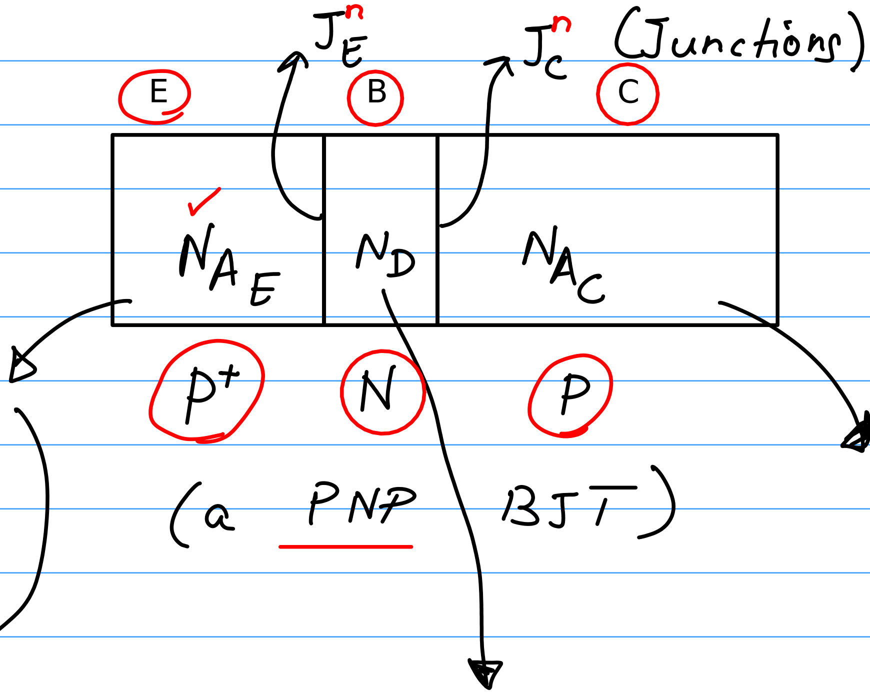
Bipolar Junction transistor

3 electrode



(Source of charge carriers)

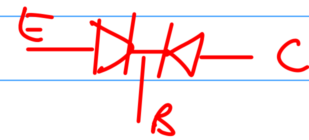
(Sink)

Dopings –

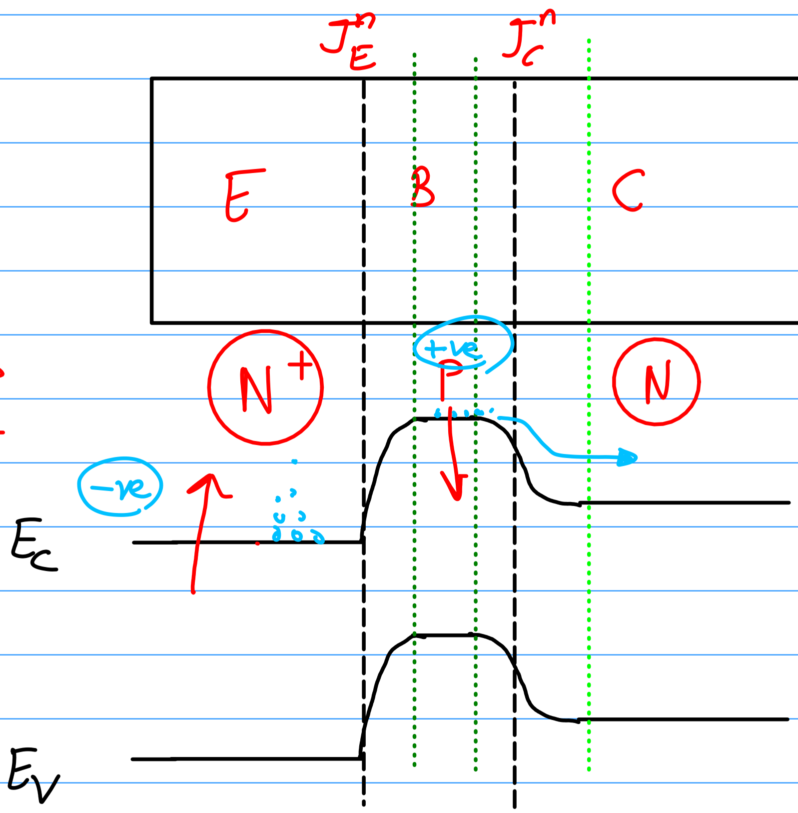
$N_{A_E} >> N_D > N_{A_C}$

Area (width)

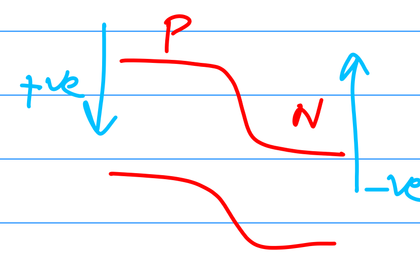
$C > E > B$



Electrical Isolation Between E & C



+ve

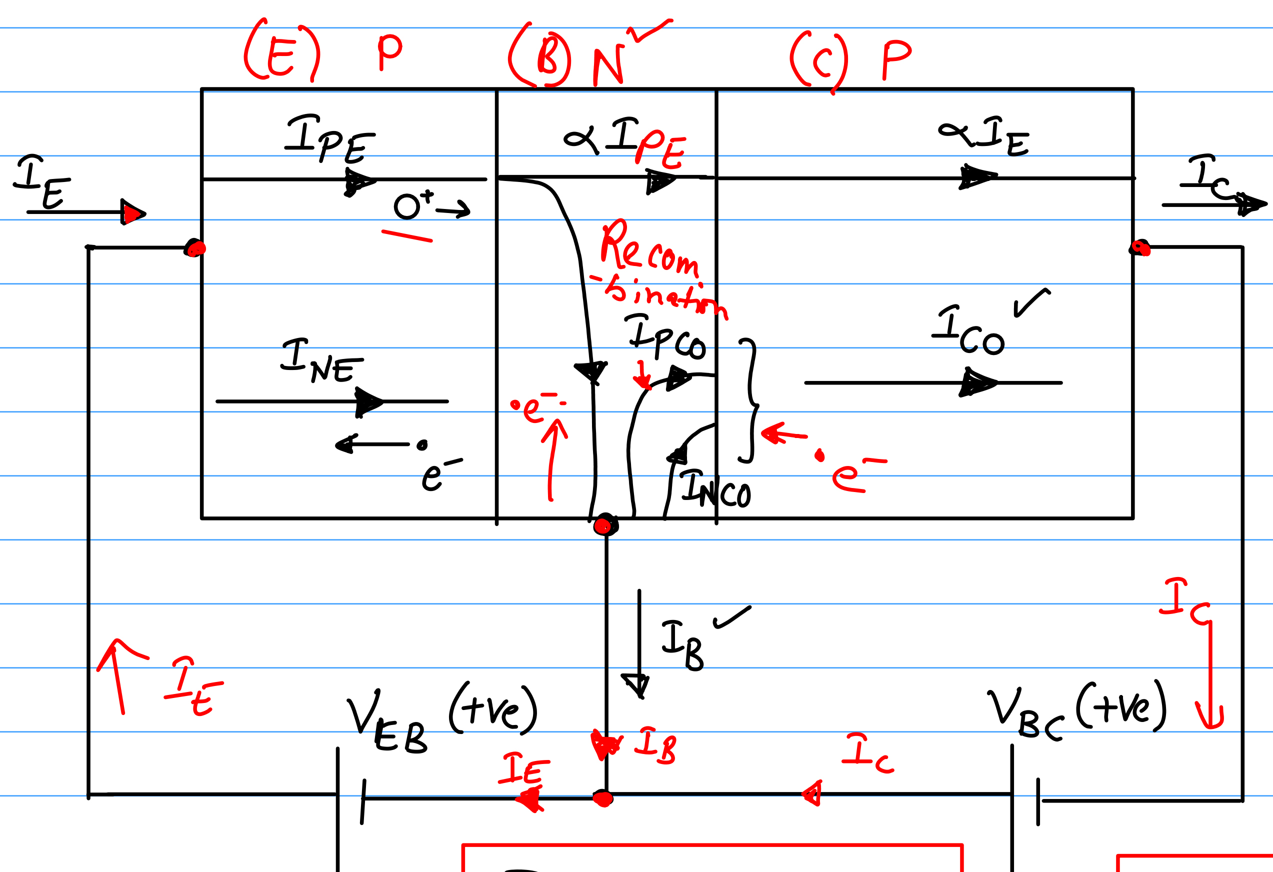


$$\frac{1}{q}\frac{dE_c}{dx} = \vec{\mathcal{E}}$$

MODES OF OPERATION

Mode	J_E^n	J_C^n	APPLICATION
1) ** Forward Active	F.B.	R.B.	$\boxed{\text{Amplification}}$
2) Saturation ON	F.B.	F.B.	Switching (Digital - ON/OFF 1/0)
3) Cut-off OFF	R.B.	R.B.	
4) Reverse Active	R.B.	F.B.	Rarely used for Amp.

OPERATION (ACTIVE MODE)



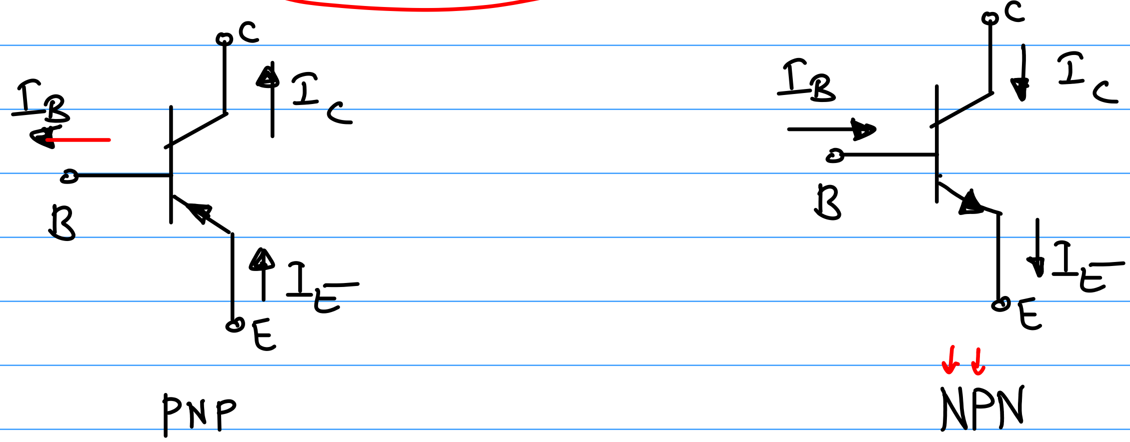
$$\boxed{I_C = \alpha I_E + I_{CO}}$$

$$\boxed{\alpha < 1}$$ **

$$\boxed{I_E = I_C + I_B}$$ (Always) [KCL]

PNP or NPN

$$I_E = I_{PE} + I_{NE} \simeq I_{PE}$$ $(\because N_{AE} >> N_D)$



By KVL-

$$\boxed{V_{CE} + V_{EB} + V_{BC} = 0}$$ [NPN or PNP] (always)

$$\because \cancel{V_C} - \cancel{V_E} + \cancel{V_E} - \cancel{V_B} + V_B - V_C = 0$$

CONFIGURATIONS

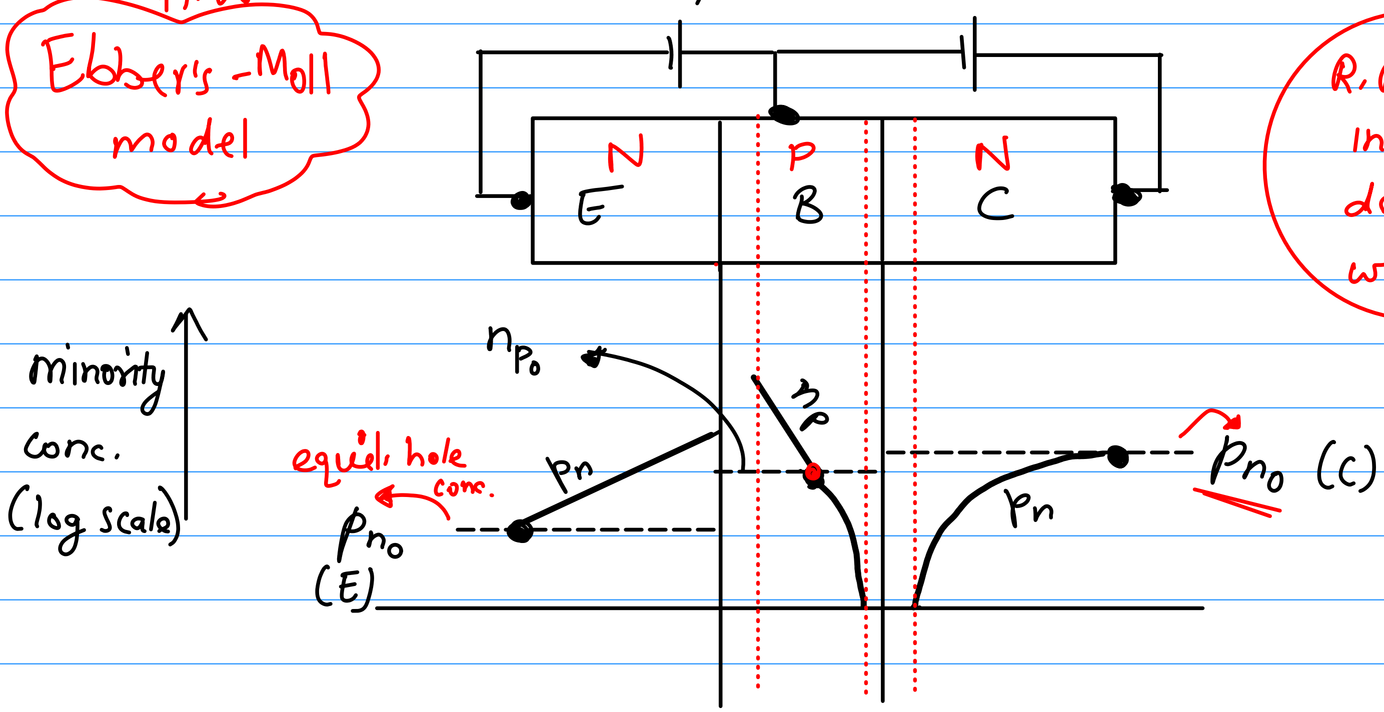
Config	i/p	o/p	Common	vol gain, A_v	Current gain, A_i	i/p resist. R_i	o/p resist. R_o
** CE (Common emitter)	B	C	E	High ✓	High ✓	High ✓	High ✓
CC [Emitter Follower] (Common collector)	B	E	C	Low $\simeq 1$ < 1	V. high	V. high	V. low
CB (common base)	E	C	B	V. high	Low $\simeq 1$ < 1	V. low	V. high

CE → power gain $A_p = A_v \cdot A_I$ = highest

EARLY EFFECT / BASE WIDTH MODULATION

H.W. Ebber's-Moll model

R.B. increases depletion width



External contacts are always under thermal equilibrium, so concentrations near the contacts are the equillibrium concentrations.

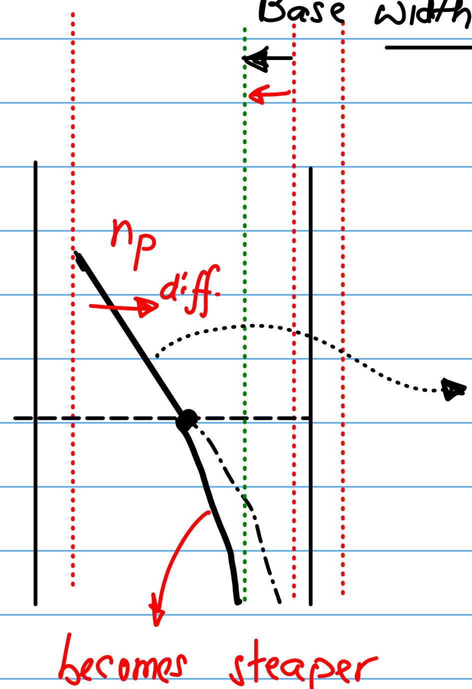
* Collector junction is R.B. so, increasing Vcb causes depletion width to increase.
* When depletion region increases into base, 3 things happen:
  1. Recombination decreases. So base current decreases (Recomb. happens in quasi-neutral base)
  2. Alpha increases because recombination decreases.
  3. Emmiter current increases because minority concentration gradient increases in the base.

