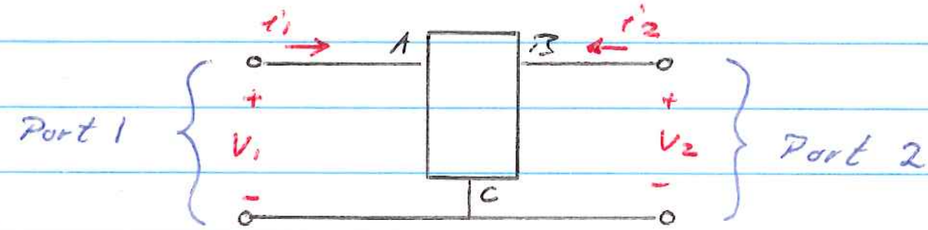
V Three-Terminal Devices

Three terminal devices such as the Bipolar Junction Transistor (BJT) or the Field-Effect Transistor (FET) form the foundation upon which modern electronics is built.

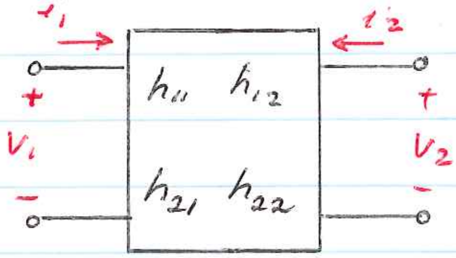
It is convenient to treat a three terminal device as a 2 port since this allows us to describe it by means of its input and output characteristics. In so doing, one terminal must be common to both the input and the output gate.



Since there are three choices for the common terminal, there exist three basic configurations how the three terminal device is utilized.

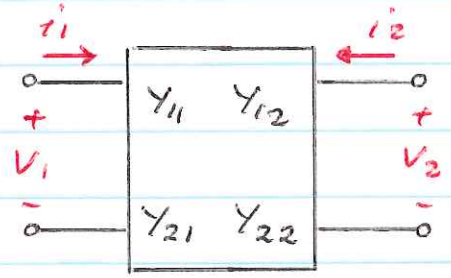
In order to formalize the description of the input and output v-i characteristics, matrix notation is frequently used. The two most common matrices to describe transistors are the Hybrid matrix [H] for BJT's and the Admittance matrix [Y] for FET's.

Def. Hybrid Matrix



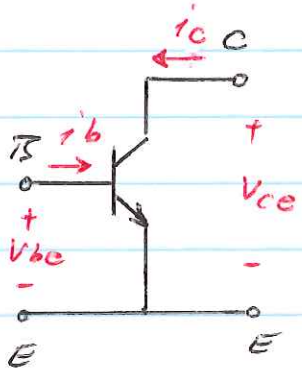
$$\left\| \begin{pmatrix} V_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} i_1 \\ V_2 \end{pmatrix} \right\|$$

Def. Admittance Matrix



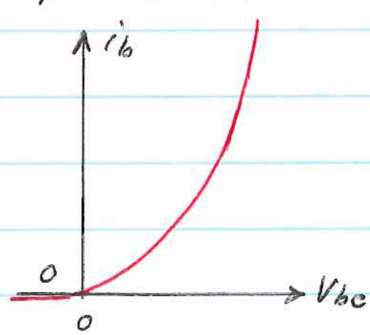
$$\left\| \begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix} \right\|$$

Alternatively, a two port can be described by it's input and output v-i characteristics. For example, a BJT with the emitter as the common terminal possesses the following input and output characteristics:

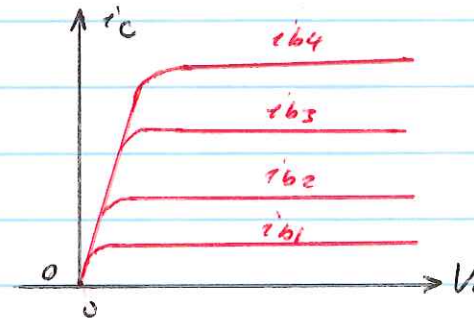


$\hat{=}$

input char.



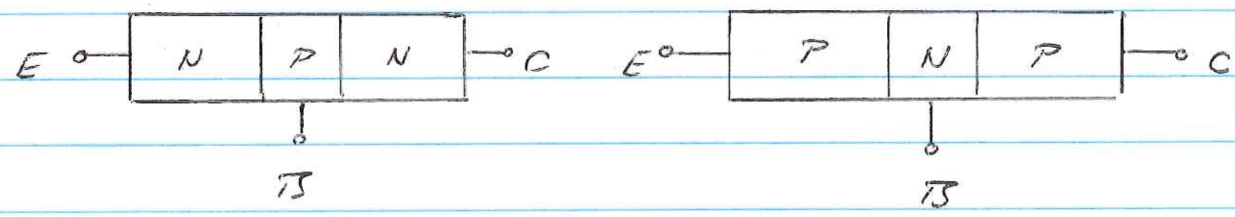
output char.



5.1 The Bipolar Junction Transistor (BJT)

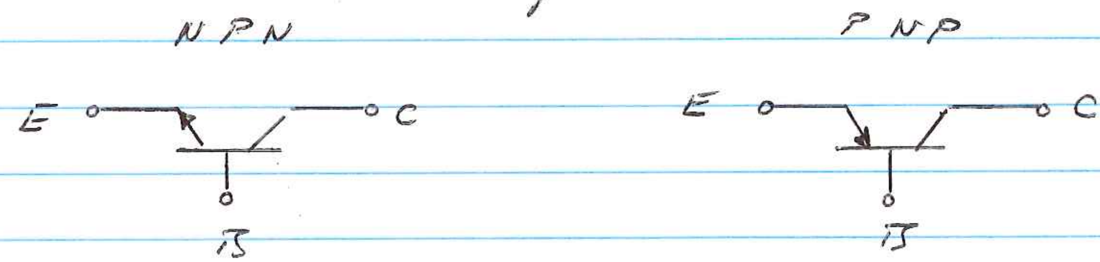
Current-Flow Mechanism

In essence, the BJT consists of two PN junctions placed back to back with a minimum distance between the resulting depletion layers. Consequently, there exist two possible implementations

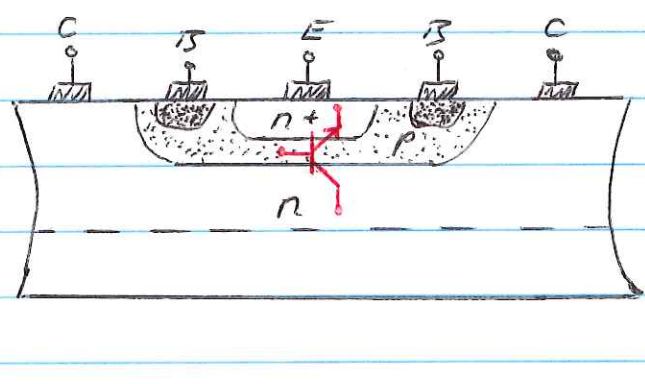


Note: Base region width w_B must be less than the diffusion length of the free carriers, i.e. $w_B < \sqrt{D \cdot \tau}$, where D = diff. const and τ = mean carrier lifetime

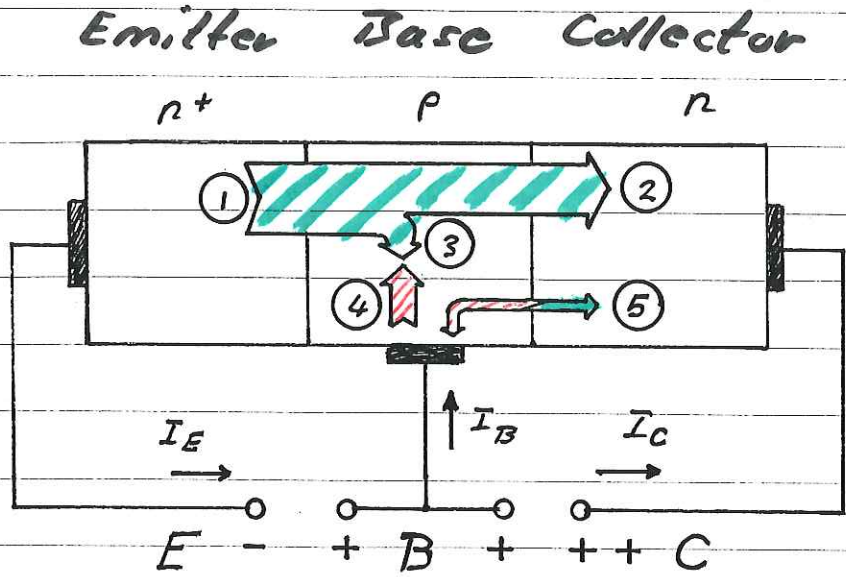
Symbol



Practical Implementation (Planar Process)



The n-p-n Transistor in the forward active state



(1) El. injected from Emitter into Base

(2) El. from Emitter that reach Collector (>90%)

