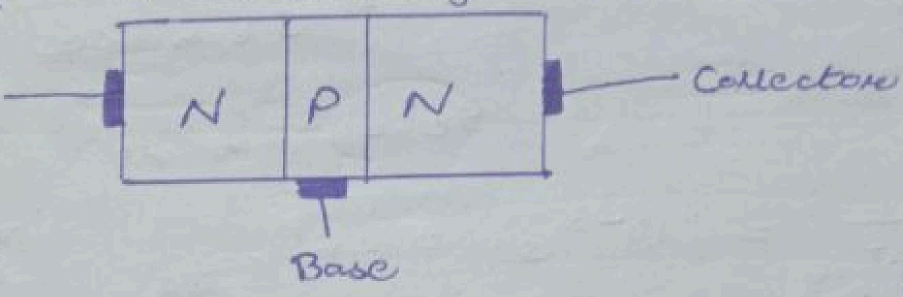
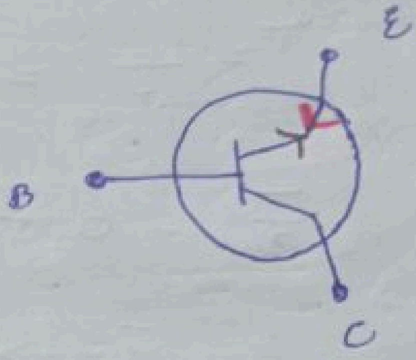
# Bipolar Junction Transistor

* Used in amplification of weak signals and also used in switching operations.




Emitter → Heavily Doped
Base → Lightly Doped.
Collector → Moderately Doped.

npn
pnp

Width

Collector > Emitter > Base.

Advantages of BJT

(i) Low operating voltage.
(ii) Higher efficiency.
(iii) Small size and ruggedness.
(iv) Does not require any filament power

Transistor = Transfer + Resistor

Active mode

$J_1 \rightarrow$ F.B. Resis = 0

$J_2 \rightarrow$ R.B. Resis = $\infty$

Bipolar → involves holes and $e^-$

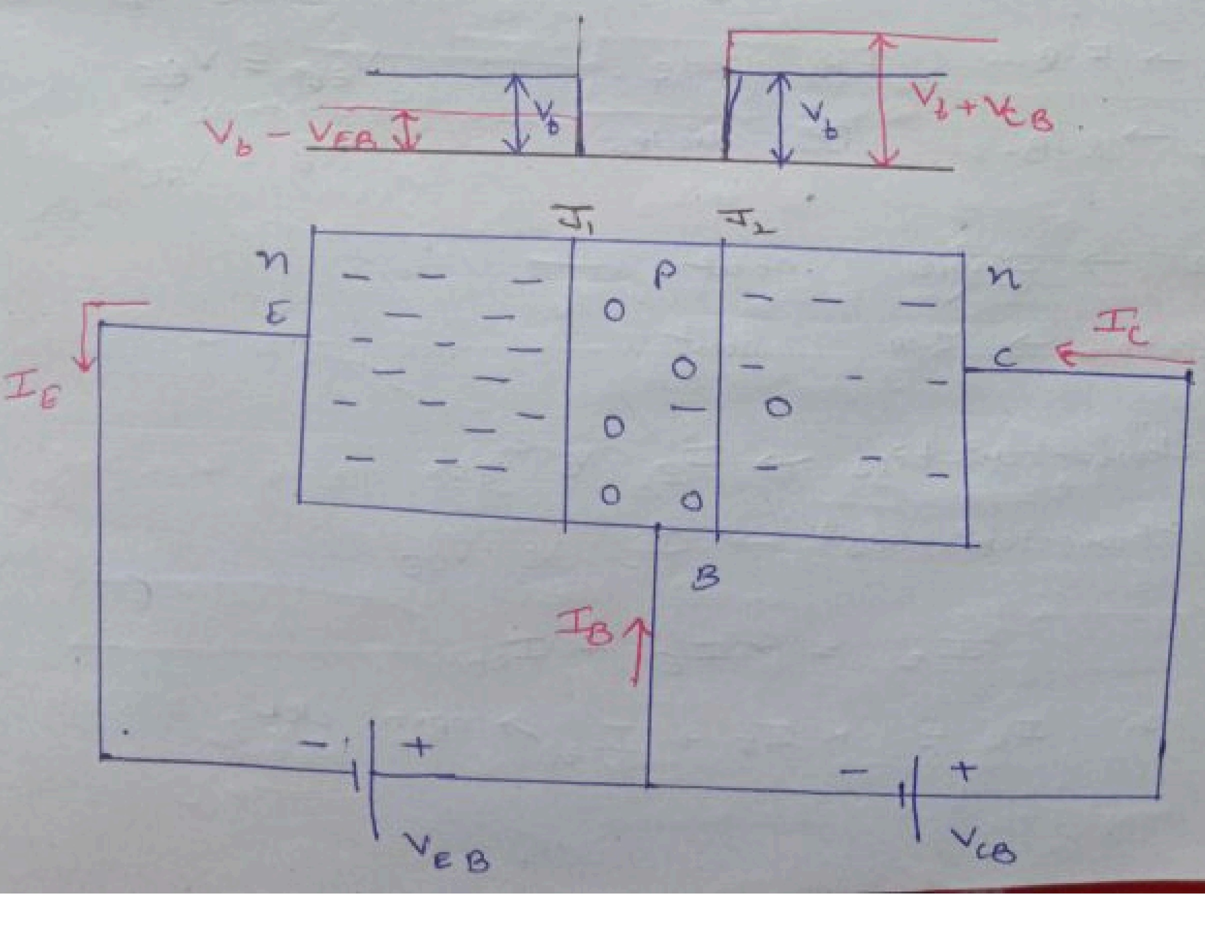
Regions of operations.

| $J_1$ | $J_2$ | Region of operation. |
|---|---|---|
| F.B. | R.B. | Active → Amplifier |
| F.B. | F.B. | Saturation → "ON" |
| R.B. | R.B. | Cutoff → OFF |
| R.B. | F.B. | Inverted → rarely used Emmitter & collector switch their roles. |

## Transistor Operation

n-p-n transistor

* Only 2% to 5% $e^-$ combine with base holes.
* 95% - 98% enter into collector.



$I_{co} \rightarrow$ reverse saturation current
or leakage current.

Measure it when emitter terminal is open ckt.

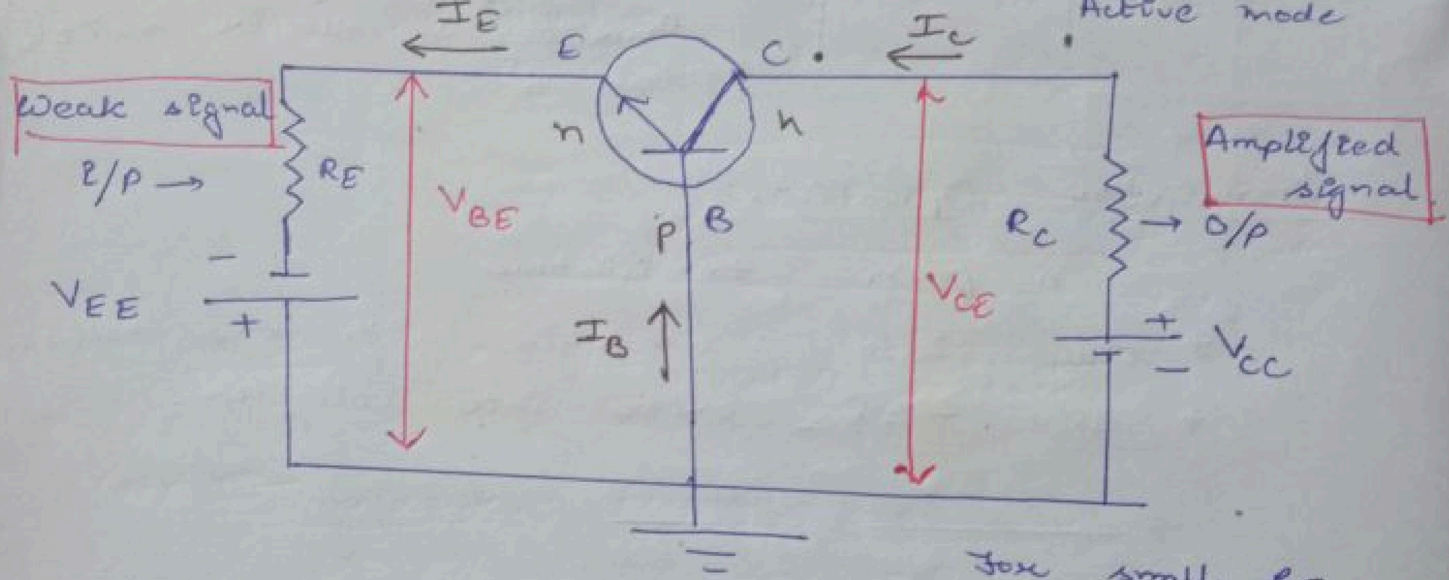
$I_{co}$ Due to minority charge carriers

$$\boxed{I_C = \alpha I_E + I_{CO}}$$

$$\boxed{I_E = I_B + I_C}$$

## Common Base Configuration of Transistor

Active mode




For small $R_E$

$J_1 \rightarrow$ F.B. EB diode.

$J_2 \rightarrow$ R.B. BC diode.

$V_{BE} = V_{EE}$

For small $R_C$

$V_{CE} = V_{CC}$

Diode $\rightarrow$ single port

Transistor $\rightarrow$ Two port

i/p characteristics $\rightarrow I_E$ Vs $V_{BE}$

o/p characteristics $\rightarrow I_C$ Vs $V_{CE}$

$$I_C = \alpha I_E + I_{CO}$$

or $I_C = \alpha I_E + I_{CBO} \rightarrow$ open ckt.

$I_E >> I_{CBO}$.

$I_C = \alpha I_E$

$$\boxed{\alpha = \frac{I_C}{I_E}}$$

$\alpha \rightarrow$ common base current gain/amplification factor

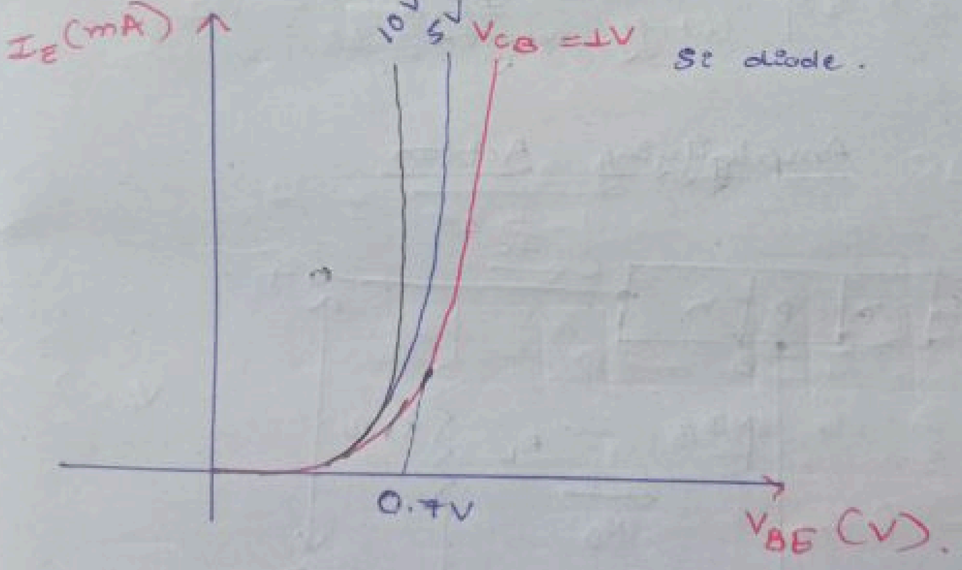
$$\alpha = \frac{o/p \text{ current}}{i/p \text{ current}}$$

$\alpha$ ranges from 0.95 to 0.98

$$[I_B = (1-\alpha) I_E].$$

Input Characteristics

Characteristics of F.B. diode.




Early Effect or Base width modulation:

$V_{CB}: \uparrow$ depletion layer around CB will increase

As width of base excluding depletion layer decreases, $I_E$ will increase because of low combination in base holes.

Conc. grad: $\uparrow$ $I_E: \uparrow$

Output Characteristics → r.b. diode

O/P I ($I_C$) Vs O/P V ($V_{CB}$) for various levels of I/P I ($I_E$).

