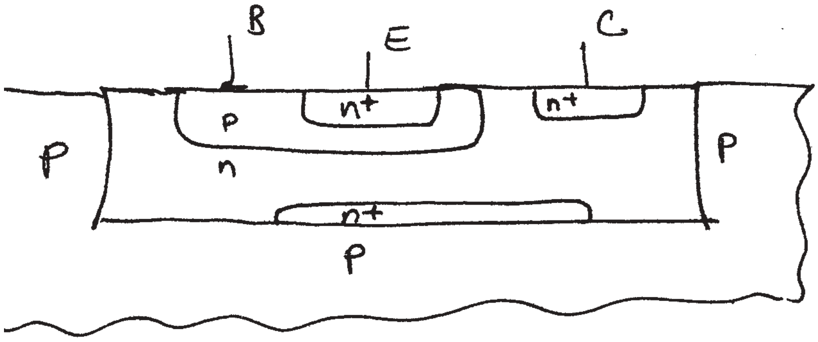
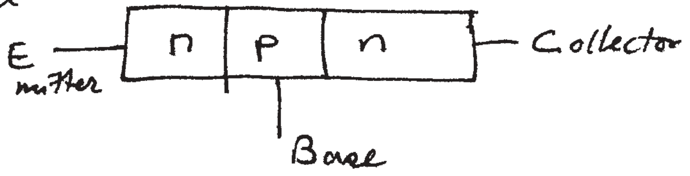
CHAPTER 4 — BIPOLAR JUNCTION TRANSISTORS

Physical structure **NPN** planar double diffused transistor



Text book model



Base region is very thin — the width is less than the diffusion length of minority carriers.

Transistor action: BE junction is fwd biased

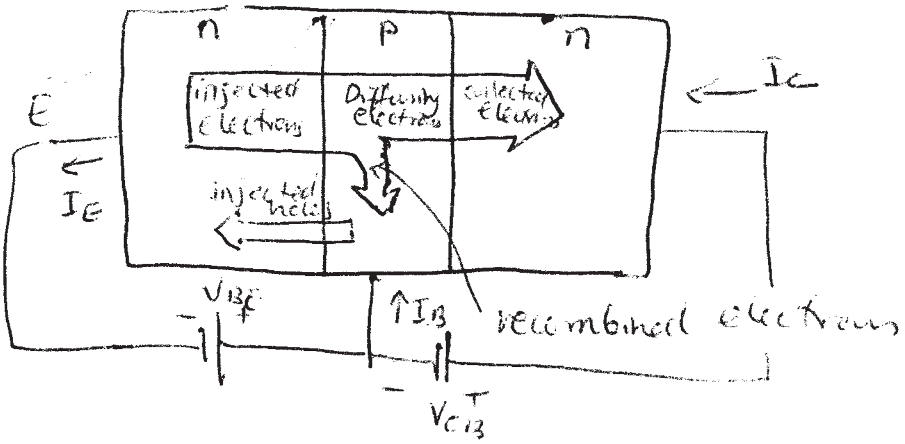
⇒ injection of holes into the emitter (from base)

" " electrons into the base (from the emitter)

BC junction is reverse biased.

⇒ high electric field in the depletion region.

Thin base → carriers injected in to the base move to the collector side in no time → carriers get collected by the collector.



The collector current:

$$i_C = I_S e^{v_{BE}/V_T}$$

I_S: current scale factor

Base current: $i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{BE}/V_T}$ β = common emitter current gain

100 – 200 even higher

Emitter current $i_E = i_C + i_B$

$$= i_C + \frac{i_C}{\beta} = i_C \left(1 + \frac{1}{\beta}\right) = i_C \frac{(\beta+1)}{\beta}$$

$$i_C = \alpha i_E = \frac{\beta}{\beta+1} i_E$$

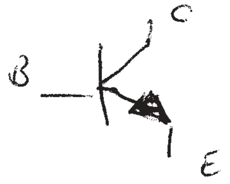
$\alpha = \frac{\beta}{\beta+1}$ = Common base current gain

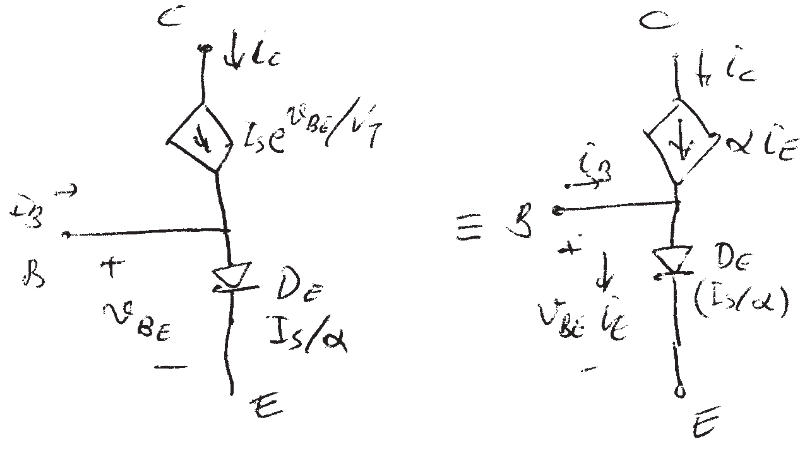
$$i_E = \left(\frac{I_S}{\alpha}\right) e^{v_{BE}/V_T}$$