(3) El. from Emitter that recombine in Base

(4) Holes from Base that recombine in Base

(5) Reverse saturation current of B-C junction

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

Note: $I_{CBO} << I_C$

$0.9 < \alpha < 0.999$

Current amplification: $I_C = f(I_B)$

we have: $I_B = (1-\alpha_F) I_E - I_{CBO}$ (1)

$I_C = \alpha_F I_E + I_{CBO}$ (2)

from (1) $I_E = I_B \frac{1}{1-\alpha_F} + I_{CBO} \frac{1}{1-\alpha_F}$ (3)

(3) in (2) $\Rightarrow$ $I_C = I_B \frac{\alpha_F}{1-\alpha_F} + I_{CBO} \left(1 + \frac{\alpha_F}{1-\alpha_F}\right)$

Def: $\boxed{\beta = \frac{d i_C}{d i_B} = \frac{\alpha}{1-\alpha}}$ small signal current amplification

note: $\alpha = f(T, I_C)$

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

e.g. $\alpha_F = 0.995$

$I_{CBO} = 1nA$

$I_B = 10\mu A$

$\Rightarrow$ $\underline{\underline{\beta_F = 199}}$ $\underline{\underline{I_C}} = 1.99 mA + 200 nA = \underline{\underline{1.9902 mA}}$

Note: The transistor has basically 4 modes of operation:

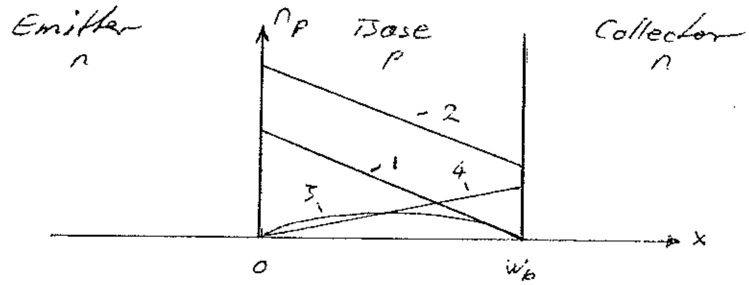
1) $V_{BE} > 0$, $V_{CB} > 0$ forward active mode
2) $V_{BE} > 0$, $V_{CB} < 0$ saturation mode
3) $V_{BE} < 0$, $V_{CB} > 0$ cutoff mode
4) $V_{BE} < 0$, $V_{CB} < 0$ reverse active mode

saturation mode: large quantity of minority carriers in base.
I_C can be large (depending on circuit configur.)

cutoff mode: No minority carriers are injected into base
$I_C \cong 0$

reverse-active mode: Minority carriers are injected into base from collector.
The β in the reverse-active mode is much smaller than that of the forward-active mode due to asymmetries in layout and doping concentrations.

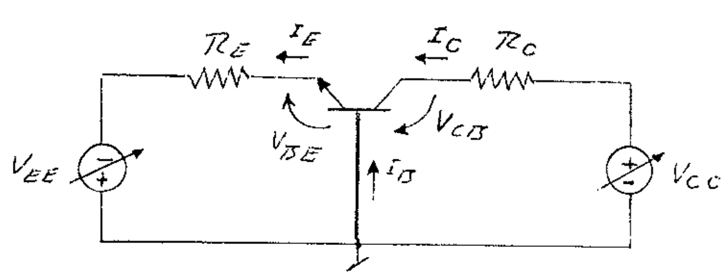
Minority carrier concentration in base:



1) forward-active mode
2) saturation mode
3) cutoff mode
4) reverse-active mode

2.2 Tr. current-voltage characteristics

Base-Emitter Junction
(Common-Base Configuration)

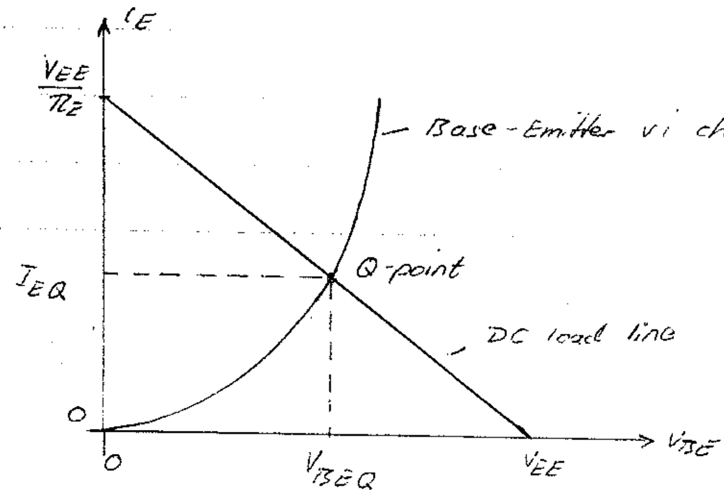


Common-Base connection of npn Transistor

Base - Emitter Loop:

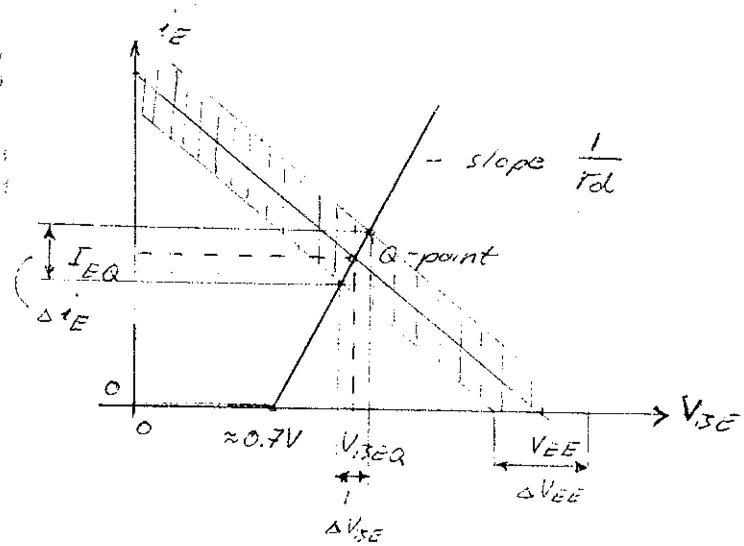
KVL: $V_{EE} = I_E \cdot R_E + V_{BE}$ (1) $\Rightarrow$ $\underline{I_E = \dfrac{V_{EE} - V_{BE}}{R_E}}$ Load line

$$\underline{I_E = I_{S_{BE}} \left[e^{\frac{V_{BE}}{V_T}} - 1 \right]}$$ (2) Diode equation



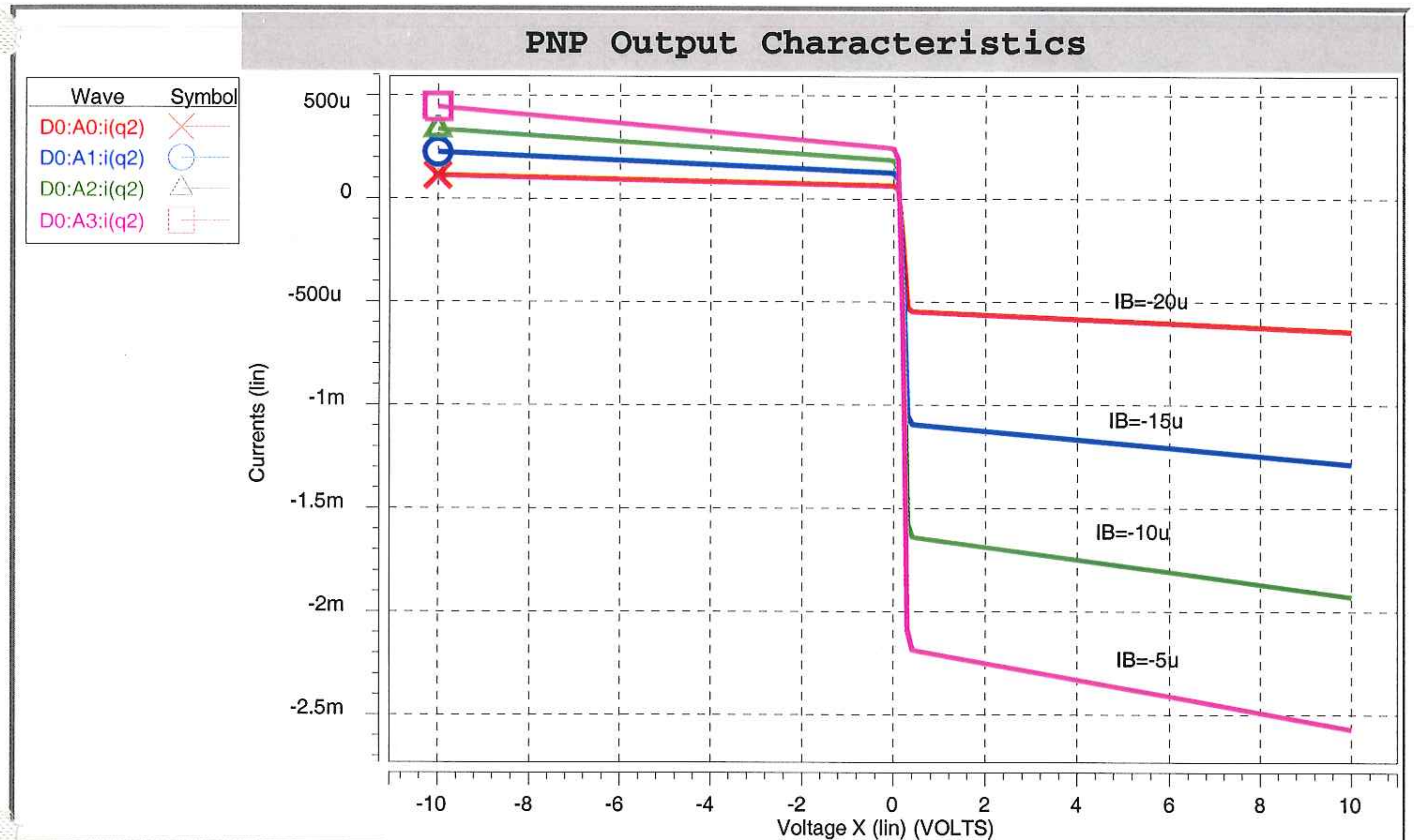
$$I_{EQ} = \frac{V_{EE} - V_{BEQ}}{R_E}$$