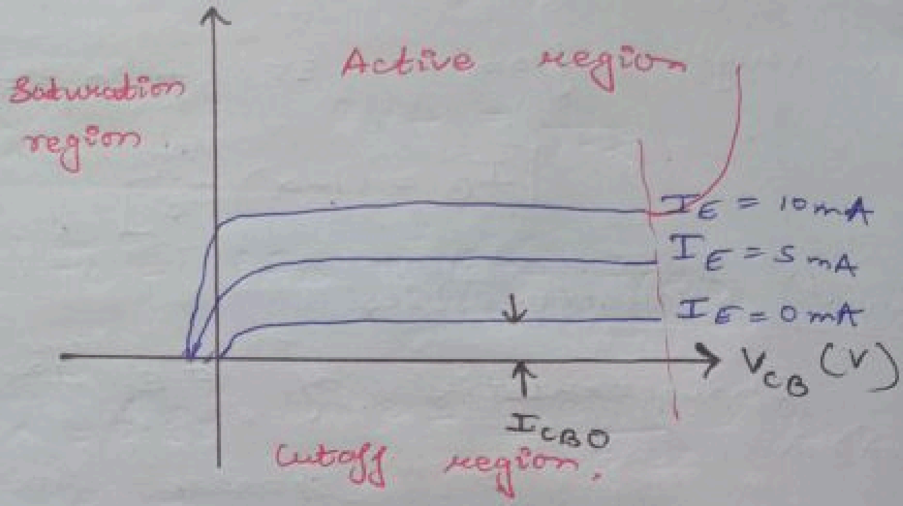
$$I_C = \alpha I_E + I_{CBO} \text{ (Independent of } V_{CB})$$

$$I_C \simeq \alpha I_E$$

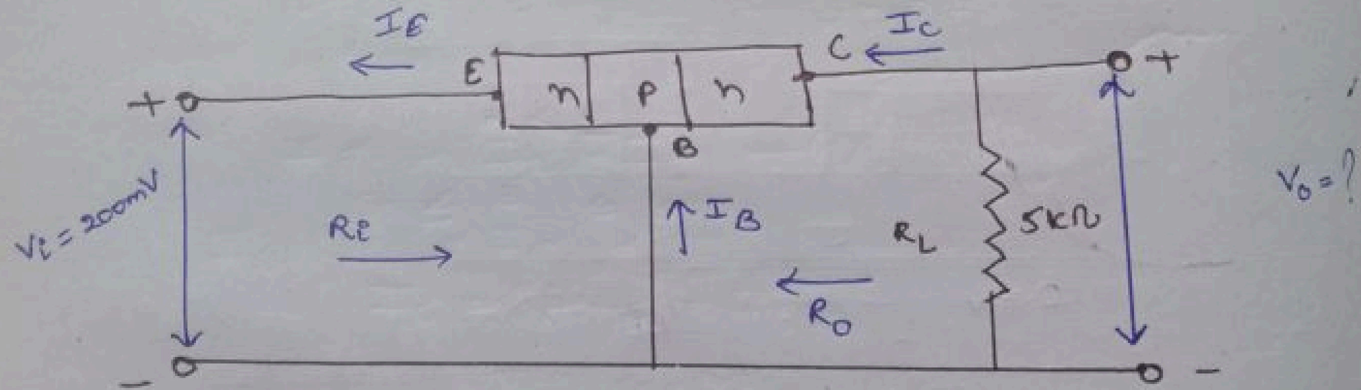
$\alpha = 0.95 - 0.98$

$\boxed{I_C \simeq I_E}$

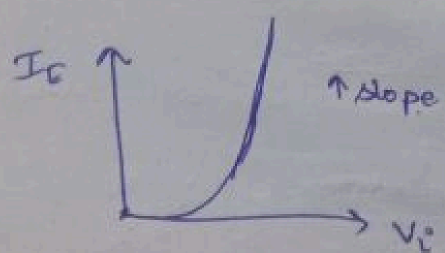
O/P ↓ $I_C$, I/P ↓ $I_E$



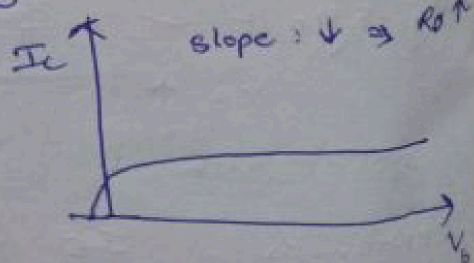

## Transistor Amplifying Action




$R_i = 20\,\Omega$




↑ slope $= \frac{1}{R_i \downarrow}$




$R_o = 1\,M\Omega$

$\simeq 100\,k\Omega$

$$V_i = I_i R_i = I_E R_i$$

$$I_E = \frac{V_i}{R_i} = \frac{200\,mV}{20\,\Omega} = 10\,mA.$$

$$I_C = \alpha I_E + I_{CBO}.$$

$$I_C \simeq \alpha I_E$$

$$I_C \simeq I_E \qquad I_C = 10\,mA$$

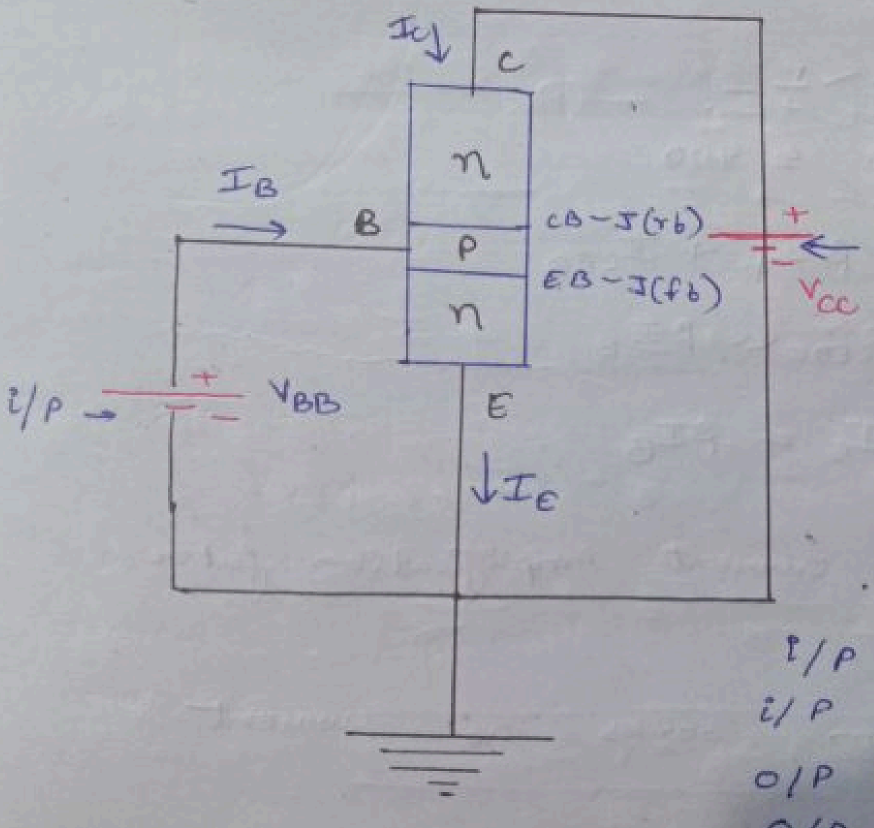
$$V_o = I_C R_L = 10\,mA \times (5\,k\Omega)$$
$$= 50\,V.$$

Voltage Amplification

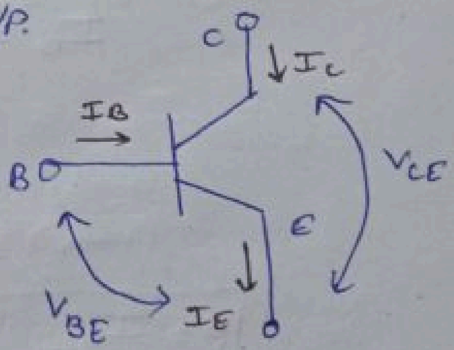
$$A_V = \frac{V_o}{V_i} = \frac{50\,V}{200\,mV} = 250$$

Current Amplification $< 1$. $\quad \frac{I_C}{I_E} = \frac{\alpha I_E}{I_E} = \alpha$. (0.95 to 0.99)

## Common Emitter Configuration Of Transistor




Amplifier → Active mode.




i/p current → $I_B$

i/p V → $V_{BE}$

O/P current → $I_C$

O/P V → $V_{CE}$

$$I_E = I_C + I_B \quad \text{——— (I)}$$

$$I_C = \alpha I_E + I_{CBO} \quad \text{——— (II)}$$

$$I_C = \alpha (I_C + I_B) + I_{CBO}$$

$$(1-\alpha) I_C = \alpha I_B + I_{CBO}$$

$$I_C = \left(\frac{\alpha}{1-\alpha}\right) I_B + \frac{1}{1-\alpha} I_{CBO}$$

$$\beta = \frac{\alpha}{1-\alpha} \qquad \beta + 1 = \frac{1}{1-\alpha}$$

$$I_C = \beta I_B + \underbrace{(\beta+1) I_{CBO}}_{I_{CEO}}$$

Case I: $\alpha = 0.98$ $\quad \beta = \frac{0.98}{1-0.98} = 49$

Case II: $\alpha = 0.95$ $\quad \beta = \frac{0.95}{1-0.95} = 19$

$$\alpha < 1$$

$$50 \leq \beta \leq 400$$

$$I_C = \beta I_B + I_{CEO}$$

$$I_{CEO} << \beta I_B$$

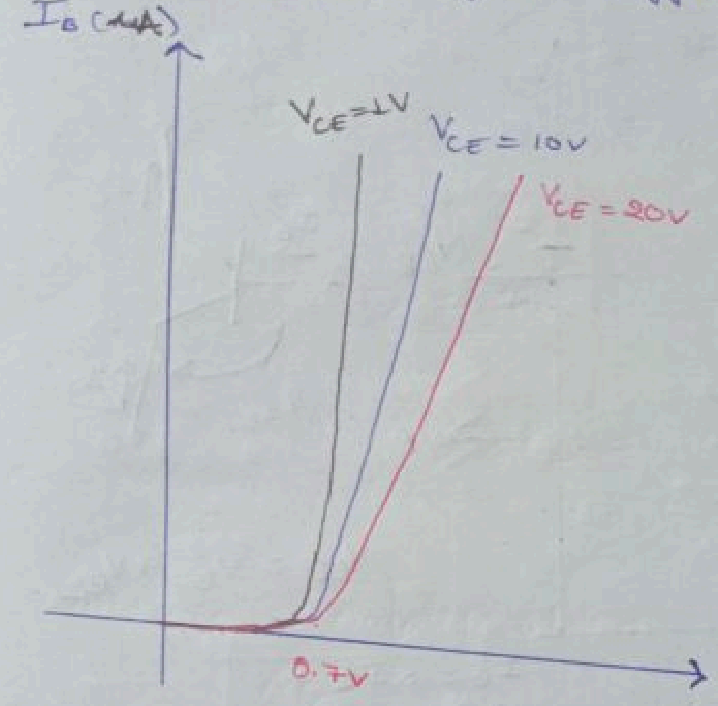
$$I_C = \beta I_B$$

$$\boxed{\beta = \frac{I_C}{I_B}}$$ current Amplification factor.

* CE configuration works as current amplifier.

Input Characteristics

$I_B$ vs $V_{BE}$ for different values of $V_{CE}$.




$$W_{eff} = W_B - W$$

$$V_{CE} = V_{CB} + V_{BE}$$

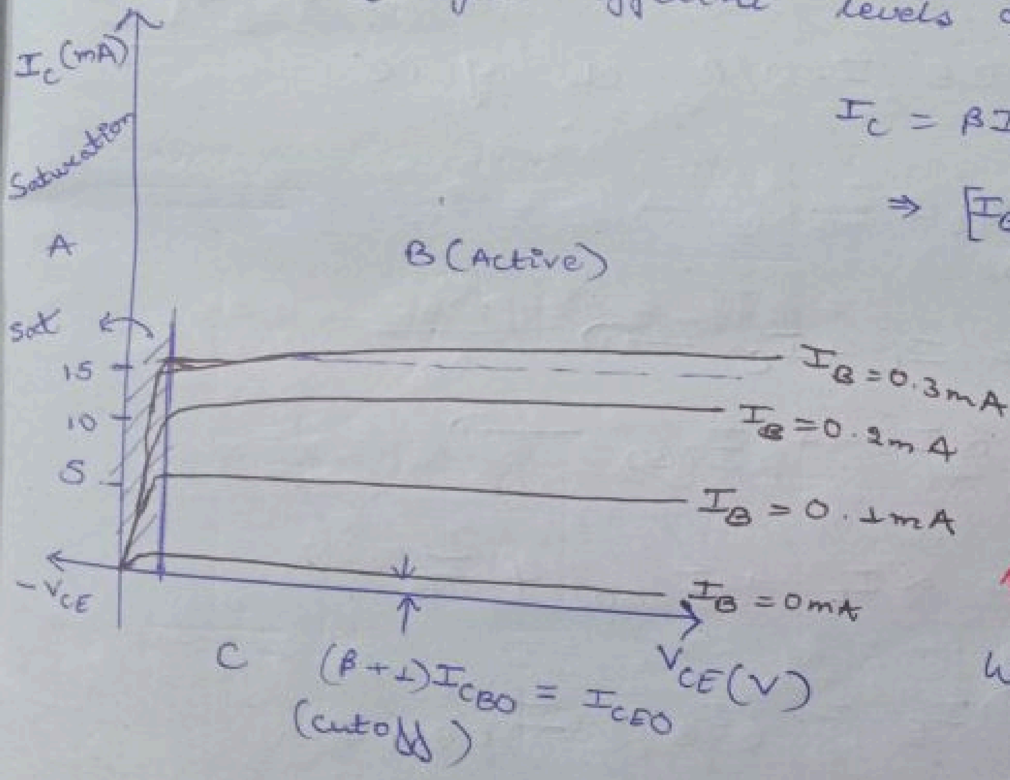
$V_{CE}:\uparrow \Rightarrow V_{CB}\uparrow \Rightarrow W\uparrow$

$\Rightarrow W_{eff}\downarrow \Rightarrow I_B\downarrow$ (i/p current)

$\boxed{V_{CE}:\uparrow \quad I_B:\downarrow}$

Output Characteristics.

