Huazhong University of Science and Technology
The Department of Electronics and Information Engineering

Electronic Circuit Analysis and Design

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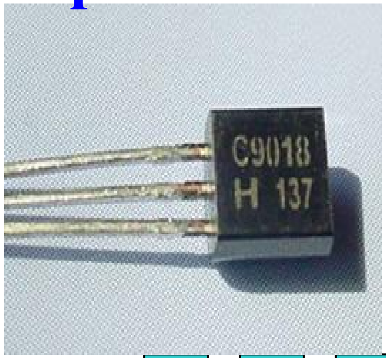
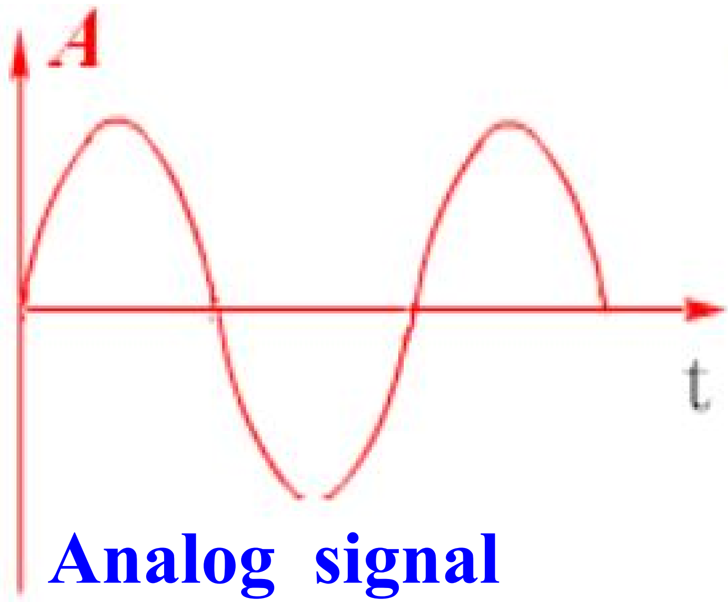
Contents

Ch6. Basic BJT Amplifiers

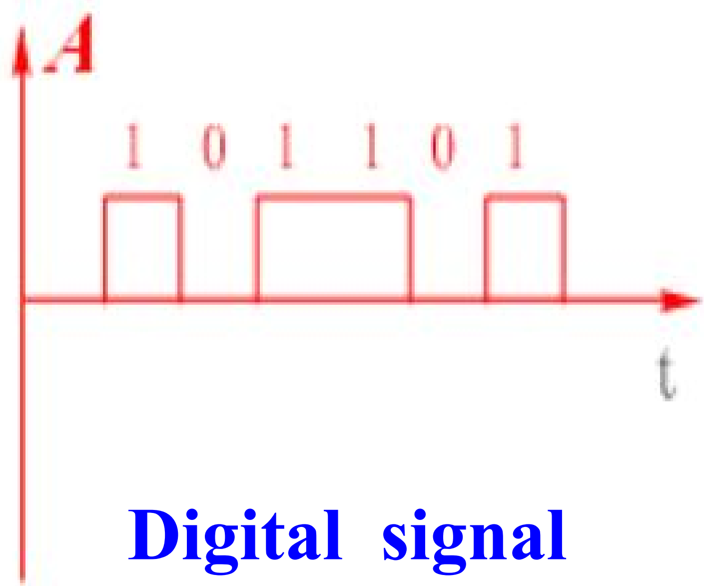


Signals

- A signal contains some type of information. There are two kinds of signals: analog and digital.



Analog signal



Digital signal

6.1 Analog Signals and Linear Amplifiers

Amplifiers

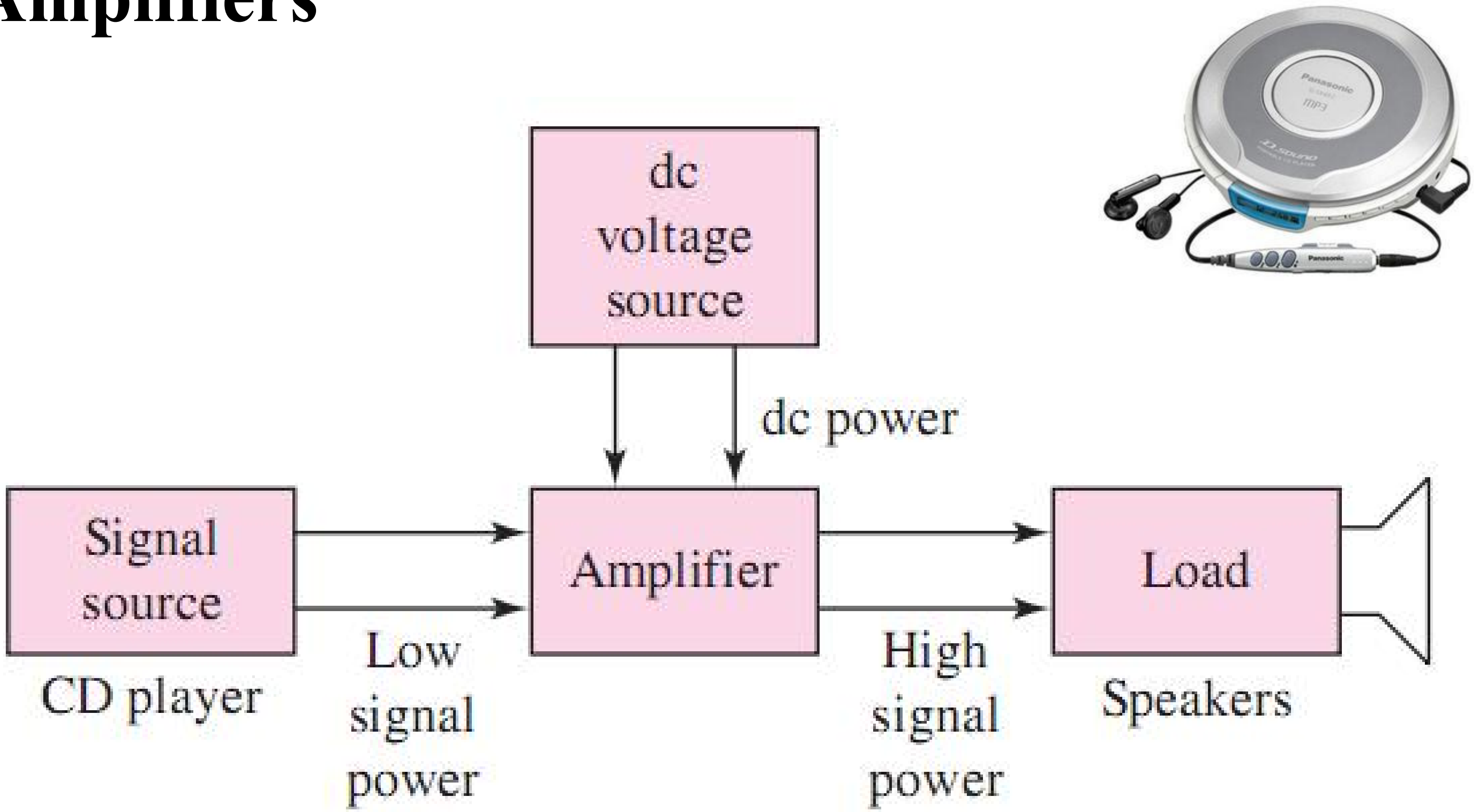
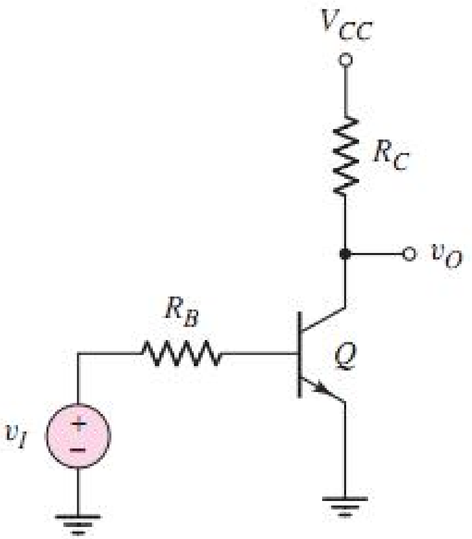


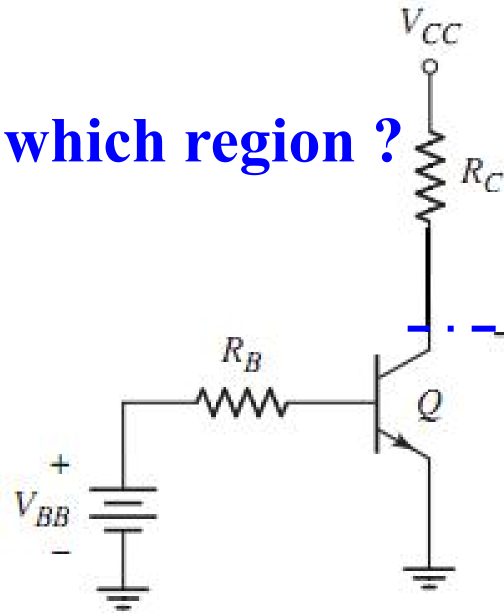
Figure 6.1 Block diagram of a compact disc player system

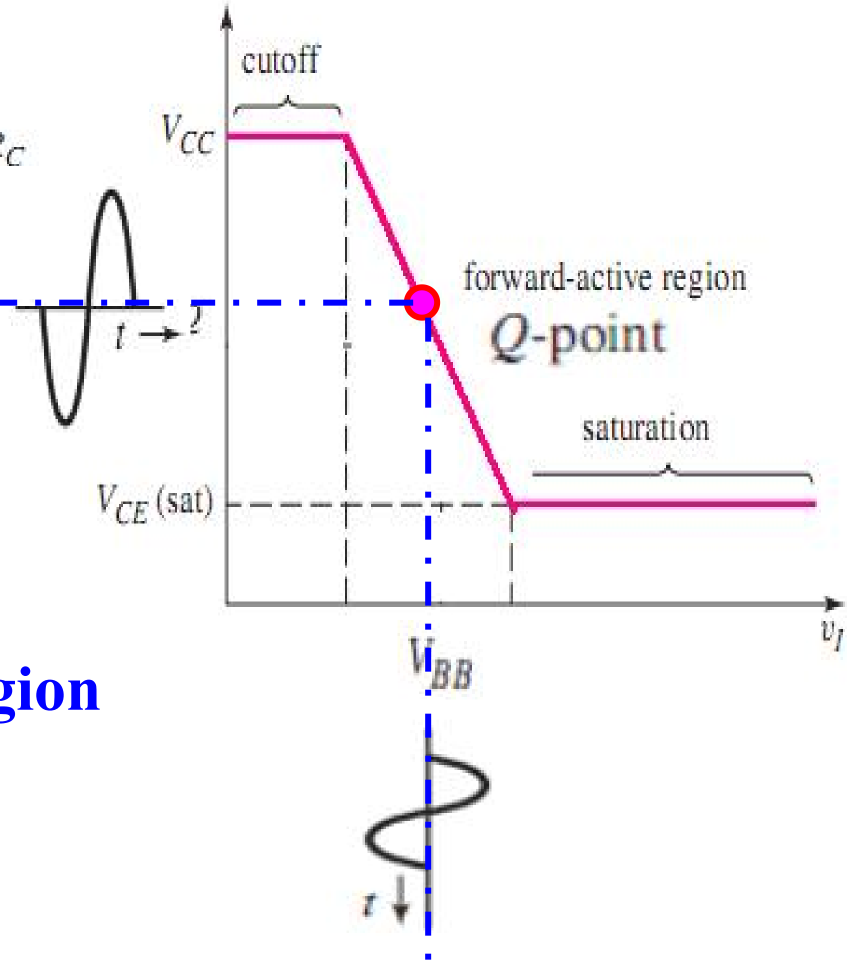
6.2 The Bipolar Linear Amplifier



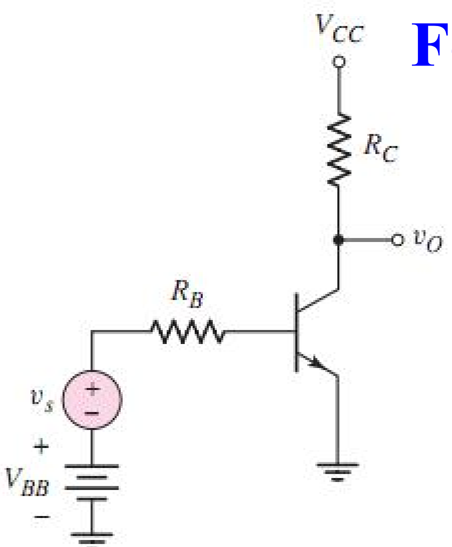
inverter circuit

which region ?





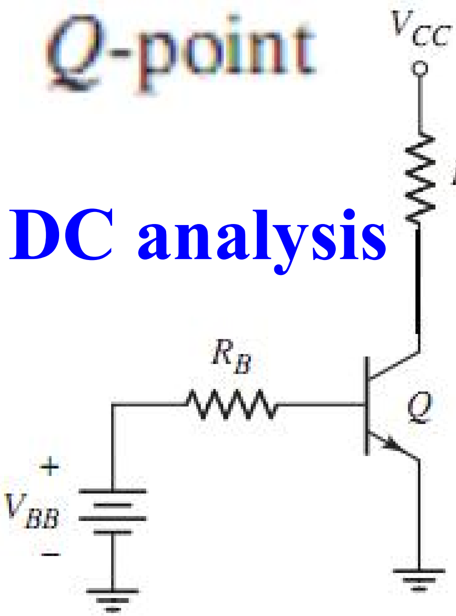
Forward active region



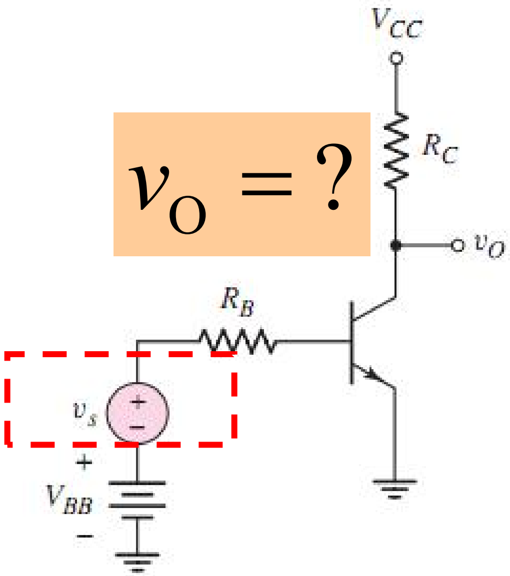
6.2 The Bipolar Linear Amplifier

Q-point

DC analysis



$v_O = ?$



DC AC

$$v_O = V_O + v_o$$

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

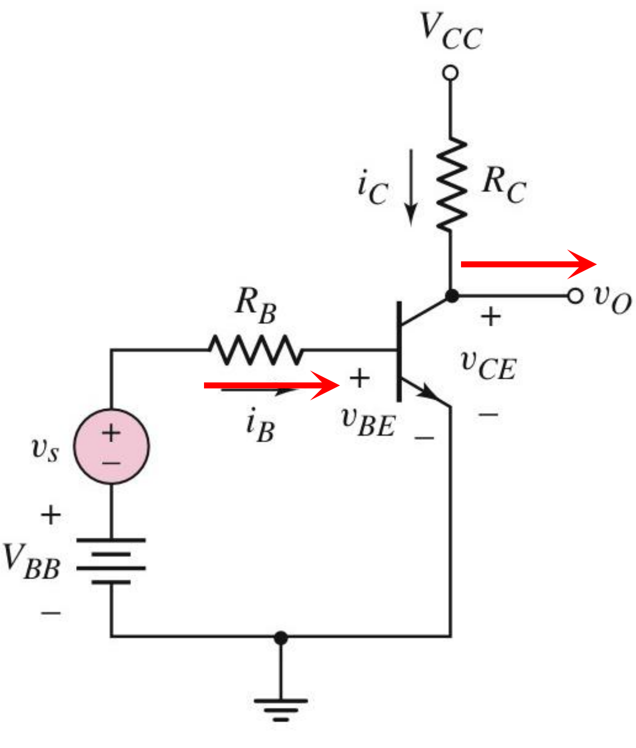
$$I_C = \beta I_B$$

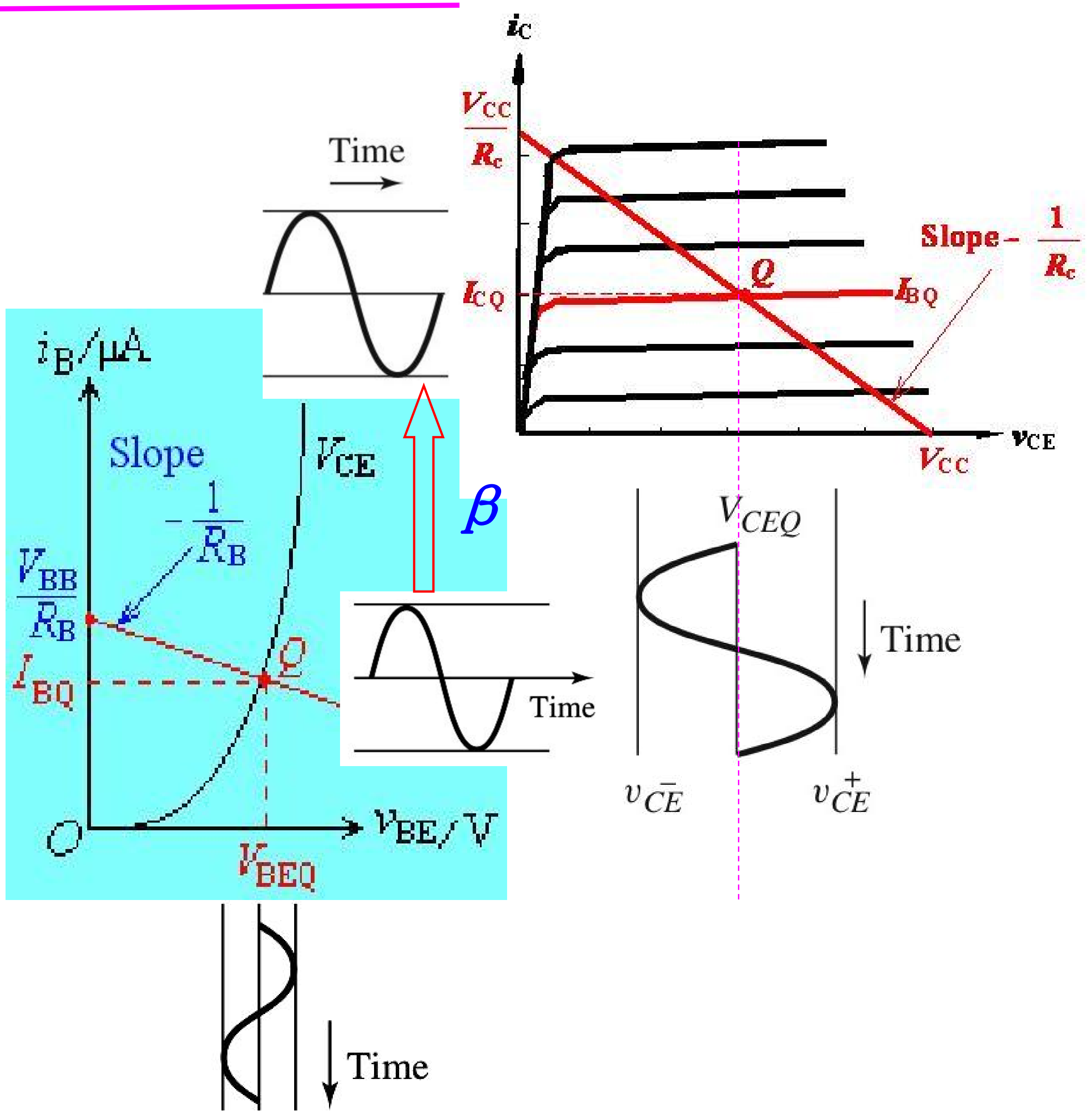
$$V_{CE} = V_{CC} - I_C R_C$$

Table 6.1 Summary of 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

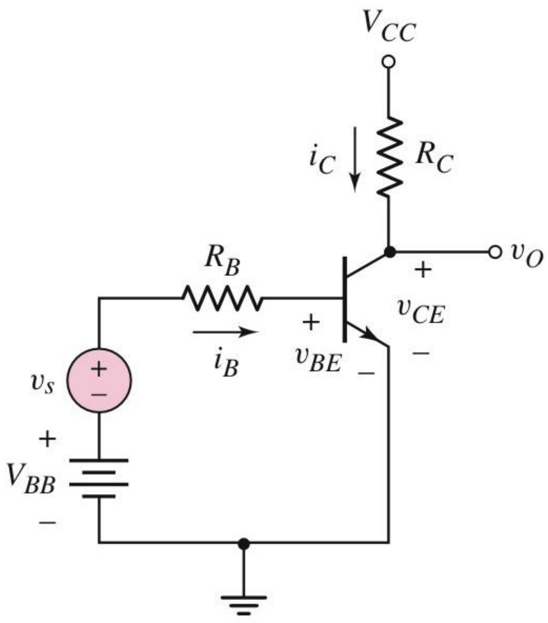
6.2.1Graphical Analysis and ac Equivalent Circuit

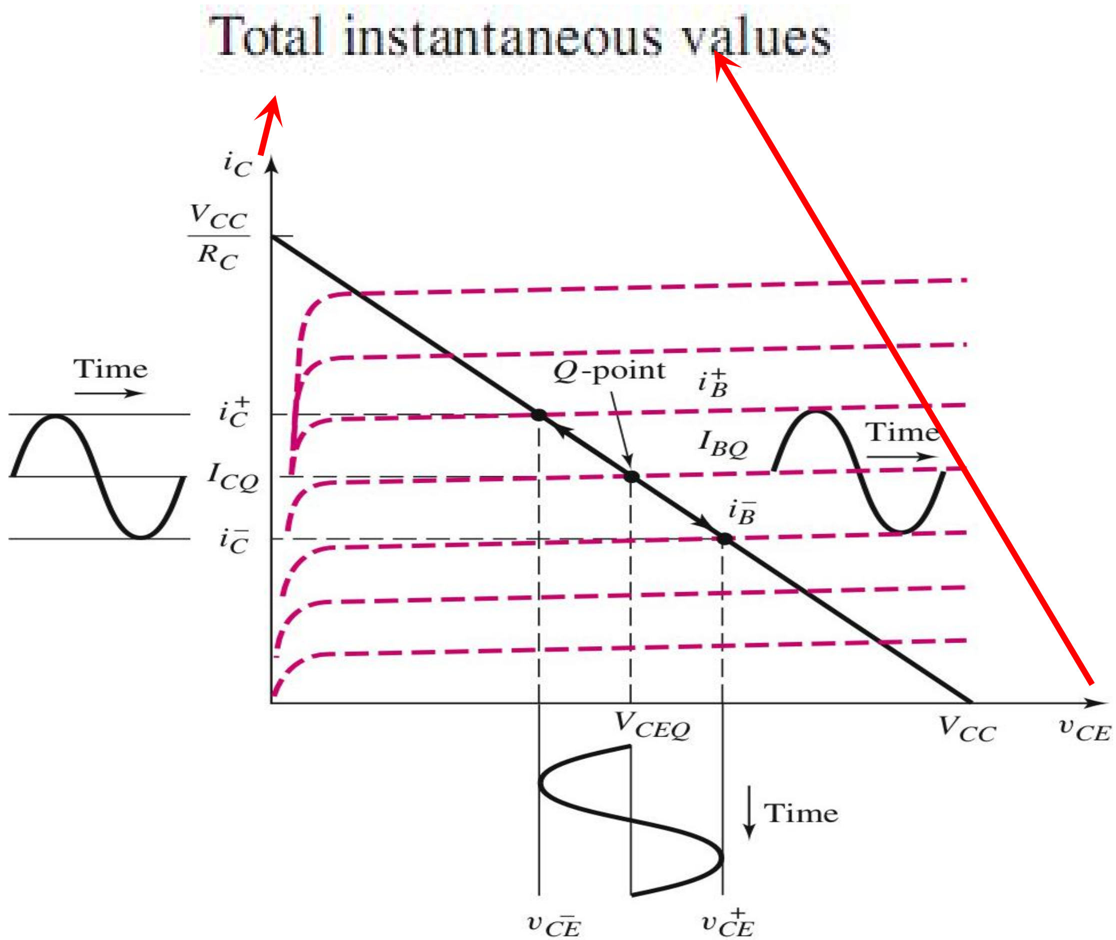




Common Emitter

6.2.1Graphical Analysis and ac Equivalent Circuit





How to get the small signal model?

6.2.1 Graphical Analysis and ac Equivalent Circuit

i_B Versus v_{BE} Characteristic

$$i_B = \frac{i_C}{\beta} = \frac{I_S e^{\frac{v_{BE}}{V_T}}}{\beta}$$

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

$$i_B = \frac{I_S}{\beta} e^{\frac{V_{BE}+v_{be}}{V_T}} = \frac{I_S}{\beta} e^{\frac{V_{BE}}{V_T}+\frac{v_{be}}{V_T}}$$

$$= \frac{I_S}{\beta} \cdot e^{\frac{V_{BE}}{V_T}} \cdot e^{\frac{v_{be}}{V_T}} = I_{\mathrm{BQ}} \cdot e^{\frac{v_{be}}{V_T}}$$

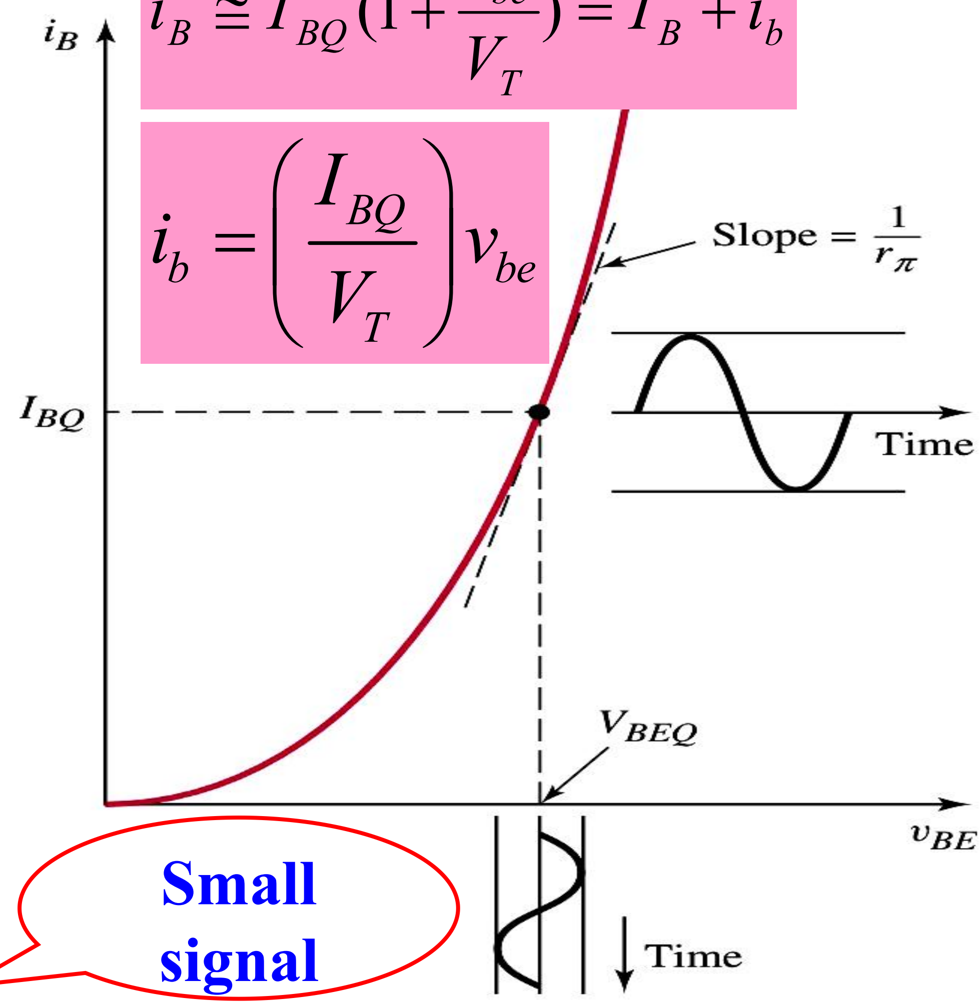
$$v_{be} \ll V_T$$

Taylor series $$e^{\frac{v_{be}}{V_T}} = 1 + \frac{v_{be}}{V_T}$$

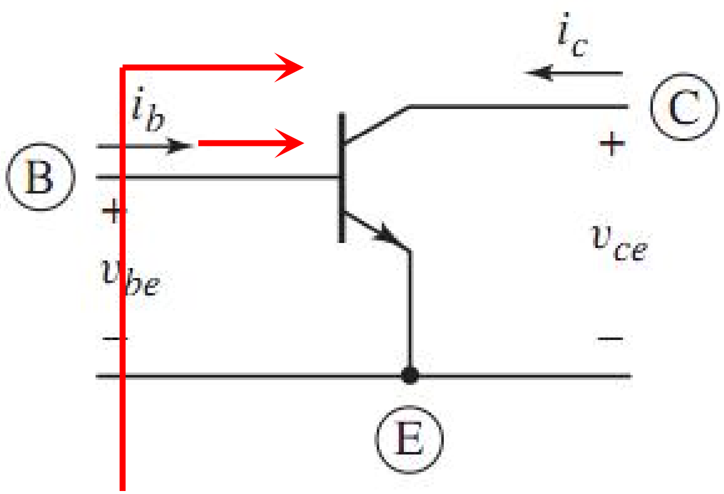
Small signal

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

$$i_b = \left(\frac{I_{BQ}}{V_T}\right) v_{be}$$



6.2.2 Small signal Hybrid-ΠEquivalent Circuit



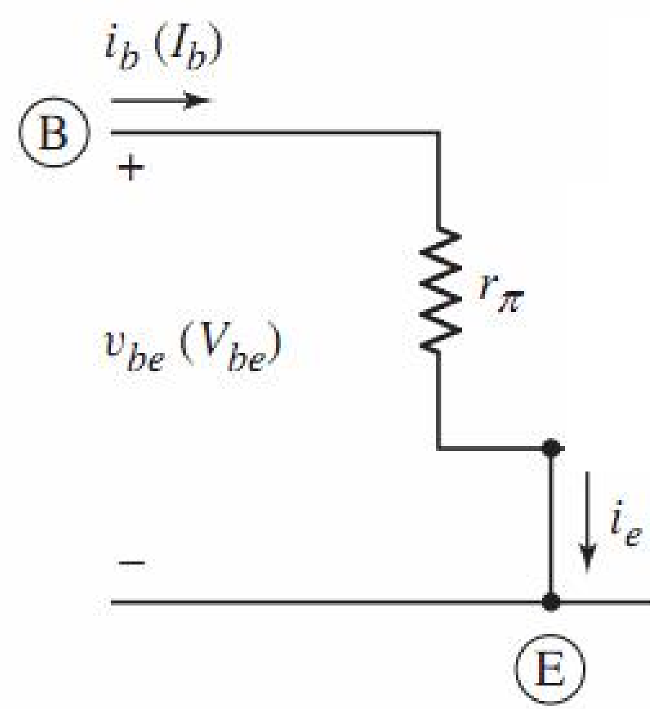


Figure 6.8 The BJT as a small-signal, two-port network

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

$$i_b = \left(\frac{I_{BQ}}{V_T}\right) v_{be}$$

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

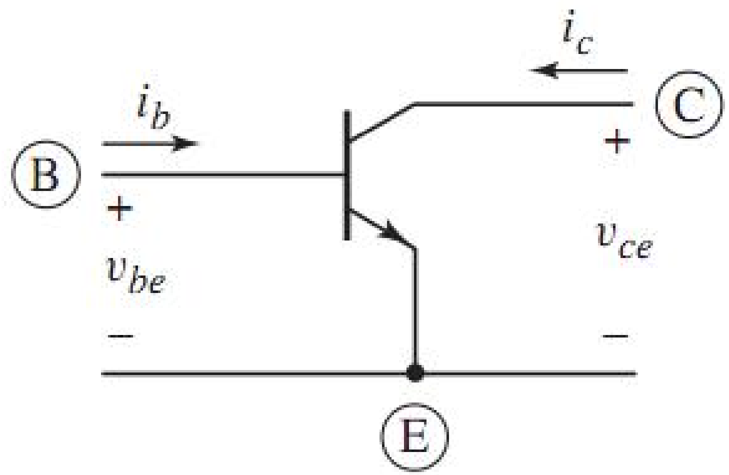
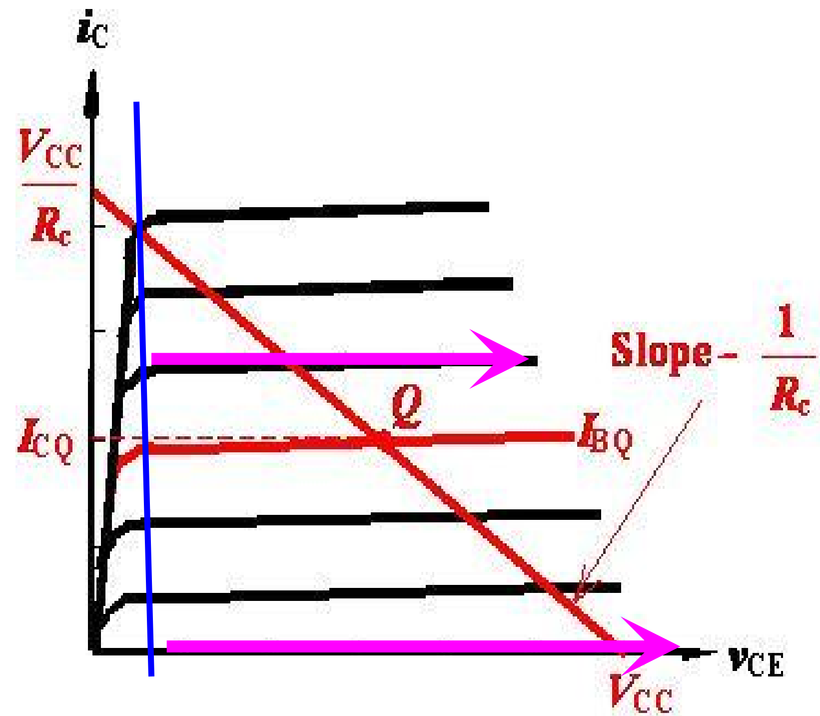


Figure 6.8 The BJT as a small-signal, two-port network

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



6.2.2 Small signal Hybrid-ΠEquivalent Circuit

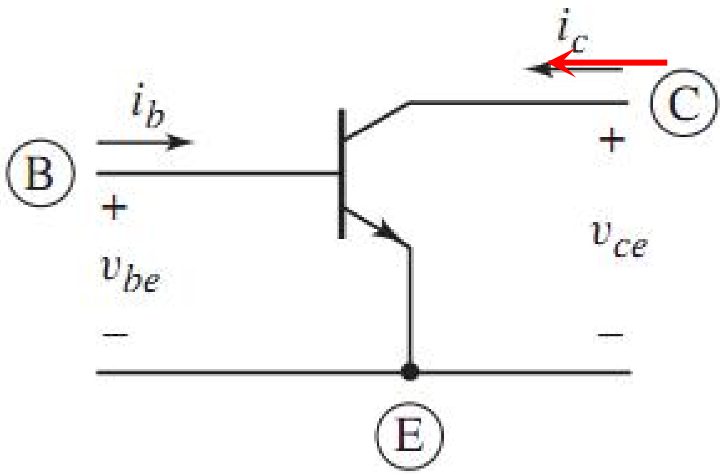


Figure 6.8 The BJT as a small-signal, two-port network

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

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

$$i_c = \left.\frac{\partial i_C}{\partial v_{BE}}\right|_{Q\text{-}pt} \cdot v_{be}$$

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

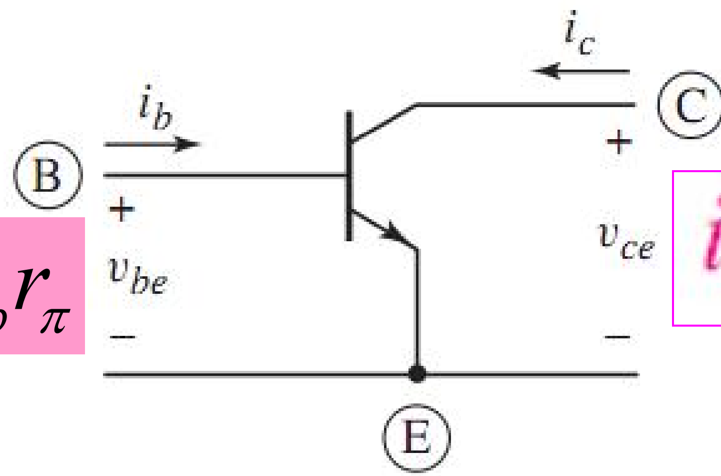
$$= \frac{I_{CQ}}{V_T}$$

Transconductance

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

$$\boxed{i_c = g_m \cdot v_{be}}$$

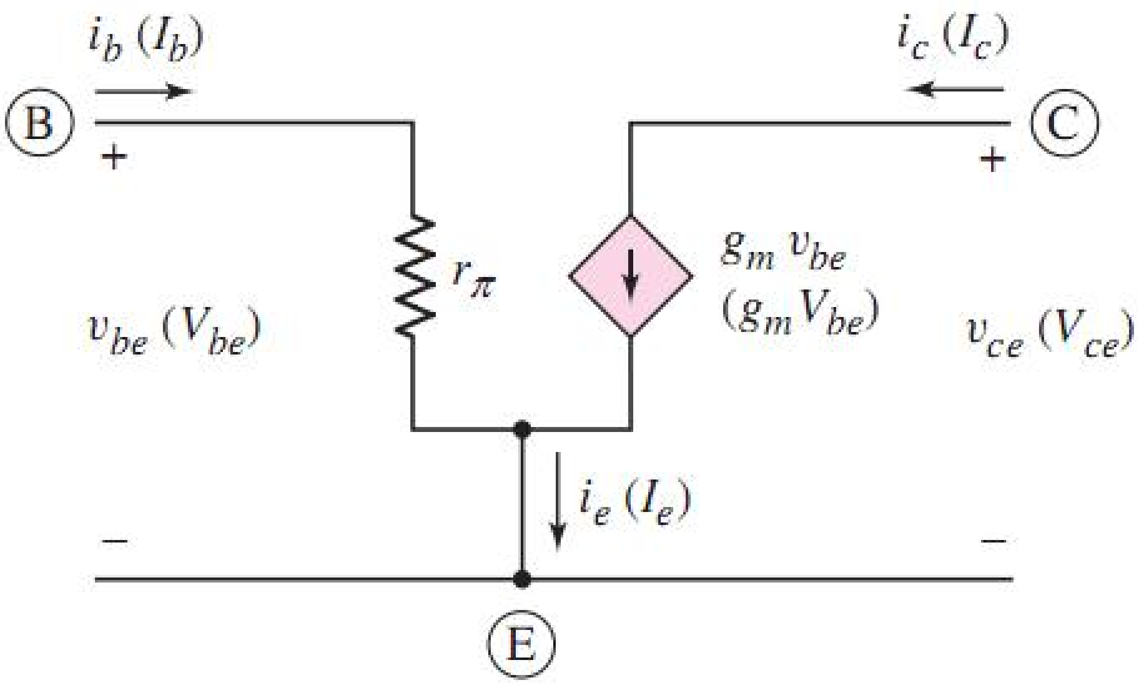
6.2.2 Small signal Hybrid-ΠEquivalent Circuit