Base width modulation

as J_C^n R.B. $\uparrow$

$W_{base\text{-}effective} \downarrow$

(B.W. Mod.)



I_E is due to diffusion of these minority carriers towards C.

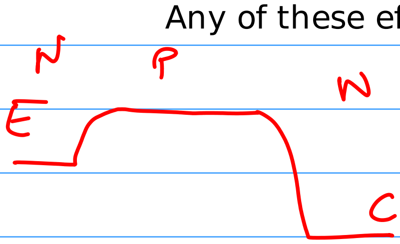
$I_E \uparrow$ (slightly)

* Punch Through:

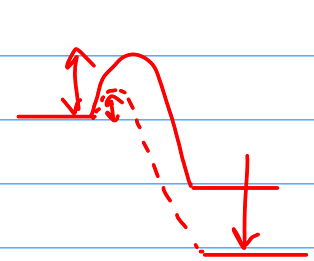
If base becomes completely depleted, then no recombination takes place in the base and collector current shoots up.
Since depletion regions have electric fields, collector and emitter are now electrically connected (base acts as short circuit) because there is a continuous electric field region from collector to emitter. Now reverse bias on Collector junction reduces barrier of emitter junction and both emitter and collector currents increase to very high values.

* Due to R.B. collector junction might also go into breakdown and that might cause current to increase rapidly.

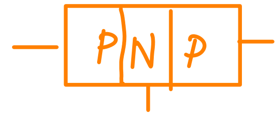
Any of these effects might cause burning of the BJT.



Punch-through



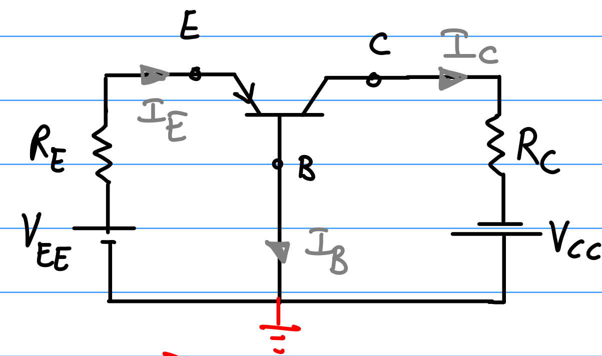
1. Common Base Config.:



i/p at E

o/p at C

Common terminal = B



* I/p Characteristics : $\underbrace{V_{EB}}_{\text{Dependent var.}} = f_1(\underbrace{I_E, V_{CB}}_{\text{independent var.}})$

* O/p Characteristics : $\underbrace{I_C}_{\text{Dependent var.}} = f_2(\underbrace{I_E, V_{CB}}_{\text{independent var.}})$

1) O/p Char : ** $\boxed{I_C = \alpha I_E + I_{CO}}$ $\boxed{I_E = I_C + I_B}$ (KCL)

I_C independent of V_{CB}

(o/p current) (o/p vol, how?)

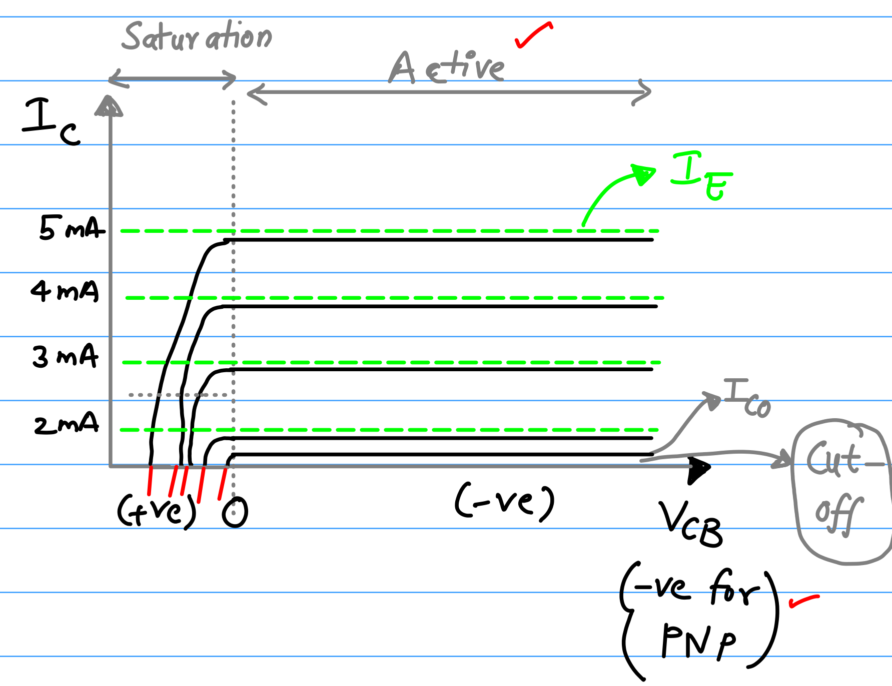
* ACTIVE :

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

$\Rightarrow \boxed{I_C \simeq \alpha I_E}$

$\alpha < 1$ but $\alpha \simeq 1$

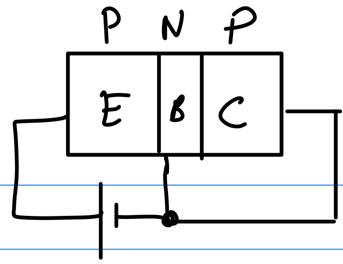
$I_C < I_E$ (slightly)



* As $V_{CB} \uparrow$ (-ve) ;

$\alpha \uparrow$, $I_E \uparrow$ (slightly) so, $I_C \uparrow$

(negligible changes)



→ Active mode

∵ S.C is treated as R.B. in BJT

* Cut-off – $\boxed{I_E = 0 \; ; \; I_C = I_{CO}}$

* Saturation – $V_{CB} = +ve$ (small) → $J_C^n = F.B.$

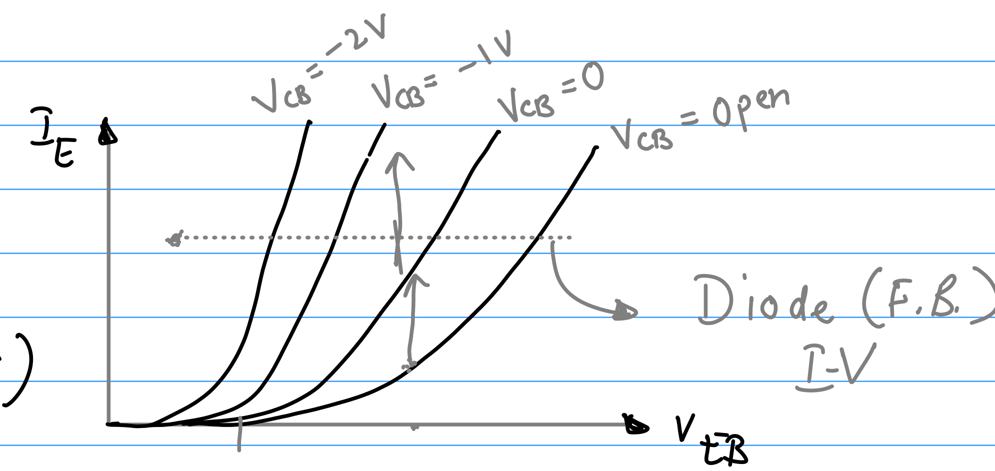
(out of C terminal) $I_C \downarrow = \alpha I_E - I_{CO}\left[\exp\left(\frac{V_{CB}\uparrow}{\eta V_T}\right) - 1\right]$

– ve sign ∵ I_E is B to C but F.B. current at J_n^C will be C to B.

as $V_{CB} \uparrow$ (+ve), I_C quickly $\downarrow$

2. I/P char. :

($I_E \uparrow$ only slightly as V_{CB} (–ve) $\uparrow$)



$V_\gamma = 0.7V$ for Si

$= 0.2$ V for Ge

Properties – (CB)

1. Lowest R_i ($< 100\,\Omega$) [i/p is F.B. Diode]

2. Highest R_o (output resistance)

3. Lowest Current gain – o/p current = I_C, i/p current = I_E

$\boxed{I_C \simeq \alpha I_E}$ ⇒ Current gain $= A_I = \frac{\text{o/p cur.}}{\text{i/p cur.}}$

$$\Rightarrow \boxed{\underbrace{A_I}_{(+ve)} = \frac{I_C}{I_E} = \alpha} \quad \left[\begin{array}{c} \alpha < 1 \\ \alpha \simeq 1 \end{array}\right]$$

4. Highest vol. gain A_V (also +ve)

5. Power Gain, $A_P = A_V \cdot A_I$ = moderate

6. Phase (or angle) difference between o/p & i/p voltages, $\phi = 0°$ ($\because A_V = +ve$)

7. Largest Bandwidth. Suitable for high frequency ops.

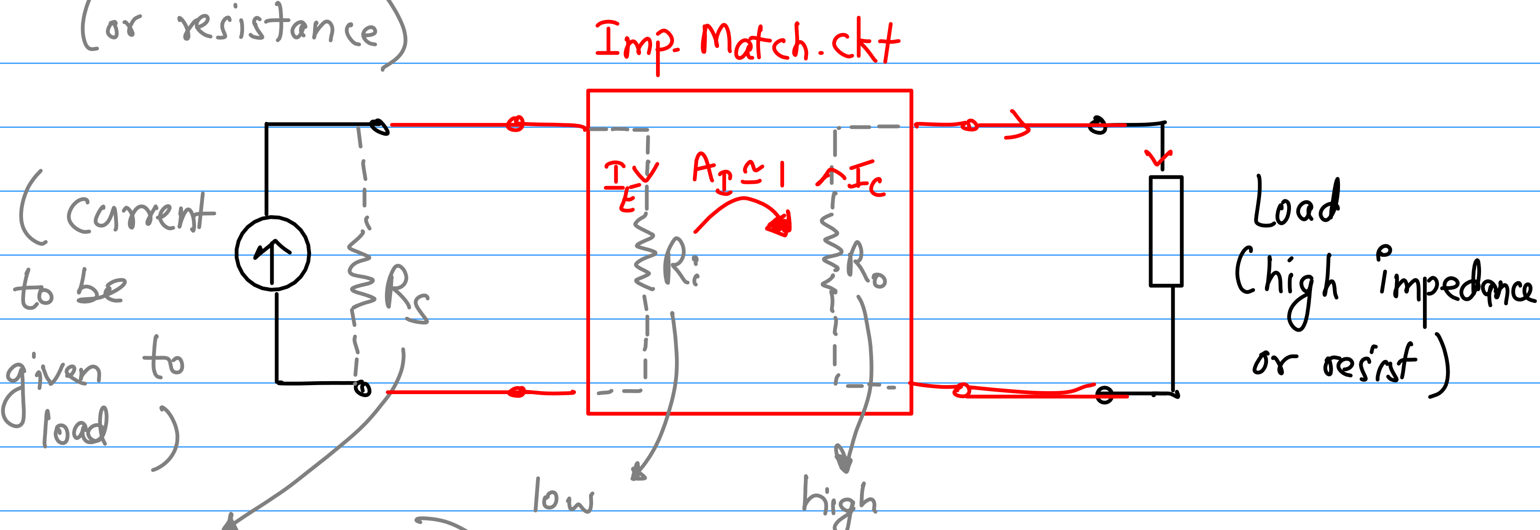
Applications –

1. Constant current source. [Since o/p current doesn't change (or depend on) o/p vol. or load.]
   CB is known as "CURRENT BUFFER" ($I_C \simeq I_E$)

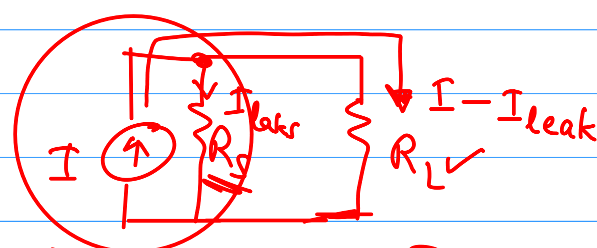
2. Non inverting vol. amplifier ($A_V = +ve$)

3. High freq. (or speed) amp.

4. Impedance matching [low imp to high imp]
   (or resistance)



Low source resistance (bad source) in parallel to current source



ideally $R_s \to \infty$ $I_{leak} = 0$

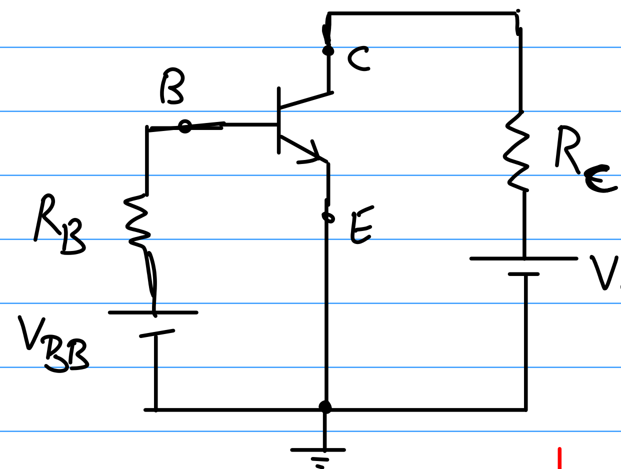
→ Common Emitter – (CE)

'i/p at B

o/p at C

E → common

(NPN BJT)



α = CB current gain

β = CE current gain

$$I_C = \alpha I_E + I_{CO} \quad \text{(always)}$$

$$I_E = I_C + I_B \quad \text{(always)} \quad \text{(KCL)}$$

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

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

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

$\alpha = 0.98$

$\beta = 49$

So, ** $\boxed{I_C = \beta I_B + (1+\beta) I_{CO}}$

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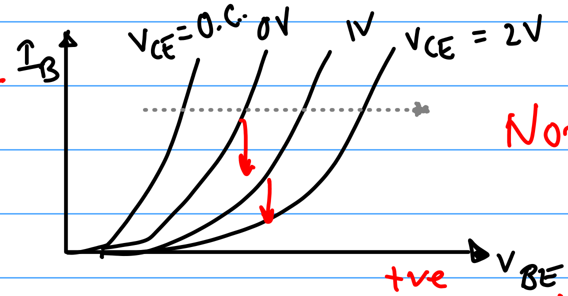
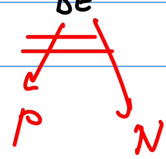
* I/p char –

'i/p current



Not f.B. current curve



(V_{CE} ↑)

i.e. V_C↑, R.B. J_C^n ↑,

α↑, I_B↓ (recomb. reduces)

1. <u>Active Mode</u> - $\boxed{I_C = \beta I_B + (1+\beta) I_{CO}}$

$I_C = f_1(I_B, V_{CE})$

I_C seems to be independent of V_{CE}

But actually as $V_{CE} \uparrow$ ($= V_C - V_E = V_C$, $\because V_E = 0$)