Practical purposes $i_C \cong i_E$

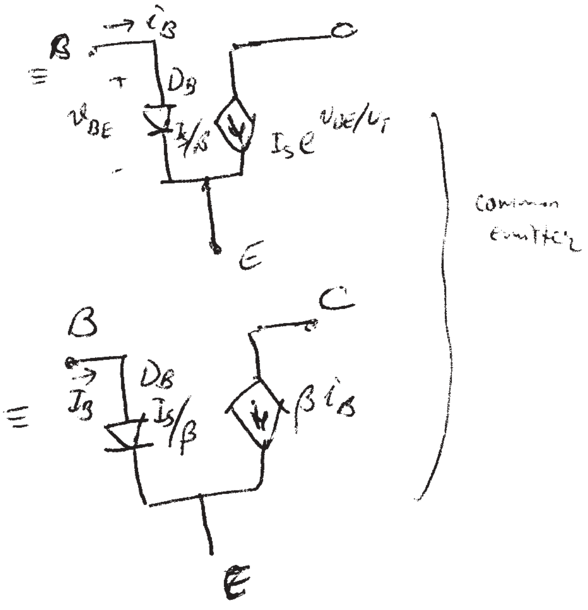
if $\beta \gg 100 \Rightarrow$ ignore base current

Equivalent circuit models:





common base

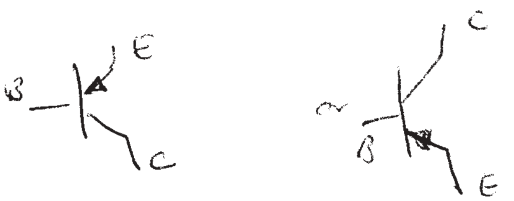


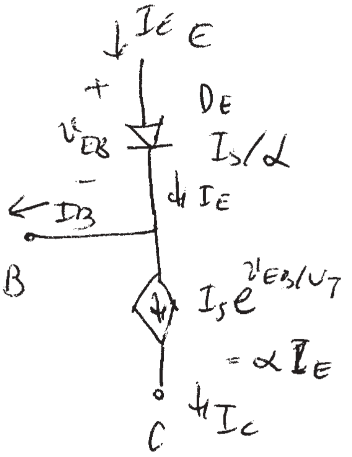
common emitter

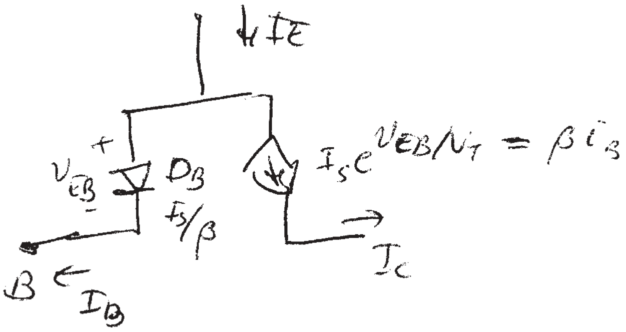
ideality factor ≃ 1

There is also I_{CBO} leakage current

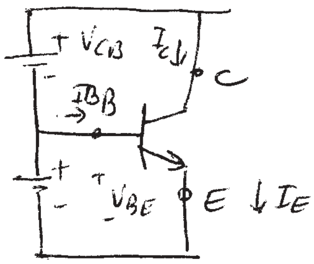
PNP Transistor



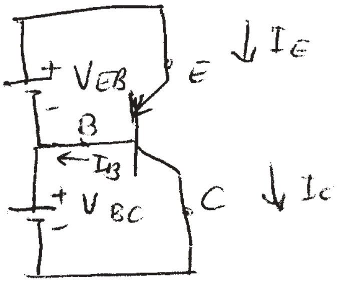




CONVENTIONS

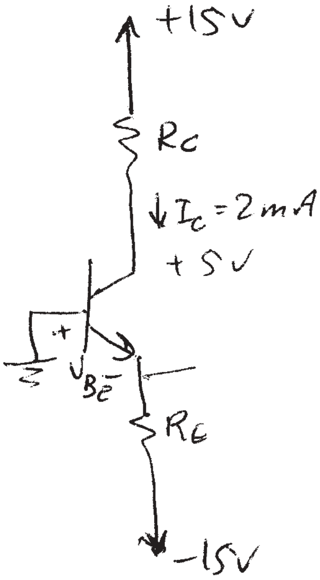


NPN



Practical approaches $|V_{BE}| \simeq 0.7V$ for silicon transistors.