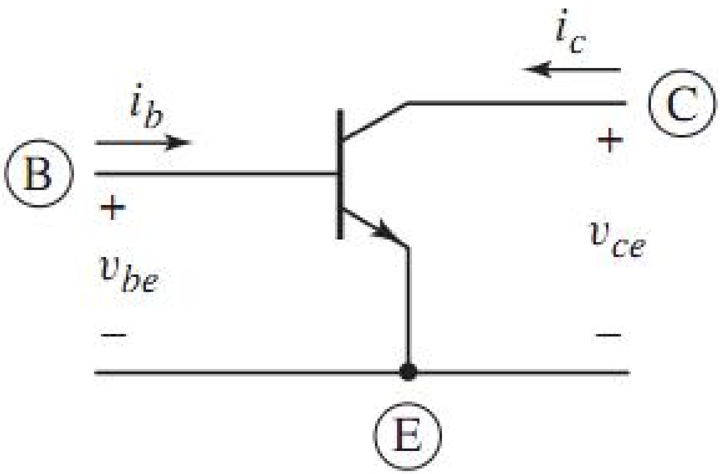
$$v_{be} = i_b r_\pi$$

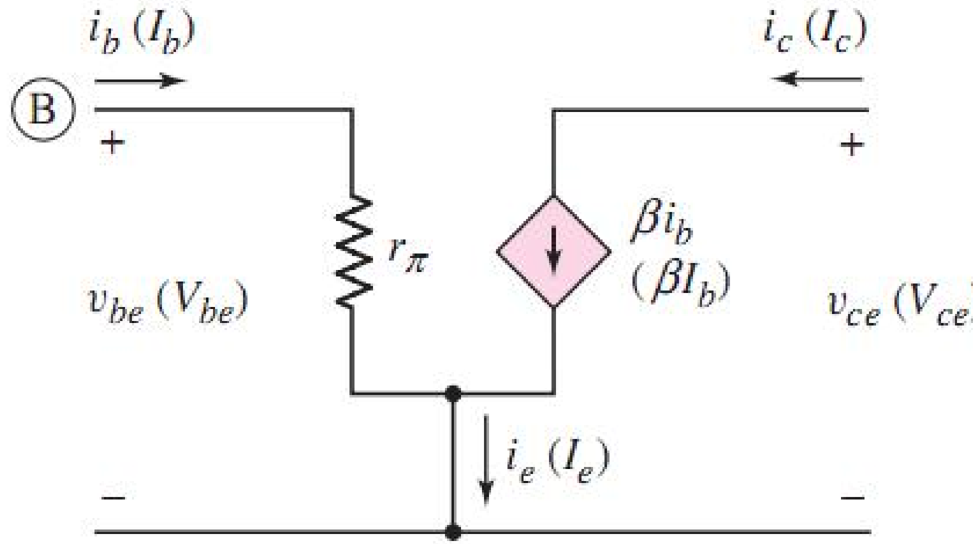
$$i_c = g_m \cdot v_{be}$$

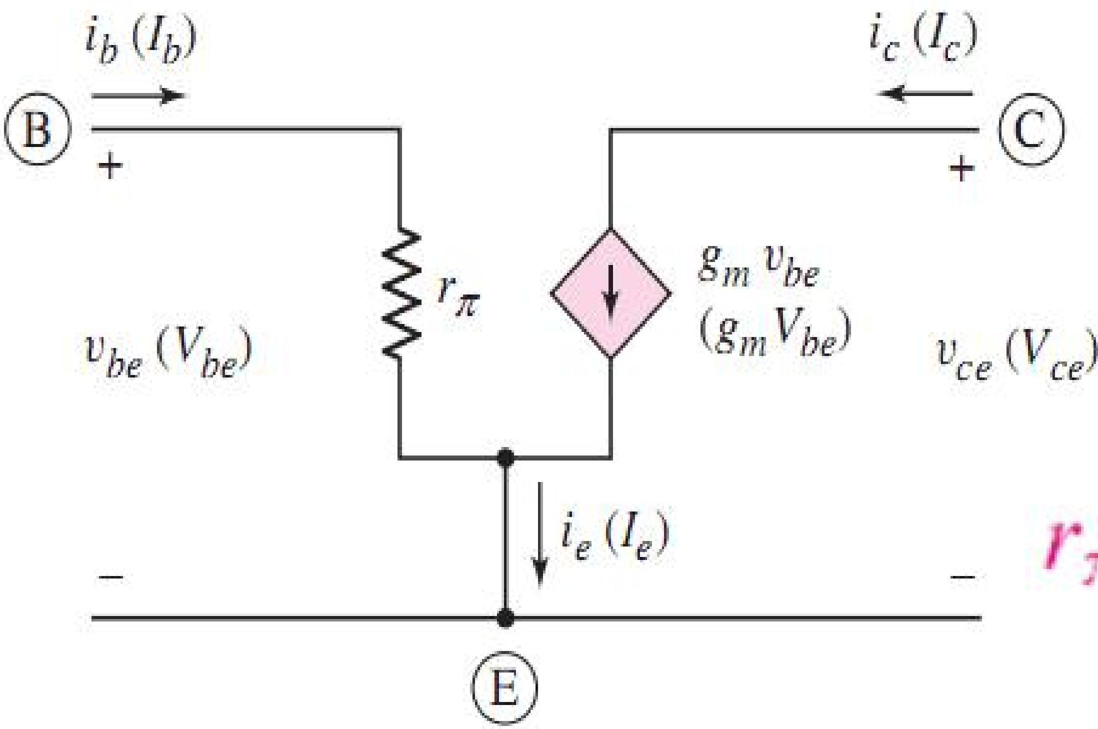
Figure 6.8 The BJT as a



6.2.2 Small signal Hybrid-ΠEquivalent Circuit





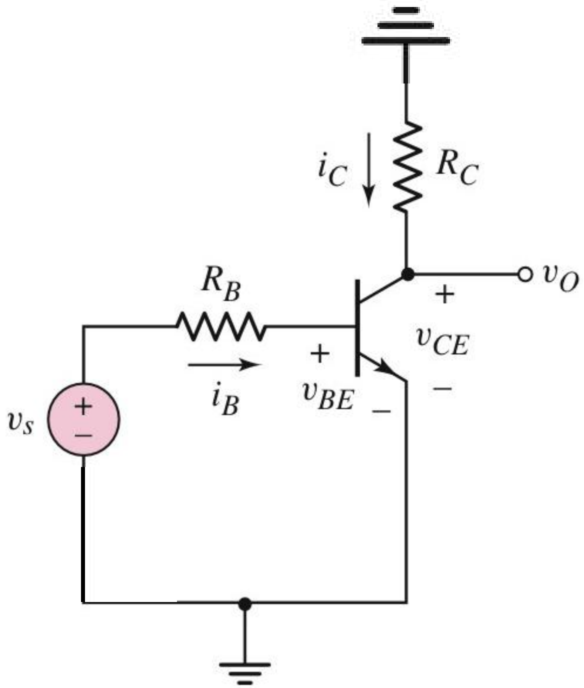


Common-Emitter Current Gain

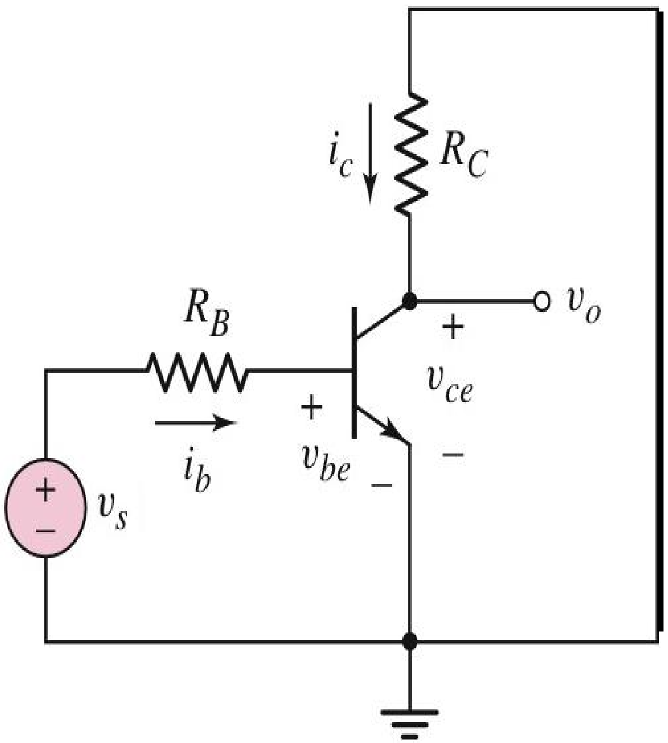
$$r_\pi g_m = \left(\frac{\beta V_T}{I_{CQ}}\right)\cdot\left(\frac{I_{CQ}}{V_T}\right) = \beta$$

6.2.2 Small signal Hybrid-ΠEquivalent Circuit

Small signal voltage gain

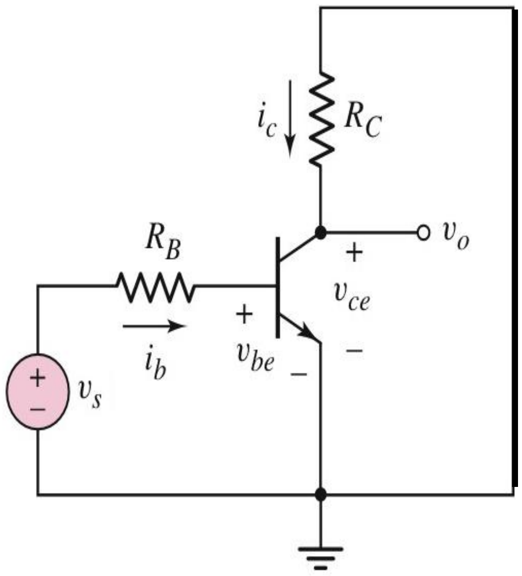


AC circuit

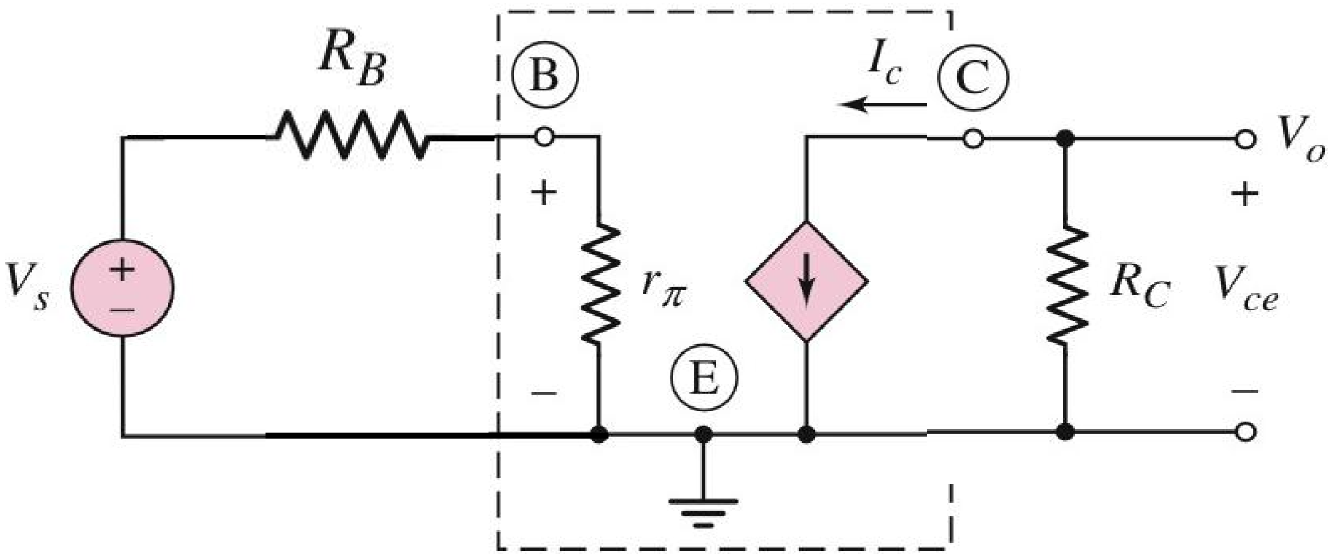


6.2.2 Small signal Hybrid-ΠEquivalent Circuit

Small signal voltage gain



Small-Signal Equivalent Circuit

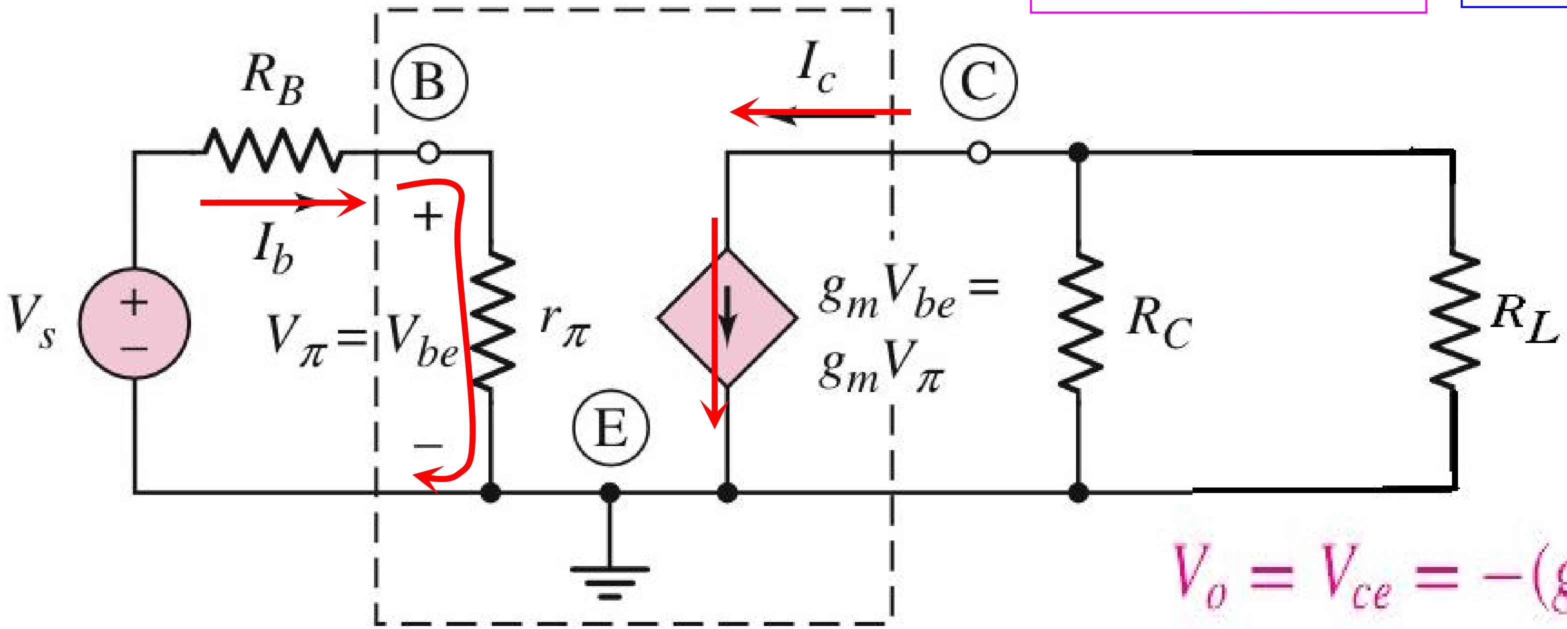


6.2.2 Small signal Hybrid-ΠEquivalent Circuit

Small signal voltage gain

$$A_v = \frac{V_o}{V_\pi} = ?$$

$$-\ g_m R_C // R_L$$



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

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

$$A_v = \frac{V_o}{V_\pi}$$

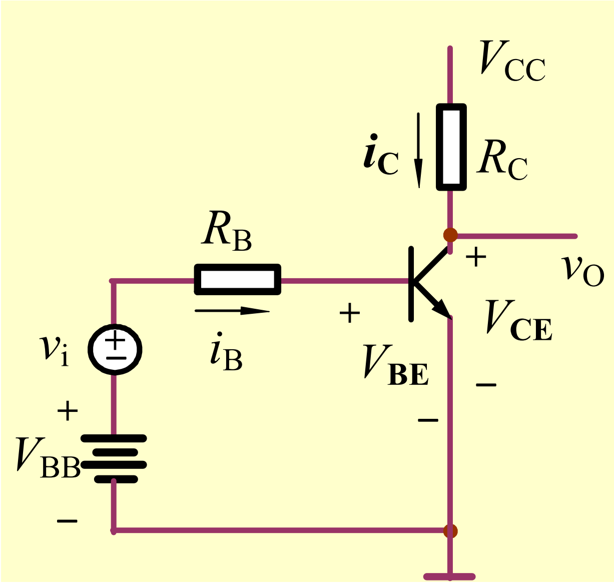
$$A_{vs} = \frac{V_o}{V_s} = -(g_m R_C) \cdot \left(\frac{r_\pi}{r_\pi + R_B}\right)$$

$$A_v = \frac{V_o}{V_\pi} = -\ g_m R_C$$

6.2.2 Small signal Hybrid-Π Equivalent Circuit

Example 1

Calculate the small-signal voltage gain of the bipolar transistor circuit shown in Fig. Assume β=100, V_{CC}=12V, V_{BE}=0.7V, R_C=6kΩ, R_B=50kΩ, V_{BB}=1.2V. If v_i=0.25sinωt V, find v_o .



Sol: (1) Find the Q-point values

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{1.2 - 0.7}{50} = 10\,\text{uA}$$

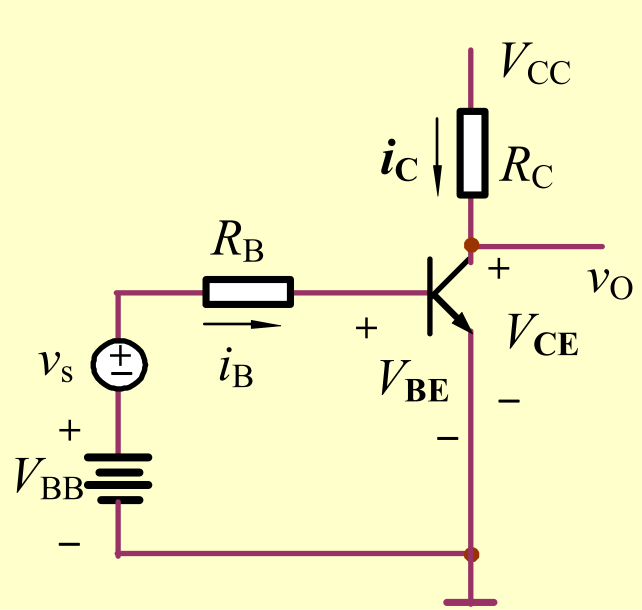
$$I_C = \beta\, I_B = 100 \times 10\,\text{uA} = 1\text{mA}$$

$$V_{CE} = V_{CC} - I_C R_C = 12 - 1\text{mA} \times 6\text{k}\boldsymbol{\Omega} = 6\text{V}$$

Which region?

6.2.2 Small signal Hybrid-ΠEquivalent Circuit

Example 1

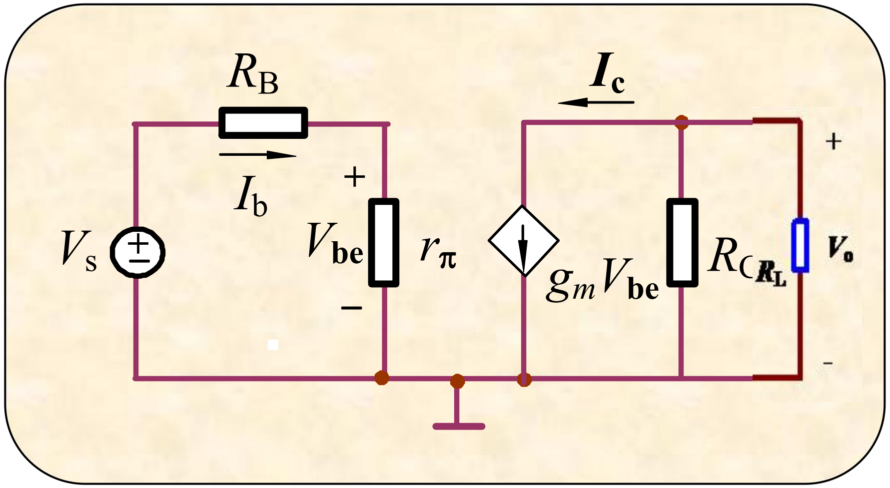


(2) Find the small-signal parameters

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{100 \times 0.026}{1} = 2.6\mathrm{k}\Omega$$

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

(3) Find AC parameters



$$A_{vs} = \frac{V_o}{V_i} \qquad = -g_m R_C \frac{r_\pi}{r_\pi + R_B}$$

$$= -38.5 \times 6 \times \frac{2.6}{2.6 + 50}$$

$$= -11.4$$

6.2.2 Small signal Hybrid-ΠEquivalent Circuit

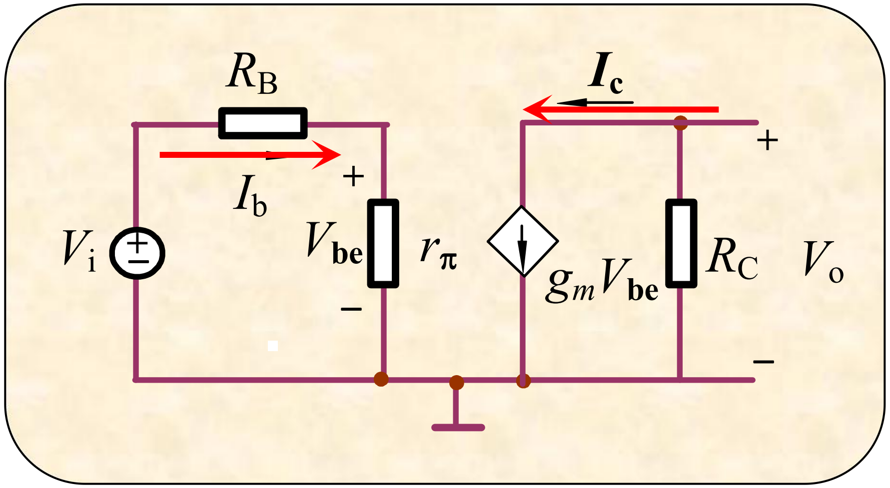
Example 1

(3) In small-signal circuit, ac base current is given by

$$i_b = \frac{v_i}{R_B + r_\pi} = \frac{0.25\sin\omega t}{50+2.6} = 4.75\sin\omega t(\mu A)$$

$$i_c = \beta\ i_b = 100 \times 4.75 \sin\ \omega t = 0.475\ \sin\ \omega t(mA)$$

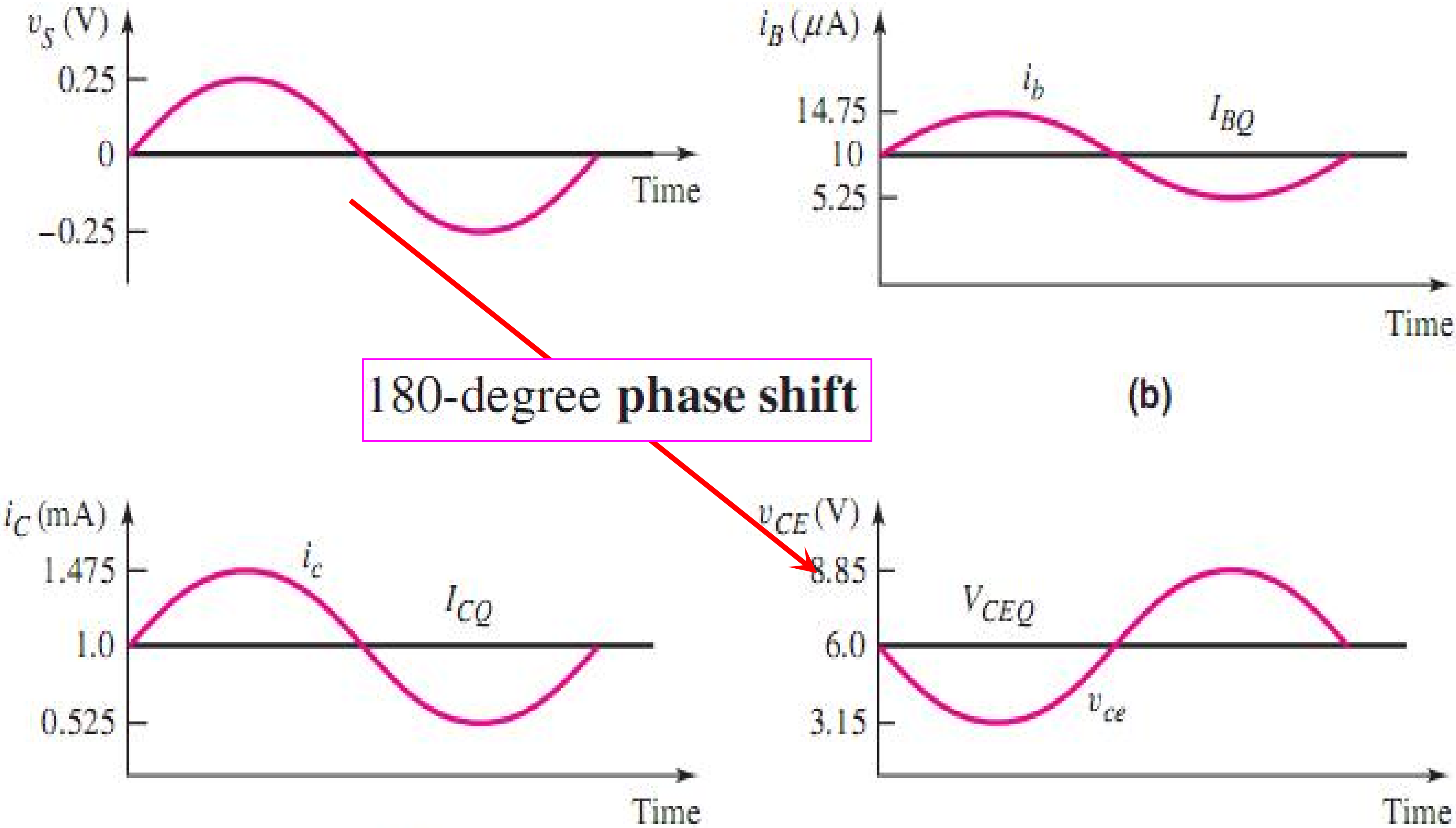
$$v_o = -i_c R_c = -(0.475\ \sin\ \omega t) \times 6 = -2.85\ \sin\ \omega t(V)$$



6.2.2 Small signal Hybrid-ΠEquivalent Circuit

$v_s = 0.25\sin\omega t$ V

$i_b = 4.75\sin\omega t(\mu A)$



$i_c = 0.475\sin\omega t(mA)$

$v_o = -2.85\sin\omega t(\text{V})$

Problem-Solving Technique: BJT AC Analysis

1. Analyze circuit with only dc sources to find Q point.
2. Replace each element in circuit with small-signal model, including the hybrid π model for the transistor.
3. Analyze the small-signal equivalent circuit after setting dc source components to zero.

6.2.2 Small signal Hybrid-ΠEquivalent Circuit

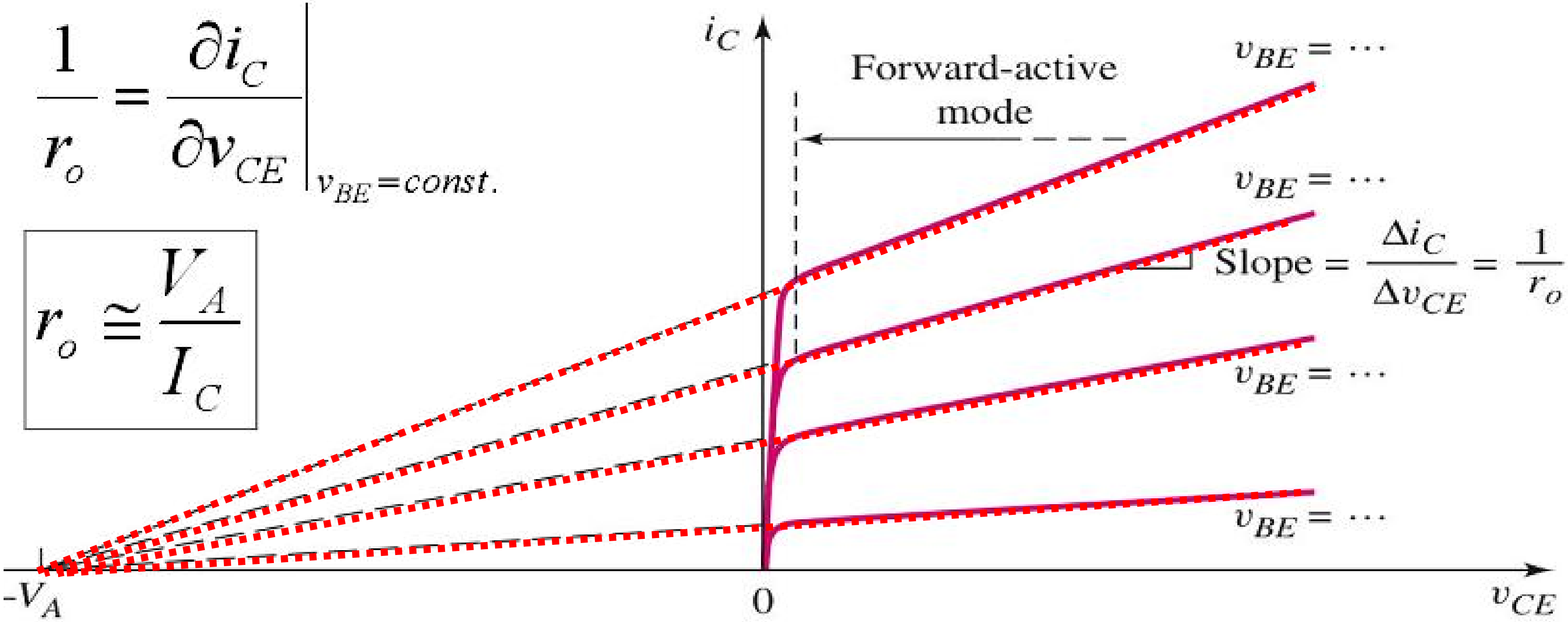
Table 6.2 Transformation of elements in dc and small-signal analysis

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

6.2.3 Hybrid-Π Equivalent Circuit , Including the Early Effect

$$\frac{1}{r_o} = \left.\frac{\partial i_C}{\partial v_{CE}}\right|_{v_{BE}=const.}$$

$$\boxed{r_o \cong \frac{V_A}{I_C}}$$

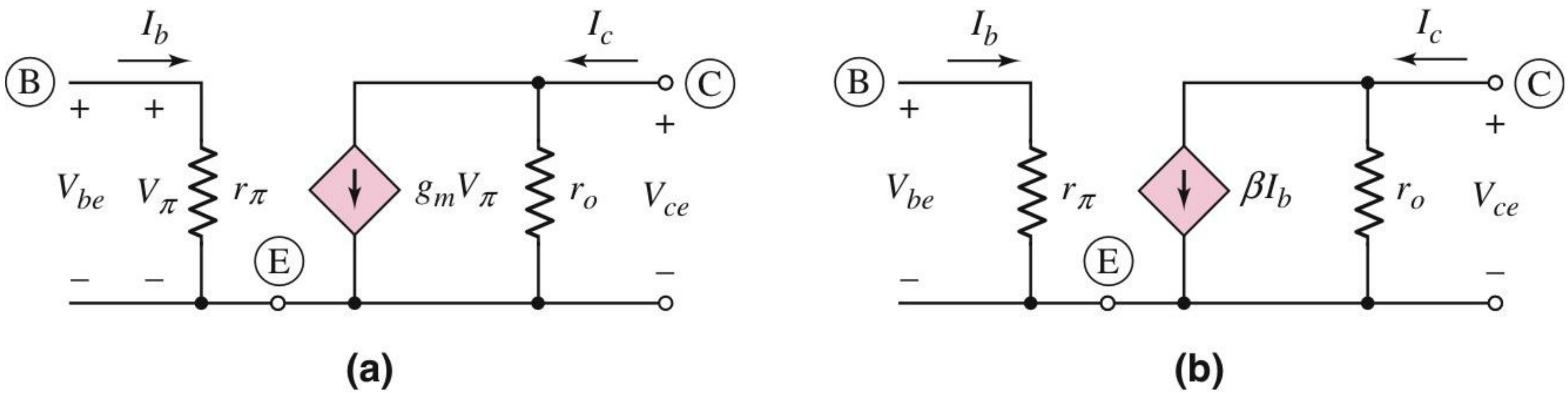


- V_A: Early voltage : a point at negative voltage axis where all curves meet

$$r_o = \frac{V_A}{I_{CQ}}$$ **small-signal transistor output resistance**

6.2.3 Hybrid-ΠEquivalent Circuit , Including the Early Effect

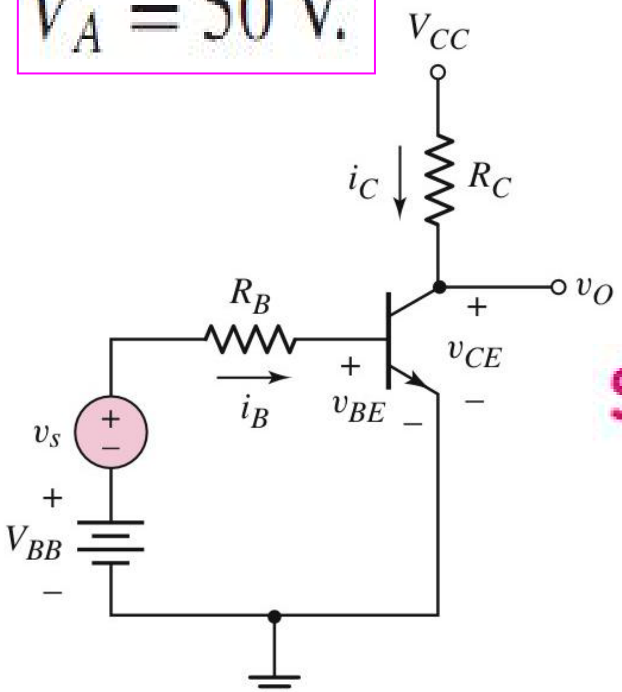
Hybrid π Model for npn with Early Effect



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

6.2.3 Hybrid-Π Equivalent Circuit , Including the Early Effect

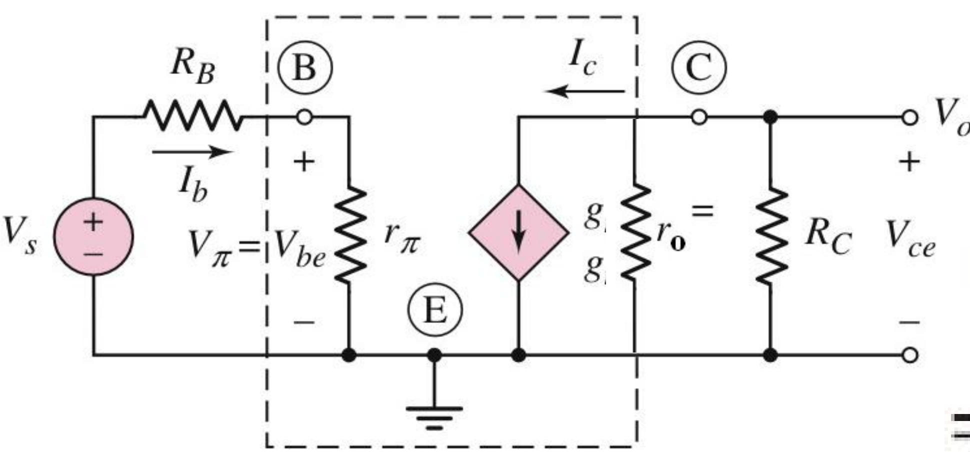
$V_A = 50\ \mathrm{V}.$



Calculate the small-signal voltage gain of the bipolar transistor circuit shown in Fig. Assume β=100, V_{CC}=12V, V_{BE}=0.7V, R_C=6kΩ, R_B=50kΩ, V_{BB}=1.2V.