So, $V_C \uparrow$, Collector junction (J_C^n) R.B $\uparrow$,

$\alpha \uparrow$ (due to early effect), so, $\beta \uparrow\uparrow$

e.g. $\alpha = 0.98$, $\beta = 49$

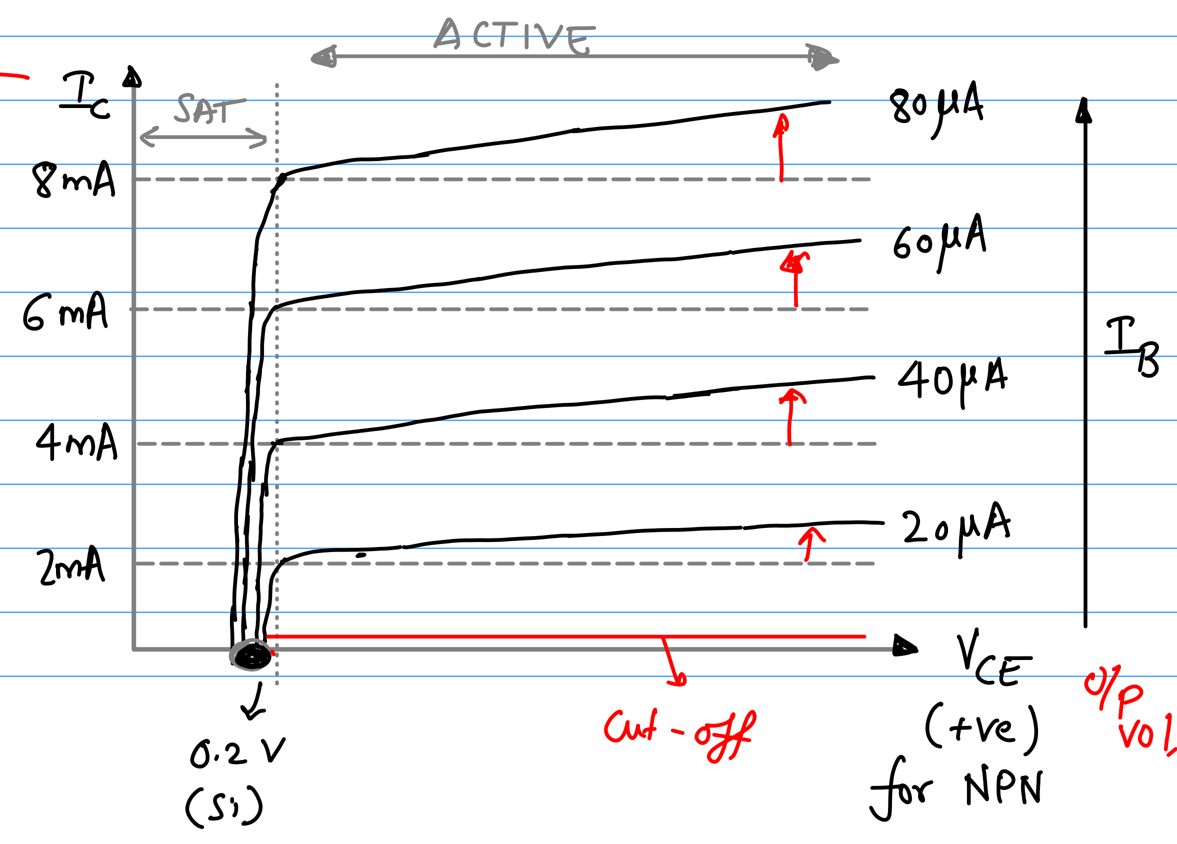
(>1% ↑) $\alpha = 0.99$, $\beta = 99$ (large increment) (>100% ↑)

as $\beta \uparrow\uparrow$, $I_B \downarrow$ ($\because$ recomb. decreases)

so, I_C also $\uparrow$.

O/p cur.

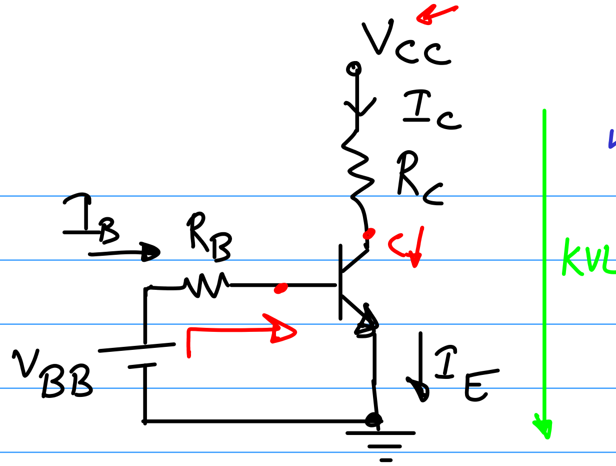
$V_{BE} = 0.7\,V$ for Si



A6

2. Saturation –

KVL



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

$\Rightarrow$ $\boxed{I_C = \dfrac{V_{CC} - V_{CE}}{R_C}}$ (or) $\boxed{V_{CE} = V_{CC} - I_C R_C}$

load line

as $V_{BB} \uparrow$, $I_B \uparrow$ ($V_{BE} \uparrow$ slightly), so, $I_C \uparrow$

($I_C \simeq \beta I_B$ (active))

so, $V_{CE} \downarrow$

But V_{CE} cannot go below 0.2V (for Si)

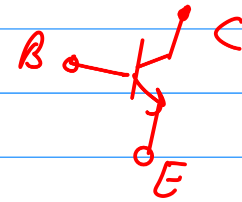
So, as $V_{BB} \uparrow$, $V_{CE} \downarrow$ & finally becomes constant at 0.2 V

So, I_C becomes constant beyond this point.

i.e. I_C doesn't $\uparrow$ as $I_B \uparrow$

(saturates)

at Saturation, $\boxed{V_{BE} = 0.8V}$
$\boxed{V_{CE} = 0.2V}$ } (Silicon)



As KVL $\rightarrow$ $V_{CB} + V_{BE} + V_{EC} = 0$

So, $V_{CB} = -0.8 + 0.2 = -0.6\,V$

or $V_{BC} = 0.6\,V$ (Forward bias for NPN J_C^n)

* So, both J_C^n & J_E^n are F.B $\Rightarrow$ Saturation

→ How to find if CE BJT is in saturation or active mode?

(i) Assume Saturation

(ii) KVL at o/p } $I_{C_{sat}} = \dfrac{V_{CC} - V_{CE\text{-}sat}}{R_C}$ (0.2 V for Si) (find $I_{C_{sat}}$)

Collector current can't ↑ above $I_{C\text{-}sat}$

(iii) find $\boxed{I_{B\text{-}min} = \dfrac{I_{C\text{-}sat}}{\beta}}$

low I_B → active mode

↑ I_B, eventually we get saturation

min base current needed to drive BJT into saturation.

(iv) Find actual base current I_B from KVL at input.

(v) * If $I_B \geqslant I_{B\text{-}min}$, BJT is in saturation & $I_{C\text{-}sat}$ is the actual I_C

* If $I_B < I_{B\text{-}min}$, BJT is in active mode

& $I_C \neq I_{C\text{-}sat}$ but $I_C = \beta I_B + (1+\beta) I_{C0}$

$\Rightarrow \boxed{I_C \simeq \beta I_B}$ ** for active mode only

* Over-drive factor $= \dfrac{I_B}{I_{B\text{-}min}}$ (>1) $\left(\begin{array}{c}\text{if BJT in} \\ \text{saturation}\end{array}\right)$ *

* Forced β = $\boxed{\beta_{forced} = \dfrac{I_{C\text{-}sat}}{I_B}}$

3. Cut-off –

for any config.

* Condition for cut-off is $\boxed{I_E = 0}$ $I_C = \alpha \underbrace{I_E}_{0} + I_{C0}$

i.e., $\boxed{I_C = I_{C0}}$

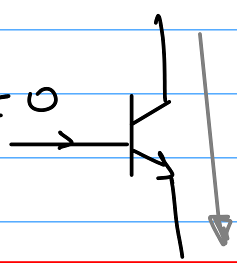
* if we make $I_B = 0$

then $I_C \overset{0+}{=} (1+\beta) I_{C0} = 100\, I_{C0}$ (if $\beta = 99$)

(NOT CUT-OFF)

So $I_B = 0$ is not sufficient for cut-off.

(i/p = O.C.) $I_B = 0$

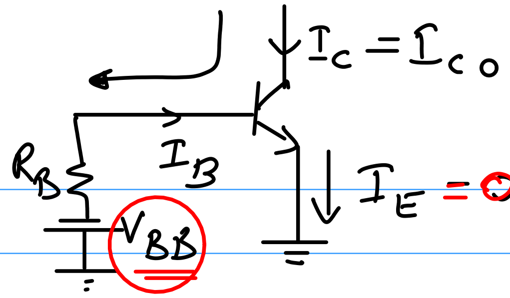


when $I_B = 0$

$I_C = I_{CEO} = (1+\beta) I_{C0} = I_E$

when $I_B = 0$ $I_C = \boxed{I_{CEO} = (1+\beta) I_{C0} = \dfrac{I_{C0}}{1-\alpha}}$

for cut-off



$I_B = -ve$ needed

i.e., B-E jn should be slightly R.B.

here $\boxed{I_B = -I_{CBO}}$

for Si, $V_{BE} = 0$ is sufficient

for Ge, $V_{BE} = -0.1\,V$ needed

So, $\boxed{I_{CEO} > I_{CBO} \gtrsim I_{CO}}$

→ Properties –

1. High i/p resistance R_i ($\sim 1\,k\Omega$)
2. High vol. gain A_V (also it is -ve)
3. High current gain A_i ($= \beta$) ($\because A_I = \frac{I_C}{I_B}$)
4. Phase diff. between o/p & i/p is

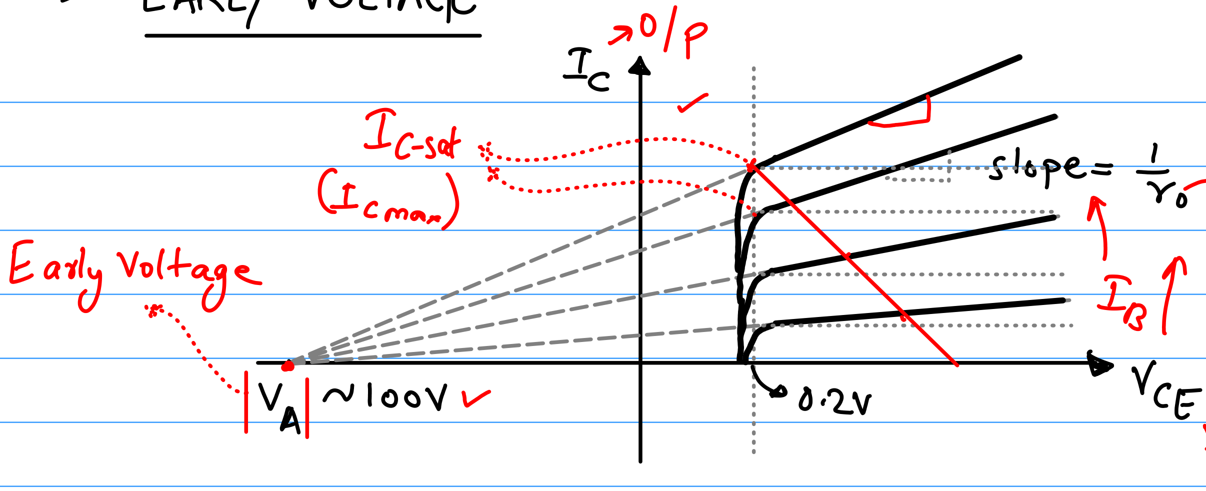
$$\boxed{\phi = 180^\circ}$$

5. Highest power Gain $A_P = A_V \cdot A_I$

* Most popular config for amplifier application.

→ EARLY VOLTAGE –

C.E. (NPN)



r_o = output resistance

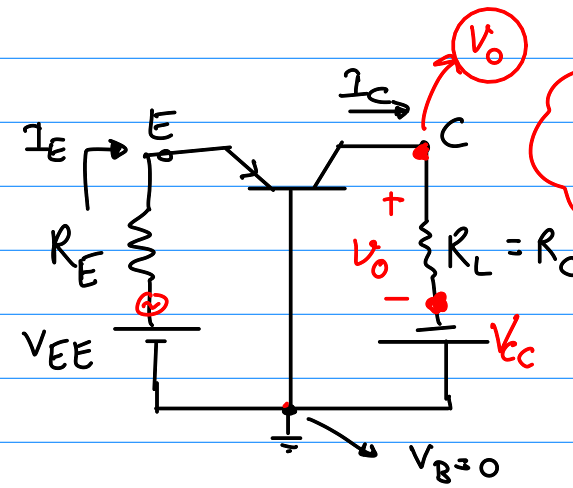
$$\text{Slope} = \frac{1}{r_o} = \frac{I_{C\text{-sat}}}{\underbrace{V_A + 0.2}_{\simeq V_A}} \Rightarrow \boxed{r_o \simeq \frac{V_A}{I_{C\text{-sat}}}} \; **$$

* if Early effect is neg. → I_C = constant with V_{CE} ⇒ $\frac{1}{r_o} = 0 \Rightarrow r_o = \infty$

→ How Amplification happens –

Assuming active region,

$$A_V = \frac{\Delta V_o}{\Delta V_i}$$



CB PNP

CB, PNP

$$\boxed{I_C \simeq \alpha I_E}$$

Let $I_E \uparrow$ by ΔI_E (by superimposing a small +ve signal on V_{EE})

then $(I_C + \Delta I_C) = \alpha\,(I_E + \Delta I_E) \Rightarrow \boxed{\Delta I_C = \alpha\,\Delta I_E}$

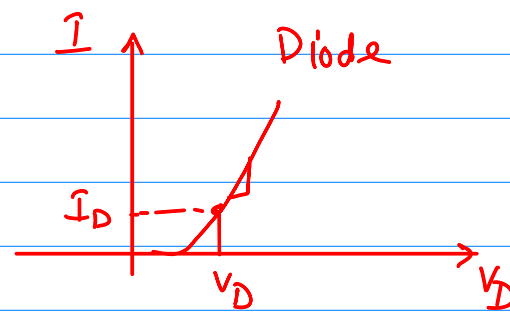
$V_o = I_C R_L = I_C R_C \Rightarrow \Delta V_o = \Delta I_C R_L = \alpha \Delta I_E R_L$

let ΔV_i = (change in i/p vol.)

& r_e = dynamic resistance of transistor

** $\boxed{r_e = \frac{\eta V_T}{I_E}}$ ✓ $\Rightarrow$ $\boxed{r_e = \frac{V_T}{I_E}}$ *** $[\because \eta = 1]$ ✓

where $V_T = \frac{T}{11,600}$



Static Resistance = $R_D = \frac{V_D}{I_D}$ ✓

Dynamic Resistance = $\boxed{r = \frac{dV_D}{dI_D}}$

for diode $\rightarrow$ $I_D = I_o\left(\exp\left(\frac{V_D}{\eta V_T}\right) - 1\right)$

$$\frac{dI_D}{dV_D} = \frac{1}{\eta V_T} I_o \left(\exp\left(\frac{V_D}{\eta V_T}\right)\right) = \frac{I_D}{\eta V_T}$$

dyn resis $\boxed{r = \frac{\eta V_T}{I_D}}$ ✓

Since emitter is f.b., it can be treated like a F.B diode so, its dyn. resist.

$$r_e = \frac{\eta V_T}{I_E}$$

$$\Delta V_i = \Delta I_E r_e \qquad \because \; r_e = \frac{dV_{EB}}{dI_E} = \frac{\Delta V_{EB}}{\Delta I_E}$$

$$A_v = \frac{\Delta V_o}{\Delta V_i} = \frac{\alpha \Delta I_E R_L}{\Delta I_E r_e}$$

$$\boxed{A_V = \frac{\alpha R_L}{r_e}} \; *$$

$A_V \propto \dfrac{R_L}{r_e}$ — R_L → o/p side; r_e → i/p side resist.

if $R_L > r_e$ (usually) $A_V > 1$

* Amplification comes from having different o/p & i/p resistance

o/p → (load) // (r_o) → BJT

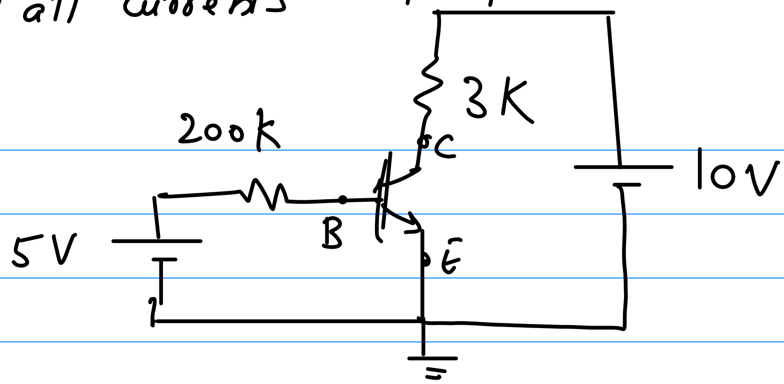
i/p → (dyn resist of BJT)

↓

Transfer + resistor = Transistor

Q1) Find all currents if $\beta = 100$ & $I_{CO} = 20nA$

(a)



DC Analysis (large signal analysis)

Sol. $$\boxed{I_C = \beta I_B + (1+\beta) I_{CO}}$$ [CE config] for active

or $$I_C = \frac{V_{CC} - V_{CE\,sat}}{R_C}$$ for sat.

