Small Signal Analysis

CM

SMALL SIGNAL MODEL OF THE BJT

- A small signal model is a linear model which is independent of signal amplitude. It may or may not have time dependence

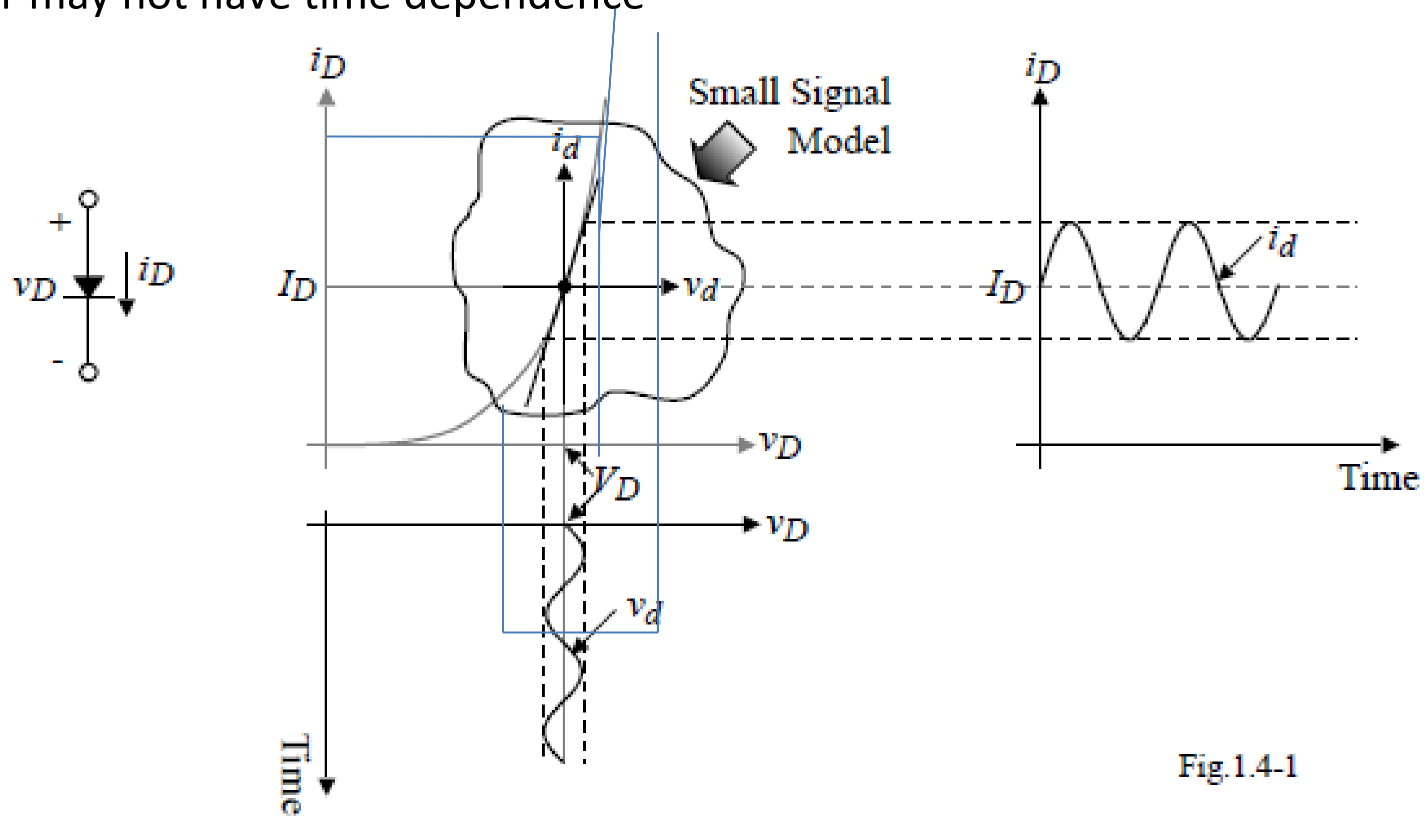
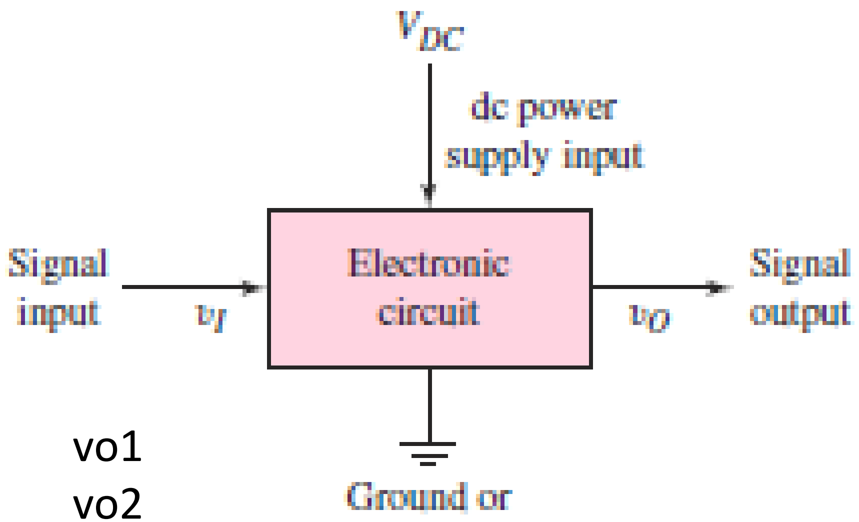
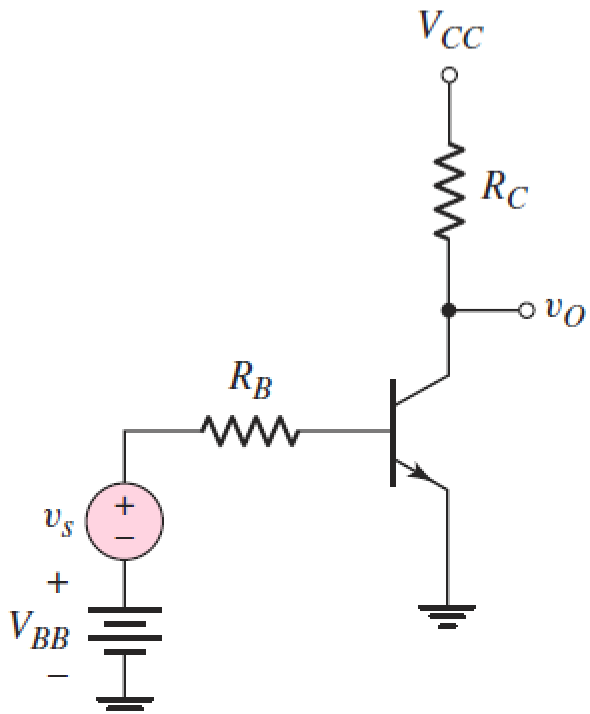


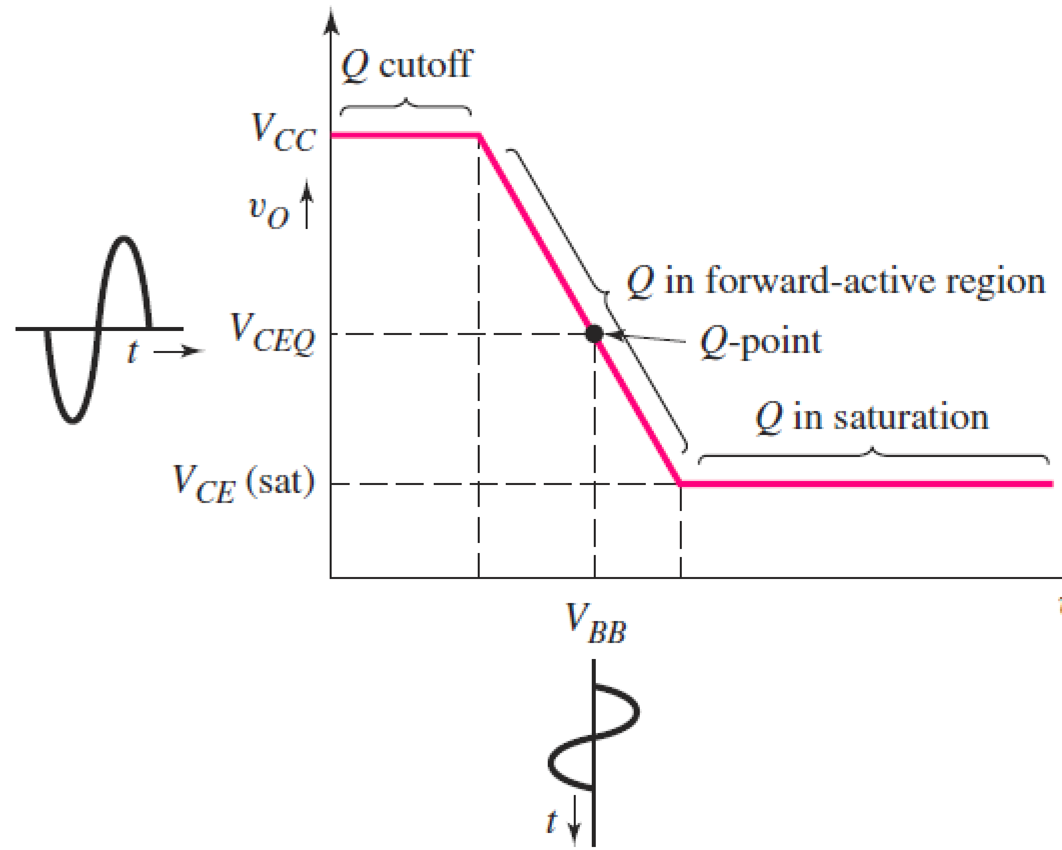
Fig.1.4-1



vi1 vo1
vi2 vo2
vi1+ vi2 vo1+vo2

A linear amplifier means that the superposition principle applies. The principle of superposition states: *The response of a linear circuit excited by multiple independent input signals is the sum of the responses of the circuit to each of the input signals alone.*


V_CC
R_C
v_O
R_B
v_s
+
−
+
V_BB
−


Q cutoff
V_CC
v_O
Q in forward-active region
V_CEQ
Q-point
t
Q in saturation
V_CE (sat)
V_BB
t

IEEE NOTATION

Variable	Meaning
i_B, v_{BE}	Total instantaneous values
I_B, V_{BE}	DC values
i_b, v_{be}	Instantaneous ac values
I_b, V_{be}	Phasor values

DESIGN OF AMPLIFIER CIRCUIT

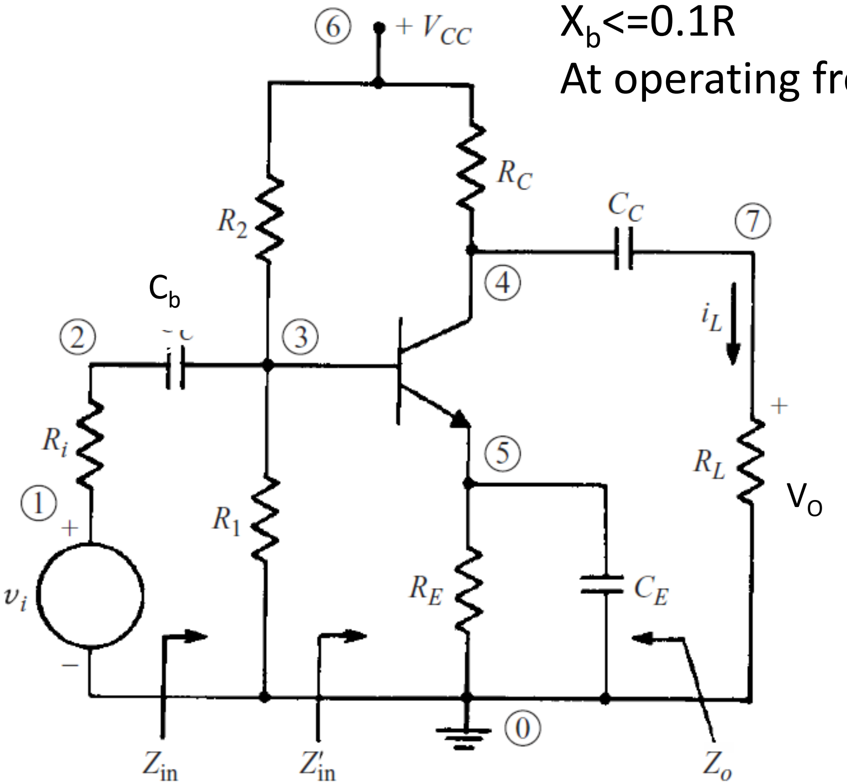
$X_b = 1/2\pi f C_b$

R

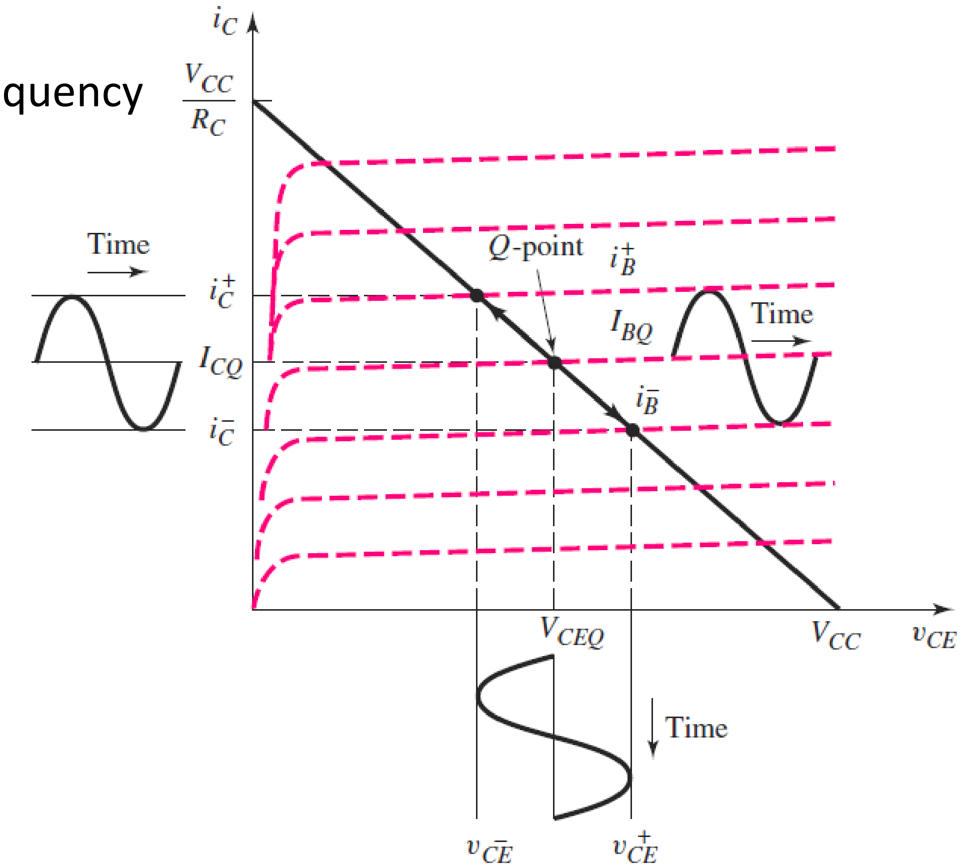
$X_b <= 0.1R$

At operating frequency

$Z = \sqrt{R^2 + X_b^2} = R$



(a)

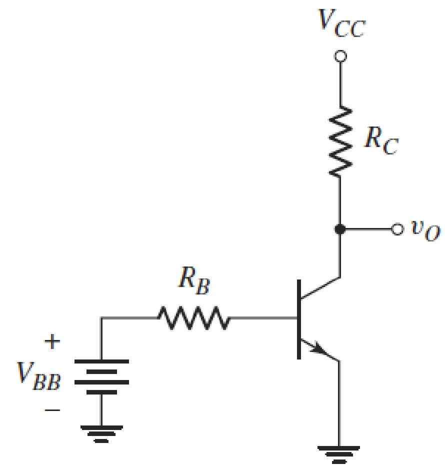


Coupling: direct , capacitive and transformer coupling

$$i_B = I_{BQ} + i_b$$

$$i_C = I_{CQ} + i_c$$

$$v_{CE} = V_{CEQ} + v_{ce}$$



$$V_{BB} = I_{BQ}R_B + V_{BEQ}$$

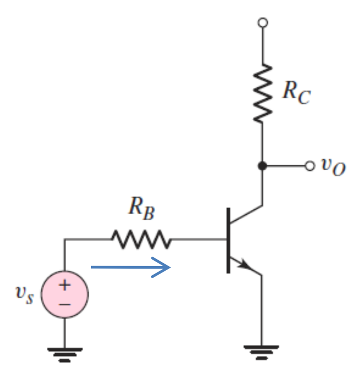
$$V_{BB} + v_s = i_B R_B + v_{BE}$$

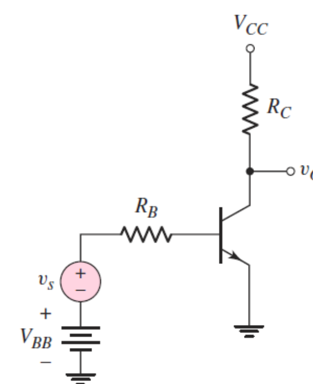
$$V_{BB} + v_s = (I_{BQ} + i_b)R_B + (V_{BEQ} + v_{be})$$

Vs→ input signal

$$V_{BB} - I_{BQ}R_B - V_{BEQ} = i_b R_B + v_{be} - v_s$$

$$v_s = i_b R_B + v_{be}$$



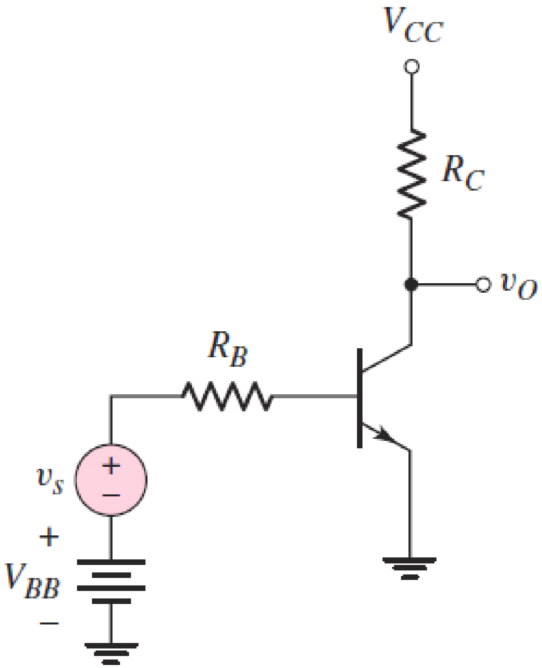


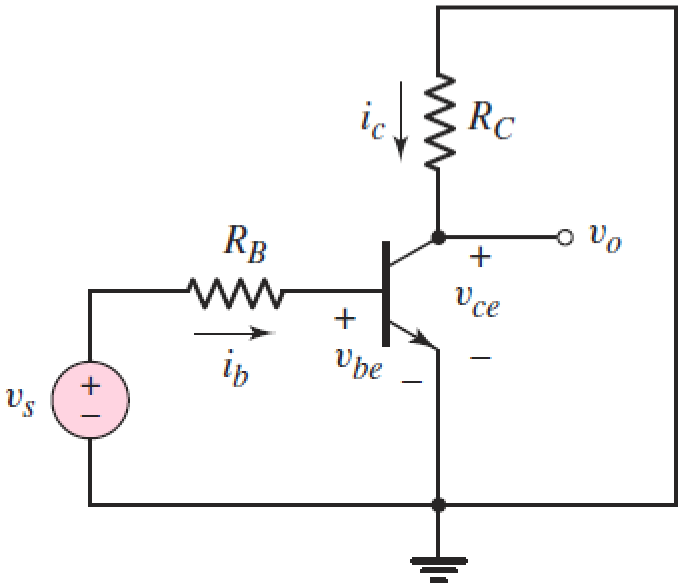
$$V_{CC} = I_{CQ}R_C + V_{CEQ}$$

$$V_{CC} = i_C R_C + v_{CE} = (I_{CQ} + i_c)R_C + (V_{CEQ} + v_{ce})$$

$$i_c R_C + v_{ce} = 0$$

$$v_s = i_b R_B + v_{be}$$





Ac equivalent circuit

$$i_C = I_S \exp\left(\frac{v_{BE}}{V_T}\right)$$

$$i_B = \frac{I_S}{\beta} \cdot \exp\left(\frac{v_{BE}}{V_T}\right)$$

$$v_{BE} = V_{BEQ} + v_{be}$$

$$i_B = \frac{I_S}{\beta} \cdot \exp\left(\frac{V_{BEQ} + v_{be}}{V_T}\right) = \frac{I_S}{\beta} \cdot \exp\left(\frac{V_{BEQ}}{V_T}\right) \cdot \exp\left(\frac{v_{be}}{V_T}\right)$$

$$i_B = I_{BQ} \cdot \exp\left(\frac{v_{be}}{V_T}\right)$$

$$i_B \cong I_{BQ}\left(1 + \frac{v_{be}}{V_T}\right) = I_{BQ} + \frac{I_{BQ}}{V_T} \cdot v_{be} = I_{BQ} + i_b$$

$V_{be}/V_T << 1$

$$v_{be} = i_b r_\pi$$

$$r_\pi = \frac{V_T}{I_{BQ}} = \frac{\beta V_T}{I_{CQ}}$$

Input resistance

$$i_C = I_S \exp\left(\frac{v_{BE}}{V_T}\right)$$

$$\left.\frac{\partial i_C}{\partial v_{BE}}\right|_{Q\text{-}pt} = \frac{1}{V_T} \cdot I_S \exp\left(\frac{v_{BE}}{V_T}\right)\Big|_{Q\text{-}pt} = \frac{I_{CQ}}{V_T}$$