(DESIGN EXAMPLE)



$V_{BE} = 0.7$ @ $I_c = 1mA$

find R_C and R_E to have $I_c = 2mA$
$V_c = 5V$

$\beta = 100$

$$V_{BE} = V_T \ln \frac{I}{I_s} = V_T (\ln I - \ln I_s)$$

$I_2 = 2 I_1 \Rightarrow$

$$V_{BE} = V_T (\ln 2I_1 - \ln I_s)$$
$$= \underset{=0.025\times}{V_T \ln 2} + \underbrace{V_T(\ln I_1 - \ln I_s)}_{0.7V}$$
$$= 0.717\ V.$$

$I_E = I_C + I_B = I_c + \frac{I_c}{100} = 2 + 0.02\ mA = 2.02mA.$

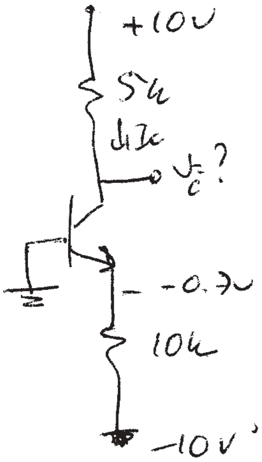
$$R_c = \frac{15-5}{2} = 5k\Omega \quad , R_E = \frac{-0.717-(-15)}{2.02} = 7.07k\Omega$$

Q.D.A quick + Dirty analysis

$I_c \simeq I_E$, $V_{BE} = 0.7V$ ⟹

$$R_C = \frac{15-5}{2} = 5k\Omega \quad , \quad R_E = \frac{-0.7-(-15)}{2} = \frac{14.3}{2} = \underline{\underline{7.15k\Omega}}$$

Example:



$I_B = ?$
$I_E = ?$
$I_c = ?$
$V_{CE} = ?$
$V_{BE} = 0.7V$
$\beta_F = 50$

$$I_E = \frac{-0.7-(-10)}{10k} = 0.93mA$$

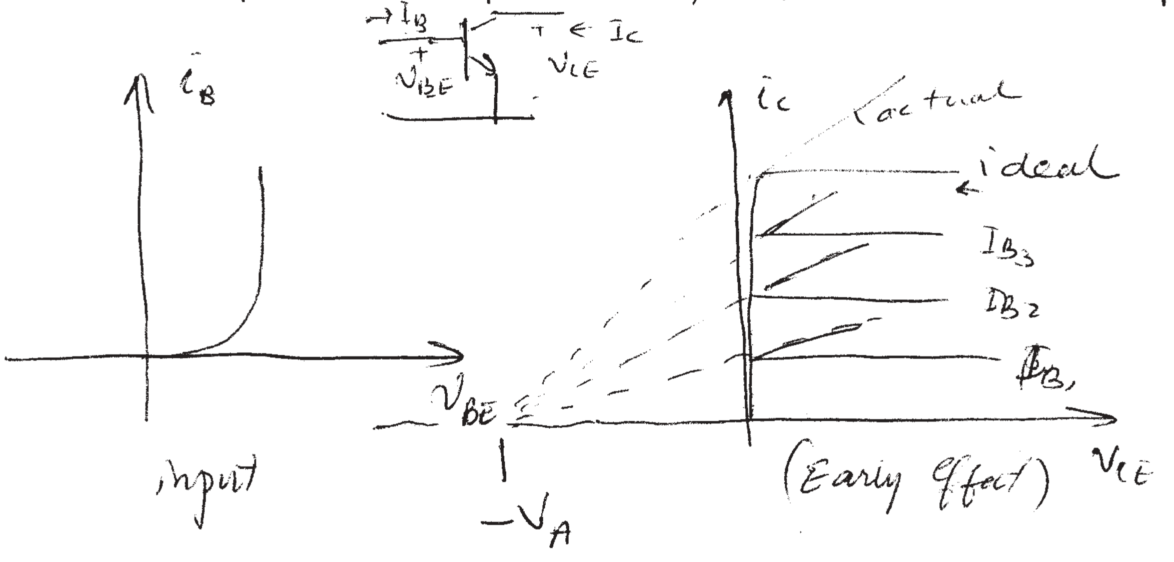
$$I_B = \frac{I_E}{\beta+1} = \frac{0.93}{51} \; mA.$$

$$I_c = \beta I_B = \frac{50}{51} \times 0.93 \; mA$$

$$V_c = 10 - I_c \times 5k = \quad V$$

$$V_{CE} = V_c - V_E = \quad -(-0.7) = \quad V$$

4.5 Graphical Representation of IV relationship



$$i_c = I_s e^{V_{BE}/V_T}\left(1+\frac{V_{CE}}{V_A}\right)$$ include the Early effect

Back to the modes of operation

(FWD) active mode $V_{BE} \simeq 0.7V$

β_F , α_F $V_{CE} > 0.2V$

Saturation mode

$$\left.\begin{array}{l} V_{BE} \simeq 0.7V \\ V_{BC} \simeq 0.7V \end{array}\right\} V_{CE} \simeq 0$$

if a $V_{CE} < 0$ is calculated for an NPN, ⇒ saturation mode.

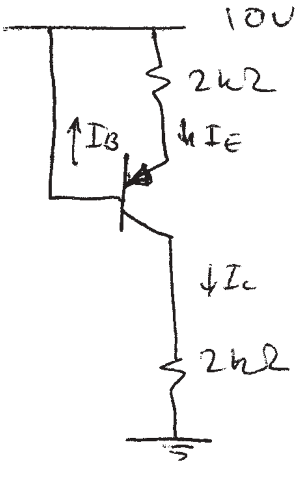
Cut off $V_{BE} < 0.5V$ (practical purposes)

Remove the transistor and measure the voltage that would be V_{BE}.