$I_C$ vs $V_{CE}$ for different levels of $I_B$.




$$I_C = \beta I_B + (\beta+1) I_{CBO}$$

$$\Rightarrow [I_B = 0,\ I_C = (\beta+1)I_{CBO}]$$

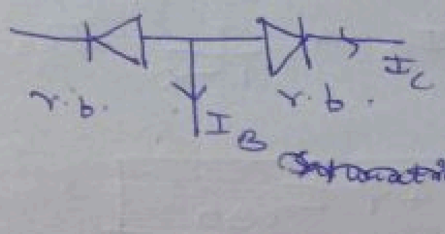
$$\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{10-5}{0.2-0.1}$$

$$\beta = 50$$

$\uparrow V_{CE} = \uparrow V_{CB} + V_{BE}$

$W_{eff}\downarrow \Rightarrow I_B\uparrow$

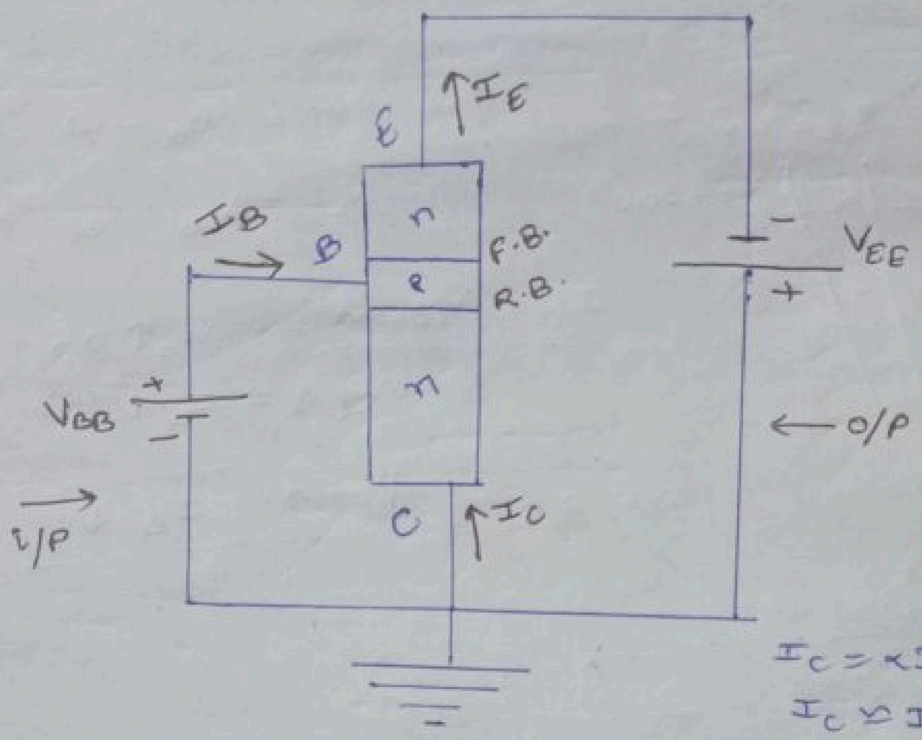
$\Rightarrow I_C\uparrow$

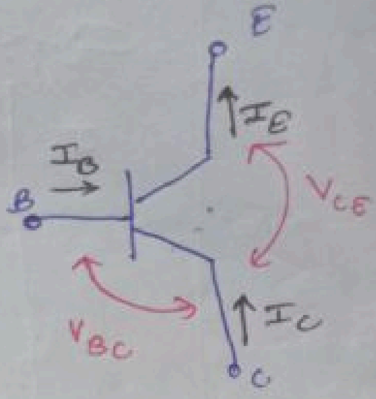



cutoff.

~~(Saturation)~~

## Common Collector Configuration of Transistor




$V_{CE} = V_{BE} + V_{BC}$

$I_C = \alpha I_E$

$I_C \simeq I_E$

* $I_E$ vs $V_{CE}$ for various levels of $I_B$.

* o/p ch. of CE $\equiv$ o/p ch. of CC

$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

$$I_E = I_C + I_B \quad \text{—(I)}.$$

$$I_C = \alpha I_E + I_{CBO} \quad \text{—(II)}$$

$$I_E = \alpha I_E + I_{CBO} + I_B.$$

$$(1-\alpha) I_E = I_B + I_{CBO}$$

$$I_E = \frac{1}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$$

$$\boxed{I_E = \gamma I_B + \gamma I_{CBO}}$$

## Relation between $\alpha, \beta, \gamma$

$$\alpha \rightarrow \alpha_{dc} = \frac{I_C}{I_E}$$

$$\alpha \rightarrow \alpha_{ac} = \frac{\Delta I_C}{\Delta I_E}\bigg|_{V_{CB} = \text{constt.}}$$

$$\beta \rightarrow \beta_{dc} = \frac{I_C}{I_B}$$

$$\beta \rightarrow \beta_{ac} = \frac{\Delta I_C}{\Delta I_B}\bigg|_{V_{CE} = \text{constt.}}$$

$$\gamma \rightarrow \gamma_{dc} = \frac{I_E}{I_B}$$

$$\gamma \rightarrow \gamma_{ac} = \frac{\Delta I_E}{\Delta I_B}\bigg|_{V_{CE} = \text{constt.}}$$

$$I_E = I_C + I_B$$

$$\frac{I_E}{I_B} = \frac{I_C}{I_B} + 1$$

$$\boxed{\gamma = \beta + 1}$$

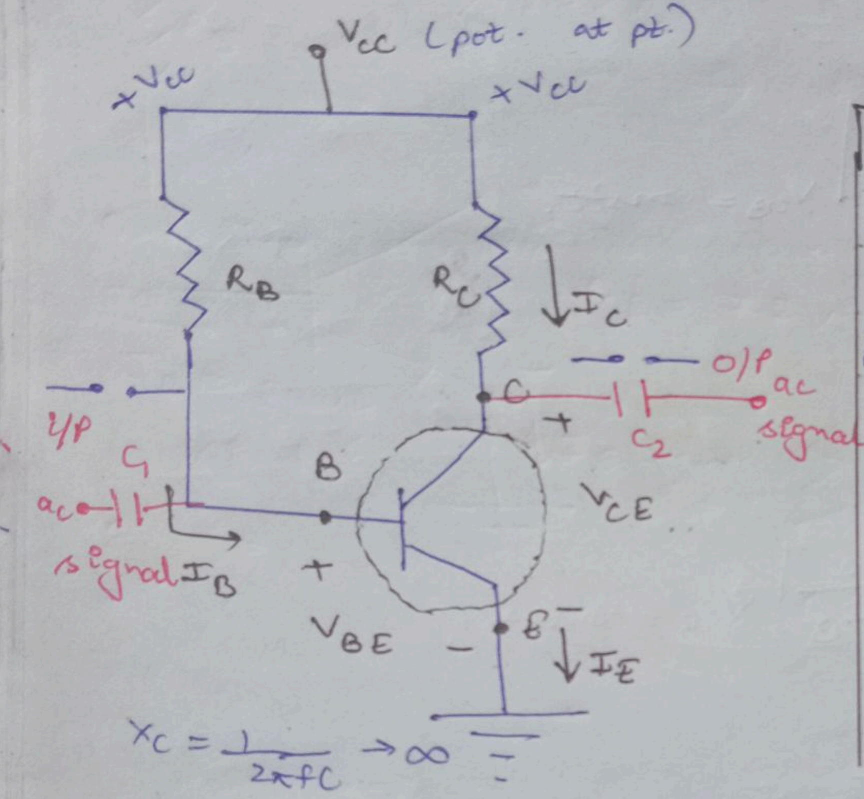
$$\boxed{\beta = \frac{\alpha}{1-\alpha}}$$

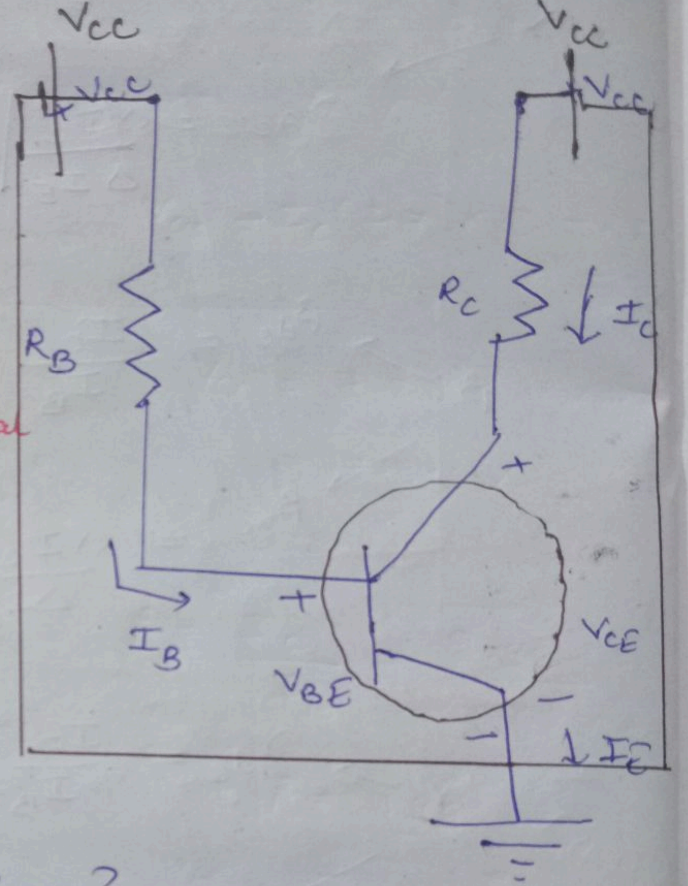
$$\boxed{\gamma = \frac{1}{1-\alpha}}$$

$$\boxed{\gamma = \beta + 1 = \frac{1}{1-\alpha}}$$

# DC Biasing of Transistors

## Fixed Bias Configuration / Base bias configuration




$I_C = ?$ $V_{CE} = ?$

$$+V_{CC} - I_B R_B - V_{BE} = 0.$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

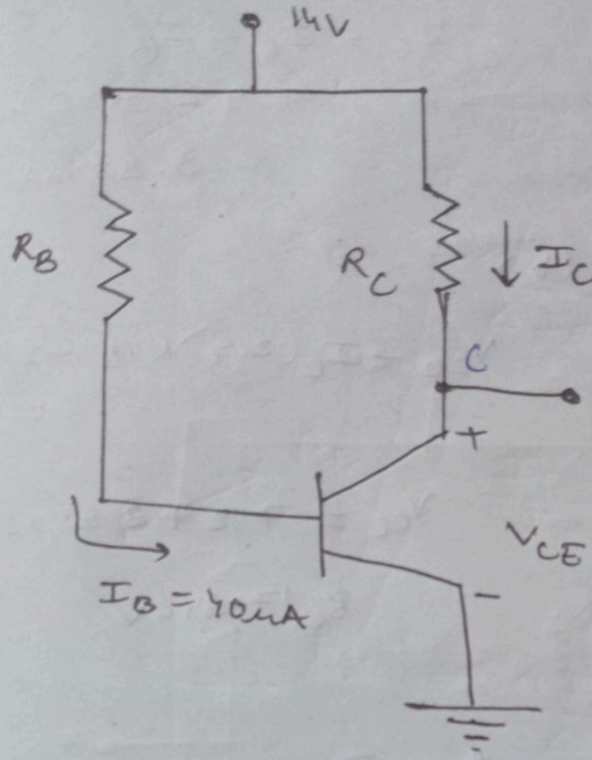
0.3 V Ge
0.7 V Si

$$I_C = \beta I_B = \frac{\beta (V_{CC} - V_{BE})}{R_B}$$

$$+V_{CC} - I_C R_C - V_{CE} = 0.$$

$$V_{CE} = V_{CC} - I_C R_C$$

Q ⇒ (a) $I_C$, (b) $R_C$ (c) $R_B$ (d) $V_{CE}$.




$\beta = 80$.

$V_{CC} = 14V$

$I_B = 40 \mu A$

$V_C = 6V$

(a) $I_C = \beta I_B$

$I_C = 80 \times 40 \times 10^{-6} A$

$= 3.2 mA$

(b) $14V - I_C R_C = 6V$.

$R_C I_C = 8V$.

$R_C = \frac{8}{3.2 \times 10^{-3}}$

$= 2.5 k\Omega$.

(c) $14 - I_B R_B - V_{BE} = 0$.

$R_B = \frac{14V - V_{BE}}{I_B}$

$= \frac{14 - 0.7}{40 \mu A}$

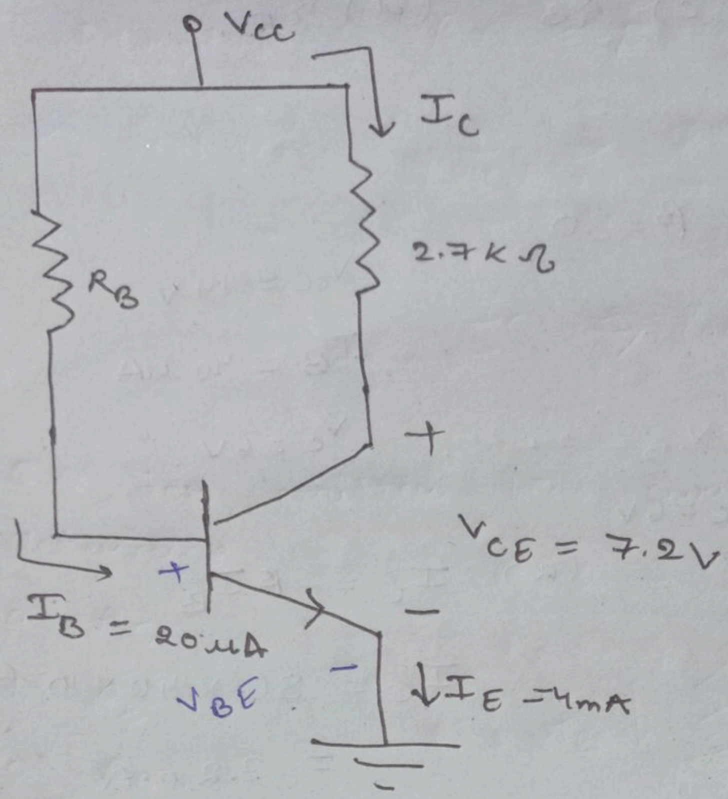
$R_B = 332.5 k\Omega$

(d) $V_{CE} = V_C - V_E$

$= 6 - 0 = 6V$.

