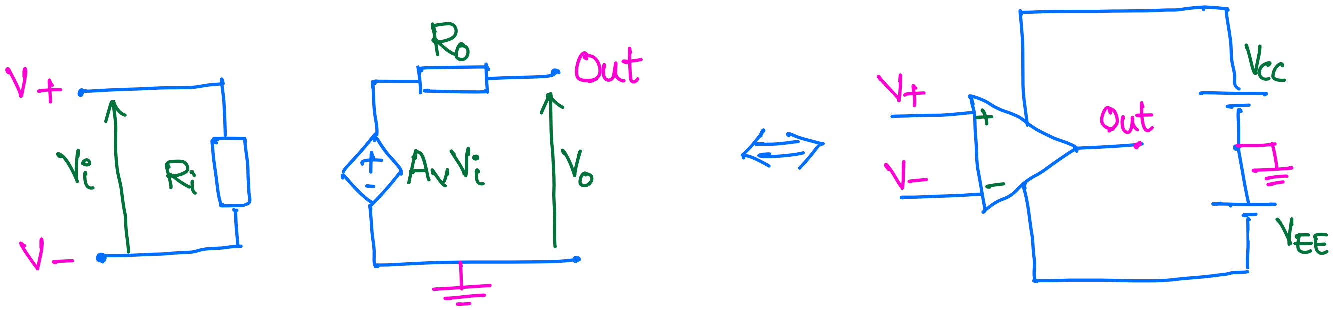
## Structure of OpAmp:




Open loop gain, $A_V = \dfrac{V_o}{V_+ - V_-} = \dfrac{V_o}{V_i}$

→ Open loop gain of opamp is very high ($= 2\times10^5$ for 741 IC)

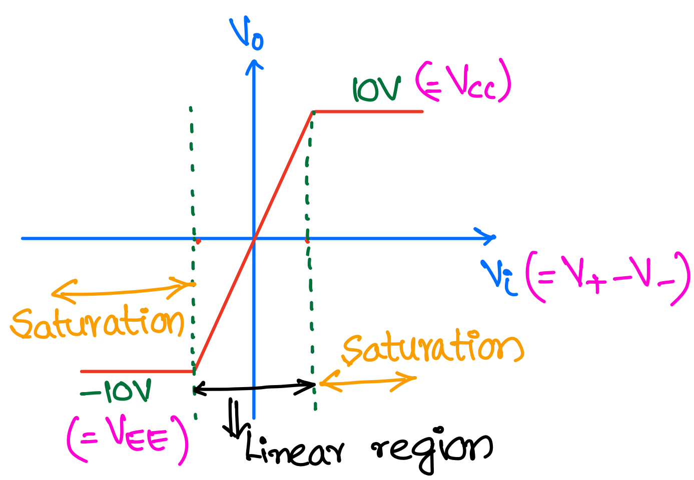
## Internal diagram of Opamp:




$R_i$ → Input resistance of opamp ($= 2\,M\Omega$ for 741 IC)

$R_o$ → Output resistance of opamp ($= 75\,\Omega$ for 741 IC)

## Open-loop characteristics of Opamp:




Let $V_{cc} = +10V$ and $V_{EE} = -10V$.

For 741; $A_v = 2\times10^5 \Rightarrow$ In linear region $\Rightarrow$

Virtual short phenomena $\Rightarrow$ $A_v = \frac{V_o}{V_i} \Rightarrow V_i$ is very small

$\Rightarrow V_+ \approx V_-$ (if opamp operates in linear region)

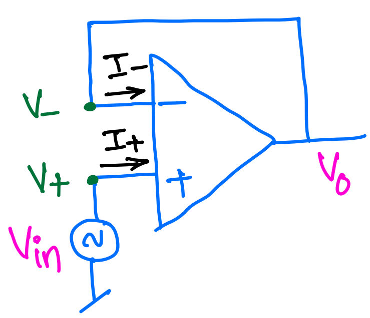
→ Also, since $R_i$ is very high $\Rightarrow$ currents at both the inverting and non-inverting terminals of opamp can be neglected.

$\therefore I_+ \approx I_- \approx 0$ (if opamp operates in linear region)

→ Opamps with negative feedback operate in linear region, if voltages are within supply voltage range.

→ Some of the opamp configurations operating in linear region are discussed below.