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

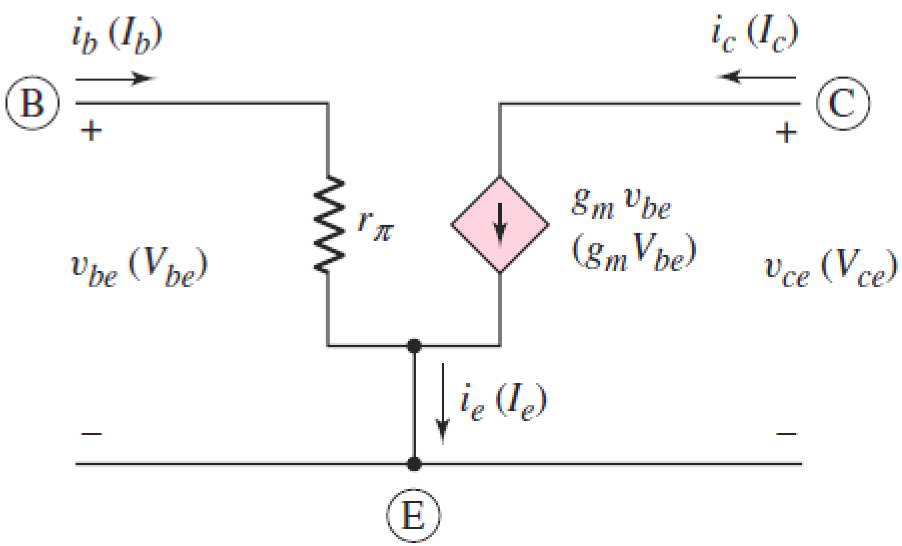
transconductance

$$v_{be} = i_b r_\pi$$

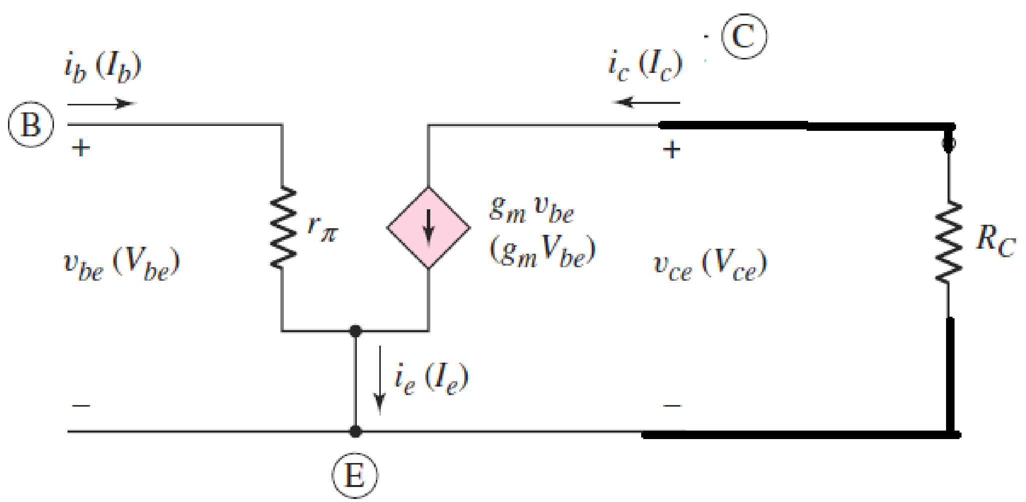
$$i_c = g_m v_{be}$$

$$v_{be} = i_b r_\pi$$

$$i_c = g_m v_{be}$$



$$i_c R_C + v_{ce} = 0$$

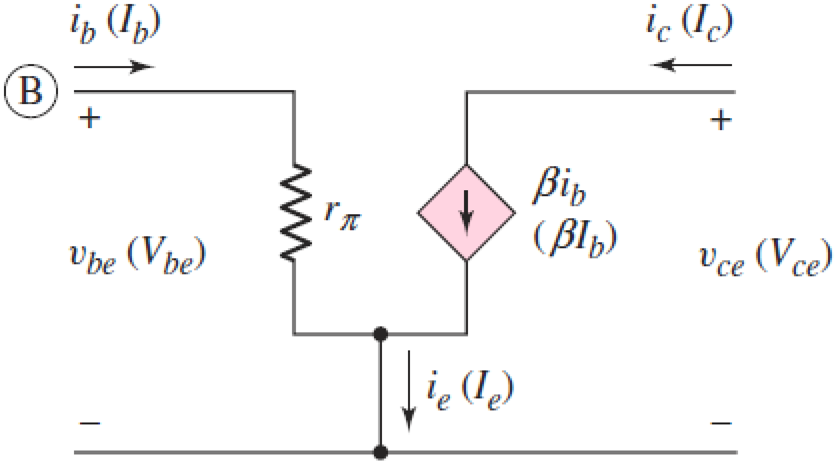


$$\Delta i_C = \left.\frac{\partial i_C}{\partial i_B}\right|_{Q\text{-}pt} \cdot \Delta i_B$$

$$i_c = \left.\frac{\partial i_C}{\partial i_B}\right|_{Q\text{-}pt} \cdot i_b$$

$$\left.\frac{\partial i_C}{\partial i_B}\right|_{Q\text{-}pt} \equiv \beta$$

$$i_c = \beta i_b$$

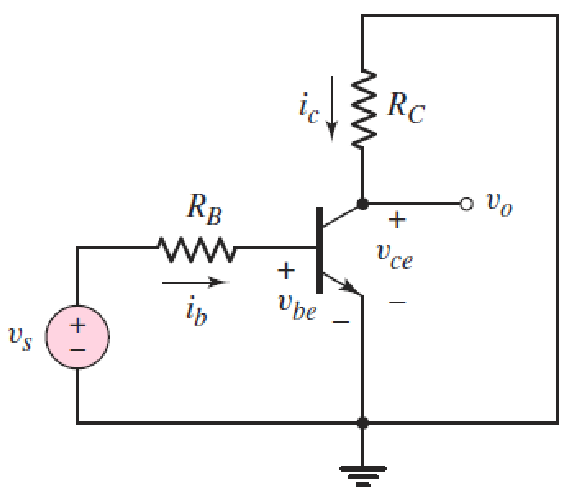


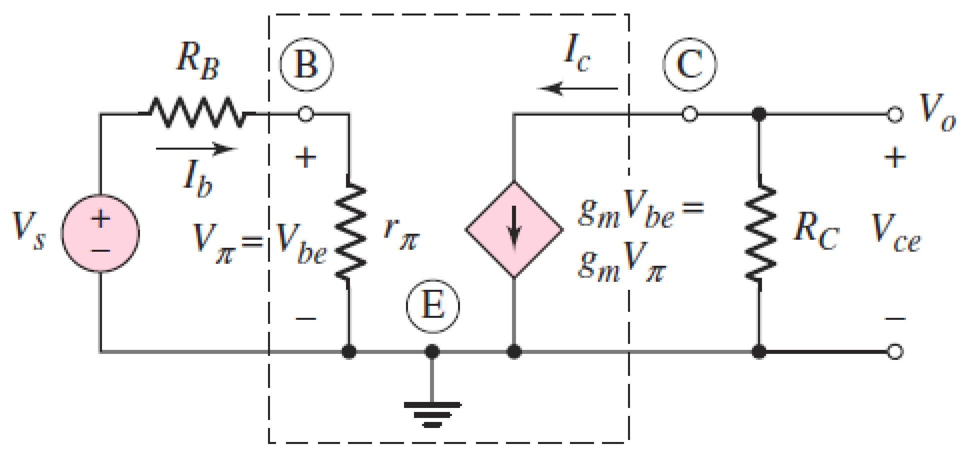
$$r_\pi g_m = \left(\frac{\beta V_T}{I_{CQ}}\right) \cdot \left(\frac{I_{CQ}}{V_T}\right) = \beta$$

$$V_o = V_{ce} = -(g_m V_\pi) R_C$$ $=-\beta/r_\pi V_\pi R_C$

Intrinsic voltage gain

$Av=-g_m R_C=-\beta R_C/r_\pi=-R_C/(r_e+R_E)$

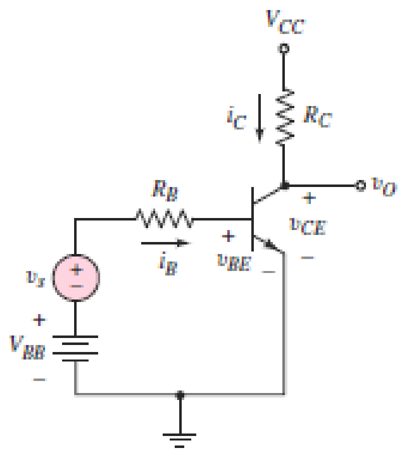


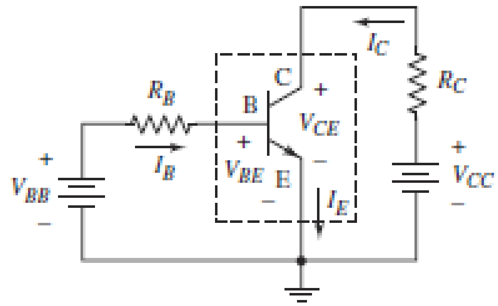


$$V_\pi = \left(\frac{r_\pi}{r_\pi + R_B}\right) \cdot V_s$$

$$A_{vo} = \frac{V_o}{V_s} = -(g_m R_C) \cdot \left(\frac{r_\pi}{r_\pi + R_B}\right)$$

Assume the transistor and circuit parameters are: $\beta = 100$, $V_{CC} = 12$ V, $V_{BE} = 0.7$ V, $R_C = 6$ kΩ, $R_B = 50$ kΩ, and $V_{BB} = 1.2$ V.





(a) DC equivalent Circuit

gm, re
voltage

$$I_B = \frac{V_{BB} - V_{BE}(\text{on})}{R_B}$$

$$I_C = \beta I_B$$

and

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

$$I_{CQ} = 1 \text{ mA and } V_{CEQ} = 6 \text{ V.}$$

AC Solution: The small-signal hybrid-π parameters are

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(100)(0.026)}{1} = 2.6\ \text{k}\Omega$$

and

$$g_m = \frac{I_{CQ}}{V_T} = \frac{1}{0.026} = 38.5\ \text{mA/V}$$

$$A_v = \frac{V_o}{V_s} = -(g_m R_C) \cdot \left(\frac{r_\pi}{r_\pi + R_B}\right)$$

or

$$= -(38.5)(6)\left(\frac{2.6}{2.6 + 50}\right) = -11.4$$

The circuit parameters for the circuit in Figure are $V_{CC} = 3.3$ V, $V_{BB} = 0.850$ V, $R_B = 180$ kΩ, and $R_C = 15$ kΩ. The transistor parameters are $\beta = 120$ and $V_{BE}(\text{on}) = 0.7$ V. (a) Determine the Q-point values I_{CQ} and V_{CEQ}. (b) Find the small-signal hybrid-π parameters g_m and r_π. (c) Calculate the small-signal voltage gain. (Ans. (a) $I_{CQ} = 0.1$ mA, $V_{CEQ} = 1.8$ V; (b) $g_m = 3.846$ mA/V, $r_\pi = 31.2$ kΩ; (c) $A_v = -8.52$).

Problem-Solving Technique: Bipolar AC Analysis

Since we are dealing with linear amplifier circuits, superposition applies, which means that we can perform the dc and ac analyses separately. The analysis of the BJT amplifier proceeds as follows:

1. Analyze the circuit with only the dc sources present. This solution is the dc or quiescent solution, which uses the dc signal models for the elements, as listed in Table 2. The transistor must be biased in the forward-active region in order to produce a linear amplifier.

2. Replace each element in the circuit with its small-signal model, as shown in Table 6.2. The small-signal hybrid-π model applies to the transistor although it is not specifically listed in the table.

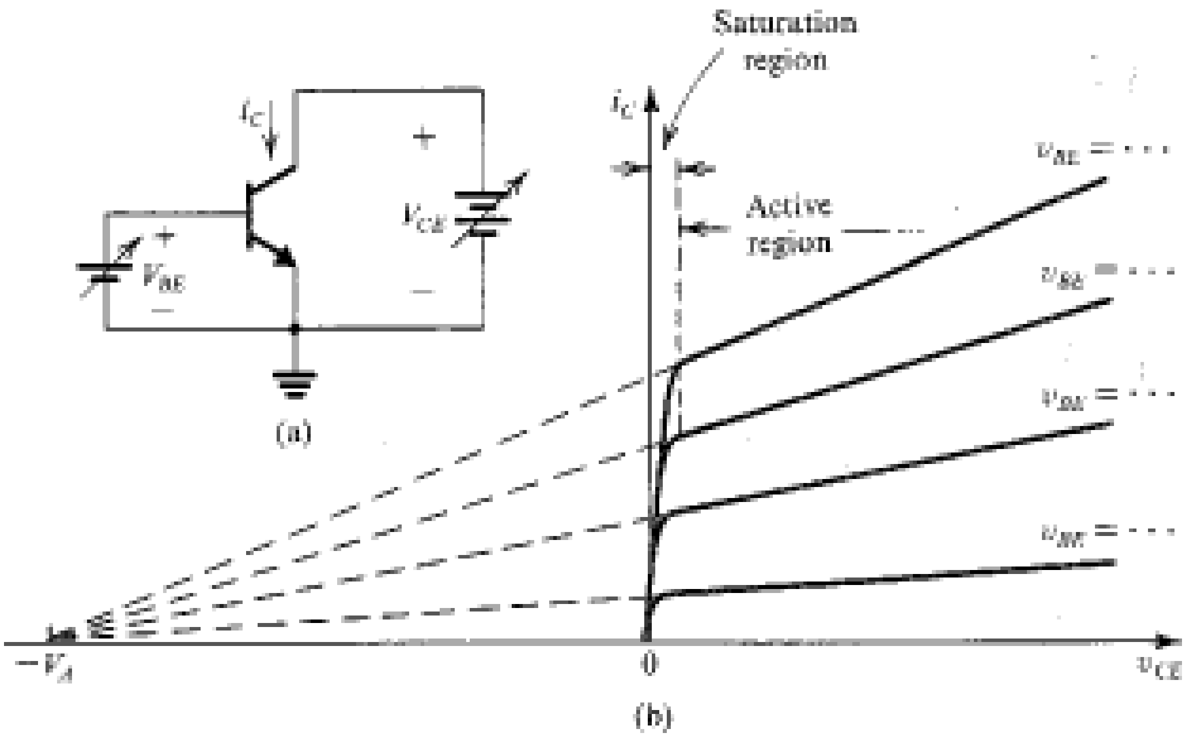
3. Analyze the small-signal equivalent circuit, setting the dc source components equal to zero, to produce the response of the circuit to the time-varying input signals only.

Table [illegible]2 Transformation of elements in dc and small-signal analysis

Element	I–V relationship	DC model	AC model
Resistor	$I_R = \dfrac{V}{R}$	R	R
Capacitor	$I_C = sCV$	Open	C
Inductor	$I_L = \dfrac{V}{sL}$	Short	L
Diode	$I_D = I_S(e^{v_D/V_T} - 1)$	$+V_\gamma - r_f$	$r_d = V_T/I_D$
Independent voltage source	$V_S = \text{constant}$	$+V_S-$	Short
Independent current source	$I_S = \text{constant}$	I_S	Open

Hybrid-π Equivalent Circuit, Including the Early Effect

$$i_C = I_S \left[\exp\left(\frac{v_{BE}}{V_T} \right) \right] \cdot \left(1 + \frac{v_{CE}}{V_A} \right)$$



V_A is the Early voltage and is a positive quantity.

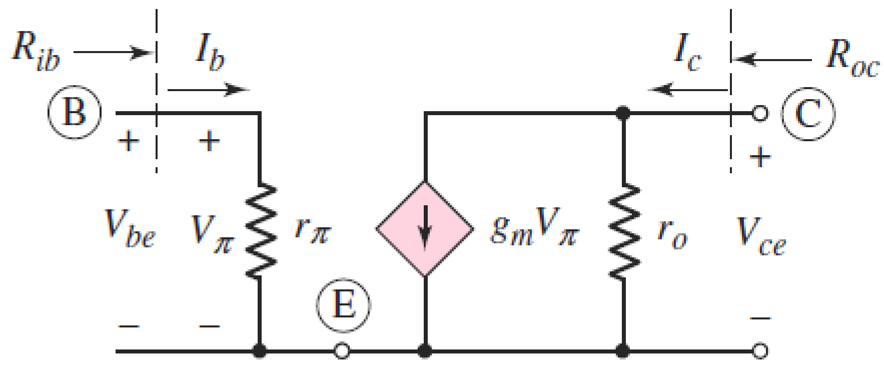
The output resistance r_o is defined as

$$r_o = [\partial v_{CE}/\partial i_C]_{Q\text{-}pt} = \left[[\partial i_C/\partial v_{CE}]_{Q\text{-}pt}\right]^{-1}$$

$$\left.\frac{\partial i_C}{\partial v_{CE}}\right|_{Q\text{-}pt} = \frac{\partial}{\partial v_{CE}}\left\{I_S\left[\exp\left(\frac{v_{BE}}{V_T}\right)\left(1+\frac{v_{CE}}{V_A}\right)\right]\right\}\Bigg|_{Q\text{-}pt}$$

$$\cong \frac{I_{CQ}}{V_A}$$

$$r_o = \frac{V_A}{I_{CQ}}$$



(a)

$$r_o = \frac{V_A}{I_{CQ}} = \frac{50}{1\ \text{mA}} = 50\,\text{k}\Omega$$

$$A_v = \frac{V_o}{V_s} = -g_m(R_C \| r_o)\left(\frac{r_\pi}{r_\pi + R_B}\right) = -(38.5)(6\|50)\left(\frac{2.6}{2.6+50}\right) = -10.2$$

$\beta = 150,$

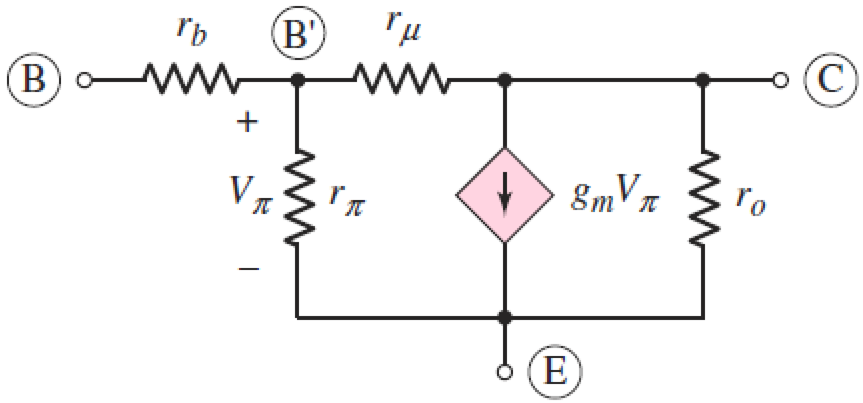
$V_A = 150$ V. The circuit parameters are $V_{CC} = 5$ V, $V_{BB} = 1$ V, $R_B = 100$ k, and $R_C = 6$ k.

(a) Determine the small-signal hybrid-π parameters g_m, r_π, and r_o.

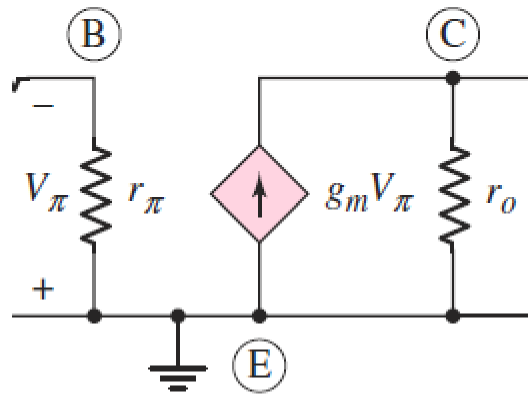
(b) Find the small-signal voltage gain $A_v = V_o/V_s$.