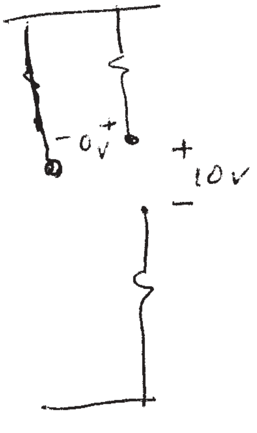
Reverse active (collector + Emitter interchanged)

$V_{BC} > 0$, $V_{BE} < 0$ → β_R α_R

Example w/ PNP



① remove the transistor

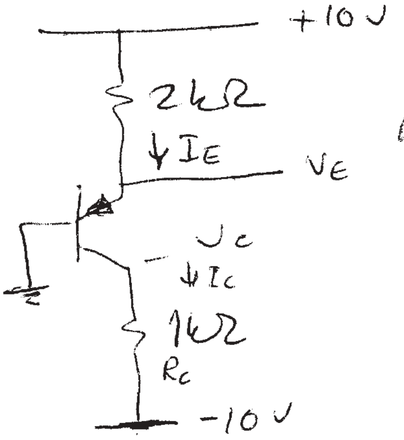


Cut-off.

$I_B \simeq 0$

$I_C \simeq 0$

$I_E \simeq 0$



$\beta >> 1$

$V_E = V_B + V_{EB} = 0+0.7 = 0.7V$

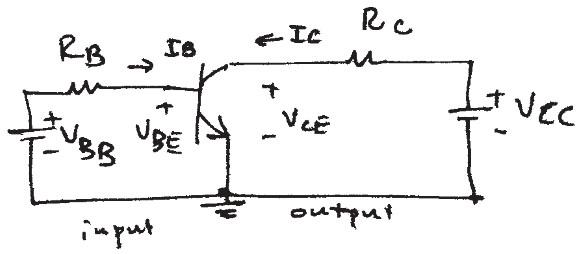
$I_E = \frac{10-0.7}{2} = \frac{9.3}{2} = 4.65 mA$

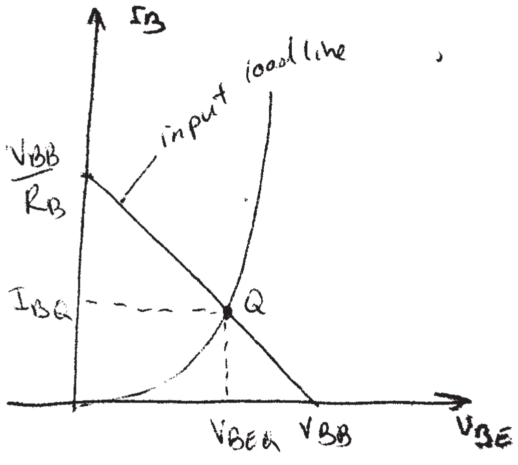
$I_C \cong I_E = 4.65 mA$

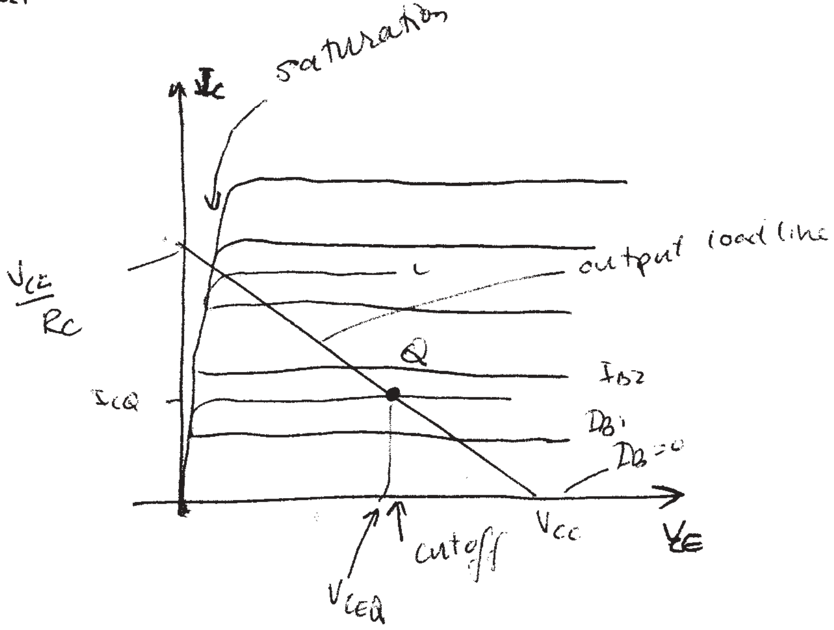
$V_C = I_C R_C + (-10) = 4.65-10 = -5.35 V$