Q ⇒ (a) $I_C$ (b) $V_{CC}$

(c) $\beta$ (d) $R_B$.




(a) $I_E = I_C + I_B$

$I_C = I_E - I_B$

$= (4 - 0.02)\,mA$

$= 3.98\,mA$

(b)

$V_{CC} - I_C(2.7)\,k\Omega - 7.2 = 0$

$V_{CC} = 7.2 + 3.98 \times 2.7$

$= 17.946V$

(c) $\beta = \dfrac{I_C}{I_B} = \dfrac{3.98\ mA}{0.02\ mA}$

$\beta = 199$

(d) $V_{CC} - I_B R_B - \overset{0.7}{V_{BE}} = 0.$

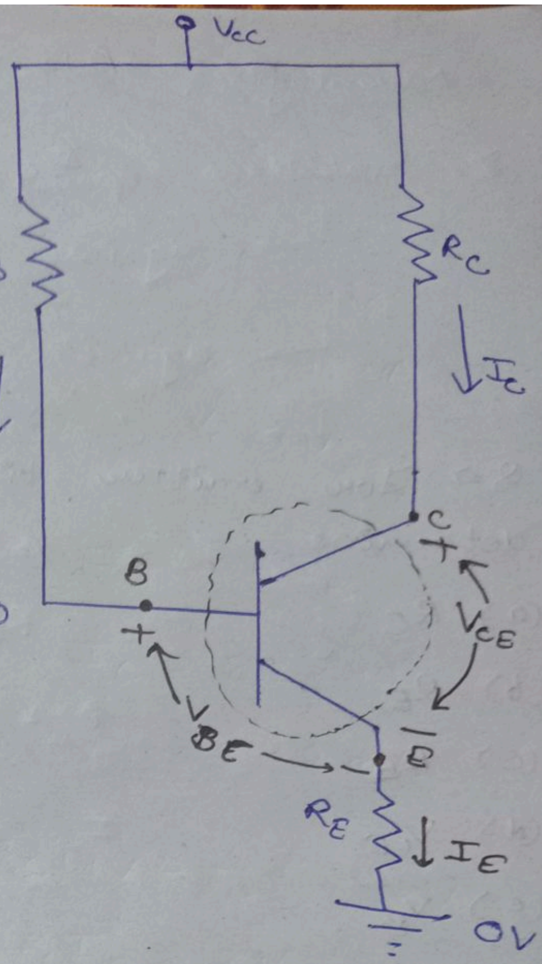
$17.94V - (20\,\mu A)\,R_B - 0.7V = 0$

$R_B = 862.3\,k\Omega$

<u>Emitter Bias Configuration</u>

$R_E$ is introduced to improve stability of operating point or Q-point ($I_{CQ}, V_{CEQ}$)

$V_{CC} - I_B R_B - V_{BE} - I_E R_E = 0V.$




$I_E = I_C + I_B = \beta I_B + I_B$

$I_E = (\beta + 1) I_B$

$V_{CC} - I_B R_B - V_{BE} - (\beta+1) I_B R_E = 0$

$V_{CC} - I_B (R_B + (\beta+1) R_E) - V_{BE} = 0$

$$\left[ I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta+1) R_E} \right]$$

$$\left[ I_C = \beta I_B \right]$$

$I_E \simeq I_C$

$V_{CC} - R_C I_C - V_{CE} - I_E R_E = 0.$

$V_{CC} - I_C (R_C + R_E) - V_{CE} = 0.$

$$\left[ V_{CE} = V_{CC} - (R_C + R_E) I_C \right]$$

Advantages of using $R_E$.

$I_C \Rightarrow$ Q-pt

(i) $T \uparrow \Rightarrow I_C : \uparrow \{ I_C = \beta I_B + (\beta+1) I_{CBO} \uparrow$

$\underset{\text{DROP}}{\underline{I_E R_E}} \uparrow \Rightarrow I_B : \downarrow \Rightarrow I_C : \downarrow$

Because of introduction of $R_E$ temp$^r$ will no longer effect on $I_C$.

(ii) $I_C = \beta I_B$

$I_C = \dfrac{\beta (V_{CC} - V_{BE})}{R_B + (\beta+1) R_E}$

$\beta + 1 \simeq \beta \qquad \beta R_E >> R_B$

$$I_C \simeq \frac{\beta(V_{CC} - V_{BE})}{\beta R_E}$$

$I_C \Rightarrow$ independent of $\beta$.

Q ⇒ For emitter bias current, determine.

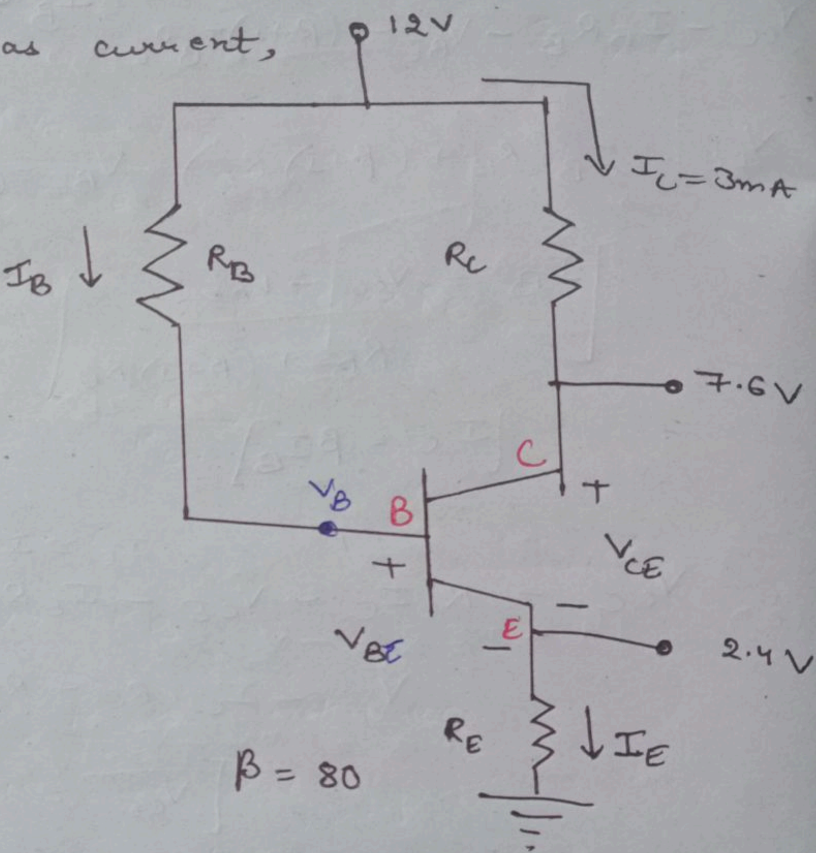
(a) $R_C$

(b) $R_E$

(c) $R_B$.

(d) $V_{CE}$

(e) $V_B$.




$V_C = 7.6V$

$V_E = 2.4V$

(e) $V_{BE} = 0.7V$

$V_B - V_E = 0.7$

$V_B = 0.7 + 2.4 = 3.1V$

(d) $V_{CE} = V_C - V_E = 7.6 - 2.4$

$= 5.2V$

(c) $12V - I_B R_B = 3.1V$

$$R_B = \frac{12 - 3.1}{I_B}$$

$I_B = I_C / \beta$

$= \frac{3 mA}{80}$

$I_B = 37.5 \mu A$

$$R_B = 237.4\ k\Omega .$$

(b) $R_E$

$$2.4 - \overset{I_C}{I_E} R_E = 0$$

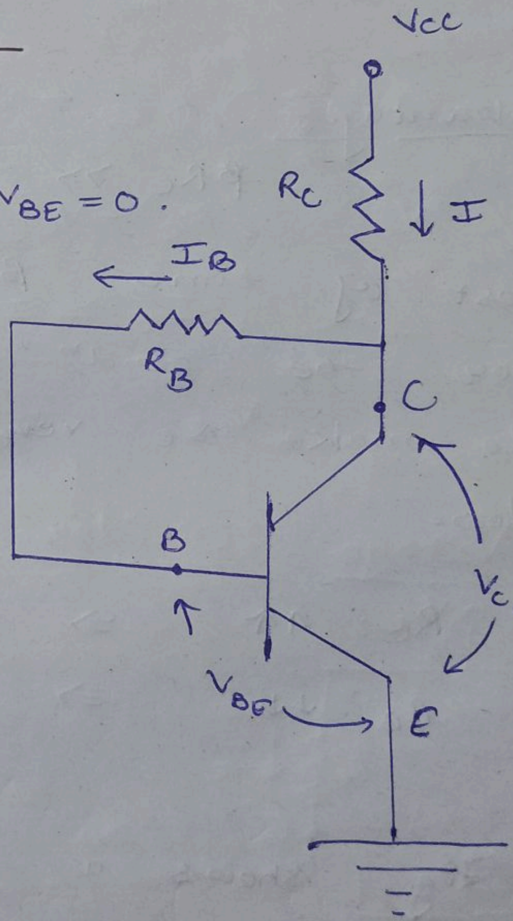
$$R_E = \frac{2.4}{3mA} = 0.8 k\Omega$$

(a) $R_C$.

$$12 - R_C I_C = 7.6 .$$

$$R_C = \frac{4.4}{3\ mA} = \cancel{1.47\ k\Omega} .\ 1.47\ k\Omega .$$

**Collector Feedback Biasing**




$$I = I_C + I_B$$

$$V_{CC} - (\overset{\beta I_B}{I_C} + I_B) R_B - I_B R_B - V_{BE} = 0 .$$

$$I_C = \beta I_B .$$

$$V_{CC} - [(\beta+1)R_C + R_B] I_B - V_{BE} = 0$$

$$I_B = \frac{V_{CC} - V_{BE}}{(\beta+1) R_C + R_B} .$$

$$\left[ I_C = \beta I_B = \frac{\beta (V_{CC} - V_{BE})}{(\beta+1) R_C + R_B} \right]$$

$$V_{CC} - I R_C - V_{CE} = 0 .$$

$$V_{CC} - (I_C + I_B) R_C - V_{CE} = 0 .$$

$$\left[ V_{CE} = V_{CC} - (I_C + I_B) R_C \right]$$

Advantages :

(1) Stabalizes operating point (Q-pt)

↳ against the variation of tempʳ.

↳ against the " " Vcc (Biasing Volta

↳ " " " " β values.

$$I_C = \frac{\beta (V_{CC} - V_{BE})}{R_B + (\beta+1) R_C}$$

$$\beta + 1 \simeq \beta \qquad \beta R_C \gg R_B .$$

$$I_C = \frac{V_{CC} - V_{BE}}{R_C}.$$

Disadvantages

$$\beta R_C \gg R_B .$$

Most of time β is unknown.

For the condⁿ to satisfy, we have to make $R_C$ very large or $R_B$ very low.