$g_m = 18.75$ mA/V, $r_\pi = 8$ k, $r_o = 308$ k;

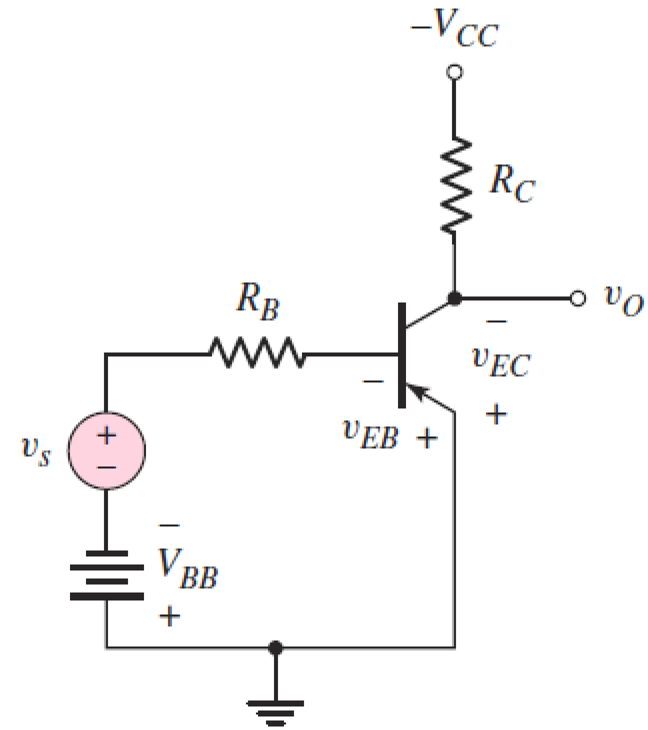
(b) $A_v = -8.17$



B
r_b
B'
r_μ
C
+
V_π
r_π
$g_m V_\pi$
r_o
−
E


B
C
−
V_π
r_π
$g_m V_\pi$
r_o
+
E

VCC=5V
RB= 50k
Rc= 3k
VBB=3.65V
β=80



(a)

$$A_v = -4.62$$

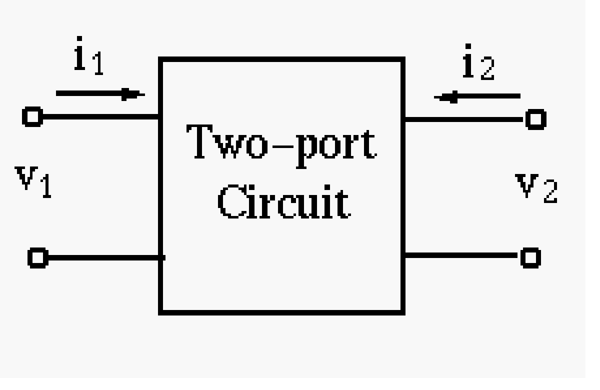
$$R_i = R_B + r_\pi = 50 + 2 = 52\,\mathrm{k\Omega}$$

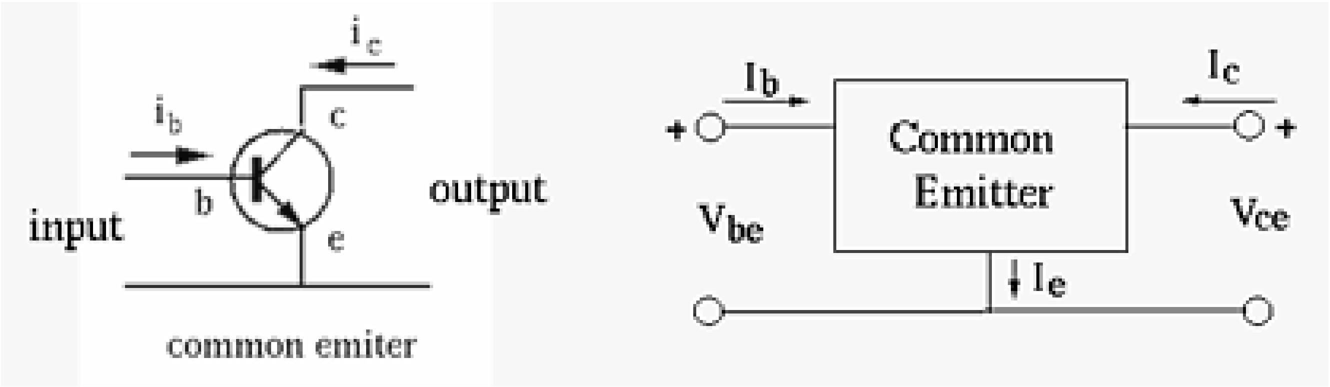
$$R_o = R_C \| r_o = 3 \| \infty = 3\,\mathrm{k\Omega}$$

Hybrid parameters

Independent signals: Input current, output voltage
dependent signals: Input voltage, output current

Vi=f1(Ii,Vo)-----(1)
Io=f2(Ii,Vo)-----(2)





$$V_{be} = h_{ie} I_b + h_{re} V_{ce}$$

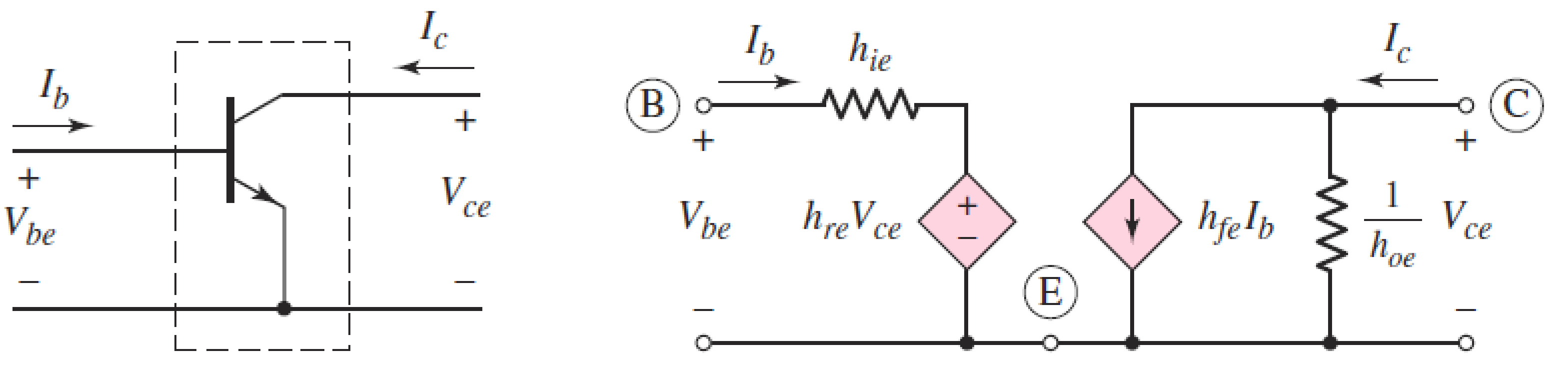
$$I_c = h_{fe} I_b + h_{oe} V_{ce}$$

h_{ie}=Vbe/Ib |v_{CE}=constant output circuit is short circuited to ac

h_{re} =V_{be}/V_{ce} | Ib=0 input circuit is open circuited to ac

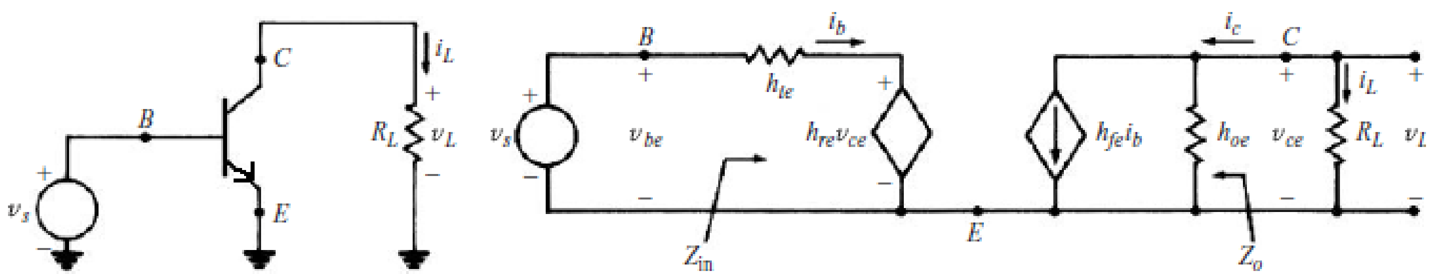
h_{fe} = I_c/I_b | v_{CE}=constant

h_{oe}= I_C/V_{ce} |Ib=0



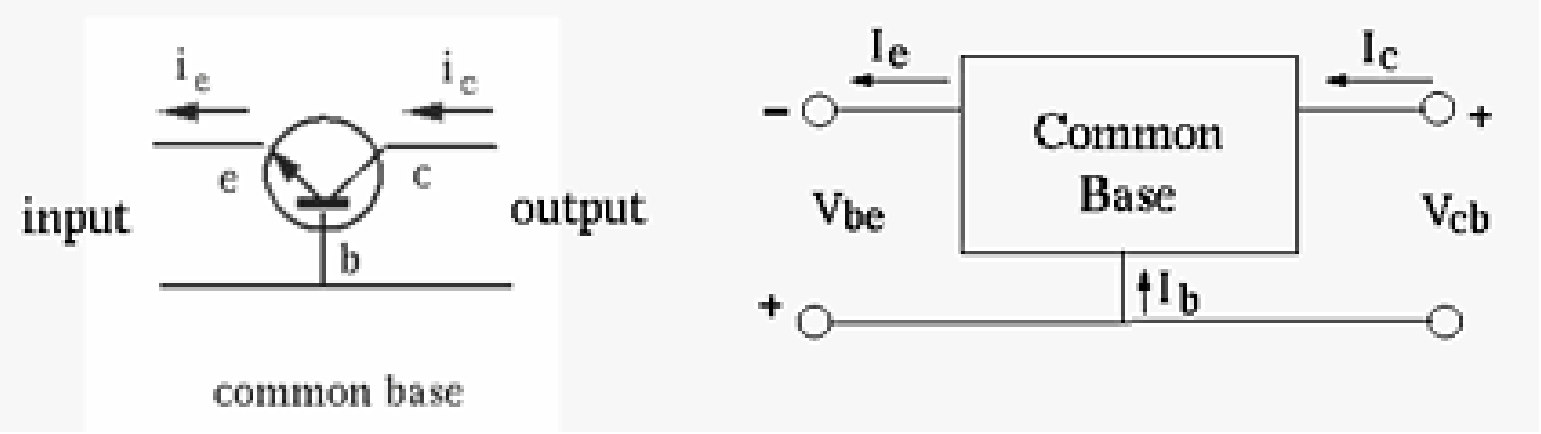
I_b
I_c
+
V_be
–
V_ce
B
C
E
h_ie
h_re V_ce
h_fe I_b
1/h_oe

(a) (b)



B
C
E
i_L
R_L
v_L
v_s
i_b
i_c
h_ie
v_be
h_re v_ce
h_fe i_b
h_oe
v_ce
Z_in
Z_o

(a) (b)

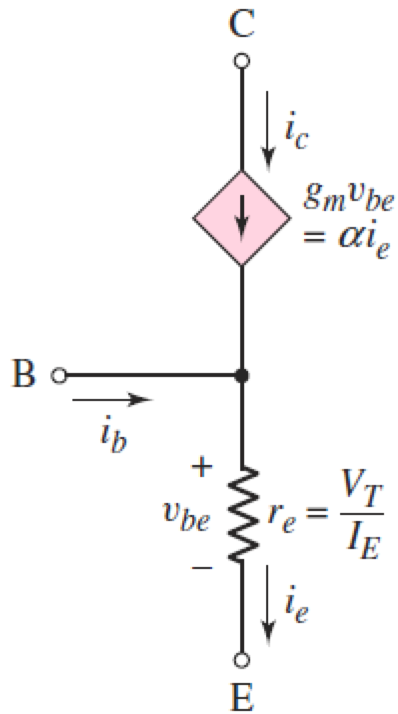


h_{ib}=Veb/Ie $|v_{CB}$=constant output circuit is short circuited to ac

$h_{rb} = V_{eb}/V_{cb}$ | Ie=0 input circuit is open circuited to ac

$h_{fb} = I_c/I_e \mid v_{CB}$=constant

$h_{ob} = I_C/V_{cb}$ |Ie=0


C
i_c
$g_m v_{be}$
$= \alpha i_e$
B
i_b
+
v_{be}
−
$r_e = \frac{V_T}{I_E}$
i_e
E

Common-Base Transistor Connection

$$v_{eb} = h_{ib} i_e + h_{rb} v_{cb}$$

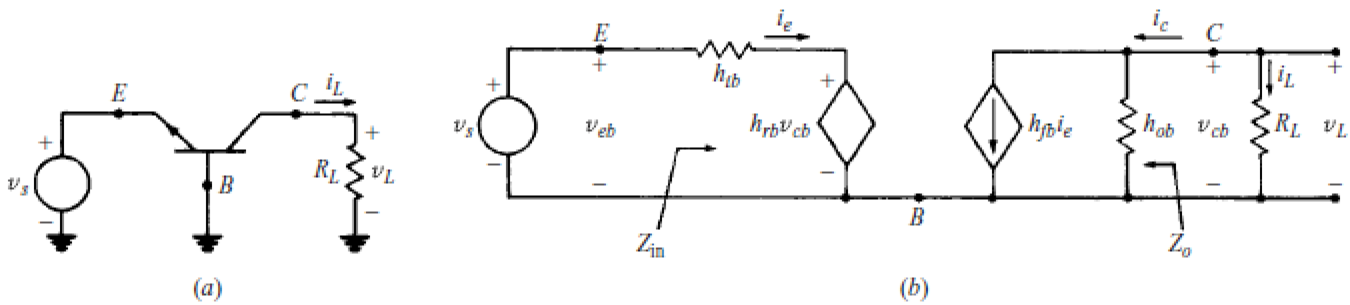
$$i_c = h_{fb} i_e + h_{ob} v_{cb}$$

Input resistance $\quad h_{ib} \equiv \left.\frac{\partial v_{EB}}{\partial i_E}\right|_Q \approx \left.\frac{\Delta v_{EB}}{\Delta i_E}\right|_Q$

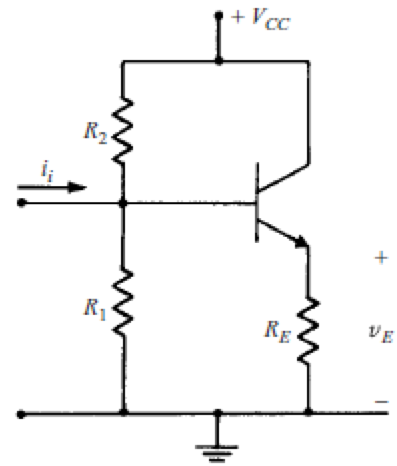
Reverse voltage ratio $\quad h_{rb} \equiv \left.\frac{\partial v_{EB}}{\partial v_{CB}}\right|_Q \approx \left.\frac{\Delta v_{EB}}{\Delta v_{CB}}\right|_Q$

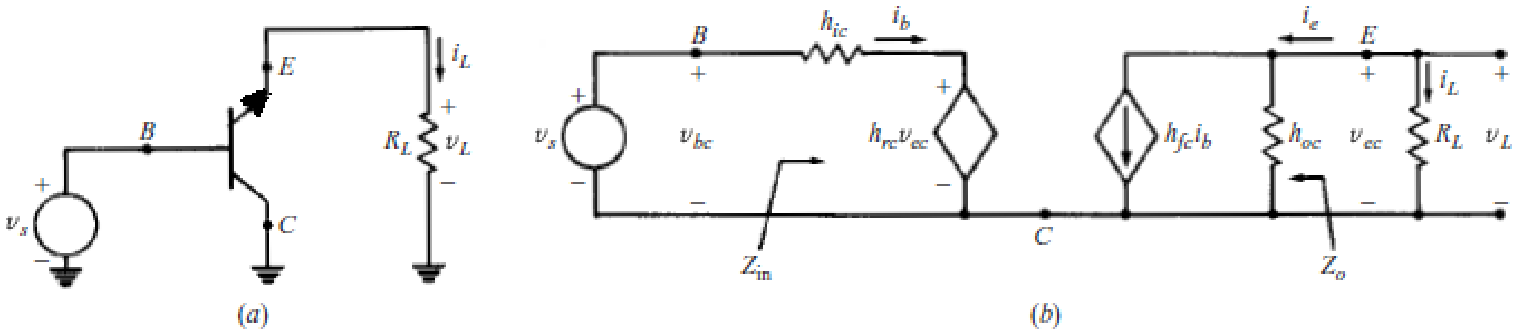
Forward current gain $\quad h_{fb} \equiv \left.\frac{\partial i_C}{\partial i_E}\right|_Q \approx \left.\frac{\Delta i_C}{\Delta i_E}\right|_Q$

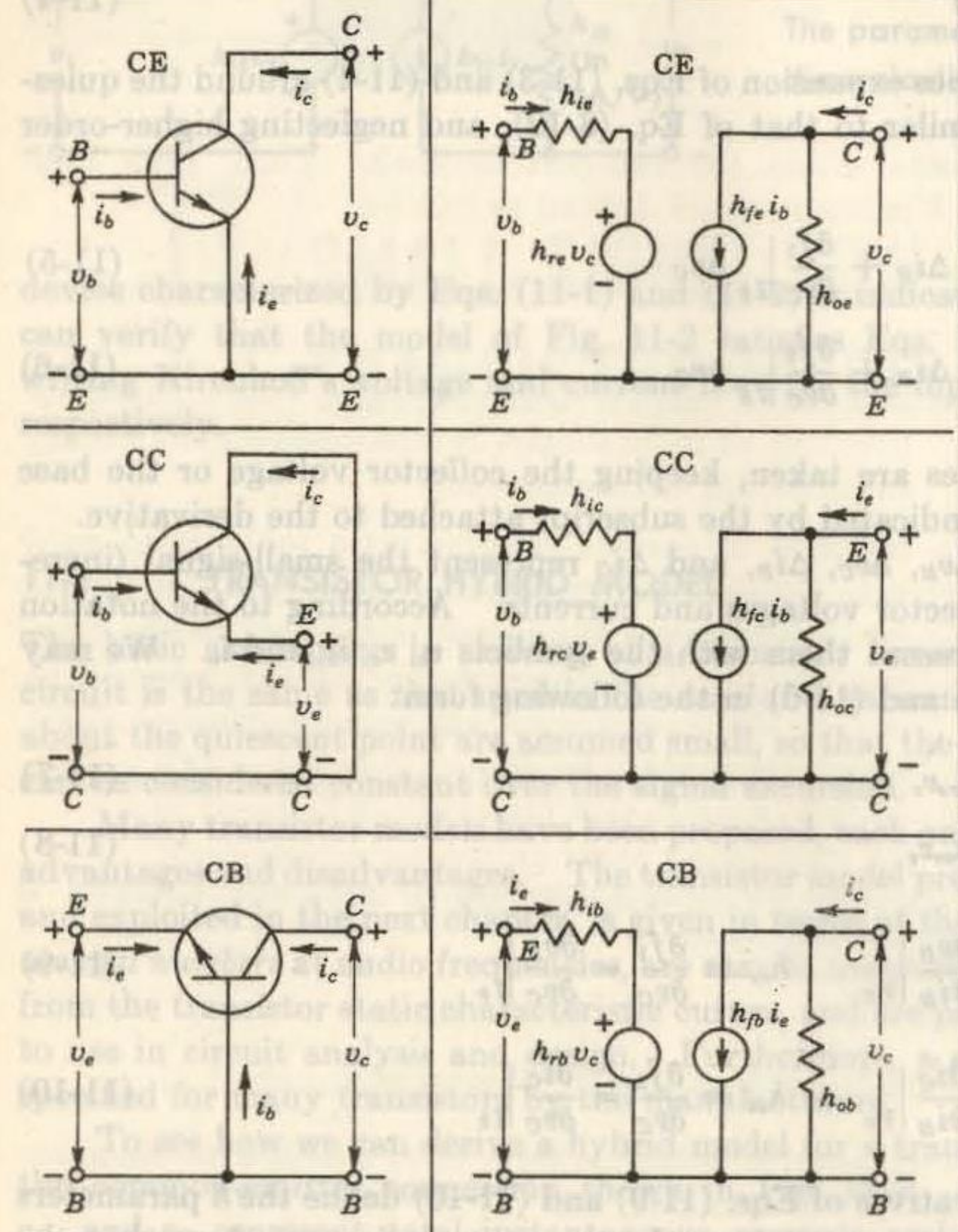
Output admittance $\quad h_{ob} \equiv \left.\frac{\partial i_C}{\partial v_{CB}}\right|_Q \approx \left.\frac{\Delta i_C}{\Delta v_{CB}}\right|_Q$



Common-Collector Amplifier







CE

$$v_b = h_{ie}i_b + h_{re}v_c$$
$$i_c = h_{fe}i_b + h_{oe}v_c$$

CC

$$v_b = h_{ic}i_b + h_{rc}v_e$$
$$i_e = h_{fc}i_b + h_{oc}v_e$$

CB

$$v_e = h_{ib}i_e + h_{rb}v_c$$
$$i_c = h_{fb}i_e + h_{ob}v_c$$

CONVERSION OF h-PARAMETERS

reasonable approximations $h_{re} << 1$ and $h_{fe}+1 >> h_{ie}h_{oe}$

$$v_{be} = h_{ie}i_b + h_{re}v_{ce}$$

$$v_{eb} = -h_{ie}i_b - h_{re}v_{ce}$$

$$i_b = -i_e - i_c = -i_e - h_{fe}i_b - h_{oe}v_{ce}$$

$$-i_b = \frac{1}{h_{fe}+1}\,i_e + \frac{h_{oe}}{h_{fe}+1}\,v_{ce}$$

$$v_{ce} = v_{cb} - v_{eb}$$

$$v_{eb} = h_{ie}\left[\frac{1}{h_{fe}+1}\,i_e + \frac{h_{oe}}{h_{fe}+1}\,v_{ce}\right] - h_{re}v_{ce}$$

$$= \frac{h_{ie}}{h_{fe}+1} i_e + \left[\frac{h_{ie} h_{oe}}{h_{fe}+1} - h_{re} \right] v_{ce}$$

$$= \frac{h_{ie}}{h_{fe}+1} i_e + \left[\frac{h_{ie} h_{oe}}{h_{fe}+1} - h_{re} \right] (v_{cb} - v_{eb})$$

$$v_{eb} \left[1 - \frac{h_{ie} h_{oe}}{h_{fe}+1} - h_{re} \right] = \frac{h_{ie}}{h_{fe}+1} i_e + \left[\frac{h_{ie} h_{oe}}{h_{fe}+1} - h_{re} \right] v_{cb}$$

reasonable approximations $h_{re} << 1$ and $h_{fe}+1 >> h_{ie}h_{oe}$

$$h_{ib} = \frac{h_{ie}}{h_{fe} + 1}$$

$$h_{rb} = \frac{h_{ie}h_{oe}}{h_{fe} + 1} - h_{re}$$

$$i_c = h_{fe} i_b + h_{oe} v_{ce}$$

$$-i_b = \frac{1}{h_{fe}+1}\, i_e + \frac{h_{oe}}{h_{fe}+1}\, v_{ce}$$

$$v_{ce} = v_{cb} - v_{eb}$$

$$v_{eb} \approx \frac{h_{ie}}{h_{fe}+1}\, i_e + \left(\frac{h_{ie} h_{oe}}{h_{fe}+1} - h_{re}\right) v_{cb}$$

$$i_c = -\left[\frac{h_{fe}}{h_{fe}+1} + \frac{h_{oe} h_{ie}}{(h_{fe}+1)^2}\right] i_e - h_{oe}\left[\frac{h_{ie} h_{oe}}{(h_{fe}+1)^2} - \frac{h_{re}+1}{h_{fe}+1}\right] v_{cb}$$

$$i_c \approx -\frac{h_{fe}}{h_{fe}+1}\, i_e + \frac{h_{oe}}{h_{fe}+1}\, v_{cb}$$

$$h_{fb} = -\frac{h_{fe}}{h_{fe}+1}$$

$$h_{ob} = \frac{h_{oe}}{h_{fe}+1}$$

$$h_{ib} = \frac{h_{ie}}{h_{fe}+1}$$

$$h_{rb} = \frac{h_{ie}h_{oe}}{h_{fe}+1} - h_{re}$$

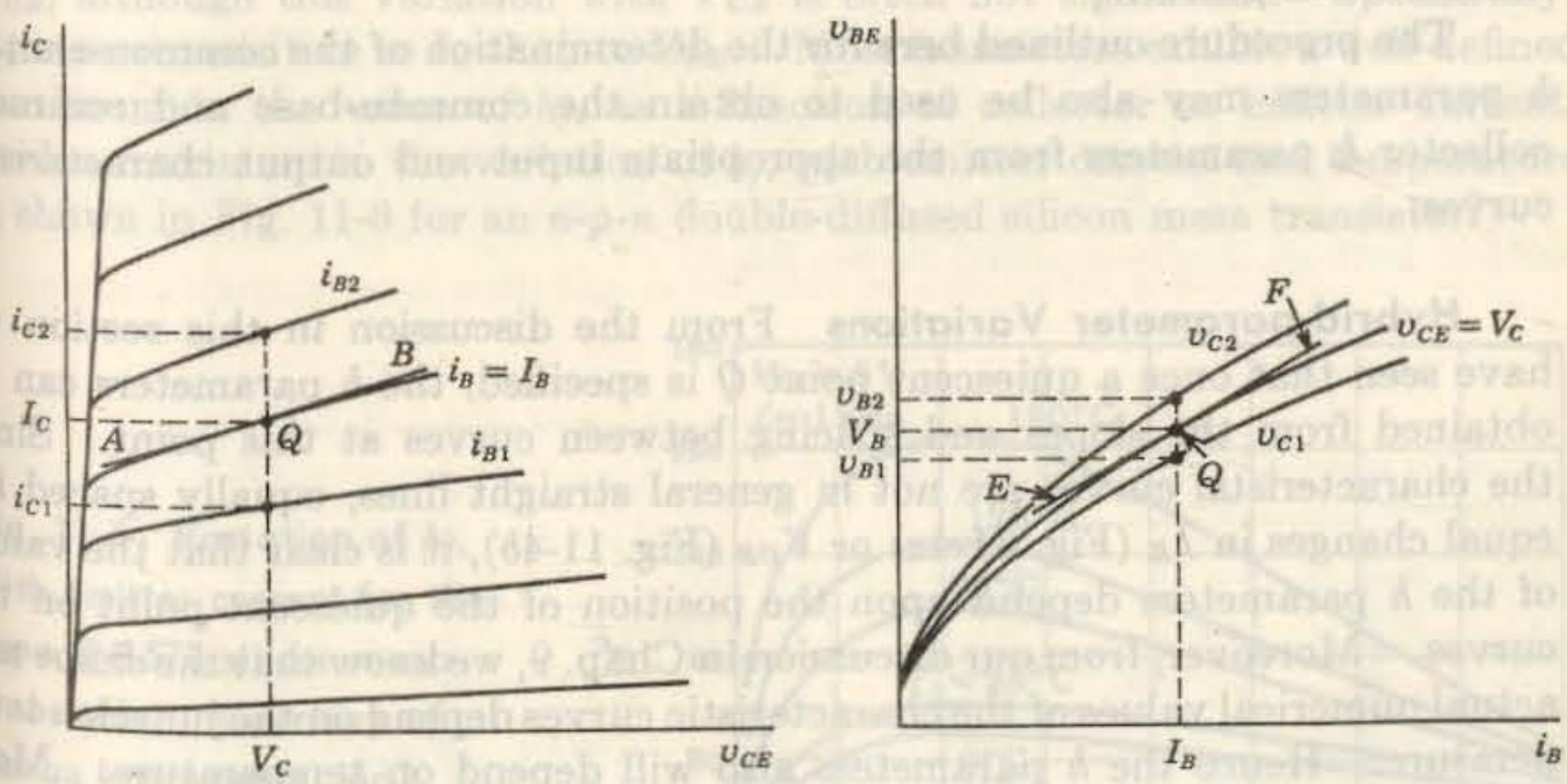
h_{fc}	$-(1 + h_{fe})$
h_{rc}	$1 - h_{re} \approx 1$
h_{oc}	h_{oe}
h_{ic}	h_{ie}

$$h_{ic} = h_{ie} \qquad h_{rc} = 1 - h_{re} \qquad h_{fc} = -(h_{fe} + 1) \qquad h_{oc} = h_{oe}$$

