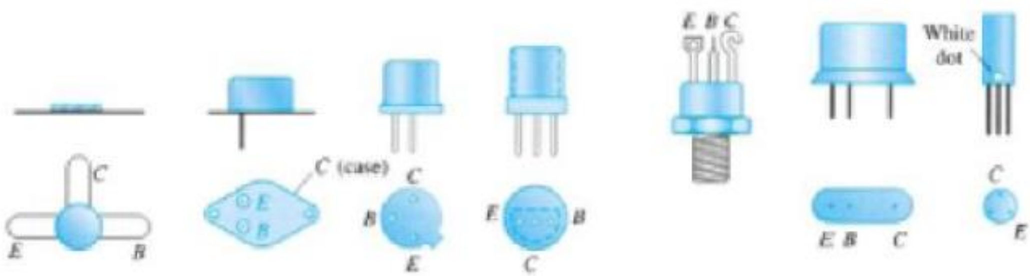
L12 - part2
sec 1
31/7/2021



ENEE2360 Analog Electronics

T8:
BJT AC Models and Analysis

Instructor : Nasser Ismail

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we will deal with small signal amplifiers in this course (not power amplifiers) X

Small Signal ac Equivalent Circuit

- In order to simplify the analysis, we replace the Transistor by an equivalent circuit (model)
- An AC model represents the AC characteristics of the transistor.
- A model uses circuit elements that approximate the behavior of the transistor.
- There are two models commonly used in small signal AC analysis of a transistor:
  - **r_e model** X
  - **Hybrid equivalent model** ** (h-parameter)

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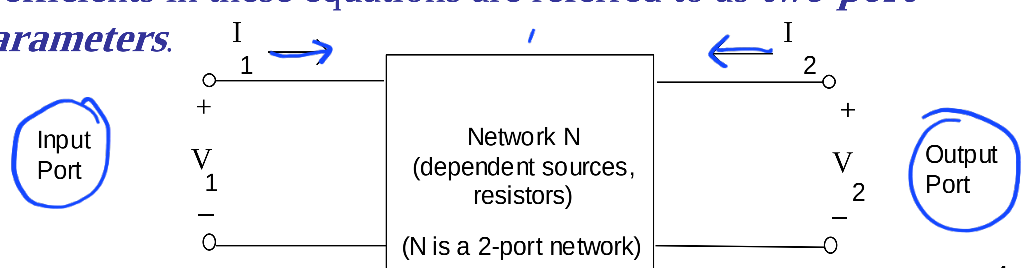
Two-port networks

- Suppose that a network N has two ports as shown below. How could it be represented or modeled?
- A common way to represent such a network is to use one of 6 possible ***two-port networks***.
- These networks are circuits that are based on one of 6 possible sets of ***two-port equations***. These equations are simply different combinations of two equations that relate the variables V_1 , V_2 , I_1 , and I_2 to one another. The coefficients in these equations are referred to as ***two-port parameters***.



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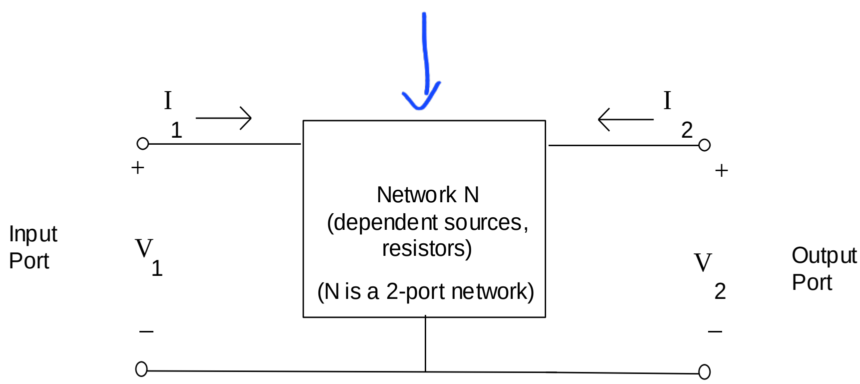
Note that I_1 , I_2 , V_1 , and V_2 are labeled as shown by convention. Often there is a common negative terminal between the input and the output so the figure above could be redrawn as:



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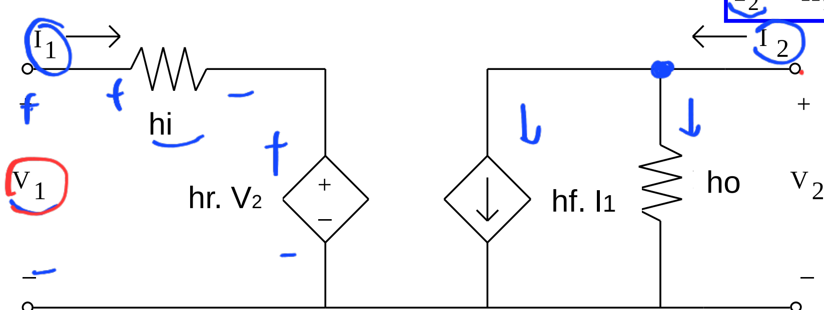
Development of the h-parameter model of BJT:

For A BJT the equivalent h parameter model can be described by the following equations:

h - parameter equations:

$$V_1 = h_i \cdot I_1 + h_r \cdot V_2$$ ← KVL

$$I_2 = h_f \cdot I_1 + h_o \cdot \cancel{V_2}$$ ← KCL



$$h_i = \frac{V_1}{I_1}\bigg|_{V_2=0} \qquad h_r = \frac{V_1}{V_2}\bigg|_{I_1=0}$$

$$h_f = \frac{I_2}{I_1}\bigg|_{V_2=0} \qquad h_o = \frac{I_2}{V_2}\bigg|_{I_1=0}$$

test $V_2=0$

$V_1 = h_i I_1 + h_r \cancel{V_2}$

$h_i = \frac{V_1}{I_1}\Big|_{V_2=0}$

$h_f = \frac{I_2}{I_1}\Big|_{V_2=0}$

$I_2 = h_f I_1 + h_o V_2$

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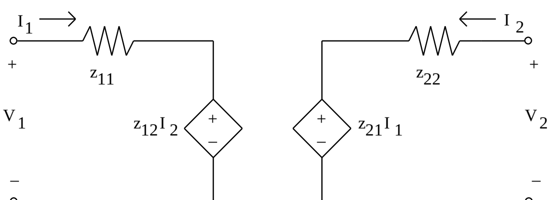
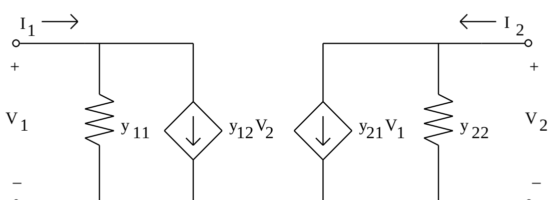
Summary:

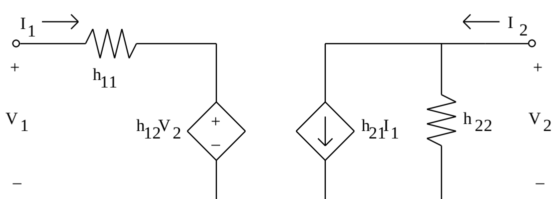
Note: This page is for information only



z-parameter model



y-parameter model



h-parameter model

z - parameter equations :

$$V_1 = z_{11} \cdot I_1 + z_{12} \cdot I_2$$
$$V_2 = z_{21} \cdot I_1 + z_{22} \cdot I_2$$

y - parameter equations :

$$I_1 = y_{11} \cdot V_1 + y_{12} \cdot V_2$$
$$I_2 = y_{21} \cdot V_1 + y_{22} \cdot V_2$$

h - parameter equations :

$$V_1 = h_{11} \cdot I_1 + h_{12} \cdot V_2$$
$$I_2 = h_{21} \cdot I_1 + h_{22} \cdot V_2$$

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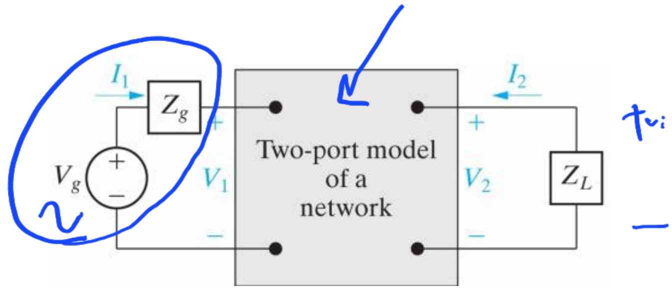
BJT Configurations

Amplifiers

- Common Emitter → CE
- Common Base → CB
- Common Collector → CC

	ac input	ac output
CE	B	C
CB	E	C
CC	B	E

same ip circuit



Terminated Two port network
Includes source and load

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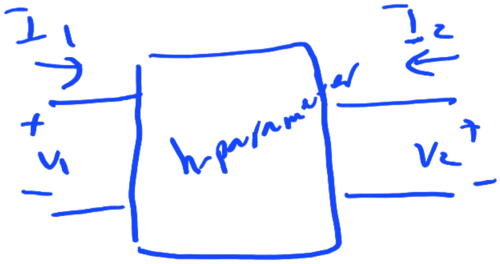
L13 1/8/2021

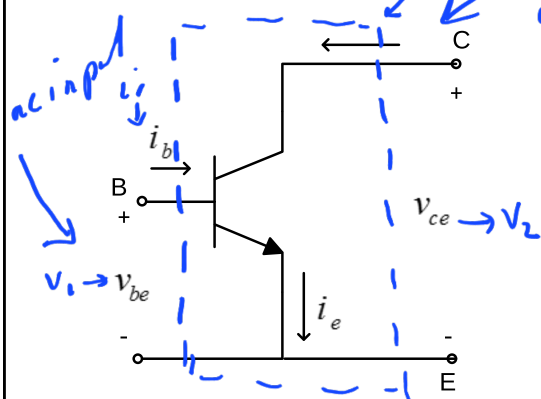


CE & CC

$h_i \rightarrow h_{ie}$
$h_r \rightarrow h_{re}$
$h_f \rightarrow h_{fe}$
$h_o \rightarrow h_{oe}$

Common Emitter Configuration

(inverting configuration, provides voltage and current gain)

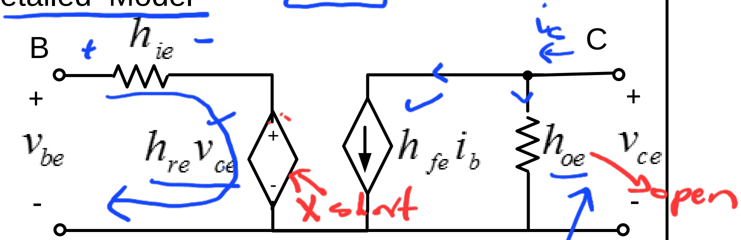


h - parameter equations :