(i) Assume sat., $V_{CE\,sat} = 0.2V$ (Si)

by KVL, $$I_{C\,sat} = \frac{V_{CC} - V_{CE\,sat}}{R_C}$$

$$I_{C\,sat} = \frac{10 - 0.2}{3k} = \frac{9.8}{3}\ mA$$

(ii) $$I_{B\,min} = \frac{I_{C\,sat}}{\beta} = \frac{9.8}{300}\ mA \simeq \frac{3.3}{100}\ mA$$

$\simeq 33\mu A$

(iii) KVL at i/p $\quad V_{BB} - R_B I_B - V_{BE} = 0$

$$\Rightarrow 5 - 200k I_B - 0.7 = 0$$

$$I_B = \frac{4.3}{200}\ mA \simeq 22\ \mu A$$

$I_B < I_{B\min}$

So, BJT is in "Active mode"

$I_B \simeq 21.5\ \mu A$

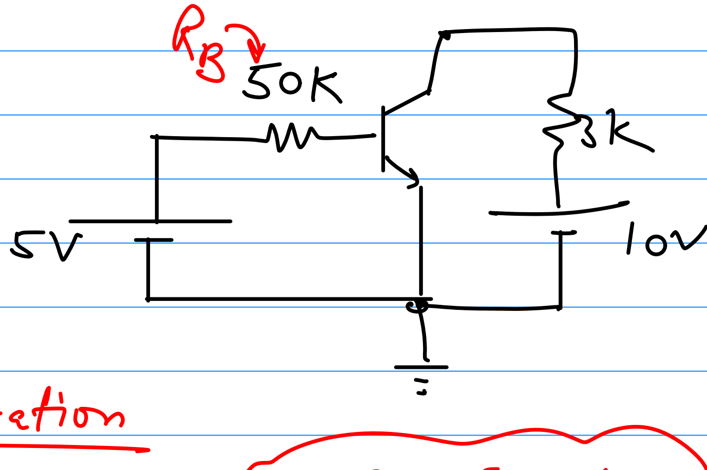
now $I_C = \beta I_B + (1+\beta) \underbrace{I_{CO}}_{(nA)\ \text{negligible}}$

$$\boxed{I_C = 100 \times 21.5\ \mu A \Rightarrow 2.15\ mA}$$

$I_E = I_C + I_B = 2.15\ mA + 0.0215\ mA$

$$\boxed{I_E = 2.17\ mA}$$

(b)



find all currents

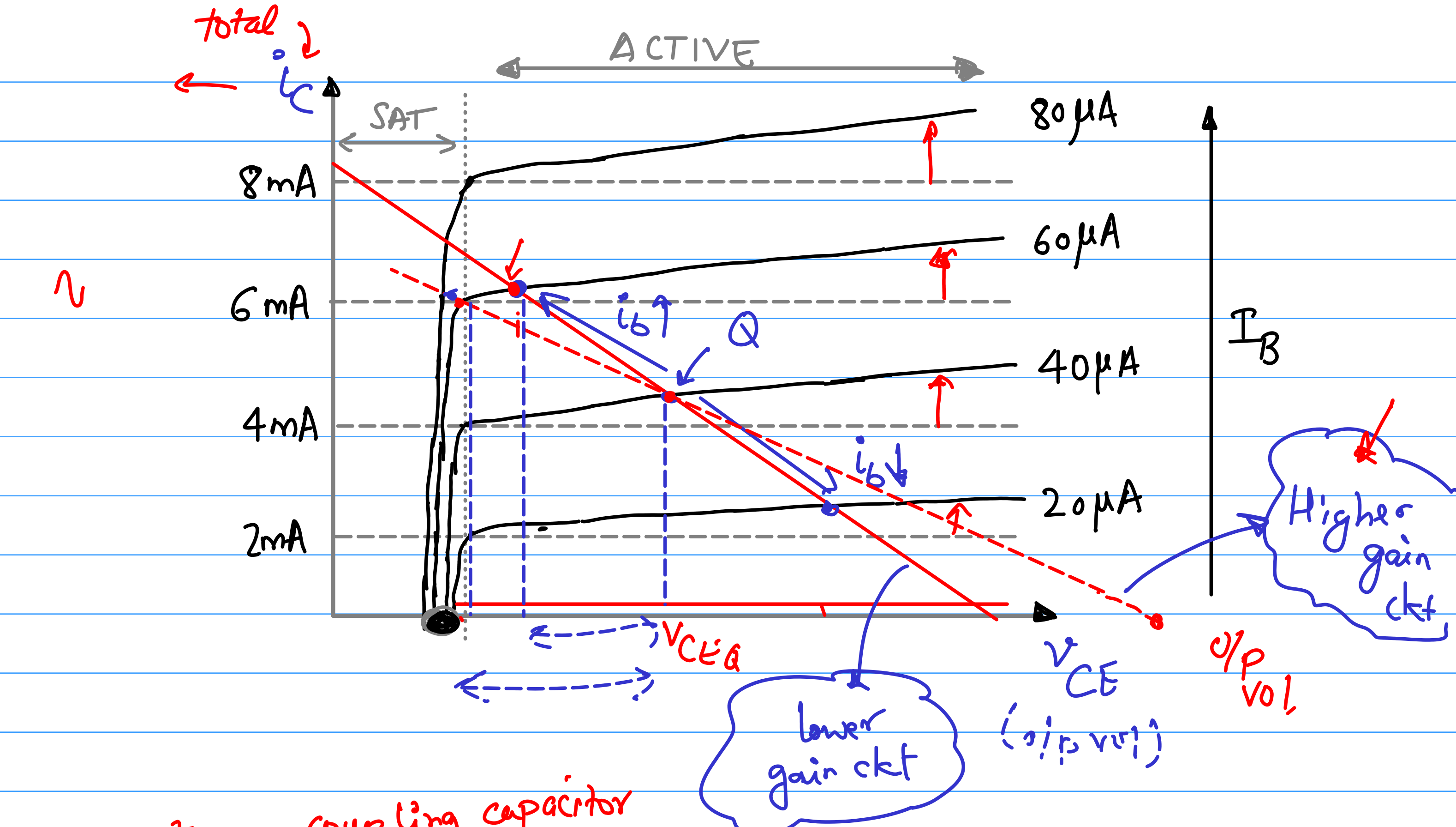
Shivam 5 Marks
427

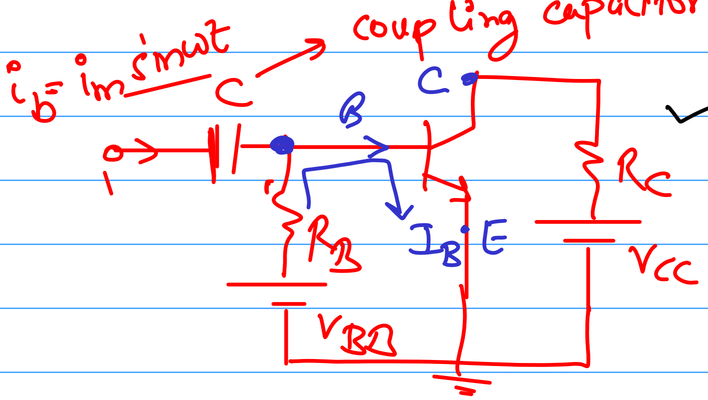
Saturation

29 - 5 marks

AI

CE → LOAD LINE – CE → 180° phase shift





$\{I_B, I_C, V_{CE}\} \rightarrow$ DC

$\{i_b, i_c, v_{be}, v_{ce}\} \rightarrow$ ac signal

$$\boxed{i_B = I_B + i_b}$$

total base current

$i_C = I_C + i_c$

$v_C = v_c + V_C$

$I_C \cong \beta I_B$ if $i_B \uparrow$, (e.g. by $\uparrow i_b$)

$i_C \cong \beta i_B$ then $i_c \uparrow$

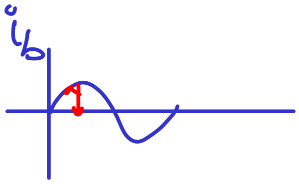
DC load line –

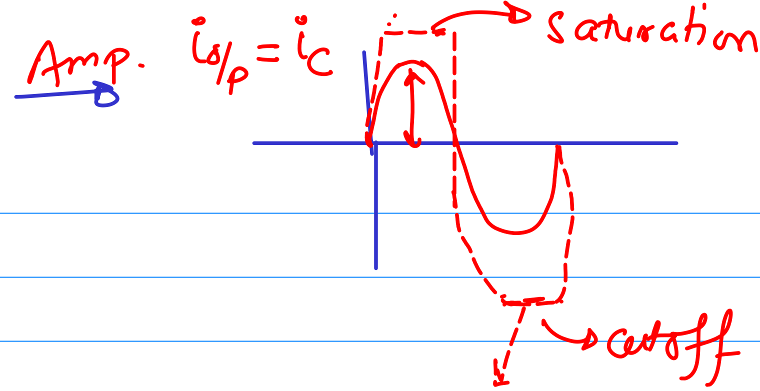
KVL –

$V_{cc} - I_C R_C - V_{CE} = 0$

$I_C = \frac{1}{R_C} V_{CC} - \frac{1}{R_C} V_{CE}$

$y = c + mx$





if amp. or gain is too high, then shape of i/p may not be preserved at o/p

" DISTORTION "

* To avoid distortⁿ in +ve or −ve side, operating point should be set in the middle (near middle) of Load line (active region range)

* Q point (bias pt.) (or operating pt.) should be stable. → Should not change with environment conditions

∵ otherwise " Distortion " will ↑

* if Q shifts away from the middle, +ve or −ve vol. swing will decrease

Bias Stabilisation –

Bias stability affected by

1. Thermal Instability
   - (i) I_{CO} → doubles for every 10° rise in temp.
   - (ii) V_{BE} → V_{BE} (cut-in) decreases at rate of $-2.3\, mV/^\circ C$
   - (iii) β → $\beta \uparrow$ slightly as temp $\uparrow$ (can ignore)

2. Transistor Replacement

   β v. sensitive to this

   ∵ of fabrication process variations

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

as $T \uparrow$, $I_{CO} \uparrow$, then $I_C \uparrow\uparrow$

↳ operating point shifts

↓

Distortion

Measuring bias stability –

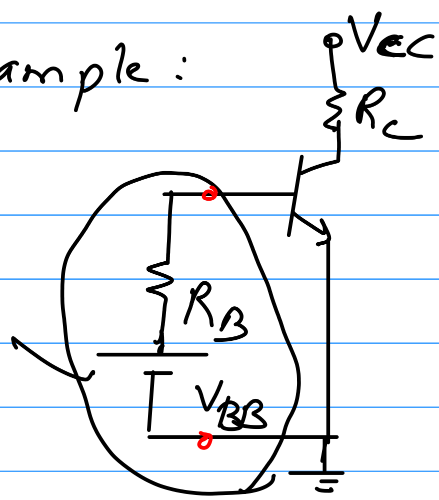
Stability factors –

$$S = \left.\frac{dI_C}{dI_{CO}}\right|_{V_{BE}\ \&\ \beta\ \text{constant}}$$

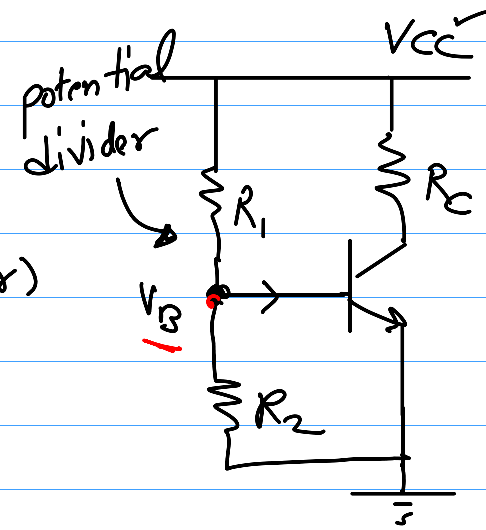
* we want S to be as small as possible.

Bad ckt– example:

* **Fixed Bias** –



(or)

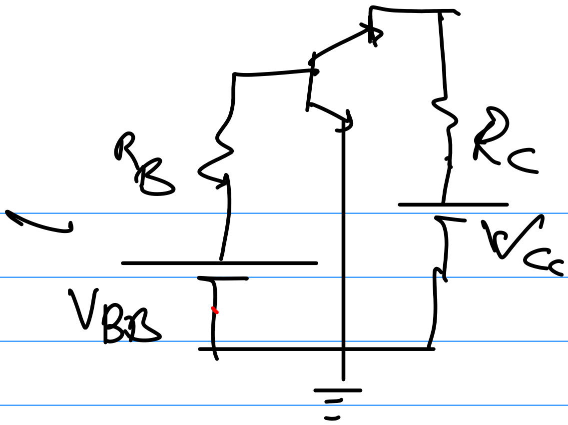


If β is high $(I_B << I_C)$ then

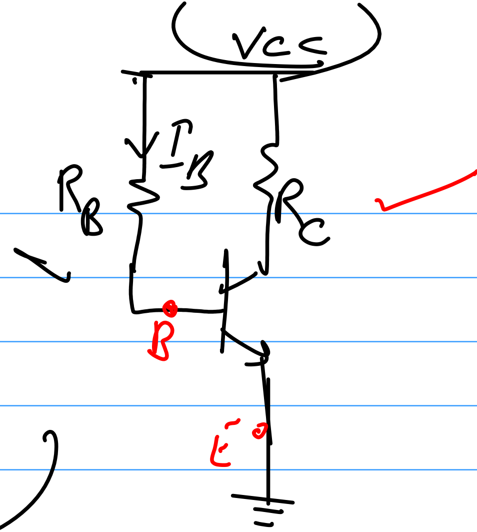
the 2 ckts are equivalent if

$$\underbrace{V_{Th} = V_{BB} = \frac{R_2}{R_1 + R_2} V_{CC} \ \&\ R_{Th} = R_B = R_1 // R_2}$$

THEVENIN's THEOREM



$\equiv$



$V_{BB} = V_{CC}$

KVL at i/p − $V_{CC} - I_B R_B - V_{BE} = 0$

$\uparrow I_B = \dfrac{V_{CC} - V_{BE}\downarrow}{R_B}$ as $T\uparrow$

$$\boxed{I_C = \beta I_B\uparrow + (1+\beta) I_{CO}\uparrow} \quad (1)$$

as $T\uparrow$, $(I_{CO}\uparrow, V_{BE}\downarrow)$ → $I_B\uparrow$, $I_C\uparrow\uparrow$

BAD

$$S = \frac{dI_C}{dI_{CO}}$$

Differentiate (1) wrt I_{CO}

$$\frac{dI_C}{dI_{CO}} = \beta \frac{dI_B}{dI_{CO}} + (1+\beta)$$

$$\frac{dI_C}{dI_{CO}} = \beta \frac{dI_B}{dI_C} \cdot \frac{dI_C}{dI_{CO}} + (1+\beta)$$

$$\boxed{\frac{dI_C}{dI_{CO}} = S = \frac{1+\beta}{1-\beta \frac{dI_B}{dI_C}}}$$

for any biasing ckt in active region.

for Fixed bias,

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

I_B is fixed

$\because V_{CC}, V_{BE}, R_B$ are Constant

$$\frac{dI_B}{dI_C} = 0$$

So, $\frac{dI_C}{dI_{CO}}$ $\boxed{S = 1+\beta}$ v. high BAD

* Self biasing − (Good ckt example)

$I_B \downarrow$ if $I_C \uparrow$

* $$\boxed{S = \frac{1+\beta}{\left(1-\beta \frac{dI_B}{dI_C}\right)}}$$

if $\frac{dI_B}{dI_C} = -ve$

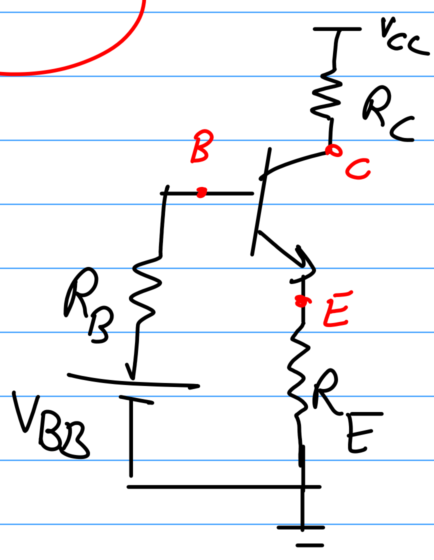
eg $= -1$.