Study examples 4.1, 4.2, 4.3, 4.4
4.5, 4.6, 4.7, 4.8

Graphical Determination of Currents







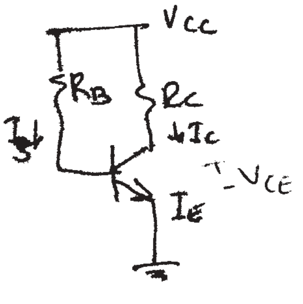
$I_B = \frac{V_{BB} - V_{BE}}{R_B}$

$I_C = \beta_F I_B$

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

—o—

Example



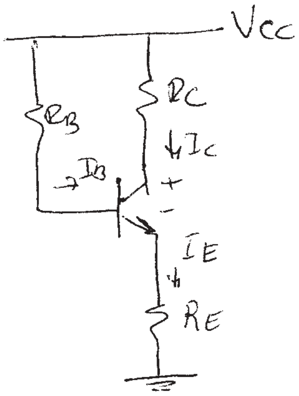
$I_C = \beta_F I_B$

$I_E = (\beta_F + 1) I_B$

$I_B = (V_{CC} - V_{BE})/R_B$

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

Example



Two voltage equations can be written

$$I_E R_E + V_{BE} + I_B R_B = V_{CC}$$

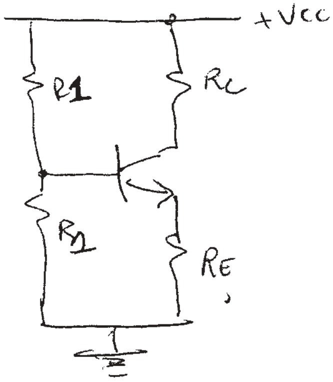
$$I_E = (\beta_F + 1) I_B$$

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

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

$$I_C = \beta_F I_C \quad , \quad V_{CE} = V_{CC} - I_C R_C - I_E R_E$$

Example:



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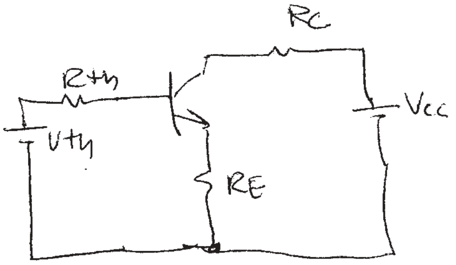
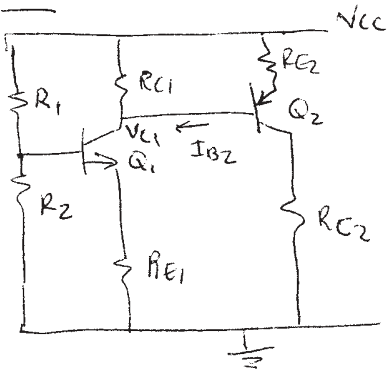


$$V_{Th} = V_{CC} \frac{R_2}{R_1 + R_2} \qquad R_{th} = R_1 \| R_2$$

$$I_B = \frac{V_{Th} - V_{BE}}{R_{th} + (\beta + 1) R_E} \qquad I_C = \beta I_B \qquad V_{CE} = V_{CC} - I_C R_C - I_E R_E$$

Example:



① ignore the effect of I_{B2}

② calculate V_{C1}

③ Determine I_{E2}

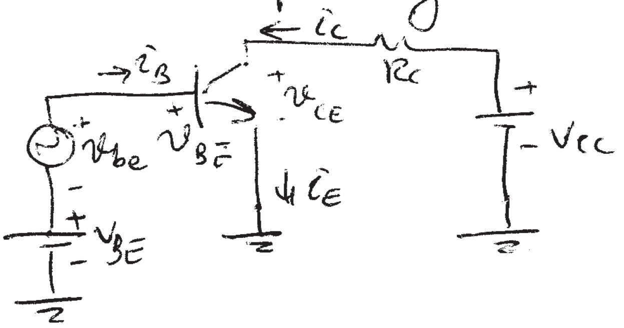
④ find I_{B2}

⑤ recalculate V_{C1}

see example 4.8

The Transistor as an amplifier

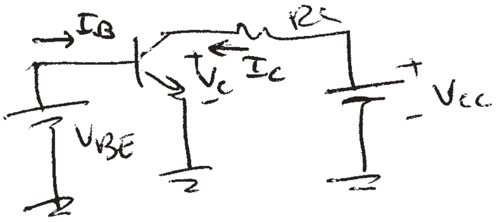
Consider the following ckt:



$|v_{be}| \ll |V_{BE}|$

"small signal"

The DC equivalent



$I_C = I_S e^{V_{BE}/V_T}$

$I_E = I_C/\alpha$

$I_B = I_C/\beta$

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

$V_{BE} > 0 \longrightarrow$ (active mode) $V_{CE} > V_{CESAT}$

Signal is applied $\rightarrow$ $v_{BE} = \underset{\substack{\uparrow \\ \text{signal}}}{v_{be}} + \underset{\substack{\uparrow \\ \text{bias}}}{V_{BE}}$

<u>collector current</u>

$$i_C = I_S e^{v_{BE}/V_T} = I_S e^{(V_{BE} + v_{be})/V_T}$$

$$= \underset{\substack{\uparrow \\ \text{bias}}}{I_C}\, e^{\overset{v_{be}/V_T}{\underset{\substack{\uparrow \\ \text{signal}}}{}}}$$

$$\left.\begin{array}{l} e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots \\ \\ \text{if} \quad x \ll 1 \Rightarrow e^x \simeq 1 + x \end{array}\right\} \begin{array}{l} |v_{be}| \ll V_T \\ e^{v_{be}/V_T} = 1 + \frac{v_{be}}{V_T} \end{array}$$