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

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

Detailed Model



$\frac{1}{h_{oe}}$ $M\Omega$

Typical Data sheet parameter values

$h_{ie} \approx 1600\ \Omega$

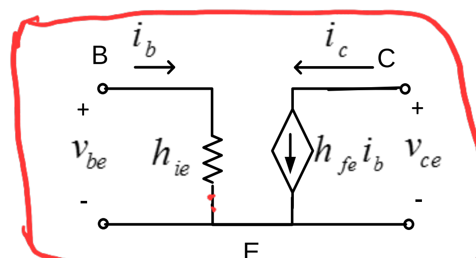
$h_{re} \approx 0.0002$

$h_{fe} \approx 80$

$h_{oe} \approx 20.10^{-6}$ Siemens

$\frac{1}{\Omega}$

Simplified Model **



ac CE equivalent circuit

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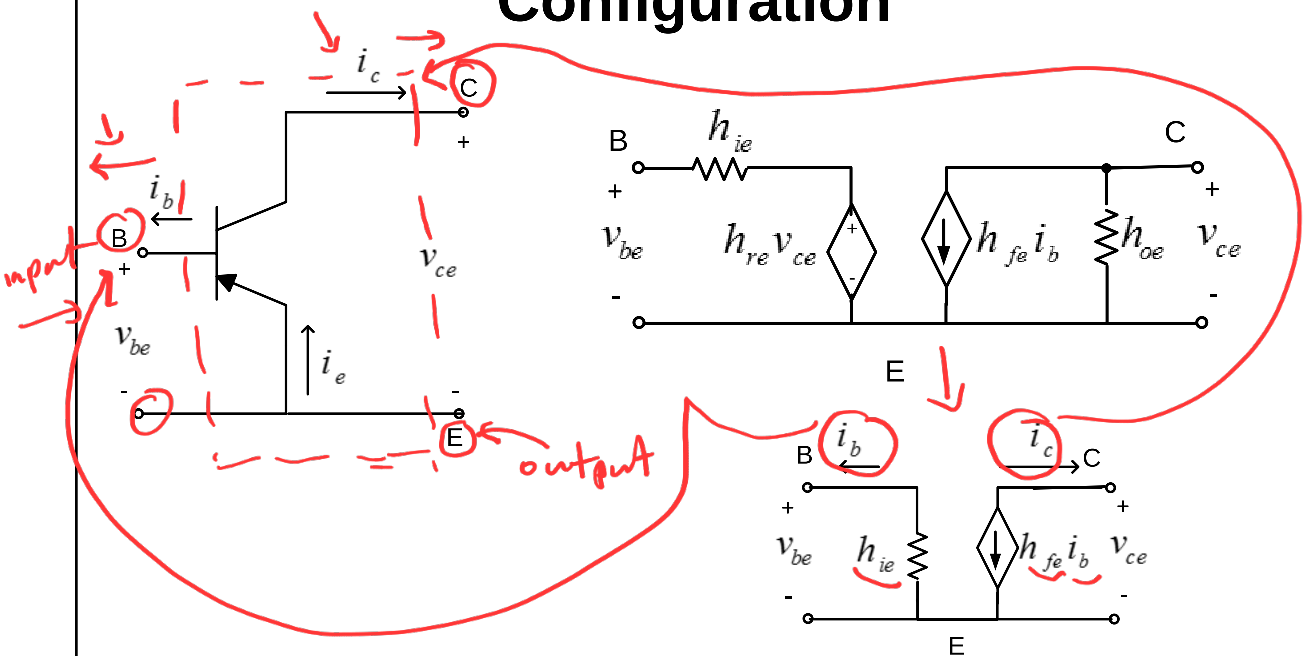
Common Emitter and Common Collector Configuration



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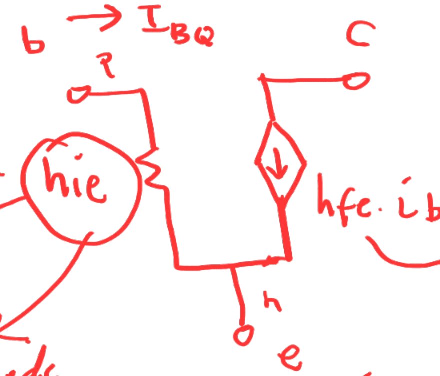

hie = ?

hfe = ?

?

diode

$r_d = \frac{V_T}{I_{DQ}}$ ← V_T ~26 mV, I_{DQ} ← dc current → from dc analysis

Value of hie → Found from dc analysis

Base Emitter is a pn junction similar to a diode
hie is the dynamic resistance of the pn junction

In a diode:

$$\boxed{h_{fe} = \frac{i_c}{i_b} = \beta}$$

$$r_d = \frac{V_T}{I_{DQ}} \Rightarrow$$

$$\boxed{h_{ie} = \frac{V_T}{I_{BQ}}} = \frac{V_T}{\boxed{\frac{I_{CQ}}{h_{fe}}}} = \frac{h_{fe} V_T}{I_{CQ}}$$

I_{BQ} dc value of base current

I_{CQ} dc value of collector current

$$h_{fe} = \beta$$

$$V_T = 25.69 \text{ mV} \ @\ 25\ ^oC$$

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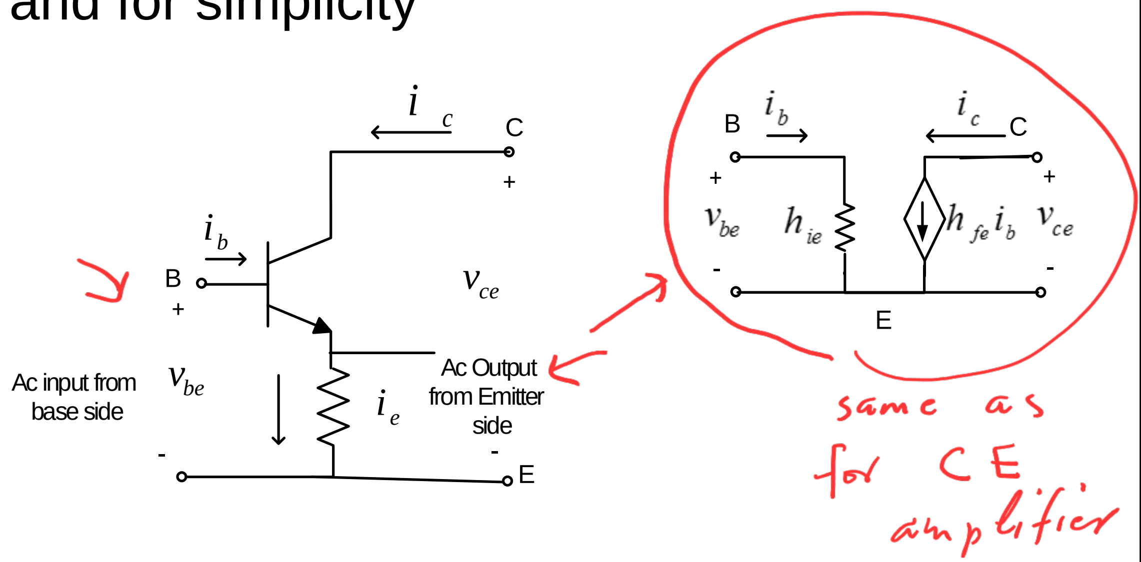
Common Collector

(provides current gain and no voltage gain)

Same Model of Common Emitter will be used due to the similarities between them and for simplicity



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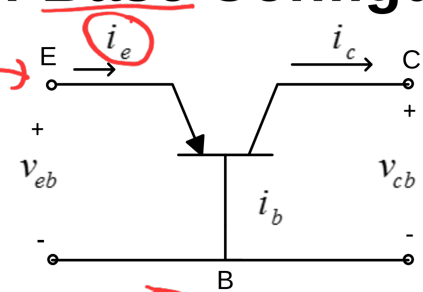
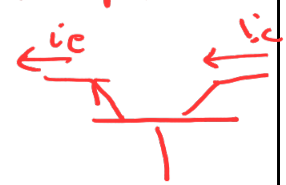
Common-Base Configuration

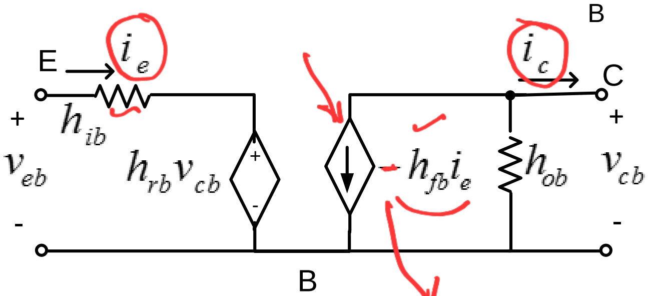
CB →

Input →

← output







h - parameter equations:

$$V_{eb} = h_{ib} \cdot I_e + h_{rb} \cdot V_{cb}$$

$$I_c = h_{fb} \cdot I_e + h_{ob} \cdot V_{cb}$$

$$h_{ib} = \left. \frac{V_{EB}}{I_E} \right|_{V_{CB}=0} \qquad h_{rb} = \left. \frac{V_{EB}}{V_{CB}} \right|_{I_E=0} \quad \times$$

$$h_{fb} = \alpha = \left. \frac{I_C}{I_E} \right|_{V_{CB}=0} \qquad h_{ob} = \left. \frac{I_C}{V_{CB}} \right|_{I_E=0} \quad \times$$

to be ignored

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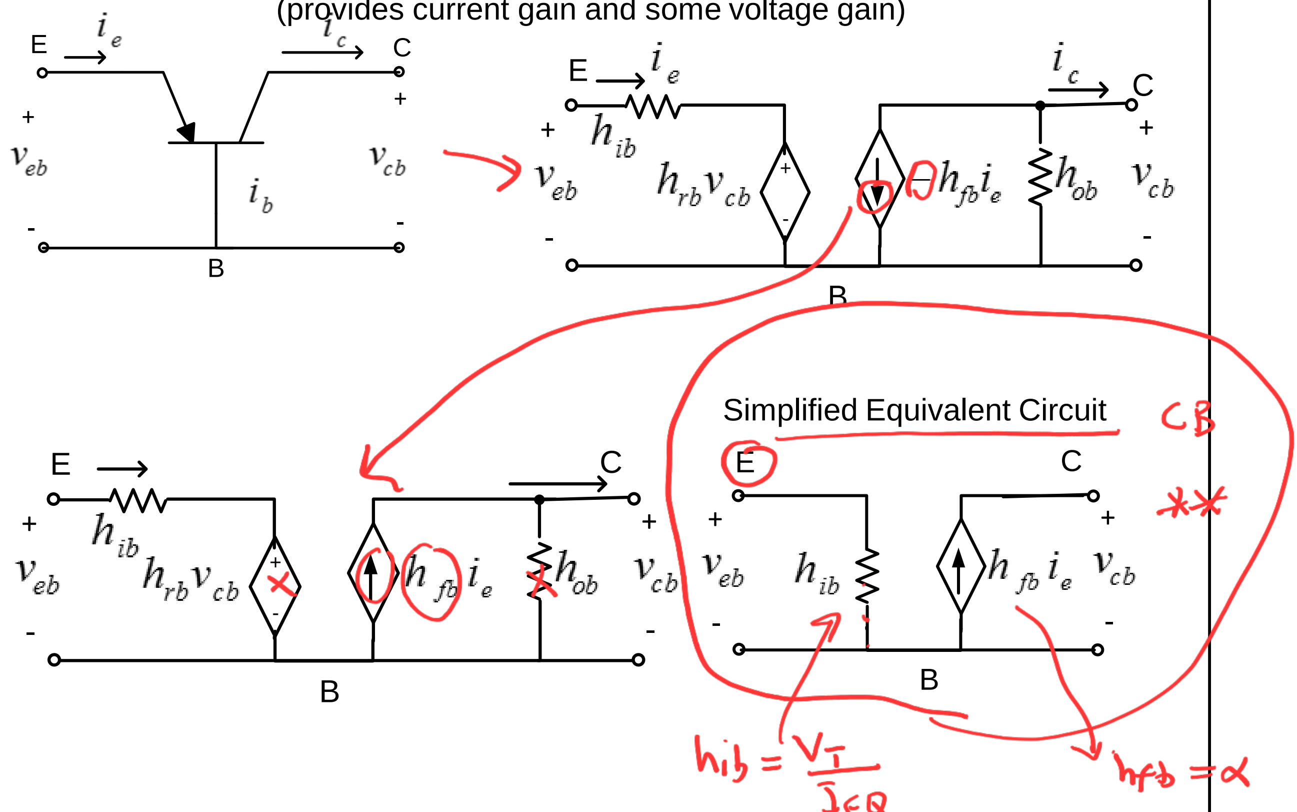
Common-Base Configuration

(provides current gain and some voltage gain)



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Common-Base Configuration

$$h_{ib} = \frac{V_T}{I_{EQ}}$$

$$h_{fb} = \alpha$$

$$V_T = 25.69\ \text{mV}\ \ @\ 25\ ^{o}\text{C}$$

$$\boxed{h_{ie} > h_{ib}}$$

$$hie = \frac{V_T}{I_{BQ}}$$

$$hie = \frac{V_T}{\frac{I_E}{\beta+1}}$$

$$hie = \frac{V_T\ (\beta+1)}{I_E}$$

$$hie = hib(\beta+1)$$

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ac small-signal analysis

BJT Amplifier Analysis

When Analyzing Amplifier Circuits, we usually want to find some or all of the following quantities **with and without Rs**:

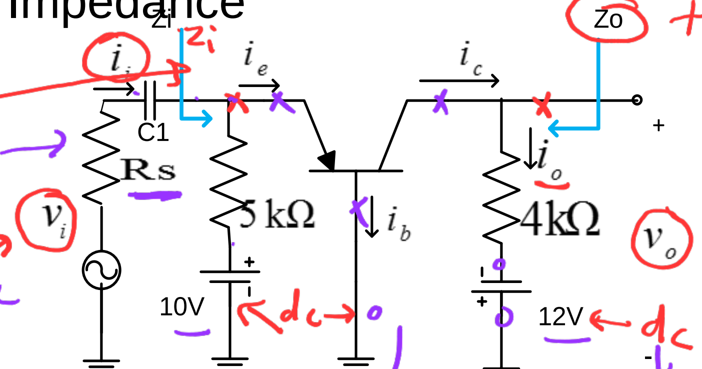
ac small signal (ss) quantities

1) Av=Vo/Vi, small signal voltage gain
2) Ai=io/ii, small signal current gain
3) Zi Input Impedance
4) Zo Output Impedance

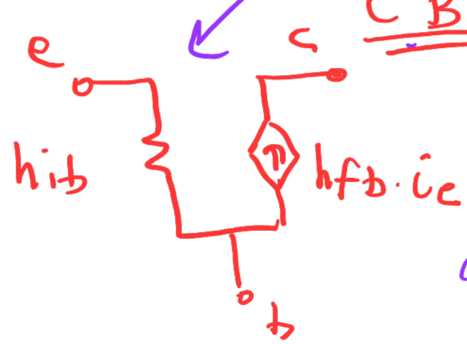
$A_v = \frac{v_o}{v_i}$ ← ac

ac analysis

to be given



CB



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ac analysis → f ↑↑ large

1. all dc sources are killed (deactivated)

V → 0 → short

I → 0 → open

2. Caps → $X_C = \frac{1}{2\pi f C}$

$X_C \cong 0$ → are replaced by a short circuit

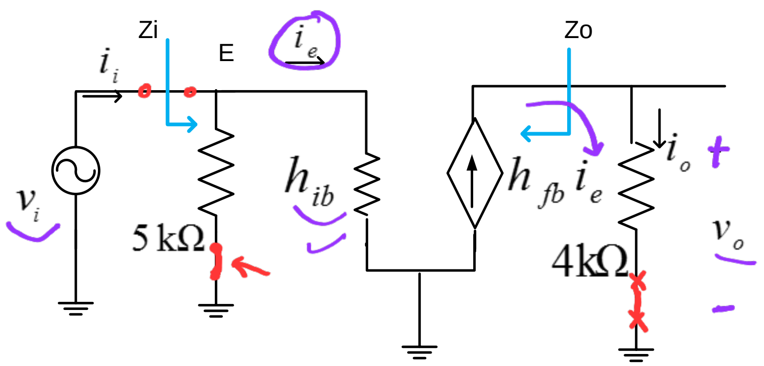
BJT Amplifier Analysis

Solution: (with Rs=0)

We draw the ac small signal equivalent circuit

Capacitors ==> replaced by short circuit

DC sources are killed ,



$$h_{ib} = \frac{V_T}{I_{EQ}}$$

$$h_{fb} = \alpha \cong 1$$

I_{EQ} must be calculated from DC analysis

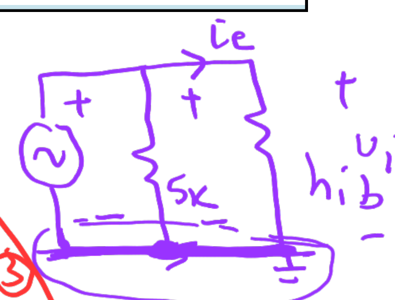
$A_v = \frac{V_o}{V_i}$;

$V_o = i_o \cdot 4K \rightarrow \frac{V_o}{i_o} = 4K$ ①

$i_o = h_{fb} \cdot i_e \rightarrow \frac{i_o}{i_e} = h_{fb}$ ②

$\boxed{i_e = i_b(h_{fe}+1)}$

$i_e = \frac{V_i}{h_{ib}} \rightarrow \frac{i_e}{V_i} = \frac{1}{h_{ib}}$ ③



① × ② × ③ = $\frac{V_o}{\cancel{i_o}} \times \frac{\cancel{i_o}}{\cancel{i_e}} \times \frac{\cancel{i_e}}{V_i} = \frac{V_o}{V_i} = A_v$

$A_v = 4K \times h_{fb} \times \frac{1}{h_{ib}}$

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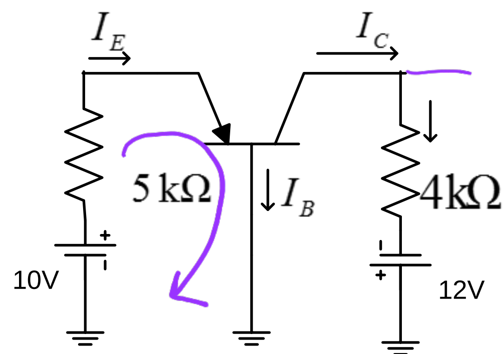
$$\boxed{A_v = 4k \cdot h_{fb} \cdot \frac{1}{h_{ib}}}$$

$$h_{ib} = \frac{V_T}{I_{EQ}}$$

dc current → dc analysis

DC Analysis

DC Equivalent Circuit:
-Cap ==> open
-Kill ac sources ==>



$$10 = 5\,k\Omega \,.\, I_{EQ} + V_{EB}$$

$$I_{EQ} = \frac{10 - 0.7}{5\,k\Omega} = 1.86\,mA$$

$$h_{ib} = \frac{V_T}{I_{EQ}} = \frac{25.69\,mV}{1.86\,mA} = 13.98\,\Omega$$

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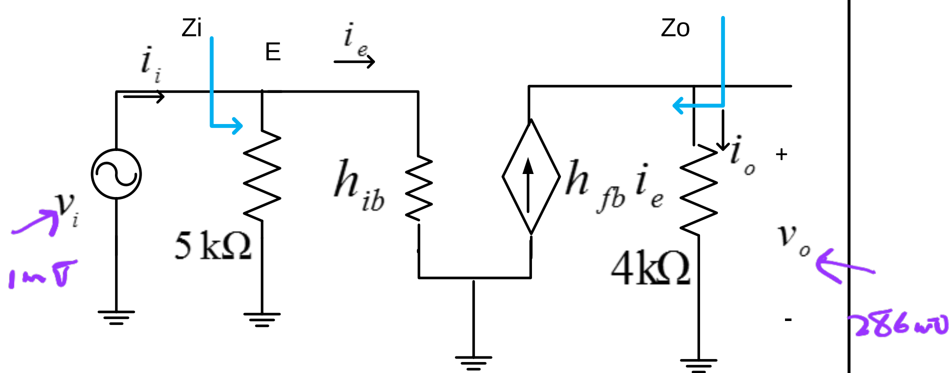
Ac ss equivalent circuit

1) $A_V = \frac{v_o}{v_i}$

$v_o = i_o . 4\,k\Omega$

$i_o = h_{fb} . i_e$

$i_e = \frac{v_i}{h_{ib}}$



$A_V = \frac{v_o}{v_i} = \frac{v_o}{i_o} . \frac{i_o}{i_e} . \frac{i_e}{v_i}$

$A_V = (4\,k\Omega).(h_{fb}).\left(\frac{1}{h_{ib}}\right)$

$= (4\,k\Omega).(1).\left(\frac{1}{13.98}\right) = 286 > 1$

voltage gain

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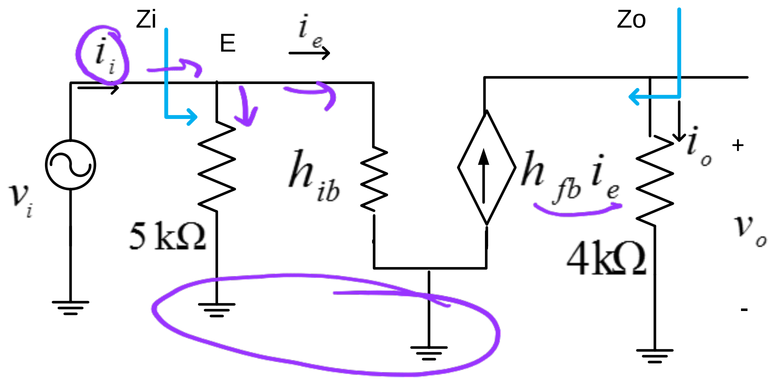
Current Gain Ai

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

$i_o = h_{fb} . i_e$

$i_e = i_i \frac{5\,k\Omega}{5\,k\Omega + h_{ib}}$



$$\Rightarrow A_i = \frac{i_o}{i_i} = \frac{i_o}{i_e} \cdot \frac{i_e}{i_i}$$

$$\Rightarrow A_i = (h_{fb}) \left(\frac{5\,k\Omega}{5\,k\Omega + h_{ib}} \right)$$

$$= (1) \left(\frac{5\,k\Omega}{5\,k\Omega + 13.98} \right) < 1$$

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BJT Amplifier Configurations

L14 1sec 1
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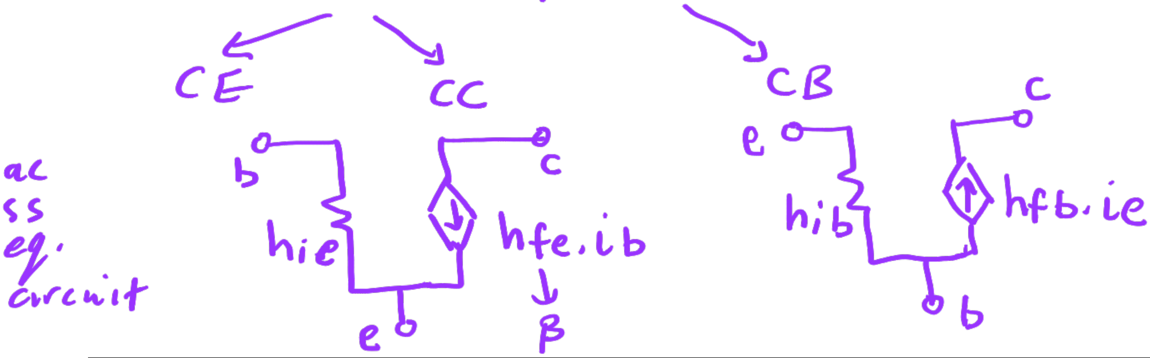
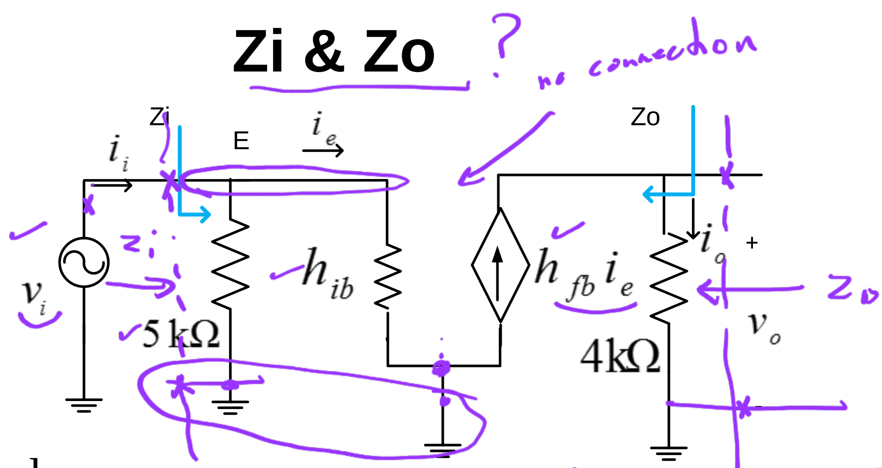
ac ss eq. circuit