then $S = \frac{\cancel{1+\beta}}{\cancel{1+\beta}} = 1$ (lowest possible)

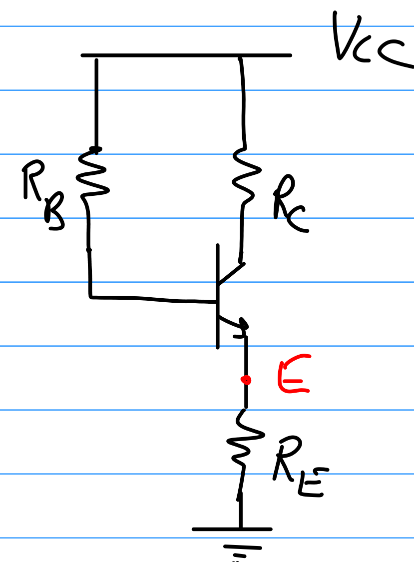
$\frac{dI_C}{dI_{C0}} = 1$

A6

$$\boxed{1 \leq S \leq (1+\beta)}$$



(or)



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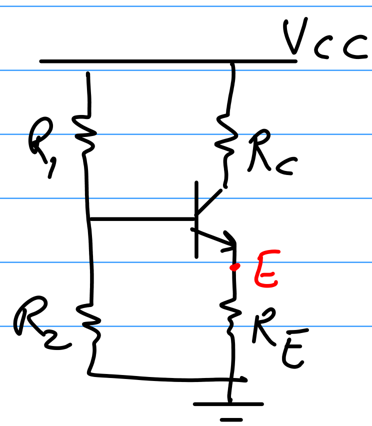
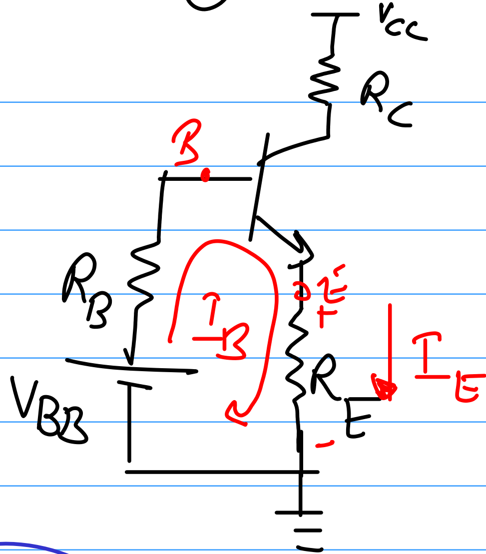


Self biasing -



i/p KVL -

$$V_{BB} - I_B R_B - V_{BE} - \underbrace{I_E R_E}_{V_E} = 0$$

$$I_E = I_C + I_B$$

$$-I_B R_B - I_B R_E - I_C R_E + V_{BB} - V_{BE} = 0$$

feedback

$$\Rightarrow \boxed{I_B = \frac{V_{BB} - V_{BE} - I_C R_E}{R_B + R_E}}$$

$$\boxed{\frac{dI_B}{dI_C} = -\frac{R_E}{R_B + R_E}}$$

$$S = \frac{1+\beta}{1-\beta\left(\frac{dI_B}{dI_C}\right)} \Rightarrow \boxed{S = \frac{1+\beta}{1+\beta\left(\frac{R_E}{R_E+R_B}\right)}}$$

$$S < 1+\beta \quad \text{(Good)}$$

if $R_E >> R_B$ then $\frac{R_E}{R_E+R_B} \simeq 1$

Good bias stability $\Bigg\}$ $S = \dfrac{1+\beta}{1+\beta\times 1} = 1$ (best case) ✓

* large R_E is desirable

* Problem with too large R_E –

O/p KVL → $V_{CC} - I_C R_C - V_{CE} - \underbrace{I_E R_E}_{V_E} = 0$

$I_C \simeq I_E$

So, $I_C \downarrow = \dfrac{V_{CC} - V_{CE}}{R_C + R_E \uparrow}$

if R_E (large) $\to \infty$, I_C (small) $\to 0$ [cut-off] ✓

(Bad Q point)

So, maybe Reduce $R_B \downarrow$

* Problem with too small R_B –

if $R_B << R_E$ then $S = 1$ (Good!)

R_B ↓ V. small, R_E ↓ moderate

but if R_B is small, $I_B \uparrow\uparrow$, Transistor goes towards (or into) saturation

(Bad Q-point)

How it works – as $T\uparrow$, $I_{co}\uparrow$, $I_c\uparrow$, $V_E\uparrow$, $I_B\downarrow$, $I_c\downarrow$

$=I_E R_E \simeq I_c R_E$

Robust system

So, change in I_c got compensated

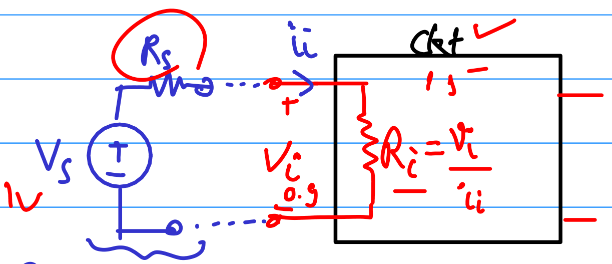
* Self biasing ckt is an example of a negative feedback amplifier.

∵ the output current (I_c) converted into voltage V_E ($\simeq I_c R_E$) reduces the input current (I_B)

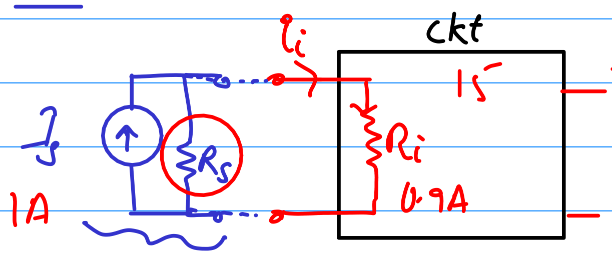
(−ve feedback)

(i/p KVL)

HW → Common Collector Config, (CC)



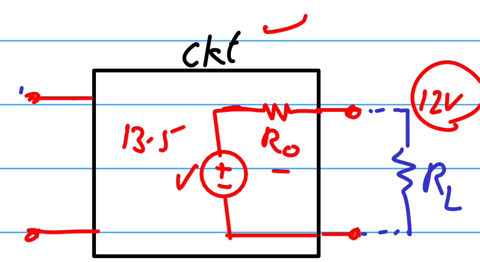
Pract. vol. source

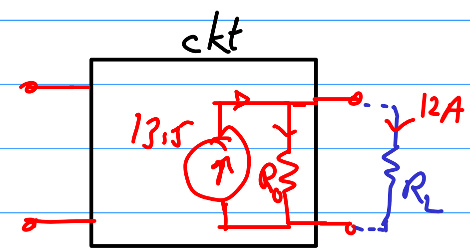


Practical Current source

entire source vol or current should "enter" the ckt which amplifies it. The entire result of amp should be transferred to the Load

Good Amp.





i/p resist of a ckt is resist seen by external source at the i/p terminals of the ckt

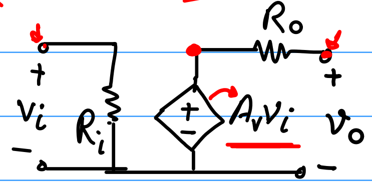
Amplifiers

Vol. Amp.

o/p = vol.

i/p = vol.

(blackboxes) Models



Desirables

R_i : High (∞)

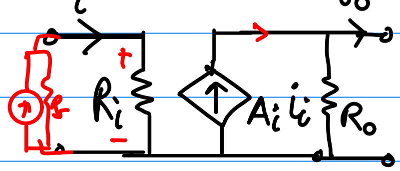
R_o : low (0)

A_v = unitless

Current Amp

o/p = current

i/p = current



Desirables

R_i : Low (0)

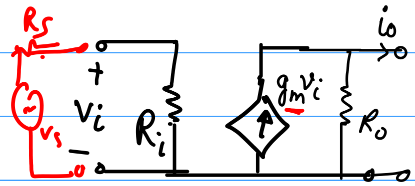
R_o : High (∞)

A_i = unitless

Trans-Conductance Amp $= \frac{i_o}{v_i}$

o/p = current

i/p = vol



Desirables

R_i : High (∞)

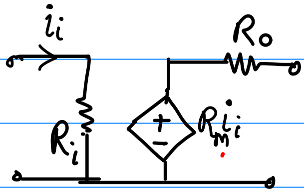
R_o : High (∞)

$g_m = \frac{1}{\Omega}$

Trans-Resistance Amp

o/p = vol.

i/p = current

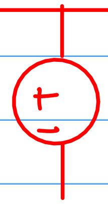


Desirables

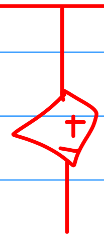
R_i : Low (0)

R_o : Low (0)

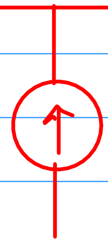
$R_m = \Omega$



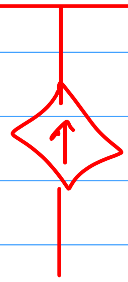
independent vol source



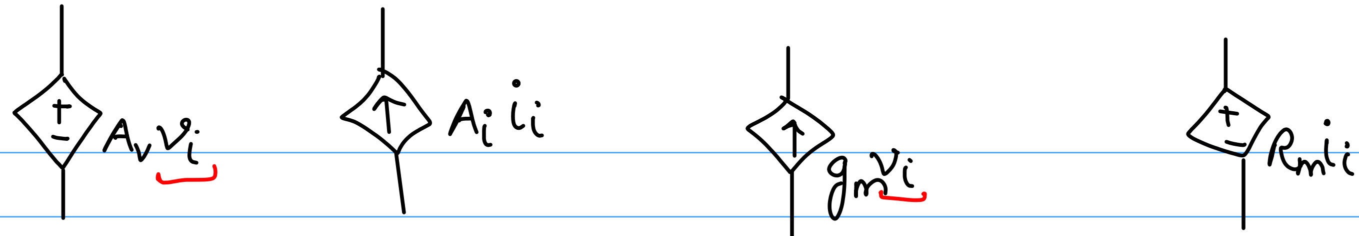
Dependent vol source



indep. curr source



dep. curr. source



Voltage Controlled Votage Source (VCVS)

Current controlled current source (CCCS)

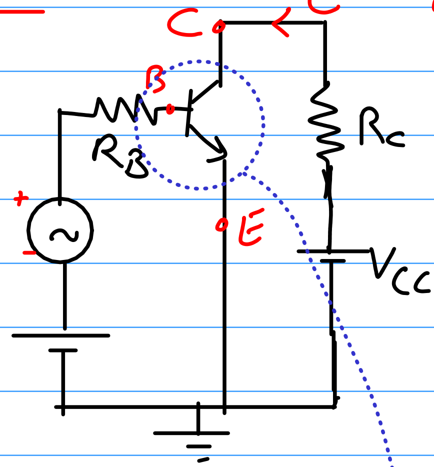
Voltage controlled current source (VCCS)

Current controlled voltage source (CCVS)

Small Signal Analysis:

(NPN) CE

$i_C = I_C + i_c$ → small signal o/p current



Small signal to be amplified ← v_s

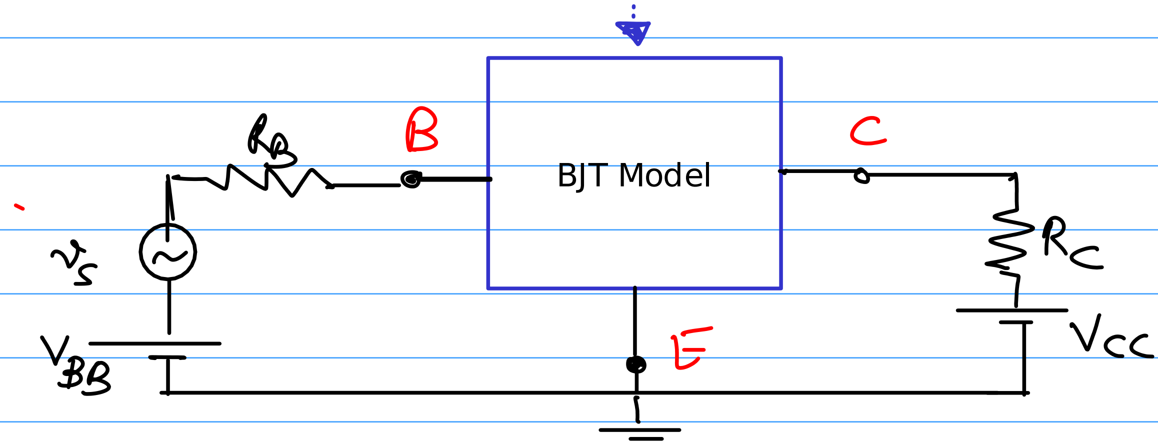
V_{BB} → Large DC bias vol.

$v_C = V_C + v_c$

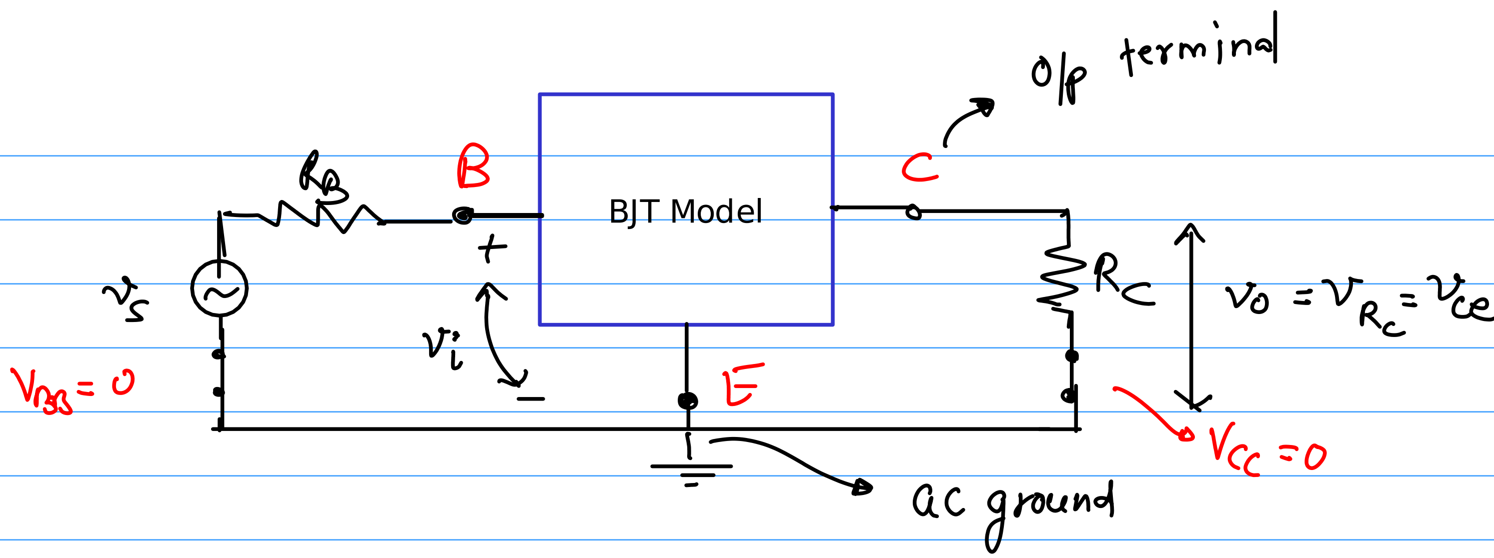
v_C → Total Collector vol

V_C → DC (bias vol.)