Solution:

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

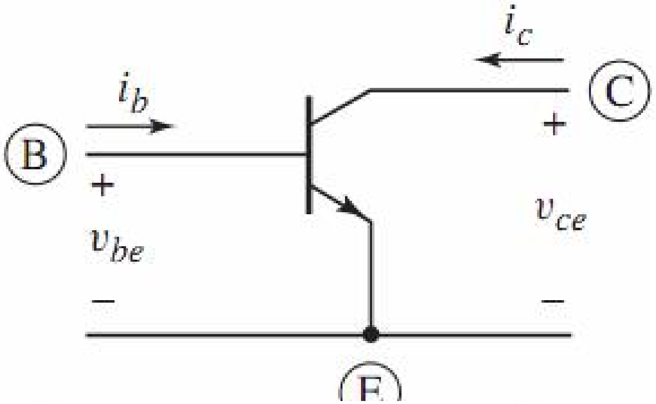


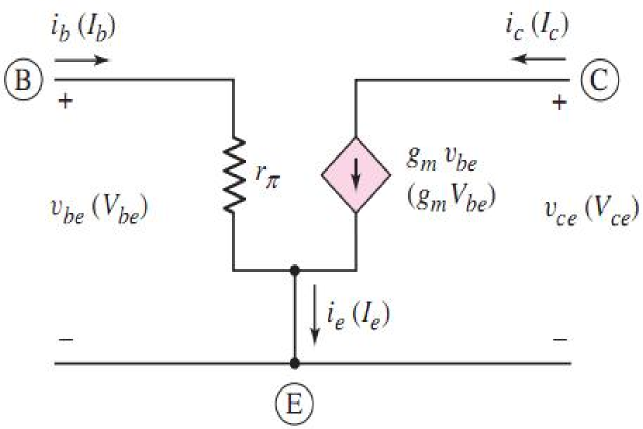
$$A_v = \frac{V_o}{V_s}$$

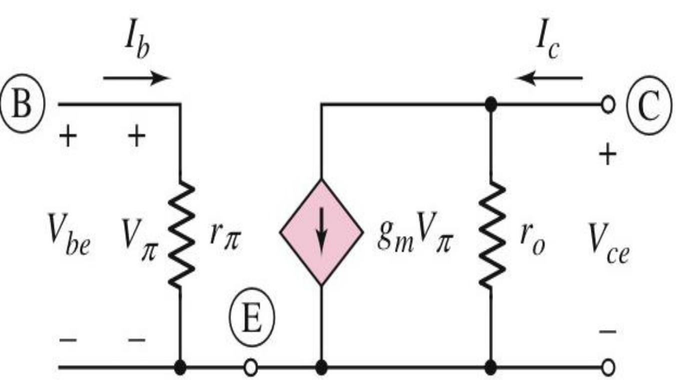
$$= -g_m (R_C \| r_o) \left(\frac{r_\pi}{r_\pi + R_B} \right)$$

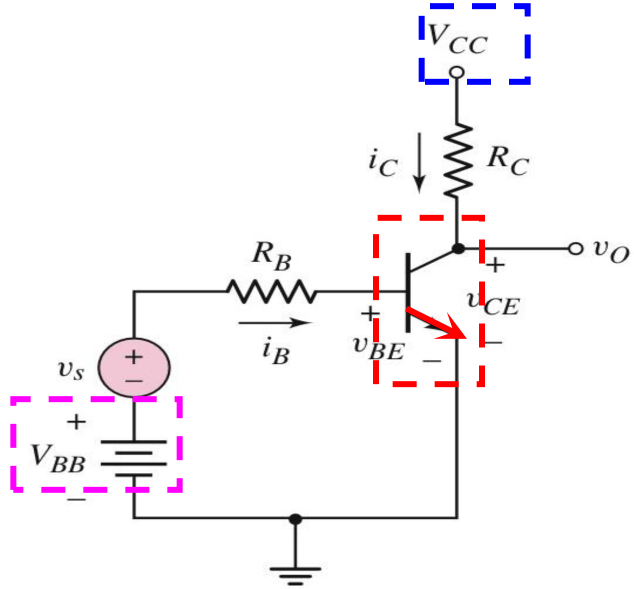
$$= -10.2 \quad -11.4$$

6.2.3 Hybrid-ΠEquivalent Circuit , Including the Early Effect





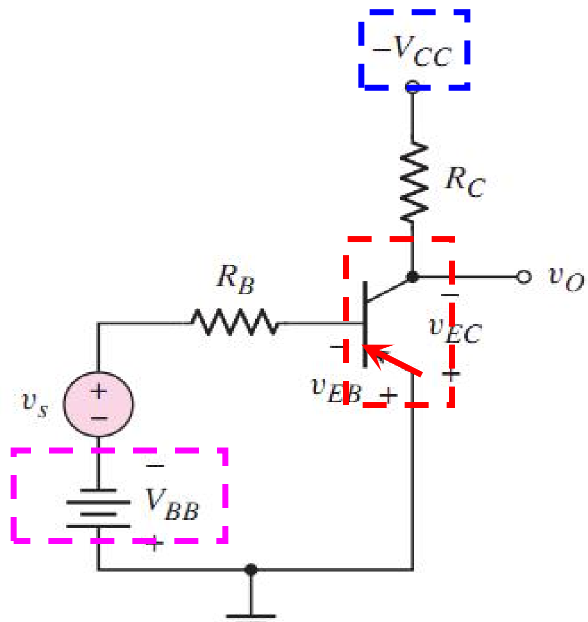




small-signal

equivalent circuit

is the same



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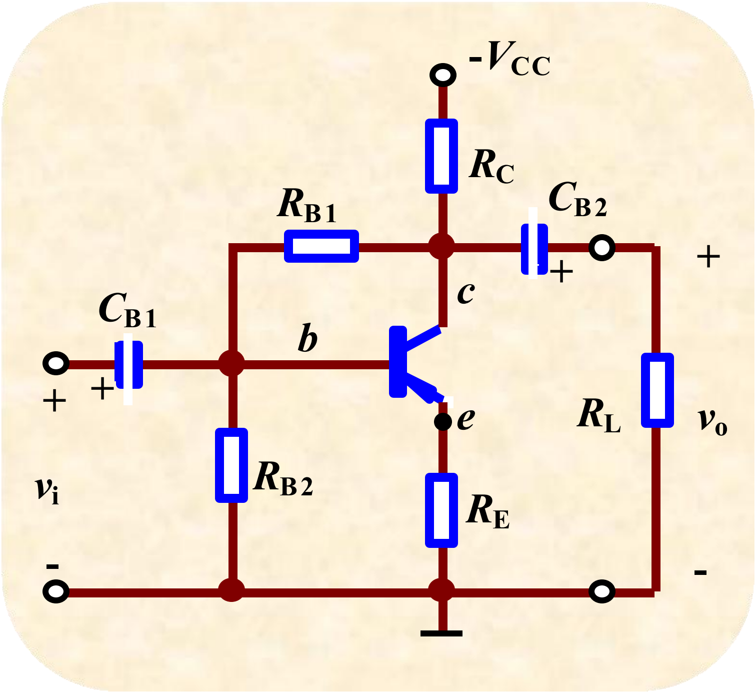
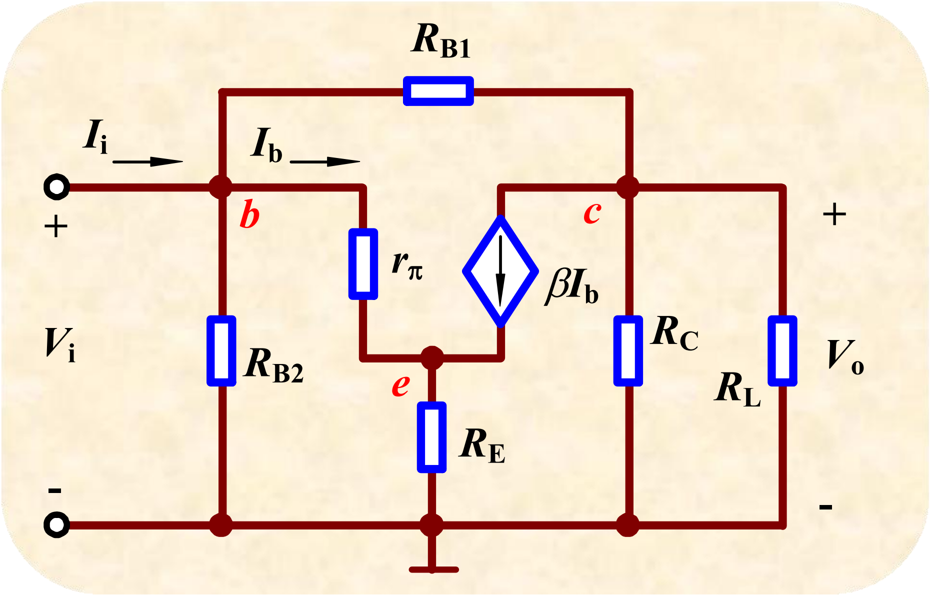
Teach yourself!

Example

The circuit shown in Fig. Draw its small-signal equivalent circuit.





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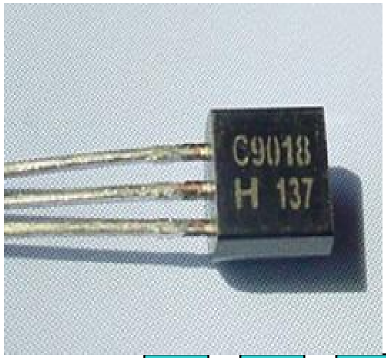
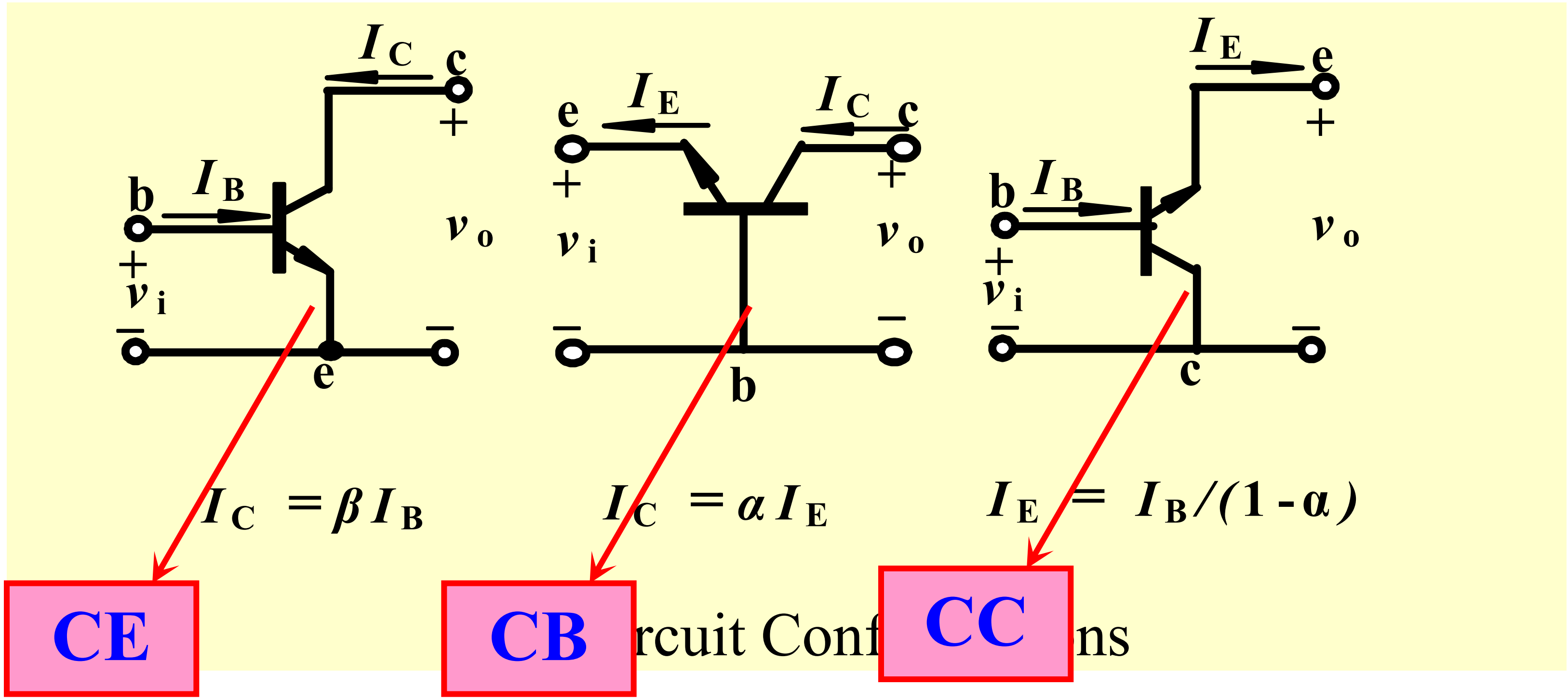
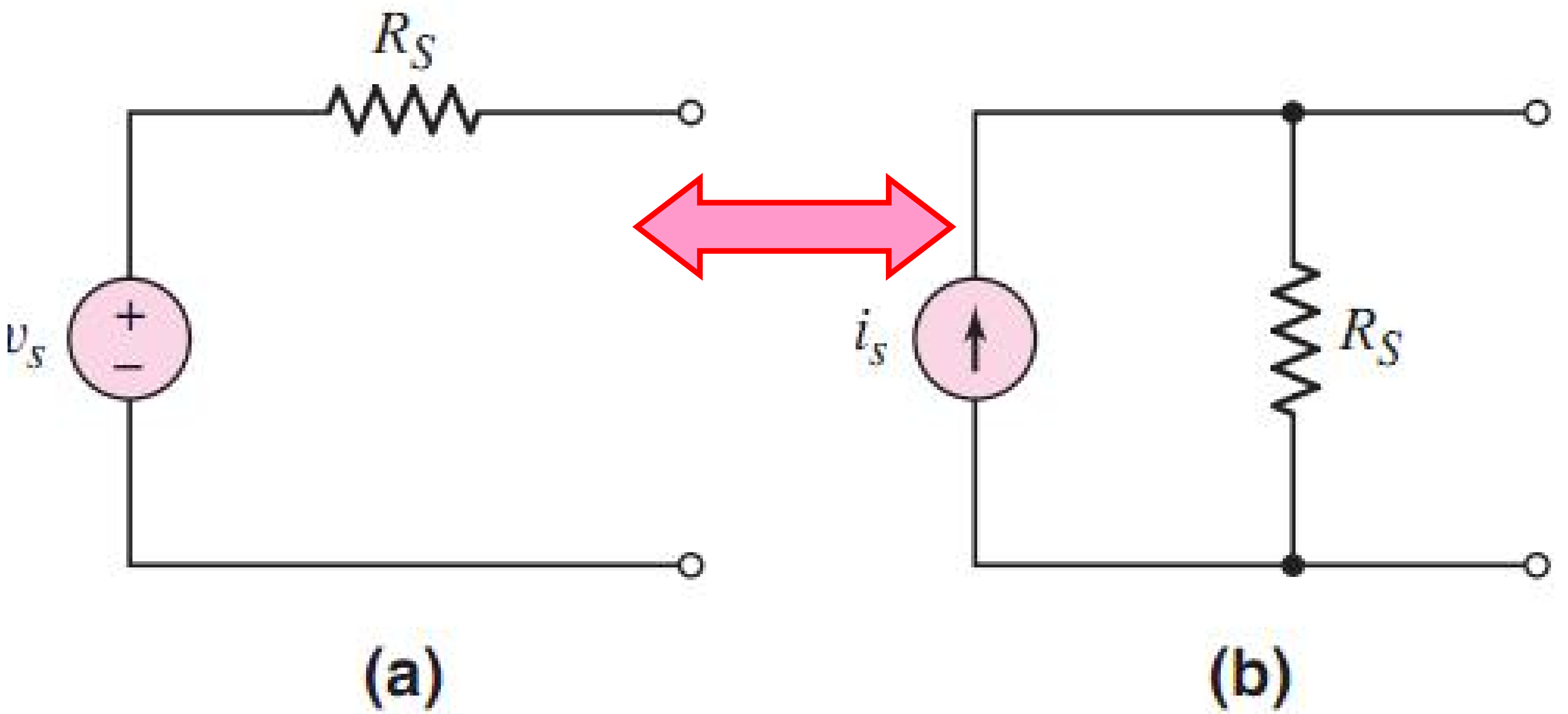


6.3 Basic Transistor Amplifier Configurations

Review



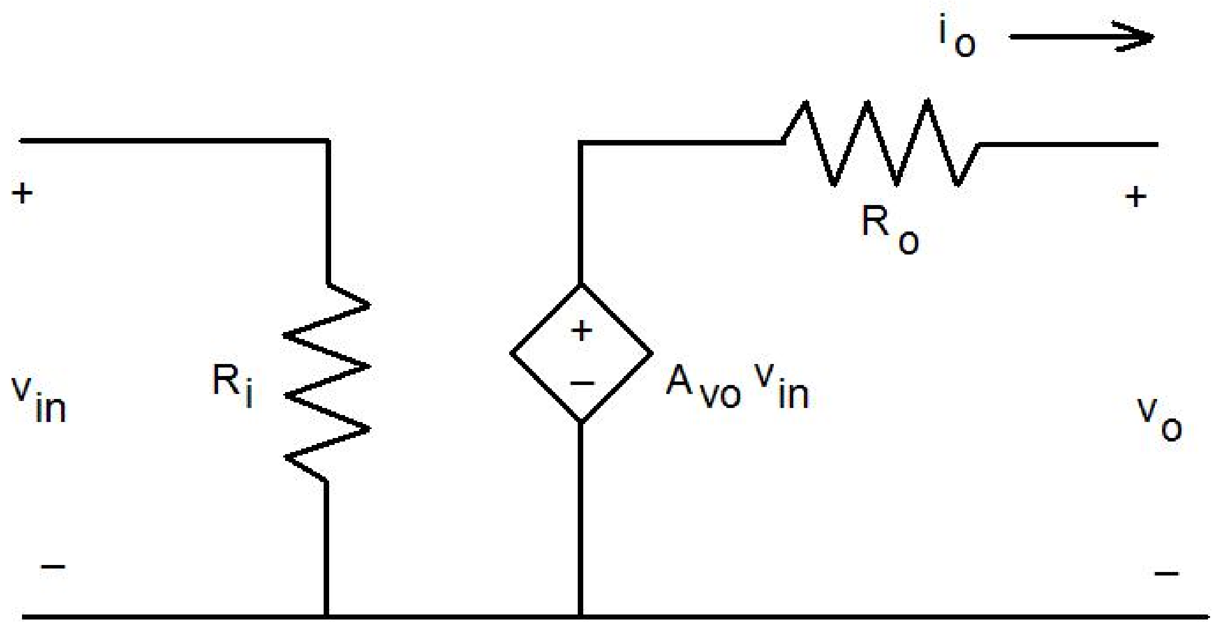
6.3 Basic Transistor Amplifier Configurations



Thevenin equivalent source Norton equivalent source

6.3 Basic Transistor Amplifier Configurations

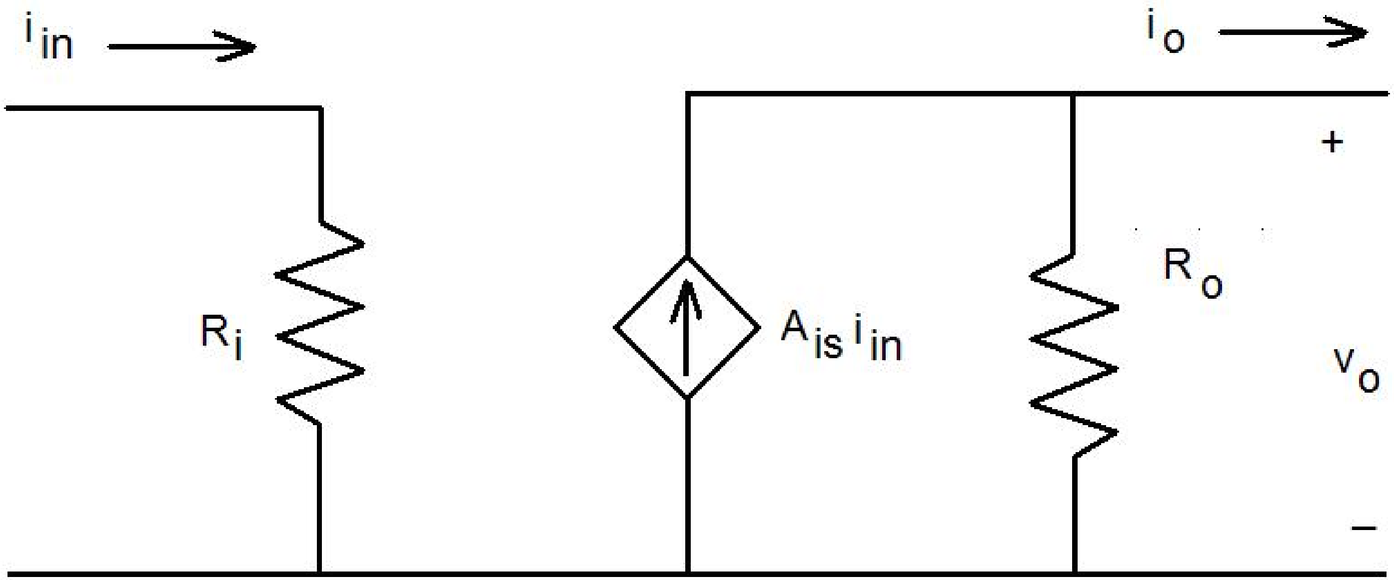
Voltage Amplifier



Output voltage proportional to input voltage

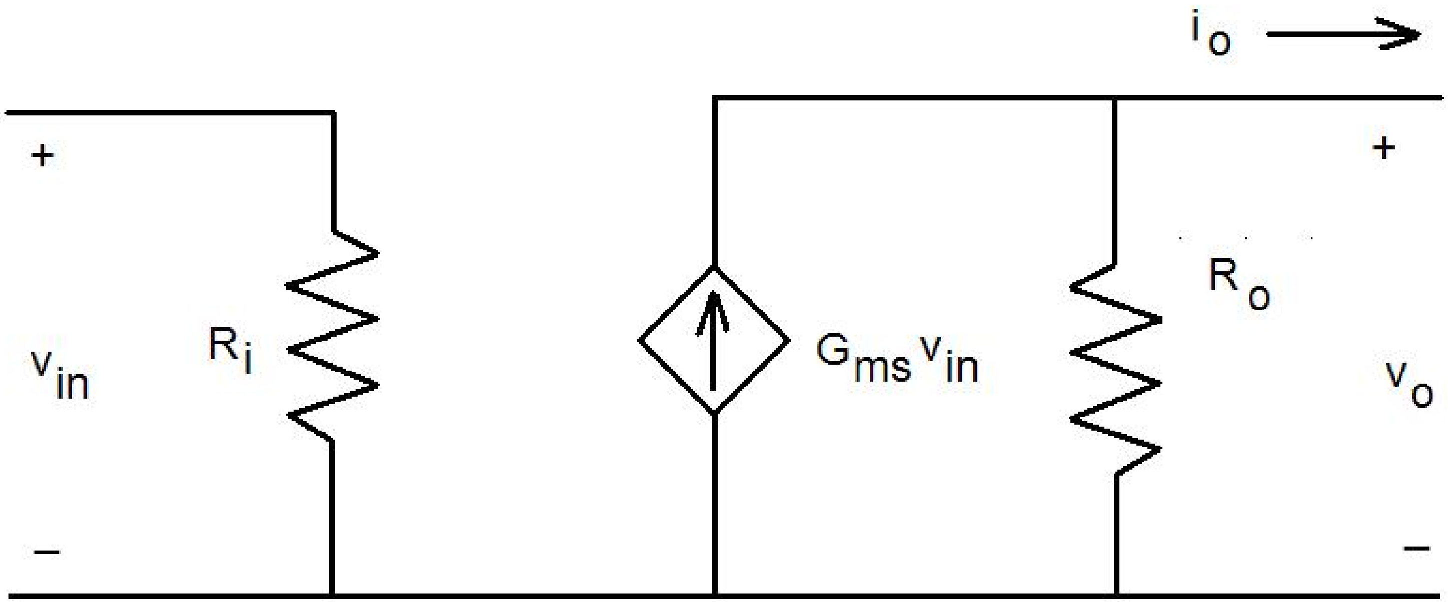
6.3 Basic Transistor Amplifier Configurations

Current Amplifier



Output current proportional to input current

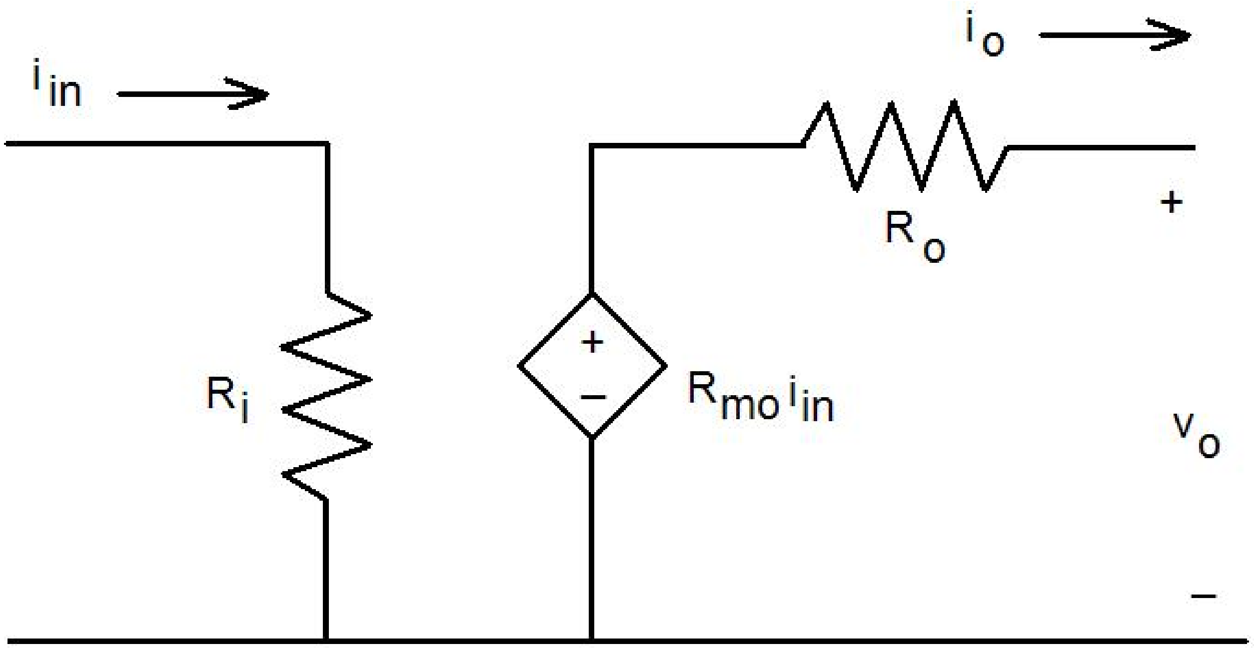
Transconductance Amplifier



Output current proportional to input voltage

6.3 Basic Transistor Amplifier Configurations

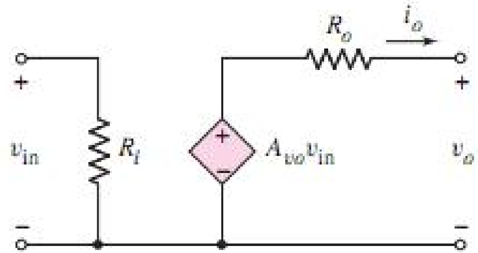
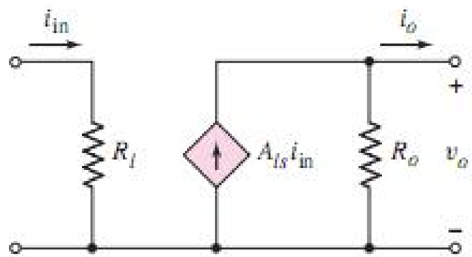
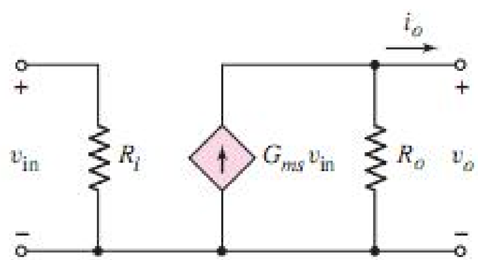
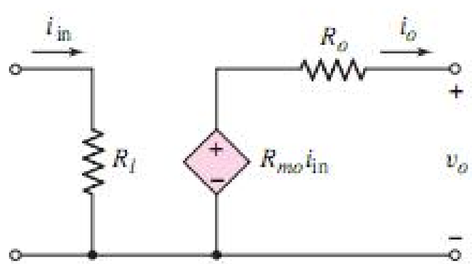
Transresistance Amplifier



Output voltage proportional to input current

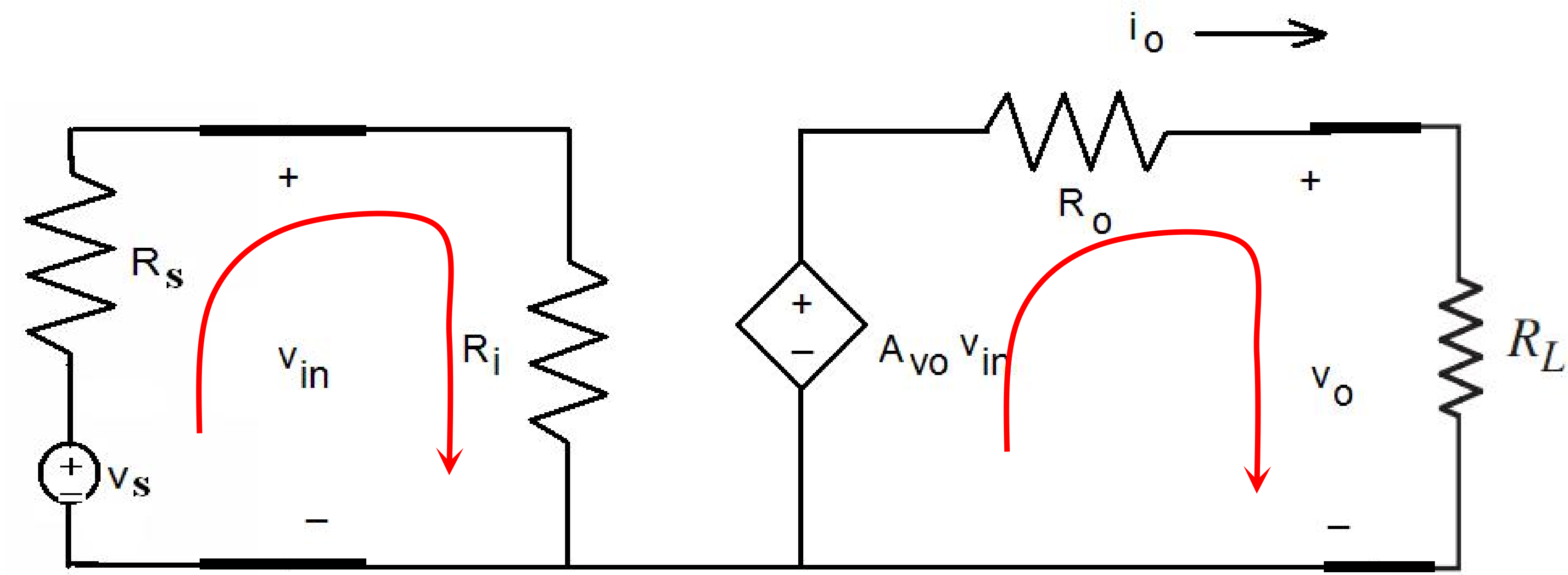
6.3 Basic Transistor Amplifier Configurations

Table 6.3 Four equivalent two-port networks

Type	Equivalent circuit	Gain property
Voltage amplifier		Output voltage proportional to input voltage
Current amplifier		Output current proportional to input current
Transconductance amplifier		Output current proportional to input voltage
Transresistance amplifier		Output voltage proportional to input current

6.3 Basic Transistor Amplifier Configurations

Voltage Amplifier

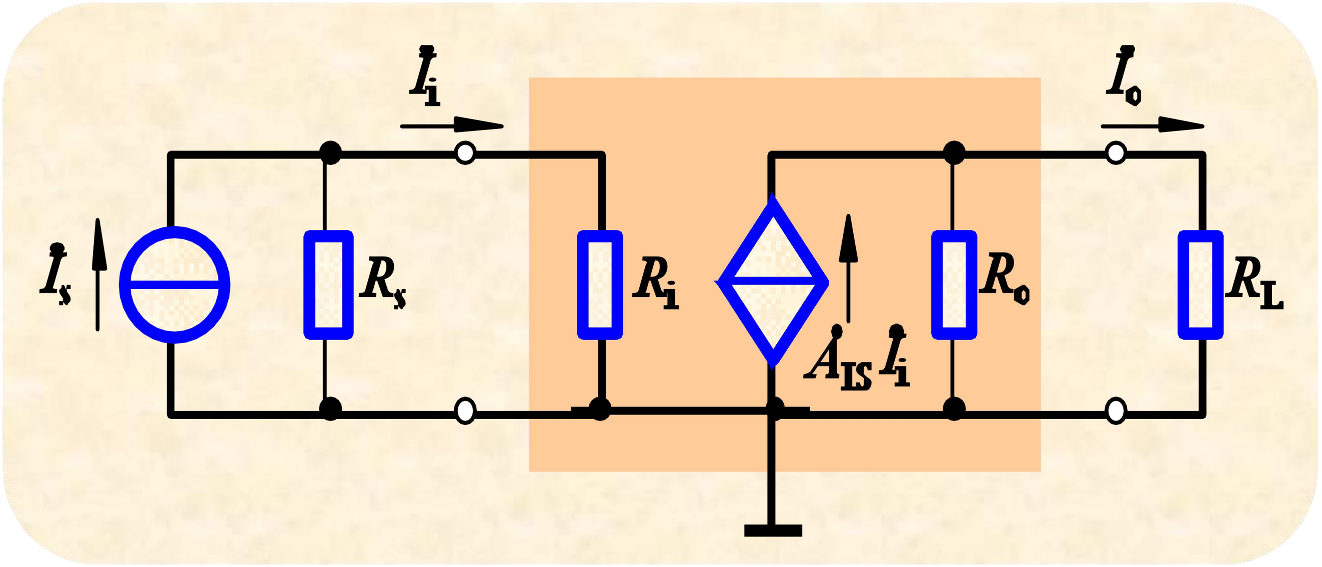


$$v_{in} = \frac{R_i}{R_i + R_S} \cdot v_s \qquad v_o = \frac{R_L}{R_L + R_o} \cdot A_{vo} v_{in}$$

$\boldsymbol{R_i >> R_s}$

$\boldsymbol{R_o << R_L}$

6.3 Basic Transistor Amplifier Configurations



$$\dot{I}_i = \dot{I}_s \frac{R_s}{R_s + R_i}$$

Current amplifier

$$R_o >> R_L$$

$$R_i << R_s$$

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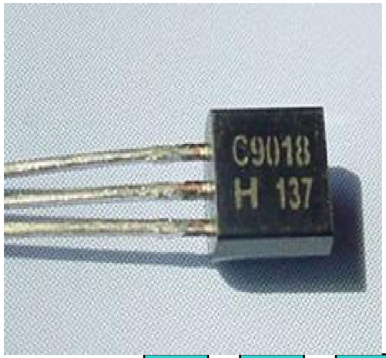
PART 2 ANALOG ELECTRONICS

Ch6. Basic BJT Amplifiers

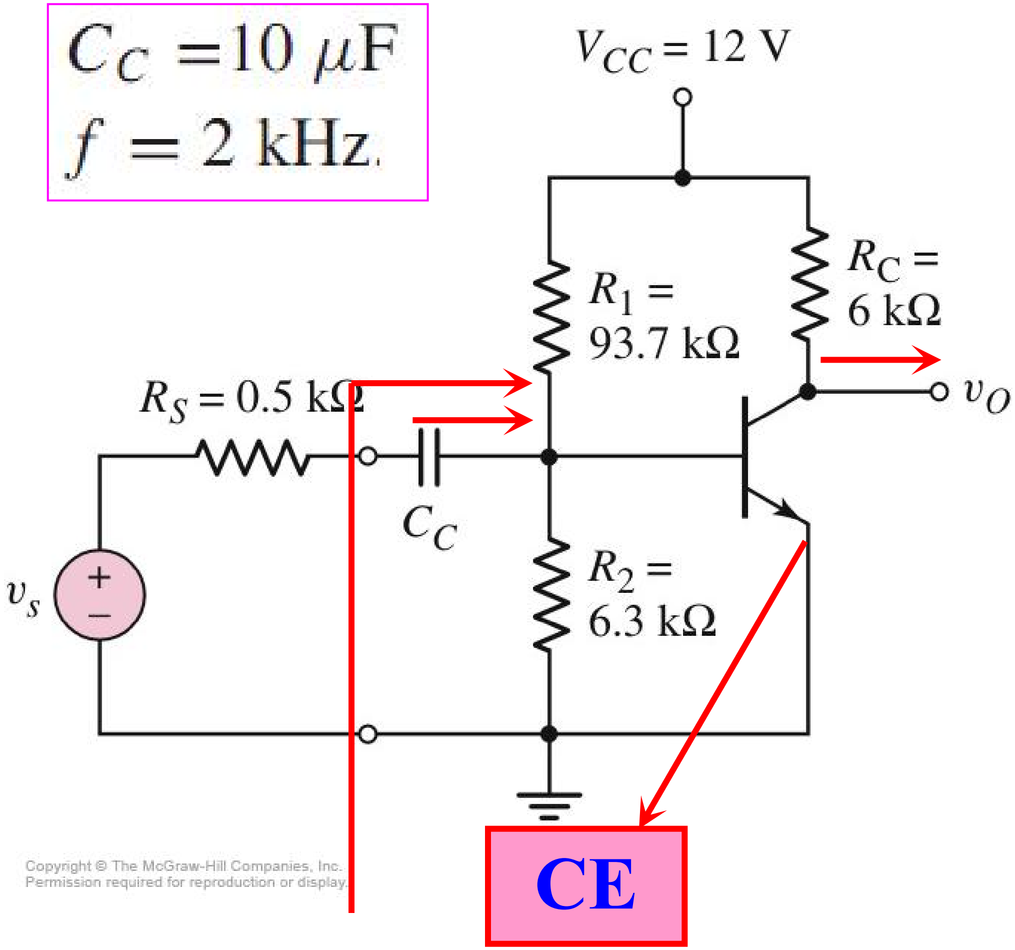


6.4 Common-Emitter Amplifiers

6.4.1 Common-Emitter Amplifier Circuit

$C_C = 10\ \mu F$

$f = 2\ \text{kHz}.$



$$|Z_c| = \frac{1}{2\pi f C_C}$$

$$= \frac{1}{2\pi(2 \times 10^3)(10 \times 10^{-6})} \cong 8\ \Omega$$

2-port Networks equivalent input impedance

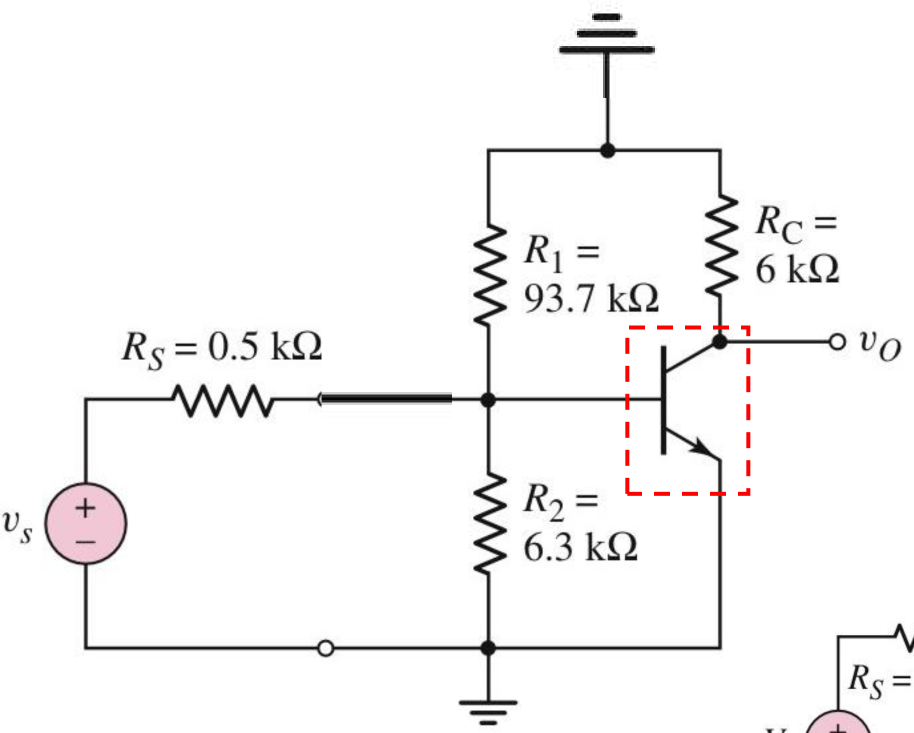
$$R_1 \| R_2 \| r_\pi$$

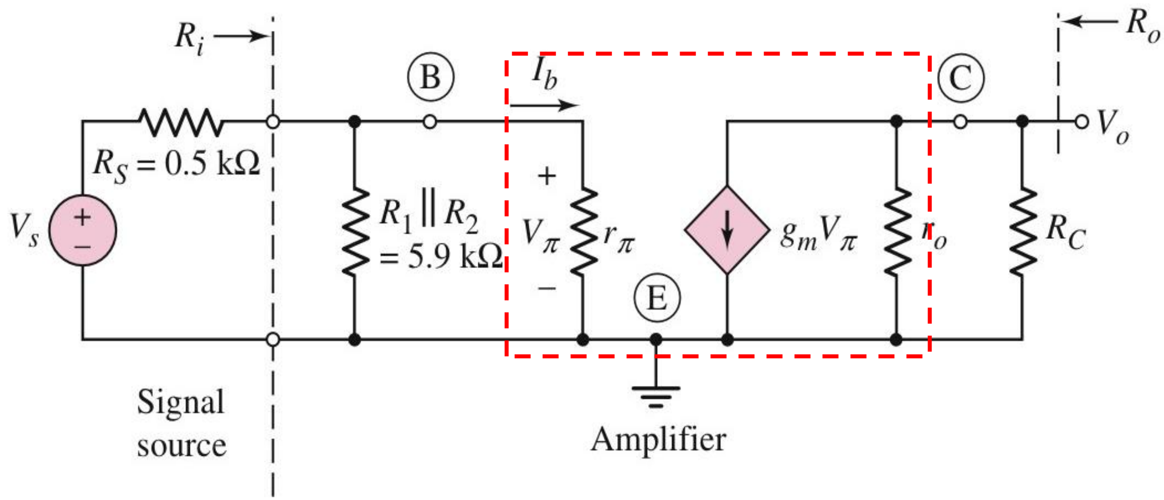
$$|Z_c| << R_1 \| R_2 \| r_\pi$$

capacitor is essentially a short circuit to signals with frequencies greater than 2 kHz.