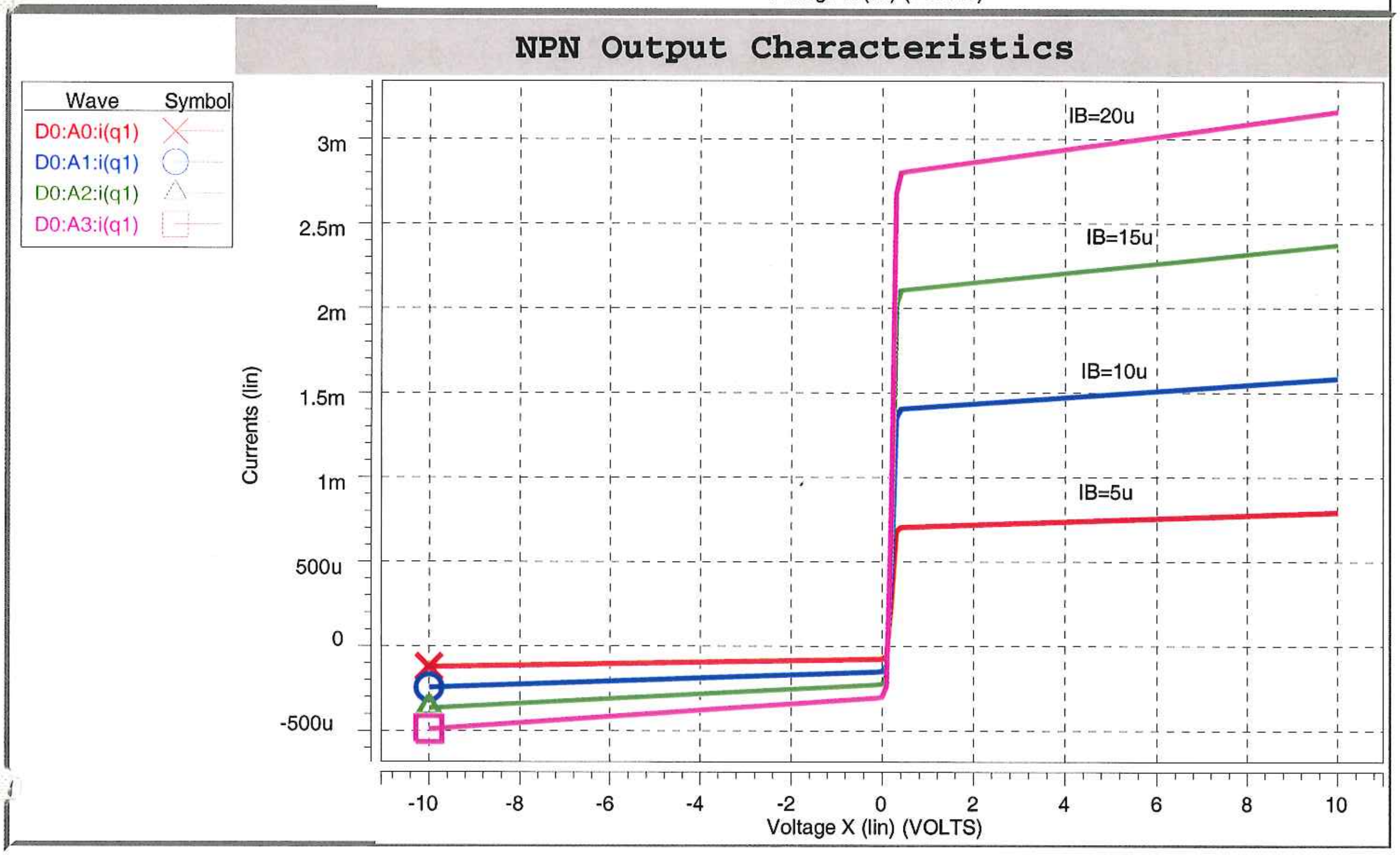
<u>linearized Base - Emitter circuit</u>



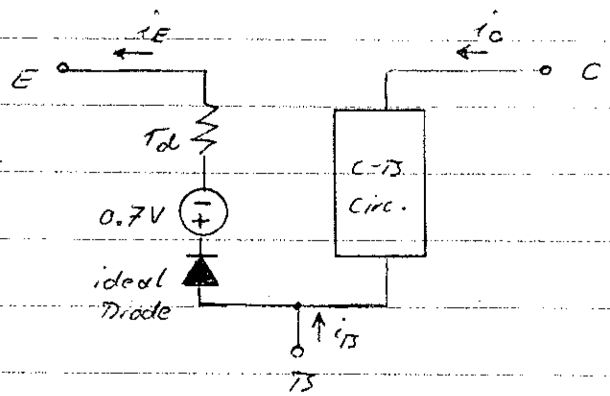
$$r_d = \frac{V_T}{I_{EQ}}$$

V-7a


PNP Output Characteristics
Wave
Symbol
D0:A0:i(q2)
D0:A1:i(q2)
D0:A2:i(q2)
D0:A3:i(q2)
500u
0
-500u
-1m
-1.5m
-2m
-2.5m
Currents (lin)
IB=-20u
IB=-15u
IB=-10u
IB=-5u
-10
-8
-6
-4
-2
0
2
4
6
8
10
Voltage X (lin) (VOLTS)


NPN Output Characteristics
Wave
Symbol
D0:A0:i(q1)
D0:A1:i(q1)
D0:A2:i(q1)
D0:A3:i(q1)
3m
2.5m
2m
1.5m
1m
500u
0
-500u
Currents (lin)
IB=20u
IB=15u
IB=10u
IB=5u
-10
-8
-6
-4
-2
0
2
4
6
8
10
Voltage X (lin) (VOLTS)

Linear equivalent circuit model



$r_d = \frac{V_T}{I_E}$ at $T = 300°K$

$r_d' = 25\,\Omega/mA$

Collector - Base Junction

Collector - Base Loop:

KVL: $V_{CC} = I_C R_C + V_{CB}$ $\Rightarrow$ $\underline{I_C = \frac{V_{CC} - V_{CB}}{R_C}}$ load line

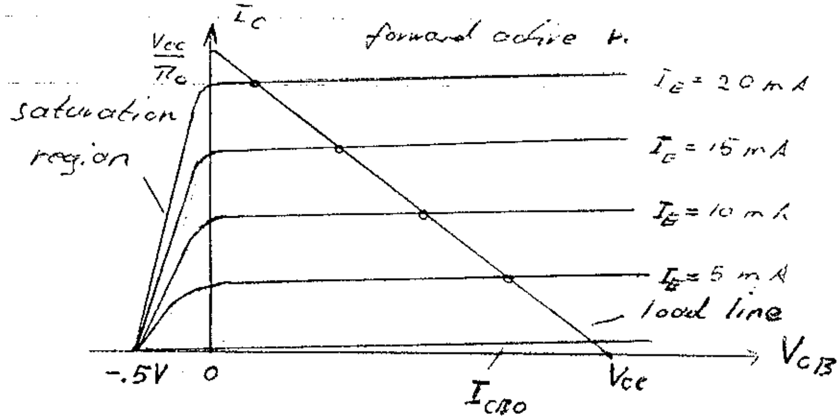
A) $\underline{V_{CB} > 0}$ $\Rightarrow$ forward active mode

$\Rightarrow$ $\underline{I_C = \alpha \cdot I_E} + I_{CBO} \cong \underline{I_E}$

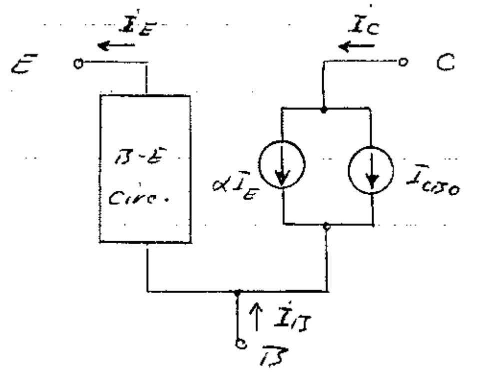
B) $\underline{V_{CB} < 0}$ CB and BE junction are forward biased