DETERMINATION OF THE h PARAMETERS FROM THE CHARACTERISTICS[2]

$$h_{fe} = \frac{\partial i_C}{\partial i_B} \approx \left.\frac{\Delta i_C}{\Delta i_B}\right|_{V_C} = \frac{i_{C2} - i_{C1}}{i_{B2} - i_{B1}}$$

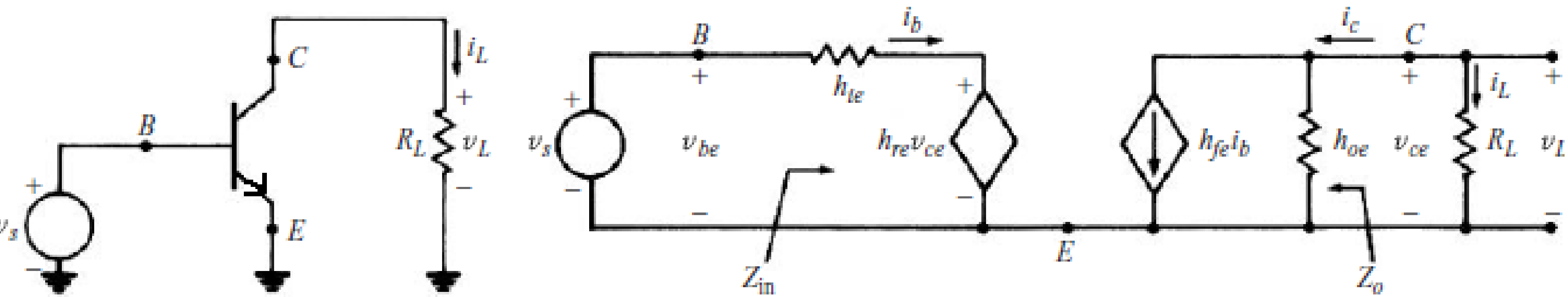
$$h_{re} = \frac{\partial v_B}{\partial v_C} \approx \left.\frac{\Delta v_B}{\Delta v_C}\right|_{I_B} = \frac{v_{B2} - v_{B1}}{v_{C2} - v_{C1}}$$



(a) (b)

$$h_{oe} = \frac{\partial i_C}{\partial v_C} \approx \frac{\Delta i_C}{\Delta v_C}\bigg|_{I_B}$$

$$h_{ie} = \frac{\partial v_B}{\partial i_B} \approx \frac{\Delta v_B}{\Delta i_B}\bigg|_{V_C}$$



(a) (b)

$$h_{ie} = 1\,\text{k}\Omega,\ h_{re} = 10^{-4},\ h_{fe} = 100,\ h_{oe} = 12\,\mu\text{S, and } R_L = 2\,\text{k}\Omega.$$

$$A_i = \frac{i_L}{i_b} = -\frac{h_{fe}}{1 + h_{oe}R_L}$$

$$-\frac{100}{1 + (12 \times 10^{-6})(2 \times 10^3)} = -97.7$$

$$v_s = v_{be} = h_{ie} i_b + h_{re} v_{ce}$$

$$v_{ce} = -h_{fe} i_b \left(\frac{1}{h_{oe}} \| R_L \right) = \frac{-h_{fe} R_L i_b}{1 + h_{oe} R_L}$$

$$A_v = -\frac{h_{fe} R_L}{h_{ie} + R_L (h_{ie} h_{oe} - h_{fe} h_{re})}$$

$$= -\frac{(100)(2 \times 10^3)}{1 \times 10^3 + (2 \times 10^3)[(1 \times 10^3)(12 \times 10^{-6}) - (100)(1 \times 10^{-4})]} = -199.2$$

$$A_v \approx -h_{fe} R_L / h_{ie}$$

$$Z_{\text{in}} = \frac{v_s}{i_b} = h_{ie} - \frac{h_{re}h_{fe}R_L}{1 + h_{oe}R_L} = 1 \times 10^3 - \frac{(1 \times 10^{-4})(100)(2 \times 10^3)}{1 + (12 \times 10^{-6})(2 \times 10^3)} = 980.5\,\Omega$$

$$Z_i \equiv \frac{V_1}{I_1}$$

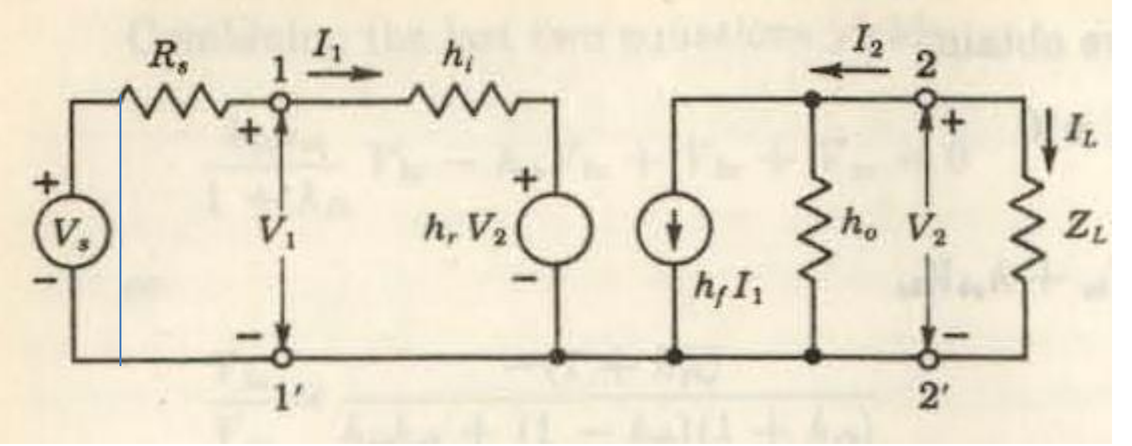
$$V_1 = h_i I_1 + h_r V_2$$

$$Z_i = \frac{h_i I_1 + h_r V_2}{I_1} = h_i + h_r \frac{V_2}{I_1}$$

$$V_2 = -I_2 Z_L = A_I I_1 Z_L$$

$$Z_i = h_i + h_r A_I Z_L = h_i - \frac{h_f h_r}{Y_L + h_o}$$

$$Y_o \equiv \frac{I_2}{V_2} \qquad \text{with } V_s = 0$$



$$I_2 = h_f I_1 + h_o V_2$$

$$Y_o = h_f \frac{I_1}{V_2} + h_o$$

Zo $= 500\,\text{k}\Omega$

$$R_s I_1 + h_i I_1 + h_r V_2 = 0$$

$$\frac{I_1}{V_2} = -\frac{h_r}{h_i + R_s}$$

$$Y_o = h_o - \frac{h_f h_r}{h_i + R_s}$$

1. Large current gain
2. Large voltage gain
3. Large power gain ($A_i A_v$)
4. Current and voltage phase shifts of 180°
5. Moderate input impedance
6. Moderate output impedance

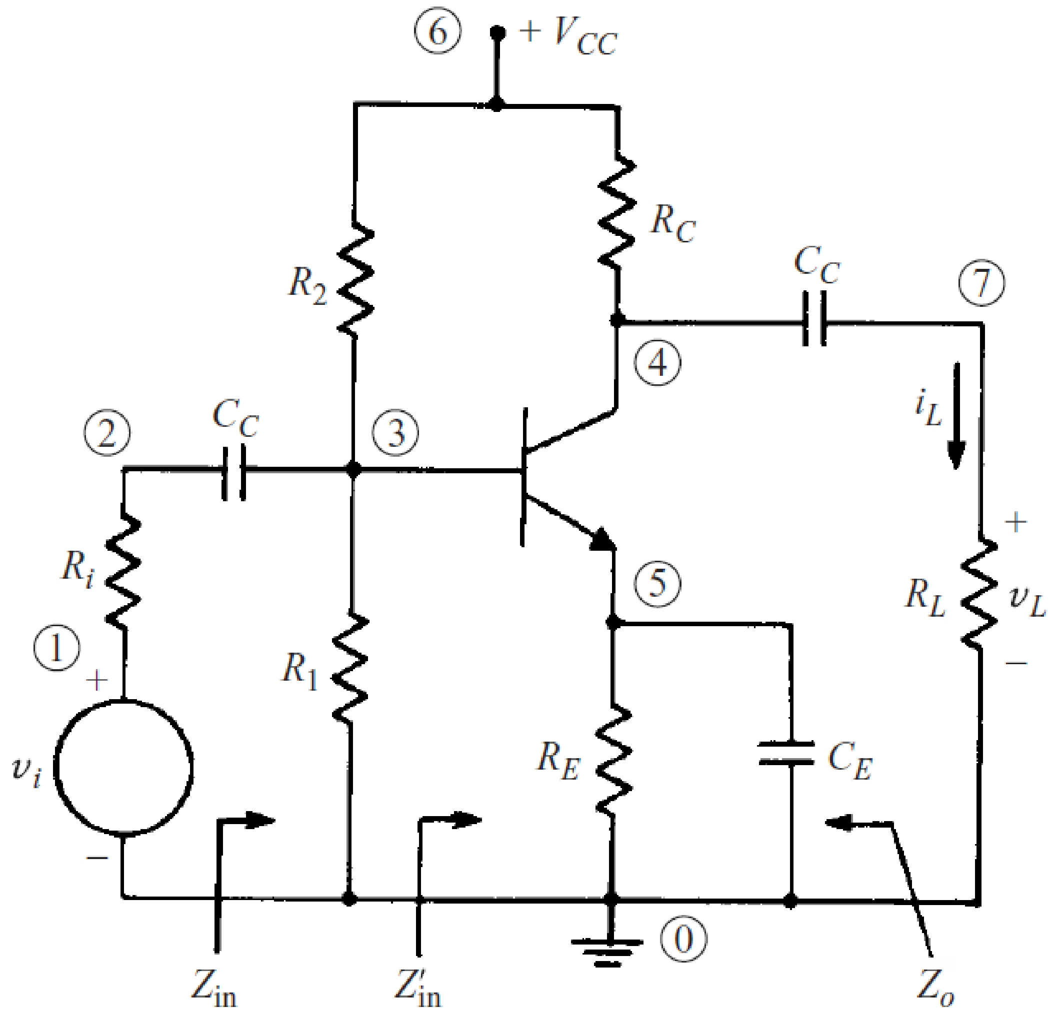
In the CB amplifier of Fig. let $h_{ib} = 30\,\Omega$, $h_{rb} = 4 \times 10^{-6}$, $h_{fb} = -0.99$, $h_{ob} = 8 \times 10^{-7}$ S, and $R_L = 20\,\mathrm{k}\Omega$. (These are typical CB amplifier values.) Find expressions for the (*a*) current-gain ratio A_i, (*b*) voltage-gain ratio A_v, (*c*) input impedance Z_{in}, and (*d*) output impedance Z_o. (*e*) Evaluate this typical CE amplifier.

1. Current gain of less than 1
2. High voltage gain
3. Power gain approximately equal to voltage gain
4. No phase shift for current or voltage
5. Small input impedance
6. Large output impedance

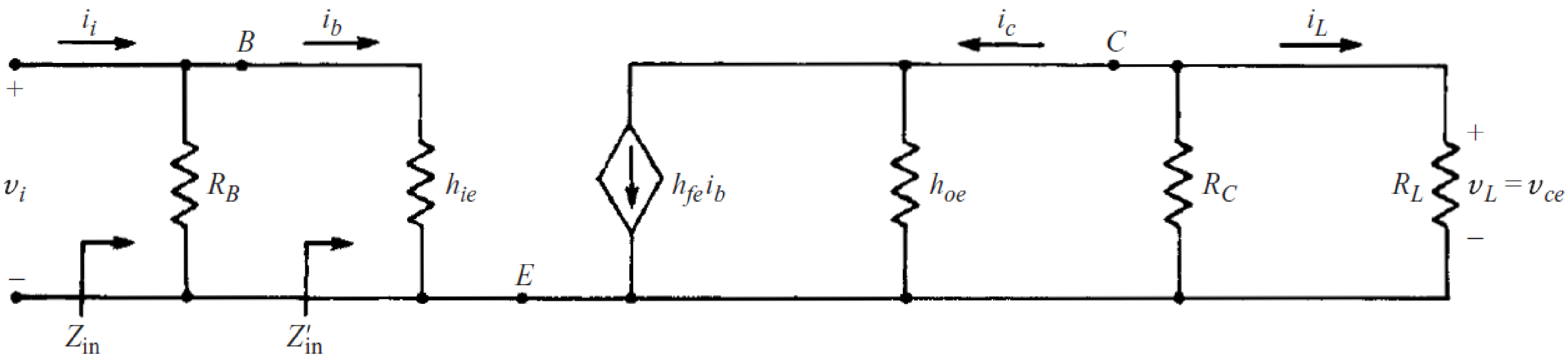
In the CC amplifier of Fig. let $h_{ic} = 1\,\text{k}\Omega$, $h_{rc} = 1$, $h_{fc} = -101$, $h_{oc} = 12\,\mu\text{S}$, and $R_L = 2\,\text{k}\Omega$. Drawing direct analogies with the CE amplifier of Example 6.2, find expressions for the (*a*) current-gain ratio A_i, (*b*) voltage-gain ratio A_v, (*c*) input impedance Z_{in}, and (*d*) output impedance Z_o. (*e*) Evaluate this typical CC amplifier.

1. High current gain
2. Voltage gain of approximately unity
3. Power gain approximately equal to current gain
4. No current or voltage phase shift
5. Large input impedance
6. Small output impedance

Jse a small-signal h-parameter equivalent circuit to analyze the amplifier of Fig. 3-10(a), giver $R_C = R_L = 800\,\Omega$, $R_i = 0$, $R_1 = 1.2\,\text{k}\Omega$, $R_2 = 2.7\,\text{k}\Omega$, $h_{re} \approx 0$, $h_{oe} = 100\,\mu\text{S}$, $h_{fe} = 90$, an $h_{ie} = 200\,\Omega$. Calculate (a) the voltage gain A_v and (b) the current gain A_i.



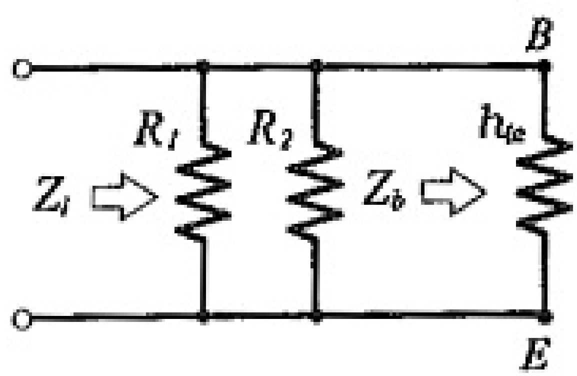
(a)



Small signal equivalent circuit

$$R_B = R_1 R_2/(R_1 + R_2) = 831\,\Omega.$$

RL'=RC||RL= 400 Ω



$$A_i = \frac{i_L}{i_b} = -\frac{h_f}{1 + h_o\ R_L}$$

$$A_v = -\frac{h_f\ R_L}{h_i + R_L(h_i\ h_o - h_f\ h_r)}$$

$$Z_i = h_i - \frac{h_f h_r}{Y_L + h_o}$$

$$Y_o = h_o - \frac{h_f h_r}{R_S + h_i}$$

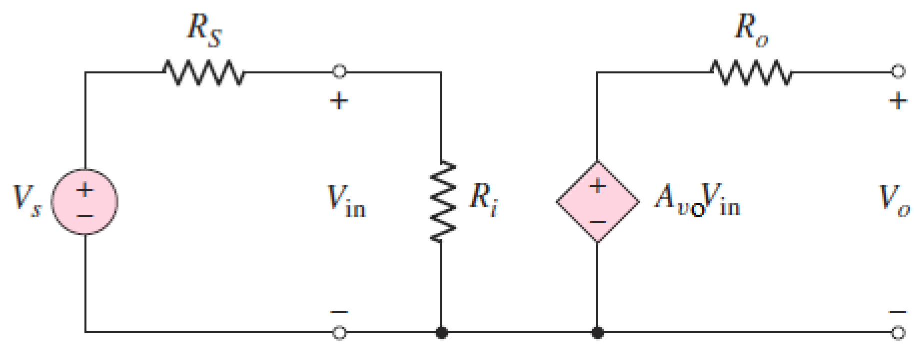
$$A_v = -\frac{\frac{h_f}{h_i h_o} h_o R_L}{1 + R_L h_o - \frac{h_f h_r R_L}{h_i}} = \frac{A_{vo} h_o R_L}{1 + R_L h_o + A_{vo} h_o h_r R_L}$$

If there is a source resistance R_s, $v_{in} = \frac{Z_i}{Z_i + R_S} v_S$

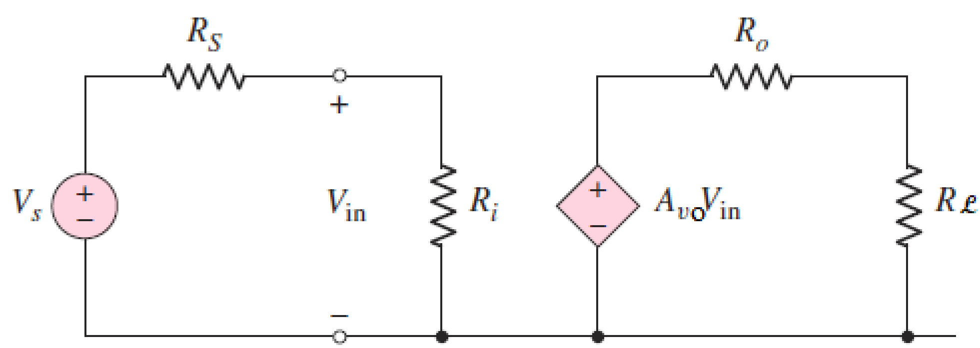
$$A_{vs} = \frac{Z_i}{Z_i + R_S} A_v$$

If there is a parallel resistance R_B

$$i_b = \frac{R_B}{R_B + h_{ie}}\ i_i \quad A_{is} = \frac{i_L}{i_i} = \frac{R_B}{R_B + h_{ie}} A_i$$



Two-port equivalent circuit for the amplifier

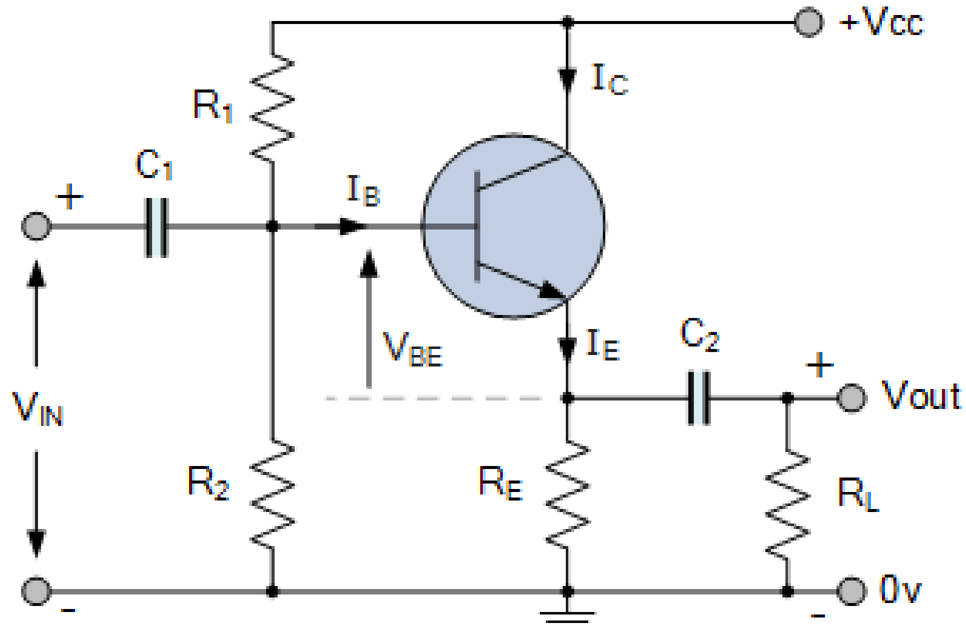


Two-port equivalent circuit for the amplifier

Av= Avo RL/(1/ho+RL)