Zi & Zo

? no connection

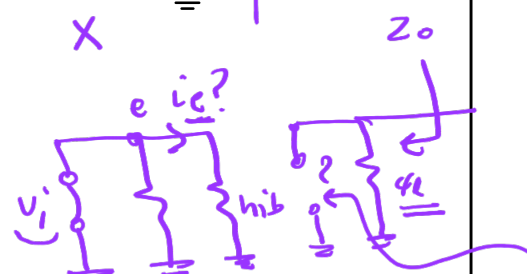


3) Input Impedance

$$Z_i = \left(h_{ib} // 5\,\mathrm{k\Omega}\right) = \left(\frac{h_{ib}.5\,\mathrm{k\Omega}}{5\,\mathrm{k\Omega} + h_{ib}}\right)$$

4) Output Impedance

$$Z_o\Big|_{\text{all independant sources killed (i.e. Vi=0 or short)}} = 4\,\mathrm{k\Omega}$$



ie → 0 , hfb.ie → 0 → open

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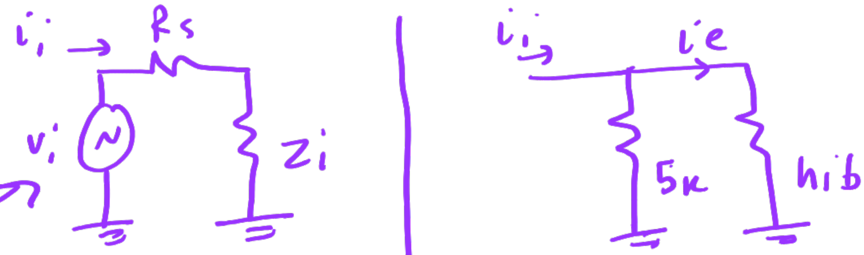


$i_e = i_i \times \frac{5k}{5k + h_{ib}}$

With Presence of Rs

with R_S

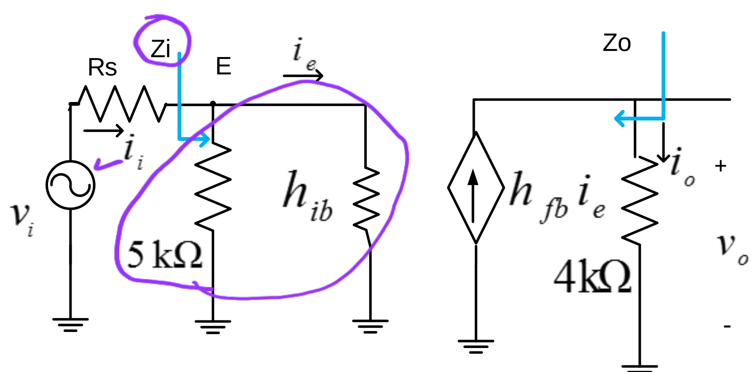
$$i_i = \frac{v_i}{Z_i + R_s}$$

For Rs = 50 Ω

$A_V = 62.5$

For Rs = 10 kΩ

$A_V = 0.4$



$R_s = 0 \rightarrow A_v = 286$

$\uparrow R_s \rightarrow A_v ? \downarrow$

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$\frac{v_o}{v_i} \leftarrow A_v$ $\quad Z_i$ ✓

$\frac{i_o}{i_i} \leftarrow A_i$ $\quad Z_o$ ✓

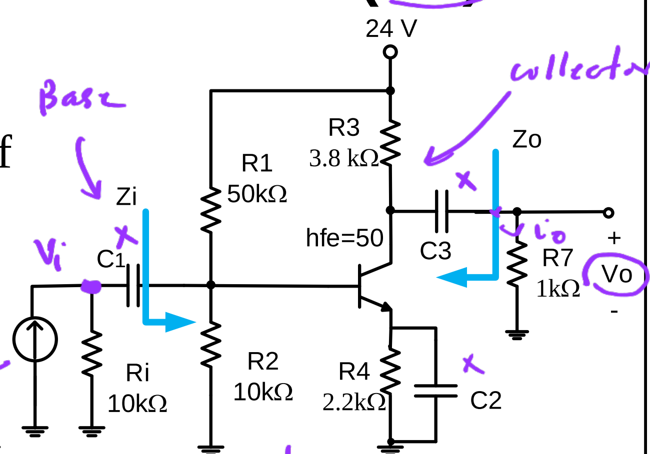
Example: Common Emitter (CE)

1) From DC Analysis, we find Q - point and value of

$$h_{ie} = \frac{V_T}{I_{BQ}}$$

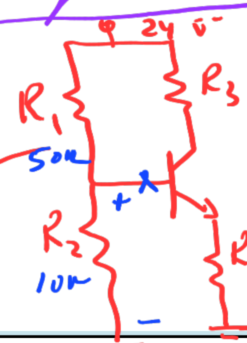
dc current

hic =



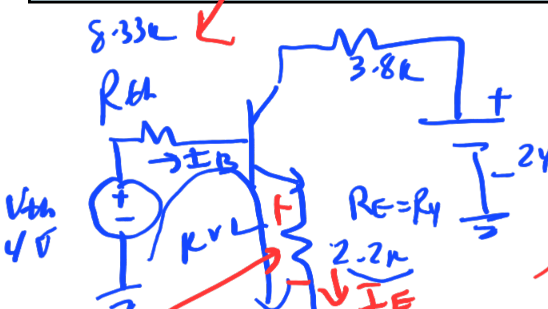
Thevenin's equivalent circuit as seen from the base

dc eq. circuit



$$V_{TH} = \frac{10\ \text{k}\Omega}{10\ \text{k}\Omega + 50\ \text{k}\Omega}.24\ \text{V} = 4\ \text{V}$$

$$R_{TH} = 10\ \text{k}\Omega\Omega//5\text{k}\Omega = 8.33\ \text{k}\Omega$$



$IE \cdot (2.2k)$

$\boxed{I_B(\beta+1)(2.2k)}$

$I_B(\beta+1)$

$$I_B = \frac{V_{th} - 0.7}{R_{th} + R_E(\beta+1)}$$

$$= \frac{4 - 0.7}{8.33k + 2.2k(50+1)}$$

* Base equivalent circuit

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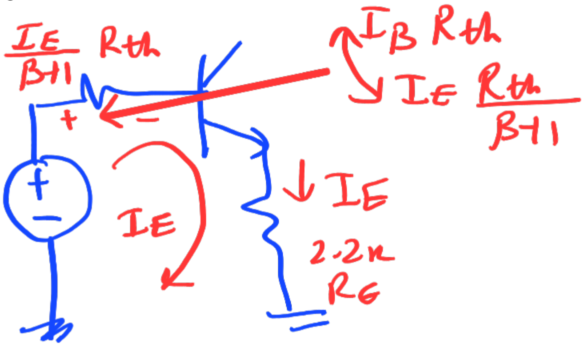
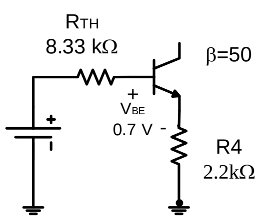


$$I_E = \frac{V_{th} - 0.7}{R_E + \frac{R_{th}}{\beta+1}}$$

* Emitter equivalent circuit

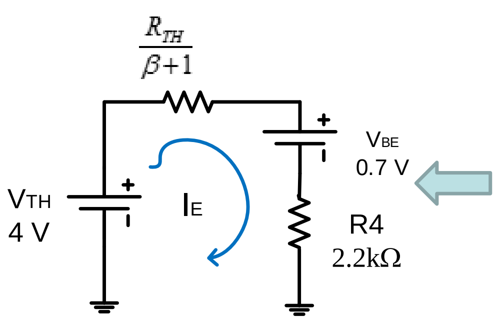


$$4 = 8.33\,\text{k}\Omega\,.\,I_B + V_{BE} + 2.2\,\text{k}\Omega.\,I_E$$

But, $I_E = (1+\beta)I_B$

$$\text{Solve for } I_E = \frac{4 - 0.7}{\frac{8.33\,\text{k}\Omega}{(1+50)} + 2.2\,\text{k}\Omega} = 1.4\,\text{mA}$$

$$h_{ie} = \frac{V_T}{I_{BQ}} = \frac{25.69\,\text{mV}}{\frac{1.4\,\text{mA}}{51}} = 928\,\Omega$$



Here we have base reflected to emitter

$$I_B \Rightarrow I_E = (\beta+1)I_B$$

$$R_B \Rightarrow \frac{R_B}{\beta+1}$$

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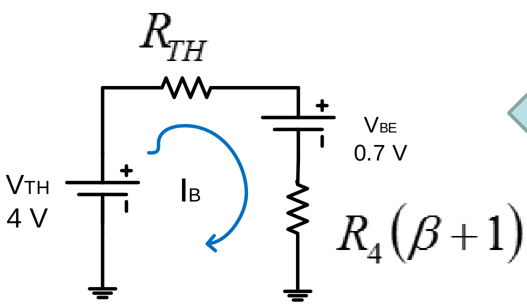
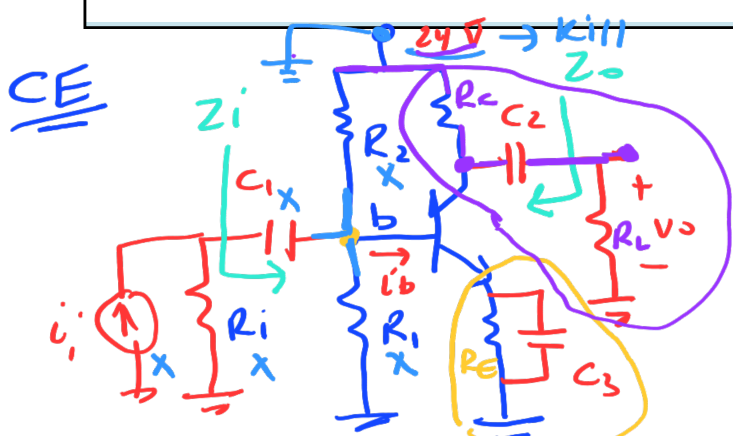


Here we have emitter reflected to base

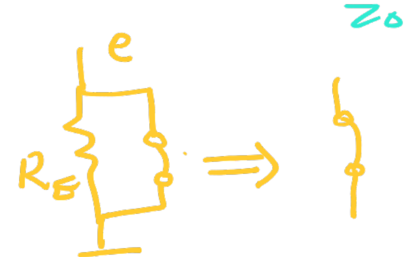
$$I_E \Rightarrow I_B = \frac{I_E}{(\beta+1)}$$

$$R_E \Rightarrow R_E(\beta+1)$$

CE



ac ss eq. circuit
to find A_v, A_i, Z_i, Z_o



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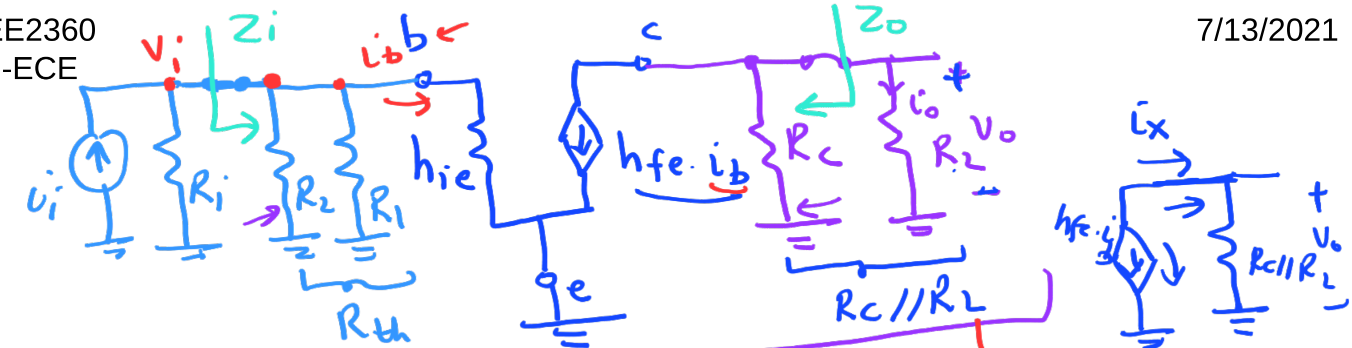