$\Rightarrow$ saturation region

I_C decreases



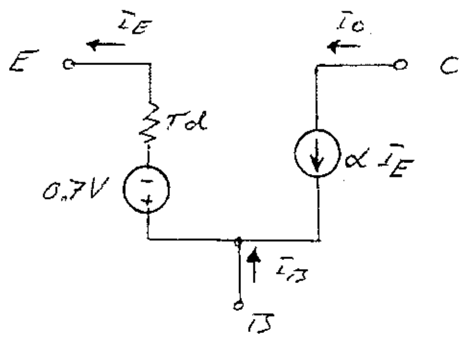
linear equivalent model for forward active region



Simplifications:

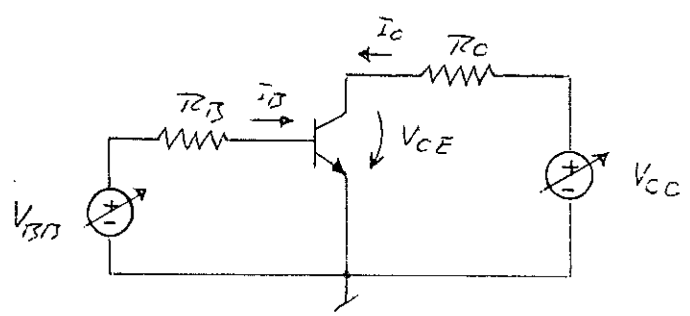
$I_E \gg I_{CBO} \cong 0$

Simplified model for forward active mode:



$$r_d = \frac{V_T}{I_E} = \alpha \frac{V_T}{I_C} = \alpha \frac{1}{g_m}$$

Common Emitter configuration



C - E loop:

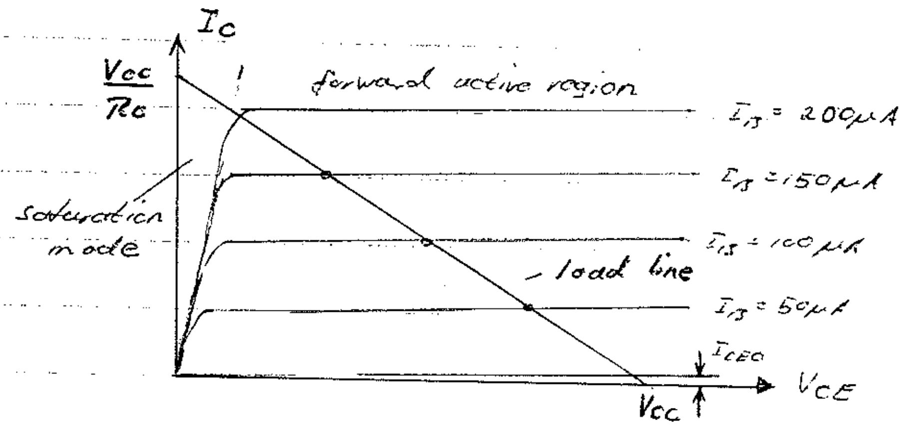
KVL: $V_{CC} = I_C \cdot R_C + V_{CE} \quad \Rightarrow \quad \underline{I_C = \dfrac{V_{CC} - V_{CE}}{R_C}}$ load line

A) $\underline{V_{CE} > V_{BE}}$ $\Rightarrow$ $V_{CB} > 0$ $\Rightarrow$ forward active region

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

B) $\underline{V_{CE} < V_{BE}}$ $\Rightarrow$ $V_{CB} < 0$ saturation mode

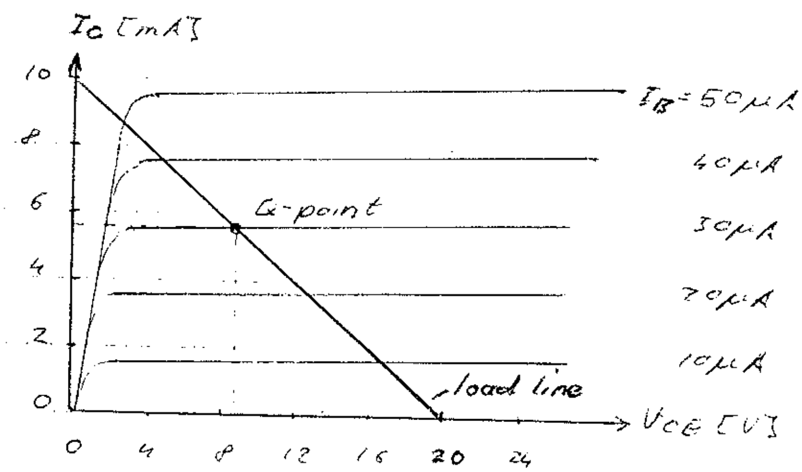
I_C decreases



Example Given: Tr. in common Emitter circuit configuration

$V_{BB} = 4V$, $V_{CC} = 20V$

$R_B = 110 k\Omega$, $R_C = 2 k\Omega$



load line

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

$\Rightarrow I_C = \dfrac{V_{CC} - V_{CE}}{R_C}$

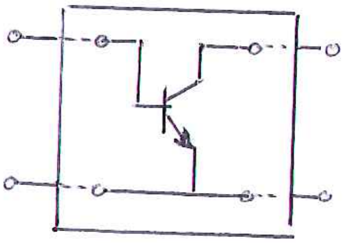
Estimate: I_B, I_C, V_{CE}

B-E Loop: KVL. $V_{BB} = I_B R_B + V_{BE}$

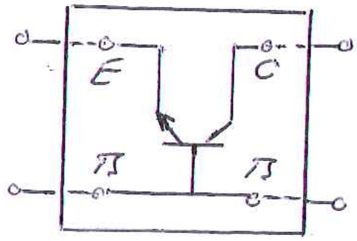
$\Rightarrow I_B = \dfrac{V_{BB} - V_{BE}}{R_B} \cong \dfrac{4 - 0.7}{110} mA = \underline{30\mu A}$

$\underline{I_{CQ} \cong 5.5 mA}$ $V_{CEQ} \cong 9V$

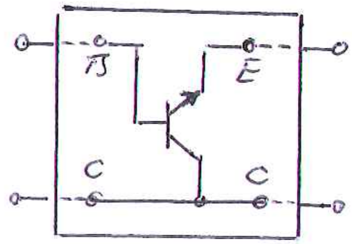
CE Configuration



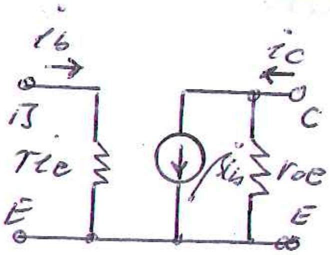
CB Configuration

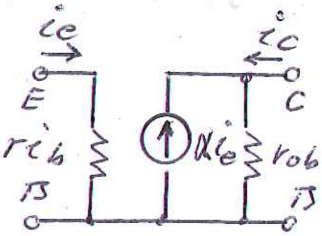


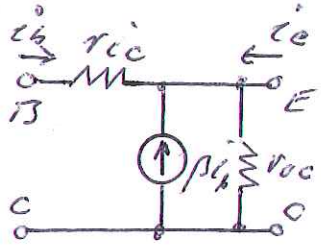
CC Configuration



AC equivalent models







$$r_{ie} = \frac{\beta}{g_m} \qquad r_{oe} = \frac{V_A}{I_{CQ}}$$

$$r_{ib} = \frac{\alpha}{g_m} \qquad r_{ob} = (\beta+1)\frac{V_A}{I_{CQ}}$$

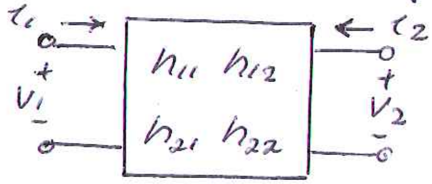
$$r_{ic} = \frac{\beta}{g_m} \qquad r_{oc} = \frac{V_A}{I_{CQ}}$$

where $g_m = \frac{I_{CQ}}{V_T}$ $\quad \alpha = \frac{\beta}{1+\beta}$ $\quad \beta = \frac{i_c}{i_b}$

Note: $\beta i_b = g_m V_{be}$ $\quad \alpha i_e = g_m V_{be}$

Matrix Representation for 2-Ports

Hybrid Parameters (h-Parameters)



$$\begin{pmatrix} V_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} i_1 \\ V_2 \end{pmatrix}$$

$$h_{11} = \frac{V_1}{i_1}\Big|_{V_2=0} \qquad h_{12} = \frac{V_1}{V_2}\Big|_{i_1=0}$$

$$h_{21} = \frac{i_2}{i_1}\Big|_{V_2=0} \qquad h_{22} = \frac{i_2}{V_2}\Big|_{i_1=0}$$