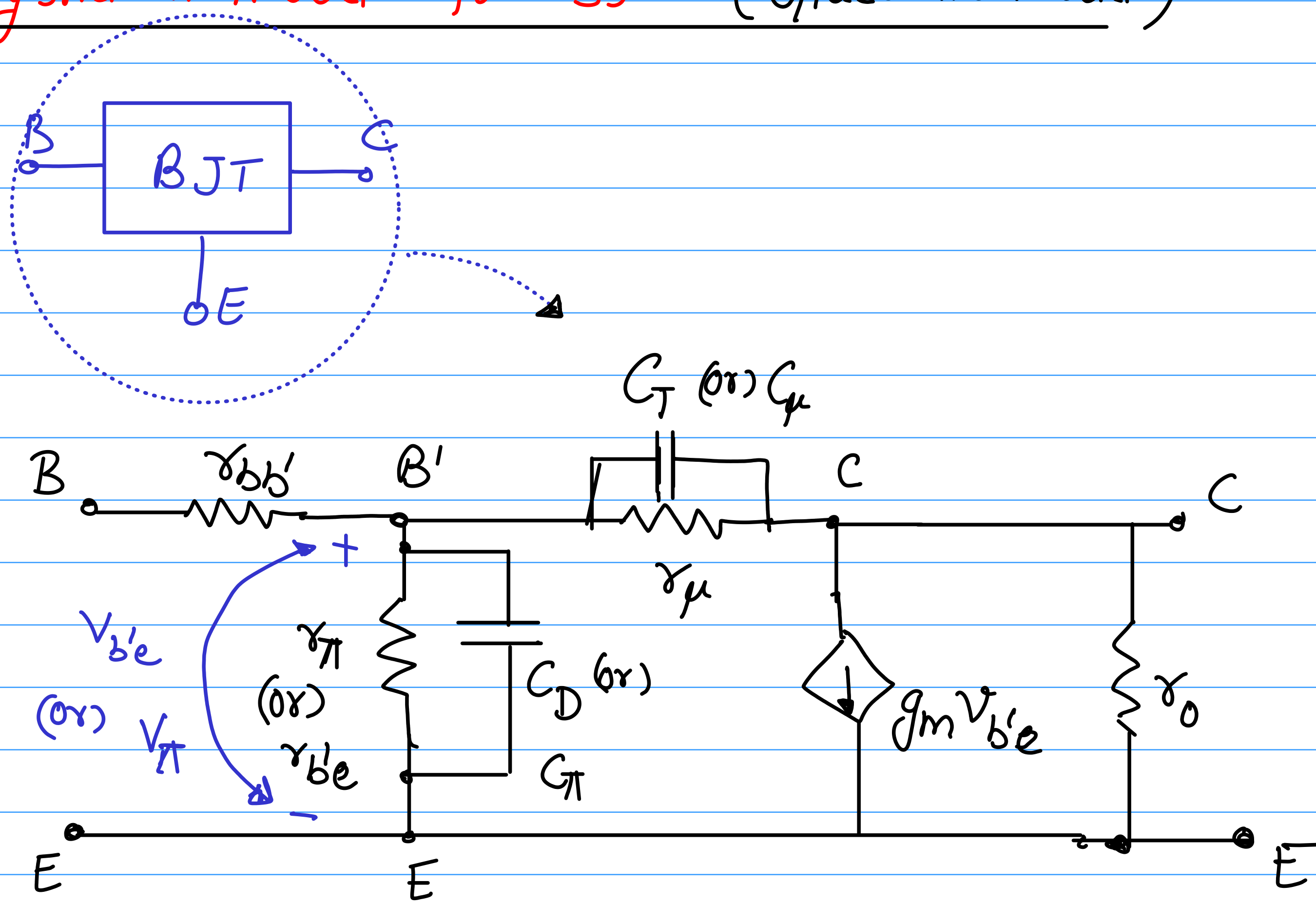
v_c → Small signal o/p vol.



* We want to see the effect of ac signal (small signal alone)
* Superposition principle says that effect of different sources can be studied individually (assuming other sources to be 0.
* So, VBB = 0, and Vcc = 0 can be assumed to see the effect of ac input signal Vs (assuming active mode biasing, which comes due to the DC voltages)



Hybrid-π model for BJT (Giacoletto model) :—



$r_{bb'}$ = Base spread resist. (~ 100 Ω)

r_π or $r_{b'e}$ = B-E f.b. j^n resistance ($\sim 1k\Omega$)

depends on dc operating current (I_{CQ})

C_D = B.E f.b. j^n capacitance (Diffusion cap)

r_μ = C-B R.B. j^n resistance (v. high)

C_T or C_μ = C.B R/B j^n capacitance (Transition cap)

g_m = Transconductance of BJT

also depends on DC operating point

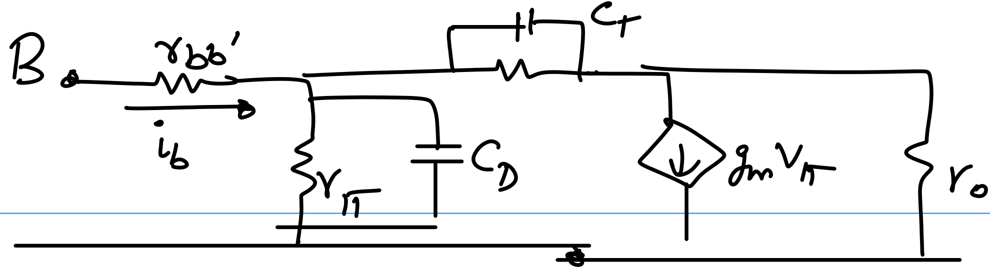
$$\boxed{g_m = \frac{|I_{CQ}|}{V_T}}$$

$$V_T = \frac{T}{11,600}$$ T → (in K)

$\simeq$ 26 mV at 300 K

r_o = o/p resistance. Models the early effect

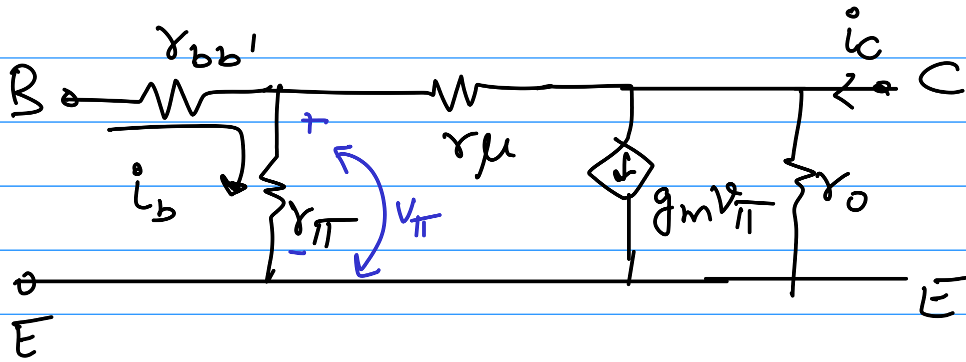
$$\boxed{r_o = \frac{V_A}{|I_{C\text{-}sat}|}}$$



if freq. is low (close to DC)

[Cap acts as O.C for DC & almost O.C. for low freq.]

So, Low freq. small signal model – [$C_D, C_T \equiv$ O.C]

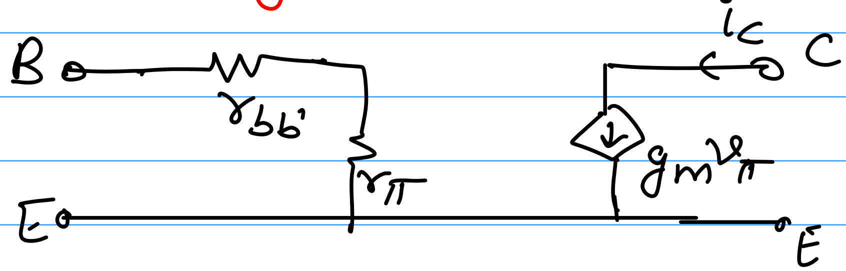


$v_\pi = i_b r_\pi$ if r_o is ignored (v.v high ~ O.C.)

(neglig. early effect)

Also since r_μ = v.v. high ~ O.C.

Simplified hybrid-π model –



$i_c = g_m v_\pi$

$v_\pi = i_b r_\pi$

$i_c = g_m i_b r_\pi$

$$g_m r_\pi = \frac{i_c}{i_b} = \beta \quad \text{(active mode)}$$

$$\boxed{g_m r_\pi = \beta}$$

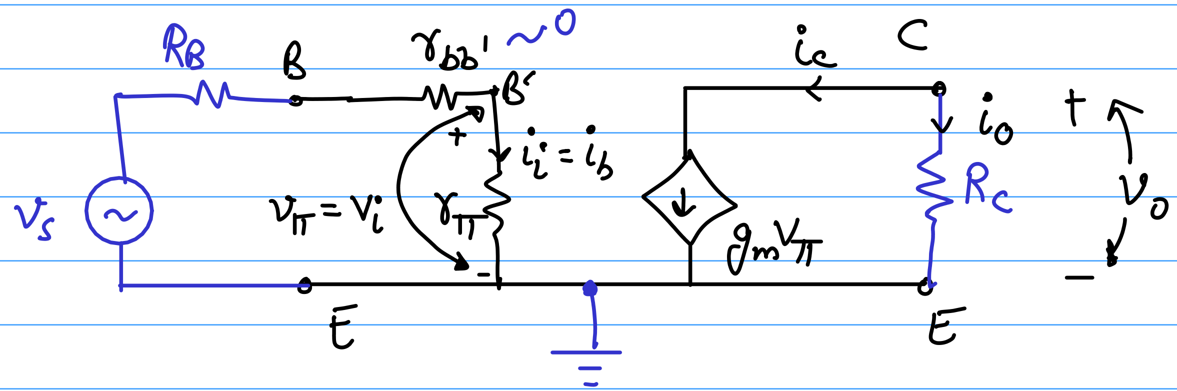
$$g_m = \frac{|I_{CQ}|}{V_T}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{\beta}{|I_{CQ}|} \cdot V_T$$

$$\boxed{r_\pi = \frac{V_T}{|I_{BQ}|}}$$

Using the low freq. Small Signal hybrid-π model —

CE Amplifier —



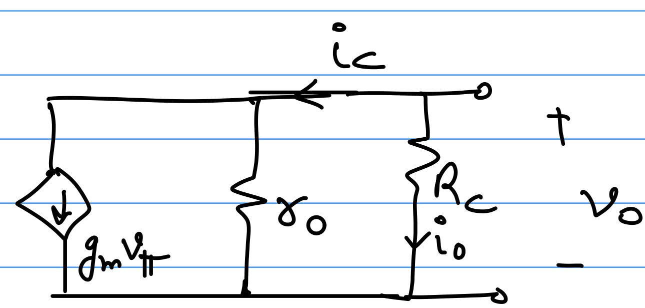
Current Gain (A_i) —

$$A_i = \frac{i_o}{i_i} = \frac{-i_c}{i_b} = -\beta$$

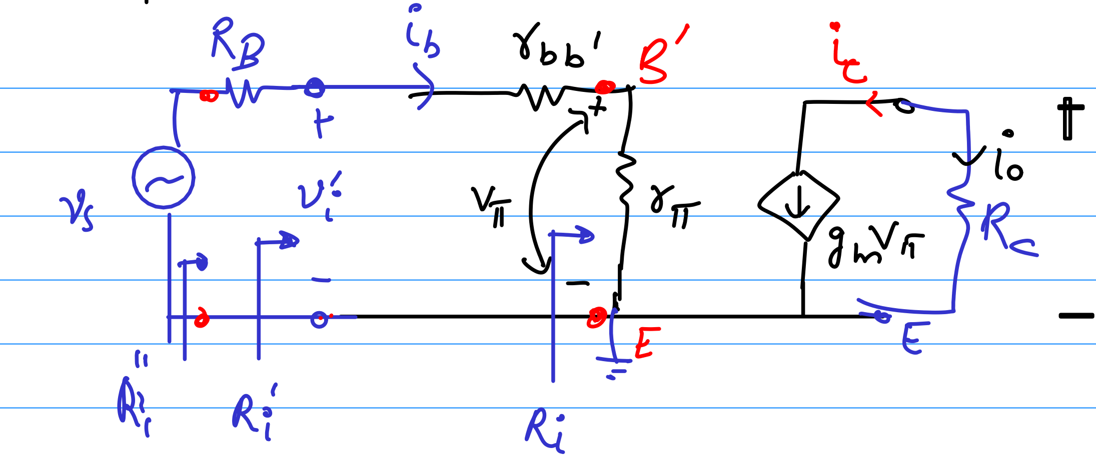
$i_o = -i_c$

$i_i = i_b$

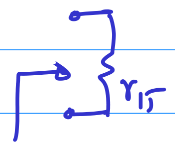
$A_i = -\beta$



→ Input Resistance (R_i) –



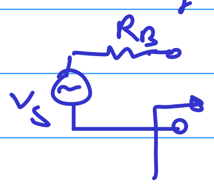
$v_o = i_o R_C = -i_c R_C$



$R_i = \frac{v_\pi (= V_i)}{i_i} = r_\pi$

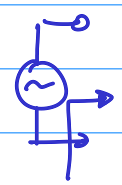
$R_i' = \frac{v_i'}{i_i} = \frac{v_i'}{i_b} = r_\pi + r_{bb'}$

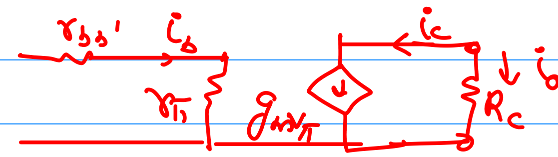
seen by



$R_i'' = R_B + r_{bb'} + r_\pi$

Seen by v_s





→ Voltage Gain –

$(A_v) = \frac{v_o}{v_i} = \frac{i_o R_c}{i_b r_\pi} = \frac{-i_c R_c}{i_b r_\pi}$

$v_o = -i_c R_C$

$\quad = -g_m V_\pi R_c$

$v_i = v_\pi$

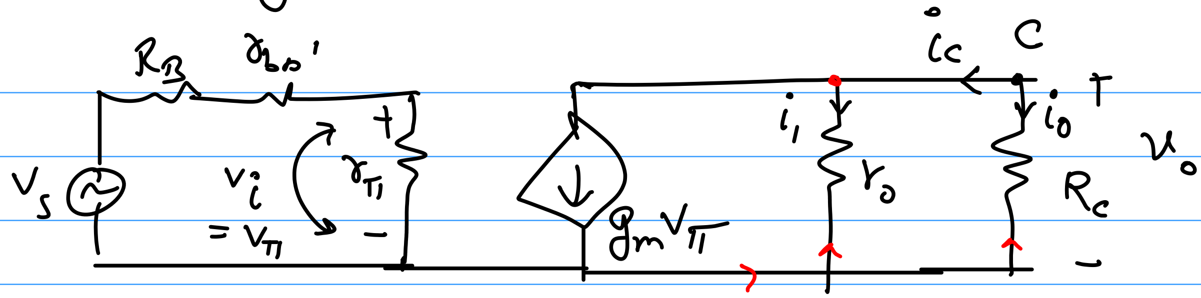
So, $A_v = \frac{-g_m \cancel{V_\pi} R_c}{\cancel{V_\pi}}$

$\quad = -g_m R_c$

$$\boxed{A_v = -\beta \frac{R_c}{r_\pi}} \Rightarrow \boxed{A_v = -g_m R_c}$$

$\because g_m = \beta / r_\pi$

If early effect is significant



$$A_v = \frac{v_o}{v_i} = ?$$

$$i_1 = \frac{v_o}{r_o} \quad \text{(Ohm's law)}$$

$$v_o = i_o R_c = -i_c R_c$$

$$i_c = g_m V_\pi + i_1$$

$$i_c = g_m V_\pi + \frac{v_o}{r_o}$$

$$v_o = -\left[g_m V_\pi + \frac{v_o}{r_o}\right] R_c$$

$$v_o\left[1 + \frac{R_c}{r_o}\right] = -g_m V_\pi R_c \Rightarrow v_o = \frac{-g_m V_\pi (R_c r_o)}{(r_o + R_c)}$$

$$R_c \| r_o = \frac{R_c r_o}{R_c + r_o}$$

$$v_o = -g_m v_\pi \left[R_c \| r_o\right]$$

$$v_i = v_\pi$$

$$\text{So,} \quad A_v = \frac{v_o}{v_i} = \frac{-g_m \cancel{v_\pi} \left[R_c \| r_o\right]}{\cancel{v_\pi}}$$