## (1) Opamp-buffer | Unity-gain Amplifier | Voltage Amplifier:

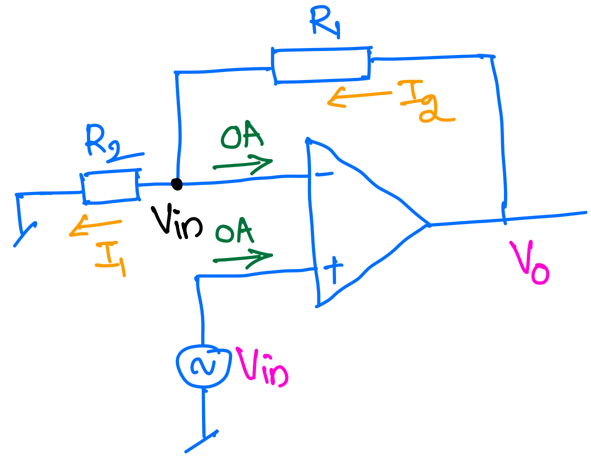



Linear region $\Rightarrow V_+ \approx V_-$ and $I_+ \approx I_- \approx 0$.

$\therefore \quad V_+ = V_{in} \Rightarrow V_- = V_{in}$

$\therefore \quad \boxed{V_o = V_{in}}$ $\Rightarrow$ Hence the name voltage-follower | unity-gain amplifier.

(2) Non-inverting Amplifier:




$I_- \approx 0A \Rightarrow$

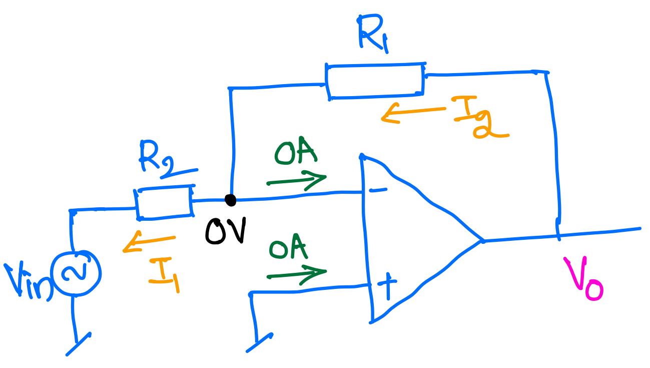
$I_1 = I_2$

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

$$\Rightarrow \frac{V_o - V_{in}}{V_{in}} = \frac{R_1}{R_2}$$

$$\Rightarrow \boxed{V_o = \left(1 + \frac{R_1}{R_2}\right) V_{in}}$$

(3) Inverting Amplifier:



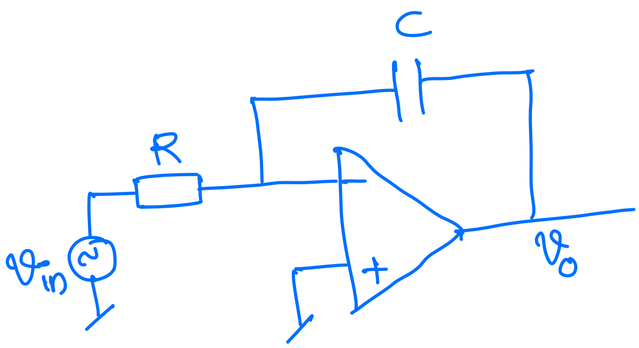

$I_+ \approx I_- \approx 0A \Rightarrow$

$I_1 = I_2$

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

$$\Rightarrow \boxed{\frac{V_o}{V_{in}} = -\frac{R_1}{R_2}}$$

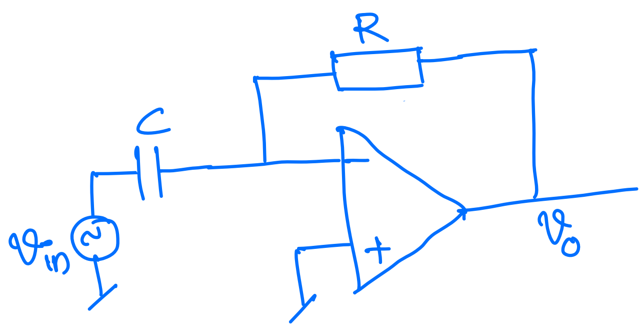
## (4) Integrator:




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

$$\Rightarrow \boxed{v_o = \frac{-1}{RC}\int v_{in}\,dt}$$

## (5) Differentiator:

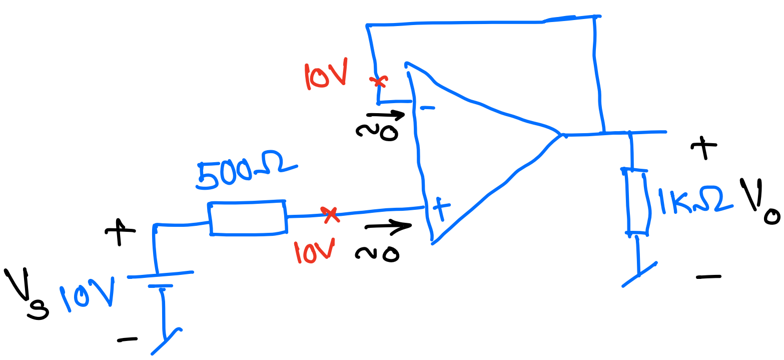



$$\frac{v_o}{R} = -C\frac{dv_{in}}{dt}$$

$$\Rightarrow \boxed{v_o = -RC\frac{dv_{in}}{dt}}$$

→ Let us now get back to the riddle of how unity gain buffer avoids loading effect.

### (1) Applying Virtual short concept:




$I_+ \approx I_- \approx 0$

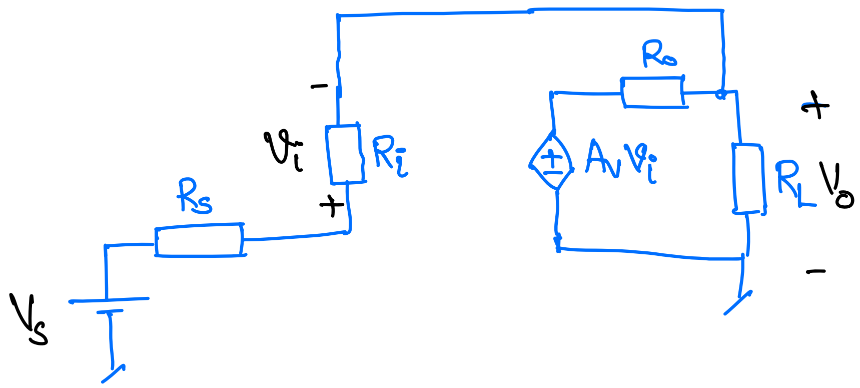
$V_+ \approx V_- \approx 10V$

$\therefore \; V_o = 10V$

$\Downarrow$

No loading effect seen!!

(2) Let's do the math rigour now (instead of applying virtual short).



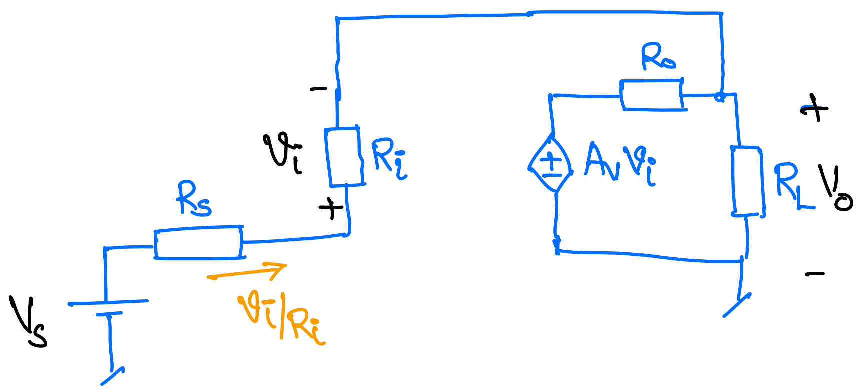

$V_s = 10V$

$R_s = 500\Omega$

$R_L = 1K\Omega$

$\left.\begin{array}{l} R_i \approx 2M\Omega \\ R_o \approx 75\Omega \\ A_v \approx 2\times10^5 \end{array}\right\}$ for 741 IC.

Apply KVL and KCL $\Rightarrow$




Take $R_o = 0$ (only to ease analysis)

$$V_o = A_v v_i \quad \text{—(1)}$$

$$V_s - V_o = (R_s + R_i)\frac{v_i}{R_i} \quad \text{—(2)}$$

(1), (2) $\Rightarrow$

$$V_s - V_o = \frac{R_s + R_i}{R_i} \times \frac{V_o}{A_v}$$

$$\Rightarrow V_o = \frac{V_s}{1 + \frac{1}{A_v}\left[1 + \frac{R_s}{R_i}\right]} \approx V_s$$

$\because A_v = 2\times10^5 \qquad R_s << R_i \quad (R_s = 500\Omega, \; R_i = 2M\Omega)$

$\therefore \quad V_o \approx V_s = 10V.$

(No loading effects seen)