6.4 Common-Emitter Amplifiers

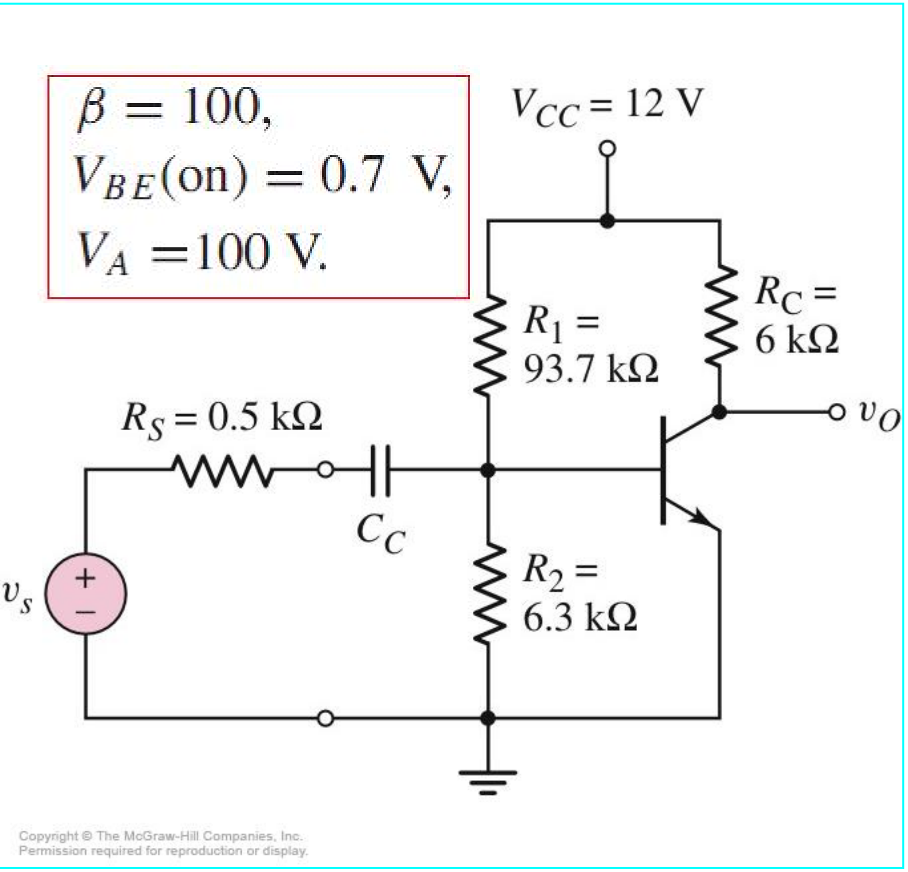
6.4.1 Common-Emitter Amplifier Circuit





6.4 Common-Emitter Amplifiers

6.4.1 Common-Emitter Amplifier Circuit



DC Solution:

$$I_{CQ} = 0.95\ \text{mA}$$

$$V_{CEQ} = 6.31\ \text{V},$$

forward-active mode

$$r_\pi = \frac{V_T \beta}{I_{CQ}} = \frac{(0.026)(100)}{(0.95)} = 2.74\ \text{k}\Omega$$

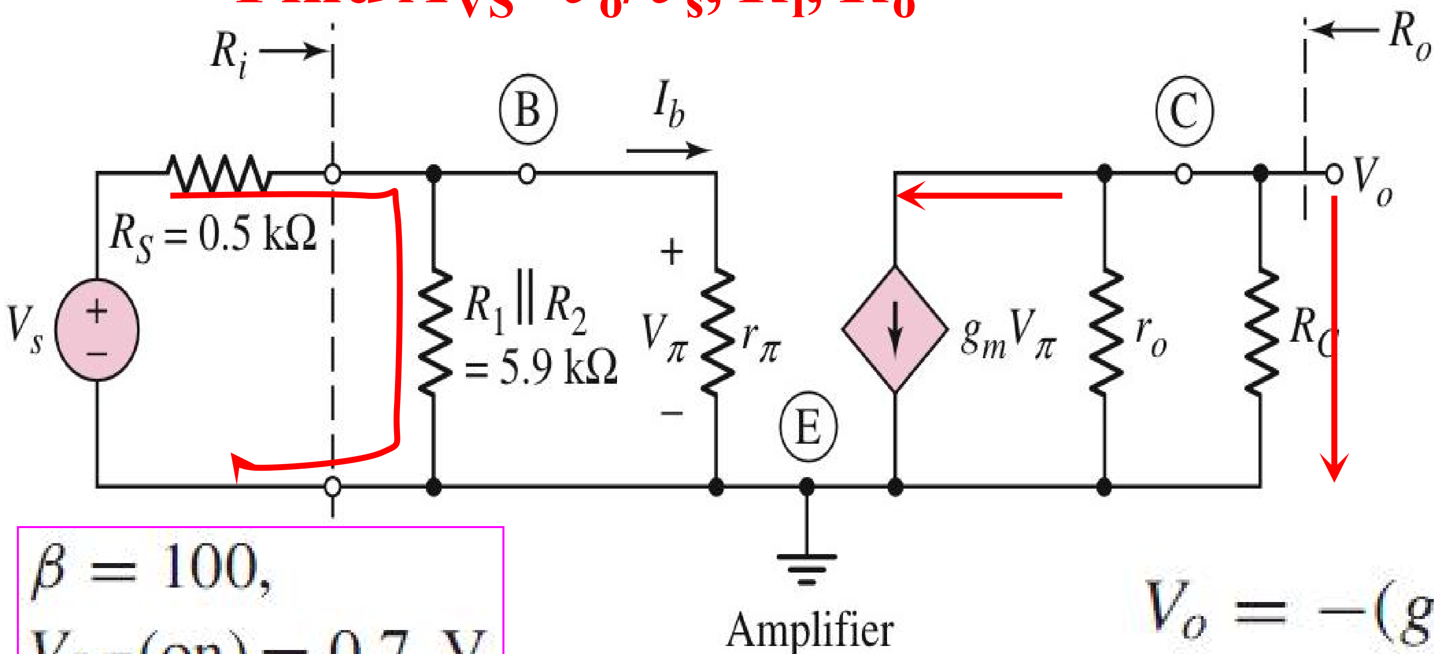
$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.95}{0.026} = 36.5\ \text{mA/V}$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{100}{0.95} = 105\ \text{k}\Omega$$

6.4 Common-Emitter Amplifiers

6.4.1 Common-Emitter Amplifier Circuit

Find $A_{VS}=v_o/v_s$, R_i, R_o



$\beta = 100,$
$V_{BE}(\text{on}) = 0.7\ \text{V},$
$V_A = 100\ \text{V}.$

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

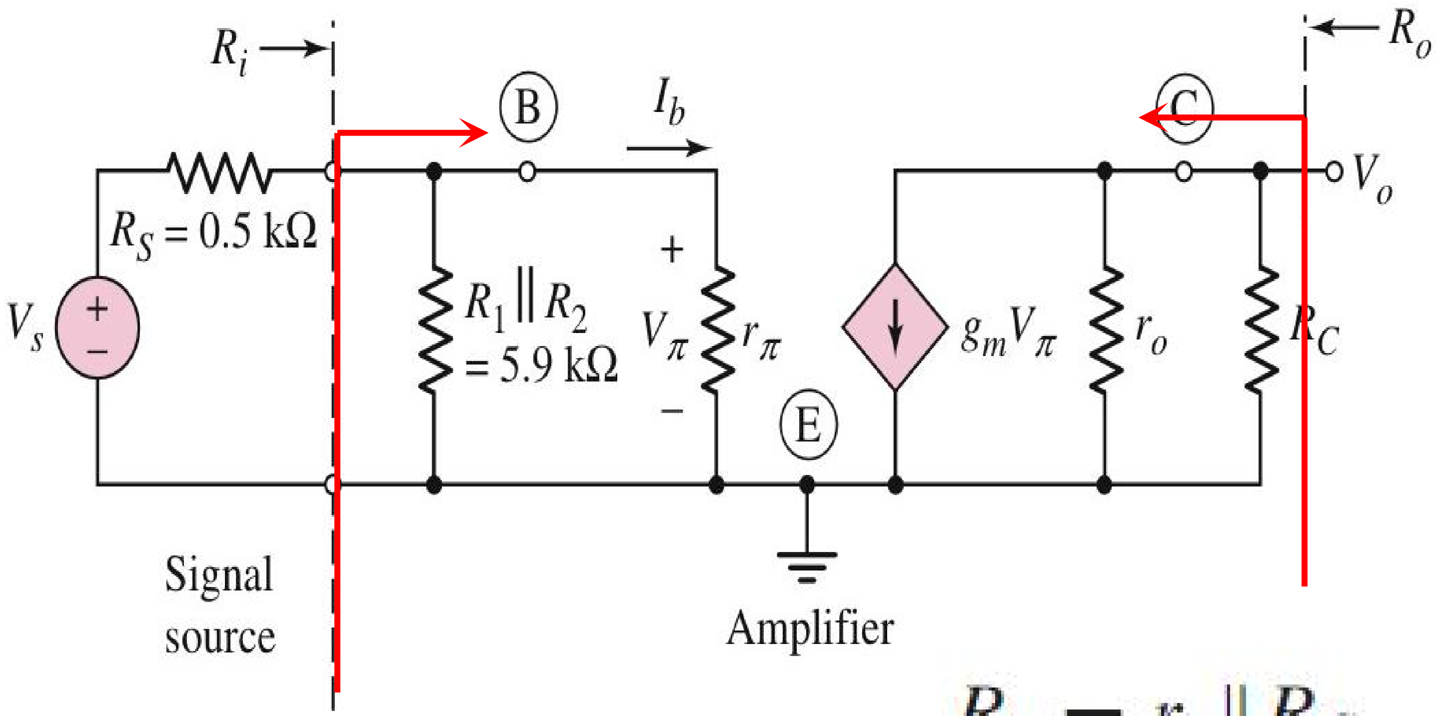
$$V_\pi = \left(\frac{R_1 \| R_2 \| r_\pi}{R_1 \| R_2 \| r_\pi + R_S}\right) \cdot V_s$$

$$A_v = \frac{V_o}{V_s} = -g_m \left(\frac{R_1 \| R_2 \| r_\pi}{R_1 \| R_2 \| r_\pi + R_S}\right)(r_o \| R_C)$$

$$= -163$$

6.4 Common-Emitter Amplifiers

6.4.1 Common-Emitter Amplifier Circuit



$$R_o = r_o \| R_C$$

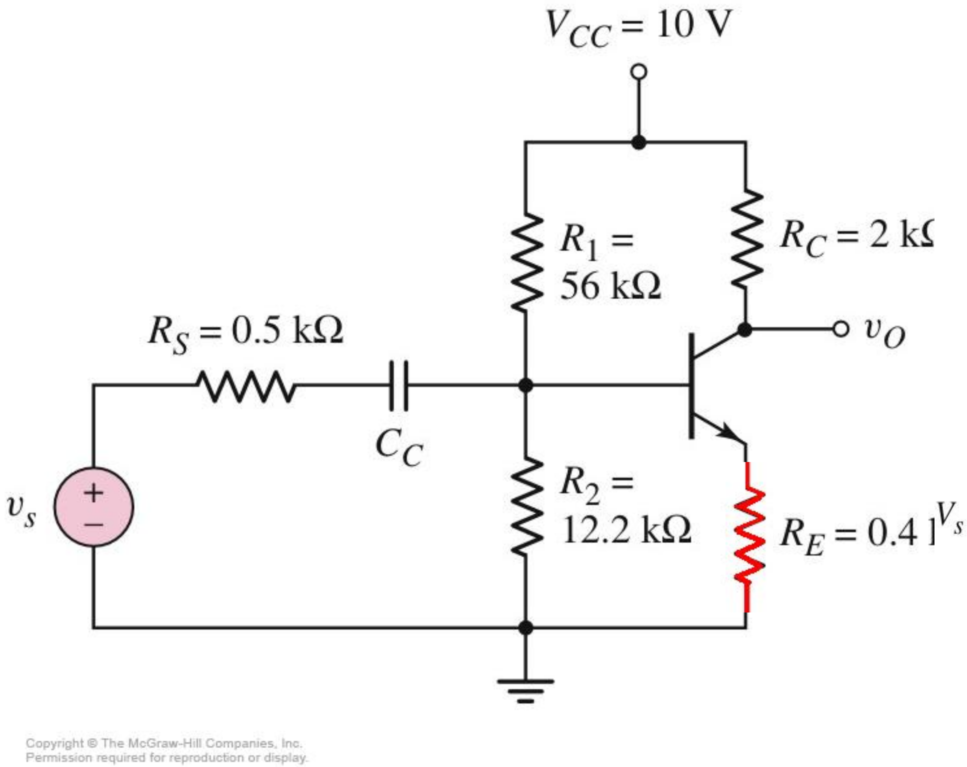
$$= 105 \| 6 = 5.68\ \text{k}\Omega$$

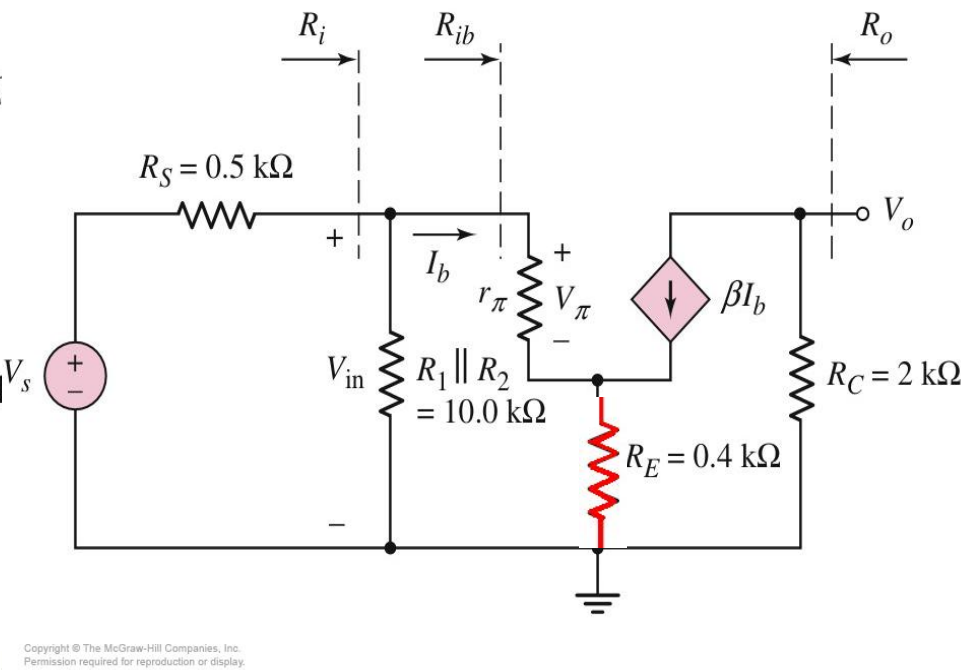
$$R_i = R_1 \| R_2 \| r_\pi$$

$$= 5.9 \| 2.74 = 1.87\ \text{k}\Omega$$

6.4 Common-Emitter Amplifiers

6.4.2 Circuit with Emitter Resistor





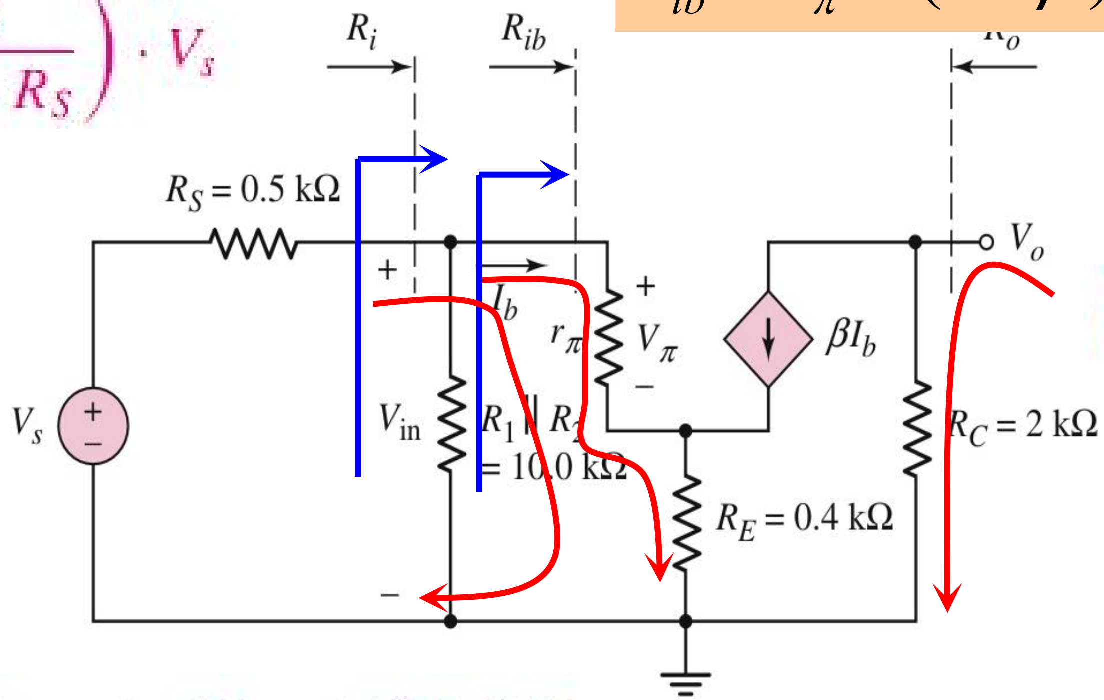
small-signal equivalent circuit

$A_V = v_o/v_{in}$, R_i, R_o **Become smaller or larger?**

6.4.2 Circuit with Emitter Resistor

$$R_{ib} = r_\pi + (1+\beta)R_E$$

$$V_{in} = \left(\frac{R_i}{R_i + R_S}\right) \cdot V_s$$



$$V_o = -(\beta I_b)R_C$$

$$V_{in} = I_b r_\pi + (I_b + \beta I_b)R_E$$

$$R_i = R_1 \| R_2 \| R_{ib}$$

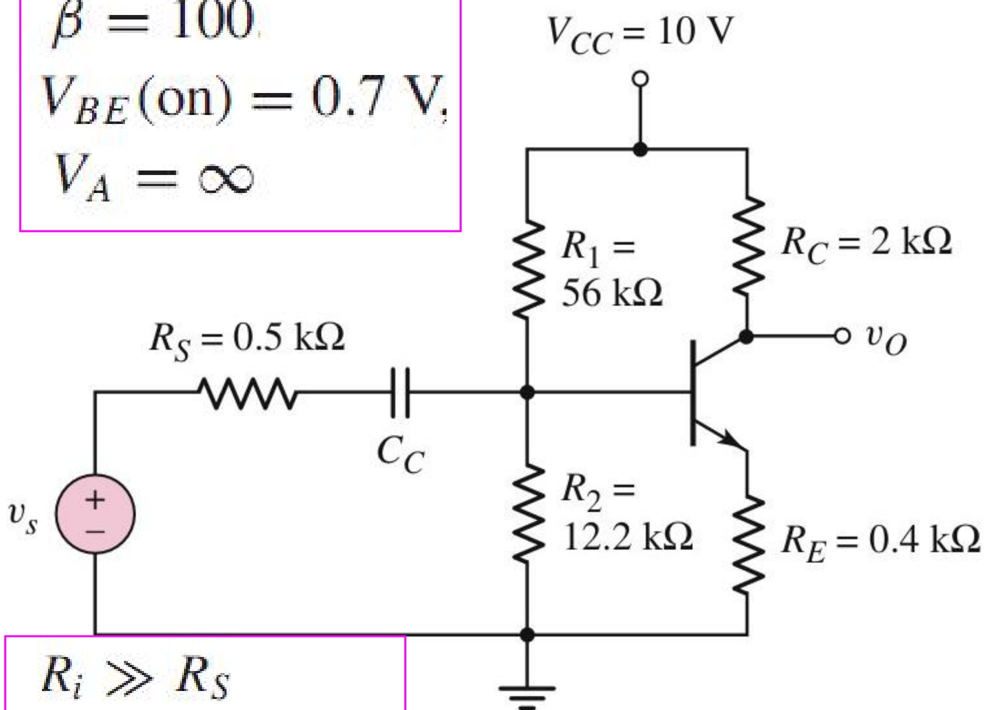
$$A_{vs} = \frac{V_o}{V_s} = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E}\left(\frac{R_i}{R_i + R_S}\right)$$

6.4.2 Circuit with Emitter Resistor

$\beta = 100$

$V_{BE}(\text{on}) = 0.7\ \text{V},$

$V_A = \infty$



 # Voltage-divider biasing stabilizes Q， but degrade ac voltage gain, how can we improve it?

$R_i \gg R_S$

$(1+\beta)R_E \gg r_\pi$

$$A_{vs} = \frac{-R_C}{R_E} = \frac{-2}{0.4} = -5.0$$

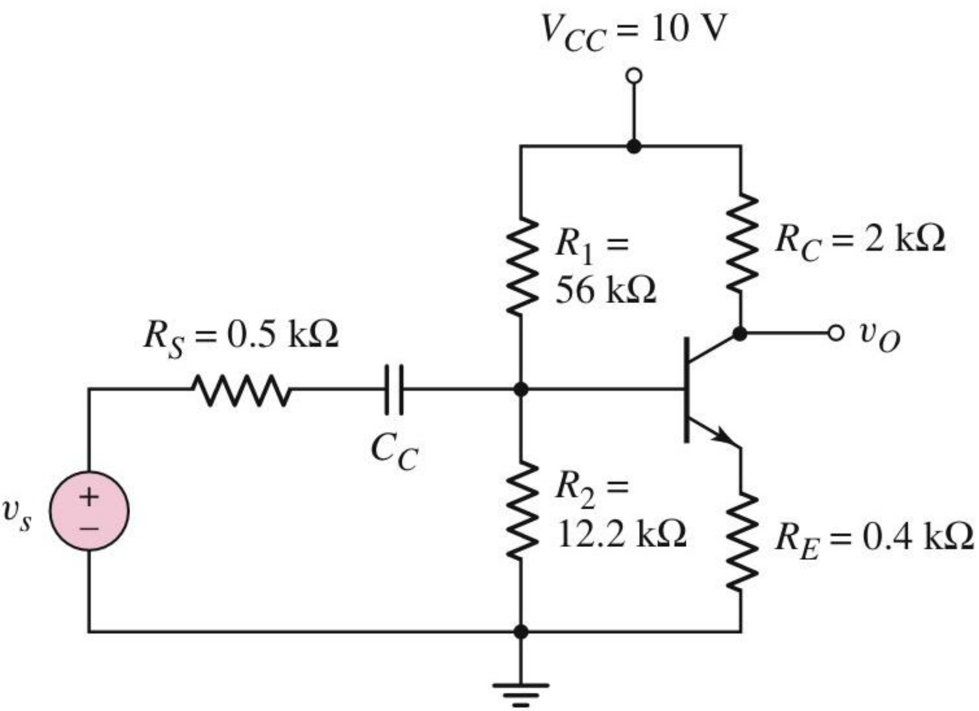
-163

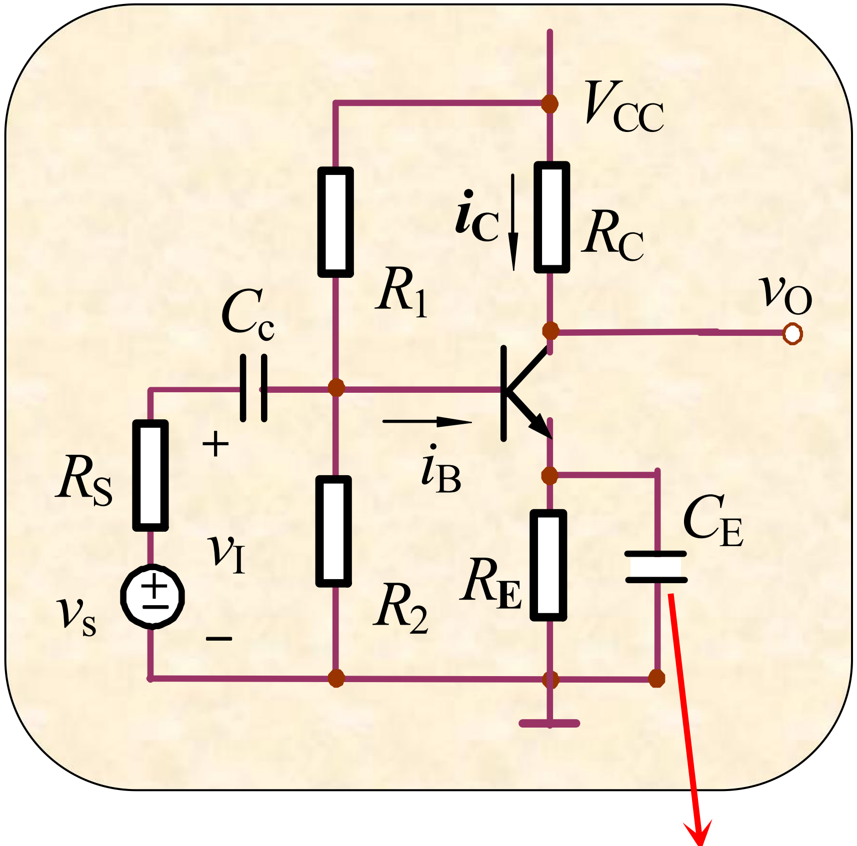
$$A_{vs} = \frac{V_o}{V_s} = \frac{\cancel{-\beta} R_C}{\cancel{r_\pi} + \cancel{(1+\beta)} R_E}\left(\cancel{\frac{R_i}{R_i + R_S}}\right) = \frac{-R_C}{R_E}$$

$A_{vs} = -4.53$

6.4 Common-Emitter Amplifiers

6.4.2 Circuit with Emitter Resistor

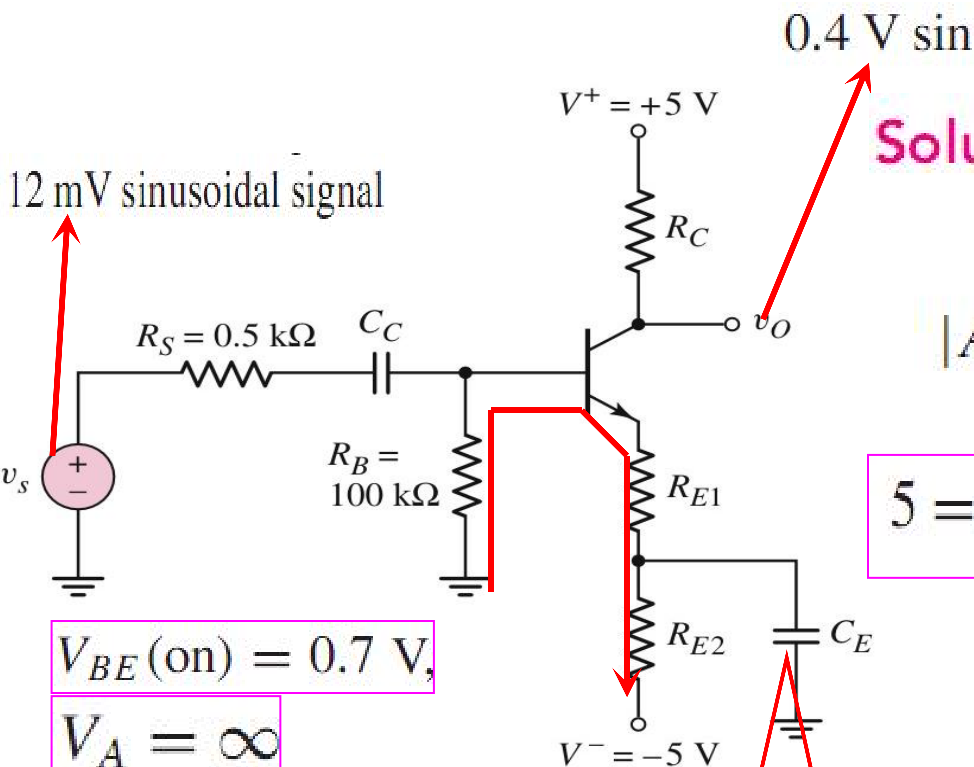




Bypass Capacitor

6.4 Common-Emitter Amplifiers

6.4.3 Circuit with Emitter Bypass Capacitor



$\boxed{V_{BE}(\text{on}) = 0.7 \text{ V},}$

$\boxed{V_A = \infty}$

$\boxed{75 \le \beta \le 125}$

$\boxed{\beta = 100}$

Design the bipolar amplifier

Solution

$$|A_v| = \frac{0.4\text{ V}}{12\text{ mV}} = 33.3$$

$$|A_v| \cong \frac{R_C}{R_{E1}} \quad \text{set } R_C/R_{E1} = 40$$

$$\boxed{5 = \underline{I_B} R_B + V_{BE}(\text{on}) + I_E\underline{(R_{E1} + R_{E2})}}$$

$$\boxed{I_E \cong I_C = 0.20 \text{ mA.}}$$

$$R_{E1} + R_{E2} = 20.5\text{ k}\Omega$$

$$\boxed{V_{CEQ} = 4 \text{ V},} \quad R_C = 9.5\text{ k}\Omega$$

$$R_{E1} = \frac{R_C}{40} = \frac{9.5}{40} = 0.238\text{ k}\Omega$$

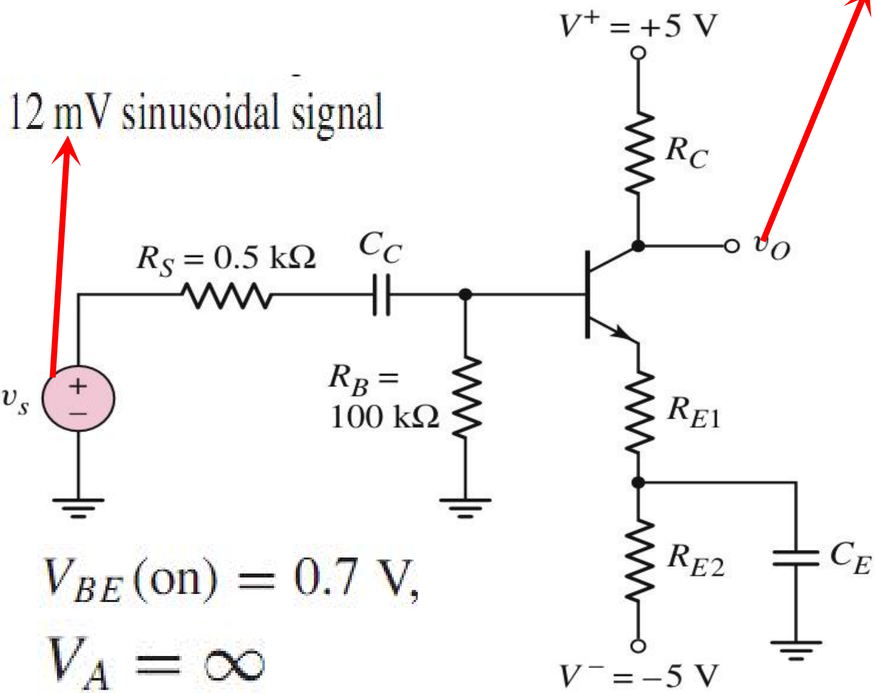
$$R_{E2} = 20.3\text{ k}\Omega$$

6.4.3 Circuit with Emitter Bypass Capacitor

Design the bipolar amplifier

0.4 V sinusoidal out

12 mV sinusoidal signal



$V_{BE}(\text{on}) = 0.7$ V,

$V_A = \infty$

$75 \le \beta \le 125$

$\beta = 100$

$\boxed{I_E \cong I_C = 0.20 \text{ mA.}}$

$\boxed{V_{CEQ} = 4 \text{ V,}}$

$$R_C = 9.5 \text{ k}\Omega$$

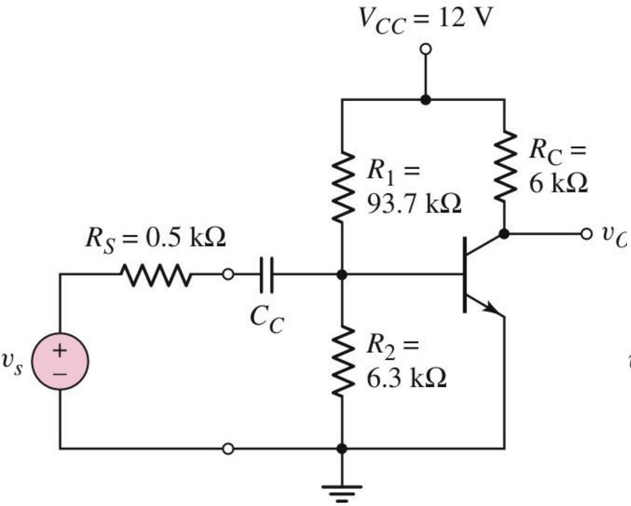
$$R_{E1} = \frac{R_C}{40} = \frac{9.5}{40} = 0.238 \text{ k}\Omega$$

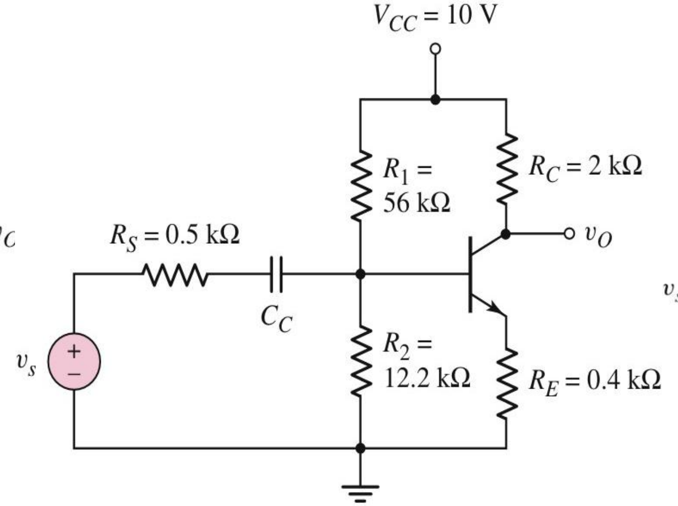
$$R_{E2} = 20.3 \text{ k}\Omega$$

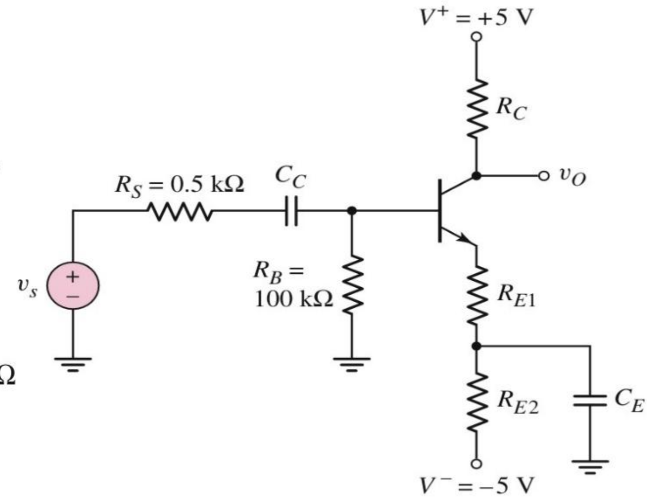
pick standard resistor values

$$\boxed{\begin{aligned} R_{E1} &= 240\ \Omega \\ R_{E2} &= 20 \text{ k}\Omega \\ R_C &= 10 \text{ k}\Omega \end{aligned}}$$