$A_v = \frac{V_o}{V_i}$

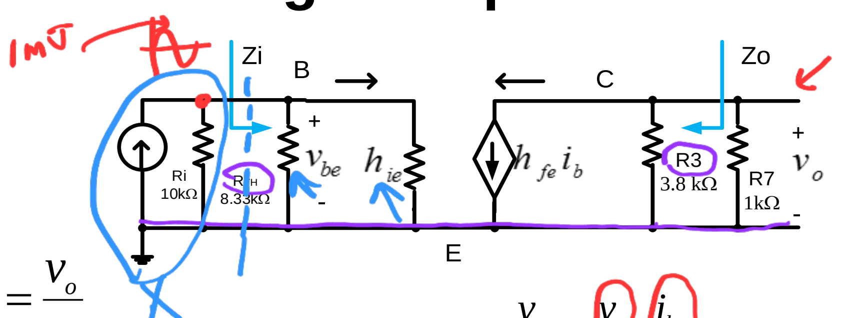
① $V_o = -h_{fe} \cdot i_b (R_L // R_C)$

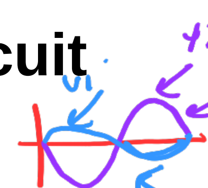
② $i_b = \frac{V_i}{h_{ie}}$

$V_o = i_x (R_L // R_C)$

$i_x = -h_{fe} \cdot i_b$

AC small signal Equivalent Circuit





1) $A_V = \frac{v_o}{v_i}$

$$A_V = \frac{v_o}{v_i} = \frac{v_o}{i_b} \cdot \frac{i_b}{v_i}$$

Rc // RL

① $v_o = -h_{fe} i_b . (R_3 // R_7)$

② $i_b = \frac{v_i}{h_{ie}}$

$$= -h_{fe} . (R_3 // R_7) . \left(\frac{1}{h_{ie}} \right)$$

$$= -50 . (3.8\,\text{k}\Omega // 1\,\text{k}\Omega) . \left(\frac{1}{928\,\Omega} \right) = -42.7$$

Phase shift 180°

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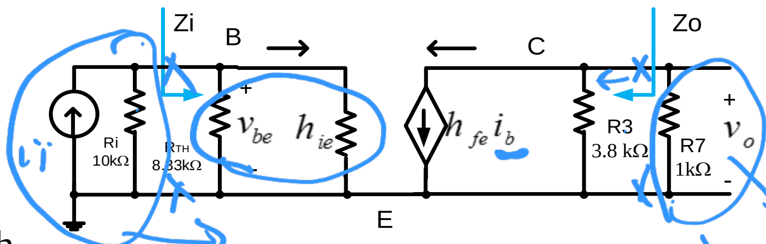
AC small signal Equivalent Circuit



RL X

2) $Z_I = R_{TH} // h_{ie}$

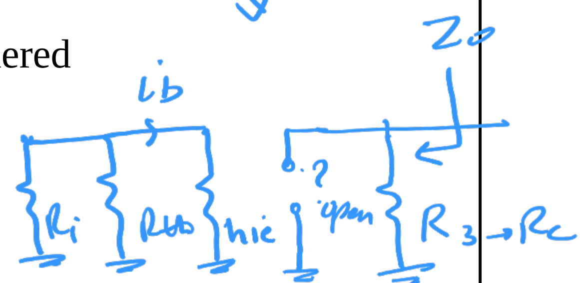
$= 8.33\,k\Omega // 928\,\Omega$

Rth = R1//R2

only elements to the right of arrow are considered according to the given direction of the arrow

3) $Z_o\big|_{\text{all independant sources killed (i.e. Vi=0 or short)}} = \underset{R_3}{3.8\,k\Omega}$

here $h_{fe}.i_b = 0$ since $i_b = 0$ (vi = 0 - killed)



$i_b = \frac{V_i}{h_{ie}} = 0$

$h_{fe}.i_b = 0 \rightarrow$ open

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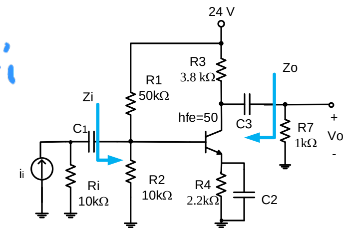
AC small signal Equivalent Circuit



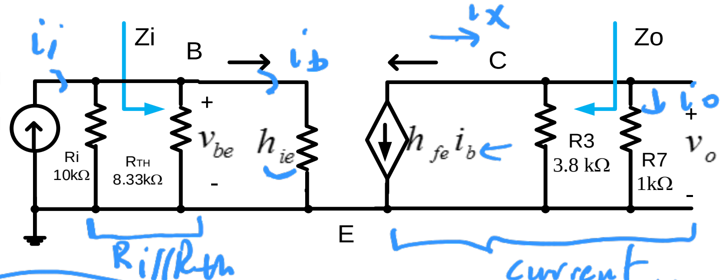
ac ss current gain

$$\frac{\cancel{i_b}}{i_i} \times \frac{i_o}{\cancel{i_b}} = \frac{i_o}{i_i} = A_i$$

4) $A_i = \dfrac{i_o}{i_i}$

1) $$i_b = (i_i)\left(\frac{R_I // R_{TH}}{(R_I // R_{TH}) + h_{ie}}\right)$$

2) $$i_o = -h_{fe} i_b \left(\frac{R_3}{R_3 + R_7}\right)$$



$$i_o = i_x \frac{R_3}{R_3+R_7}$$

$$i_x = -h_{fe} \cdot i_b$$

$$A_i = \frac{i_o}{i_i} = \frac{i_o}{\cancel{i_b}} \cdot \frac{\cancel{i_b}}{i_i} = -h_{fe}\left(\frac{R_3}{R_3 + R_7}\right) \cdot \left(\frac{R_I // R_{TH}}{(R_I // R_{TH}) + h_{ie}}\right) = \underline{\underline{-33}}$$

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$i_b \Rightarrow i_e$?

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

$i_b = \frac{i_e}{\beta+1}$

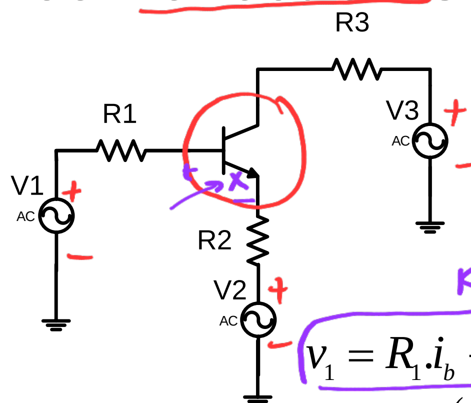
Reflection → simplification technique

From Emitter to base

or " Base to Emitter

Impedance Reflection Concept

v1,v2,v3 are all ac sources

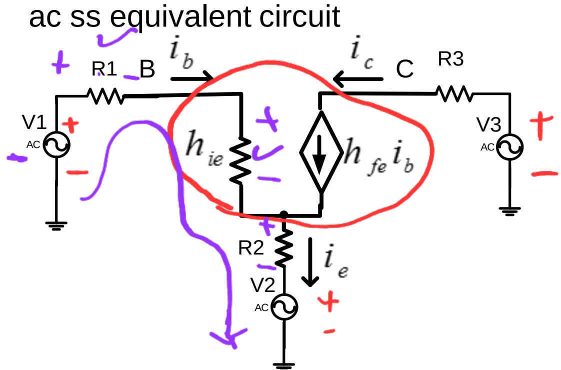


KVL

$$v_1 = R_1.i_b + h_{ie}.i_b + R_2.i_e + v_2$$

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

ac ss equivalent circuit



$$v_1 = R_1.i_b + h_{ie}.i_b + R_2.(\beta+1)i_b + v_2$$

$$i_b = \frac{v_1 - v_2}{R_1 + h_{ie} + R_2.(\beta+1)} \Leftarrow \text{base loop}$$

equivalent circuit equation

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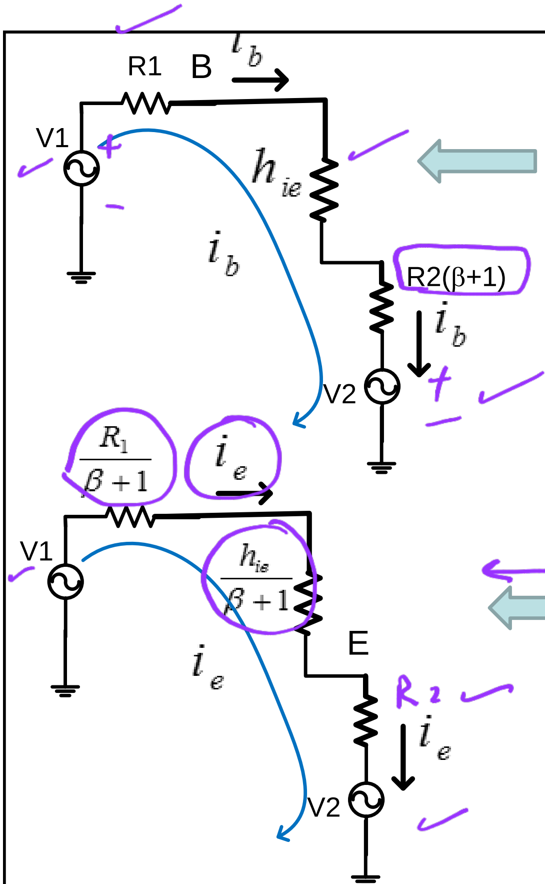
$\beta = h_{fe}$



$$i_b = \frac{v_1 - v_2}{R_1 + h_{ie} + R_2.(\beta+1)} \Leftarrow \text{base loop}$$

equivalent circuit equation

Reflection from Emitter to base

$i_e \to i_b(\beta+1)$

Instead of i_b use i_e

$$i_e = \frac{v_1 - v_2}{\frac{R_1}{(\beta+1)} + \frac{h_{ie}}{(\beta+1)} + R_2} \Leftarrow \text{Emitter loop}$$

equivalent circuit equation

Reflection from base to emitter

$i_b \Rightarrow \frac{i_e}{\beta+1}$

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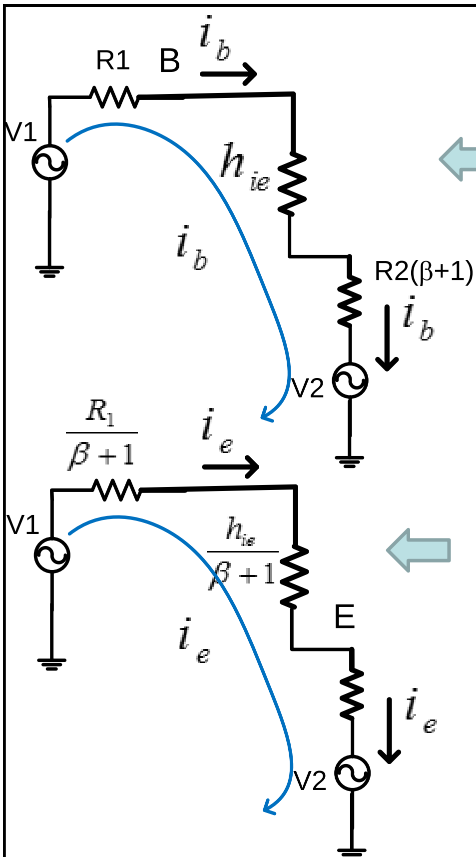
please read



base equivalent circuit

(reflection from emitter to base)

Here we must change i_e to i_b which requires division by $(h_{fe}+1)$, but voltage must remain the same and thus the resistance must be multiplied by the same factor $(h_{fe}+1)$

Emitter equivalent circuit

(reflection from base to emitter)

Here we must change i_b to i_e which requires multiplication by $(h_{fe}+1)$, but voltage must remain the same and thus the resistance must be divided by the same factor $(h_{fe}+1)$