=AvohoRL/1+hoRL

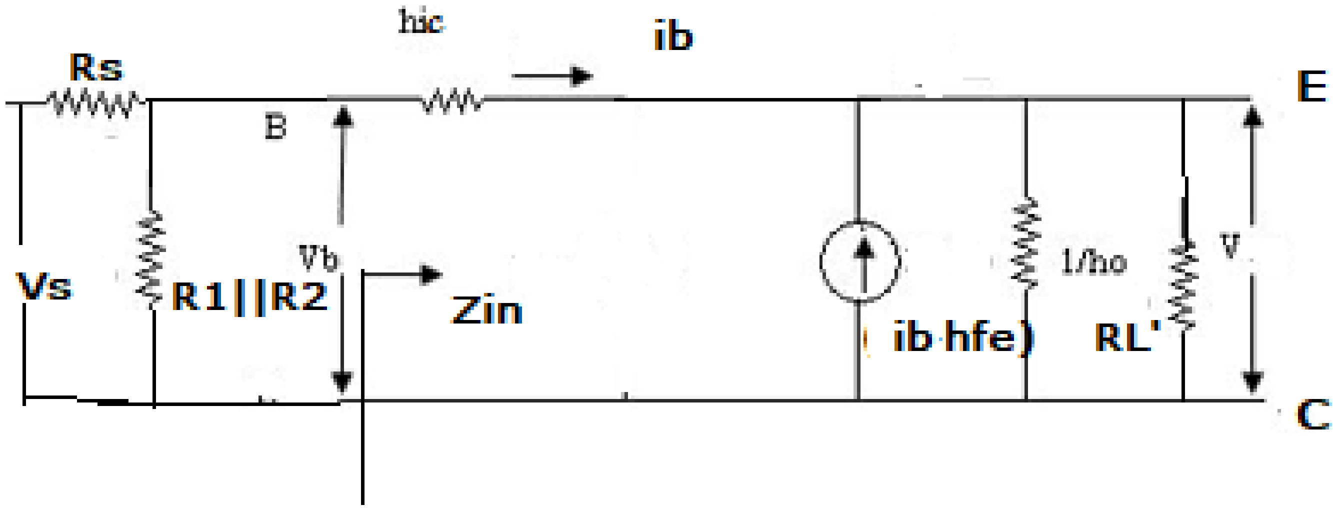
$$A_i = \frac{i_L}{i_b} = -\frac{h_f}{1 + h_o\ R_L}$$ =(1+hfe)/(1+hoeRL)



RL'=RE||RL

$$Z_{ic} = h_{ie} + \frac{(1 + h_{fe})}{Y_L + h_{oe}}$$

hie+(1+hfe)(RL’||1/hoe)

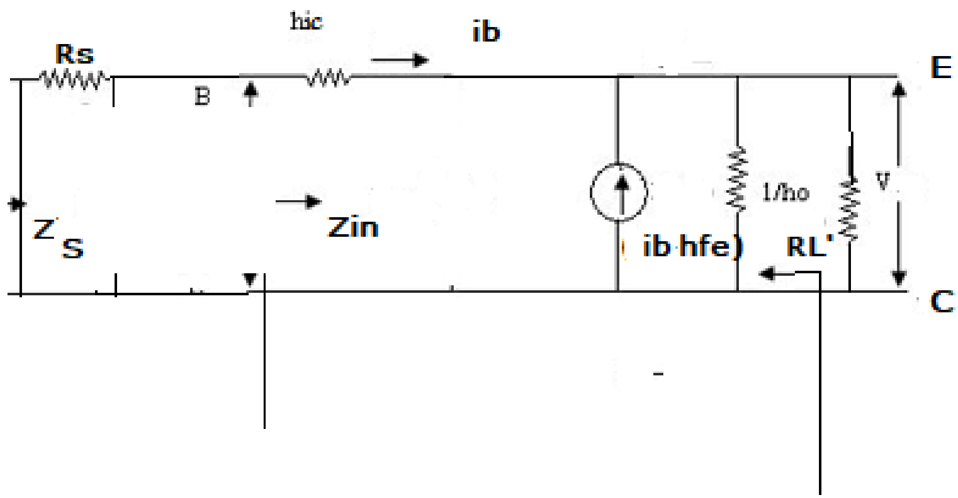


Zib=hie/1+hfe

vb=hieib + (RL'||1/hoe)(1+hfe)ib

Zin=vb/ib= hie+(RL'||1/hoe)(1+hfe)

vin=vb =(Zin'/Zin'+RS)vs



(Rs+hie)ib+vo=0

ib/vo=-1/Rs+hie

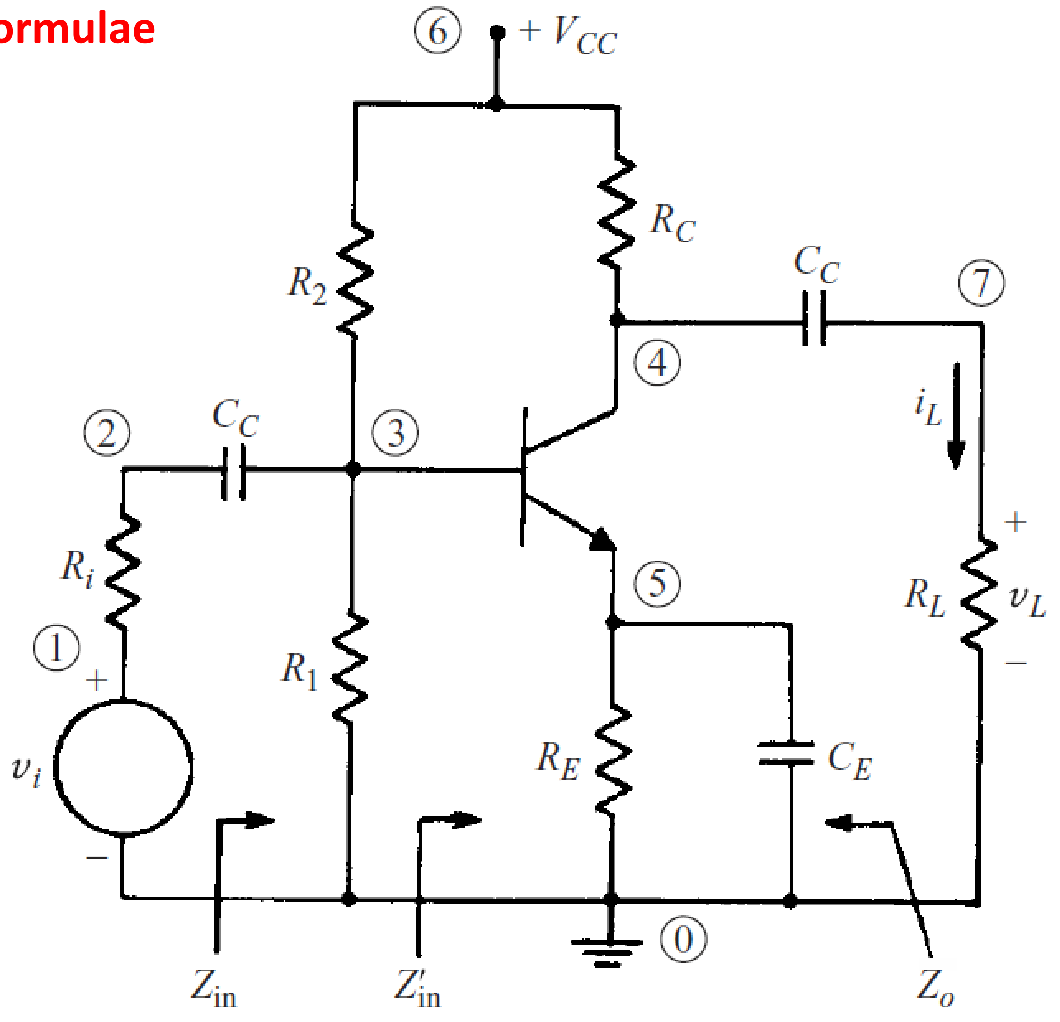
io=(hfe+1)ib+hoevo

io/vo=(hfe+1)ib/vo+hoe

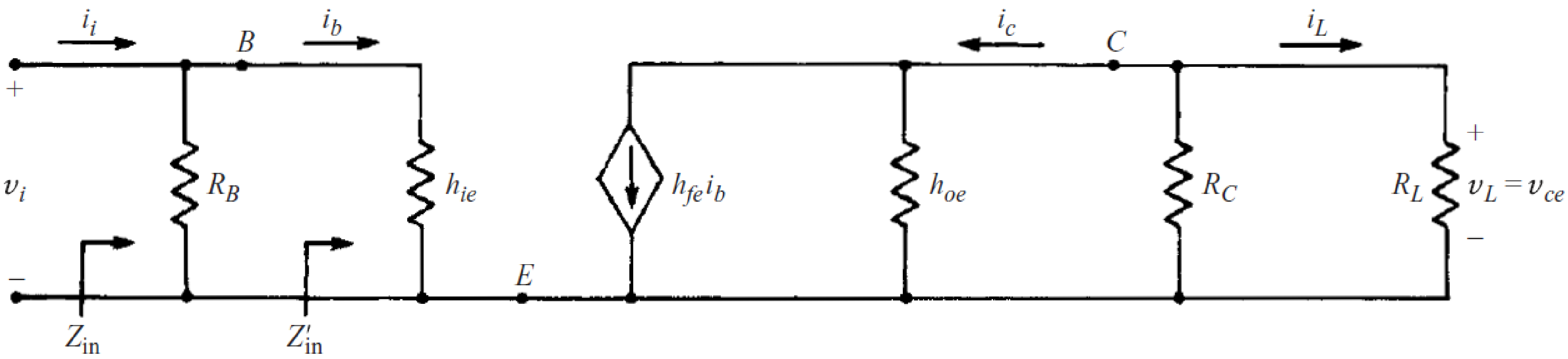
Yo =-(hfe+1)/(Rs+hie) +hoe

Jse a small-signal h-parameter equivalent circuit to analyze the amplifier of Fig. 3-10(a), give $R_C = R_L = 800\,\Omega$, $R_i = 0$, $R_1 = 1.2\,\text{k}\Omega$, $R_2 = 2.7\,\text{k}\Omega$, $h_{re} \approx 0$, $h_{oe} = 100\,\mu\text{S}$, $h_{fe} = 90$, and $h_{ie} = 200\,\Omega$. Calculate (a) the voltage gain A_v and (b) the current gain A_i.

Do not use formulae



(a)



Small signal equivalent circuit

$$R_B = R_1 R_2/(R_1 + R_2) = 831\ \Omega.$$

RL'=RC||RL= 400 Ω

$$A_{vo} = \frac{-h_{fe}}{h_{ie} h_{oe}} = -\frac{90}{200 \times 100 \times 10^{-6}} = -4.5 \times 10^3$$

$$A_v = \frac{A_{vo} h_o R_L}{1 + R_L h_o + A_{vo} h_o h_r R_L} = -4.5 \times 10^3 \times \frac{100 \times 10^{-6} \times 400}{1 + 100 \times 10^{-6} \times 400}$$

$$= -45 \times \frac{4}{1+0.04} = -173.08$$

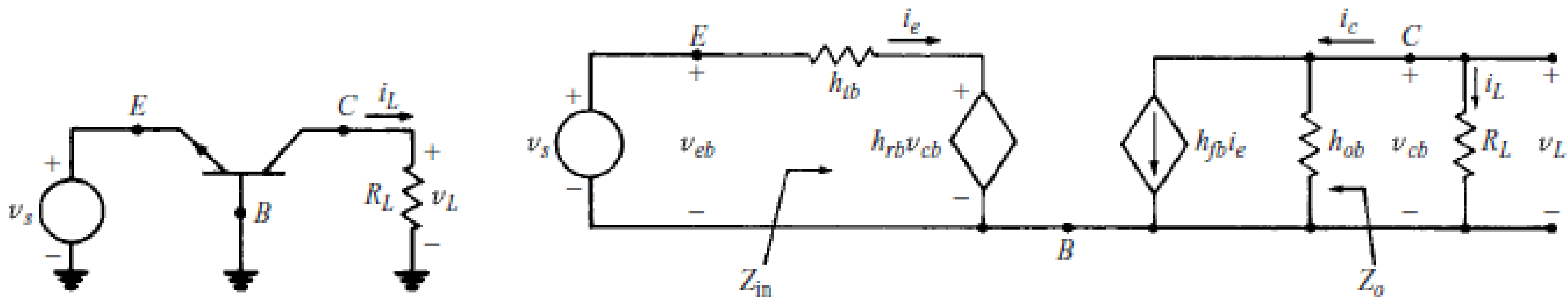
$$i_b = \frac{R_B}{R_B + h_{ie}}\ i_i$$

$$A_i = \frac{i_L}{i_b} = -\frac{h_f}{1 + h_o\ R_L}$$

$$A_i = \frac{i_L}{i_b} = \frac{-h_{fe}}{1 + R_L h_{oe}} = -\frac{90}{1 + 800 \times 100 \times 10^{-6}} = -43.27$$

$$A_{is} = \frac{i_L}{i_i} = \frac{R_B}{R_B + h_{ie}} A_i = -\frac{831}{831 + 200} 43.27 = -34.87$$

Effect of coupling capacitance and bypass capacitance



(a) (b)

$hib=hie/1+hfe$

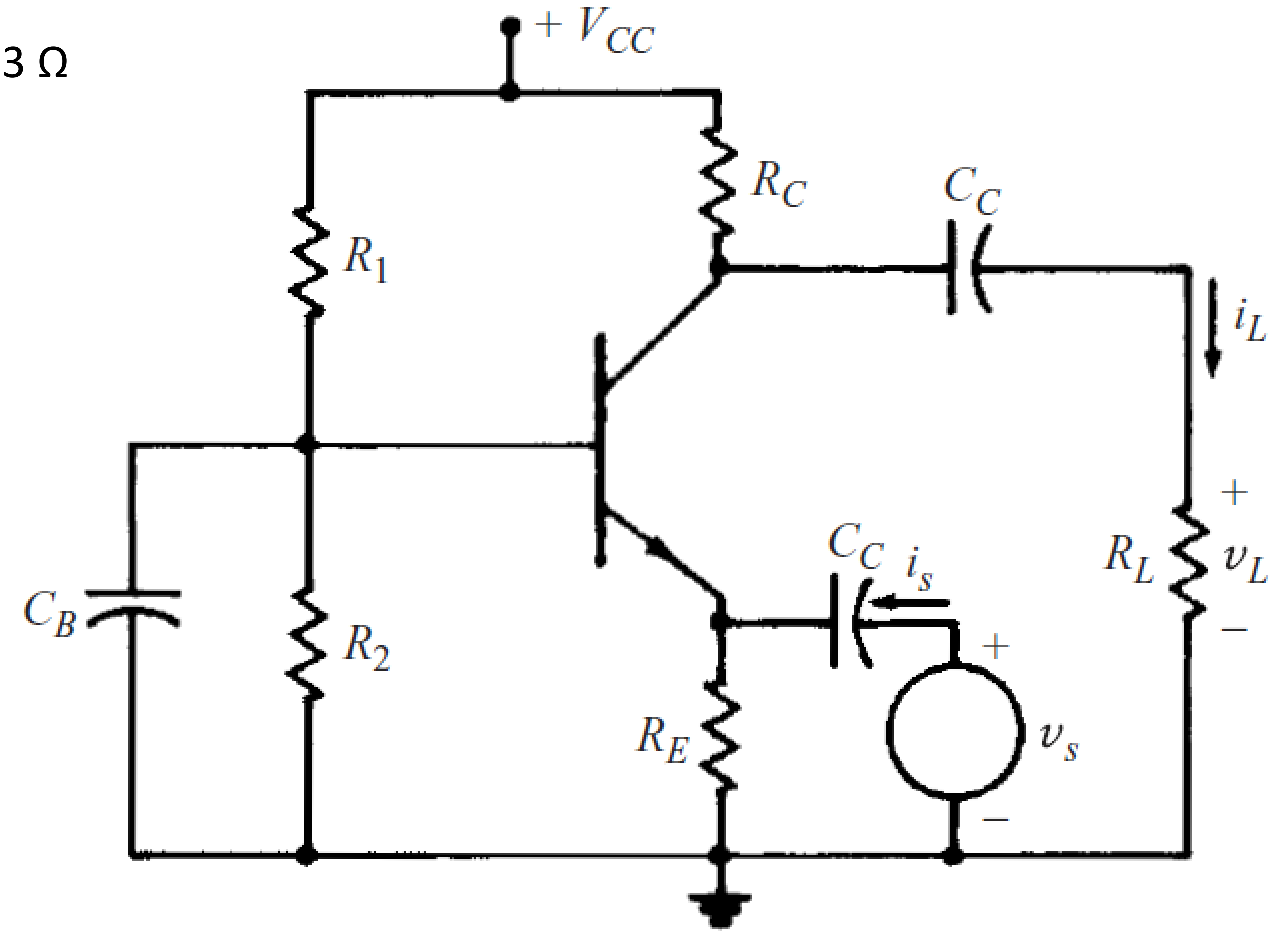
$hrb=-hre$

$hfb=-hfe/1+hfe$

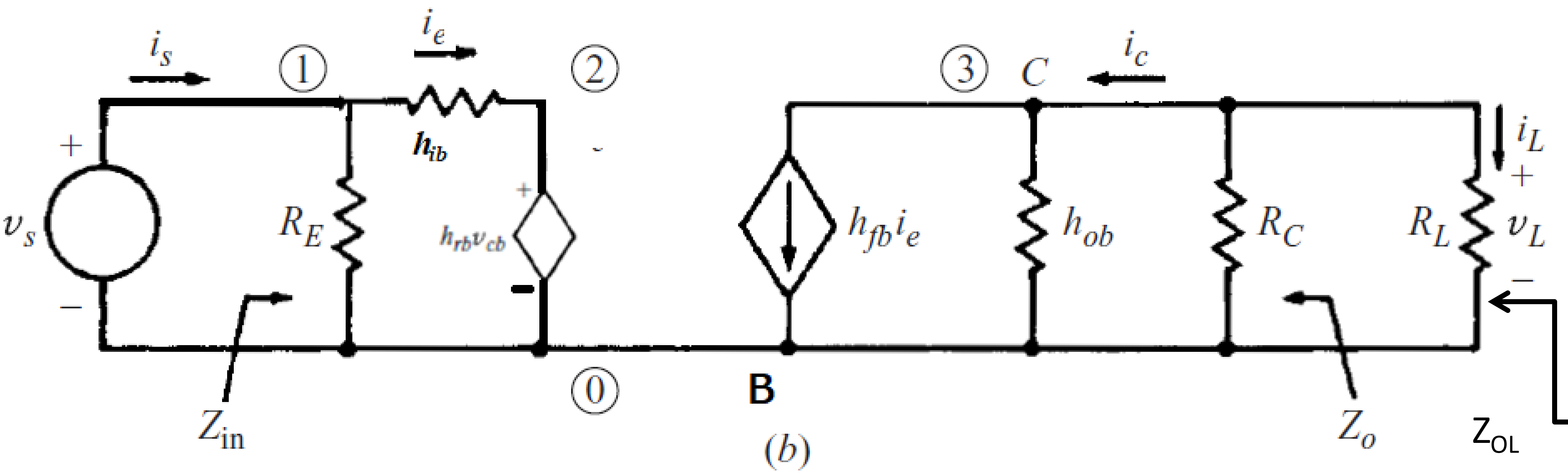
$hob=hoe/1+hfe$

In the CB amplifier of Fig (*a*), let $R_1 = R_2 = 50\ \text{k}\Omega$, $R_C = 2.2\ \text{k}\Omega$, $R_E = 3.3\ \text{k}\Omega$, $R_L = 1.1\ \text{k}\Omega$, $C_C = C_B \to \infty$, $h_{rb} \approx 0$, $h_{ib} = 25\ \Omega$, $h_{ob} = 10^{-6}\ \text{S}$, and $h_{fb} = -0.99$. Find and evaluate expressions for (*a*) the voltage-gain ratio $A_v = v_L/v_s$ and (*b*) the current-gain ratio $A_i = i_L/i_s$.