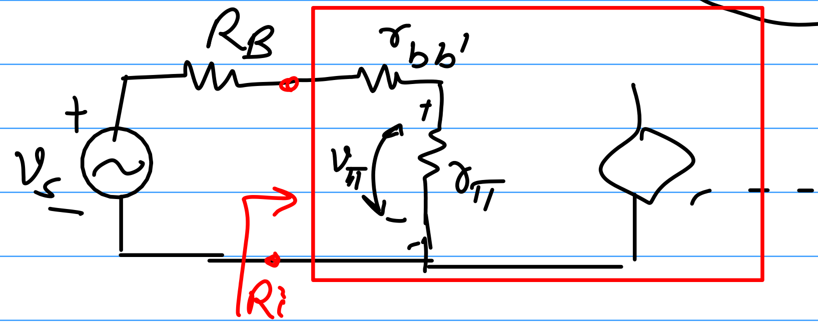
$$\boxed{A_v = -g_m \left[R_c \| r_o\right]} = -g_m\left(\frac{R_c r_o}{R_c + r_o}\right)$$

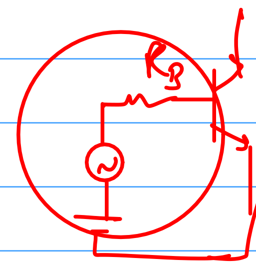
A_v has reduced due to early effect ($\because (R_c \| r_o) < R_c$)

→ Overall vol. gain − $A_{vs} = \dfrac{v_o}{v_s}$

A_v (internal vol. gain)

$$\underline{A_{vs}} = \frac{v_o}{v_i} \times \frac{v_i}{v_s} = \frac{v_o}{v_\pi} \times \frac{v_\pi}{v_s}$$





* Vi is only a fraction of the source Vs

$$v_\pi = v_i = \left[\frac{r_\pi}{(R_B + r_{bb'} + r_\pi)}\right] \times v_s \Rightarrow \frac{v_\pi}{v_s} = \frac{r_\pi}{(R_B + r_{bb'} + r_\pi)}$$

if $\boxed{R_i = r_{bb'} + r_\pi}$ → i/p resistance seen between B & E terminal

$$\frac{v_\pi}{v_s} = \frac{r_\pi}{R_B + R_i}$$

if $r_{bb'} << r_\pi$

$$\boxed{R_i \simeq r_\pi}$$

$$\boxed{\frac{v_\pi}{v_s} \simeq \frac{R_i}{R_B + R_i}}$$

Shivam **

Sahil 389
Shashank 421 **

$$A_{vs} = \frac{v_o}{v_\pi} \times \frac{v_\pi}{v_s} = A_v \times \frac{v_\pi}{v_s}$$

$$\boxed{A_{vs} = -g_m (R_c \| r_o) \times \frac{R_i}{R_B + R_i}}$$

To get highest A_{vs} $\left(A_{vs} = A_v\right)$

$$\frac{R_i}{R_B + R_i} \simeq 1$$

So, $\boxed{R_i >> R_B}$ is desirable

$R_i \simeq 1k\Omega$ for CE

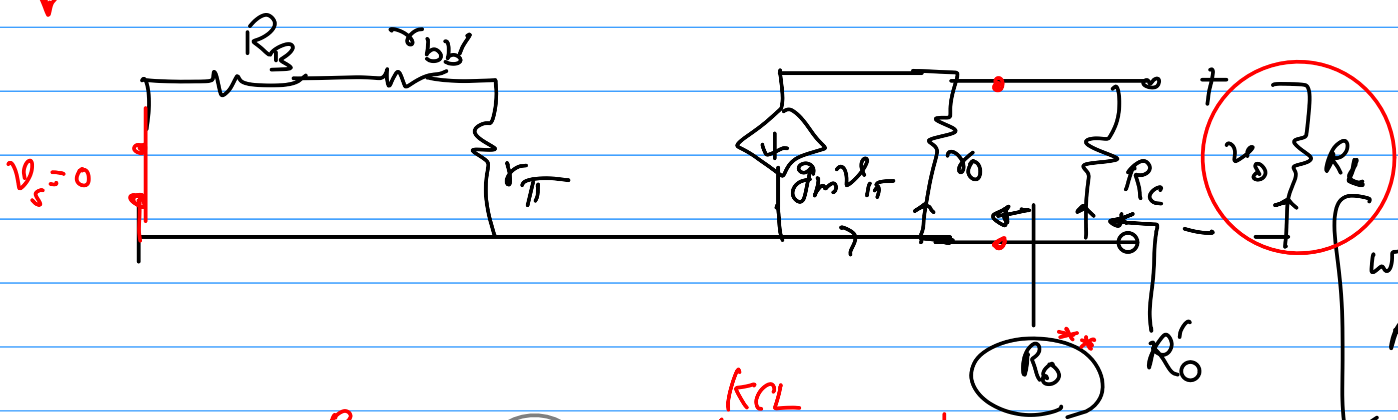
* So, R_B should be small

Sarthak 379 ***

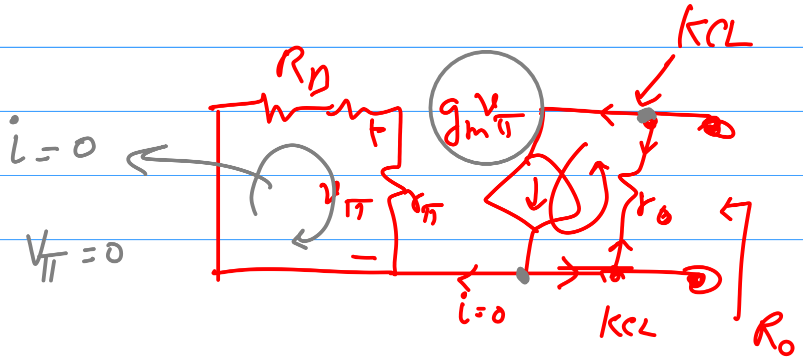
but if R_B is too small,
BJT saturates → not an amplifier.

→ Output resistance R_o →

Steps:
1. Remove the load if any
2. Remove all sources. i.e. all voltage sources (independent) to be short circuited and all current sources (independent) should be open circuited
3. Find the equivalent (net) resistance between the output terminals $= R_o$

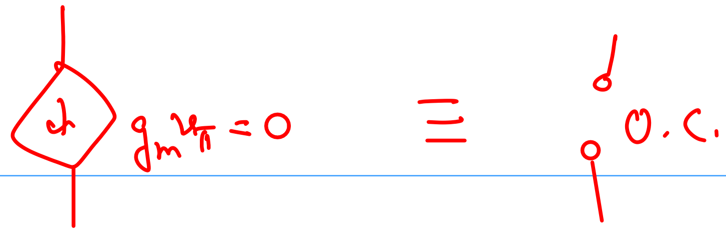


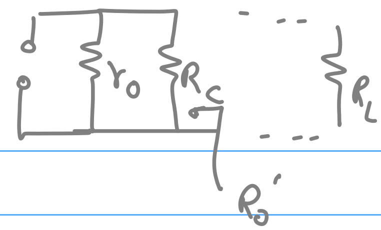
which means R_C is load



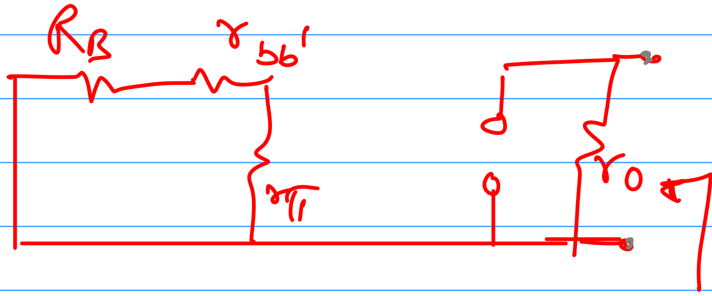
$v_\pi = 0$ $\left[\because v_s = 0\right]$

$g_m v_\pi = 0$





$R_o' = R_C \| r_o$



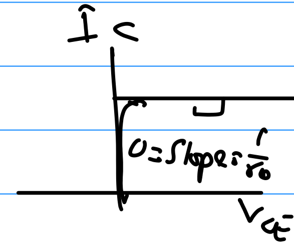
$R_o = r_o \| \infty = r_o$

** Subject 18

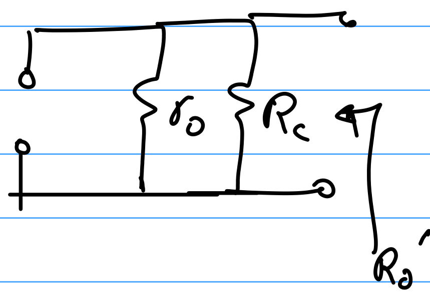
$$\boxed{R_o = r_o}$$ ** (if R_C is the load)

if early effect is negligible, $r_o \to \infty$

$$\boxed{R_o \to \infty}$$



R_o' –



$$\boxed{R_o' = r_o \| R_C}$$

* Ro should be as high as possible so that entire curent gmVi can go to the load

→ Power Gain –

$$\boxed{A_p = A_i \cdot A_v} = (-\beta)(-g_m R_C)$$ neglecting early effect

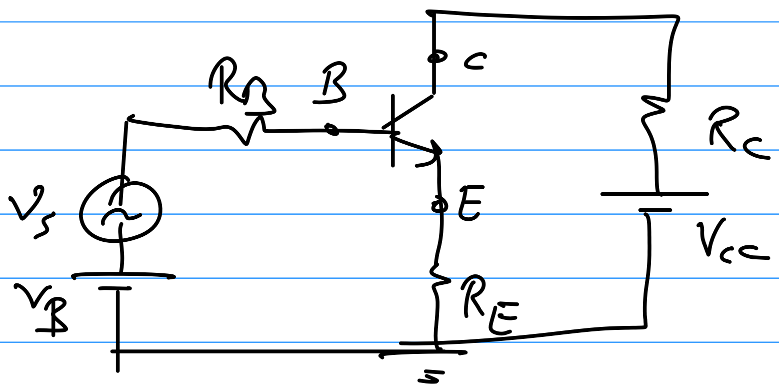
$A_p = \frac{v_o}{v_i} \cdot \frac{i_o}{i_i} = A_v A_i$

$A_p = + \frac{\beta^2 R_C}{r_\pi} = \beta^2 \left(\frac{R_C}{r_\pi}\right)$

$$\boxed{A_p \propto \beta^2}$$

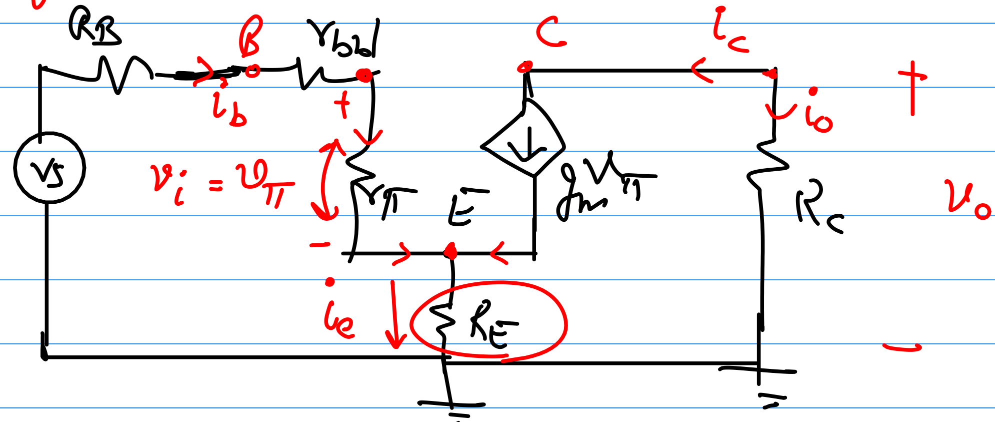
So, highest power gain in C.E.

CE with Emitter resistance (Self-biasing) :



Small signal equivalent ckt ↴

(ignoring early effect)



$$i_o = -i_c = -g_m v_\pi \qquad i_e = i_b + i_c$$

(KCL at E)

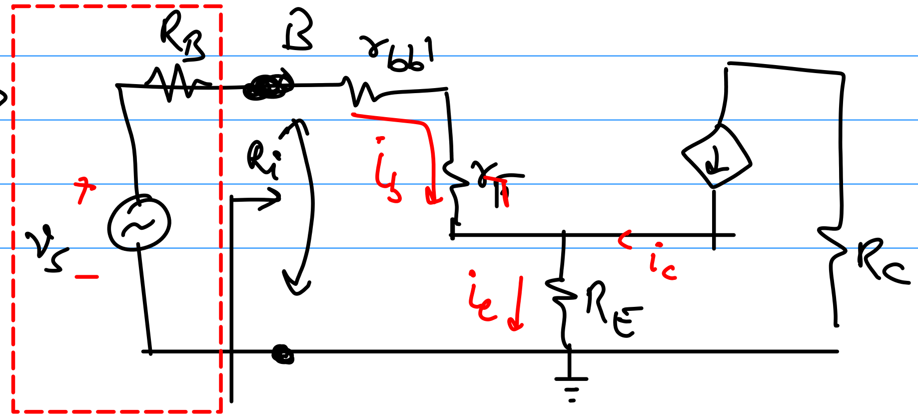
→ Current Gain — $A_i = \frac{i_o}{i_i} = \frac{-i_c}{i_b} = \frac{-g_m v_\pi}{v_\pi / r_\pi} = -g_m r_\pi = -\beta$

$$\boxed{A_i \simeq -\beta}$$

(Same as before (without R_E))

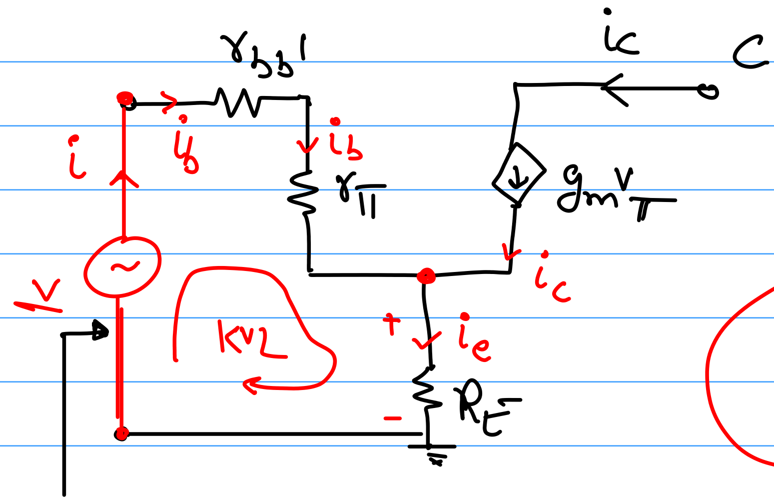
* Re resistance does not affect the current gain

→ R_i →



HW

? $R_i = \underline{r_{bb'}} + \underline{r_{\pi}} + \underline{(\quad\quad) R_E}$



$$R_i = \frac{v}{i_b}$$

$R_i = \frac{v}{i}$

$$v - i_b r_{bb'} - i_b r_{\pi} - i_e R_E = 0$$

$$i_e = i_c + i_b = \beta i_b + i_b$$

$$\boxed{i_e = (1+\beta)\, i_b}$$

$$v - i_b r_{bb'} - i_b r_{\pi} - (1+\beta)\, i_b R_E = 0$$

$$v = i_b \left(r_{bb'} + r_{\pi} + (1+\beta) R_E \right)$$

$$\frac{v}{i_b} = \boxed{R_i = r_{bb'} + r_{\pi} + (1+\beta)\, R_E} \; **$$

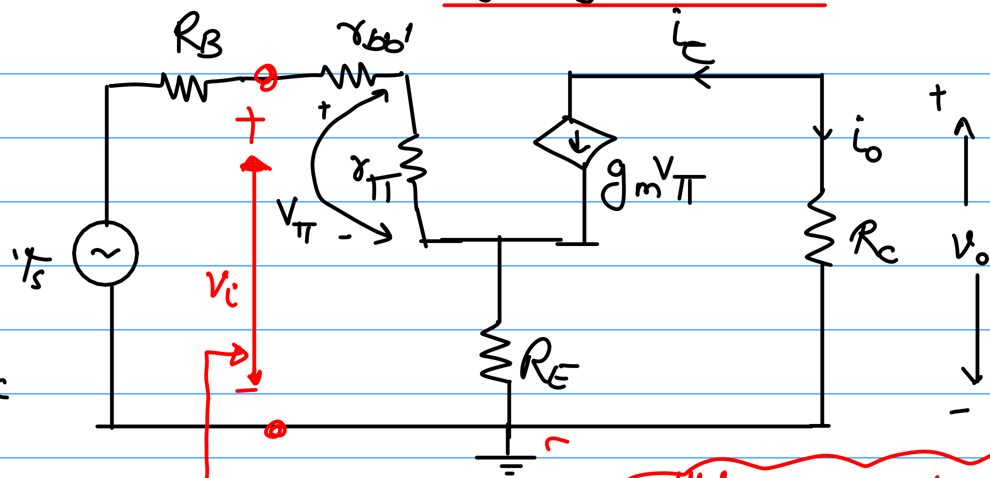
if $R_E = 0 \Rightarrow R_i = r_{bb'} + r_{\pi}$