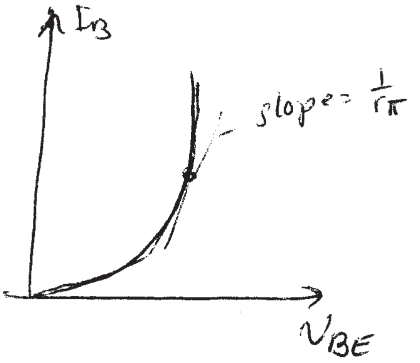
$$i_C = I_C + I_C \frac{v_{be}}{V_T} = I_C + i_c$$

Eg-

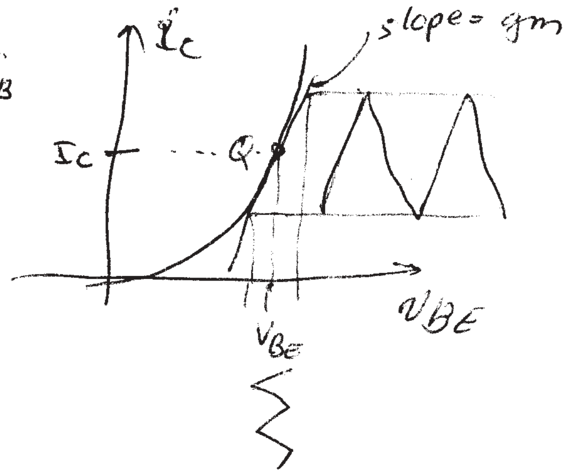
$$\underset{\text{signal}}{\underset{\uparrow}{i_c}} = \frac{I_C}{V_T} \underset{\uparrow\text{signal}}{v_{be}} \equiv g_m v_{be}$$

g_m - transconductance

$$\boxed{g_m = \frac{I_C}{V_T}}$$



$\longrightarrow$ $I_C = \beta i_B$



$$g_m = \left.\frac{\partial i_C}{\partial v_{BE}}\right|_Q$$

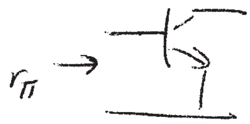
Base current

$$i_B = \frac{i_C}{\beta} = \frac{I_C}{\beta} + \frac{1}{\beta}\frac{I_C}{V_T} v_{be}$$

$$i_B = I_B + i_b \Rightarrow i_b = \frac{g_m}{\beta} v_{be} = \frac{1}{r_\pi} v_{be}$$

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

small signal input resistance looking into the base.



Emitter current.

$$i_E = \frac{i_C}{\alpha} = \underset{\text{bias}}{\underset{\uparrow}{\frac{I_C}{\alpha}}} + \underset{\uparrow\text{signal}}{\frac{i_c}{\alpha}}$$

$$i_e = \frac{i_c}{\alpha} = \frac{I_C}{\alpha V_T} v_{be}$$

$$= \frac{I_E}{V_T} v_{be}$$

$$i_e = \frac{1}{r_e} v_{be}$$

Small signal resistance between base and emitter looking into the emitter.

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

$r_e = \frac{\alpha}{g_m} \cong \frac{1}{g_m}$, $v_{be} = i_b r_\pi = i_e r_e$

$r_\pi = \frac{i_e}{i_b} r_e = (\beta+1) r_e$

$g_m = \frac{I_C}{V_T}$, $r_\pi = \frac{\beta}{g_m}$, $r_e = \frac{1}{g_m}$:

Voltage gains :

$$\begin{aligned} v_C &= V_{CC} - i_C R_C \\ &= V_{CC} - (I_C + i_c) R_C \\ &= (V_{CC} - R_C I_C) - i_c R_C \\ &= V_C - i_c R_C = \underset{\substack{\uparrow \\ \text{bias}}}{V_C} + \underset{\substack{\uparrow \\ \text{signal}}}{v_c} \end{aligned}$$

where

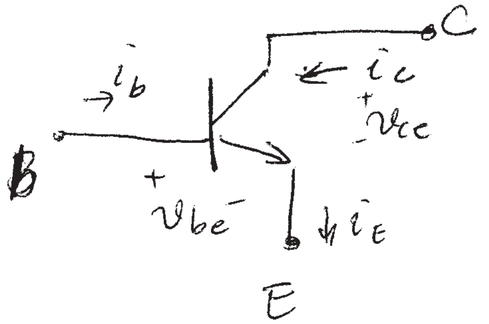
$$v_c = -i_c R_C = -g_m v_{be} R_C$$

$$v_c = (-g_m R_C) v_{be}$$

Voltage gain (small signal, from the base to the collector)

$$\equiv \frac{v_c}{v_{be}} = -g_m R_C$$

Small Signal Equivalent Ckt models



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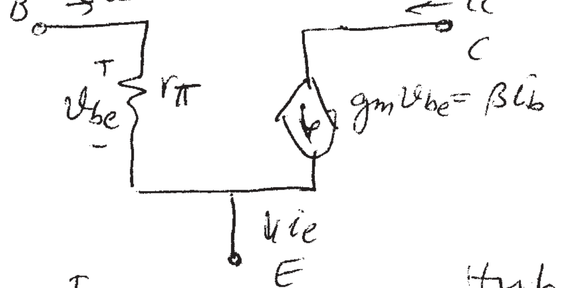
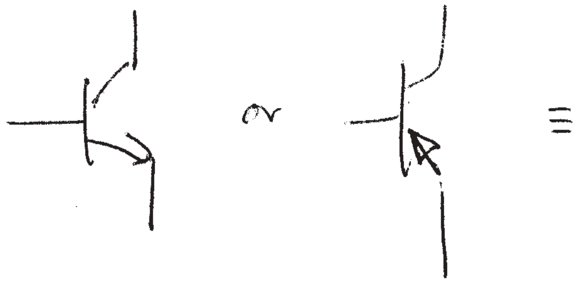