RC||RL=733 Ω



(*a*)



(b)

ZOL=1/hob||RC||RL=732.8 Ω

$v_L = -h_{fb} x i_e x Z_{OL}$

$vs = vi = h_{ib} \times i_e$

Av=-hfbxZOL/hib

=0.99x732.8/25=29.02

iL=vL/RL=-hfbxiexZOL/RL

Ai=iL/ie=-hfbxZOL/RL

Ai=Avxhib/RL=29.02x25/1100=0.6595

Ais=3.3/(3.3+0.025)x0.6595=0.6545

Zin=hib||RE

=24.8 Ω

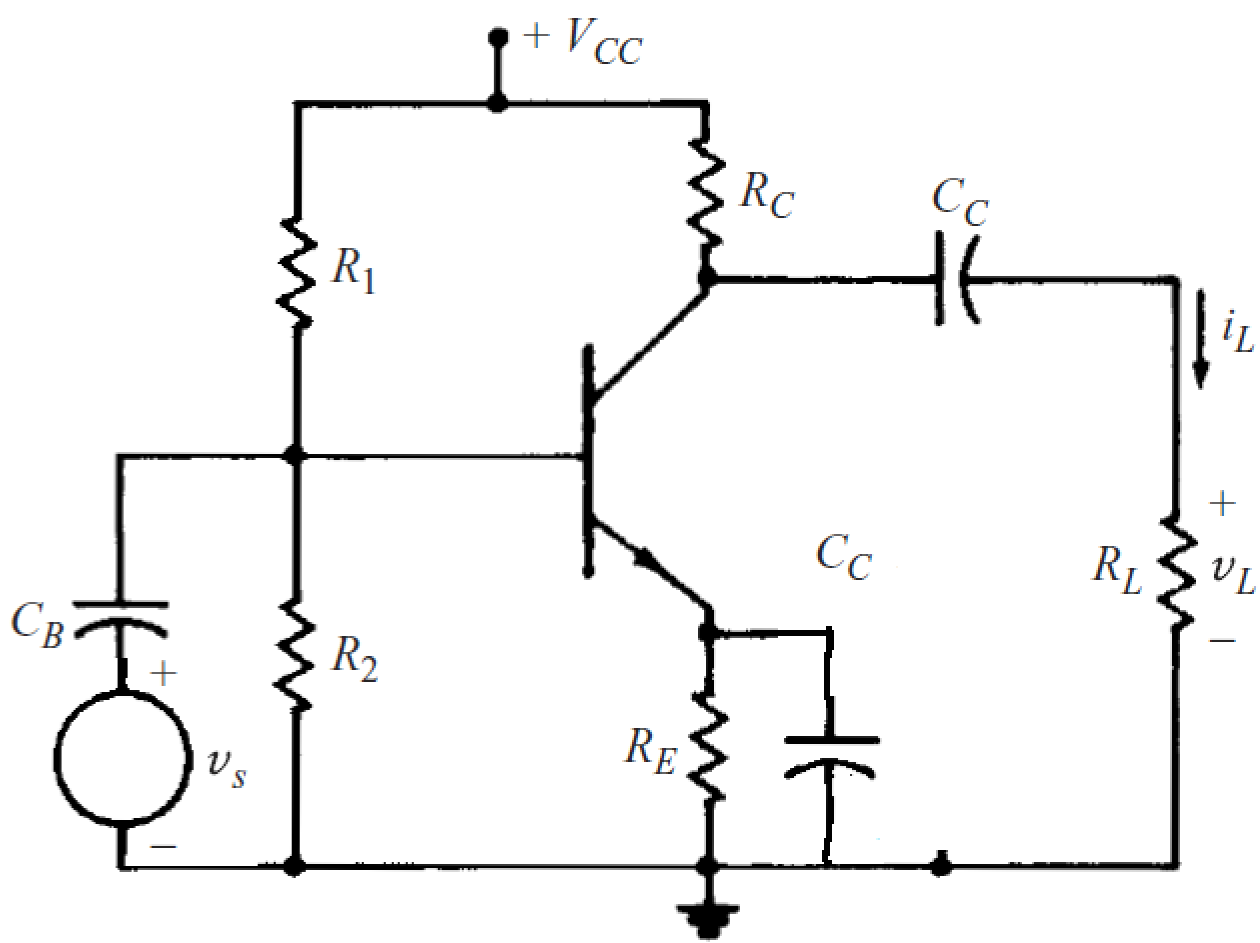
Zo=1/hob||Rc

=2.195 kΩ

$$i_e = \frac{R_E}{R_E + h_{ib}} i_s$$

$$A_{is} = \frac{i_L}{i_s} = \frac{R_E}{R_E + h_{ib}} A_i$$

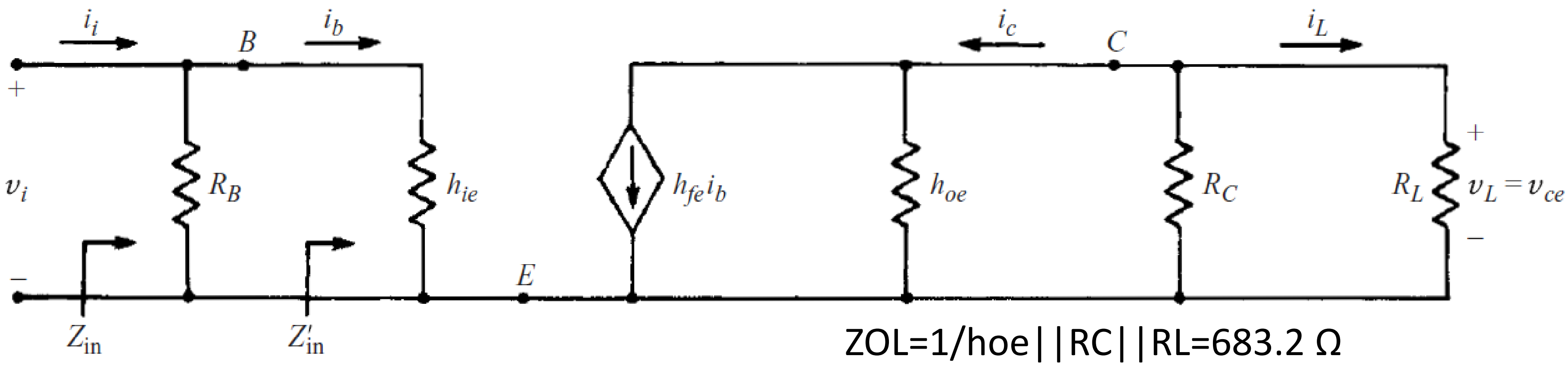
Same Circuit in CE mode



(a)

hfb=-hfe/1+hfe ➔ *hfe=-hfb/1+hfb=-0.99/(1-0.99)=99*
hib=hie/1+hfe ➔ *hie=25*100=2500 Ω*
hrb=-hre ➔ *hre=0*
hob=hoe/1+hfe ➔ $hoe=10^{-4}$ ℧

RB=R1||R2
=25kΩ



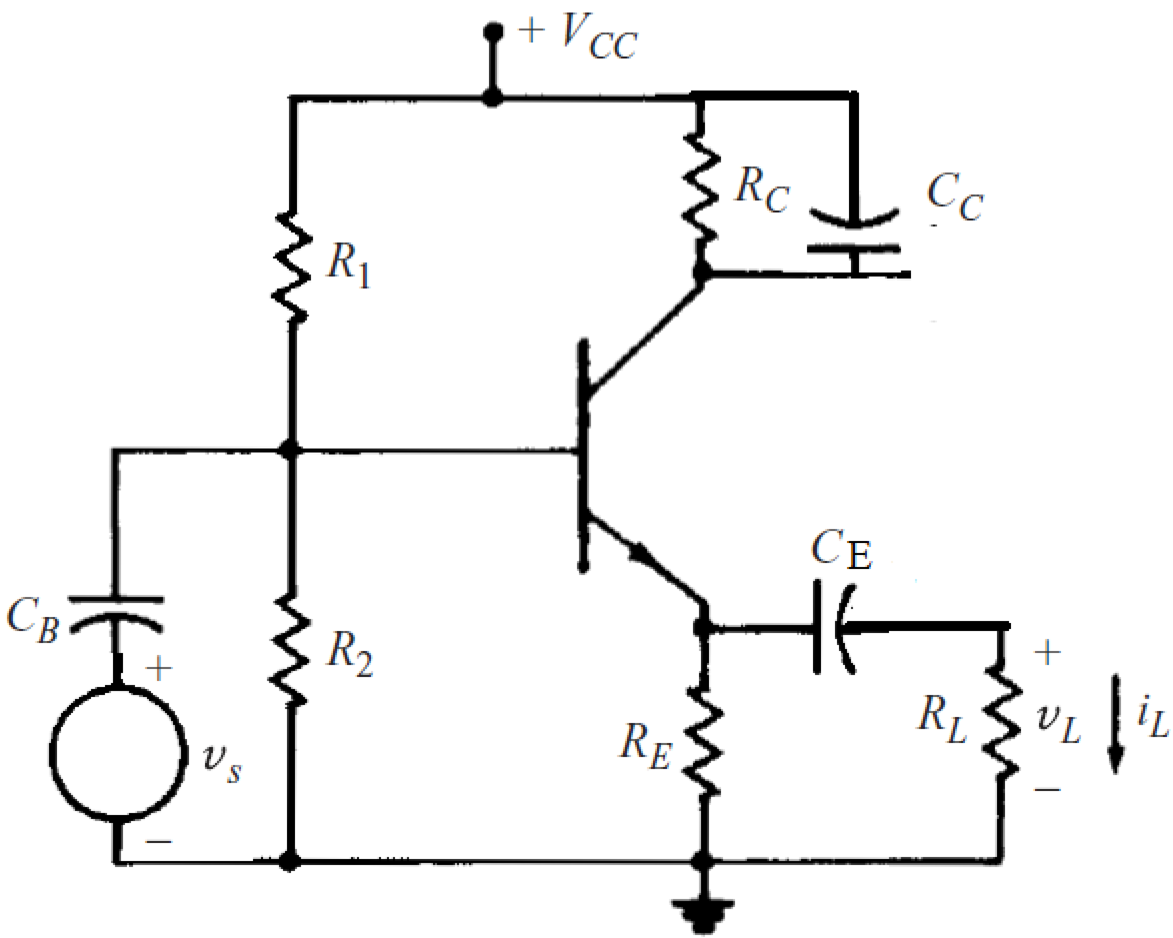
Zin=hie||RB
=2.252 kΩ
Zo=1/hoe||Rc
=1.8 kΩ

$$A_{is} = \frac{i_L}{i_s} = \frac{R_B}{R_B + h_{ie}} A_i$$

ZOL=1/hoe||RC||RL=683.2 Ω
VL=-hfexibxZ_{OL}
Vs=vi=hiexib
Av=-hfexZOL/hie
=-99x683.2/2500=-27.05

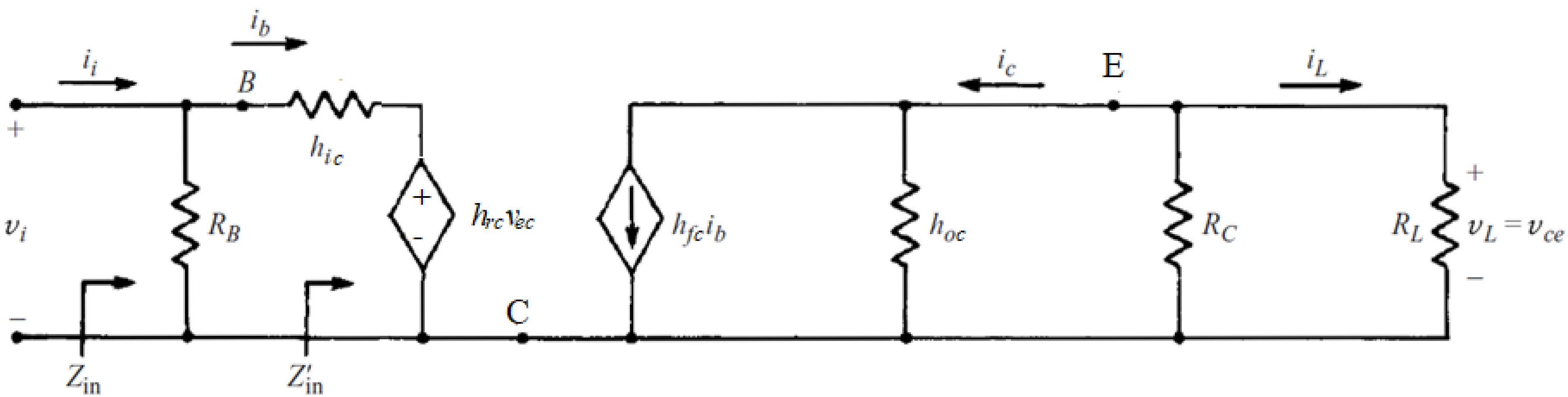
iL=vL/RL=-h_{fe}xi_bxZ_{OL}/R_L
Ai=iL/ib=-hfexZOL/RL
Ai=A_v×h_{ie}/R_L=-27.05x2500/1100=-61.49
Ais=-25/(25+2.475)x61.49=-55.95

Same Circuit in CC mode

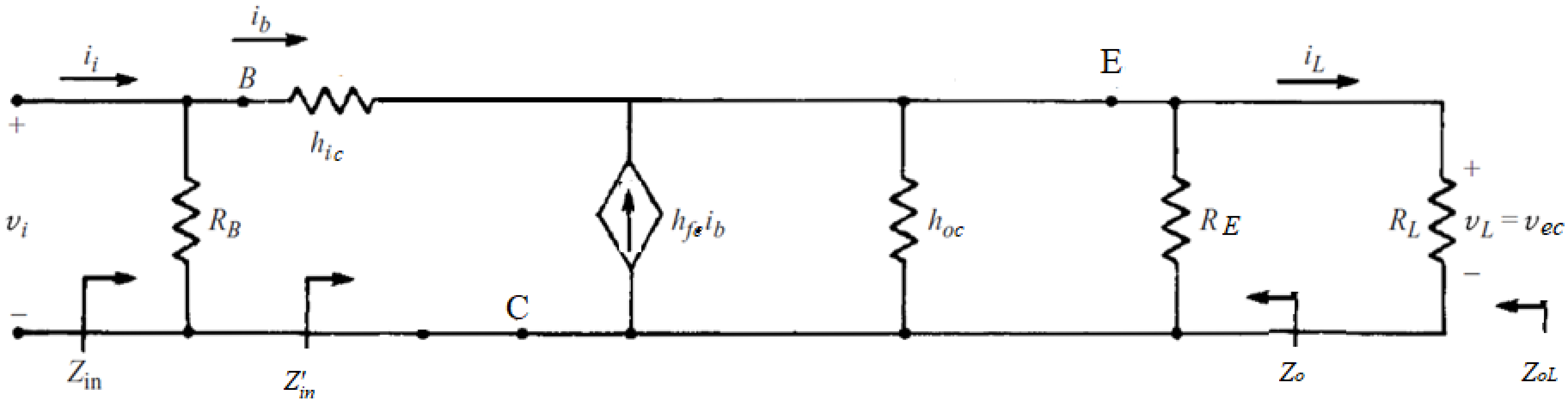


(a)

hic=hie=2500Ω
hrc=1-hre=1
hfc=-(1+hfe)=-100
hoc=hoe=10^4 *Ω =10 KΩ*



III



$$Z'_{in} = h_{ic} + \frac{(1 + h_{fe})}{Y_L + h_{oe}}$$

Without considering RL

=2.5+100x(R_E||1/hoe)
=2.5+100x3.3||10
=2.5+100x2.481
=250.575 kΩ

Zin=RB||Zin' = 25||250.575 =22.73 kΩ

Considering R_L
Z'_{inL}=2.5+100x(R_E||RL||1/hoe)
=2.5+100x(3.3||1.1||10)
=2.5+100x0.762
=78.7 kΩ
ZinL==RB||Z'inL = 25||78.7=18.97 KΩ

Zo=RE||1/hoc||[hie/(1+hfe)]
=3.3||10||0.025KΩ= 24 Ω

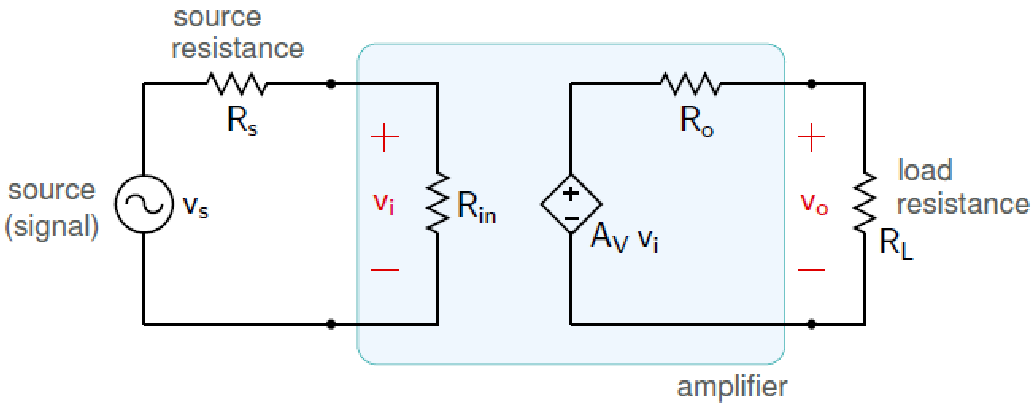
Let Z=1/hoc||RE||RL= 762Ω
VL=(1+hfe)xibxZ
Vs=vi=Z'_{inL}xi_b
Av=(1+h_{fe})xZ/Z'_{inL}
=100x0.762/78.675=0.968

iL=vL/RL=(1+hfe)xibxZ/RL
Ai=iL/ib=(1+hfe)xZ/RL
Ai=AvxZ'$_{inL}$/RL=0.968x78.675/1.1=69.27
Ais=-25/(25+Z'inL)x69.27=16.7

Consider vs=20sin(2000πt) mV

Draw input and output voltage and current waveforms with proper level

General representation of an amplifier



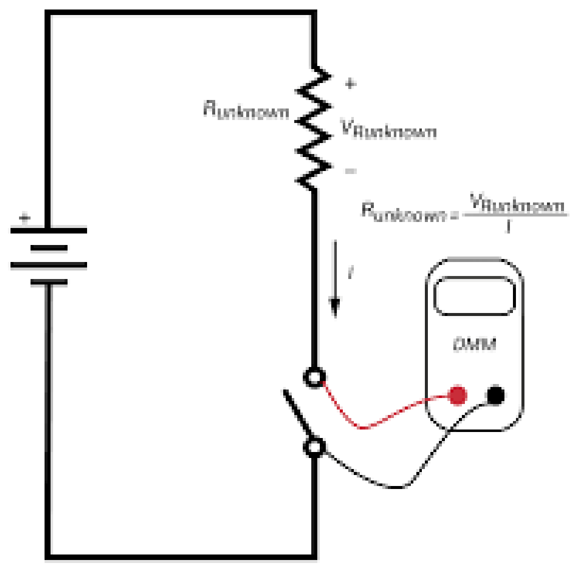
* An amplifier is represented by a voltage gain, an input resistance $R_{\rm in}$, and an output resistance R_o. For a voltage-to-voltage amplifier, a large $R_{\rm in}$ and a small R_o are desirable.
* The above representation involves AC quantities *only*, i.e., it describes the AC equivalent circuit of the amplifier.
* The DC bias of the circuit can affect parameter values in the AC equivalent circuit (A_V, $R_{\rm in}$, R_o). For example, for the common-emitter amplifier, $A_V \propto g_m = I_C/V_T$, I_C being the DC (bias) value of the collector current.
* Suppose we are given an amplifier as a "black box" and asked to find A_V, $R_{\rm in}$, and R_o. What experiments would give us this information?

Measurement of Voltage gain

If $R_L \to \infty$, $i_l \to 0$, and $v_o \to A_V\, v_i$.

We can remove R_L (i.e., replace it with an open circuit), measure v_i and v_o, then use $A_V = v_o/v_i$.

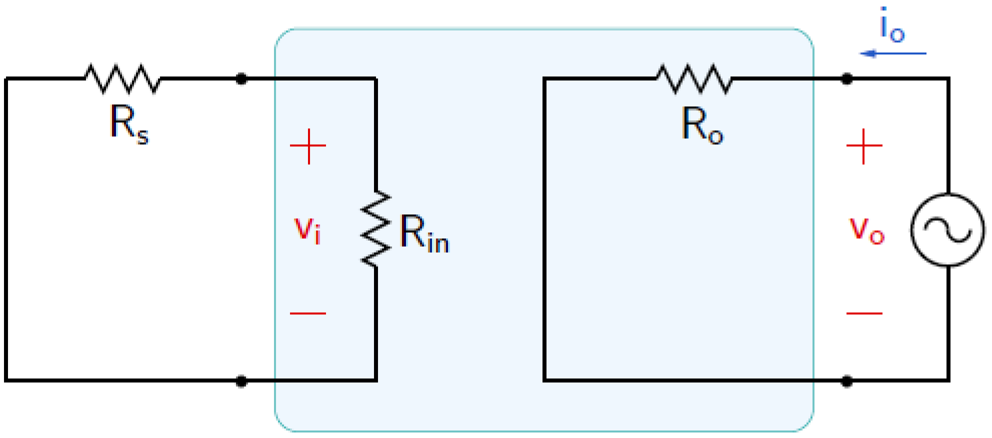
Measurement of v_i and i_i yields $R_{\text{in}} = v_i/i_i$.

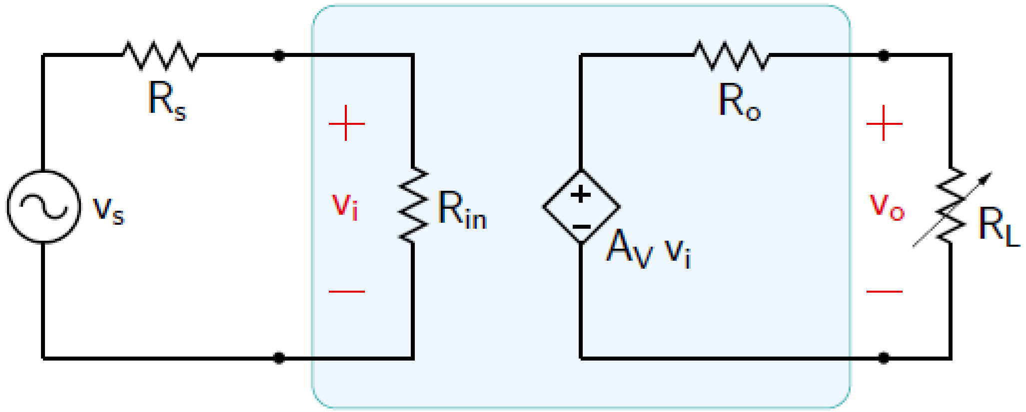


Method 1:

If $v_s \to 0$, $A_V\, v_i \to 0$.