Hybrid Parameters for BJTs

CE Configuration

$$\left|\begin{array}{ll} h_{11e} = \dfrac{\beta}{g_m} = \beta\dfrac{V_T}{I_{CQ}} & h_{12e} \cong 0 \\ h_{21e} = \beta & h_{22e} = \dfrac{I_{CQ}}{V_A} \end{array}\right|$$

CB Configuration

$$\left\|\begin{array}{ll} h_{11b} = \dfrac{\alpha}{g_m} = \alpha\dfrac{V_T}{I_{CQ}} & h_{12b} \cong 0 \\ h_{21b} = -\alpha & h_{22b} = \dfrac{I_{CQ}}{(\beta+1)V_A} \end{array}\right\|$$

CC Configuration

$$\left\|\begin{array}{ll} h_{11c} = \dfrac{\beta}{g_m} = \beta\dfrac{V_T}{I_{CQ}} & h_{12c} = 1 \\ h_{21c} = -(\beta+1) & h_{22c} = \dfrac{I_{CQ}}{V_A} \end{array}\right\|$$

Numerical Example

$$\left|\begin{array}{ll} \beta = 100 & V_A = 100\,V \\ I_{CQ} = 1\,mA & \end{array}\right|$$

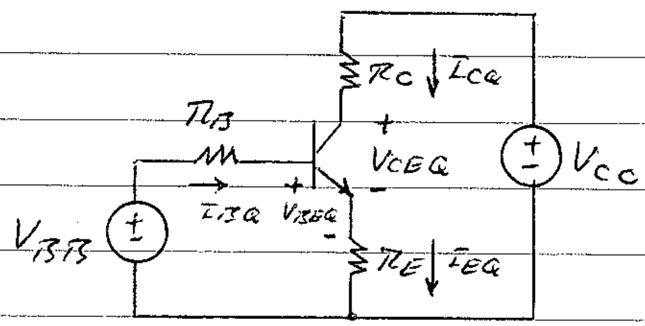
$$\left|\begin{array}{ll} h_{11e} = 2.5\,k\Omega & h_{12e} = 0 \\ h_{21e} = 100 & h_{22e} = 10^{-5}\,S \end{array}\right|$$

$$\left|\begin{array}{ll} h_{11b} = 25\,\Omega & h_{12b} = 0 \\ h_{21b} = -.99 & h_{22b} = 10^{-7}\,S \end{array}\right|$$

$$\left|\begin{array}{ll} h_{11c} = 2.5\,k\Omega & h_{12c} = 1 \\ h_{21c} = -101 & h_{22c} = 10^{-5}\,S \end{array}\right|$$

2.4 Biasing

Basic Configuration



Objective:
Describe the transistor Q-point, i.e. I_{CQ} and V_{CEQ}, as a function of the two source voltages and the three resistors R_B, R_C and R_E.

Approach:
Apply KVL for both the input loop (V_{BB}, V_{BEQ}, ...) and the output loop (V_{CC}, V_{CEQ}, ...) and use the known relationships between the currents I_{BQ}, I_{CQ} and I_{EQ} of the BJT.

Input loop:

KVL: $V_{BB} = I_{BQ} R_B + V_{BEQ} + I_{EQ} R_E$

Device: $I_{EQ} = (1+\beta) I_{BQ}$

$I_{CQ} = \beta \cdot I_{BQ}$

$$\therefore \quad V_{BB} = I_{BQ} R_B + V_{BEQ} + (1+\beta) I_{BQ} R_E$$

or

$$I_{BQ} = \frac{V_{BB} - V_{BEQ}}{R_B + (1+\beta) R_E}$$

$$I_{CQ} = \frac{V_{BB} - V_{BEQ}}{R_B/\beta + (1+1/\beta) R_E} \qquad I_{CQ} \cong \frac{V_{BB} - V_{BEQ}}{R_B/\beta + R_E}$$

Output loop:

KVL: $V_{CC} = I_{CQ}R_C + V_{CEQ} + I_{EQ}R_E$

Device: $I_{EQ} = I_{CQ}(1 + 1/\beta)$

$\therefore \quad V_{CC} = I_{CQ}R_C + V_{CEQ} + I_{CQ}(1+1/\beta)R_E$

or

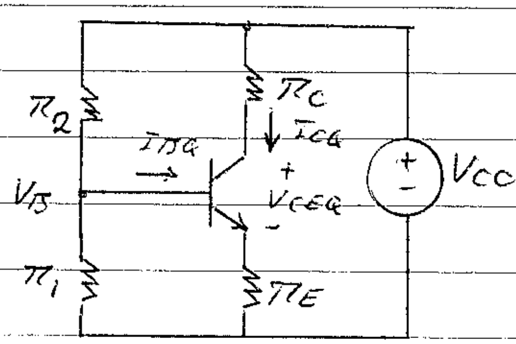
$\| V_{CEQ} = V_{CC} - I_{CQ}(R_C + [1+1/\beta]R_E) \|$ $\quad | V_{CEQ} \cong V_{CC} - I_{CQ}(R_C + R_E) |$

Q-point Equations:

$$\boxed{\begin{aligned} I_{CQ} &= \frac{V_{BB} - V_{BEQ}}{R_B/\beta + (1+1/\beta)R_E} \\ \\ V_{CEQ} &= V_{CC} - I_{CQ}(R_C + [1+1/\beta]R_E) \end{aligned}}$$

Practical Q-point Networks

A) Biasing with Voltage Divider



Question

What are the equivalent values of R_B and V_{BB}?

From basic configuration we deduce that

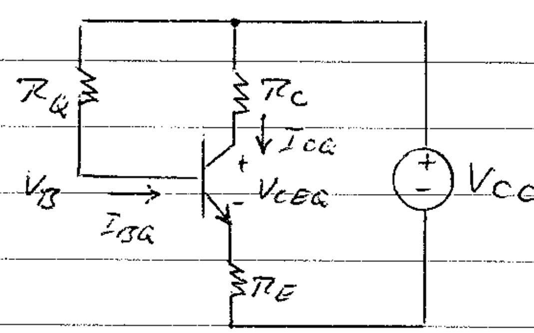
$$\left| V_{BB} = V_B \right|_{I_{BQ}=0} \qquad R_B = \frac{V_{BB} - V_B}{I_{BQ}}$$

$$\therefore \quad \left\| \begin{aligned} V_{BB} &= V_{CC}\frac{R_1}{R_1+R_2} \\ R_B &= \frac{R_1 \cdot R_2}{R_1 + R_2} \end{aligned} \right\|$$

Thus

$$\left\| I_{CQ} = \frac{V_{CC}\frac{R_1}{R_1+R_2} - V_{BEQ}}{\frac{R_1 \cdot R_2}{(R_1+R_2)\beta} + (1+1/\beta)R_E} \right\|$$

B) <u>Biasing with Base injection</u>

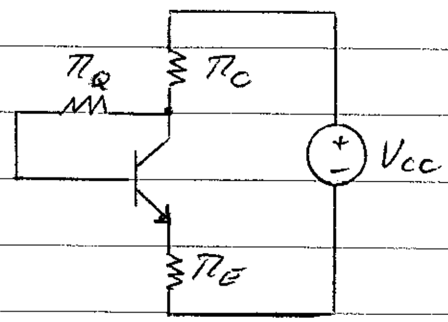


We deduce from the basic configuration that

$$\left\| \left. V_{BB} = V_B \right|_{I_{BQ}=0} = V_{CC} \qquad R_B = \frac{V_{BB} - V_B}{I_{BQ}} = R_Q \right\|$$

$$\left\| I_{CQ} = \frac{V_{CC} - V_{BEQ}}{R_Q/\beta + (1+1/\beta)R_E} \right\|$$

C) Voltage Feedback Biasing



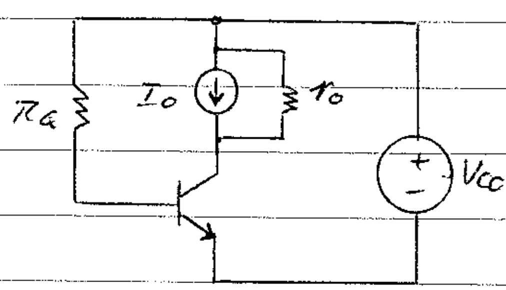
We deduce from basic configuration

$$\left\| \; V_{BB} = V_B \Big|_{I_{BQ}=0} = V_{CC} \qquad R_B = \frac{V_{BB} - V_B}{I_{BQ}} = R_Q + (1+\beta) R_C \; \right\|$$

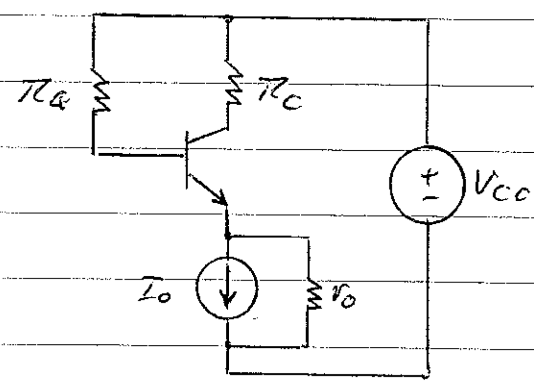
$$\left\| \; I_{CQ} = \frac{V_{CC} - V_{BEQ}}{R_Q/\beta + (1 + 1/\beta)(R_C + R_E)} \; \right\|$$