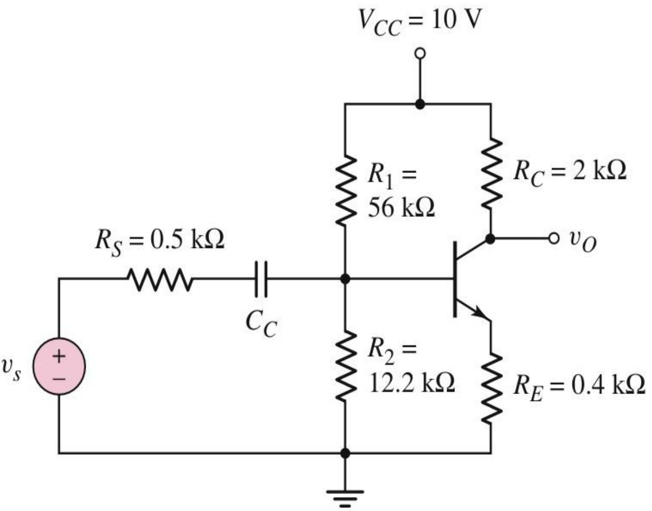
6.4 Common-Emitter Amplifiers





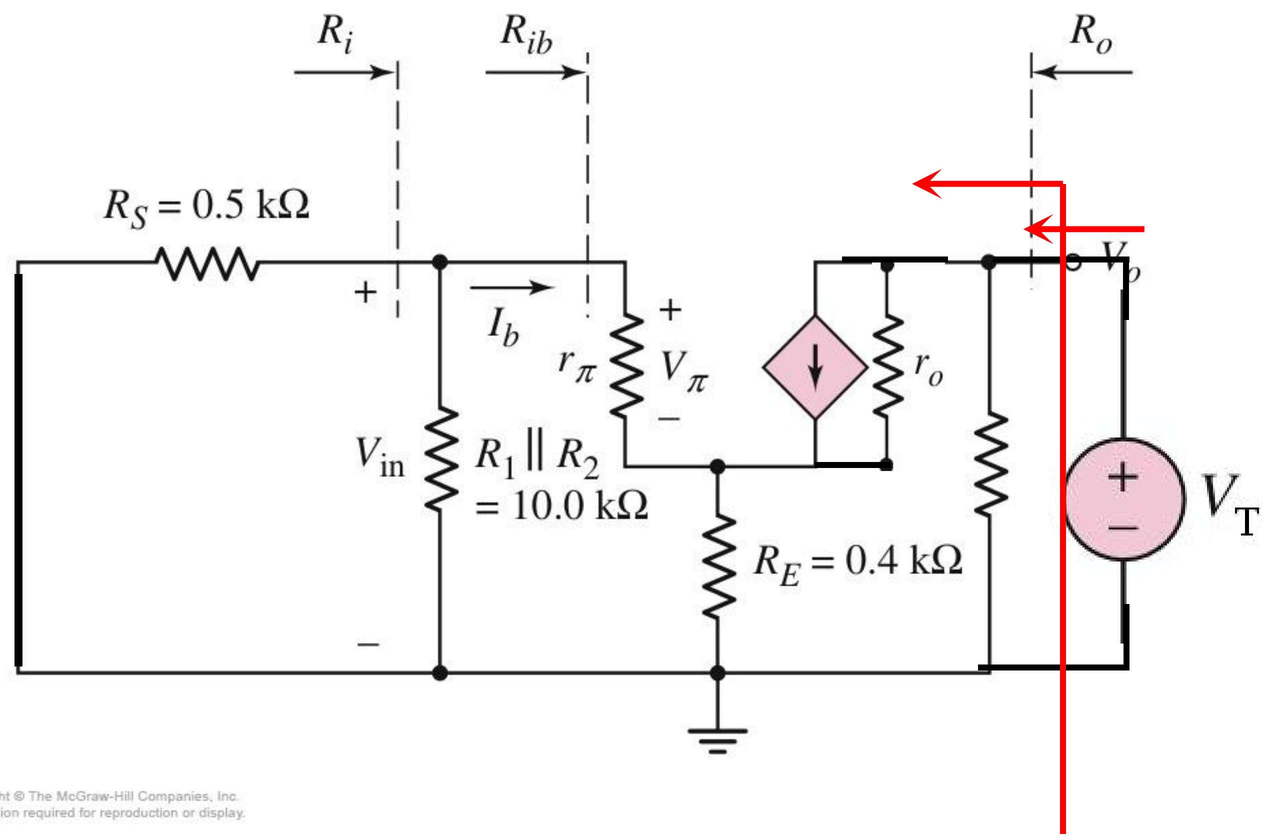


Small Signal Voltage Gain	$-g_m R_C // r_o$	$= \dfrac{-\beta[R_C // r_o]}{r_\pi + (1+\beta)R_E}$	$= \dfrac{-\beta[R_C // r_o]}{r_\pi + (1+\beta)R_{E1}}$
Input impedance	$R_1 \| R_2 \| r_\pi$	$R_1 // R_2 // [r_\pi + (1+\beta)R_E]$	$R_1 // R_2 // [r_\pi + (1+\beta)R_{E1}]$
Output impedance	$\approx R_c$	$\approx R_c$	$\approx R_c$



$V_{CC} = 10$ V
$R_1 =$ 56 kΩ
$R_C = 2$ kΩ
$R_S = 0.5$ kΩ
v_O
C_C
v_s
$R_2 =$ 12.2 kΩ
$R_E = 0.4$ kΩ

Find R_o



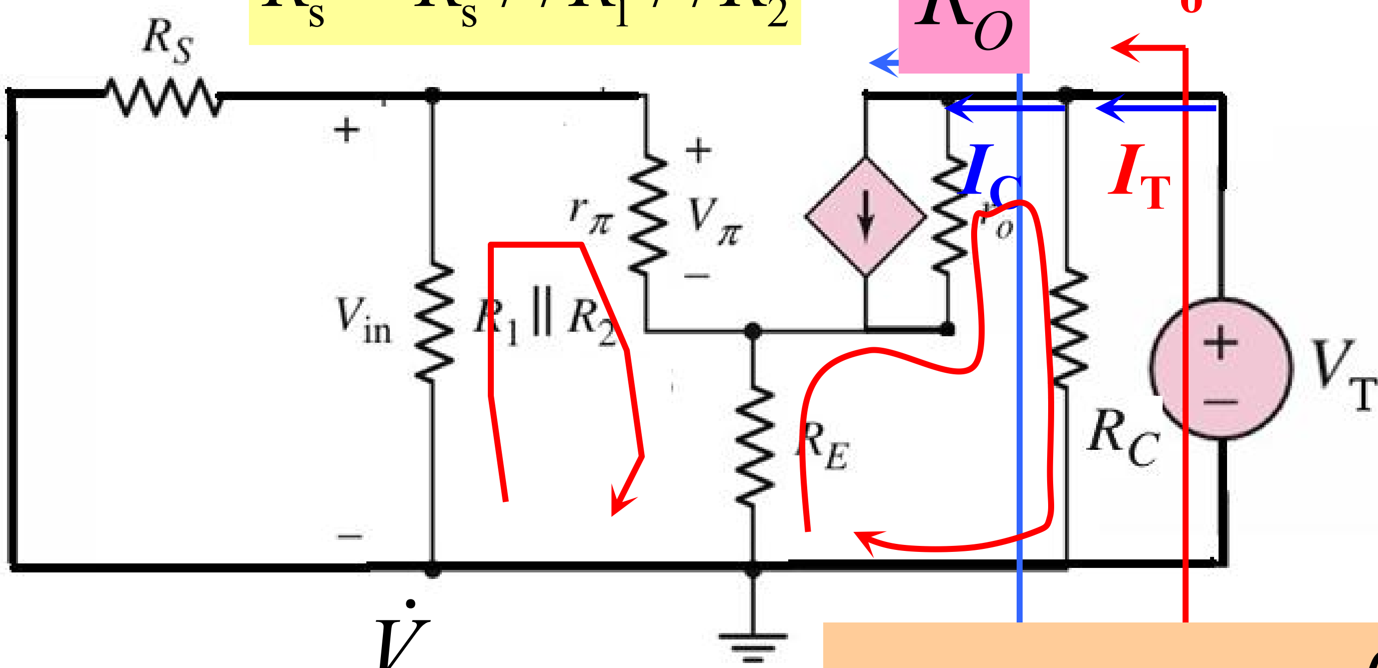
R_i
R_{ib}
R_o
$R_S = 0.5$ kΩ
I_b
r_π
V_π
r_o
V_o
V_{in}
$R_1 \| R_2 = 10.0$ kΩ
$R_E = 0.4$ kΩ
V_T

$R_s' = R_s // R_1 // R_2$

R_O'

R_o

Find R_o

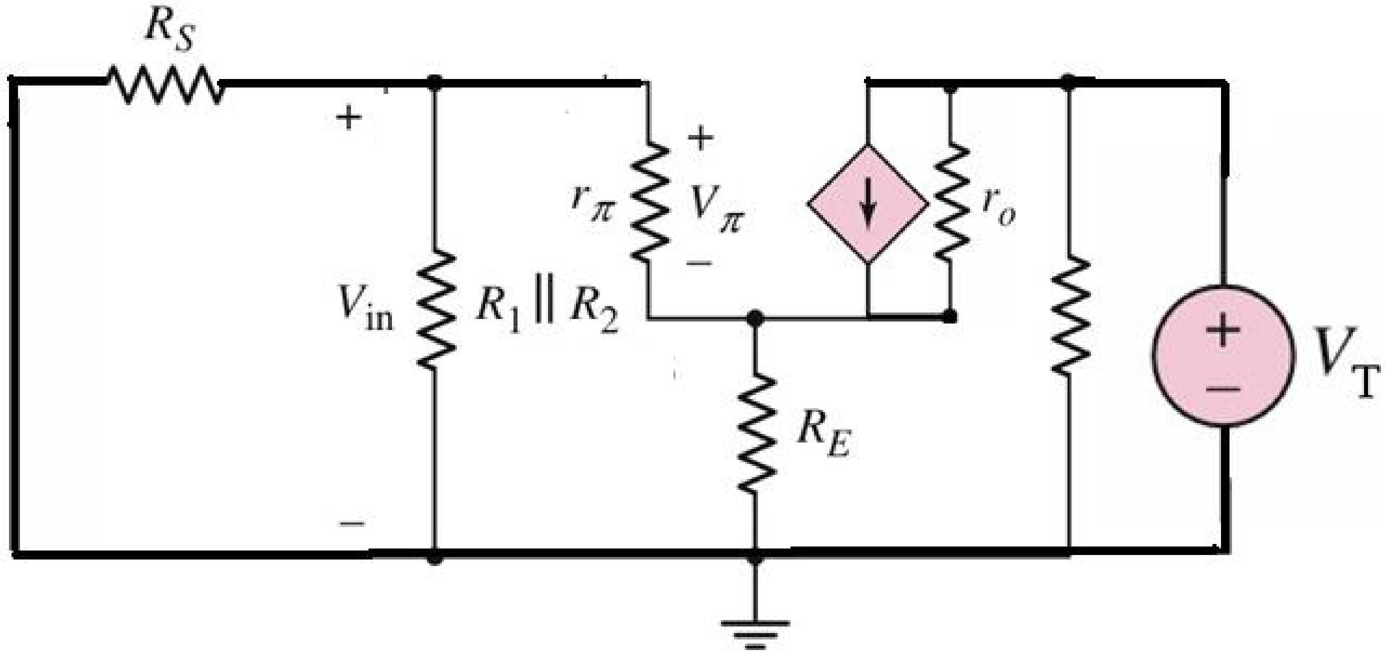


$$R_o' = \frac{\dot{V}_T}{\dot{I}_c}$$

$$\boldsymbol{R_o = R_c // R_o'} = \frac{\dot{V}_T}{\dot{I}_T}$$

$$R_o' = r_o\left(1 + \frac{\beta \cdot R_E}{r_\pi + R_s' + R_E}\right)$$

$$\begin{cases} \dot{I}_b(r_\pi + R_s') + (\dot{I}_b + \dot{I}_c)R_E = 0 \\ \dot{V}_T - (\dot{I}_c - \beta \cdot \dot{I}_b)r_o - (\dot{I}_c + \dot{I}_b)R_E = 0 \end{cases}$$



$$\boldsymbol{R_o = R_c \,//\, R_o'}$$

$$R_o' = r_o\left(1 + \frac{\beta \cdot R_E}{r_\pi + R_s' + R_E}\right)$$

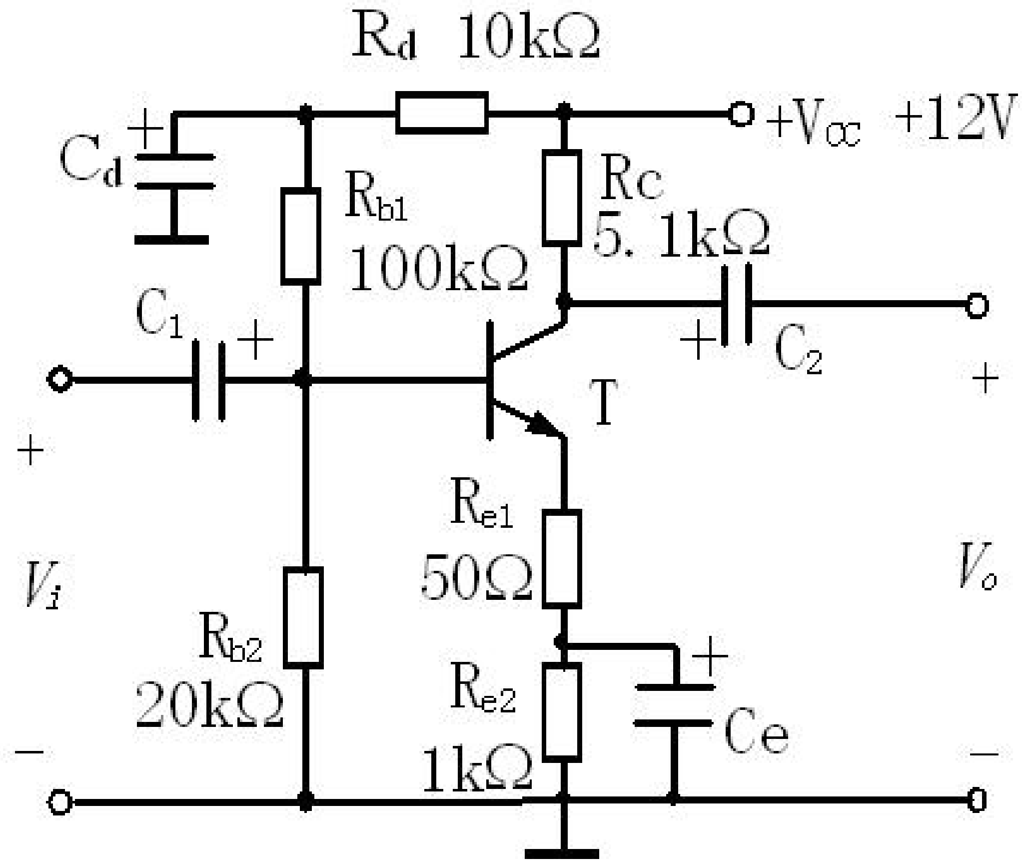
$$\boldsymbol{R_o' >> R_c} \qquad \boldsymbol{R_o \approx R_c}$$

Summary of CE amplifier

- Large voltage gain $-g_{\mathrm{m}}R_{\mathrm{C}}//r_o$
- Inverting amplifier
- Large current gain $I_{\mathrm{C}} = \beta I_{\mathrm{B}}$
- Input resistance is relatively low. $R_1 \| R_2 \| r_\pi$
- Output resistance is relatively high. $\mathbf{R_C}$

$\beta = 50$,

$V_{BE} = 0.7V$;



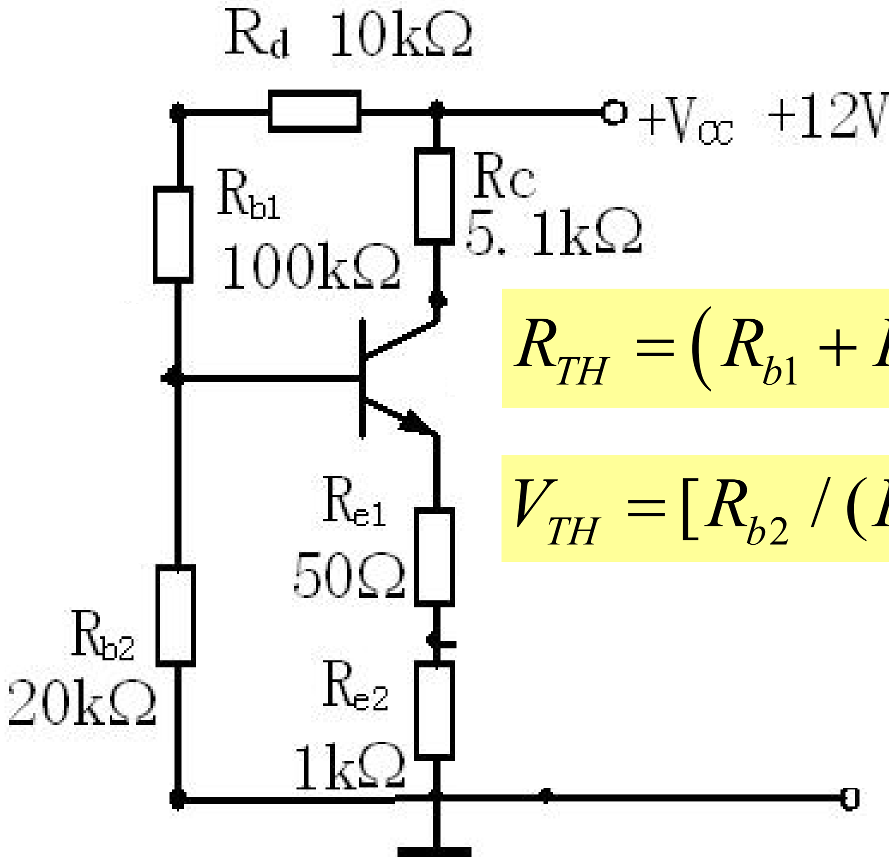
1、Calculate（I_B、I_C、V_{CE}）；

2、Sketch the small signal equivalent circuit;

3、Find R_i and R_o ;

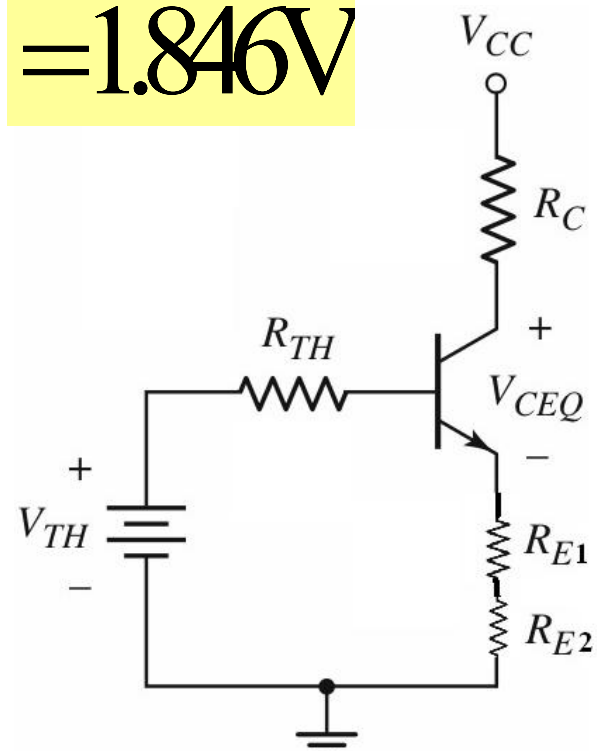
4、Find $A_v = V_o / V_i$;

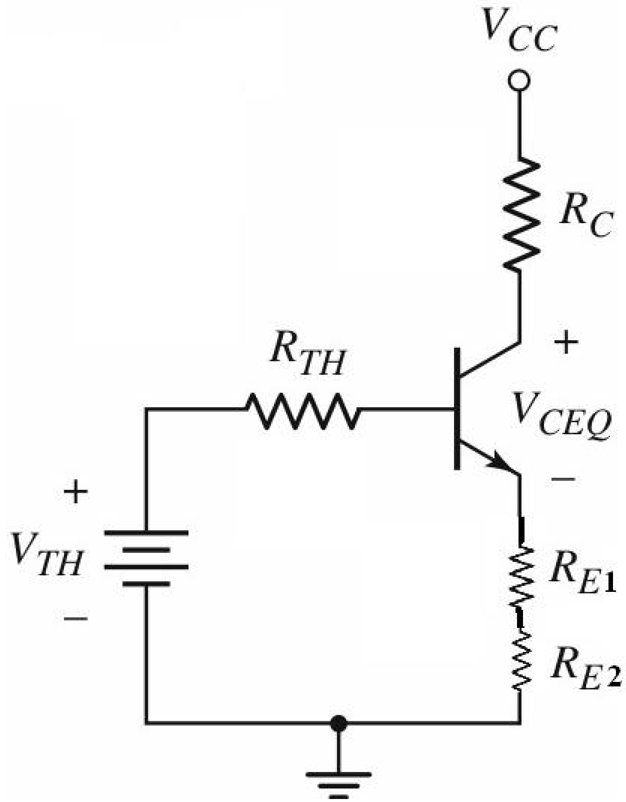
DC Solution:



$$R_{TH} = \left(R_{b1} + R_d\right) // R_{b2} = 16.9k\Omega$$

$$V_{TH} = [R_{b2} / (R_{b1} + R_{b2} + R_d) V_{CC} = 1.846V$$





$$I_{\mathrm{B}} = \frac{V_{\mathrm{TH}} - V_{\mathrm{BE}}}{R_{\mathrm{TH}} + (1+\beta)\left(R_{\mathrm{E1}} + R_{\mathrm{E2}}\right)}$$

$$= 16\mu\mathrm{A}$$

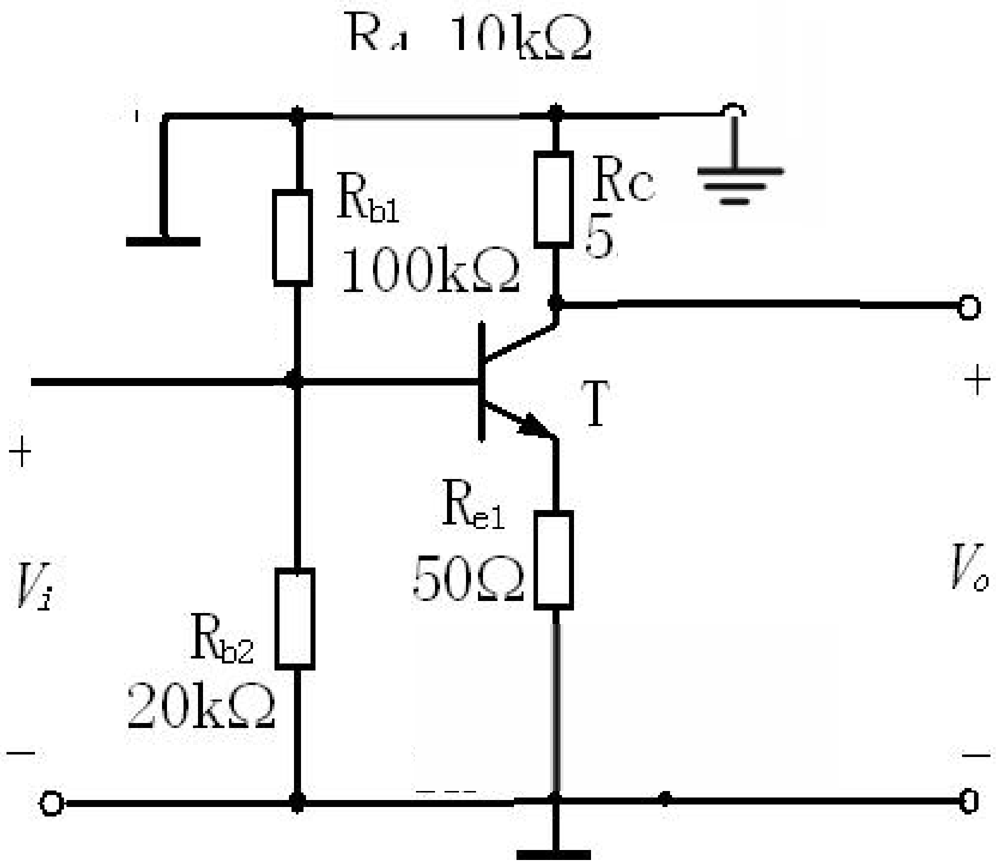
$$I_{\mathrm{C}} = \beta I_{\mathrm{B}} \quad = 0.8\mathrm{mA}$$

$$V_{\mathrm{CEQ}} = V_{\mathrm{CC}} - I_{\mathrm{C}} R_{\mathrm{C}} - I_{\mathrm{E}}\left(R_{\mathrm{E1}} + R_{\mathrm{E2}}\right)$$

$$= V_{\mathrm{CC}} - I_{\mathrm{C}}\left(R_{\mathrm{C}} + R_{\mathrm{E1}} + R_{\mathrm{E2}}\right)$$

$$= 7.1\mathrm{V}$$

AC CIRCUIT



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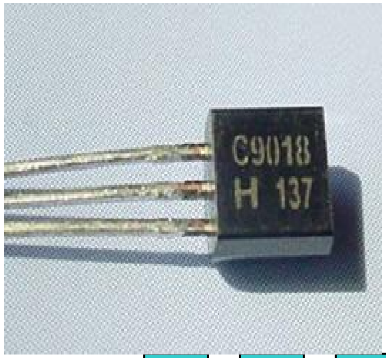


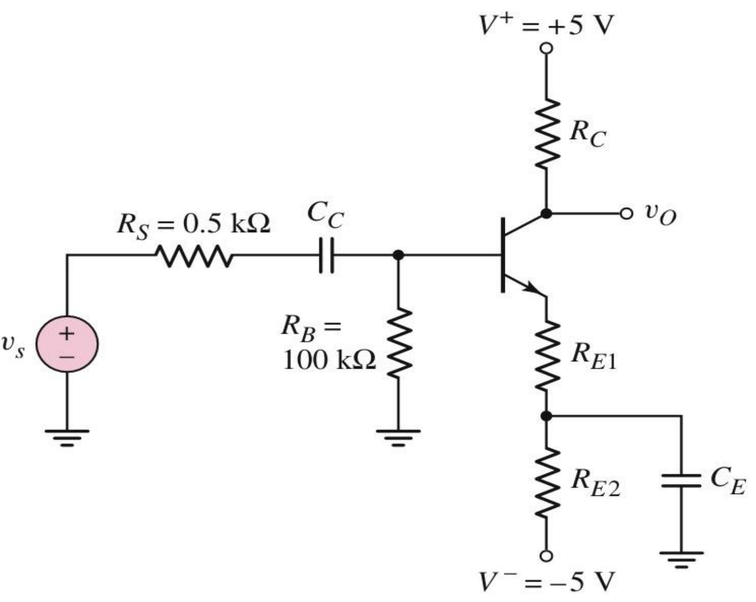
6.5 AC Load line Analysis

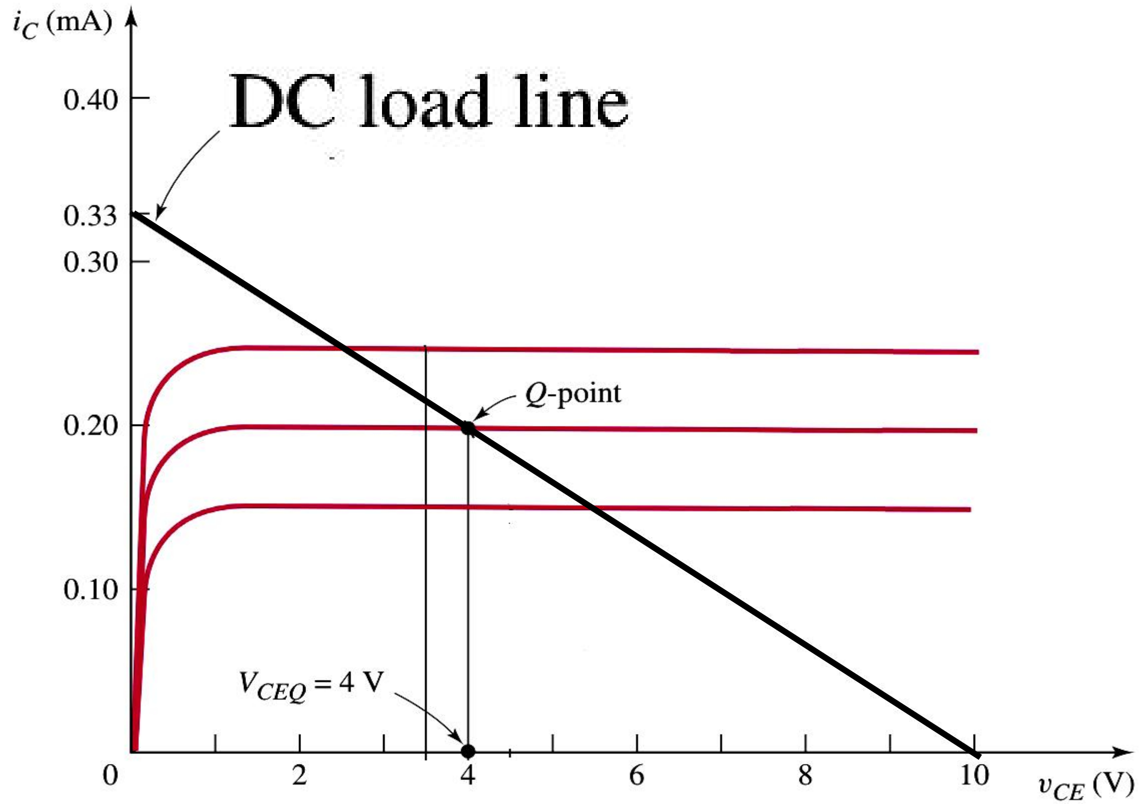
6.5.1 AC load line

$$\text{slope} \cong \frac{-1}{R_C + R_{E1} + R_{E2}} = \frac{-1}{30.2\ \text{k}\Omega}$$

Review DC load line

$$V_{CE} = V^{+} - (V^{-}) - I_{EQ}(R_C + R_{E1} + R_{E2})$$





$$V_{CE} = (V^{+} - V^{-}) - I_C\left[R_C + (R_{E1} + R_{E2})\right]$$

6.5 AC Load line Analysis

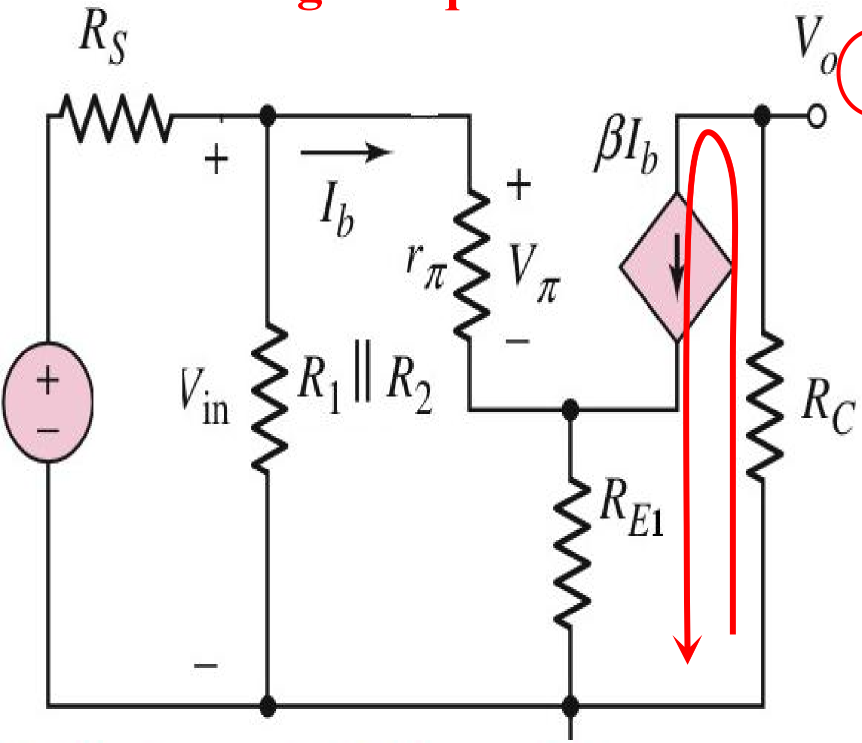
6.5.1 AC load line

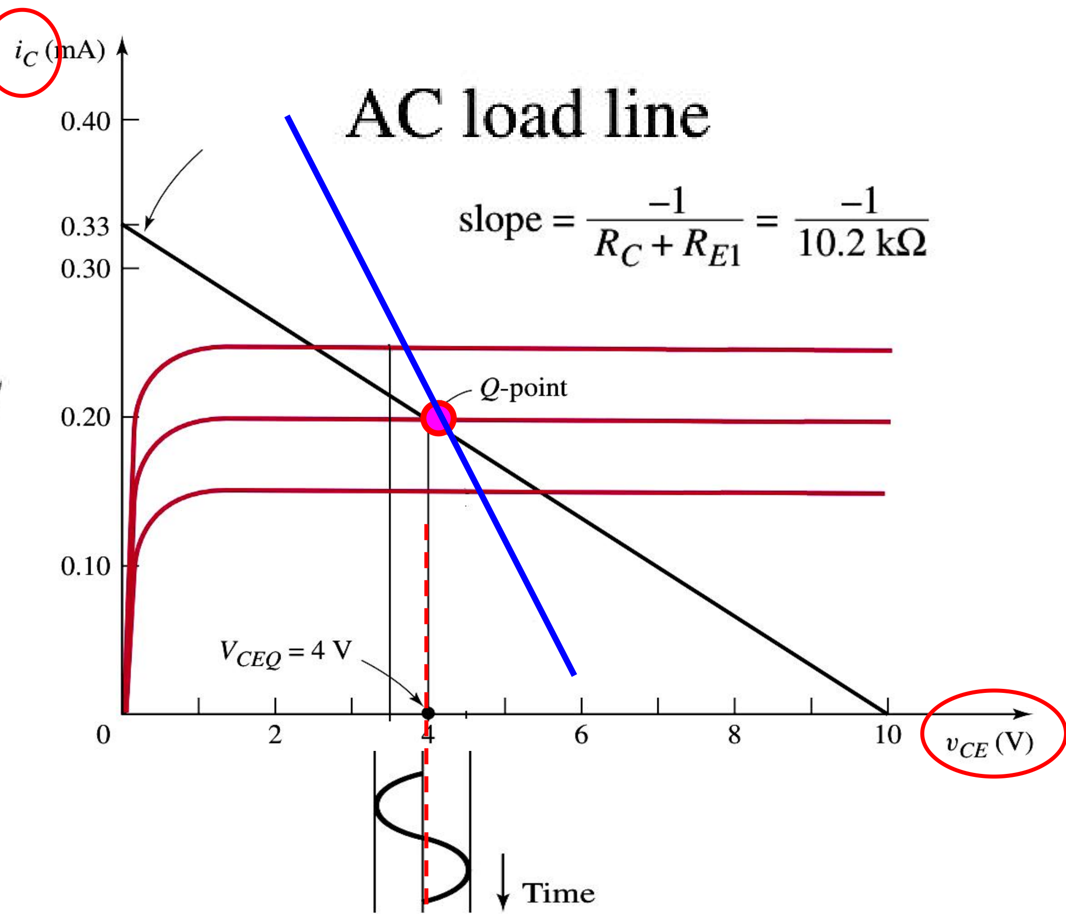
$v_{ce} = v_{CE} - V_{CEQ}$

$i_c = i_C - I_{CQ}$

$$\text{Slope} = \frac{-1}{R_C + R_{E1}}$$

The small-signal equivalent circuit





$$i_c R_C + v_{ce} + i_e R_{E1} = 0$$

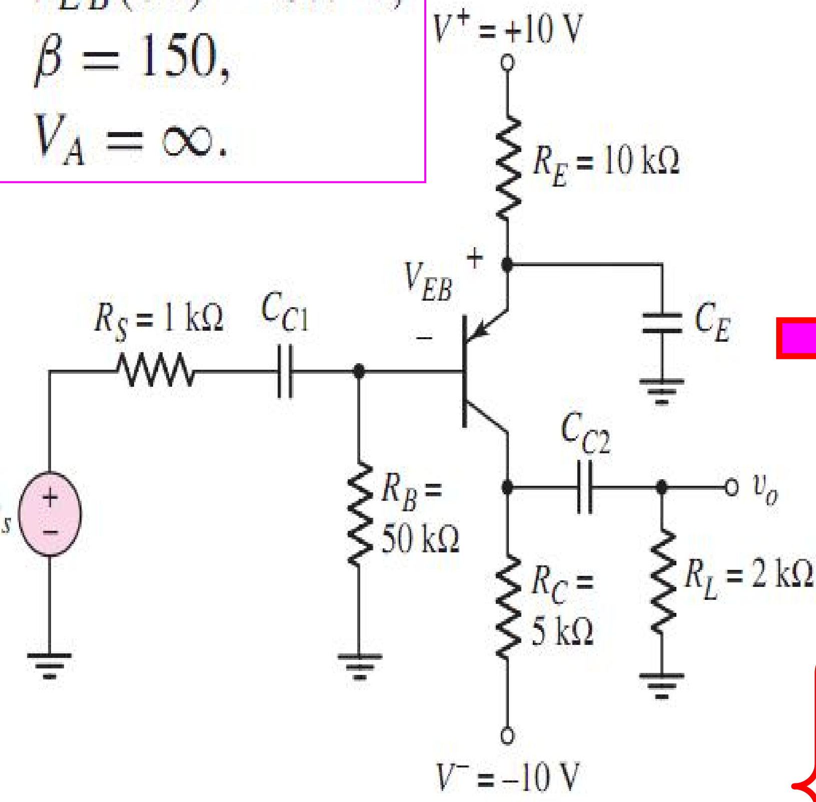
$$v_{ce} = -i_c(R_C + R_{E1})$$

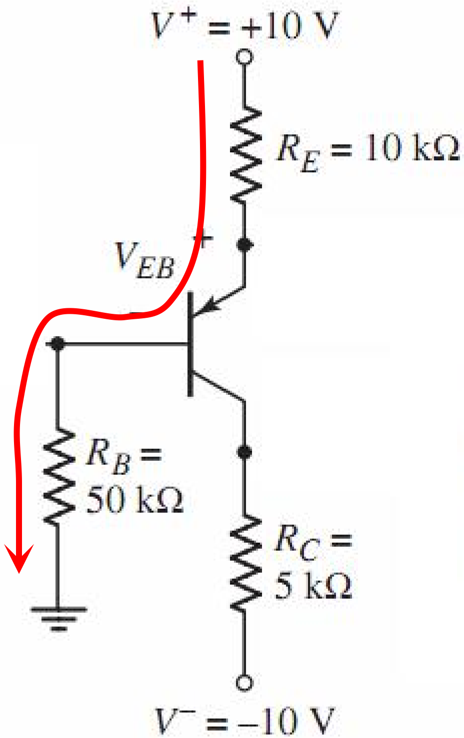
$$i_C = [-1/(R_C+R_{E1})] \cdot v_{CE} + [1/(R_C+R_{E1})] V_{CEQ} + I_{CQ}$$