$R_C$ : ↑↑ ⇒ $V_0$ : ↑↑ cost ↑

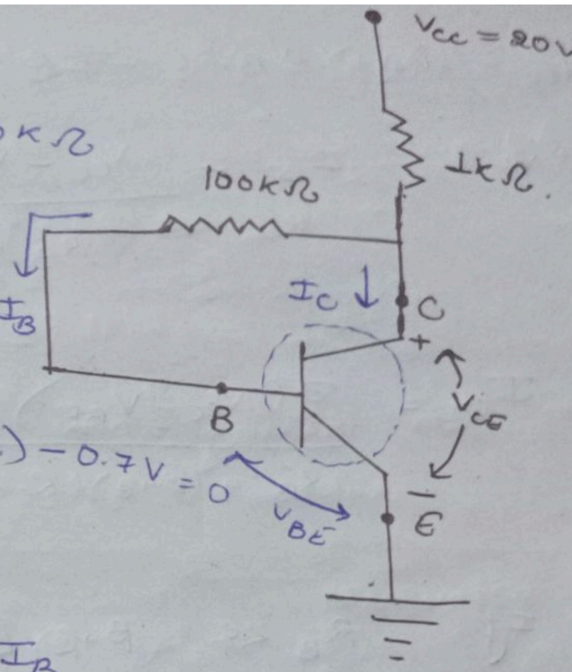
$R_B$ ↓↓ ⇒ R. B. of collector Base J ↓

Q ⇒ Fig shows a silicon transistor biased by collector feedback method. Determine the operating point. β = 100

$V_{cc} = 20\,V$ $\quad \beta = 100.$

$R_C = 1\,k\Omega.$ $\quad R_B = 100\,k\Omega$

$Q\text{-pt} \equiv (I_C, V_{CE})$




$$V_{cc} - (\overset{\beta I_B}{\cancel{I_C}} + I_B)(1k\Omega) - I_B(100k\Omega) - 0.7V = 0$$

$$\frac{V_{cc} - 0.7}{(\beta+1)(1k\Omega) + 100k\Omega} = I_B$$

$$I_B = \frac{20 - 0.7\,V}{201\,k\Omega} = 0.0960\,mA$$

$$= 96\,\mu A$$

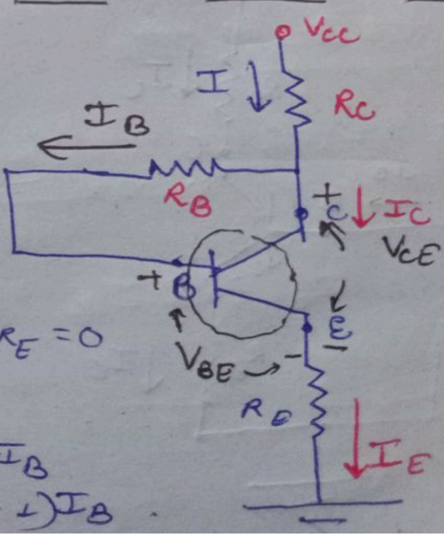
$$I_C = \beta I_B = 9.6\,mA$$

$$V_{cc} - (I_C + I_B)1k\Omega - V_{CE} = 0.$$

$$V_{CE} = 10.304\,V$$

$$Q\text{-pt} \equiv (9.6\,mA,\ 10.304\,V)$$

**Collector Feedback Biasing with Emitter Resistance**




$$V_{cc} - IR_C - I_B R_B - V_{BE} - I_E R_E = 0$$

$$I = I_C + I_B.$$

$$V_{cc} - (I_C + I_B)R_C - I_B R_B - V_{BE} - I_E R_E = 0$$

$$I_E = I_C + I_B = \beta I_B + I_B$$
$$= (\beta+1)I_B.$$

$V_{CC} - (\beta+1) I_B R_C - I_B R_B - V_{BE} - (\beta+1) I_B R_E = 0$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta+1)(R_C + R_E)}$$

$$I_C = \frac{\beta (V_{CC} - V_{BE})}{R_B + (\beta+1)(R_C + R_E)} = \beta I_B$$

If $R_B << (\beta+1)(R_C + R_E)$

$I_C$ will be independent of $\beta$.

KVL in O/P loop

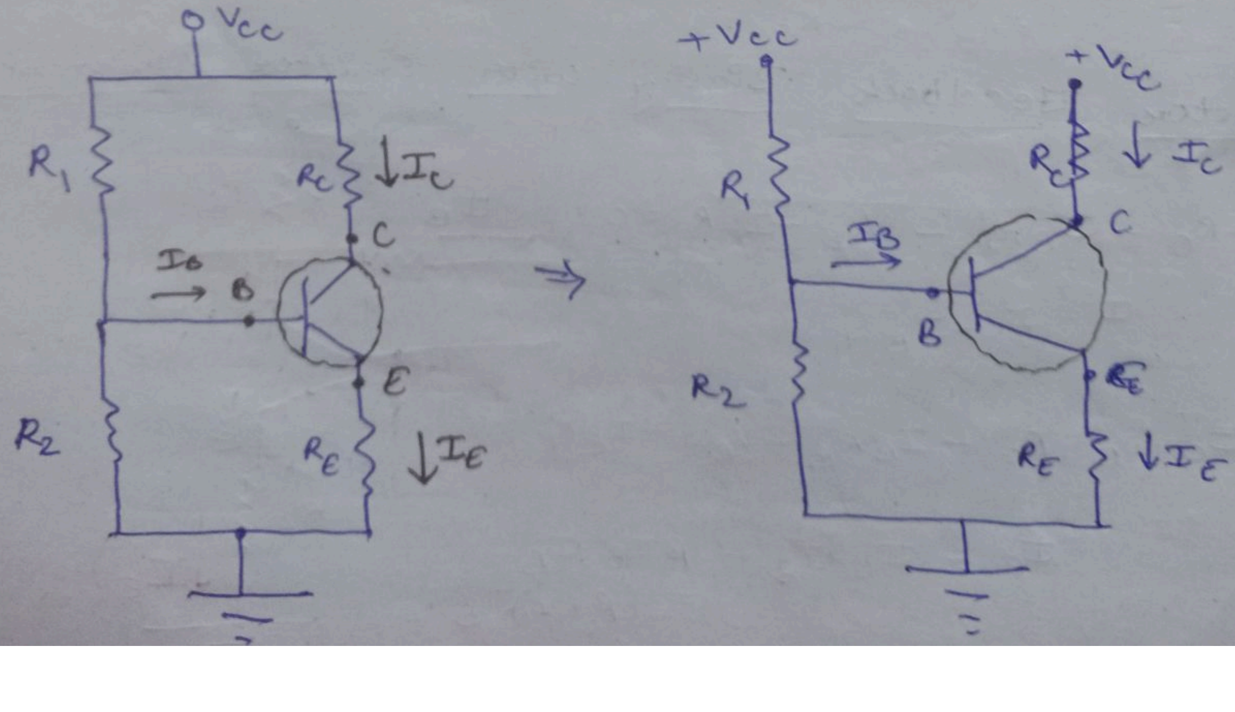
$V_{CC} - (I_C + I_B) R_C - V_{CE} - I_E R_E = 0$

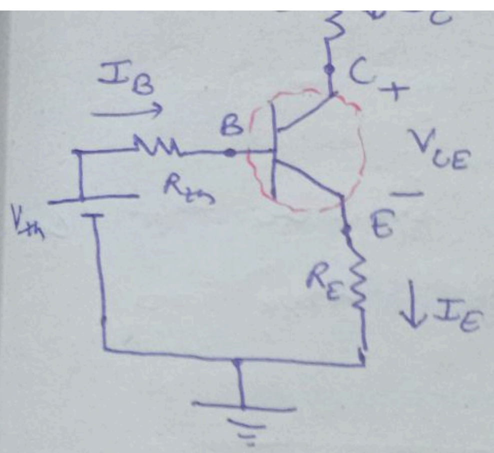
$V_{CC} - I_E R_C - V_{CE} - I_E R_E = 0$

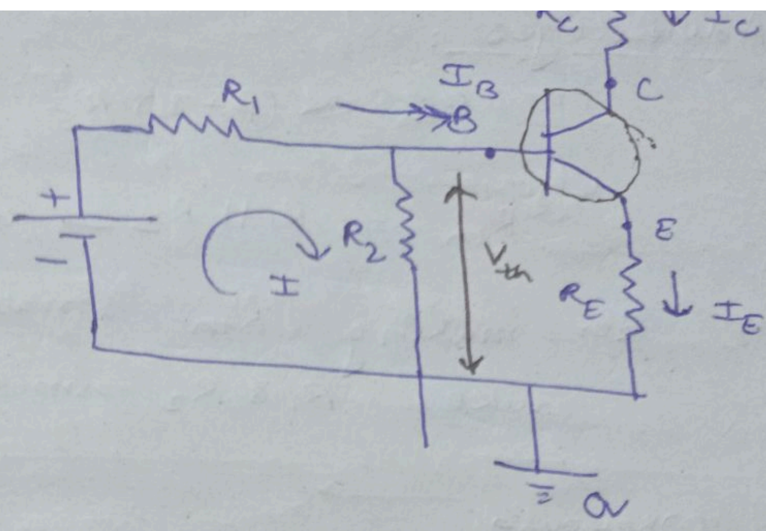
$I_E \simeq I_C$

$[V_{CE} = V_{CC} - I_C (R_C + R_E)]$

## Voltage Divider Bias





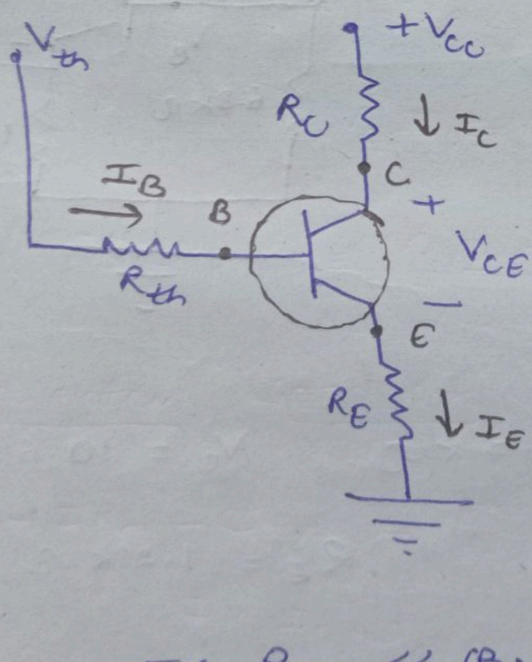


$$R_{th} = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2}.$$

$$I = \frac{V_{CC}}{R_1 + R_2}$$

$$V_{th} = I R_2 = \frac{R_2 V_{CC}}{R_1 + R_2}.$$

Emitter Bias



$$V_{th} - I_B R_{th} - V_{BE} - I_E R_E = 0.$$

$$V_{th} - I_B R_{th} - V_{BE} - (\beta+1) I_B R_E = 0.$$

$$I_B = \frac{V_{th} - V_{BE}}{R_{th} + (\beta+1) R_E}.$$

$$I_C = \beta I_B = \frac{\beta(V_{th} - V_{BE})}{R_{th} + (\beta+1) R_E}$$

If $R_{th} \ll (\beta+1) R_E \Rightarrow I_C$ independent of $\beta$.

$$V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0$$

$$I_E \simeq I_C$$

$$V_{CE} = V_{CC} - I_C (R_C + R_E)$$

Advantages :

$$R_{th} << (\beta + 1) R_E$$

$R_{th} = R_1 \parallel R_2 \rightarrow$ always smaller than $R_1$ & $R_2$

For making $R_{th}$ small we have to take $R_1$ & $R_2$ small.

Whereas

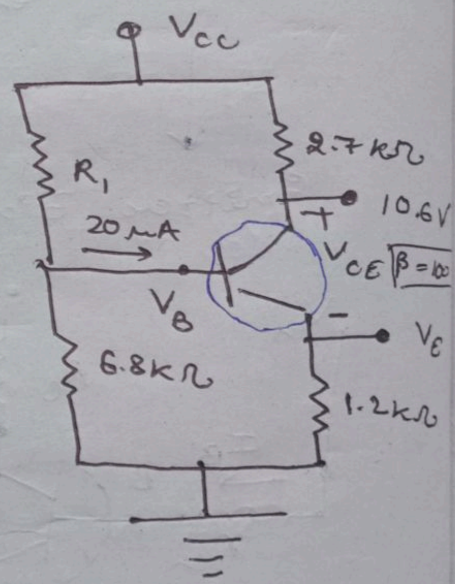
$$R_B << (\beta + 1) R_E$$

$\downarrow$

It is single resistance.

$R_B \rightarrow$ very small.

Q ⇒ For the voltage divider bias configuration, determine




(a) $I_C$

(b) $V_E$

(c) $V_{CC}$

(d) $V_{CE}$

(e) $V_B$

(f) $R_1$

$I_B = 20\,\mu A$ $\quad R_C = 2.7\,k\Omega$ $\quad V_C = 10.6\,V$

$\beta = 100$ $\quad R_2 = 6.8\,k\Omega$ $\quad R_E = 1.2\,k\Omega$

(a) $$I_C = \beta I_B = 100 \times 20 \times 10^{-6}\,A$$

$$= 2\,mA$$

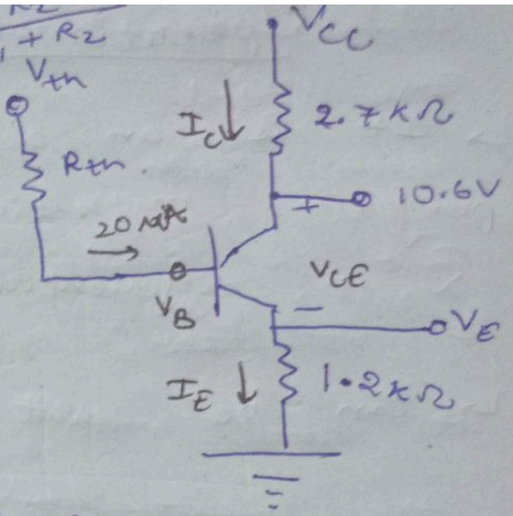
$$V_{th} = \frac{V_{cc} R_2}{R_1 + R_2}$$

$$V_{cc} - I_c(2.7k\Omega) = 10.6V$$

$$R_{th} = \frac{R_1 R_2}{R_1 + R_2}$$

$$V_{cc} = (2mA)(2.7k\Omega) + 10.6V$$

$$V_{cc} = 16V$$




(b) $V_E$

$$I_E = I_C + I_B = 2mA + 20\mu A$$

$$= 2.02mA \quad \text{(I)}$$

$$I_E \simeq I_C \quad \text{(II)}$$

$$I_E \simeq 2mA \qquad \text{diff} = 0.02\ mA$$

$$V_E - (1.2k\Omega) I_E = 0$$

(I) $V_E = (2.02)mA\,(1.2k\Omega) = 2.424\ V$

(II) $V_E = 2.4\ V$

diff $0.024\ V$

(d) $V_{CE} = V_C - V_E = 10.6 - 2.424$

$$= 8.176\ V$$

(e) $V_B$

$$V_{BE} = V_B - V_E$$

$$0.7V = V_B - 2.424V$$

$$V_B = 3.124\ V$$

(f) Pt. at point

$$V_{th} \simeq V_B$$

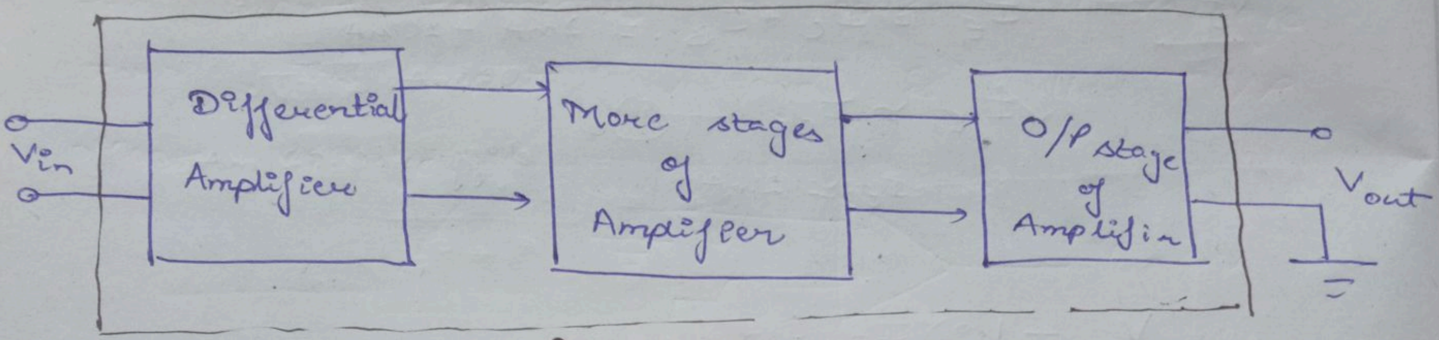
$$V_{th} = \frac{V_{cc} R_2}{R_1 + R_2} = \frac{16 \times 6.8\,k\Omega}{R_1 + 6.8k\Omega} = 3.124\ V$$