D) Current Source Biasing

Version A



Version B



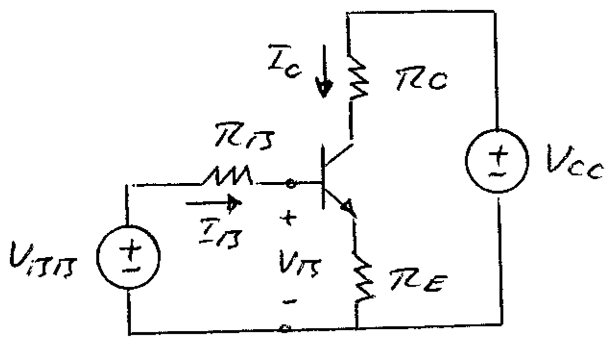
$$\left\| \; I_{CQ} = I_o + \frac{V_{CC} - V_{CEQ}}{r_o} \; \right\|$$

$$\left\| \; I_{CQ} = (1 - 1/\beta) \left[I_o + \frac{V_{CC} - V_{CEQ} - I_{CQ} R_C}{r_o} \right] \; \right\|$$

<u>Note</u>: R_Q is <u>not</u> a free parameter. It has to be adjusted to provide the corresponding I_B.

Bipolar Transistor Biasing Summary

Basic Configuration



Def.:

$$V_{BB} = V_B \Big|_{I_B = 0}$$

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

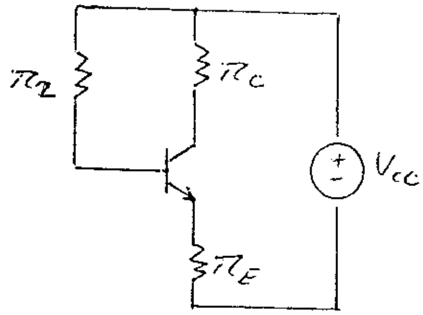
Q-Point Equations:

$$I_{CQ} = \frac{V_{BB} - V_{BEQ}}{\frac{R_B}{\beta} + \left(1 + \frac{1}{\beta}\right) R_E}$$

$$V_{CEQ} = V_{CC} - I_{CQ}\left(R_C + \left[1 + \frac{1}{\beta}\right] R_E\right)$$

Silicon: $V_{BEQ} \cong 0.7V$

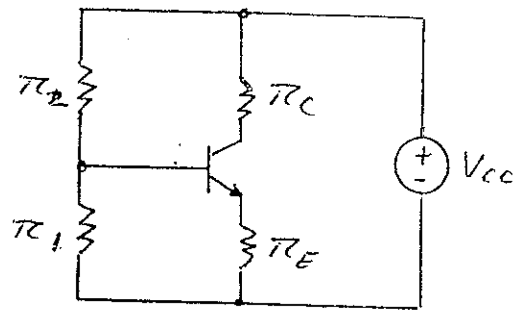
Base current Bias



$$R_B = R_2$$

$$V_{BB} = V_{CC}$$

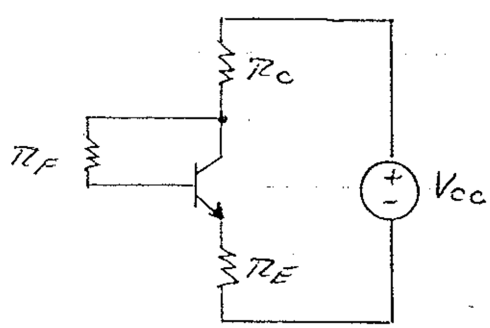
Voltage divider Bias



$$R_B = R_1 \parallel R_2$$

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

Voltage Feedback Bias



$$R_B = R_F + (1+\beta) R_C$$

$$V_{BB} = V_{CC}$$

Examples

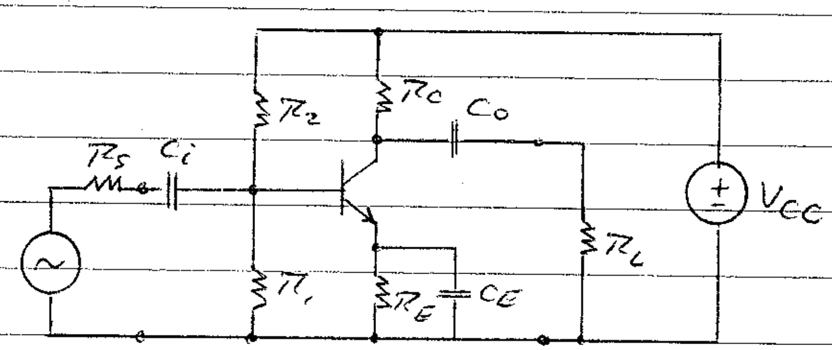
(1) Design a common emitter amplifier which realizes a voltage gain of −100. Pick an appropriate Q-point and determine the resulting values for the amplifiers input and output resistance.

$V_{CC} = 10V$, Transistor: $\beta_F = 150$, $V_A = 80V$, $R_S = 50\Omega$

$R_L = 10K\Omega$

Approach:

1. Circuit Topology



2. Q-point considerations

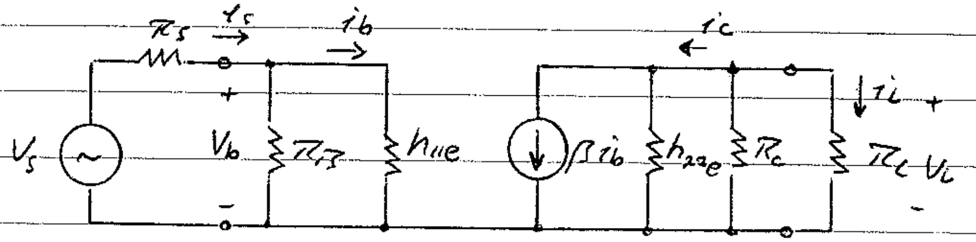
$I_{CQ} \cong \dfrac{V_{BB} - V_{BEQ}}{R_B/\beta + R_E}$	where $V_{BB} = V_{CC} \cdot \dfrac{R_1}{R_1 + R_2}$
$V_{CEQ} \cong V_{CC} - I_{CQ}(R_C + R_E)$	$R_B = R_1 \parallel R_2$

select $|I_{CQ} \cong 1mA|$ $\quad\therefore\quad$ $h_{11e} = \beta \dfrac{V_T}{I_{CQ}} \cong 4.5k\Omega$

$V_{CEQ} \cong V_{CC} - I_{CQ}(R_C + R_E)$ $\quad$ $h_{22e} \cong \dfrac{I_{CQ}}{V_A} \cong 12.5\mu S$

3. AC considerations

ac equivalent circuit (C_i, C_o and C_E act as ac shorts)



$R_B = R_1 \| R_2$

equations:

Input loop:	$V_s = (i_b + \frac{V_b}{R_B}) R_s + i_b h_{ie}$	(1)
Output loop:	$V_L = -(R_L \| R_C \| \frac{1}{h_{22e}})$	(2)
Ohm's law:	$V_b = i_b h_{ie}$	(3)

from (1) and (3)

$$V_s = i_b \left(R_s \left[1 + \frac{h_{ie}}{R_B} \right] + h_{ie} \right) \quad (4)$$

$$\therefore \quad \frac{V_L}{V_s} = A_V = - \frac{R_L \| R_c \| \frac{1}{h_{22e}} \cdot \beta}{R_s \left[1 + \frac{h_{ie}}{R_B} \right] + h_{ie}}$$

or

$$\boxed{A_V = - \frac{R_L \| R_c \| \frac{1}{h_{22e}}}{R_s \left[1/\beta + \frac{r_d}{R_B} \right] + r_d}} \quad (5)$$

If $r_d << R_B$

$$R_L \| R_c \| \frac{1}{h_{22e}} \cong A_V \cdot r_d \cong 3 k\Omega$$

$$\therefore \quad R_c \cong 4.5 k\Omega$$

Select $\boxed{\begin{array}{l} R_{c\,nom} = 4.7 k\Omega \\ V_{CEQ} \cong 4.9 V \end{array}}$ (to maximize the output swing)

$\therefore \quad \boxed{\begin{array}{l} R_E \cong 400 \Omega \\ V_{BQ} \cong 1.1 V \end{array}}$

Select		
	$R_E = 470\Omega$	560Ω
	$R_1 = 10k\Omega$	$4.7k\Omega$
∴	$R_2 \cong 68k\Omega$	$33k\Omega$
	$R_B \cong 8.7k\Omega$	$4.1k\Omega$

4. Check Specifications

• Q-point:

$I_{CQ} \cong \dfrac{V_{CC}\frac{R_1}{R_1+R_2} - V_{BEQ}}{R_B/\beta + R_E}$	$\cong 1.1mA$	$0.91mA$
$V_{CEQ} \cong V_{CC} - I_{CQ}(R_C + R_E)$	$\cong 4.3V$	$5.2V$