6.5 AC Load line Analysis

6.5.1 AC load line

$V_{EB}(\text{on}) = 0.7\text{ V},$
$\beta = 150,$
$V_A = \infty.$





$I_{BQ} = 5.96\ \mu\text{A}$

$I_{CQ} = 0.894\text{ mA}$

$V_{ECQ} = 6.53\text{ V}$

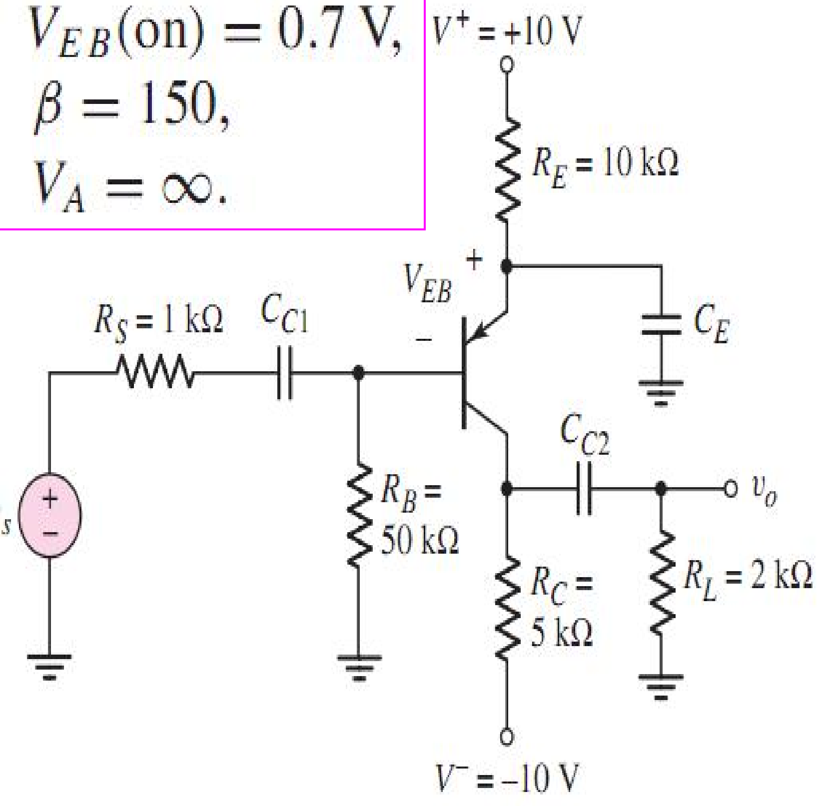
$$\begin{cases} V^+ = (1+\beta)I_{BQ}R_E + V_{EB}(\text{on}) + I_{BQ}R_B \\ I_{CQ} = \beta I_{BQ} \\ V_{ECQ} = (V^+ - V^-) - I_{CQ}R_C - I_{EQ}R_E \end{cases}$$

DC Circuit

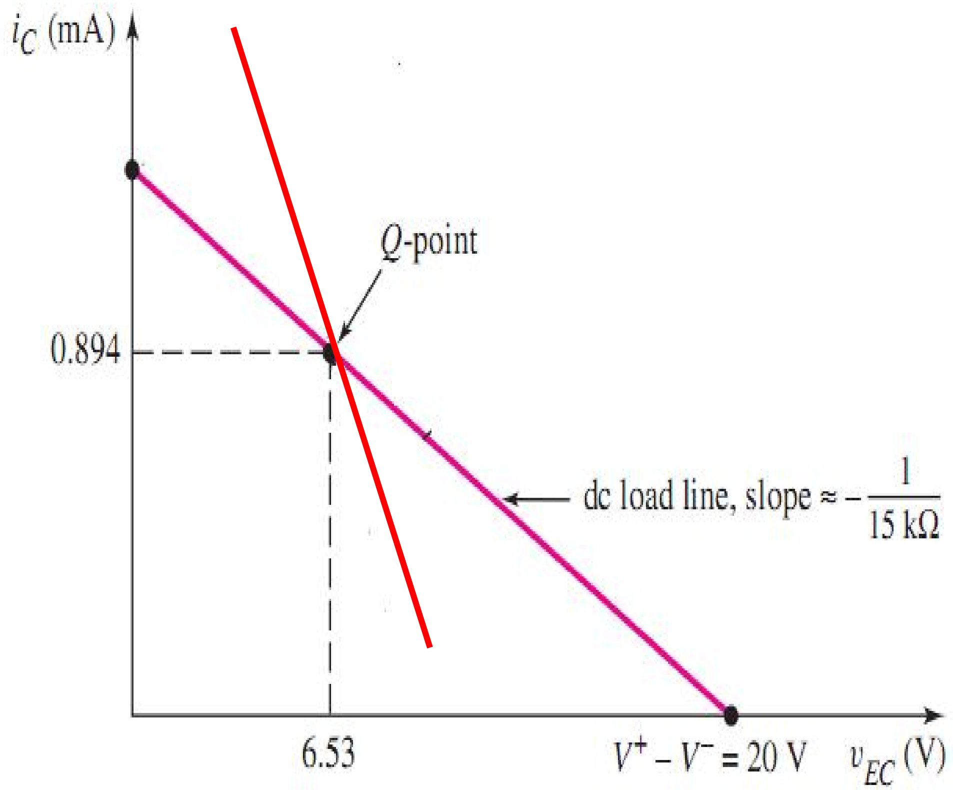
6.5 AC Load line Analysis

6.5.1 AC load line

$V_{EB}(\text{on}) = 0.7\text{ V},$
$\beta = 150,$
$V_A = \infty.$



$$\text{ac load line, slope} = -\frac{1}{R_C \| R_L} = -\frac{1}{1.43\text{ k}\Omega}$$



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6.5 AC Load line Analysis

6.5.1 AC load line

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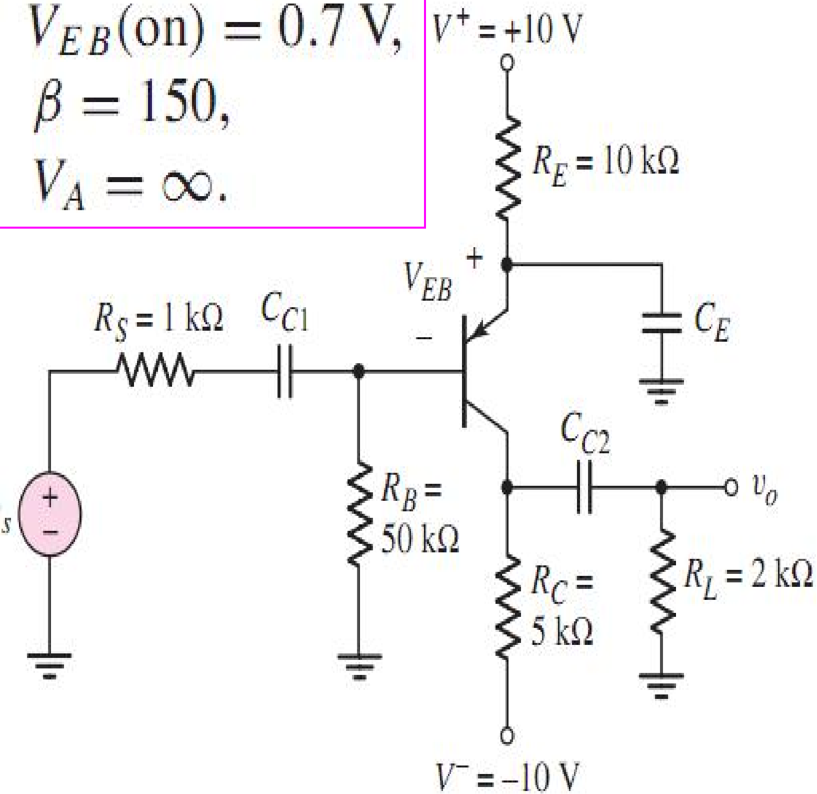
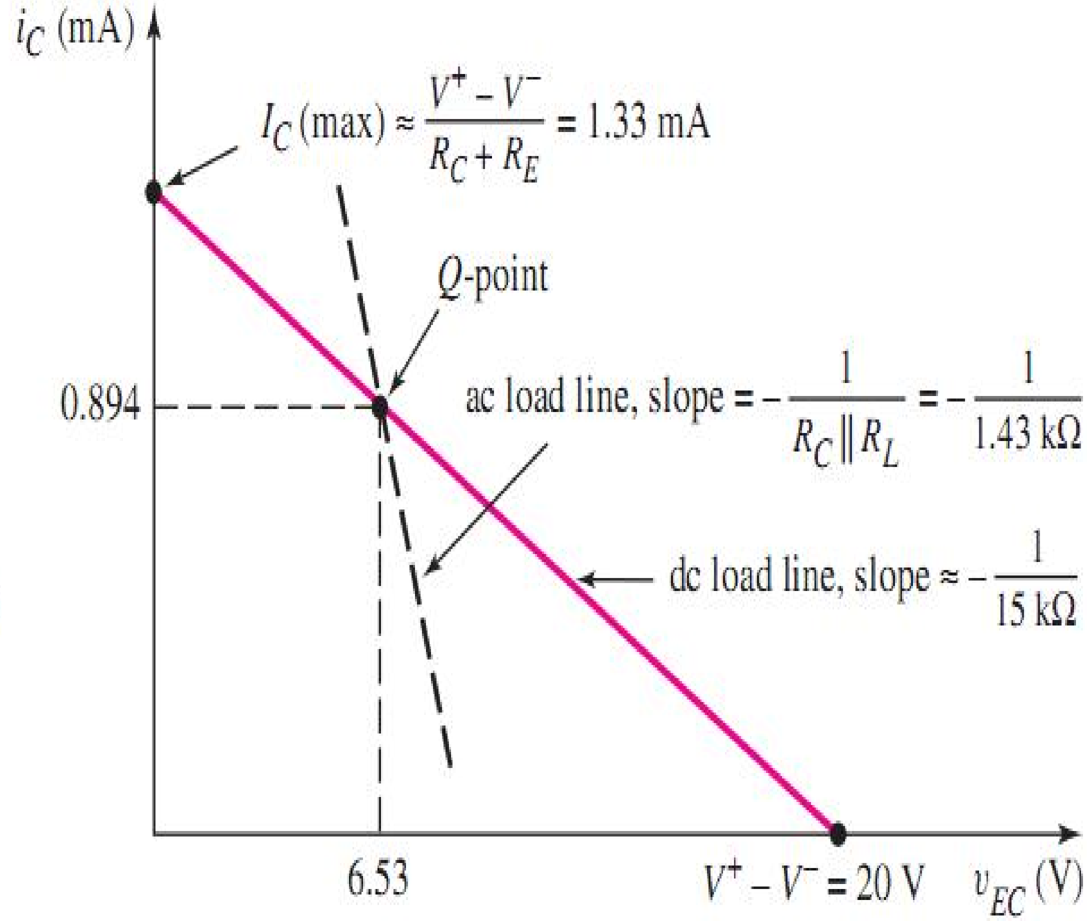
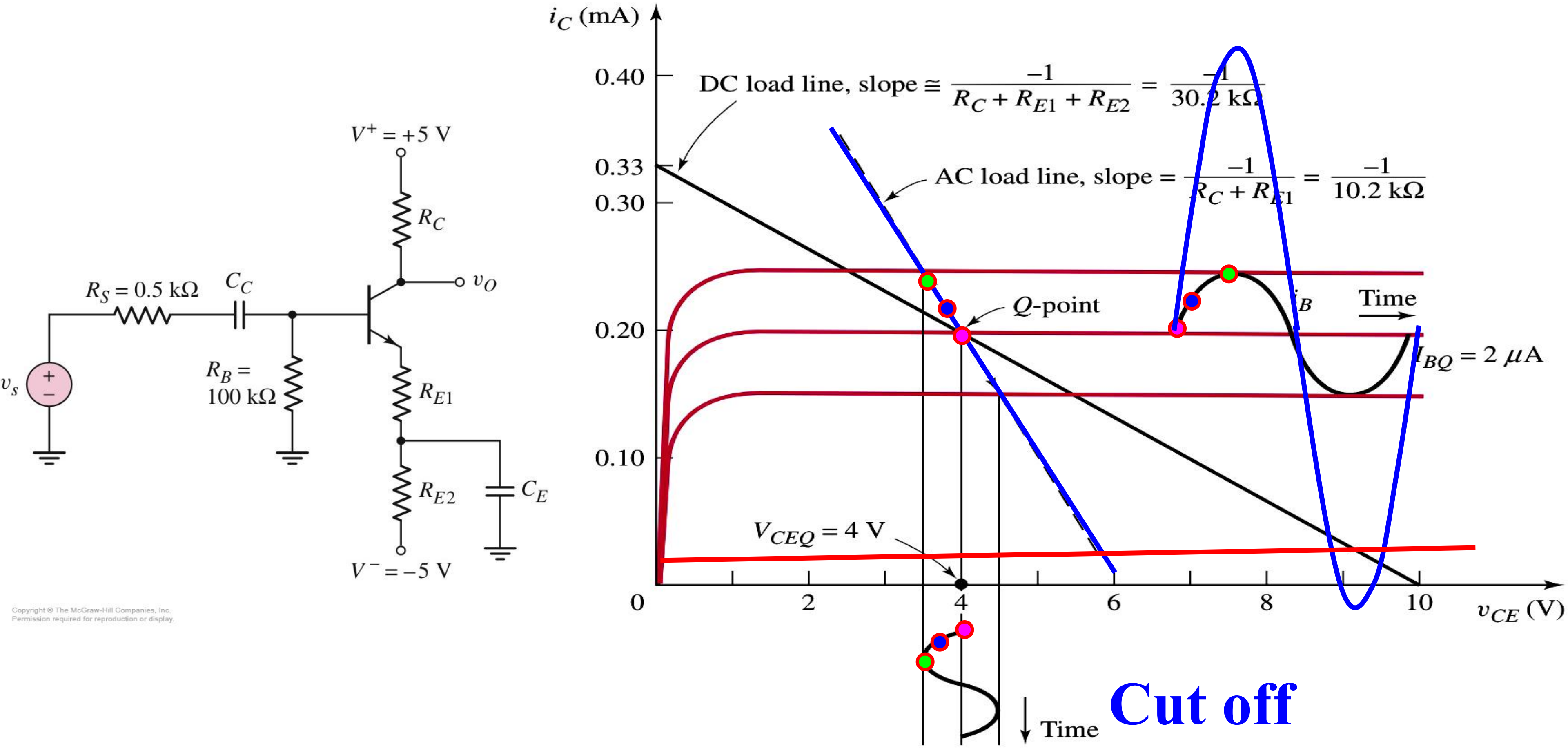




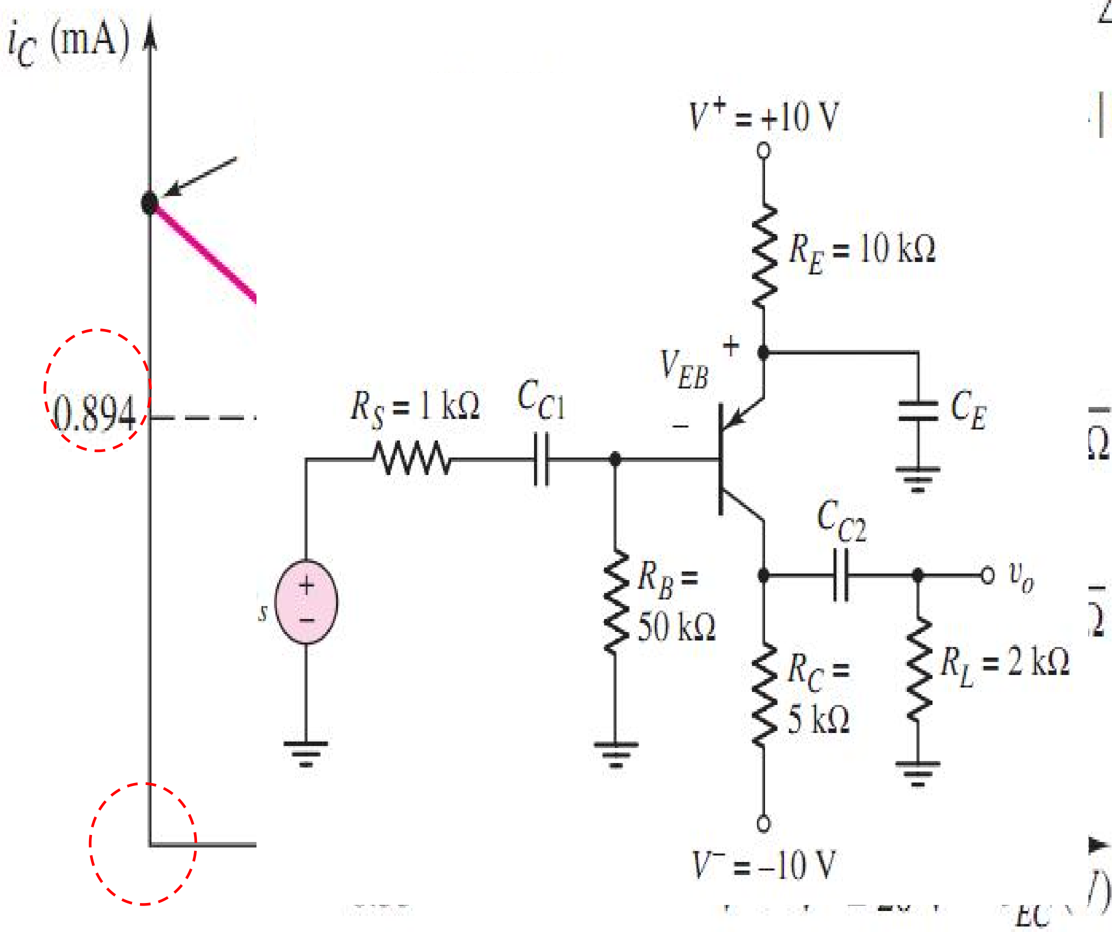
6.5 AC Load line Analysis

6.5.2 Maximum Symmetrical Swing



Maximum Symmetrical Swing

6.5.2 Maximum Symmetrical Swing



$$\Delta i_c = 2(0.894) = 1.79 \text{ mA}$$

$$|(R_C \| R_L) = (1.79)(5\|2) = 2.56 \text{ V}$$

Figure 6.46

$$i_C = I_{CQ} + \tfrac{1}{2}|\Delta i_c| = 0.894 + 0.894 = 1.79 \text{ mA}$$

The max of v_o

6.5.2 Maximum Symmetrical Swing

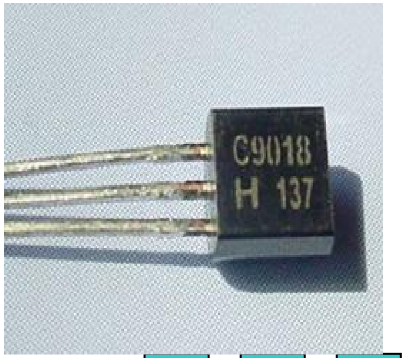
Problem-Solving Technique: Maximum Symmetrical Swing

1. **Write dc load line equation that relates I_{CQ} and V_{CEQ}.**
2. **Write ac load line equations that relates i_c and v_{ce}**
3. **In general, $i_c = I_{CQ} - I_C(\text{min})$, where $I_C(\text{min})$ is zero or other minimum collector current.**
4. **In general, $v_{ce} = V_{CEQ} - V_{CE}(\text{min})$, where $V_{CE}(\text{min})$ is some specified minimum collector-emitter voltage.**
5. **Combine above 4 equations to find optimum I_{CQ} and V_{CEQ}.**

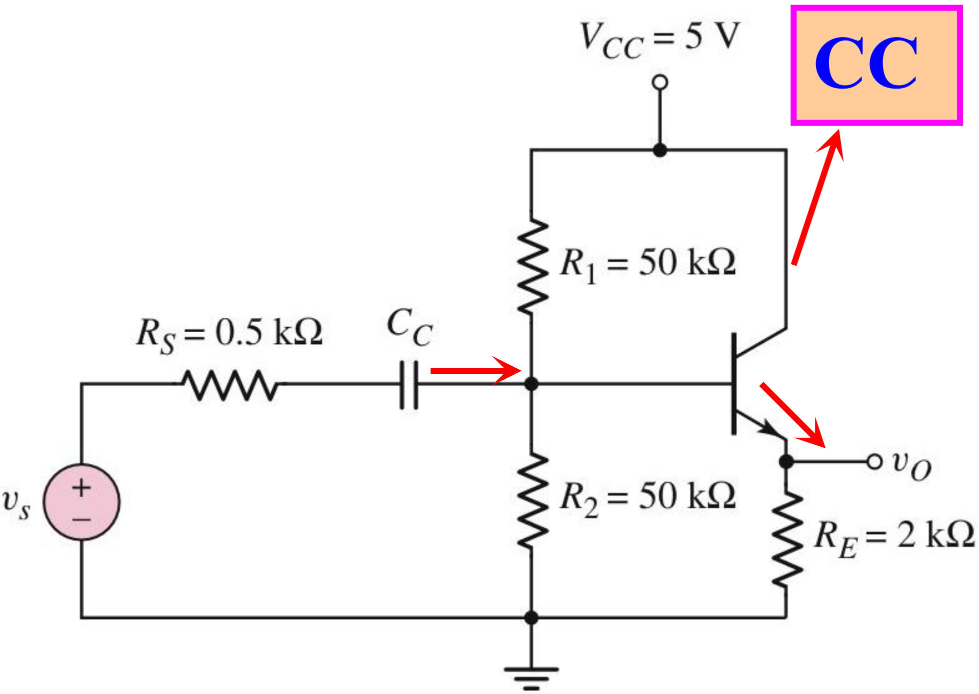
Contents

Ch6. Basic BJT Amplifiers

6.0 Preview
6.1 Analog Signals and Linear Amplifiers
6.2 The Bipolar Linear Amplifier
6.3 Basic Transistor Amplifier Configurations
6.4 Common-Emitter Amplifiers
6.5 AC Load Line Analysis
6.6 Common-Collector (Emitter-Follower) Amplifier
6.7 Common-Base Amplifier
6.8 The Three Basic Amplifiers: Summary and Comparison
6.9 Multistage Amplifiers
6.10 Power Considerations
6.11 Design Application
6.12 Summary



6.6.1 Small signal voltage gain

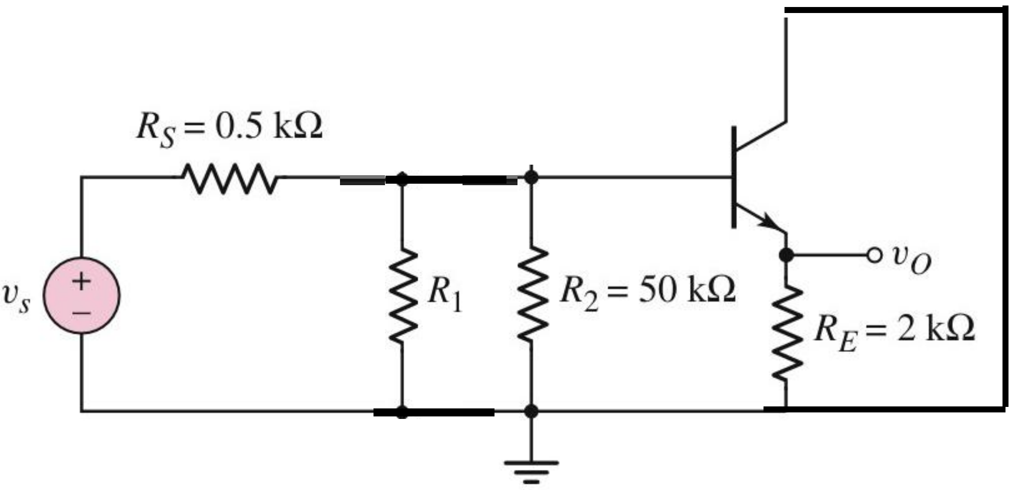


Emitter-Follower

Small-signal equivalent circuit

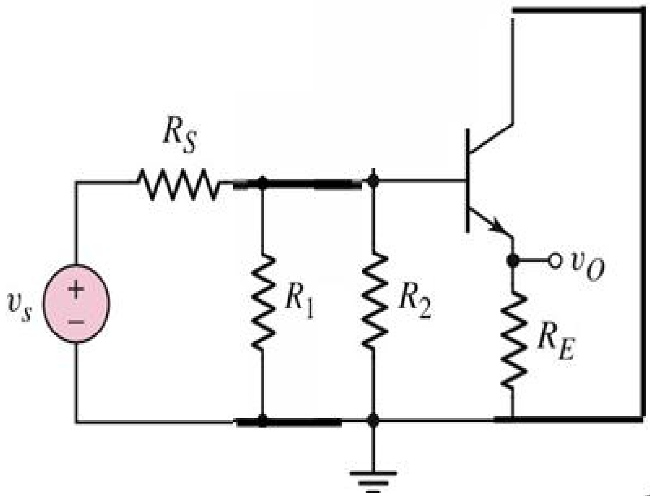
6.6 Common-Collector (Emitter-Follower) Amplifier

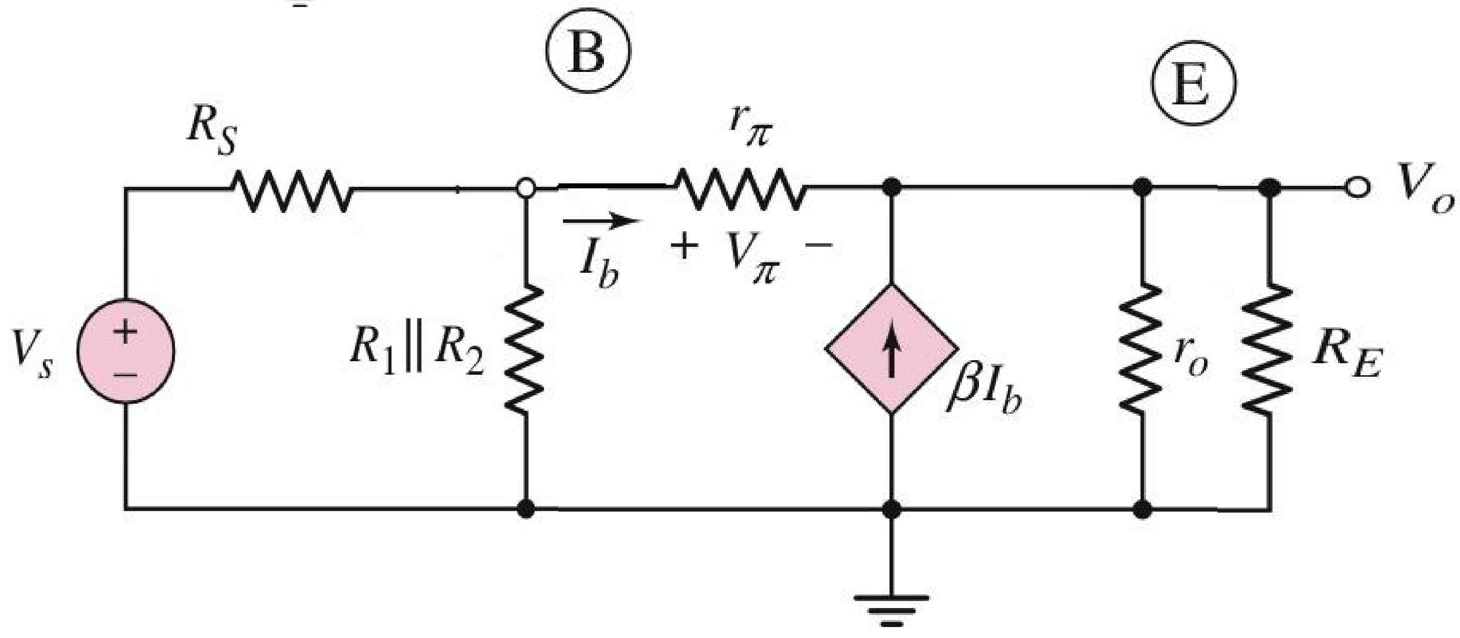
6.6.1 Small signal voltage gain



6.6 Common-Collector (Emitter-Follower) Amplifier

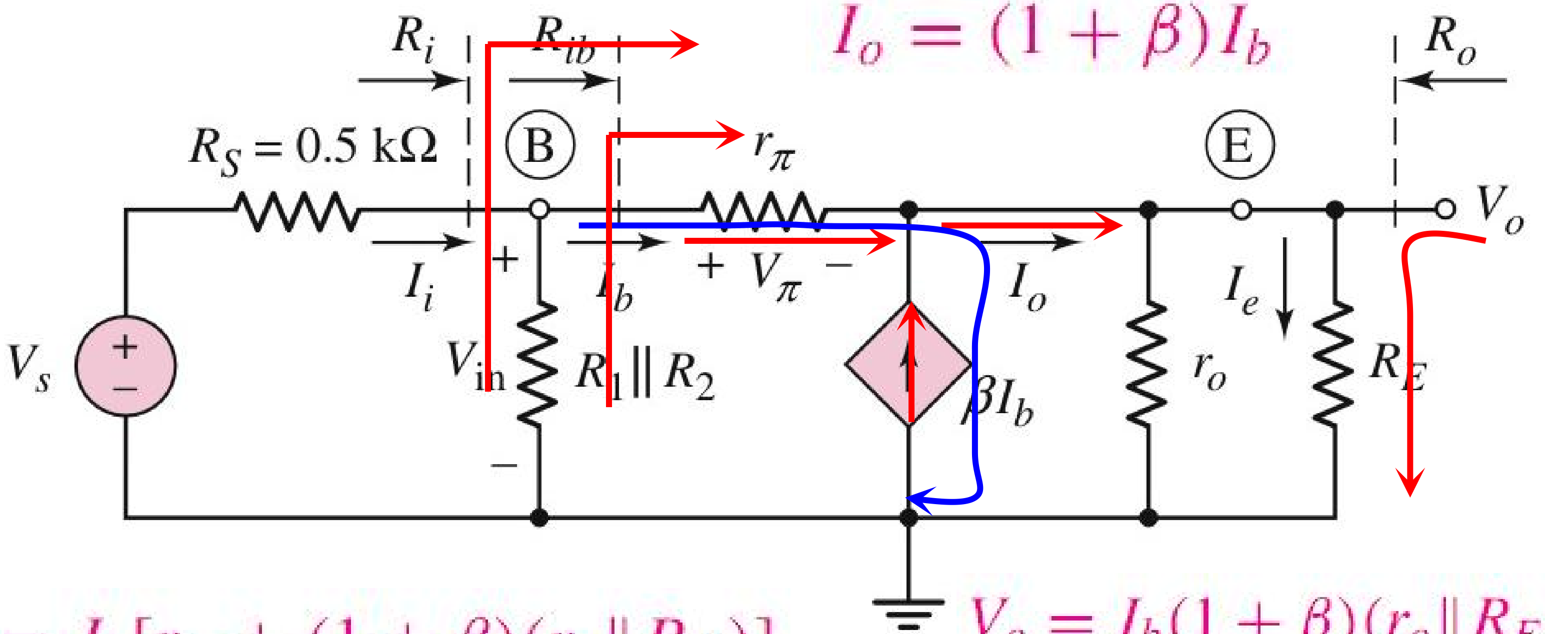
6.6.1 Small signal voltage gain





6.6 Common-Collector (Emitter-Follower) Amplifier

6.6.1 Small signal voltage gain



$$I_o = (1+\beta)I_b$$

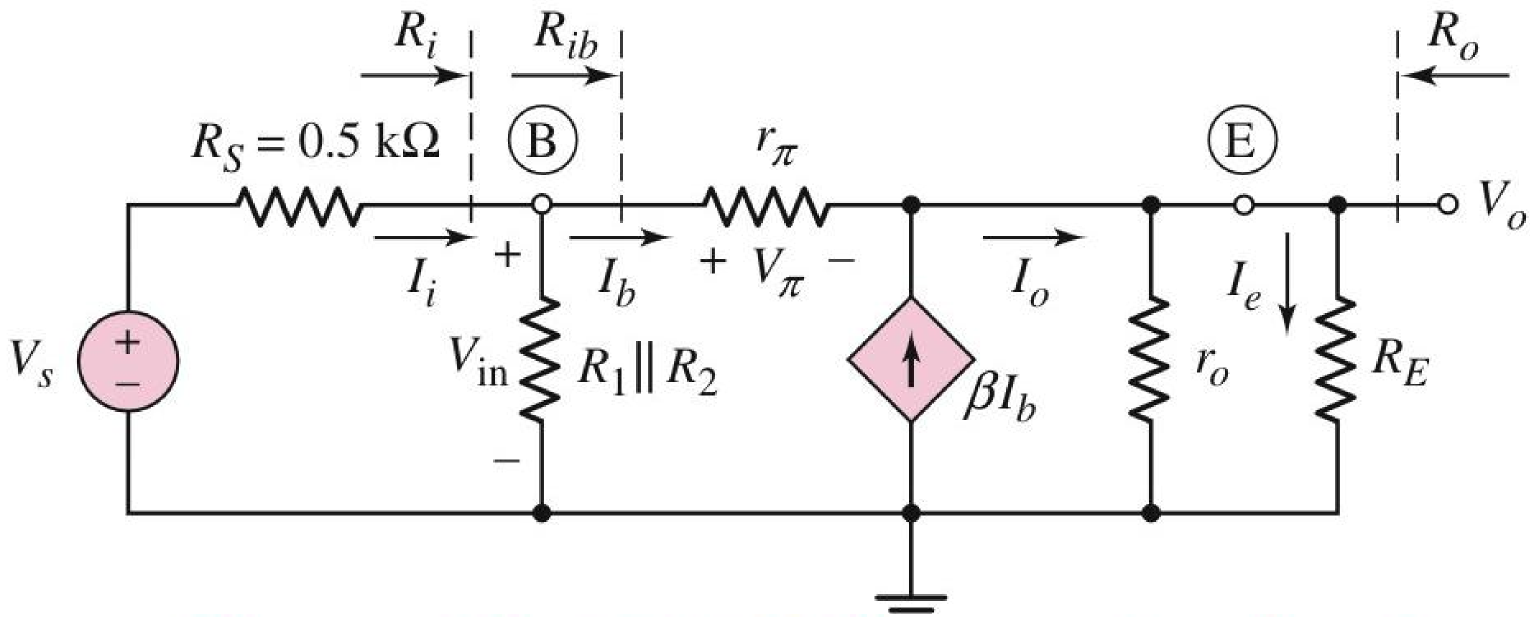
$$V_o = I_b(1+\beta)(r_o \| R_E)$$

$$V_{in} = I_b[r_\pi + (1+\beta)(r_o \| R_E)]$$

$$R_{ib} = \frac{V_{in}}{I_b} = r_\pi + (1+\beta)(r_o \| R_E)$$

$$R_i = R_1 \| R_2 \| R_{ib} \quad V_{in} = \left(\frac{R_i}{R_i + R_S}\right) \cdot V_s$$

6.6.1 Small signal voltage gain



$$A_{vs} = \frac{V_o}{V_s} = \frac{(1+\beta)(r_o \| R_E)}{r_\pi + (1+\beta)(r_o \| R_E)} \cdot \left(\frac{R_i}{R_i + R_S}\right)$$