$R_1 = 28\,k\Omega$

# Operational Amplifier (Op-Amp)

↳ It is an active element designed to perform mathetical operations like +, −, ×, ÷, differentiation & integration.

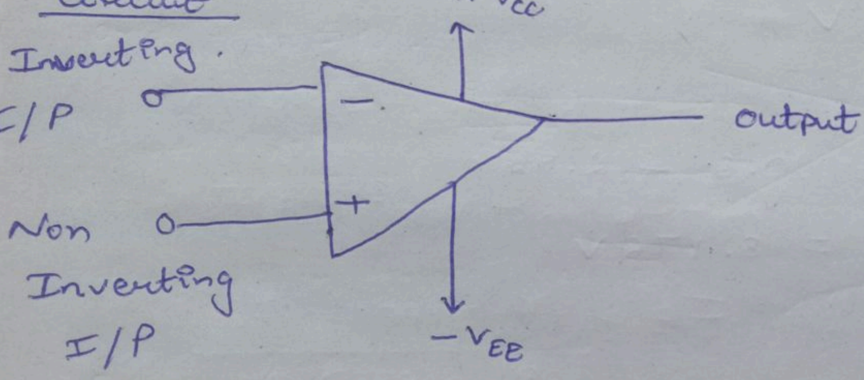
↳ can be used for AC as well as DC.



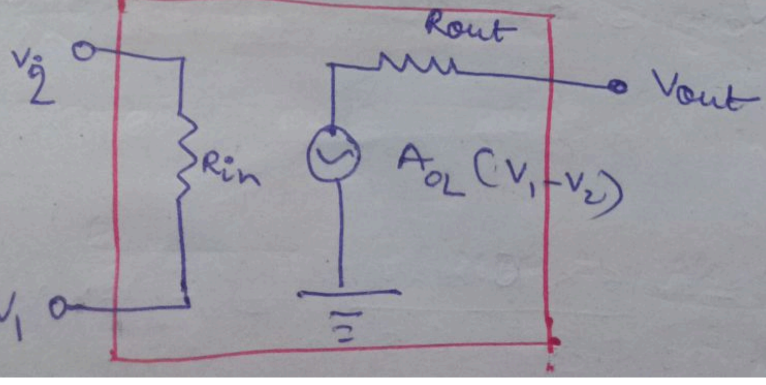

Op - Amp.

↳ An op-Amp is a multistage. direct coupled Amplifier.

## Circuit




## Equivalent ckt

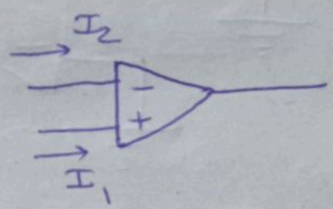


# Op - Amp Characteristics

| Characteristics | Ideal Op-Amp | Practical Op-Amp (741) |
|---|---|---|
| Open Loop Gain ($A_{OL}$) | $\infty$ | $10^6$. |
| Input Resistance ($R_i$) | $\infty$ | $1M\Omega$ to $2M\Omega$ |
| O/P Resistance ($R_o$) | 0 | $50\Omega$ to $100\Omega$. |
| Open loop Bandwidth | $\infty$ | $= 1MHz$. |
| Offset voltage. | 0 | $< 10mV$. |
| Offset Current | 0 | $10\,nA$ |
| Common Mode Rejection Ratio (CMRR) | $\infty$ | $90\,dB$. |
| Slew Rate | $\infty$ | $1V/\mu sec$. |

Input Bias Current

$$\left[ I_a = \frac{I_1 + I_2}{2} \right]$$




Ideally it is zero.

Practically is 100's of nA.

Input Offset current

Alxebric difference b/w the current's into inverting & non-inverting terminals.

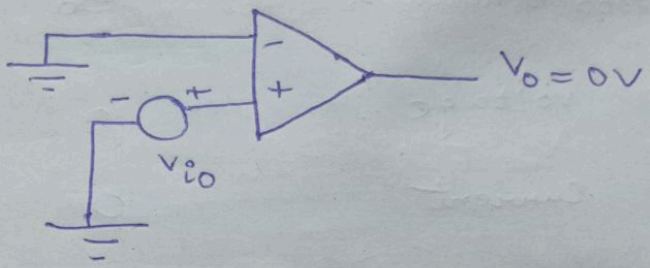
$$I_{i_o} = |I_1 - I_2| \rightarrow \text{few } nA.$$

## Input offset voltage

For ideal op-Amp output should be zero when both i/p are grounded.

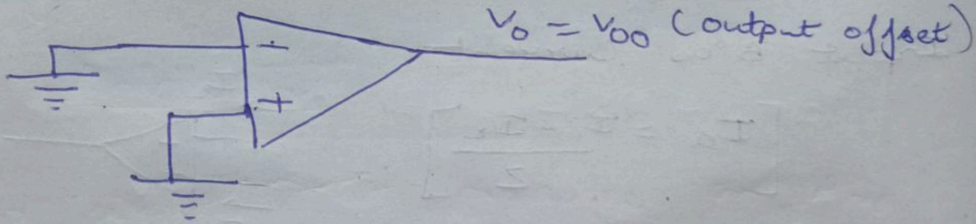
But in practical op-Amp the O/P voltage is not zero when both i/p are grounded.

A small amount of voltage is applied at the input terminals to make O/P voltage zero. This input voltage is called i/p offset voltage.




## O/P offset Voltage

It is O/P voltage of Op-Amp when $V_1 = 0$ and $V_2 = 0$.




## Common Mode Rejection Ratio (CMRR)

It may be defined as the ratio of differential voltage gain ($A_d$) to the common mode gain ($A_{CM}$).

$$A_d = \frac{V_o}{V_1 - V_2 \rightarrow V_d}$$

~~CMRR =~~ $$CMRR = \frac{|A_d|}{|A_{CM}|}$$

$$A_{CM} = \frac{V_o}{V_{cm}}$$

$$V_{cm} = \frac{V_1 + V_2}{2}$$

Higher CMRR indicates better rejection of common input.

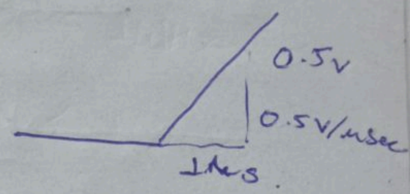
For ideal differential amplifier $A_{CM} = 0$.

Hence, $CMRR = \infty$

## Slew Rate

It is the measure of how fast the output voltage of Op-Amp can change w.r.t. time.

$$\text{Slew Rate (SR)} = \left.\frac{dV_o}{dt}\right|_{max}$$




Unit → V/μS

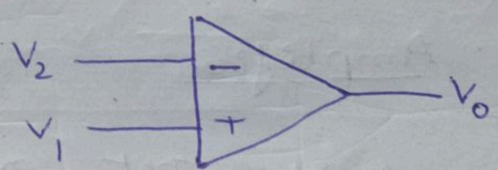
For ideal Op-Amp SR is ∞

## Transfer Characteristics of Op-Amp

Plot of O/P voltage ($V_o$) Vs difference i/p ($V_d$)

$V_o = A_{OL}(V_1 - V_2)$

$V_o = A_{OL} V_d$.

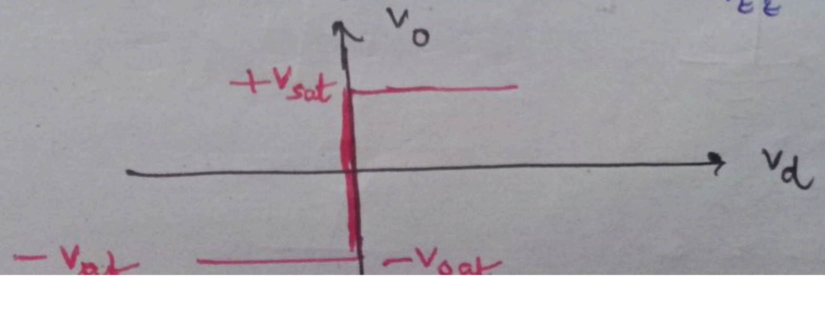



① Ideal Op-Amp.

For ideal, $A_{OL} = \infty$.

If $V_d > 0 \Rightarrow V_o = +\infty = +V_{cc} = +V_{sat}$

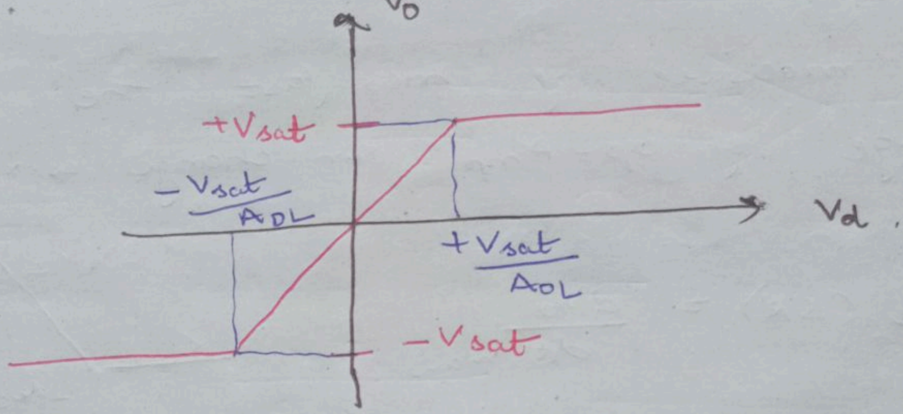
If $V_d < 0 \Rightarrow V_o = -\infty = -V_{EE} = -V_{sat}$



(2) Non - Ideal Op - Amp.

$A_{OL}$ = large but finite

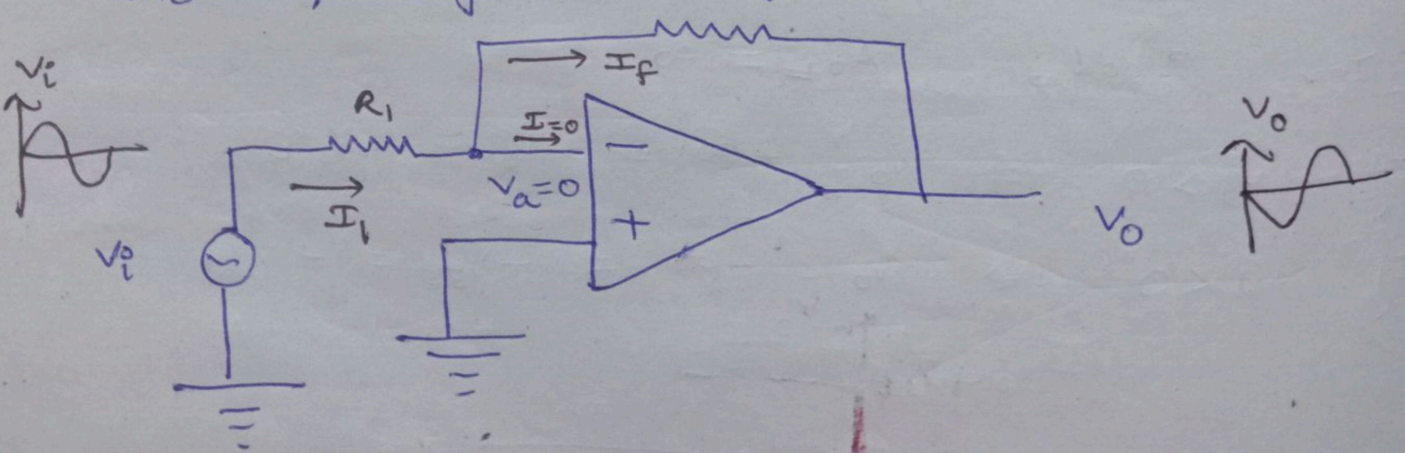
If $V_d$ lies in the range $-\frac{V_{sat}}{A_{OL}}$ to $+\frac{V_{sat}}{A_{OL}}$, O/P will vary linearly with $V_d$.