• AC Gain

$$\boxed{A_V \cong - \frac{R_C \parallel R_L \parallel \frac{1}{h_{oe}}}{R_S\left[1/\beta + \frac{r_d}{R_B}\right] + r_d} \cong -110}$$

Adjust Gain by either

- Reducing R_C by 10%
- Reducing I_{CQ} by 10% (i.e. increase R_E by 10% or reduce R_1 by approx. 10%)

e.g. $\boxed{R_C = 4.3k\Omega}$

$I_{CQ} \cong 1.1mA$
$V_{CEQ} \cong 4.7V$
$A_V \cong -100$

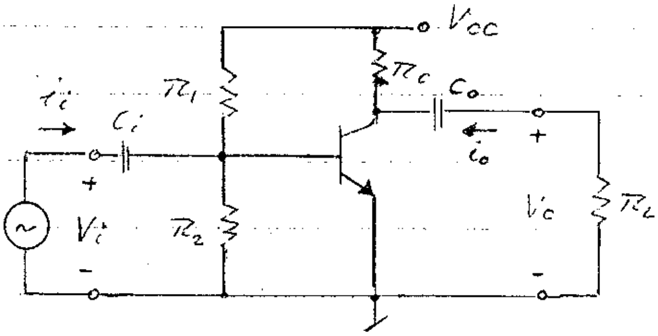
or

$\boxed{R_E \cong 520\Omega}$

$I_{CQ} \cong 1.0mA$
$V_{CEQ} \cong 4.8V$
$A_V \cong -100$

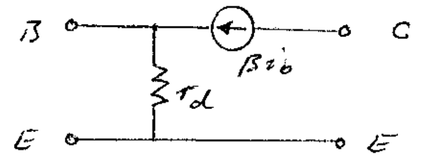
2.5 Common Emitter Amplifier
(Small signal behavior)

Complete Amplifier Circuit with Biasing

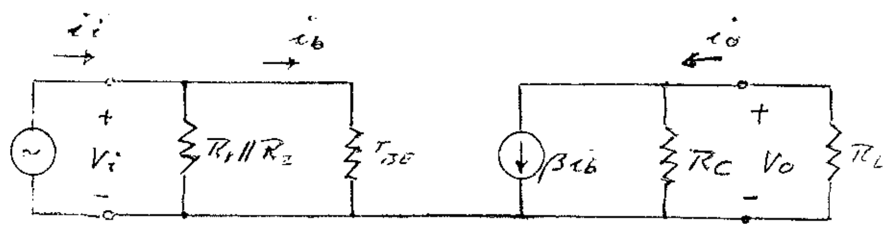


C_i, C_o : Infinite Coupling Capacitors
They block DC currents while permitting AC signals to pass

Recall: Common Emitter equiv. C.

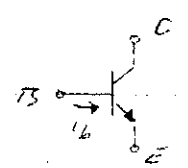


Small signal equivalent circuit

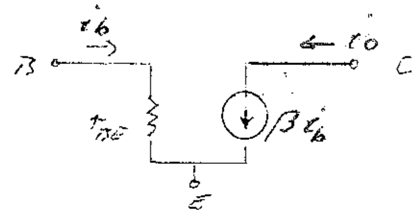


$r_{BE} = (1+\beta)\, r_d$

where



$\Rightarrow$



A) small-signal voltage gain

$$\boxed{A_V = \frac{V_o}{V_i} = -\frac{\beta \cdot R_C \parallel R_L}{r_{BE}}}$$

input

$V_i = i_b\, r_{BE}$

$i_i = i_b + \frac{V_i}{R_B}$

output

$V_o = -i_o R_L$

$i_o = \beta i_b + \frac{V_o}{R_C}$

e.g. $\beta_a = 100$ $\quad (I_{CQ} \cong 5mA)$

$R_C = R_L = 1k\Omega \quad \Rightarrow \quad \underline{A_V = -100}$

$r_{BE} = 500\,\Omega$

B) small-signal <u>current gain</u>

$$\boxed{A_i = \frac{i_o}{i_i} = \beta \, \frac{R_C \parallel R_L}{R_L}}$$

e.g. $\beta = 100$

$R_C = R_L = 1k\Omega \quad \Rightarrow \quad \underline{\underline{A_i = 50}}$

C) <u>Input resistance</u> (current source i_i at input)

$$\boxed{R_{in} = \frac{v_i}{i_i} = R_1 \parallel R_2 \parallel r_{BE}}$$

e.g. $R_1 = 120k\Omega$

$R_2 = 8.2k\Omega \quad \Rightarrow \quad \underline{\underline{R_i \cong 470\Omega}}$

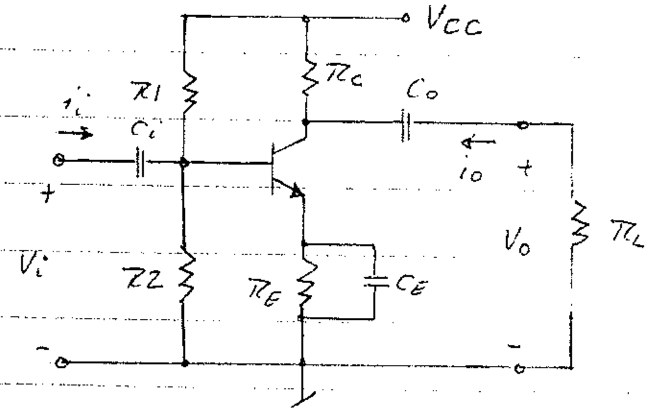
$r_{BE} = 500\Omega$

D) <u>Output resistance</u> (current source i_o at output)

$$\boxed{R_{out} = \frac{v_o}{i_o} = R_C}$$

$R_C = 1k\Omega \quad \Rightarrow \quad \underline{\underline{R_o = 1k\Omega}}$

Common Emitter Amplifier with current feedback

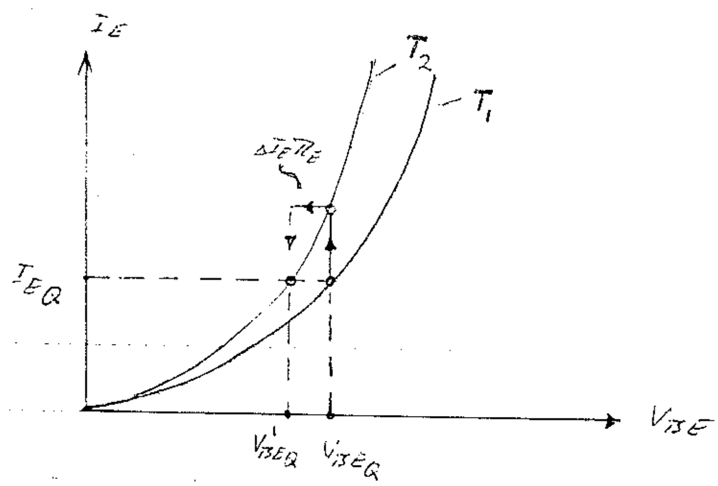


C_i, C_o: infinite coupling capacitors

C_E: infinite bypass capacitor (short circuit for signal frequencies)

⇒ A.C performance of amplifier does not change.*

Tr. input characteristics



$T_2 > T_1$

Since $I_{EQ} \cong$ const ⇒ $V_{CQ} \cong$ const.

⇒ R_E stabilizes Q-point

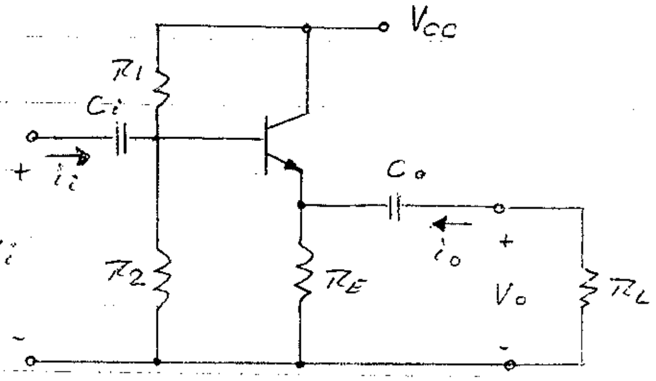
* note: without C_E: $A_V = -\beta \dfrac{R_C \| R_L}{r_{BE} + (1+\beta) R_E} \cong -\dfrac{R_C \| R_L}{r_d + R_E}$

e.g. $R_C = R_L = 1k\Omega$

$\beta = 100$, $r_{BE} = 600\Omega$ ⇒ $\underline{A_V \cong -5}$

$R_E = 100\Omega$

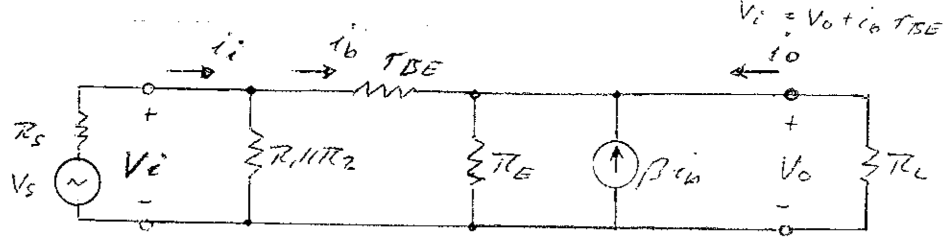
2.6 Common Collector Circuit (Emitter Follower)