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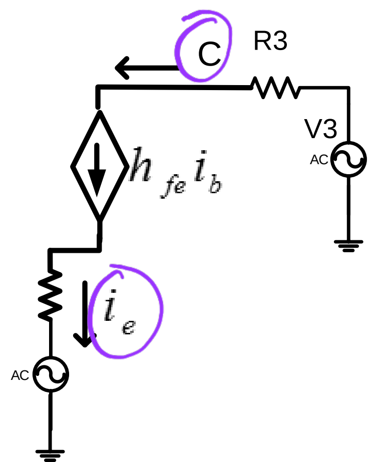
Collector Equivalent Circuit



Note: there is no reflection from emitter to collector or vise versa since the i_e and i_c are almost the same

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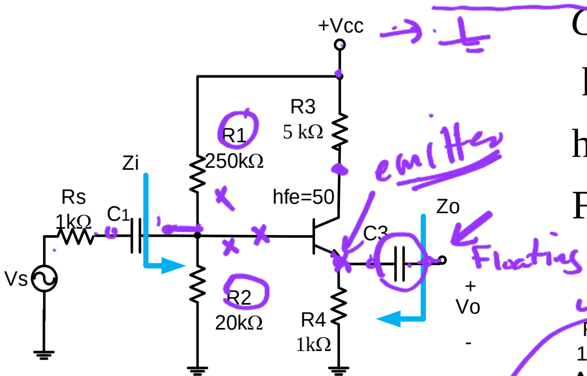
Common Collector Amplifier



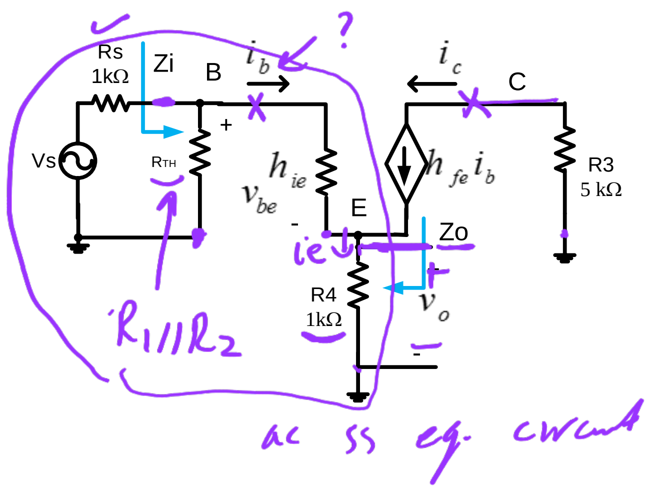
Given

$h_{ie} = 1k\Omega$

$h_{fe} = \beta = 50$

Find Av, Ai, Zi , Zo

AC small signal Equivalent Circuit



1) $A_V = \dfrac{v_o}{v_s}$

$v_o = 1k\Omega \cdot i_e$ ①

$i_e = i_b(h_{fe} + 1)$ ②

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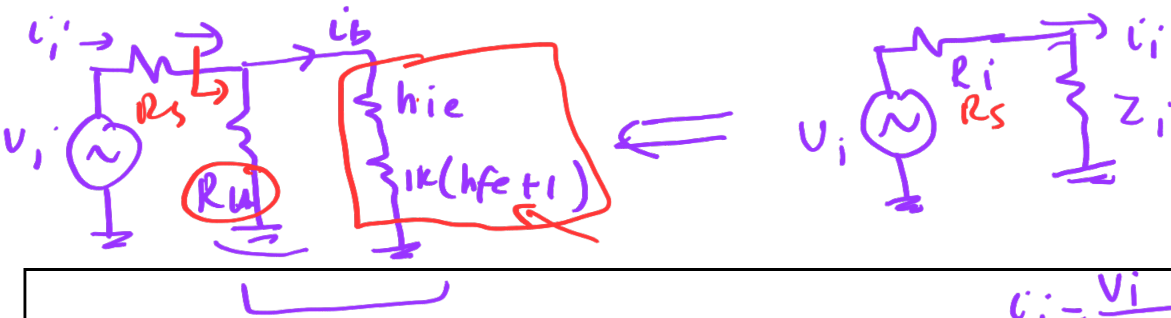
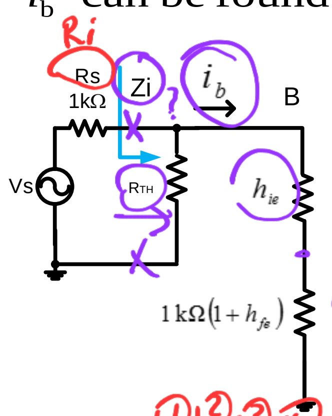


$$i_i = \frac{V_i}{Z_i + R_i}$$

i_b can be found from base equivalent circuit



$$R_{TH} = 20\,\mathrm{k\Omega} // 250\,\mathrm{k\Omega}$$

$$i_b = i_i \frac{R_{TH}}{(R_{TH}) + (h_{ie} + 1\,\mathrm{k\Omega}(h_{fe}+1))} \quad (3)$$

$$i_i = \frac{V_S}{R_S + (R_{TH} // (h_{ie} + 1\,\mathrm{k\Omega}(h_{fe}+1)))} \quad (4)$$

$$\therefore A_V = \frac{v_o}{v_S} = \frac{v_o}{i_e} \cdot \frac{i_e}{i_b} \cdot \frac{i_b}{i_i} \cdot \frac{i_i}{v_S} =$$

$$= (1\mathrm{k\Omega}).(h_{fe}+1)\left(\frac{R_{TH}}{(R_{TH}) + (h_{ie} + 1\,\mathrm{k\Omega}(h_{fe}+1))}\right)\left(\frac{1}{R_S + (R_{TH} // (h_{ie} + 1\,\mathrm{k\Omega}(h_{fe}+1)))}\right)$$

$$= 0.915 < 1$$

CC amplifier doesn't provide any voltage gain

$A_v \le 1$

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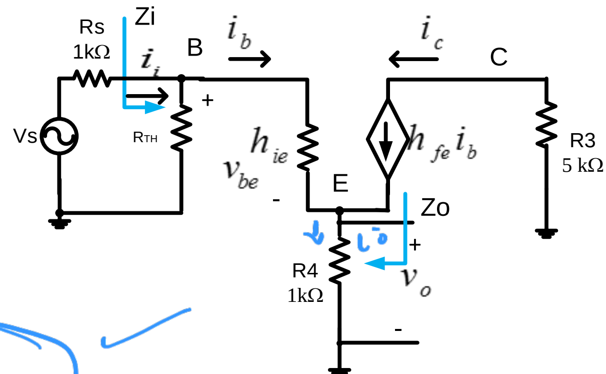
$$2)A_i = \frac{i_o}{i_i}$$

$$i_o = \frac{v_o}{1\,\text{k}\Omega}$$

$$i_o = i_e = i_b(h_{fe}+1)$$

$$i_b = i_i \frac{R_{TH}}{(R_{TH}) + (h_{ie} + 1\,\text{k}\Omega(h_{fe}+1))}$$



$$A_i = \frac{i_o}{i_i} = \frac{i_o}{i_e} \cdot \frac{i_e}{i_b} \cdot \frac{i_b}{i_i}$$

$$= 1(h_{fe}+1)\left(\frac{R_{TH}}{R_{TH} + [hie + 1k(hfe+1)]}\right) = 13.39 > 1$$

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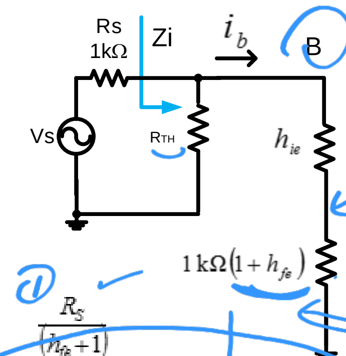
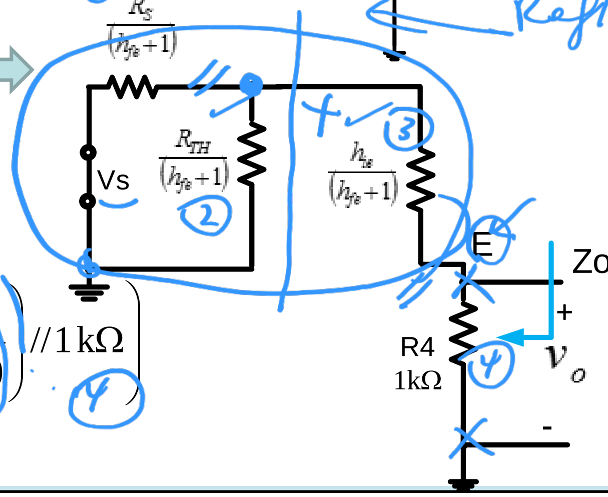
$$3)\ Z_I = \left(R_{TH} // \left(h_{ie} + 1\,k\Omega(h_{fe}+1)\right)\right)$$
$$= 13.66\,k\Omega \quad (\text{high})$$



Emitter Equivalent Circuit
$\& V_S = 0$

$$Z_o\big|_{Vs=0} = \left(\frac{(R_S // R_{TH}) + h_{ie}}{(h_{fe}+1)} // 1\,k\Omega\right)$$
$$= \left(\left(\left(\frac{R_S}{(h_{fe}+1)}\right) // \left(\frac{R_{TH}}{(h_{fe}+1)}\right)\right) + \frac{h_{ie}}{(h_{fe}+1)}\right) // 1\,k\Omega$$
$$= 36.8\,\Omega \quad (\text{low})$$

1 2 3 4



CC amplifier

Av ≤ 1

Ai >>

Zi ↑↑

Zo ↓↓

End of L14

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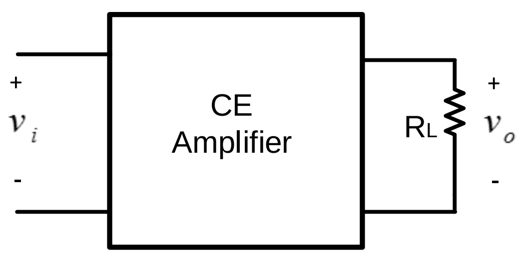
L15
5/8/2021
see separate pdf file

CC Amplifier as a Buffer

- The value of load resistor RL affects the voltage gain Av,
- This effect is called loading effect and can be substantial



$h_{ie} = 1000\,\Omega$

$h_{fe} = 140$

- A buffer (interface) can be used between the amplifier and the load to reduce this loading effect and keep the high gain
- CC Amplifier is also known as Emitter Follower

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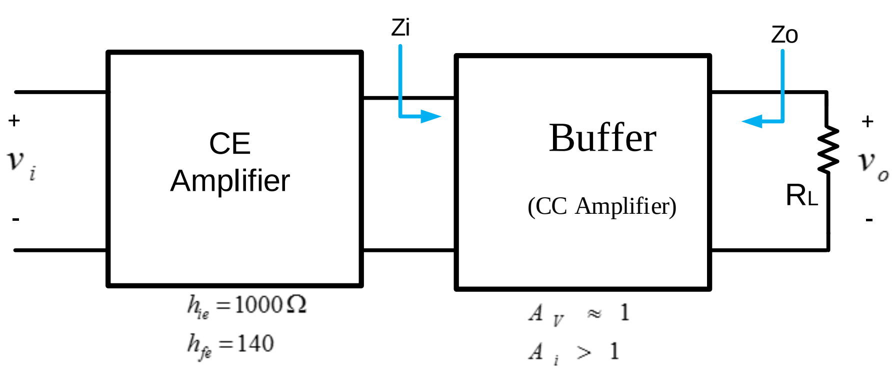
CC Amplifier as a Buffer

- The buffer must have the following characteristic:

$$A_V \approx 1$$
$$A_I > 1$$
$$Z_I >> \text{high}$$
$$Z_o << \text{low}$$

- The above characteristic are present in the CC amplifier the load to reduce this loading effect and keep the high gain



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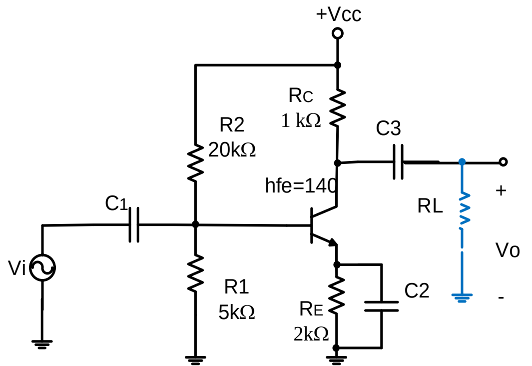
Example