For very small values of $V_d$ Op-Amp can be operated in linear region and for higher values of $V_d$ Op-Amp will be in saturation region.

## Inverting Amplifier

An Op - Amp circuit that produces an Amplified O/P signal that is 180° out of phase with the i/P signal.



Applying KCL at node A,

$$I_1 = I_f$$

$$\frac{V_i - V_a}{R_1} = \frac{V_a - V_o}{R_f}$$

$$V_a = 0$$

$$\frac{V_i}{R_1} = -\frac{V_o}{R_f}$$

$$\boxed{V_o = -\frac{R_f}{R_1} \times V_i}$$

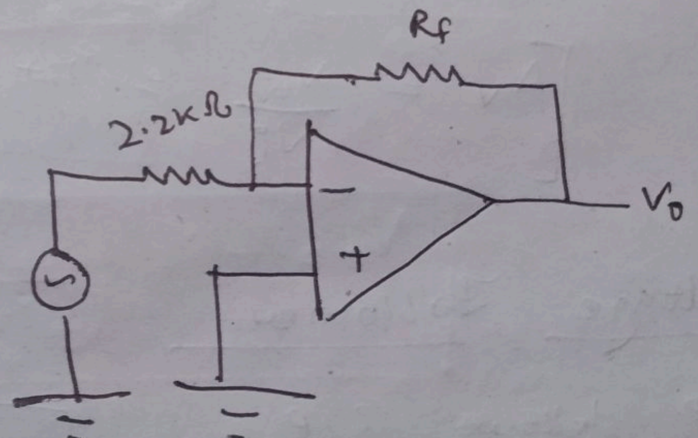
Gain, $A = \frac{V_o}{V_i} = -\frac{R_f}{R_1}$

$$\boxed{A = -\frac{R_f}{R_1}} \quad *$$

<u>Concept</u> of <u>Virtual Ground</u>.

$V_a = 0V$.

Q ⇒ . For given op-Amp config. determine the value of $R_f$ required to produce a closed loop gain of $-100$.




For inverting Amplifier

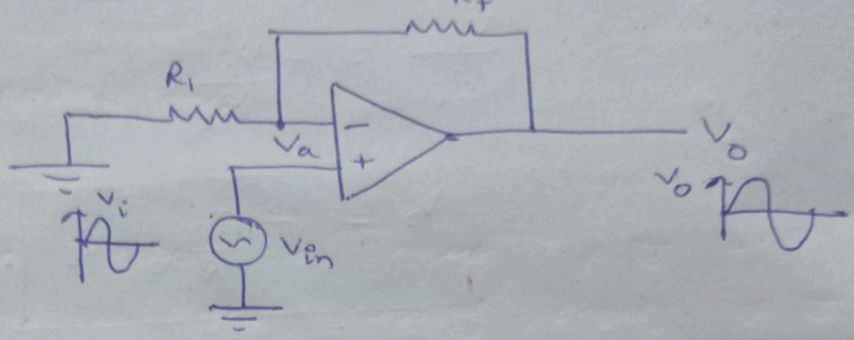
$$A_v = \frac{V_o}{V_i} = -\frac{R_f}{R_1}$$

$$\frac{-R_f}{2.2\times10^3} = -100$$

$$R_f = 2.2 \times 10^5\ \Omega.$$

## Non Inverting Amplifier

A non-inverting amplifier is an op-Amp circuit designed to provide voltage gain. The input is directly applied to non-inverting terminal.




$$V_a = \frac{V_o \times R_1}{R_1 + R_f}$$

From concept of virtual ground $V_a = V_{in}$

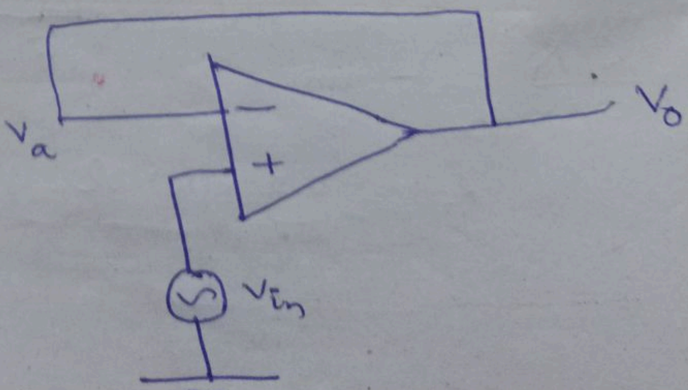
$$V_{in} = \frac{V_o \times R_1}{R_1 + R_f}$$

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

$$\left[ A_v = \frac{V_o}{V_i} = 1 + \frac{R_f}{R_1} \right]$$

## Voltage Follower

O/P follows I/P.




$V_a = V_o$.

$V_a = V_{in}$

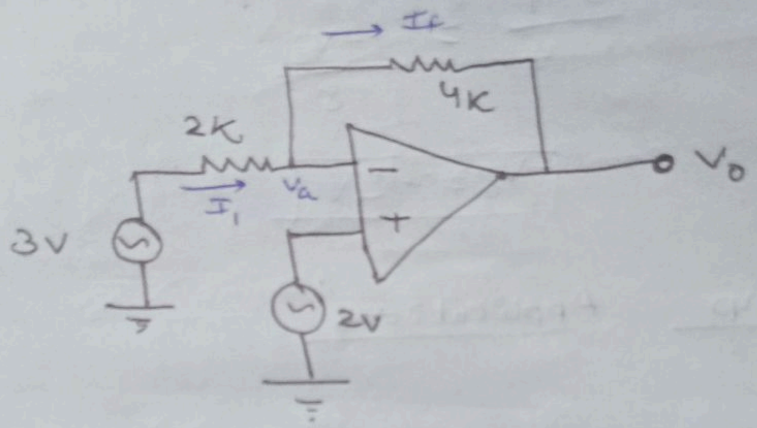
$V_o = V_{in}$

$A_v = \frac{V_o}{V_i} = 1$

↳ It is used as Buffer

↳ It is used in instrumentation amplifier.

Q ⇒ $V_o = ?$




Sol:

$V_a = 2V$

$$I_1 = I_f$$

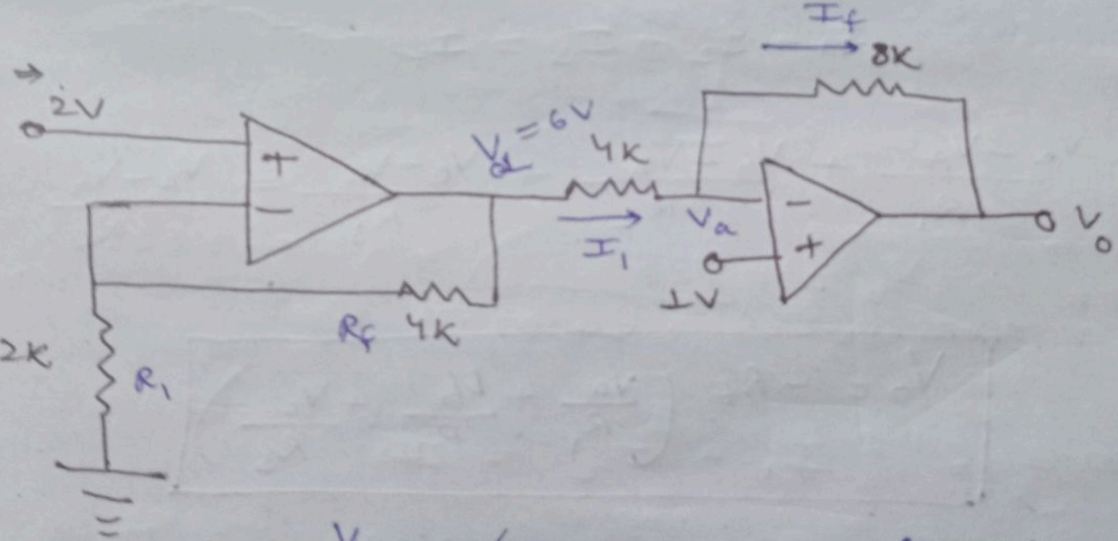
$$\frac{3-V_a}{2} = \frac{V_a - V_o}{4}$$

$$\frac{1}{2} = \frac{2-V_o}{4}$$

$$2 - V_o = 2 \qquad \cancel{V_o = -1V}$$

$$V_o = 0V.$$

Q →




$$V_{o1} = \left(1 + \frac{R_f}{R_1}\right) V_i = \left(1 + \frac{4}{2}\right) \times 2 = 6V$$

By concept of virtual ground

$$V_a = 1V$$

KCL, $\qquad I_1 = I_f$

$$\frac{V_{02} - V_a}{4} = \frac{V_a - V_0}{8}$$

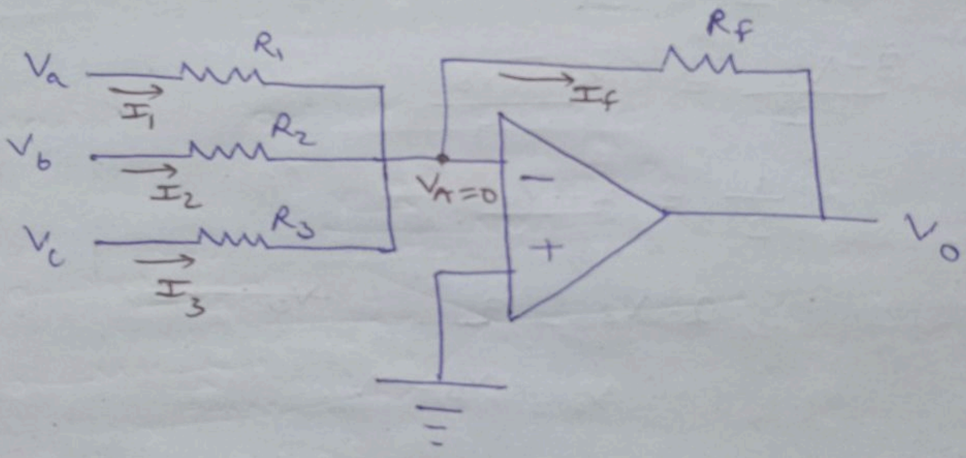
$$\frac{6-1}{4} = \frac{1-V_0}{8}$$

$$\boxed{V_0 = -9V}$$

## OP- Amp Applications

**Adder:**

It can accept two or more inputs and produces output as the sum of these inputs.




$$I_1 + I_2 + I_3 = I_f$$

$$\frac{V_a - V_A}{R_1} + \frac{V_b - V_A}{R_2} + \frac{V_c - V_A}{R_3} = \frac{V_A - V_0}{R_f}$$

$$\boxed{V_0 = -R_f\left(\frac{V_a}{R_1} + \frac{V_b}{R_2} + \frac{V_c}{R_3}\right)}$$

If $R_1 = R_2 = R_3 = R$, then

$$V_0 = -\frac{R_f}{R}(V_a + V_b + V_c)$$

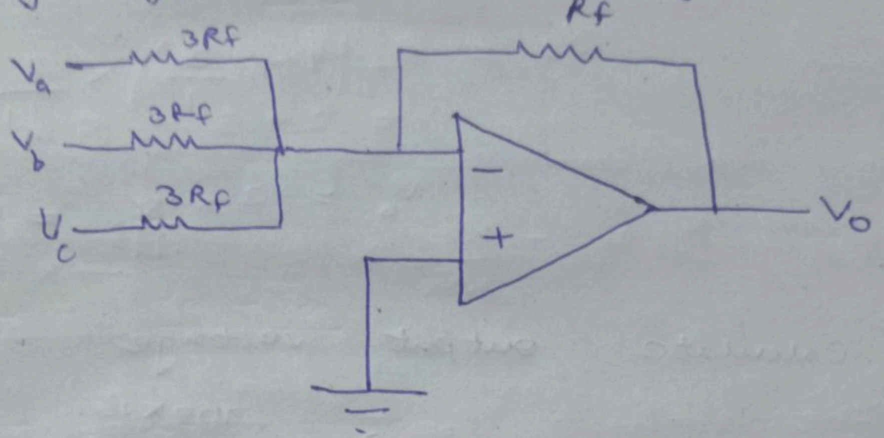
If $R_f = R$

$$\left[ V_o = -(V_a + V_b + V_c) \right]$$

In this case, adder works with unity gain.

## Averaging Amplifier

It gives an O/P voltage proportional to average of all input voltages.



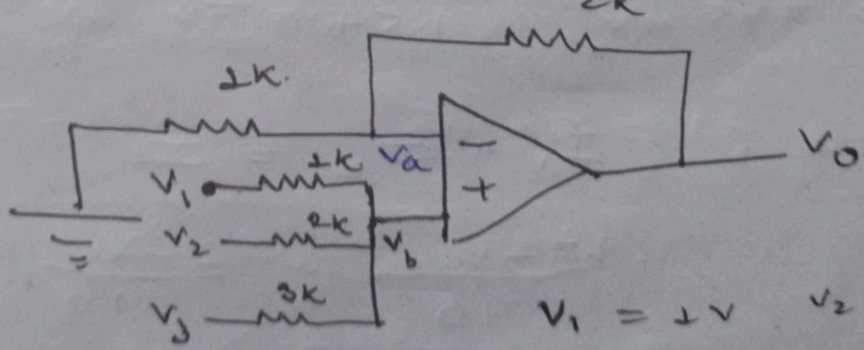

$$V_o = -\frac{R_f}{R_i}(V_a + V_b + V_c)$$

$R_i = 3R_f$

$$\boxed{V_o = -\frac{(V_a + V_b + V_c)}{3}}$$

− sign → 180° out of phase.