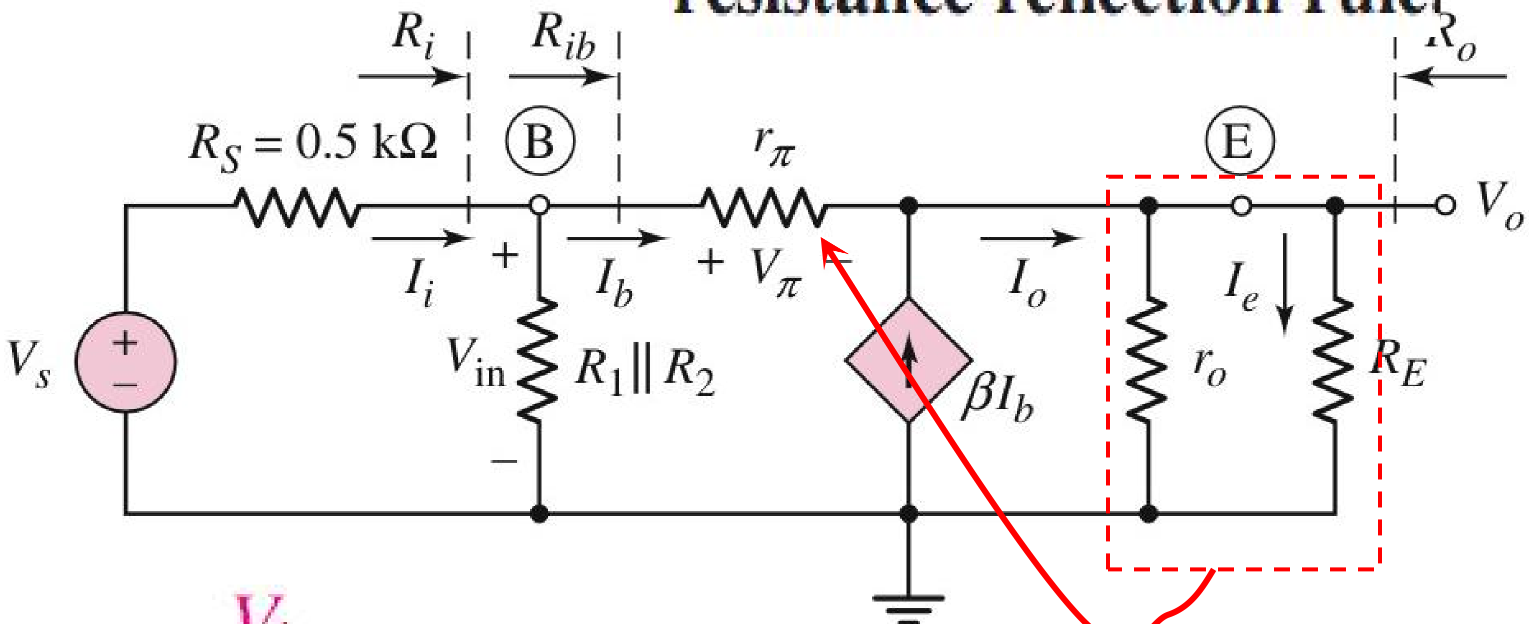
$$A_v = \frac{V_O}{V_i} = \frac{(1+\beta)(r_o \| R_E)}{r_\pi + (1+\beta)(r_o \| R_E)} < 1$$

$$(1+\beta)(r_o \| R_E) \gg r_\pi$$

$$A_v = 1$$ **Follower**

6.6.2 Input and output impedance

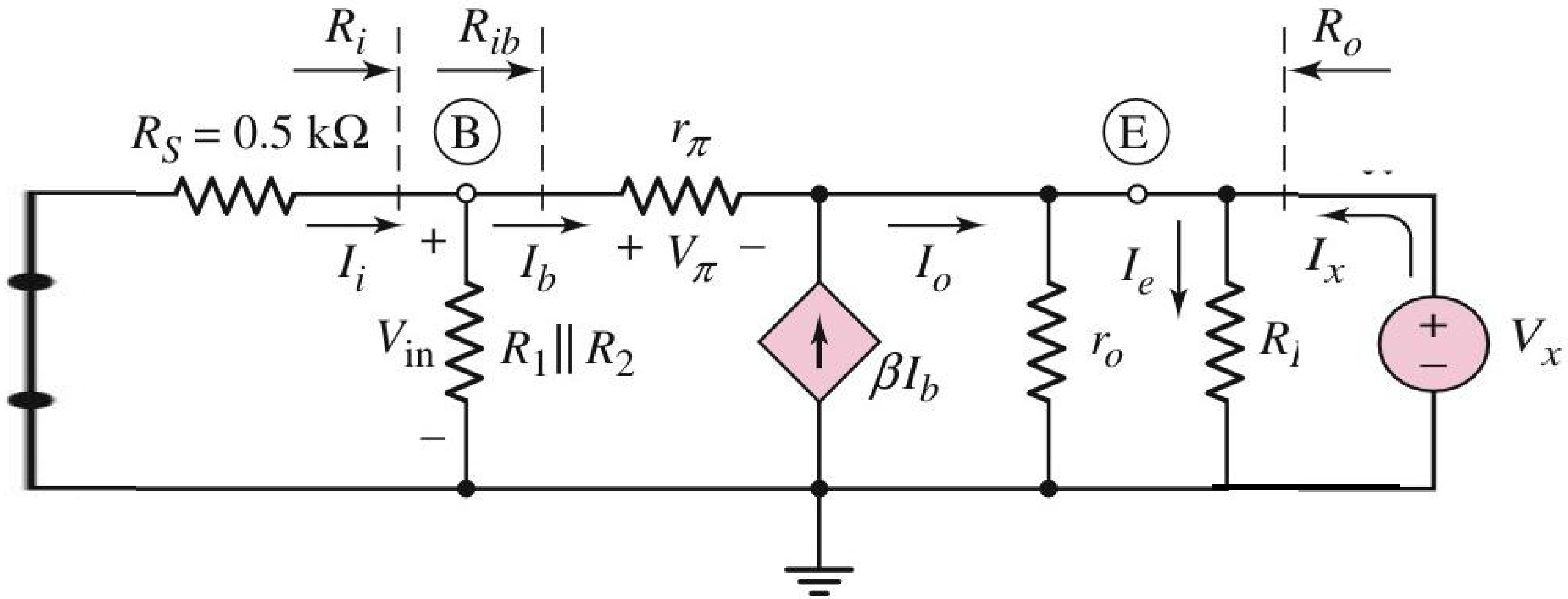
resistance reflection rule.



$$R_{ib} = \frac{V_{in}}{I_b} = r_\pi + \underline{(1+\beta)(r_o \| R_E)}$$

$$R_i = R_1 \| R_2 \| R_{ib}$$

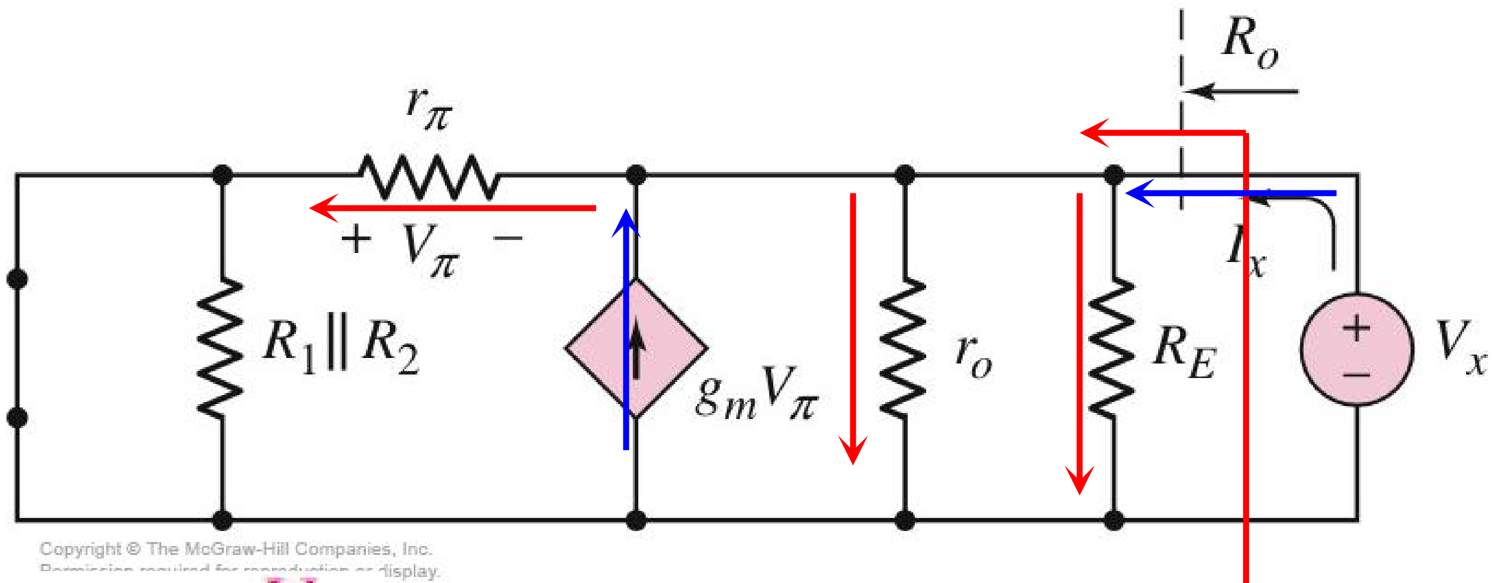
6.6.2 Input and output impedance



$$R_o = \frac{V_x}{I_x}$$

R_S =0

6.6.2 Input and output impedance



$$R_o = \frac{V_x}{I}$$

$$I_x + g_m V_\pi = \frac{V_x}{R_E} + \frac{V_x}{r_o} + \frac{V_x}{r_\pi}$$

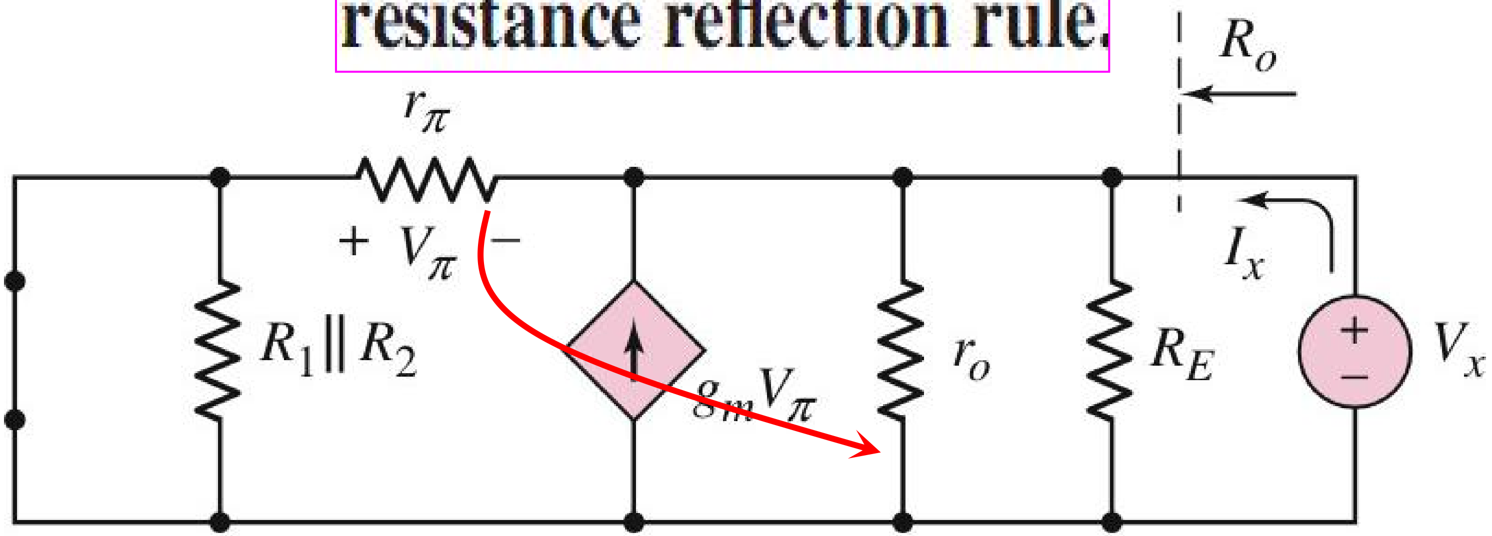
$$V_\pi = -V_x$$

$$\frac{I_x}{V_x} = \frac{1}{R_o} = g_m + \frac{1}{R_E} + \frac{1}{r_o} + \frac{1}{r_\pi}$$

$$R_o = \frac{1}{g_m} \| R_E \| r_o \| r_\pi$$

6.6.2 Input and output impedance

resistance reflection rule.



$$R_o = \frac{1}{g_m} \| R_E \| r_o \| r_\pi$$

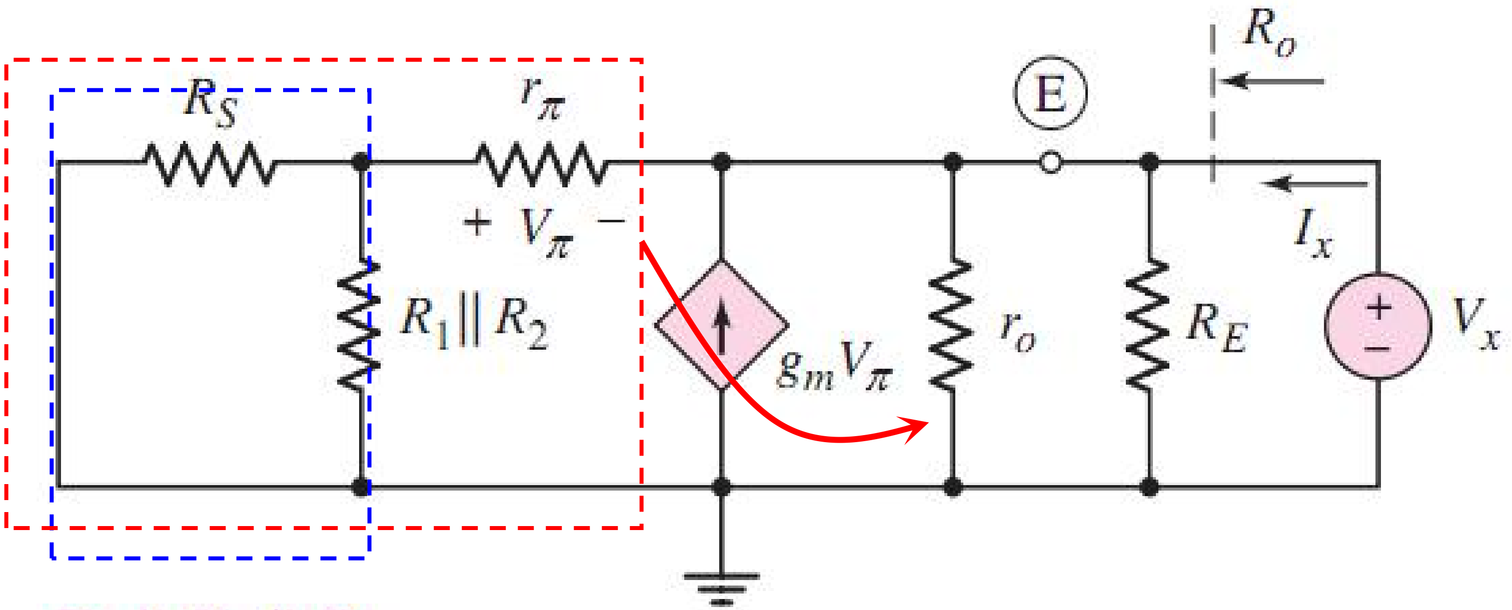
$$\boxed{R_o = \frac{r_\pi}{1+\beta} \| R_E \| r_o}$$

$$\frac{1}{R_o} = \left(g_m + \frac{1}{r_\pi}\right) + \frac{1}{R_E} + \frac{1}{r_o} = \left(\frac{1+\beta}{r_\pi}\right) + \frac{1}{R_E} + \frac{1}{r_o}$$

6.6.2 Input and output impedance

$R_S \neq 0$

resistance reflection rule.



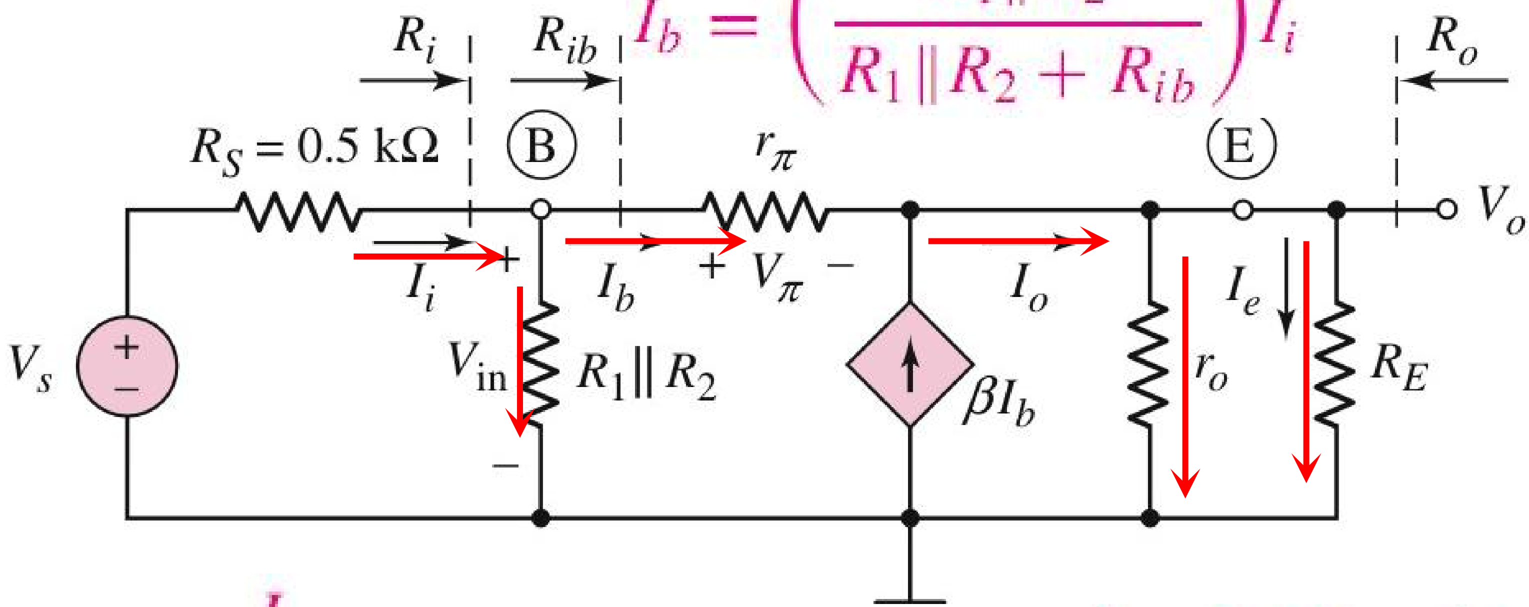
$R_1 || R_2 || R_S$

$r_\pi + R_1 || R_2 || R_S$

$$R_o = \left(\frac{r_\pi + R_1 || R_2 || R_S}{1 + \beta} \right) || R_E || r_o$$

6.6.3 Small Signal Current Gain

$$I_b = \left(\frac{R_1 \| R_2}{R_1 \| R_2 + R_{ib}}\right) I_i$$

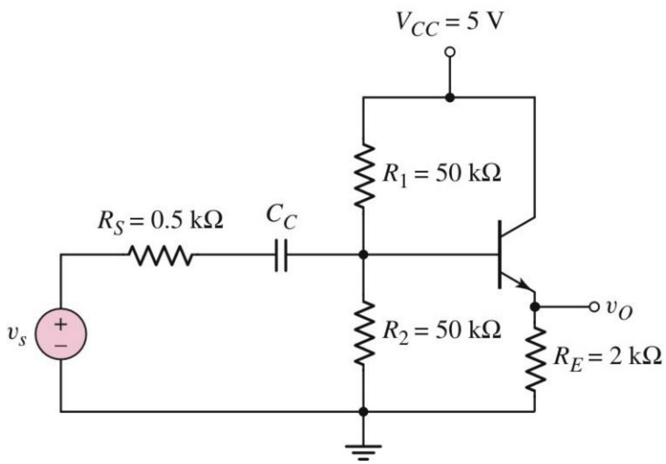


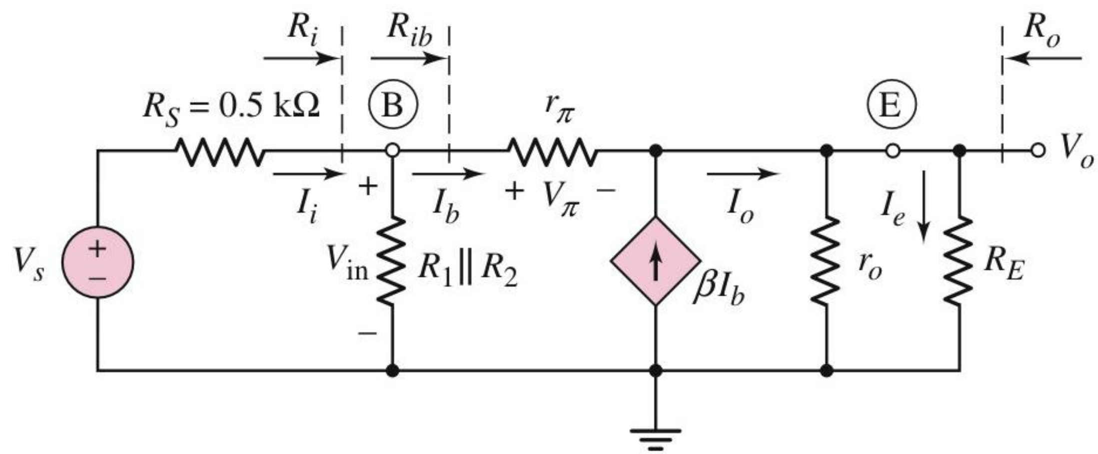
$$A_i = \frac{I_e}{I_i} \qquad I_o = (1+\beta) I_b = (1+\beta)\left(\frac{R_1 \| R_2}{R_1 \| R_2 + R_{ib}}\right) I_i$$

$$I_e = \left(\frac{r_o}{r_o + R_E}\right) I_o \qquad A_i = \frac{I_e}{I_i} = (1+\beta)\left(\frac{R_1 \| R_2}{R_1 \| R_2 + R_{ib}}\right)\left(\frac{r_o}{r_o + R_E}\right)$$

$\boxed{R_1 \| R_2 \gg R_{ib}}$ and $\boxed{r_o \gg R_E}$ $\qquad \boxed{A_i \cong (1+\beta)}$

6.6 Common-Collector (Emitter-Follower) Amplifier





Small signal voltage gain

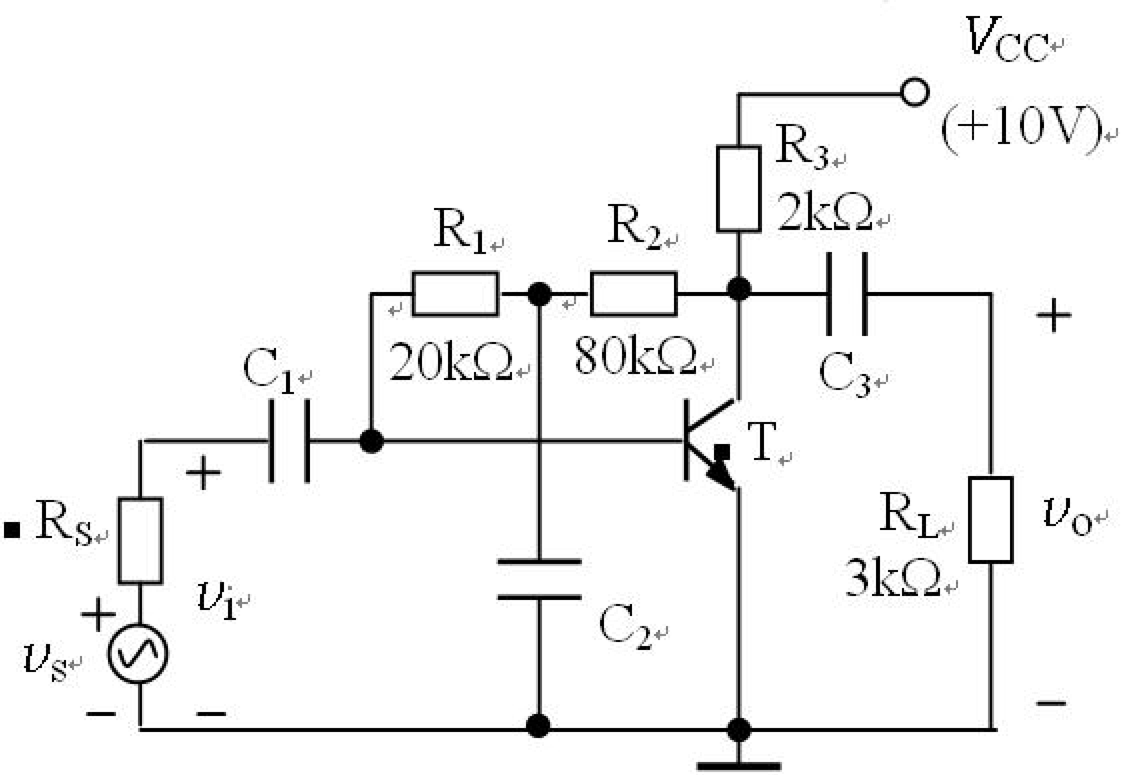
$$A_v = \frac{V_O}{V_i} = \frac{(1+\beta)(r_o \| R_E)}{r_\pi + (1+\beta)(r_o \| R_E)}$$

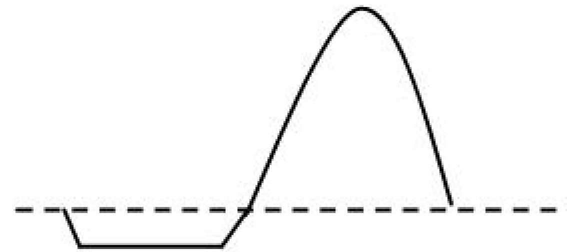
Input impedance

$$R_i = R_1 \| R_2 \| [r_\pi + (1+\beta)(r_o \| R_E)]$$

Output impedance

$$R_o = \left(\frac{r_\pi + R_1 \| R_2 \| R_S}{1+\beta}\right) \| R_E \| r_o$$





1、Calculate（I_B、I_C、V_{CE}）；

2、Sketch the small signal equivalent circuit;

3、Find R_i and R_o ;

4、Find $A_v = V_o / V_i$;

5、 R_S=200Ω， Find $A_{vs} = V_o / V_s$;

6、The output voltage is shown as figure, which distortion?

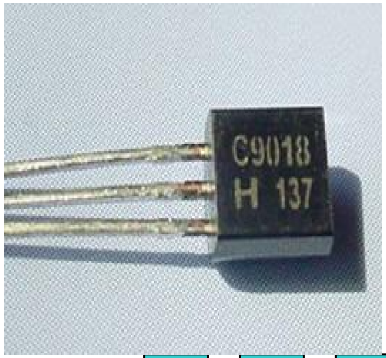
Huazhong University of Science and Technology
The Department of Electronics and Information Engineering

Electronic Circuit Analysis and Design

Dr. Tianping Deng

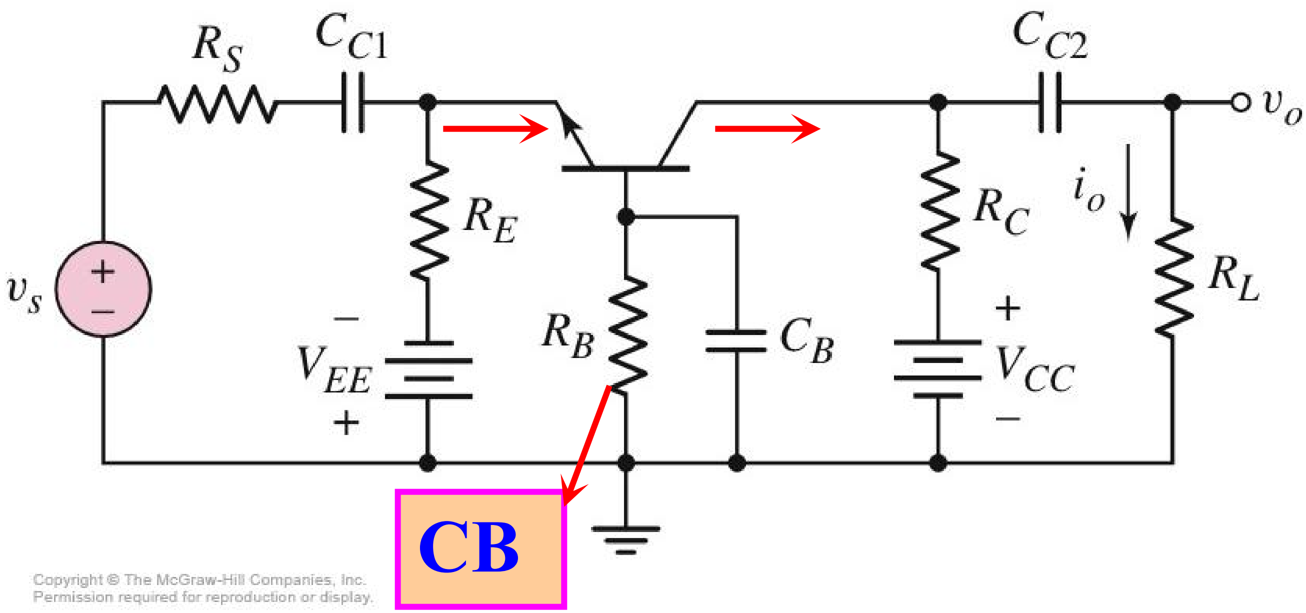
Email: dengtp@hust.edu.cn

Ch6. Basic BJT Amplifiers



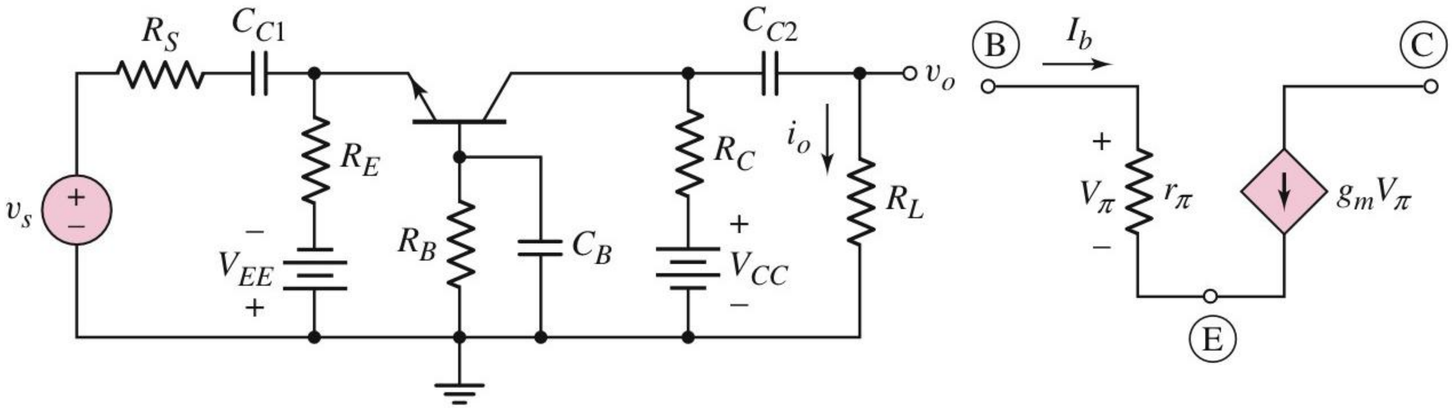
6.7 Common-Base Amplifier

6.7.1Small Signal Voltage and Current Gains

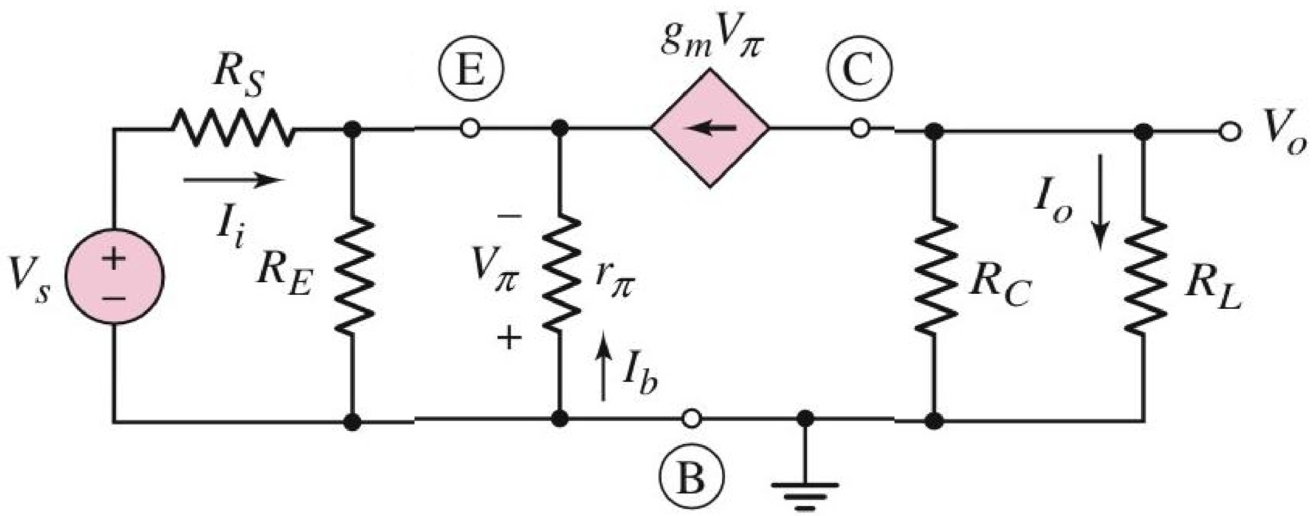


6.7 Common-Base Amplifier

6.7.1Small Signal Voltage and Current Gains

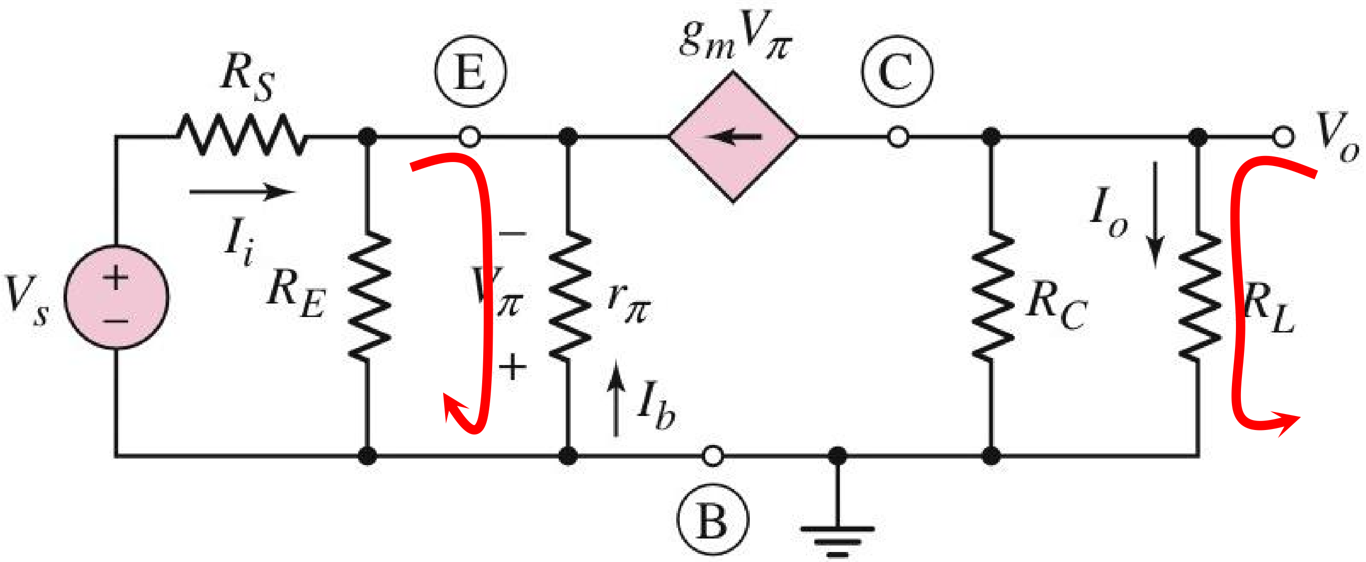


Small-signal equivalent circuit



6.7 Common-Base Amplifier

6.7.1 Small Signal Voltage and Current Gains



Input loop $\quad V_{\text{in}} = -I_{\text{b}} r_{\pi}$

Output loop $\quad V_{\text{o}} = -I_{\text{c}} R'_{\text{L}} = -\beta I_{\text{b}} R'_{\text{L}} \quad R'_{\text{L}} = R_{\text{c}} // R_{\text{L}}$