C_i, C_o : infinite coupling cap.

small signal equivalent circuit

input	output
$V_S = V_i + i_i R_S$	$V_o = -i_o R_L$
$i_i = i_b + \frac{V_i}{R_B}$	$i_o = -(1+\beta) i_b + \frac{V_o}{R_E}$
$V_i = V_o + i_b r_{BE}$	



$r_{BE} = (1+\beta) r_d$

A) small signal voltage gain

$$\boxed{A_V = \frac{V_o}{V_i} = \frac{1}{1 + r_d / R_E /\!/ R_L}}$$

e.g. $r_d = 5\Omega$

$R_E = R_L = 200\Omega$ $1K\Omega$

$\Rightarrow$ $A_V = 0.95$ 0.99

B) small signal current gain

$$\boxed{A_i = \frac{i_o}{i_i} = -(1+\beta)\frac{R_E}{(R_E + R_L)} \frac{1}{\left(1 + \frac{\beta R_E + r_{BE}}{R_1 /\!/ R_2}\right)}}$$

e.g. $R_E = R_L = 200\Omega$ $1K\Omega$ -8.3

$\beta = 100$, $r_{BE} = 500\Omega$ $\Rightarrow$ $A_i = -25$

$R_1 /\!/ R_2 = 20K\Omega$

c) Input resistance

$$\boxed{R_i = \frac{v_i}{i_i} = (R_1 \| R_2) \| (r_{BE} + [1+\beta] R_E \| R_L)}$$

e.g. $R_E = R_L = 200\Omega$

$\beta = 100$; $r_{BE} = 500$ $\Rightarrow$ $R_i = 7.22\ K\Omega$

$R1 \| R2 = 20K\Omega$

D) Output resistance

$$\boxed{R_o = \frac{v_o}{i_o} = R_E \| \frac{r_{BE} + R1 \| R2 \| R_S}{1+\beta}}$$

e.g. $R_E = 200\ \Omega$; $R_S = 100\ \Omega$

$\beta = 100$; $r_{BE} = 500$ $\Rightarrow$ $R_o \cong 6\ \Omega$

$R1 \| R2 = 20K\Omega$

This type of circuit is primarily used to provide a low source impedance (R_o is small) for driving subsequent loads.
(R_i is rather great even though R_L is very small).

Class A CC Amplifier Power Efficiency

Total average Power:

$$\overline{P_{Tot}} = \overline{2V_{CC} \cdot (I_{CQ} + i_c \sin(\omega t))} = 2V_{CC} \cdot I_{CQ}$$

where $I_{CQ} \cong \dfrac{V_{CC} - V_{BE}}{R_E}$

$$\therefore \quad \overline{P_{Tot}} = \frac{2V_{CC}(V_{CC} - V_{BE})}{R_E}$$

Average load Power: (Max)

$$\overline{P_{L_{Max}}} = \overline{V_{L_{Max}}^2 \frac{1}{R_L} \sin^2(\omega t)} = \frac{V_{L_{Max}}^2}{2R_L}$$

where $V_{L_{Max}} = I_{CQ} \dfrac{R_E R_L}{(R_E + R_L)} = \dfrac{(V_{CC} - V_{BE}) R_L}{(R_E + R_L)}$

$$\therefore \quad \overline{P_{L_{Max}}} = \frac{(V_{CC} - V_{BE})^2 R_L}{2(R_E + R_L)^2}$$

Power Efficiency:

$$\eta_{Max} = \frac{\overline{P_{L_{Max}}}}{\overline{P_{Tot}}} = \frac{(V_{CC} - V_{BE})^2 R_L \cdot R_E}{4(R_E + R_L)^2 V_{CC}(V_{CC} - V_{BE})}$$

$$\therefore \quad \eta_{Max} = \frac{(V_{CC} - V_{BE}) R_L R_E}{4V_{CC}(R_E + R_L)^2}$$

For max Efficiency: $R_E = R_L$

$$\therefore \quad \eta_{Max} = \frac{(V_{CC} - V_{BE})}{16 V_{CC}}$$

Class AB CC Amplifier Power Efficiency

Total average Power:

$$\overline{P_{Tot_{Max}}} = V_{CC} \cdot \frac{V_{LMax}}{R_L} \overline{\sin(\omega t)} = V_{CC} \frac{V_{LMax}}{R_L} \frac{2}{\pi}$$

Half-wave only

where $V_{LMax} \cong V_{CC} - V_{BE}$

$$\therefore \overline{P_{Tot_{Max}}} = \frac{V_{CC}(V_{CC} - V_{BE})}{R_L} \frac{2}{\pi}$$

Average load Power: (Max)

$$\overline{P_L} = V_{LMax}^2 \frac{1}{R_L} \overline{\sin^2(\omega t)} = \frac{V_{LMax}^2}{2 R_L}$$

$$\overline{P_{LMax}} = \frac{(V_{CC} - V_{BE})^2}{2 R_L}$$

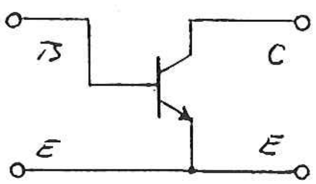
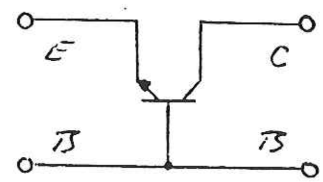
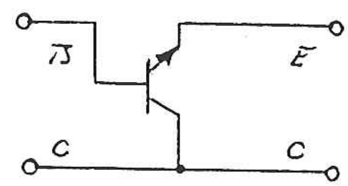
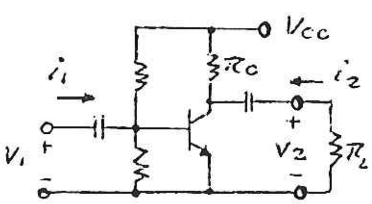
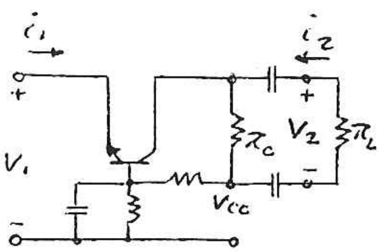
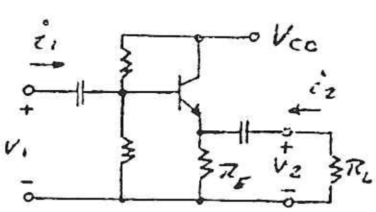
Power Efficiency:

$$\eta_{Max} = \frac{\overline{P_{LMax}}}{\overline{P_{Tot_{Max}}}} = \frac{(V_{CC} - V_{BE})^2 \; R_L \cdot \pi}{2 R_L \, V_{CC}(V_{CC} - V_{BE}) \cdot 2}$$

$$\therefore \eta_{Max} = \frac{(V_{CC} - V_{BE})}{V_{CC}} \frac{\pi}{4}$$

$$\therefore \frac{\eta_{Max\,AB}}{\eta_{Max\,A}} = 4\pi$$

Bipolar Transistor Circuits – Summary

Common Emitter	Common Base	Common Collector
		
$\boxed{r_{cb} \cong \beta \frac{V_A}{I_C}}$	$\boxed{r_d \cong \frac{kT}{qI_C}}$	
$[h_e] \cong \begin{bmatrix} \beta r_d & 0 \\ \beta & \frac{\beta}{r_{cb}} \end{bmatrix}$	$[h_b] \cong \begin{bmatrix} r_d & 0 \\ -\alpha & \frac{1}{r_{cb}} \end{bmatrix}$	$[h_c] \cong \begin{bmatrix} \beta r_d & 1 \\ -\beta & \frac{\beta}{r_{cb}} \end{bmatrix}$
		
$A_V \cong -\frac{R_C \Vert R_L}{r_d}$	$A_V \cong \frac{R_C \Vert R_L}{r_d + R_S}$	$A_V \cong \frac{1}{1 + \frac{r_d}{R_E \Vert R_L}}$
$A_i \cong \frac{\beta}{(1+\frac{R_L}{R_C})(1+\beta\frac{r_d}{R_B})}$	$A_i \cong -\frac{1}{1+\frac{R_L}{R_C}}$	$A_i \cong -\frac{\beta}{(1+\frac{R_L}{R_E})(1+\beta\frac{R_E \Vert R_L}{R_B})}$
$R_i \cong R_B \Vert \beta r_d$	$R_i \cong r_d$	$R_i \cong R_B \Vert (\beta R_E \Vert R_L)$
$R_o \cong R_C$	$R_o \cong R_C$	$R_o \cong r_d + \frac{R_S}{\beta}$

$r_d = \frac{V_T}{I_{EQ}} \cong \frac{V_T}{I_{CQ}}$