- First we consider effect of load (RL) on amplifier voltage gain
- Then we use a buffer and see its effect on reducing effect of RL



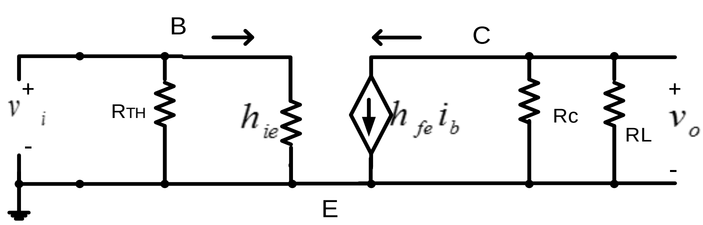
$$1)\ \text{with } R_L = \infty$$

$$v_o = -h_{fe} i_b . (R_C)$$

$$i_b = \frac{v_i}{h_{ie}}$$

$$A_V = \frac{v_o}{v_i} = \left(-h_{fe} R_C\right) . \frac{1}{h_{ie}} = -140$$

$$2)\ \text{with } R_L = 50\,\Omega$$



$$A_V = \frac{v_o}{v_i} = \left(-h_{fe} R_C // R_L\right) . \frac{1}{h_{ie}} = -6.87$$

Av have been reduced from -140 to -6.87

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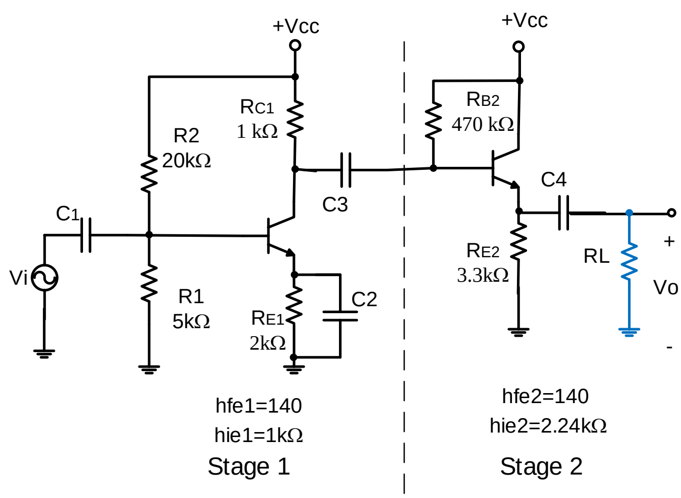
Amplifier + Buffer + Load

Now let us look at the new circuit with the buffer



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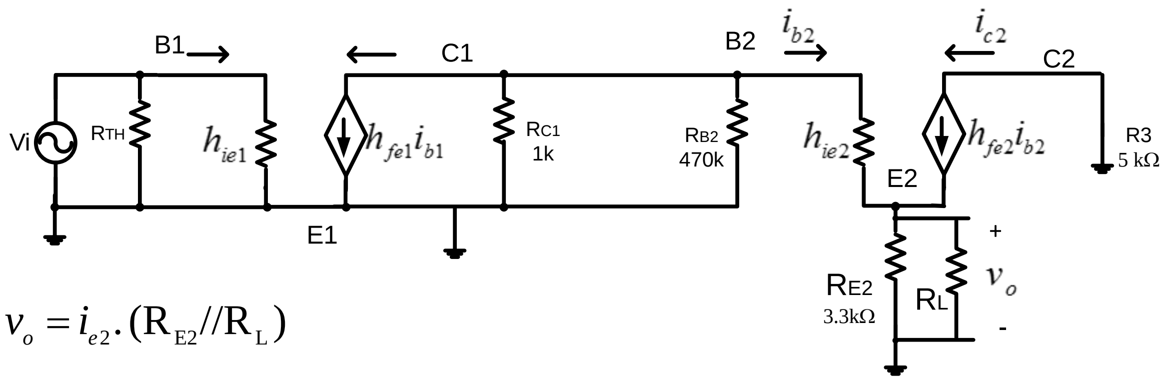
ac ss equivalent Circuit



$$v_o = i_{e2}.(R_{E2}//R_L)$$

$$i_{e2} = i_{b2}(1+h_{fe2})$$

$$i_{b2} = -h_{fe1}.i_{b1}\frac{(R_{C1}//R_{B2})}{((R_{C1}//R_{B2})+(h_{ie2}+(R_{E2}//R_L)(1+h_{fe2})))}$$

$$i_{b1} = \frac{V_i}{h_{ie1}}$$

$$\Rightarrow Av = \frac{v_o}{v_i} = \frac{v_o}{i_{e2}}.\frac{i_{e2}}{i_{b2}}.\frac{i_{b2}}{i_{b1}}.\frac{i_{b1}}{v_i} = -95.6$$

This is much better than the case without buffer

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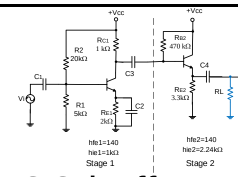
Multistage Amplifiers



- The previous example of a CE amplifier with a CC buffer is an example of a multistage amplifier (two-stage amplifier)
- Multistage amplifiers can be used to get more gain and to improve the performance of the amplifier
- These amplifiers such that the Output of first stage is connected to input of second stage
- Capacitor C3 is a decoupling capacitor that separates the two stages for DC bias point stability, this makes the two stages completely separate in DC analysis and their Q-points are not affected by each other
- C2 is used as a bypass capacitor for stage 1 and allows stabilization of the Q-point, if C2 is removed the input impedance of the amplifier can be improved

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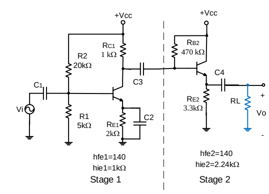

Cascaded Systems

- The output of one amplifier is the input to the next amplifier
- The overall voltage gain is determined by the product of gains of the individual stages
- The DC bias circuits are isolated from each other by the coupling capacitors
- The DC calculations are independent of the cascading
- The AC calculations for gain and impedance are interdependent

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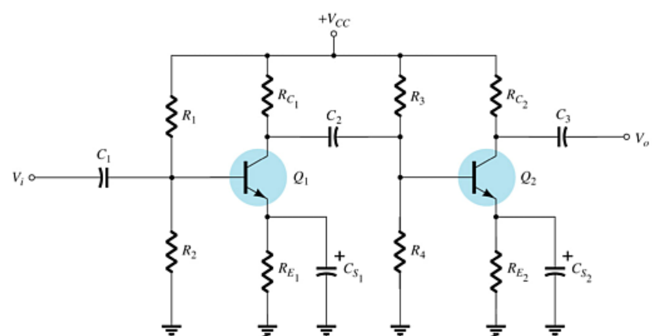
R-C Coupled BJT Amplifiers

Voltage gain:

$$A_v = A_{v1} A_{v2}$$

Input impedance, first stage:

$$Z_i = R_1 \,||\, R_2 \,||\, h_{ie1}$$



Output impedance, second stage:

$$Z_o = R_C$$

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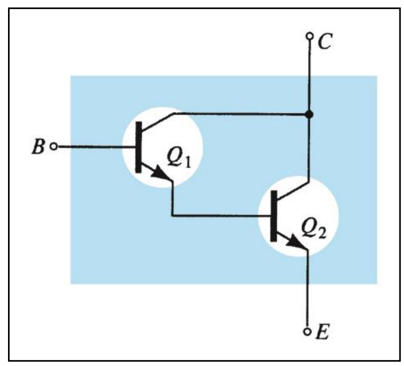
Darlington Connection

- The Darlington circuit provides very high current gain, equal to the product of the individual current gains:
  - $\beta_D = \beta_1 \beta_2$
- The practical significance is that the circuit provides a very high input impedance.



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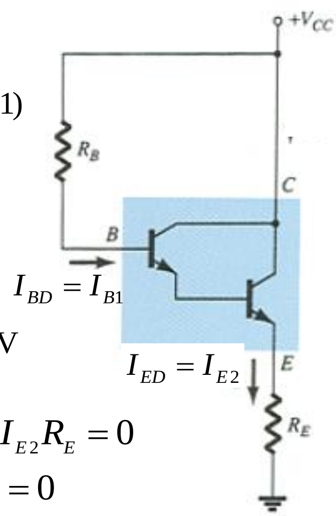
DC Bias of Darlington Circuits

Base current: $I_{BD} = I_{B1} = \dfrac{V_{CC} - V_{BED}}{R_B + (\beta_D + 1)R_E}$

Emitter current:

$$I_{ED} = I_{E2}$$
$$I_{E2} = I_{B2}(\beta_2 + 1)$$
$$I_{B2} = I_{E1}$$
$$I_{E1} = I_{B1}(\beta_1 + 1)$$
$$I_{E2} = I_{B1}(\beta_2 + 1)(\beta_1 + 1)$$
$$I_{ED} = \beta_D I_{BD}$$



Emitter voltage: $V_E = I_{ED} R_E$

Base voltage:

$$V_B = V_E + V_{BE}$$
$$V_{BED} = V_{BE1} + V_{BE2} \cong 1.4\ \text{V}$$

KVL for input loop :

$$V_{CC} - I_{B1}R_B - V_{BE1} - V_{BE2} - I_{E2}R_E = 0$$
$$V_{CC} - I_{BD}R_B - V_{BED} - I_{ED}R_E = 0$$

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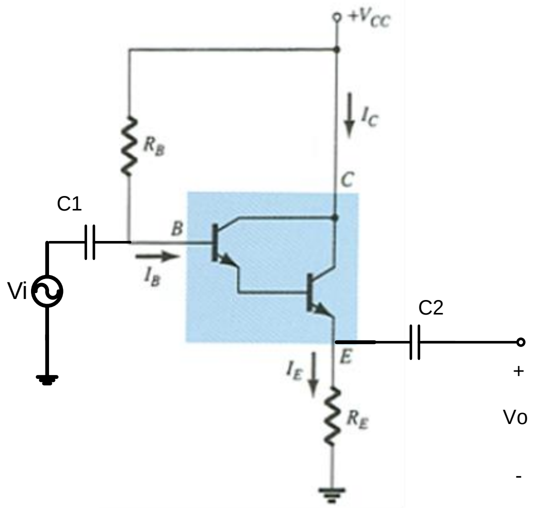
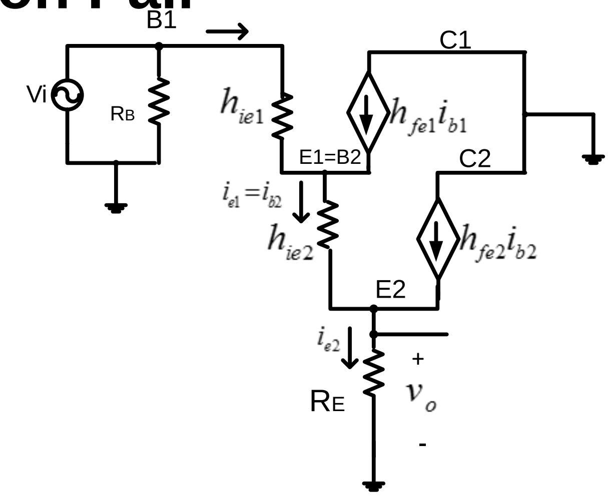
Darlington Pair





Find Ratio of $\dfrac{i_{e2}}{i_{b1}}$ and A_v

$$i_{e2} = i_{b2}(h_{fe2}+1)$$
$$i_{b2} = i_{e1}$$
$$i_{e1} = i_{b1}(h_{fe1}+1)$$

$$i_{e2} = i_{b1}(h_{fe1}+1)(h_{fe2}+1)$$
$$i_{ed} = h_{fed}\, i_{bd}$$
$$h_{fed} = (h_{fe1}+1)(h_{fe2}+1)$$
$$\cong h_{fe1}h_{fe2}$$
$$\cong h_{fe}^{\ 2} \quad ,(\text{if } h_{fe1} = h_{fe2} = h_{fe})$$