Q → Calculate output voltage




$V_1 = 1V \quad V_2 = 2V \quad V_3 = 3V$

$I_1 + I_2 + I_3 = 0$ → Ideal OP-Amp
No current flows inside.

$$\frac{V_1-V_b}{1}+\frac{V_2-V_3}{2}+\frac{V_3-V_b}{3}=0$$

$$V_b=\frac{18}{11}V$$

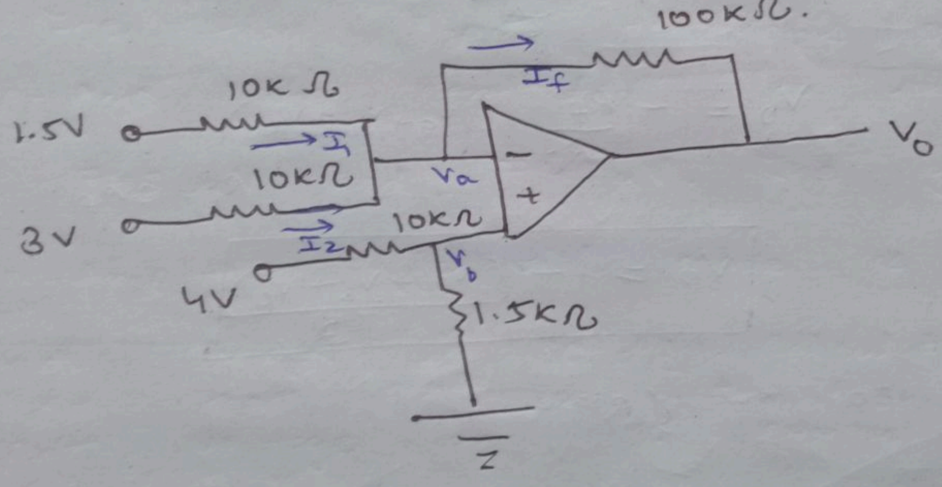
For non-inverting amplifier,

$$V_0=\left(1+\frac{R_f}{R_1}\right)V_i$$

$$=\left(1+\frac{2}{1}\right)\times\frac{18}{11}$$

$$V_0=3\times\frac{18}{11}=4.9V$$

Q ⇒ Calculate output voltage.




$$V_b=\left(\frac{1.5}{1.5+10}\right)\times 4=0.522V$$

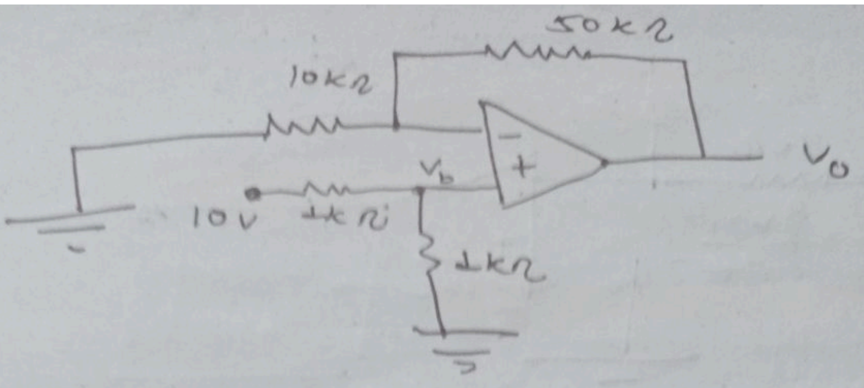
KCL, $I_1+I_2=I_f$

$$\frac{1.5-V_a}{10}+\frac{3-V_a}{10}=\frac{V_a-V_0}{100}$$

concept of virtual short, $V_a=V_b=0.522V$

$$V_0=-34.56V$$

Q>

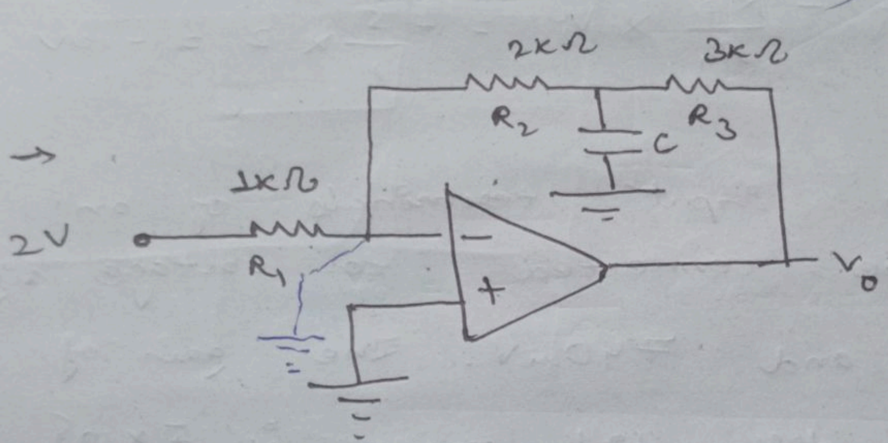



$$V_b = \frac{1}{1+1} \times 10 = 5V$$

For non-inverting amplifier,

$$V_o = \left(1 + \frac{50}{10}\right) \times 5 = 30V$$

Q →




For DC → C → open

$$R_f = R_2 + R_3 = 2 + 3 = 5\,k\Omega$$

$$V_o = -\frac{R_f}{R_1} \times V_i = -\frac{5}{1} \times 2 = -10V$$

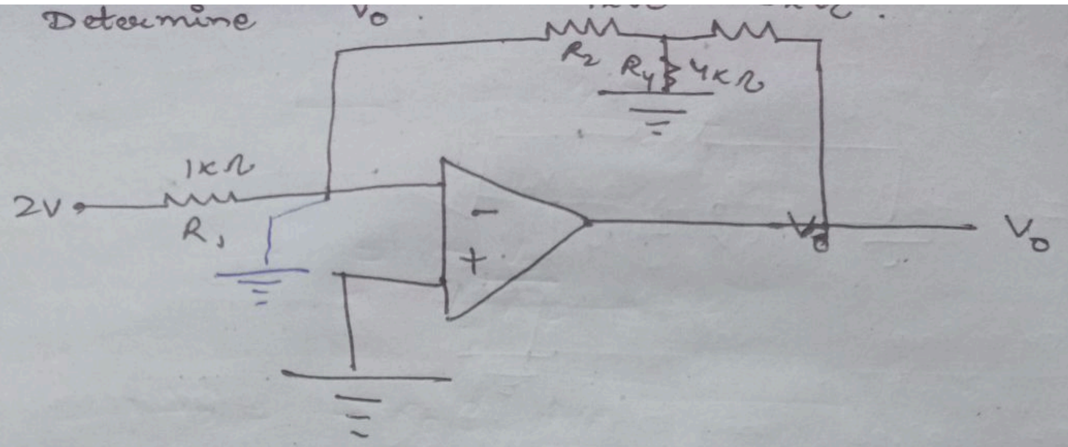
For AC → C → ~~closed~~ short

$$R_f = R_3 \qquad R_2 \to 0$$

$$V_o = -\frac{R_f}{R_1} \times V_i = -\frac{3}{1} \times 2$$

$$= -6V$$

Q→ Determine $V_o$.




$$R_f = R_2 \| R_4 + R_3$$
$$= 2 + 3 = 5\,k\Omega$$

$$V_o = -\frac{R_f}{R_1} \times V_i = -\frac{5}{1} \times 2 = -10V$$

Q⇒ The two input terminals of an op-Amp are connected to voltage signals of 745 μV and 740 μV. The gain of Op-Amp in differential mode is 5×105 and CMRR is 80 dB. Calculate the output voltage and % error due to common mode.

$V_1 = 745\,\mu V$ $\quad$ $V_2 = 740\,\mu V$

$A_d = 5 \times 10^5$ $\quad$ CMRR = 80 dB.

$V_o = ?$ $\quad$ % error = ?

$V_d = V_1 - V_2$
$= 5\,\mu V$

$V_c = \frac{V_1 + V_2}{2}$
$= \frac{745 + 740}{2}$

$$V_o = A_d V_d + A_c V_c.$$

$$CMRR = \frac{A_d}{A_c}$$

$$\text{CMRR in dB} = 20 \log \frac{A_d}{A_c}$$

$$80 = 20 \log \frac{A_d}{A_c}$$

$$\frac{A_d}{A_c} = 10^4 \qquad A_c = 50$$

$$V_o = 5 \times 10^5 \times 5 \times 10^{-6} + 50 \times \left(\frac{745a + 74}{2}\right.$$

$$V_o = 2.537\,V$$

For ideal OP-Amp.

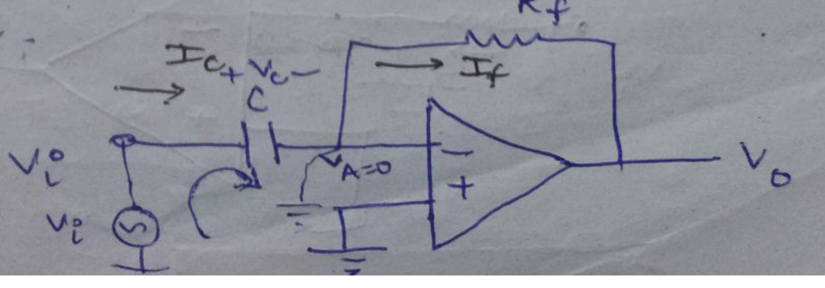
$$V_o = A_d V_d$$
$$= 5 \times 10^5 \times 5 \times 10^{-6}$$
$$= 2.5\,V$$

$$\%\ \text{error} = \frac{2.537 - 2.5}{2.5} \times 100\%$$
$$= 1.484\,\%$$

**Differentiator**

Ckt that performs mathematical differentiation of i/p signal.

The output of differentiator is proportional to rate of change of its i/p signal.



$$I_c = I_f$$

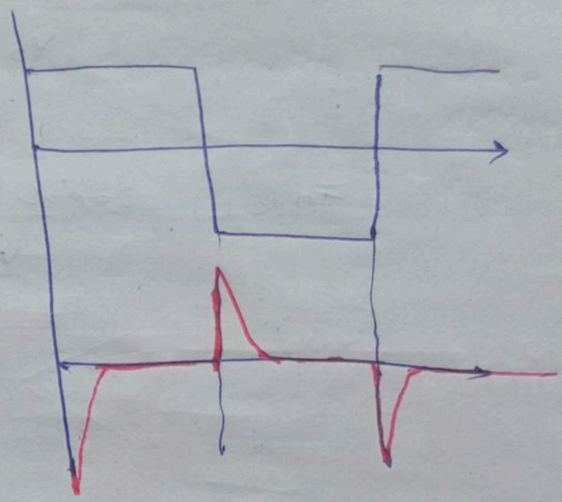
$$-V_i + V_c = 0$$

$$V_c = V_i$$

$$C\frac{dV_c}{dt} = \frac{V_A - V_0}{R_f}$$

$$C\frac{dV_i}{dt} = -\frac{V_0}{R_f}$$

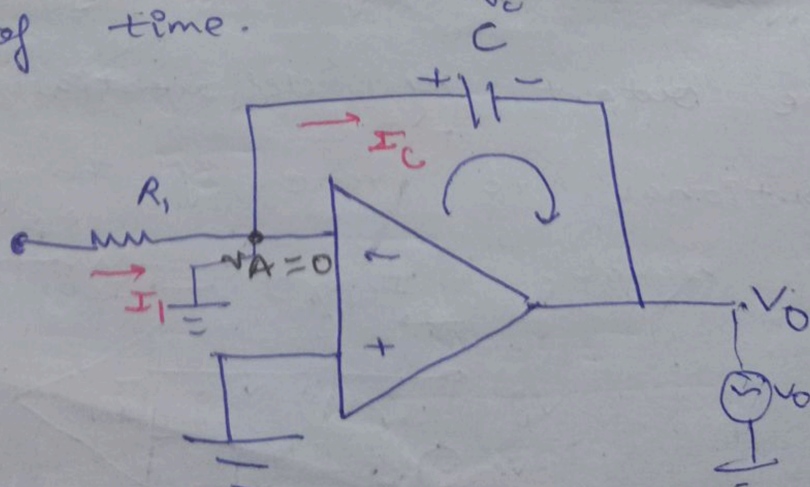
$$\boxed{V_0 = -R_f C \frac{dV_i}{dt}}$$



## Integrator

Ckt that performs integration of i/P signals.

The O/P of integrator is proportional to area of i/P waveform over a period of time.



$v_c + V_o = 0$ $\qquad I_1 = I_C$

$V_c = -V_o$ $\qquad \frac{V_i - V_A}{R_1} = C \frac{dV_c}{dt}$ $\qquad I_c = C \frac{dV_c}{dt}$

$$\frac{V_i}{R_1} = -C \frac{dV_o}{dt}$$

$$\int_0^t \frac{V_i}{R_1} dt = -C \int_0^t \frac{dV_o}{dt} dt$$

$$\frac{1}{R_1} \int_0^t V_i \, dt = -C V_o$$

$$\boxed{V_o = -\frac{1}{R_1 C} \int_0^t V_i \, dt}$$