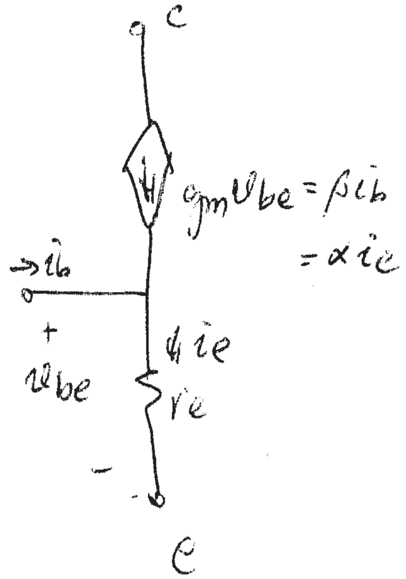
$g_m = \frac{I_C}{V_T}$

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

Hybrid π model

T model



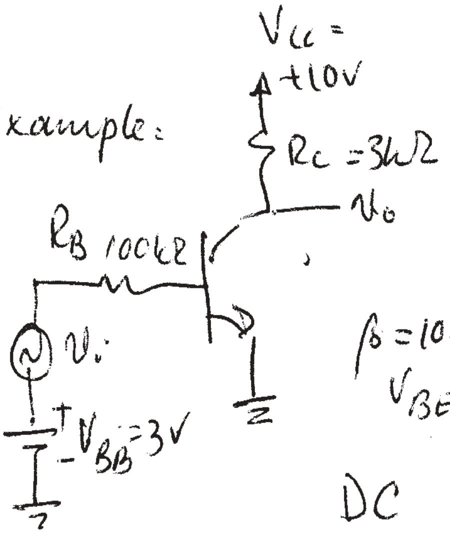


$g_m = \frac{I_c}{V_T}$ $\quad r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m} \simeq \frac{1}{g_m} = \frac{V_T}{I_c}$

$v_{be} = (i_b + \beta i_b) r_e = (1+\beta) i_b r_e = r_\pi i_b$

$\Rightarrow r_\pi = (1+\beta) r_e$

Example:



$\beta = 100$
$V_{BE} = 0.7V$

$\boxed{\text{find } \frac{v_o}{v_i}}$

DC analysis

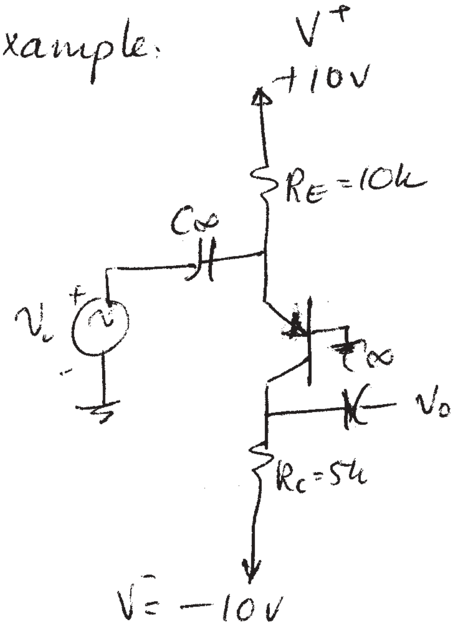
AC Analysis

Transistor Biasing

- Why do we need biasing?
  I_C, V_{CE}

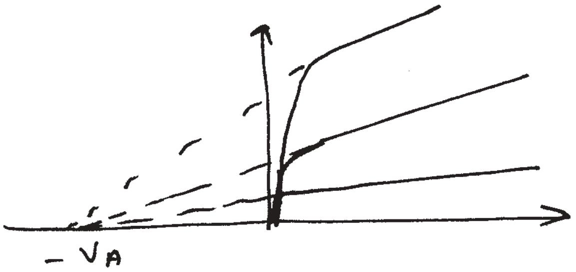
- Biasing from two sources
- Biasing from single source
- Feedback biasing
- Voltage Divider biasing
- Current source biasing
- Design for bias ckts.