Now, connect a test source v_o, and measure $i_o \to R_o = v_o/i_o$.





$$v_o = \frac{R_L}{R_L + R_o} A_V \, v_i .$$

$$\text{If } R_L \rightarrow \infty, \; v_{o1} = A_V \, v_i .$$

$$\text{If } R_L = R_o, \; v_{o2} = \frac{1}{2} A_V \, v_i = \frac{1}{2} \, v_{o1} .$$

Procedure:

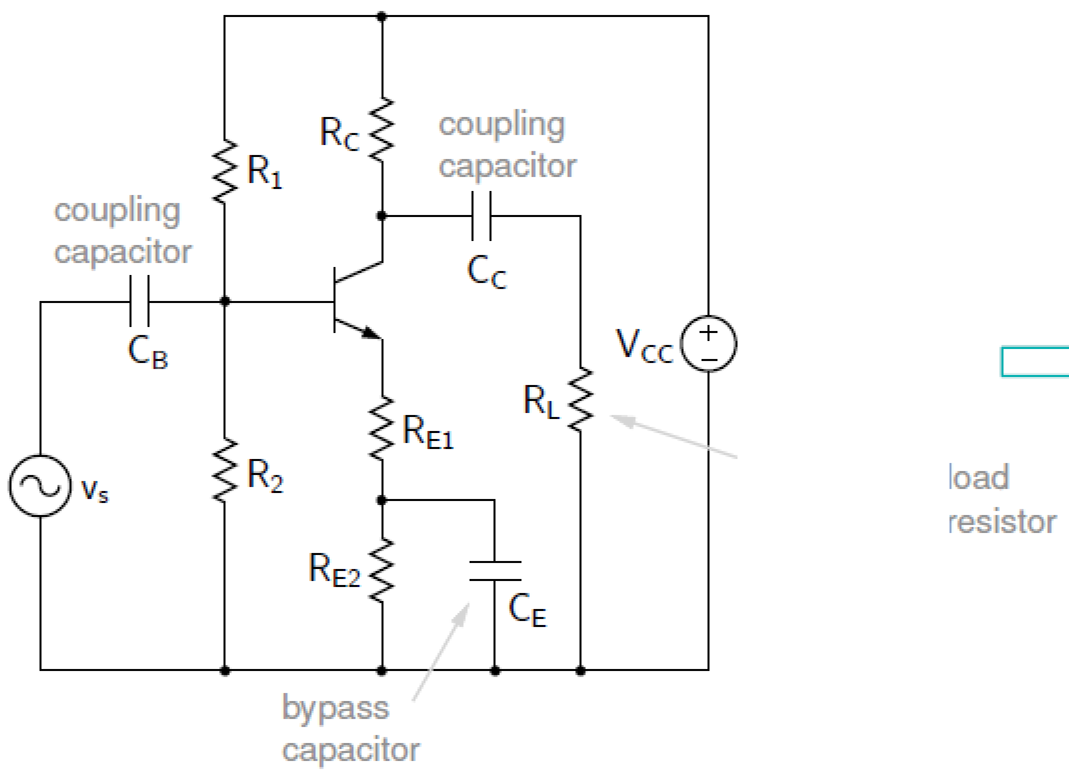
Measure v_{o1} with $R_L \rightarrow \infty$ (i.e., R_L removed).

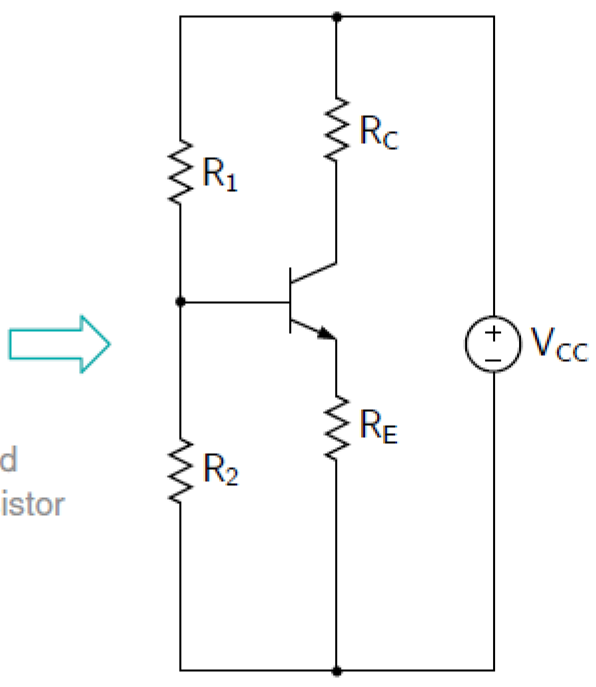
Vary R_L and observe v_o.

When v_o is equal to $v_{o1}/2$, measure R_L (after removing it).

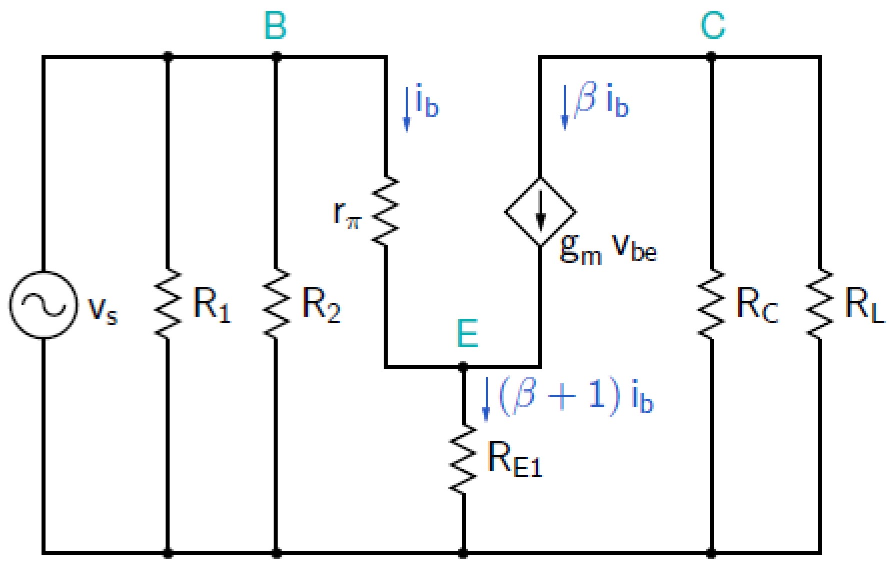
R_o is the same as the measured resistance.

Common-emitter amplifier with partial bypass





DC circuit



AC circuit

$$v_s = i_b\, r_\pi + (\beta + 1)\, i_b\, R_{E1} \rightarrow i_b = \frac{v_s}{r_\pi + (\beta + 1)\, R_{E1}}.$$

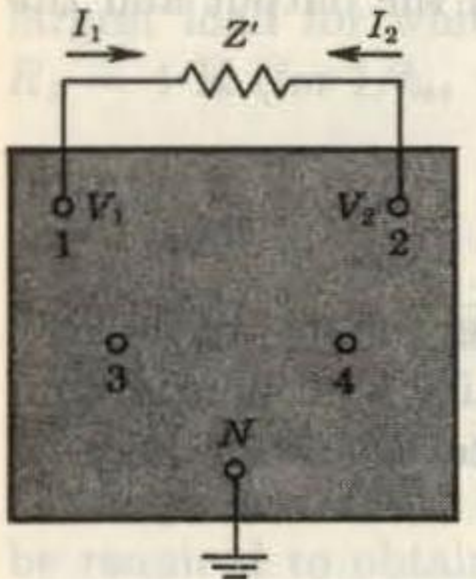
$$v_o = -\beta\, i_b \times (R_C \parallel R_L) \rightarrow \frac{v_o}{v_s} = -\frac{\beta\,(R_C \parallel R_L)}{r_\pi + (\beta + 1)\, R_{E1}}$$

$=-Rc||RL/(r\pi/\beta\ \ +RE1)$

$=-RC||RL/(re+RE1)$

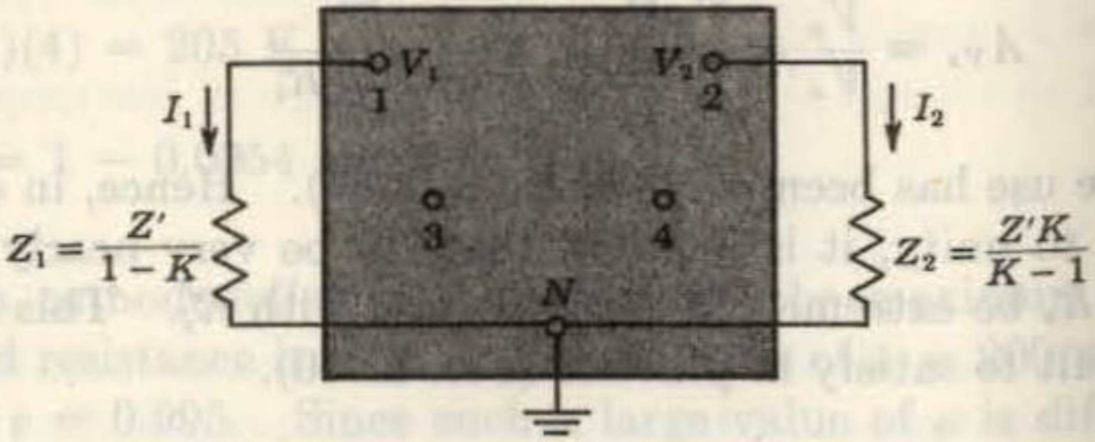
$=-R_C/R_{E1}$

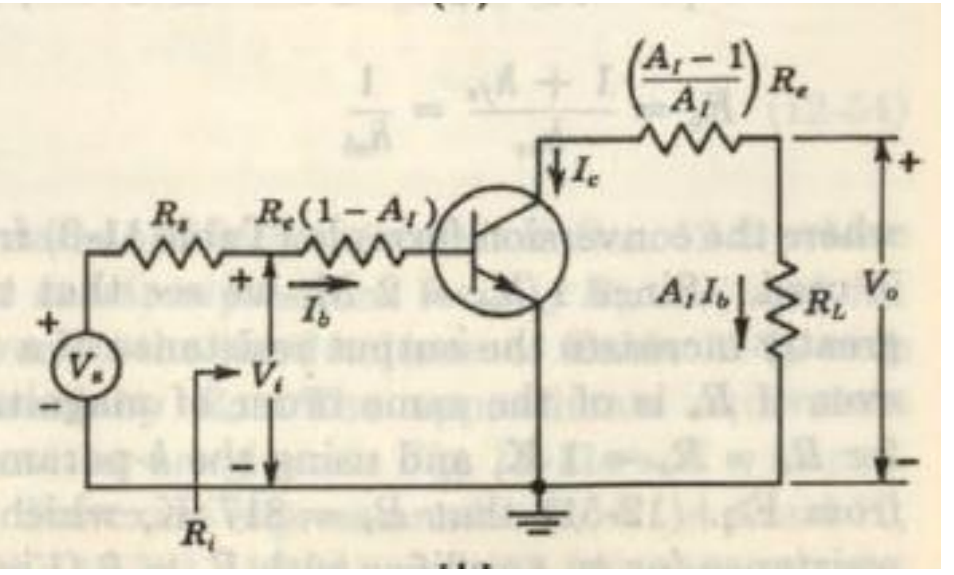
MILLER'S THEOREM



$$I_1 = \frac{V_1 - V_2}{Z'} = \frac{V_1(1-K)}{Z'} = \frac{V_1}{Z'/(1-K)} = \frac{V_1}{Z_1}$$

$$Z_2 \equiv \frac{Z'}{1 - 1/K} = \frac{Z'K}{K-1}$$



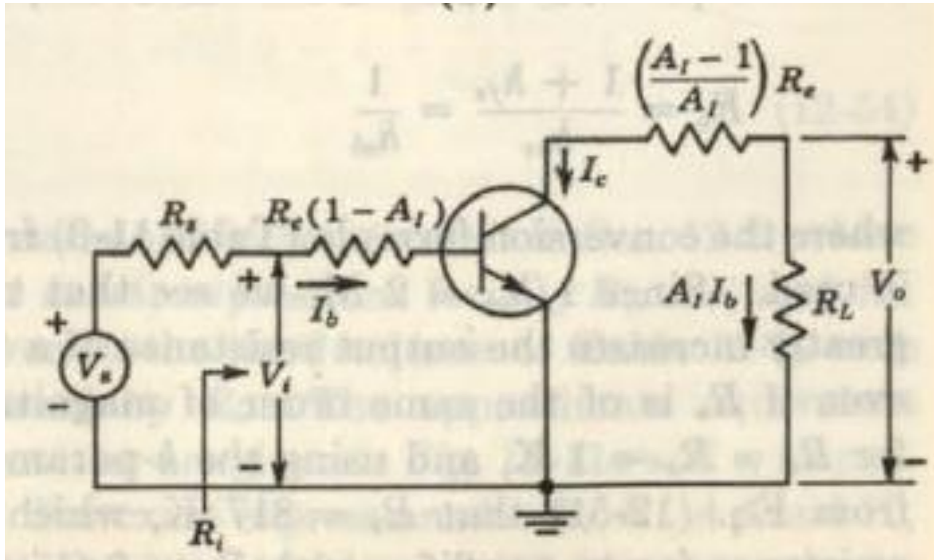


$\left(\frac{A_I - 1}{A_I}\right) R_e$
I_c
R_s
$R_e(1 - A_I)$
I_b
$A_I I_b$
R_L
V_o
V_s
V_i
R_i

Mayukhmali Das
12:34 PM
Yes mam
Mayukhmali Das
12:42 PM
Mam, many students are trying to join
Please allow them
Mayukhmali Das
2:41 PM
Ok mam
Mayukhmali Das
2:54 PM
98
Mam roll number 98
Sandip Dutta
2:55 PM
Sandip Dutta
Sagnik Das
2:55 PM
75
Snehasish Roy
2:55 PM
Snehasish Roy 001910701013
Aditya Bikram Mitra
2:55 PM
83 present
Souvik Barman
2:55 PM
Souvik Barman Roll no 76
Sandip Dutta
2:55 PM
Sandip Dutta - 17
Keshav Jasrotia
2:55 PM
Keshav Jasrotia (003)

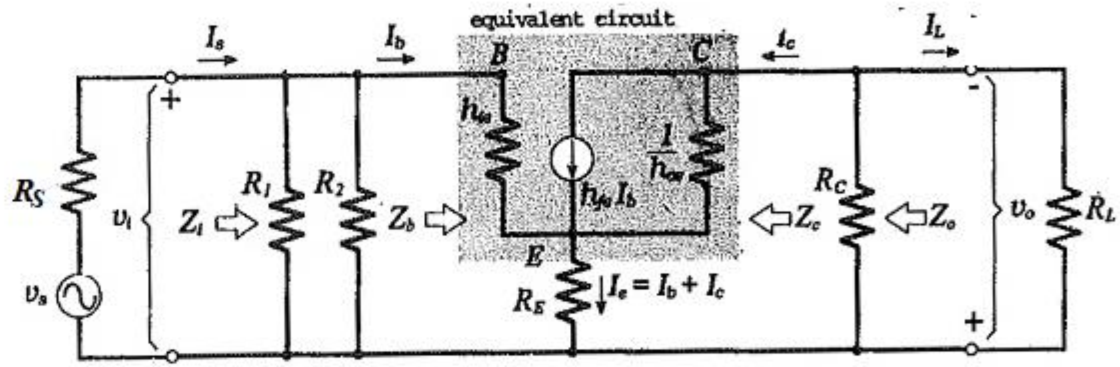
Mayukhmali Das
2:56 PM
Roll 98 Mayukhmali Das
Debadri Sengupta 001910701045
Rahul Saha 01910701009 Rahul Saha
Akansha Mukherjee
arpit mishra Roll number - 001910701092
Sarit Roy Chaudhury, 001910701096
Arpit Mishra - 001910701092
Mayukhmali Das Roll - 001910701098
001910701045 Debadri Sengupta
Akansha Mukherjee 001910701094
Rahul Saha
2:58 PM
001910701009 Rahul Saha
arpit mishra
2:59 PM
Arpit mishra 001910701092
Abhijit Deogharia
2:59 PM
001910701024 abhijit deogharia

Arijit Saha
2:55 PM
Arijit Saha Roll 19
TANMOY HALDER 1054
Roudrini Mukherjee Roll No. 001910701053
41 sagar sarkar
Umar Faruk Sarkar
2:55 PM
Umar Faruk Sarkar - 78
Arunim Ray
2:55 PM
Arunim Ray roll-42
Mayukhmali Das
2:55 PM
Mam , Mik not working ......roll 98 001910701098
Utso Majumder
2:55 PM
Utso Majumder - Roll No 70
Rishav Basu
2:55 PM
Rishav Basu 40
Sagnik Das
2:55 PM
Sagnik Das 75
Abhishek Sarkar
2:55 PM
Abhishek Sarkar- 27
Shubham singh
2:55 PM
Roll number 8 - Shubham Kumar Singh



$$A_I = \frac{-h_{fe}}{1 + h_{oe}R'_L} = \frac{-h_{fe}}{1 + h_{oe}\left(R_L + \frac{A_I - 1}{A_I} R_e\right)}$$

$$A_I = \frac{h_{oe}R_e - h_{fe}}{1 + h_{oe}(R_L + R_e)}$$



(Rs’+hie)/hfe

$$v_i = I_b h_{ie} + I_e R_E$$
$$= I_b h_{ie} + R_E(I_b + I_c)$$
$$= I_b h_{ie} + R_E(I_b + h_{fe} I_b)$$
$$= I_b [h_{ie} + R_E(1 + h_{fe})]$$

$$Z_b = \frac{v_i}{I_b} = \frac{I_b [h_{ie} + R_E(1 + h_{fe})]}{I_b}$$

$$\mathbf{Z_b = h_{ie} + R_E(1 + h_{fe})}$$

$$\mathbf{Z_i = R_1 \| R_2 \| Z_b}$$

Including Rs ➔ $Z_{is} = R_s + Z_i$

$$vo = i_L R_L$$
$$i_L = -h_{fe} ib - h_{oe} v_{ce} - v_0/R_C$$
$$= -h_{fe} i_b - h_{oe}(v_o - i_e R_E) - v_o/R_C$$
$$v_o = (-h_{fe} i_b - h_{oe}(v_o - i_e R_E) - v_o/R_C) R_L$$
$$v_o(1 + h_{oe} R_L + R_L/R_C) == -h_{fe} i_b R_L + h_{oe}(1 + h_{fe}) i_b R_E R_L$$
$$= [-h_{fe} R_L + h_{oe}(1 + h_{fe}) R_E R_L] v_i / [(h_{ie} + R_E(1 + h_{fe})]$$

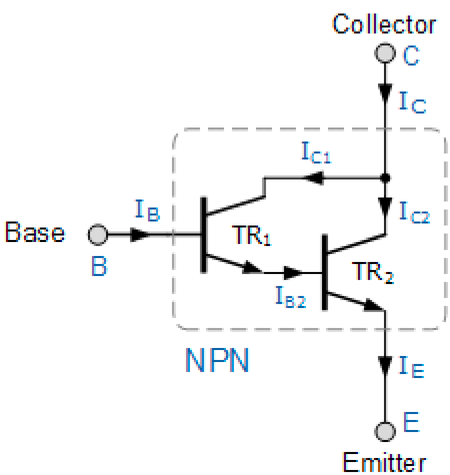
$$A_v = v_o/v_i = [-h_{fe} R_L + h_{oe}(1 + h_{fe}) R_E R_L] / [(h_{ie} + R_E(1 + h_{fe})] * [(1+$$

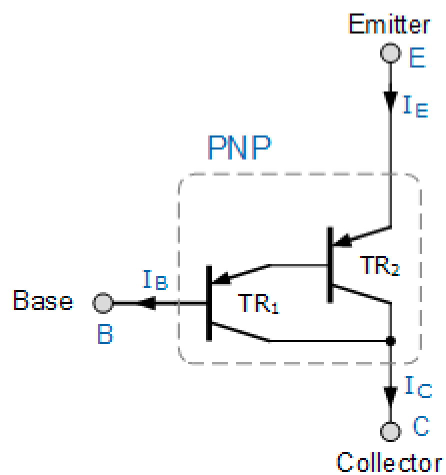
$$A_v = vo/vi = \frac{[-hfe + hoe(1+hfe)RE]RL}{[(hie+RE(1+hfe)][(1+hoeRL+ RL}$$

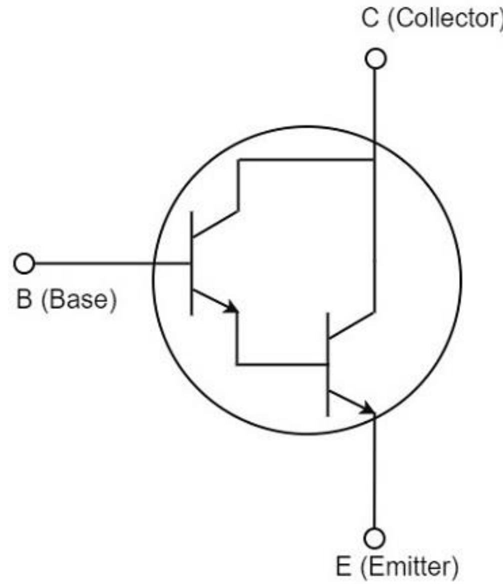
$$= \frac{[-hfe + hoe(1+hfe)RE\ ]R_L \| RC \| 1/hoe}{[(hie+RE(1+hfe)]}$$

$$R_o = \frac{1}{h_{oe}} \frac{(1 + h_{fe}) R_e + (R_s + h_{ie})(1 + h_{oe} R_e)}{R_e + R_s + h_{ie} - h_{re} h_{fe}/h_{oe}}$$

The **Darlington Transistor** named after its inventor, Sidney Darlington is a special arrangement of two standard NPN or PNP bipolar junction transistors (BJT) connected together. The Emitter of one transistor is connected to the Base of the other to produce a more sensitive transistor with a much larger current gain being useful in applications where current amplification or switching is required.







Darlington Transistor pairs can be made from two individually connected bipolar transistors or a one single device commercially made in a single package with the standard: Base, Emitter and Collector connecting leads and are available in a wide variety of case styles and voltage (and current) ratings in both NPN and PNP versions.

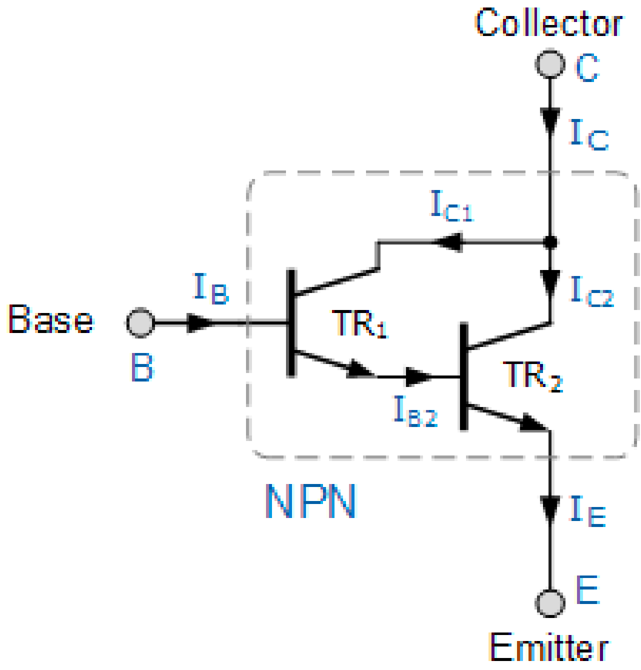
Characteristics

The following are the important characteristics of Darling ton amplifier.

Extremely high input impedance (MΩ).

Extremely high current gain (several thousands).

Extremely low output impedance (a few Ω).