* Using R_E has increased R_i by $(1+\beta) R_E$

(Neglecting Early Effect)

→ Voltage Gain –

(internal gain)



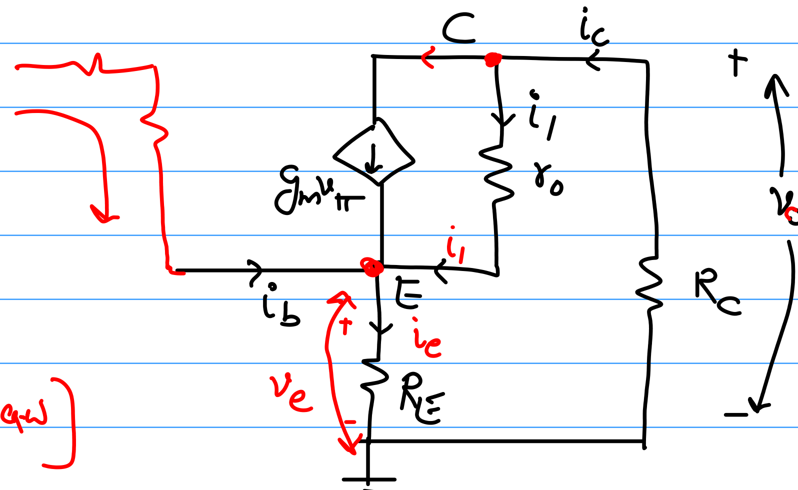
$$\boxed{A_v = \frac{v_o}{v_\pi}}$$

$$v_o = -i_c R_c = -g_m v_\pi R_c$$

$$A_v = \frac{-g_m v_\pi R_c}{v_\pi} \Rightarrow \boxed{A_v = -g_m R_c}$$

HW $A_v = \frac{v_o}{v_i} = ?$

→ Including r_o :



$$v_o = -i_c R_c$$

$$i_c = g_m v_\pi + i_1$$

$$i_1 = \frac{v_{ce}}{r_o} \quad \text{(ohm's law)}$$

$$v_{ce} = v_o - v_e \quad (= v_c - v_e = v_o - v_e) \quad (v_c = v_o)$$

$$v_e = i_e R_E \cong i_c R_E \quad [i_e = i_c + i_b \simeq i_c] \quad \text{(assuming high } \beta\text{)}$$

$$\text{So,} \quad v_{ce} = v_o - (i_c) R_E \quad \Rightarrow i_c = g_m v_\pi + \frac{1}{r_o}\left[v_o - i_c R_E\right]$$

$$i_c\left[1 + \frac{R_E}{r_o}\right] = g_m v_\pi + \frac{v_o}{r_o}$$

$$i_c = \left(\frac{r_o}{r_o + R_E}\right)\left[g_m v_\pi + \frac{v_o}{r_o}\right] \qquad v_o = -i_c R_c$$

$$v_o = -\frac{r_o}{r_o+R_E}\left[g_m v_\pi + \frac{v_o}{r_o}\right] R_c$$

$$v_o\left[1+\frac{R_c}{r_o+R_E}\right] = -g_m v_\pi\left(\frac{r_o}{r_o+R_E}\right)R_c$$

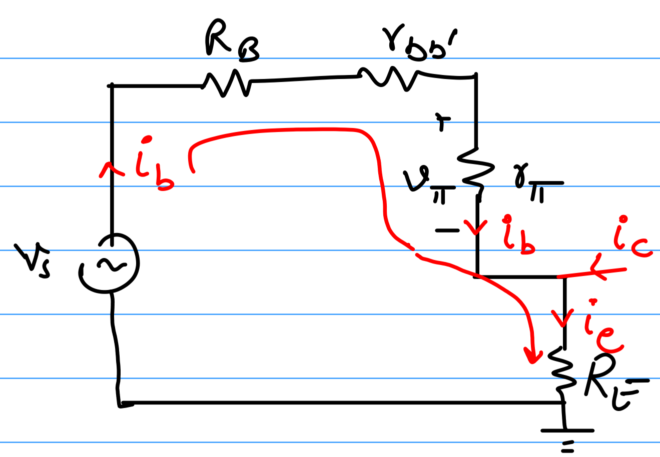
$$A_v = \frac{v_o}{v_\pi} = \frac{-g_m\left(\frac{r_o}{r_o+R_E}\right)R_c}{r_o+R_E+R_c} \times (r_o+R_E)$$

** $$\boxed{A_v = -\frac{g_m r_o R_c}{r_o+R_c+R_E}}$$

CE without R_E, $A_v = -g_m\left(\frac{r_o R_c}{r_o+R_c}\right)$

* R_E provides −ve feedback which reduces the voltage gain.

→ Overall voltage Gain — $A_{vs} = A_v \times \frac{v_\pi}{v_s}$



$i_e = i_c + i_b$
$= \beta i_b + i_b$
$= (1+\beta) i_b$

$$v_s - i_b R_B - i_b r_{bb'} - i_b r_\pi - (1+\beta) i_b R_E = 0$$

$$\Rightarrow i_b = \frac{v_s}{R_B + r_{bb'} + r_\pi + (1+\beta)R_E}$$

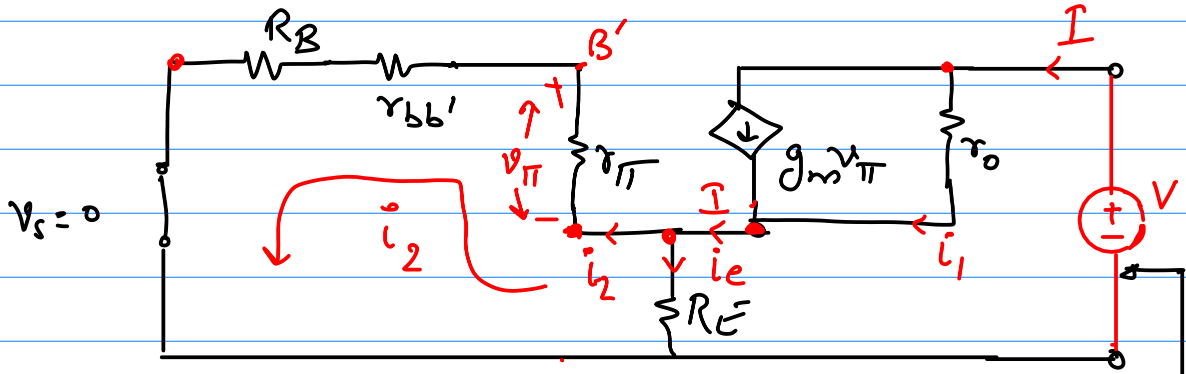
$$v_\pi = i_b r_\pi \Rightarrow v_\pi = \frac{v_s\, r_\pi}{R_B + r_{bb'} + r_\pi + (1+\beta)R_E}$$

$$\Rightarrow \boxed{\frac{v_\pi}{v_s} = \frac{r_\pi}{R_B + r_{bb'} + r_\pi + (1+\beta)R_E}}$$

$$\Rightarrow \boxed{A_{vs} = \underbrace{\overbrace{-g_m R_c}^{A_v}}\left[\frac{r_\pi}{R_B + \underbrace{r_{bb'} + r_\pi + (1+\beta)R_E}_{R_i}}\right]} \qquad \boxed{= \frac{-g_m R_c\, r_\pi}{R_B + R_i}}$$

* A_{vs} has reduced due to use of R_E resistance. [-ve feedback]

→ Output Resistance R_o :



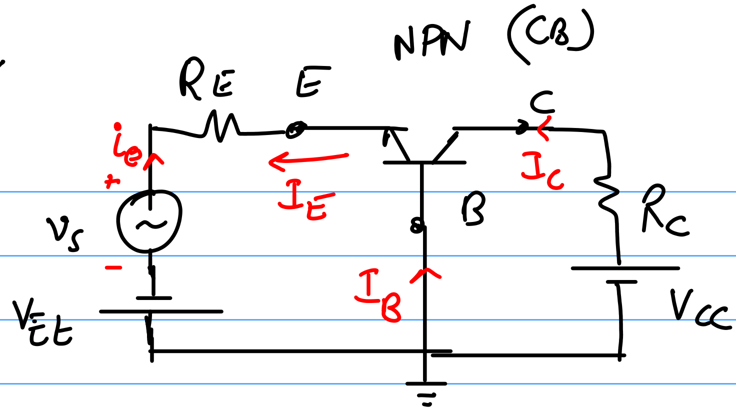
$$R_o = \frac{V}{I}.$$

$$V = f\ (I)$$

HW find $R_o = \frac{V}{I}$

(first ignore r_o, find R_o,
then solve with r_o)

→ CB amplifier :

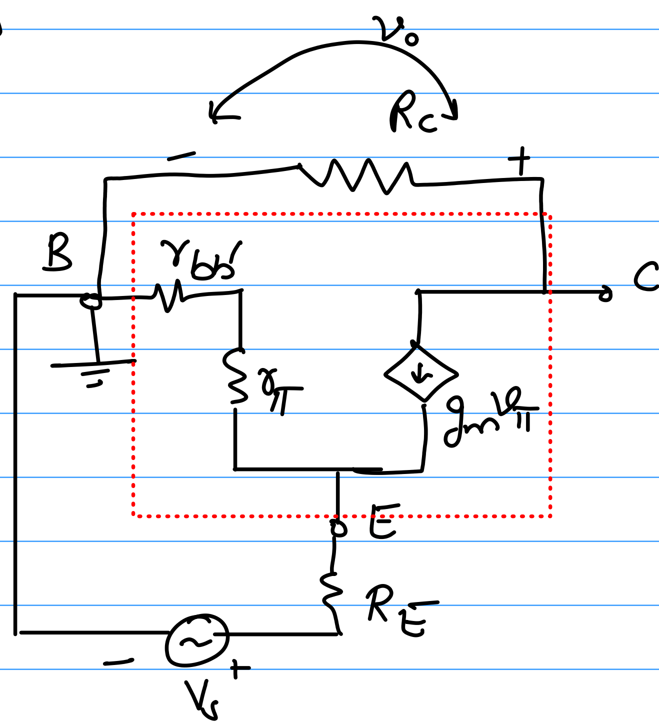


Small signal equivalent –

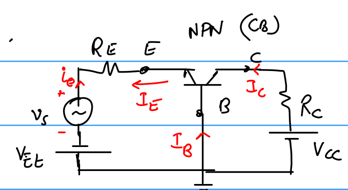
1) first draw small signal model of BJT alone

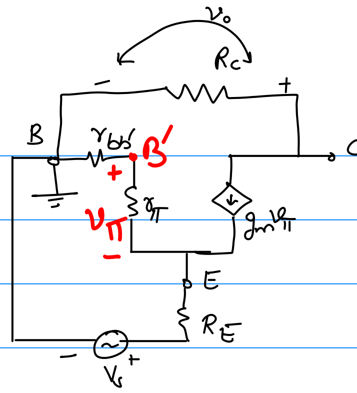
1.2) Name all the terminals

2) Then connect external components in appropriate places



ignoring early effect





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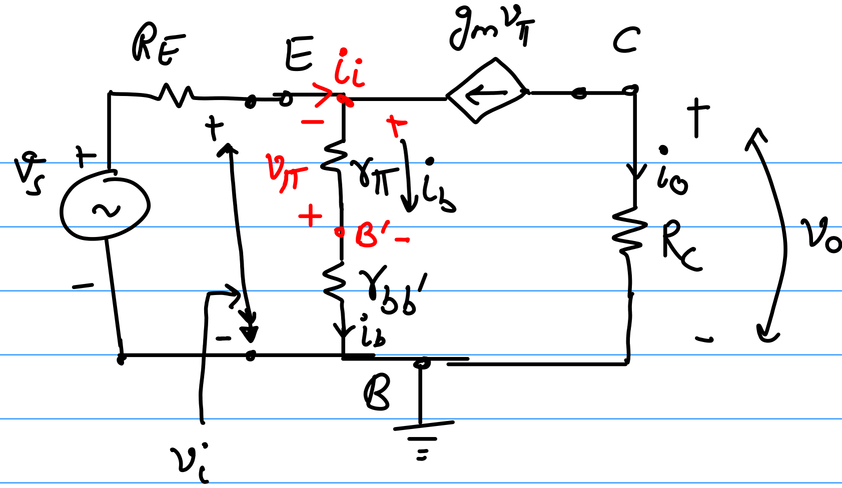


$$\boxed{R_i = \frac{v_i}{i_i}} \rightarrow \quad \text{KVL} - \quad +v_i + v_\pi - i_b r_{bb'} = 0$$

$$v_\pi = -i_b r_\pi \quad , \quad \text{by KCL,} \quad i_b = i_i + g_m v_\pi$$

KVL

$$i_b = i_i + g_m(-i_b r_\pi)$$

$$i_i = i_b[1 + g_m r_\pi]$$

$$\boxed{i_b = \frac{i_i}{1 + g_m r_\pi}}$$

$$v_i + \left(\frac{-i_i}{1+g_m r_\pi}\right) r_\pi - \left(\frac{i_i}{1+g_m r_\pi}\right) r_{bb'} = 0$$

$$v_i = i_i \left[\frac{r_\pi}{1+g_m r_\pi} + \frac{r_{bb'}}{1+g_m r_\pi}\right]$$

$$** \quad \boxed{R_i = \frac{v_i}{i_i} = \frac{r_\pi + r_{bb'}}{1 + g_m r_\pi}}$$

Comparing with CE R_i

$= r_\pi + r_{bb'}$

$$\underset{(CB)}{R_i} < \underset{(CE)}{R_i}$$

AI

→ Current Gain A_i :

$$A_i = \frac{i_o}{i_i}$$

$$i_o = -g_m v_\pi$$

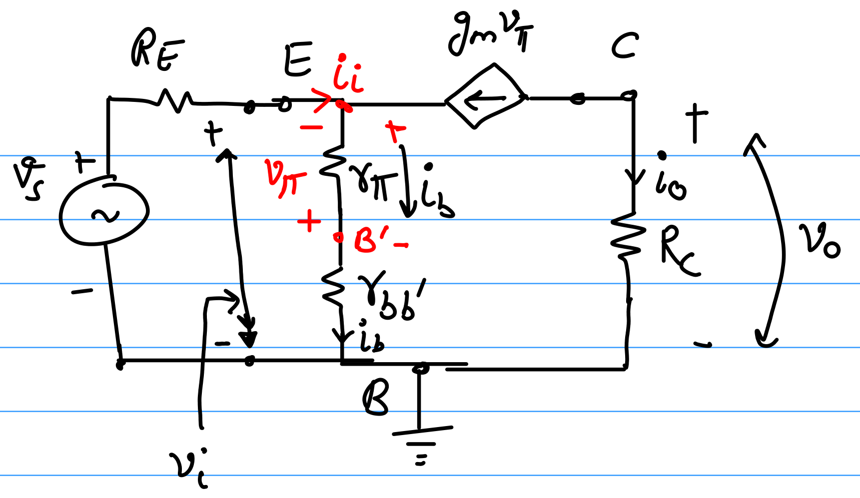
$$i_i = ?$$

$$i_i + g_m v_\pi = i_b$$

$$v_\pi = -i_b r_\pi$$

$$i_i = i_b\left[1 + g_m r_\pi\right]$$

$$= -v_\pi\left[\frac{1+g_m r_\pi}{r_\pi}\right]$$



$$A_i = \frac{+g_m \cancel{v_\pi}}{+\cancel{v_\pi}\left[\frac{1+g_m r_\pi}{r_\pi}\right]}$$

$$\boxed{A_i = \frac{g_m r_\pi}{1+g_m r_\pi} = \frac{\beta}{1+\beta} = \alpha}$$