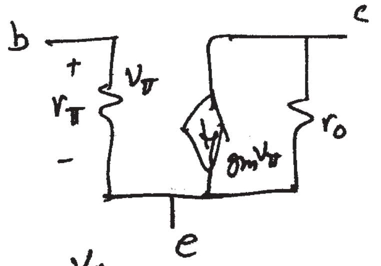
Example:



improving for the early voltage

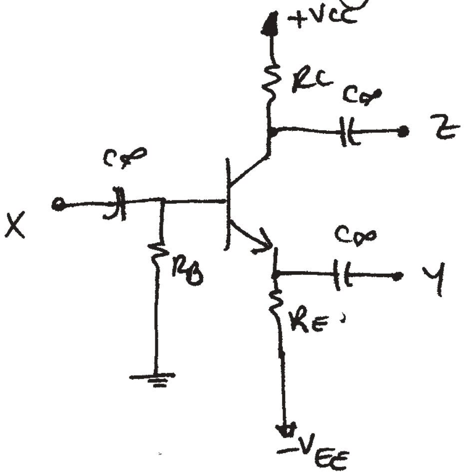
To take the Early voltage into account, a resistor is added to the small signal model.





$$r_o \simeq \frac{V_A}{I_c}$$

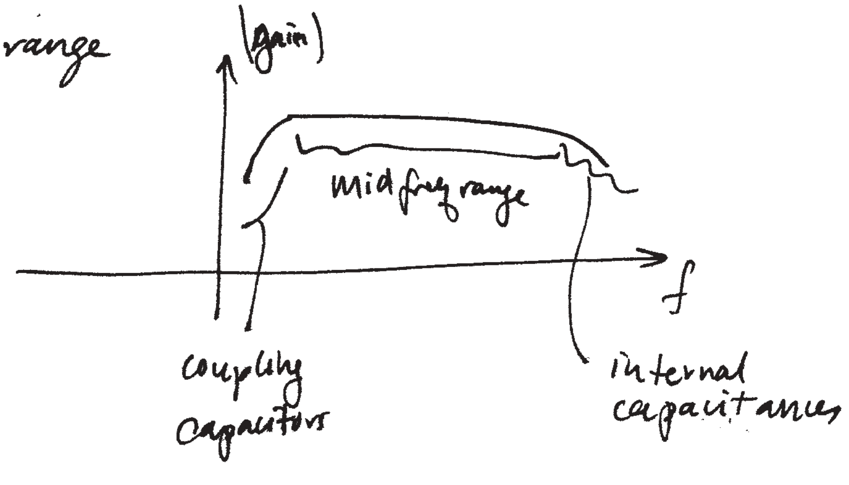
Basic Single Stage BJT Amplifier



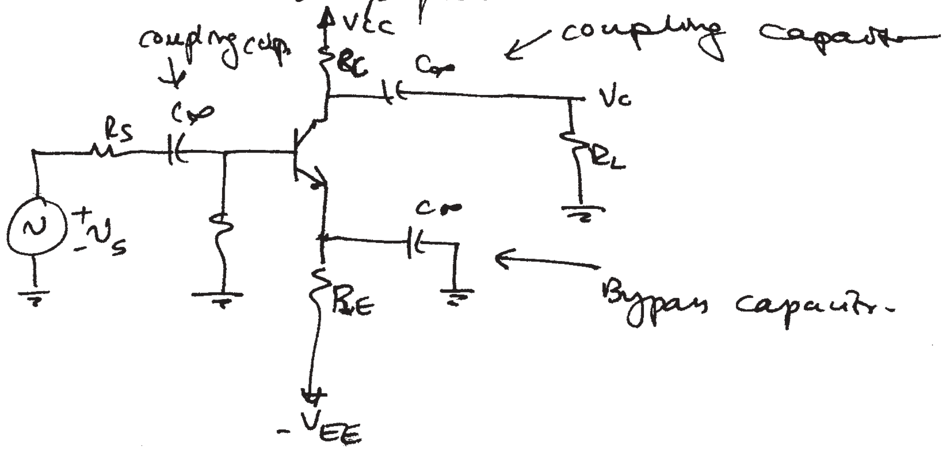
universal amplifier.

		input	output
Common Emitter	Y → ground	X	Z
Common Base	X → ground	Y	Z
Common Collector	Z → ground	X	Y

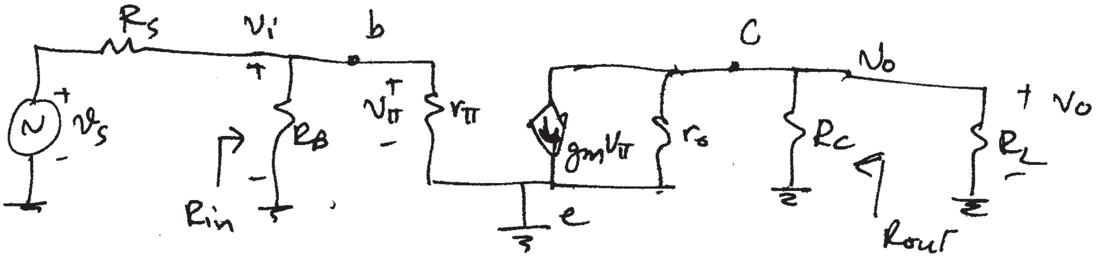
mid frequency range



Common Emitter Amplifier



Small signal equivalent :



$R_{in} = R_B \| r_\pi$

$R_{out} = R_C \| r_o$

$V_o = -(r_o \| R_c \| R_L) g_m V_\pi$

$V_i = V_\pi$

$\frac{v_o}{v_i} = -g_m (R_c \| R_L \| r_o)$

$\frac{v_o}{v_s} = v_o$

#4
Homework : 4.10
4.20
4.30
4.40
4.50

#5
Homework 4.60
4.70
~~4.75~~
4.80
4.90