TR_1 drives the base of TR_2

$$I_C = I_{C1} + I_{C2}$$

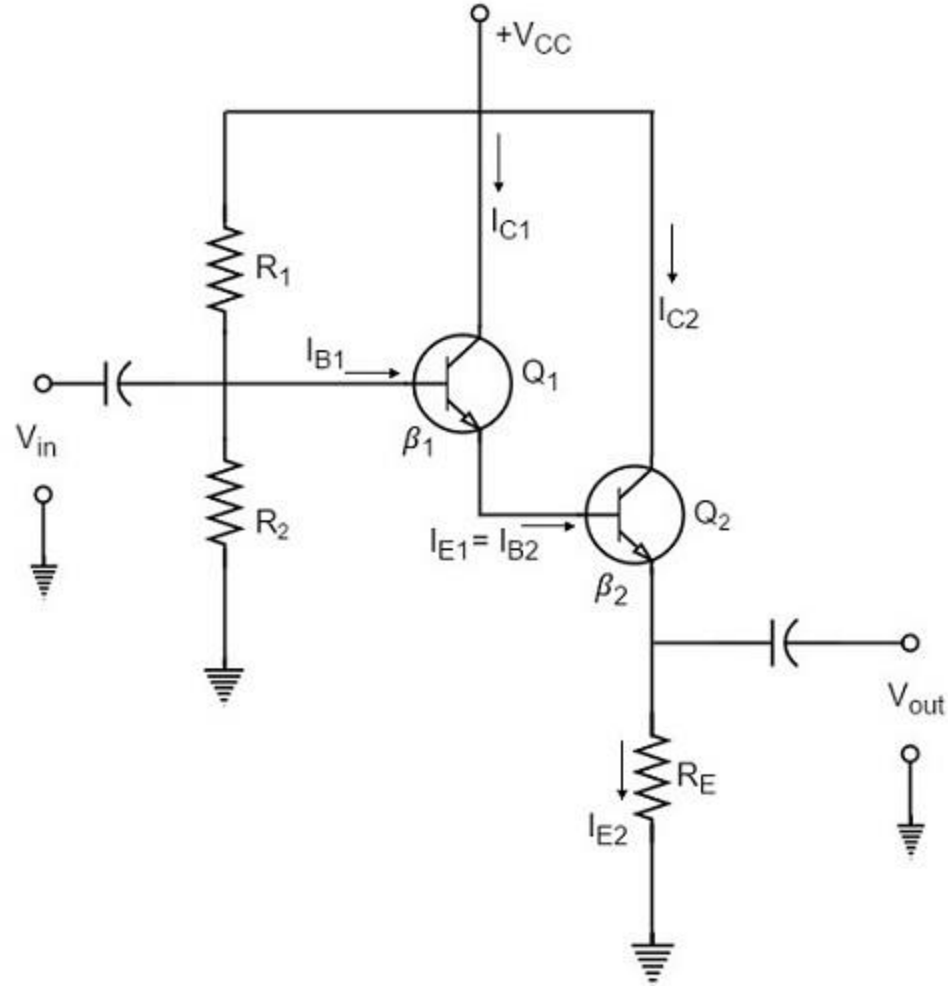
$$I_C = \beta_1.I_B + \beta_2.I_{B2}$$

$$I_{B2} = I_{E1} = I_{C1} + I_B = \beta_1.I_B + I_B = (\beta_1 + 1).I_B$$

$$I_C = \beta_1.I_B + \beta_2.(\beta_1 + 1).I_B$$

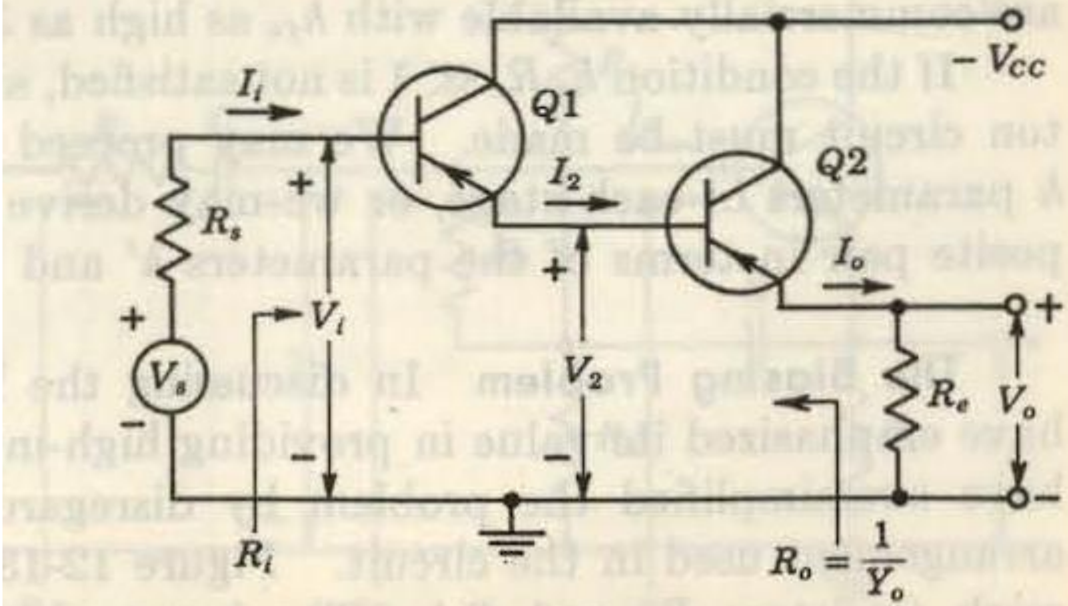
$$I_C = \beta_1.I_B + \beta_2.\beta_1.I_B + \beta_2.I_B$$

$$I_C = \left(\beta_1 + (\beta_2.\beta_1) + \beta_2\right).I_B$$



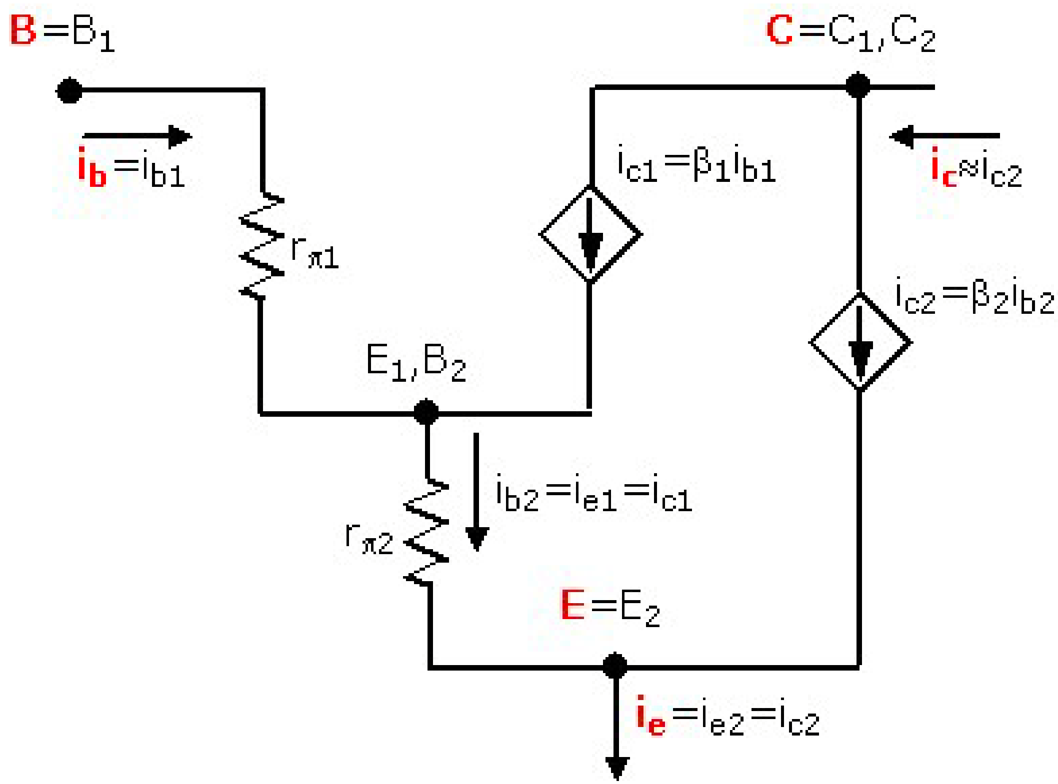
hie1+hie2β2+β1β2RE

$$A_V = A_{V1}A_{V2} = \left(1 - \frac{h_{ie}}{R_{i2}}\right)\left(1 - \frac{h_{ie}}{A_{I1}R_{i2}}\right) \approx 1 - \frac{h_{ie}}{A_{I1}R_{i2}} - \frac{h_{ie}}{R_{i2}}$$

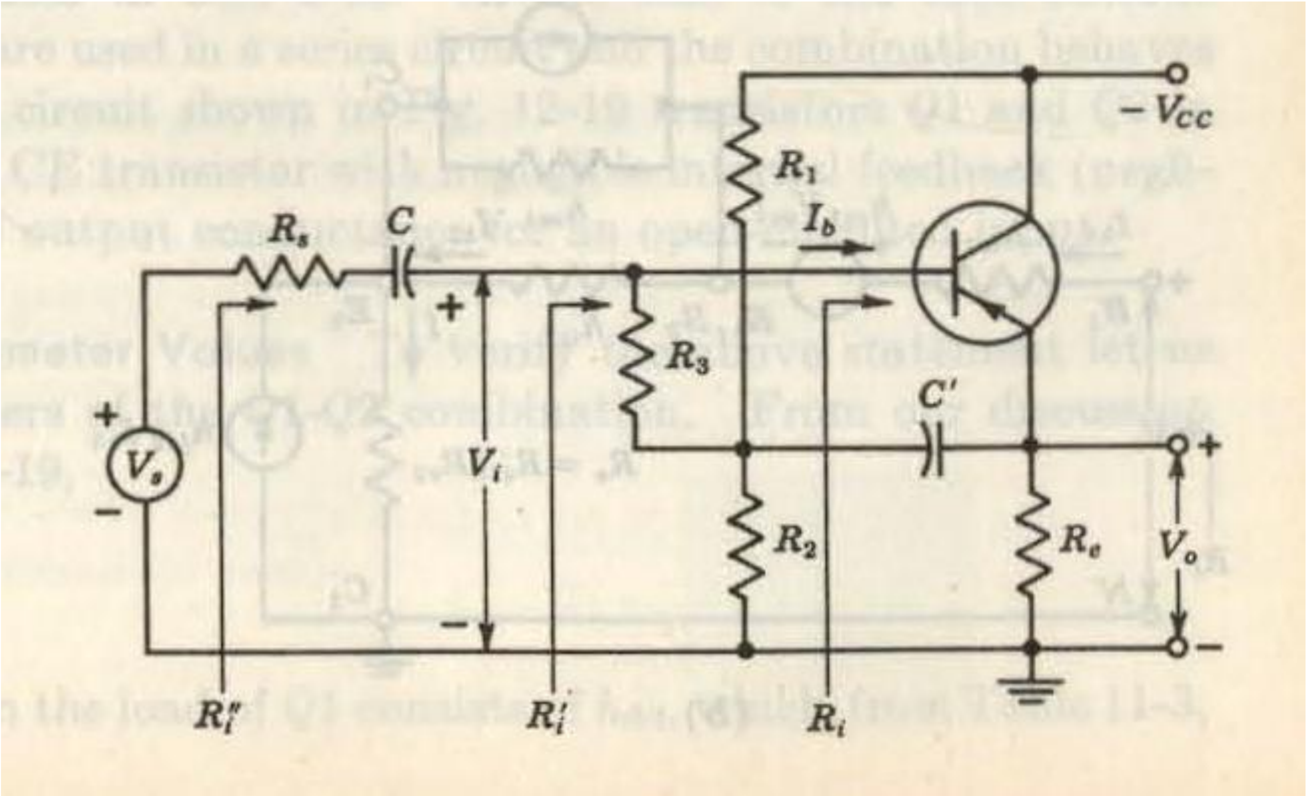


$$R_{i1} = h_{ie} + A_{I1}R_{i2} \approx \frac{(1 + h_{fe})^2 R_e}{1 + h_{oe}h_{fe}R_e}$$

$$R_{o2} \approx \frac{\dfrac{R_s + h_{ie}}{1 + h_{fe}} + h_{ie}}{1 + h_{fe}} = \frac{R_s + h_{ie}}{(1 + h_{fe})^2} + \frac{h_{ie}}{1 + h_{fe}}$$



$$
\begin{aligned}
R_{in} &= R_B \,||\, [\beta_1 r_{\pi 2} + \beta_1 \beta_2 (R_E \,||\, R_L)] \\
&= R_B \,||\, [\beta_1 \beta_2 (r_{e2} + (R_E \,||\, R_L)]
\end{aligned}
$$



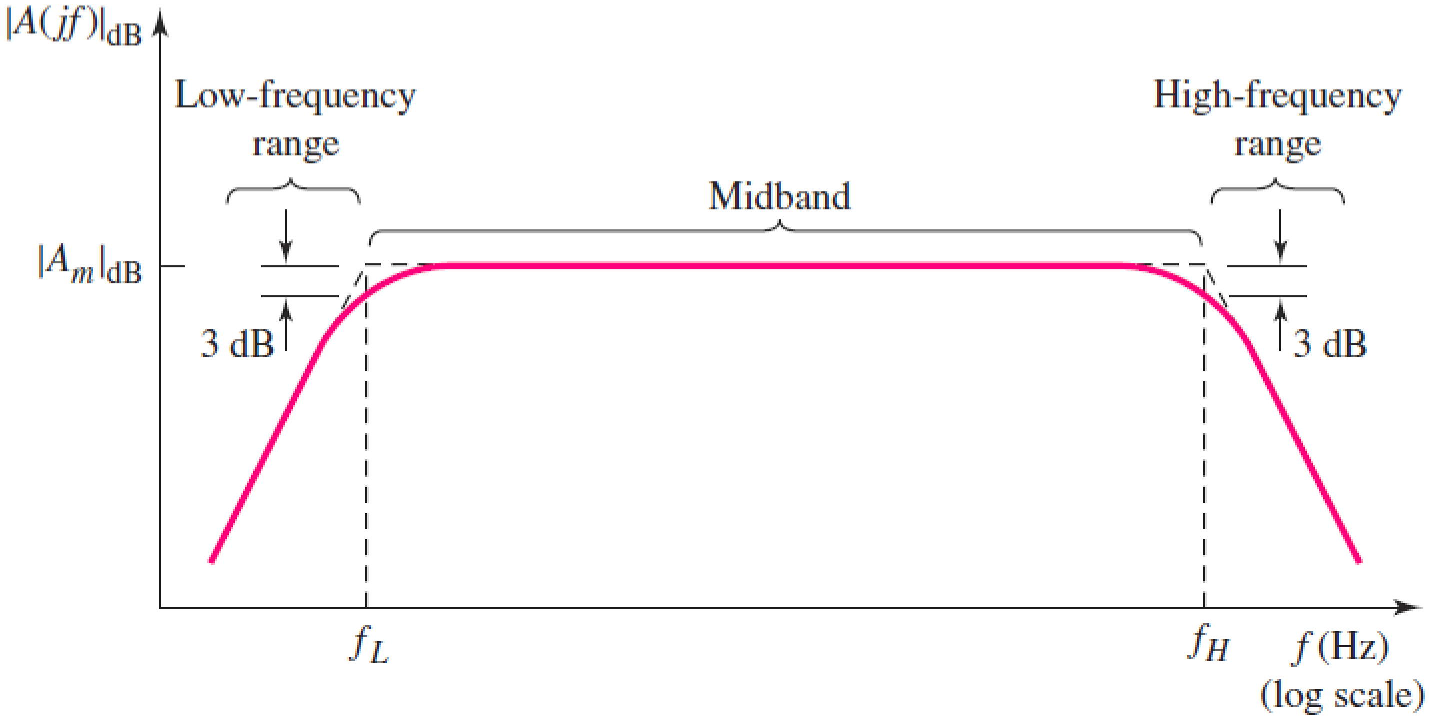
$$R_{\text{eff}} = \frac{R_3}{1 - A_V}$$

Multistage Amplifier

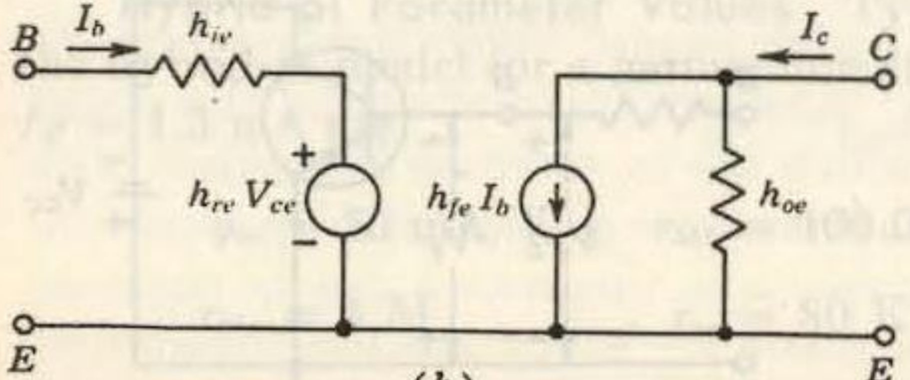
Cascaded

$A_V = A_{v1} A_{v2} \ldots A_{vn}$

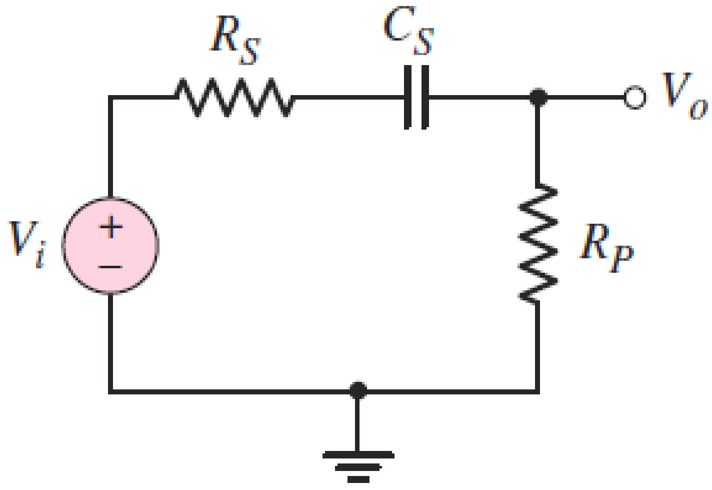
AvdB=20logAv



1/wC → open

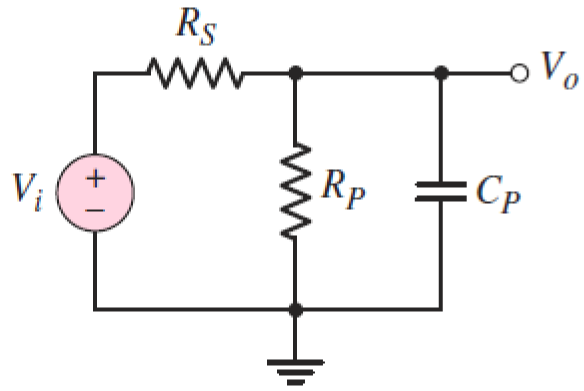


(b)



$$\frac{V_o(s)}{V_i(s)} = \frac{R_P}{R_S + R_P + \dfrac{1}{sC_S}}$$

$$\frac{V_o(s)}{V_i(s)} = \left(\frac{R_P}{R_S + R_P}\right)\left[\frac{s(R_S + R_P)C_S}{1 + s(R_S + R_P)C_S}\right] = K\left(\frac{s\tau_s}{1 + s\tau_s}\right)$$



$$\frac{V_o(s)}{V_i(s)} = \left(\frac{R_P}{R_S + R_P}\right)\left[\frac{1}{1 + s(R_S \| R_P)C_P}\right] = K\left(\frac{1}{1 + s\tau_P}\right)$$

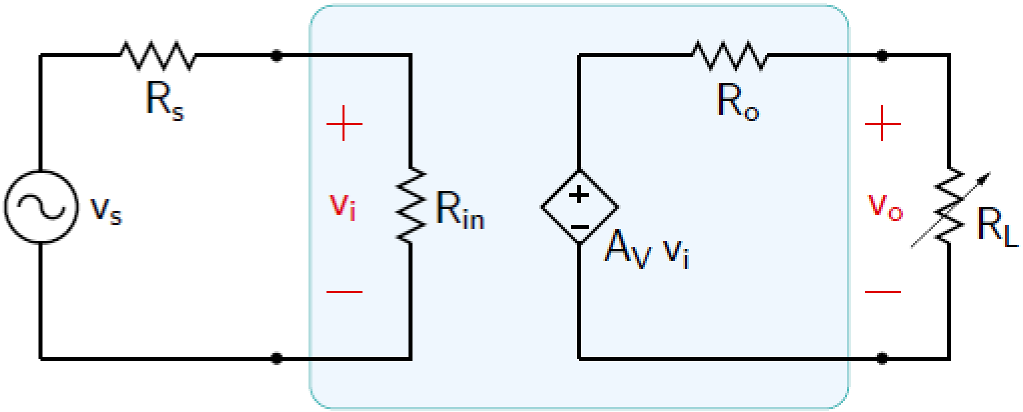
-RC/(RE+re)

θ=-arctan (w/wh)

$$R_S = 1\ \text{k}\Omega,$$

$$R_P = 10\ \text{k}\Omega,\ C_S = 1\ \mu\text{F, and } C_P = 3\ \text{pF.}$$

Determine the corner frequencies



Souvik Barman
2:28 PM
001910701076 076
Roudrini Mukherjee
2:28 PM
001910701053
Ayantik Das
2:28 PM
Ayantik Das Roll 089
INDRANIL Pal
2:28 PM
001910701057
Souvik Das
2:28 PM
001910701010
sagar sarkar
2:28 PM
041
sayak mandal
2:28 PM
001910701014
Keshav Jasrotia
2:28 PM
001910701003
Mayukhmali Das

$$\frac{V_o(s)}{V_i(s)} = \left(\frac{R_P}{R_S + R_P}\right)\left[\frac{s(R_S + R_P)C_S}{1 + s(R_S + R_P)C_S}\right] = K\left(\frac{s\tau_s}{1 + s\tau_s}\right) =$$

$$\tau_s = (R_S + R_P)C_S$$

$$|A_V| = K\frac{1}{\sqrt{1 + (1/w\tau_s)^2}} = K\frac{1}{\sqrt{1 + (w_l/w)^2}}$$

$$w_l = \frac{1}{(R_S + R_P)C_S}$$

$$\theta = \tan^{-1}(1/w\tau_s) = \tan^{-1}(w_l/w)$$

At $w = w_l$ $\theta = 45^o$