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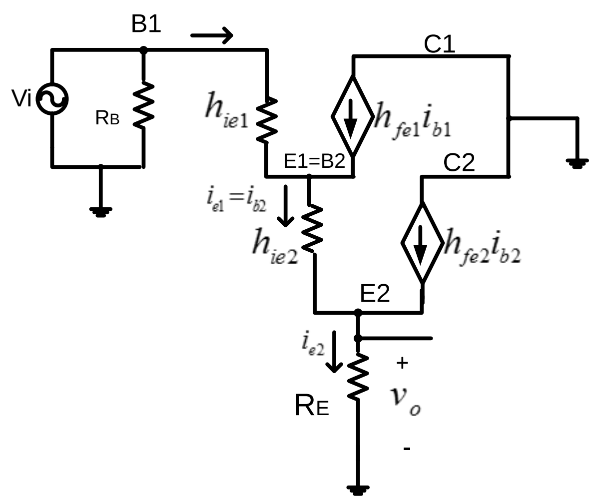
2) Find $\mathrm{A_v} = \dfrac{v_o}{v_i}$

$$v_o = i_{e2} R_E$$

$$i_{e2} = i_{b1}(h_{fe1}+1)(h_{fe2}+1)$$

$$i_{b1} = \frac{v_i}{Z_i}$$



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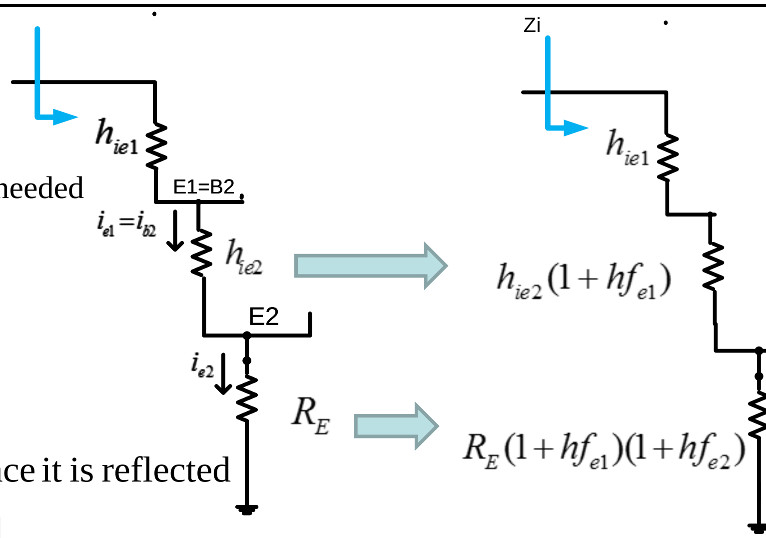
3) Find Z_I

base equivalent circuit is needed



$h_{ie2} \Rightarrow h_{ie2}((h_{fe1}+1)$ since it is reflected from emitter1 to base1

$R_E \Rightarrow R_E(h_{fe1}+1)(h_{fe2}+1)$

since it is reflected twice

1)From E2 to B2 (B2 = E1)

2) From E1 to B1

$$Z_I = h_{ie1} + h_{ie2}(h_{fe1}+1) + R_E(h_{fe1}+1)(h_{fe2}+1)$$

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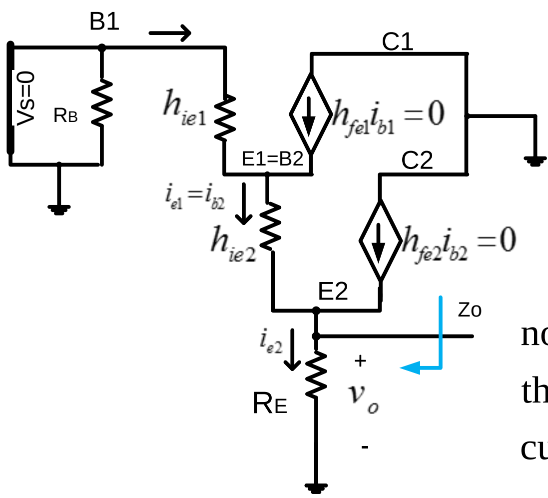
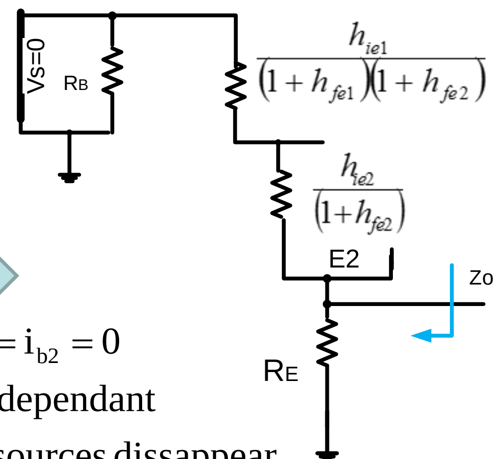
4) Find $Z_o\big|_{Vs=0}$

Zo

Emitter equivalent circuit is needed





note $i_{b1} = i_{b2} = 0$

the two dependant

current sources dissappear

$$Z_0 = \left(\frac{h_{ie1}}{(h_{fe1}+1)(h_{fe2}+1)} + \frac{h_{ie2}}{(h_{fe2}+1)} \right) // R_E$$

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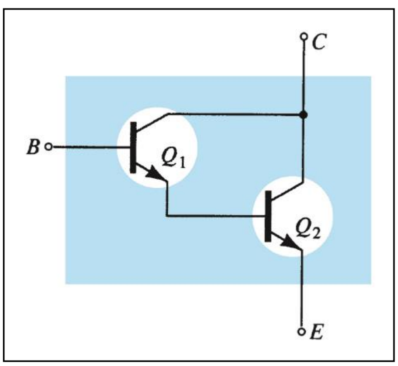
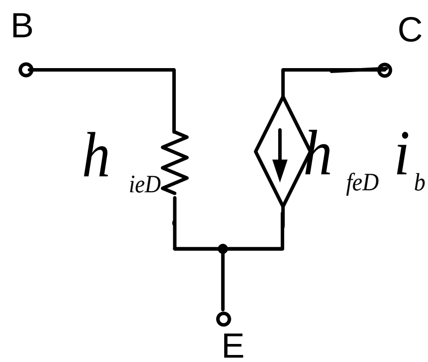
Darlington Simplified Model





$$h_{ieD} \cong 2h_{ie}$$

$$h_{feD} \cong h_{fe1}.h_{fe2}$$

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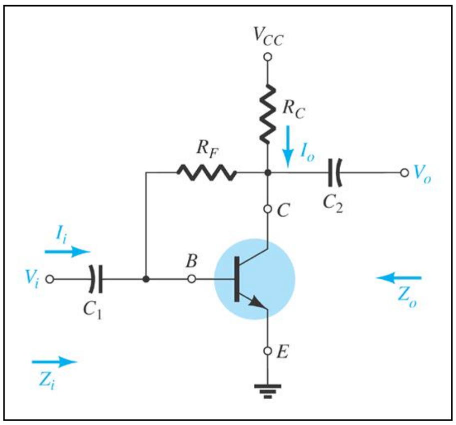
Base To Collector Feedback



Exercise : Find Av, Zi and Zo

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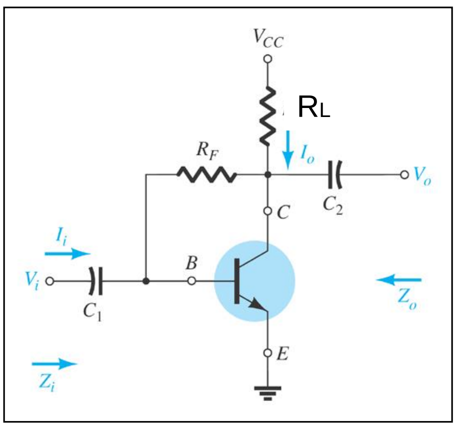
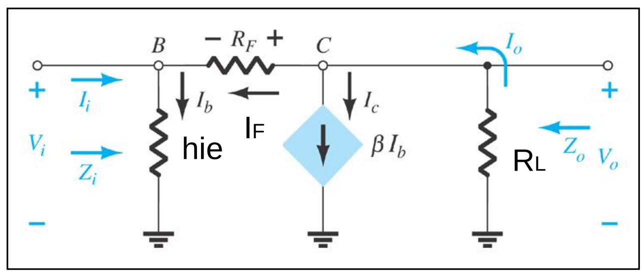
Base To Collector Feedback





Exercise : Find A_V, Zi and Zo

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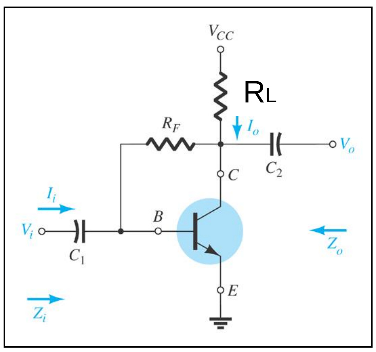
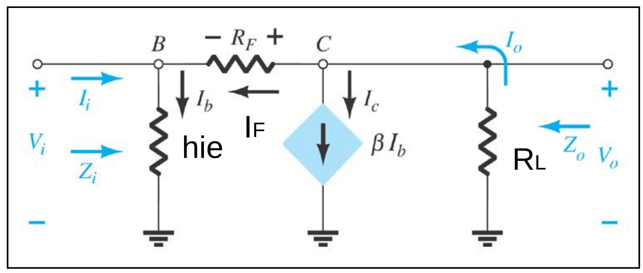
Base To Collector Feedback





$$v_0 = -i_o . R_L$$

$$i_o = h_{fe} . i_b + i_F$$

$$i_F = \frac{v_o - v_i}{R_F}$$

$$i_b = \frac{v_i}{h_{ie}}$$

$$v_0 = -\left(h_{fe} . \frac{v_i}{h_{ie}} + \frac{v_o - v_i}{R_F} \right) . R_L$$

$$v_0 = -R_L h_{fe} . \frac{v_i}{h_{ie}} - \frac{v_o R_L}{R_F} + \frac{v_i R_L}{R_F}$$

$$v_0 \left(1 + \frac{R_L}{R_F} \right) = v_i \left(\frac{R_L}{R_F} - R_L . \frac{h_{fe}}{h_{ie}} \right)$$

$$Av = \frac{\left(\frac{R_L}{R_F} - R_L . \frac{h_{fe}}{h_{ie}} \right)}{\left(1 + \frac{R_L}{R_F} \right)}$$

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$$Z_0\Big|_{v_i=0} = R_F \, // \, R_L$$

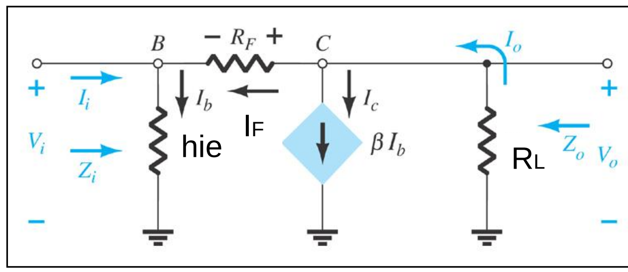
$$Z_i = \frac{v_i}{i_i}$$

$$i_i = i_b - i_F = \left(\frac{v_i}{h_{ie}} - \frac{v_o - v_i}{R_F}\right)$$

$$Z_i = \frac{v_i}{i_i} = \frac{v_i}{\left(\frac{v_i}{h_{ie}} - \frac{v_o - v_i}{R_F}\right)}$$

$$= \frac{v_i}{\left(\frac{R_F v_i - h_{ie}(v_o - v_i)}{R_F h_{ie}}\right)}$$

$$= \frac{v_i R_F h_{ie}}{\left(R_F v_i - h_{ie}(v_o - v_i)\right)}$$



$$= \frac{v_i R_F h_{ie}}{\left((R_F + h_{ie})v_i - h_{ie} v_o\right)}$$

$$= \frac{R_F h_{ie}}{\left((R_F + h_{ie}) - h_{ie}\frac{v_o}{v_i}\right)}$$

$$= \frac{R_F h_{ie}}{\left((R_F + h_{ie}) - h_{ie} A_v\right)}$$

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