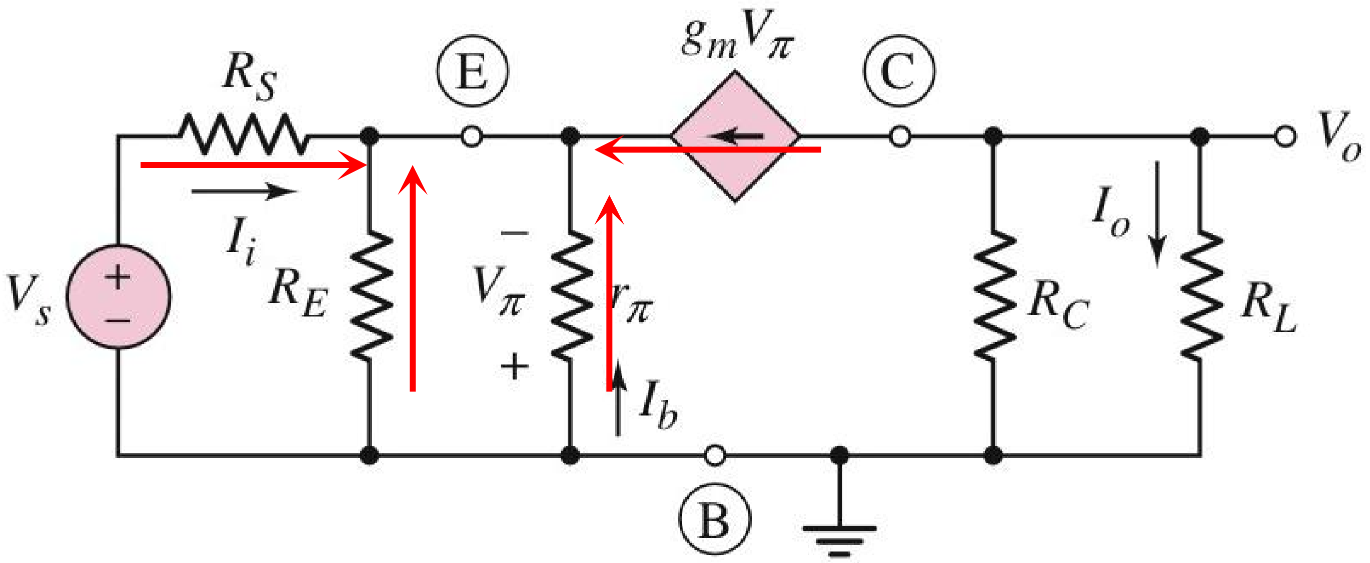
Voltage gain

$$A_v = \frac{V_{\text{o}}}{V_{\text{in}}} = \frac{-\beta I_{\text{b}} R'_{\text{L}}}{-I_{\text{b}} r_{\pi}} = \frac{\beta R'_{\text{L}}}{r_{\pi}}$$

$$A_{vs} = \frac{V_{\text{o}}}{V_{\text{S}}} = ?$$

6.7 Common-Base Amplifier

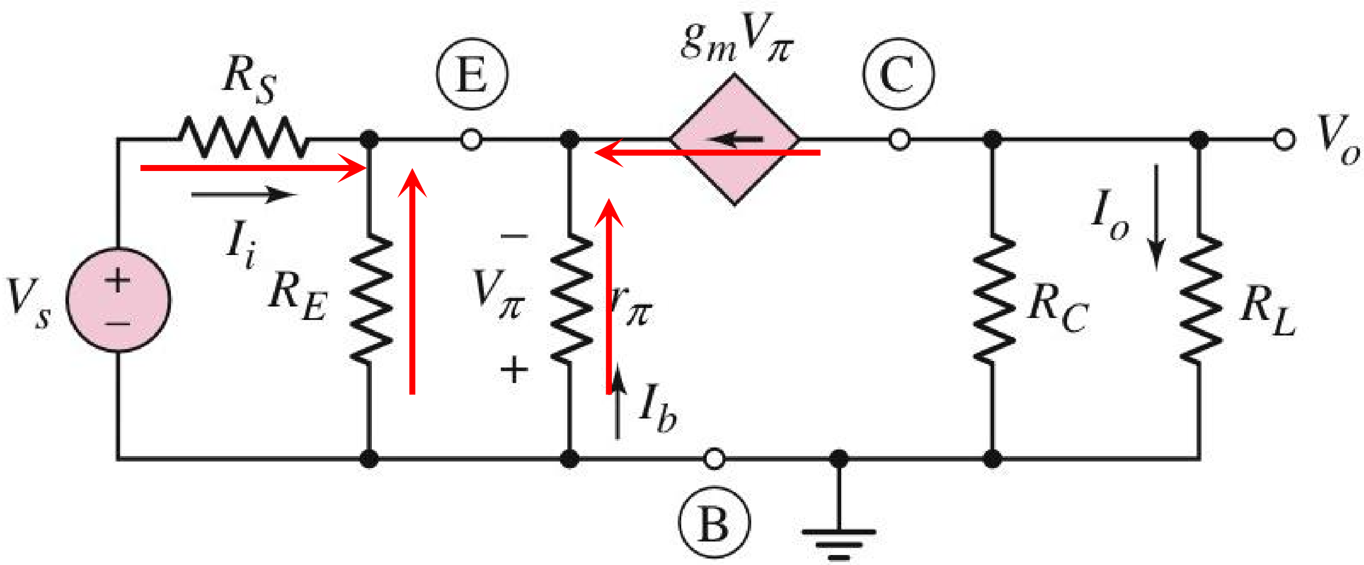
6.7.1Small Signal Voltage and Current Gains



$$g_m V_\pi + \frac{V_\pi}{r_\pi} + \frac{V_\pi}{R_E} + \frac{V_s - (-V_\pi)}{R_S} = 0$$

$$V_\pi \left(\frac{1+\beta}{r_\pi} + \frac{1}{R_E} + \frac{1}{R_S} \right) = -\frac{V_s}{R_S}$$

6.7.1 Small Signal Voltage and Current Gains



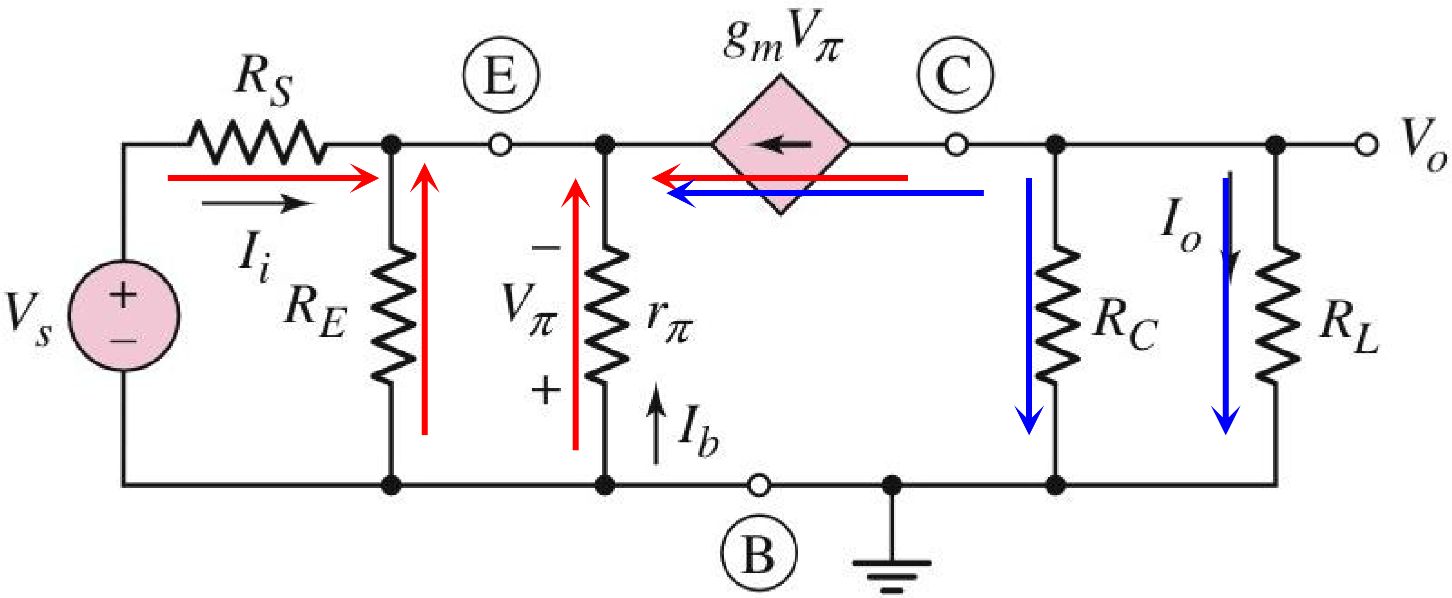
$$A_v = \frac{V_o}{V_{in}} = \frac{\beta\left(R_C // R_L\right)}{r_\pi} = g_m\left(R_C // R_L\right)$$

$$V_\pi = -\frac{V_s}{R_S}\left[\left(\frac{r_\pi}{1+\beta}\right) \| R_E \| R_S\right]$$

$$A_v = \frac{V_o}{V_s} = +g_m\left(\frac{R_C \| R_L}{R_S}\right)\left[\left(\frac{r_\pi}{1+\beta}\right) \| R_E \| R_S\right]$$

6.7 Common-Base Amplifier

6.7.1Small Signal Voltage and Current Gains



$$I_i + \frac{V_\pi}{r_\pi} + g_m V_\pi + \frac{V_\pi}{R_E} = 0 \Rightarrow V_\pi = -I_i \left[\left(\frac{r_\pi}{1+\beta} \right) \Big\| R_E \right]$$

$$I_o = -(g_m V_\pi) \left(\frac{R_C}{R_C + R_L} \right)$$

$R_E \to \infty$

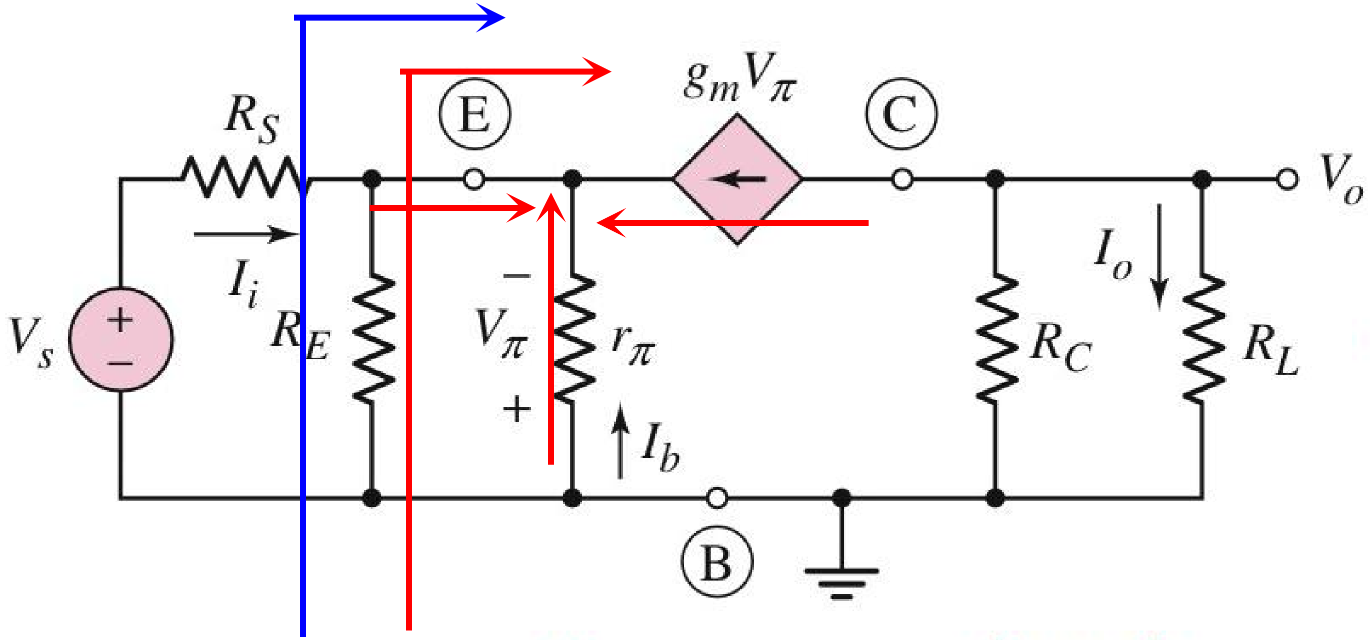
$R_L \to 0$

$$A_i = \frac{I_o}{I_i} = g_m \cancel{\left(\frac{R_C}{R_C + R_L} \right)} \left[\left(\frac{r_\pi}{1+\beta} \right) \Big\| \cancel{R_E} \right]$$

$$A_{io} = \frac{g_m r_\pi}{1+\beta} = \frac{\beta}{1+\beta} = \alpha$$

6.7 Common-Base Amplifier

6.7.2 Input and output impedance



$$R_{ie} = \frac{V_\pi}{I_i}$$

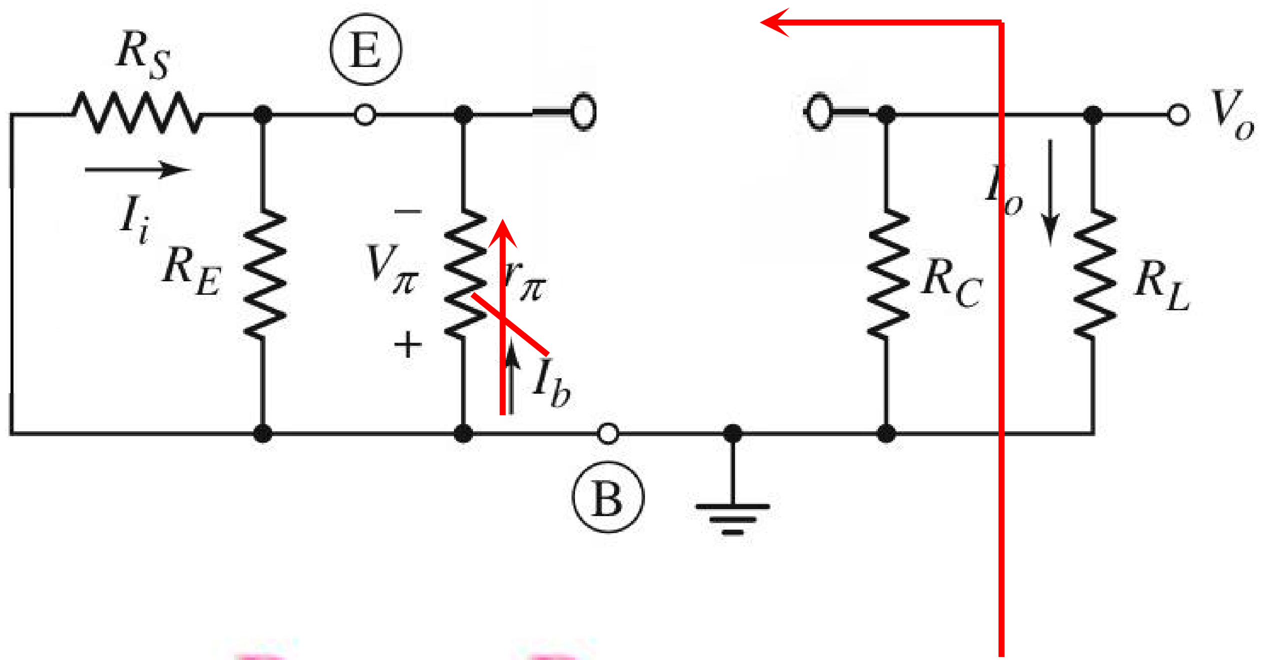
$$I_i = I_b + g_m V_\pi = \frac{V_\pi}{r_\pi} + g_m V_\pi = V_\pi\left(\frac{1+\beta}{r_\pi}\right)$$

$$R_{ie} = \frac{V_\pi}{I_i} = \frac{r_\pi}{1+\beta} \equiv r_e$$

$$\boxed{R_i = R_E \,//\, R_{ie} = R_E \,//\, \frac{r_\pi}{1+\beta}}$$

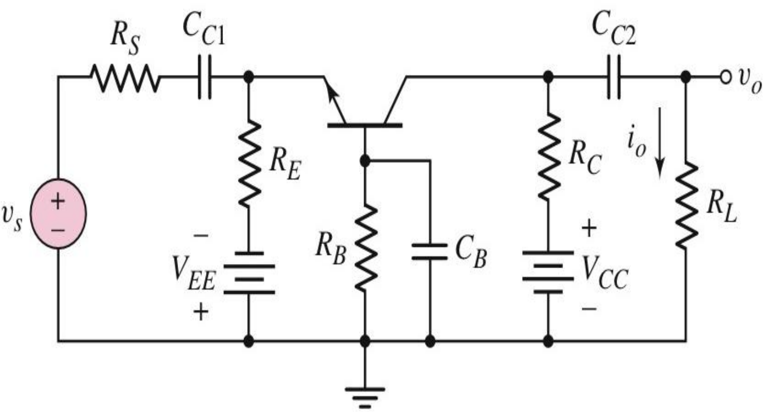
6.7 Common-Base Amplifier

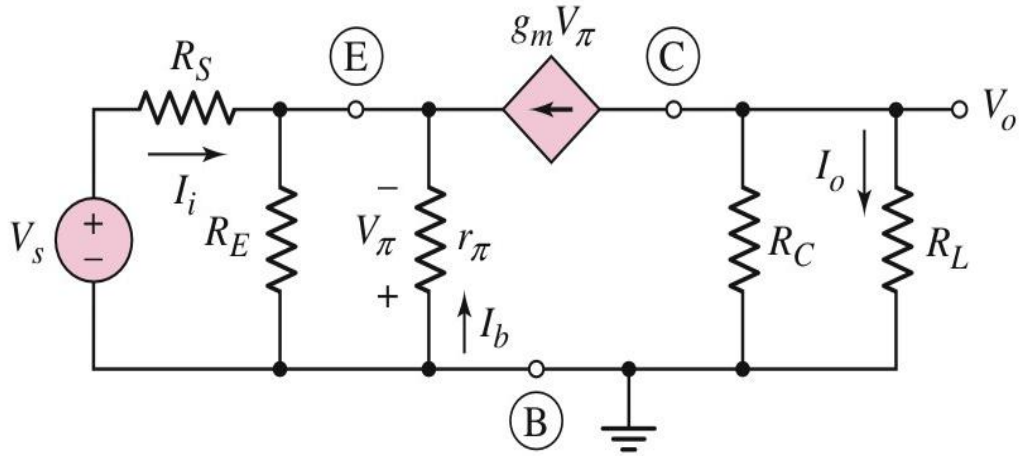
6.7.2 Input and output impedance



$$R_o = R_C$$

6.7 Common-Base Amplifier





Small Signal Voltage Gain

$$A_v = \frac{V_o}{V_\pi} = \frac{\beta R'_L}{r_\pi}$$

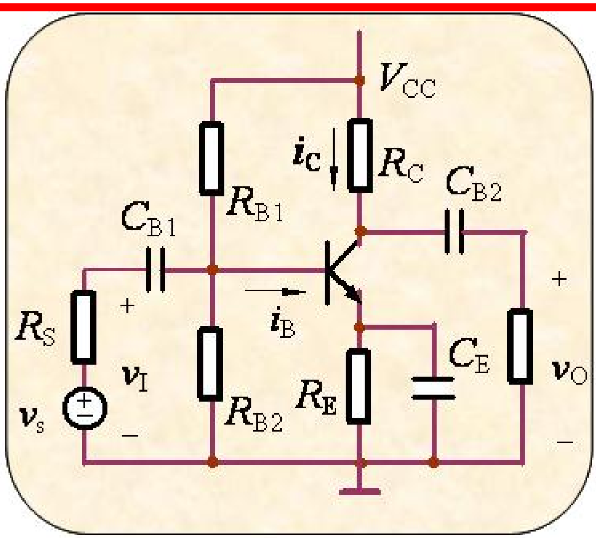
Input impedance

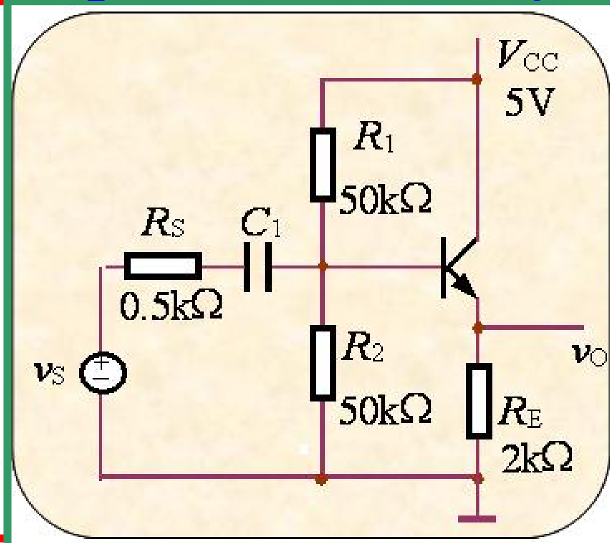
$$R_i = R_E // R_{ie} = R_E // \frac{r_\pi}{1+\beta}$$

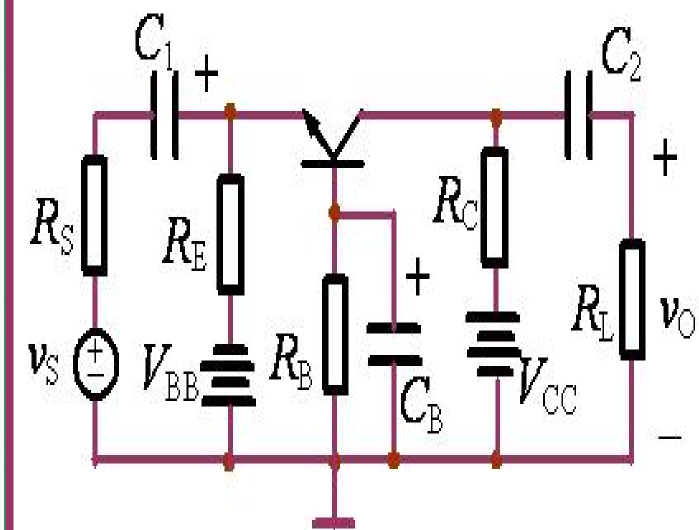
Output impedance

$$R_o = R_C$$

6.8 The Three Basic Amplifier: Summary and Comparison







$$A_V = -\frac{\beta\cdot(R_C//R_L)}{r_\pi}$$

$$\frac{(1+\beta)(R_E//r_o)}{r_\pi+(1+\beta)(R_E//r_o)}$$

$$\frac{\beta\cdot(R_C//R_L)}{r_\pi}$$

$$R_i = R_{B1}//R_{B2}//r_\pi$$

$$R_1//R_2//[r_\pi+(1+\beta)(R_E//r_o)]$$

Large

$$R_E//\frac{r_\pi}{1+\beta}$$

Small

$$R_o \approx R_C$$

$$R_E//\frac{R_S'+r_\pi}{1+\beta}$$

Small

$$R_o \approx R_C$$

6.8 The Three Basic Amplifier: Summary and Comparison

Summary of Single Stage BJT Amplifiers

	C-E (R_E=0)	Emitter Degenerated C-E	C-C	C-B
Terminal Voltage Gain	Inverting & large	Inverting & moderate	1	Non-inverting & Large
Terminal Current Gain	Inverting & large	Inverting & large	Non-inverting & Large	1
Input Resistance	Moderate	Large	Large	Low
Output Resistance	Moderate	Moderate	Low	Moderate

1、The basic BJT amplifiers has:

(A) 、CE (B)、CC (C)、 CB

1） which has the lest input resistance (C)

2） which has the lest output resistance (B)

3）which can amplify the ac voltage (A C)

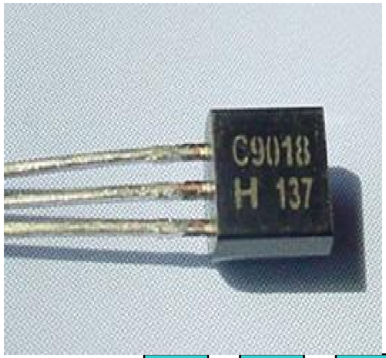
4） which can amplify the ac current (A B)

5）the input and the output has the same phase is (B、)C

6） the input and the output has the opposite phase is (A)

Contents

Ch6. Basic BJT Amplifiers



6.9 Multistage Amplifiers

(1) The Reason of Using Multistage Circuit

A single transistor amplifier will not be able to meet the combined specifications of a given amplification factor, input resistance, and output resistance.

(2) Cascade Configuration

3 circuits are connected in series, or cascaded. Each circuit can be CE, CC, or CB configuration

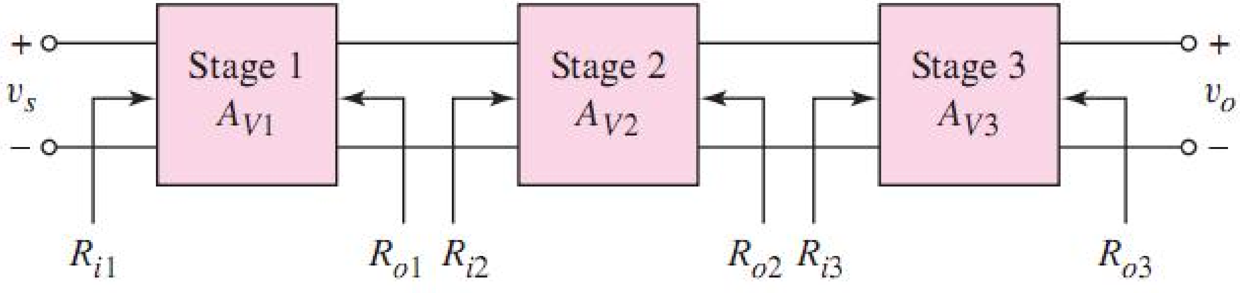


Figure 6.68 A generalized three-stage amplifier

6.9 Multistage Amplifiers

(3) Loading effect

E.g. R_{i2} is the load of stage 1.

$$R_{i2} = R_{L1} \qquad R_{o1} = R_{S2}$$

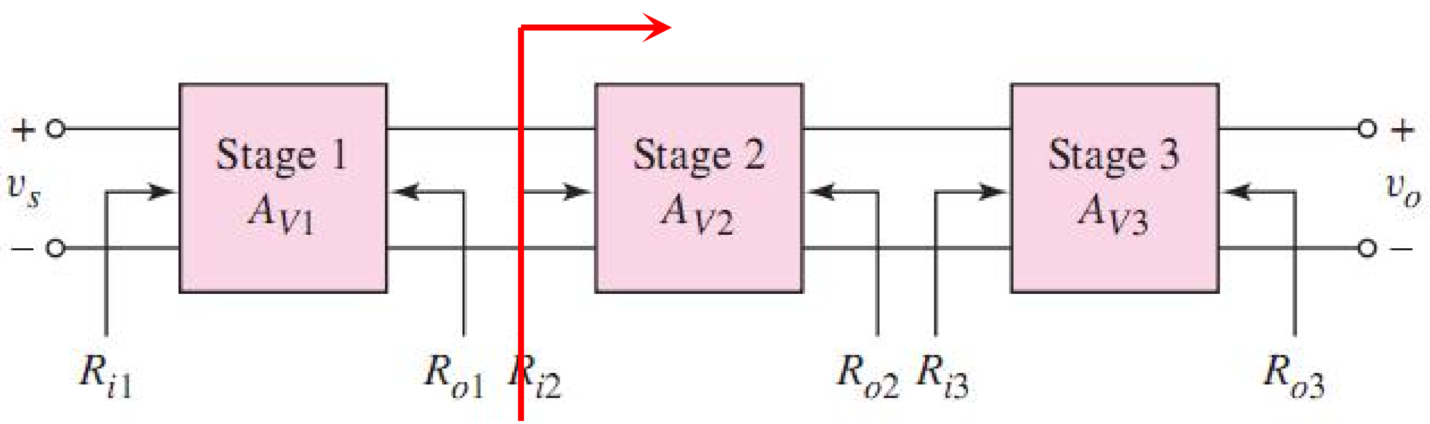
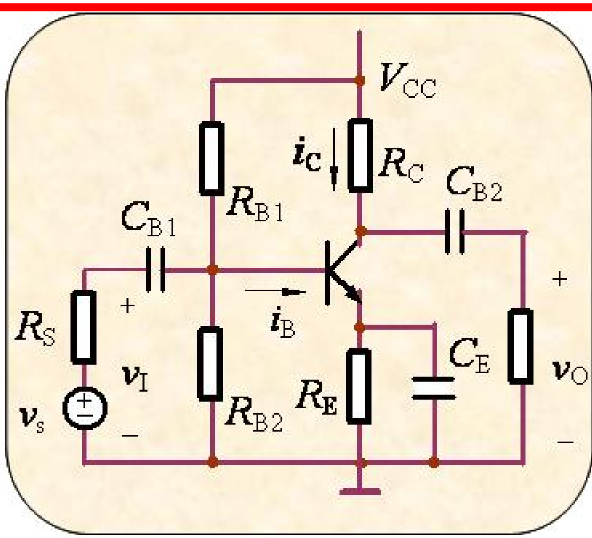
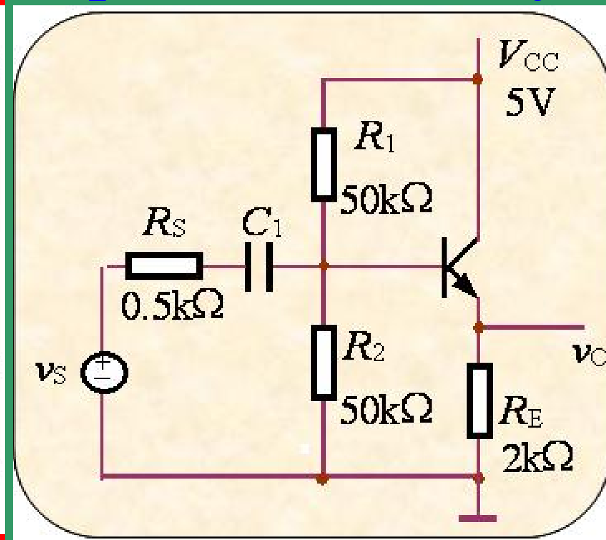
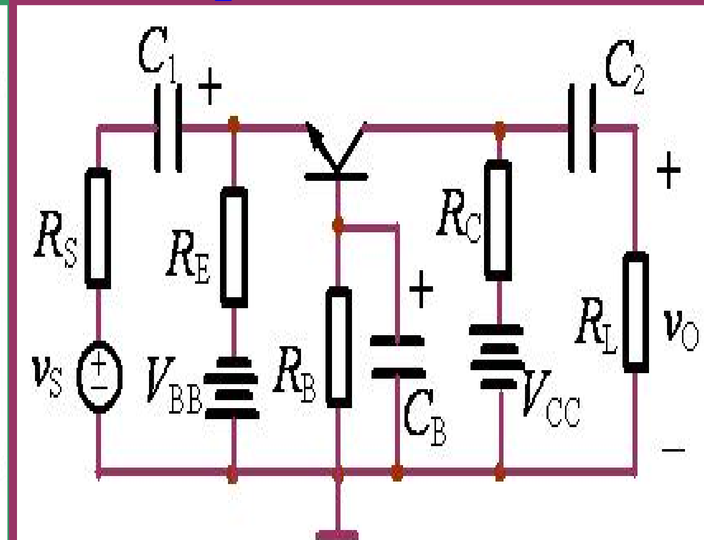


Figure 6.68 A generalized three-stage amplifier

6.8 The Three Basic Amplifier: Summary and Comparison







$$A_V = -\frac{\beta\cdot(R_C // R_L)}{r_\pi}$$

$$\frac{(1+\beta)(R_E // r_o)}{r_\pi + (1+\beta)(R_E // r_o)}$$

$$\frac{\beta\cdot(R_C // R_L)}{r_\pi}$$

$$R_i = R_{B1} // R_{B2} // r_\pi$$

$$R_1 // R_2 // [r_\pi + (1+\beta)(R_E // r_o)]$$

Large

$$R_E // \frac{r_\pi}{1+\beta}$$

Small

$$R_o \approx R_C$$

$$R_E // \frac{R'_S + r_\pi}{1+\beta}$$

Small

$$R_o \approx R_C$$

6.9 Multistage Amplifiers

6.9.1 Multistage Analysis: Cascade Configuration

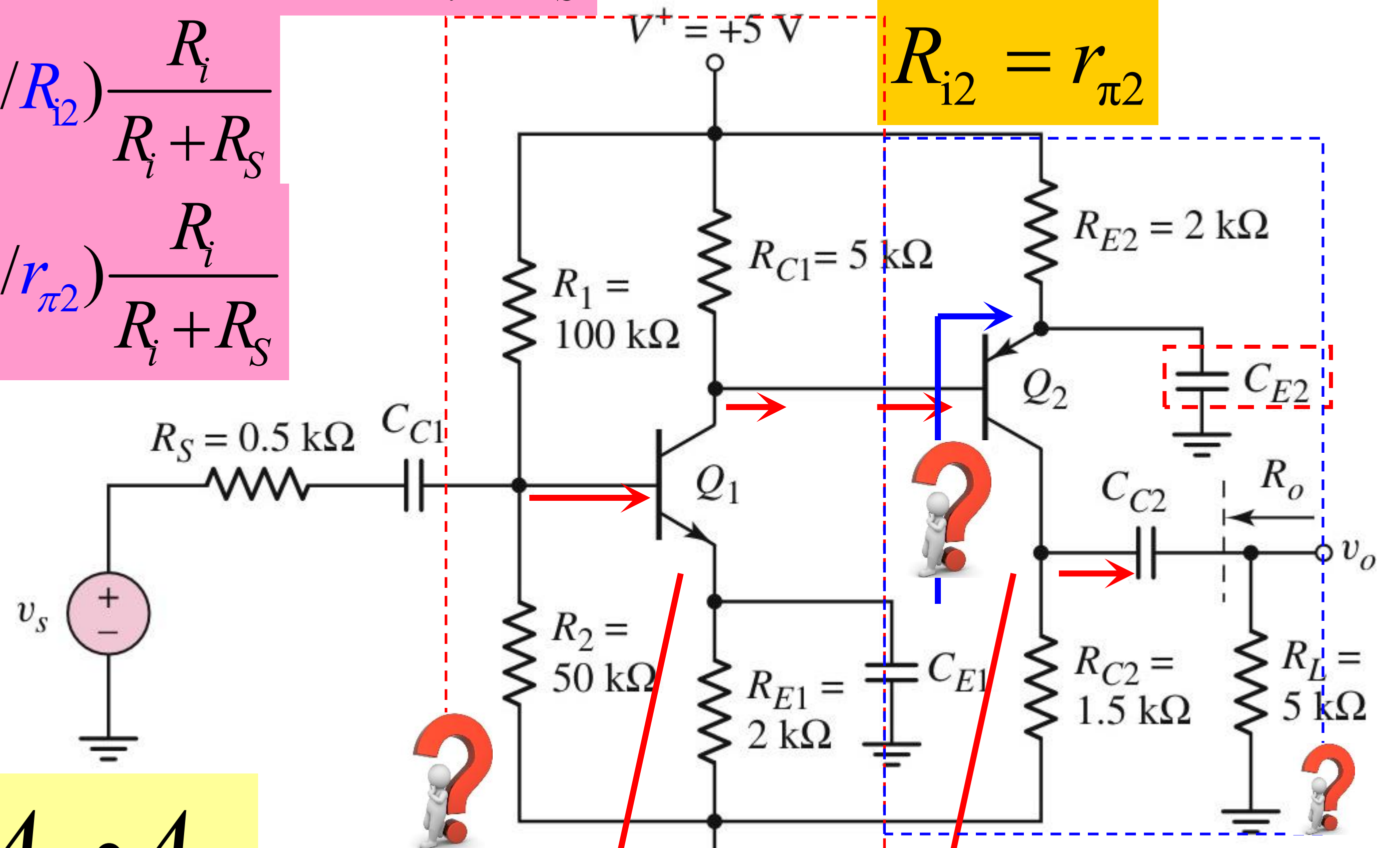
$$A_{V1S} = \frac{V_{O1}}{V_S} = -g_{m1}(R_C // R_{L1}) \frac{R_i}{R_i + R_S}$$

$$= -g_{m1}(R_{C1} // R_{i2}) \frac{R_i}{R_i + R_S}$$

$$= -g_{m1}(R_{C1} // r_{\pi 2}) \frac{R_i}{R_i + R_S}$$

$$A_{V2} = -g_{m2}(R_{C2} // R_L)$$

$$R_{i2} = r_{\pi 2}$$

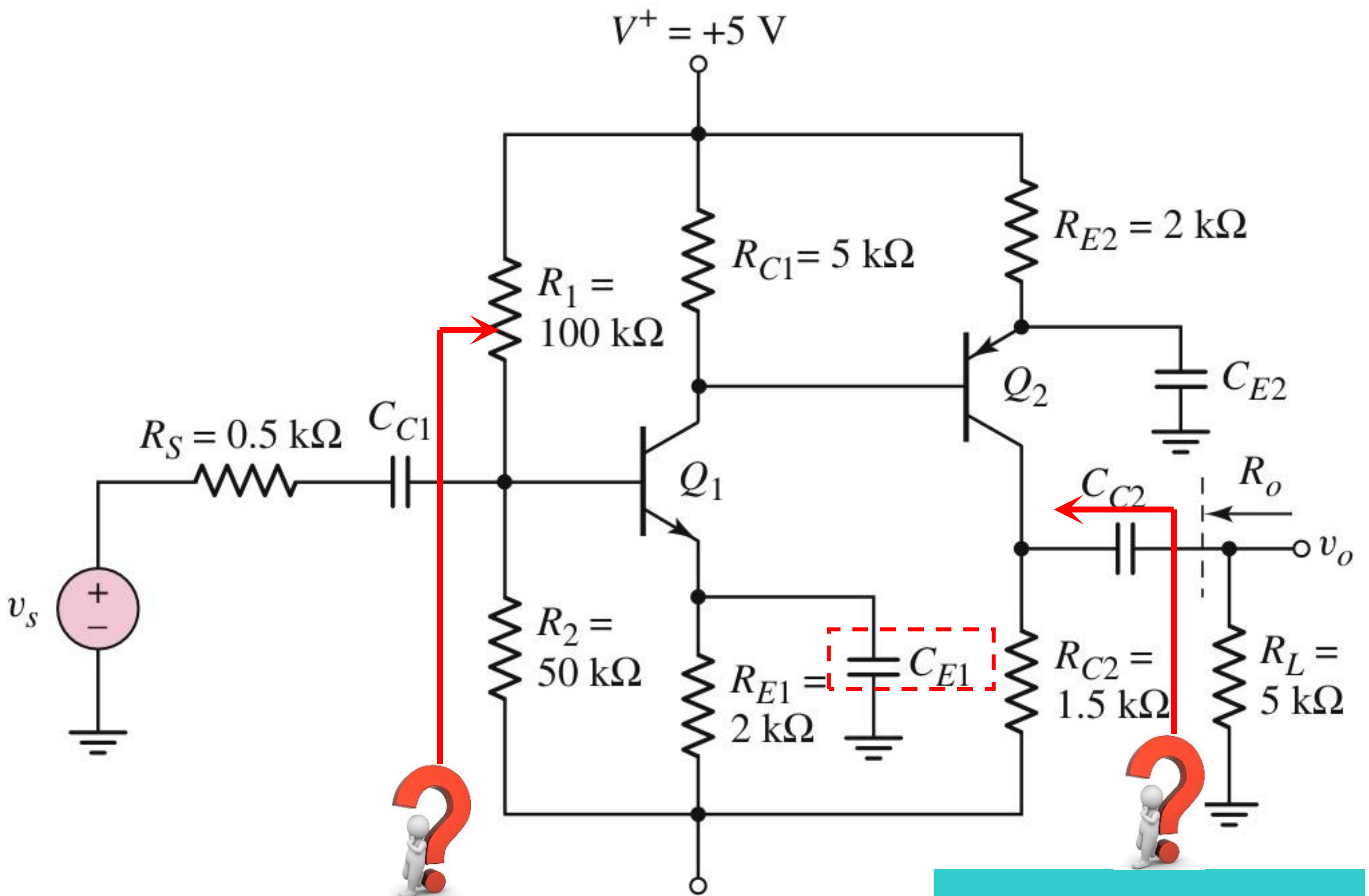


$$A_V = A_{V1} \bullet A_{V2}$$

$$A_v = \frac{V_o}{V_s} = g_{m1} g_{m2} (R_{C1} \| r_{\pi 2})(R_{C2} \| R_L) \left(\frac{R_i}{R_i + R_S} \right)$$

6.9 Multistage Amplifiers

6.9.1 Multistage Analysis: Cascade Configuration

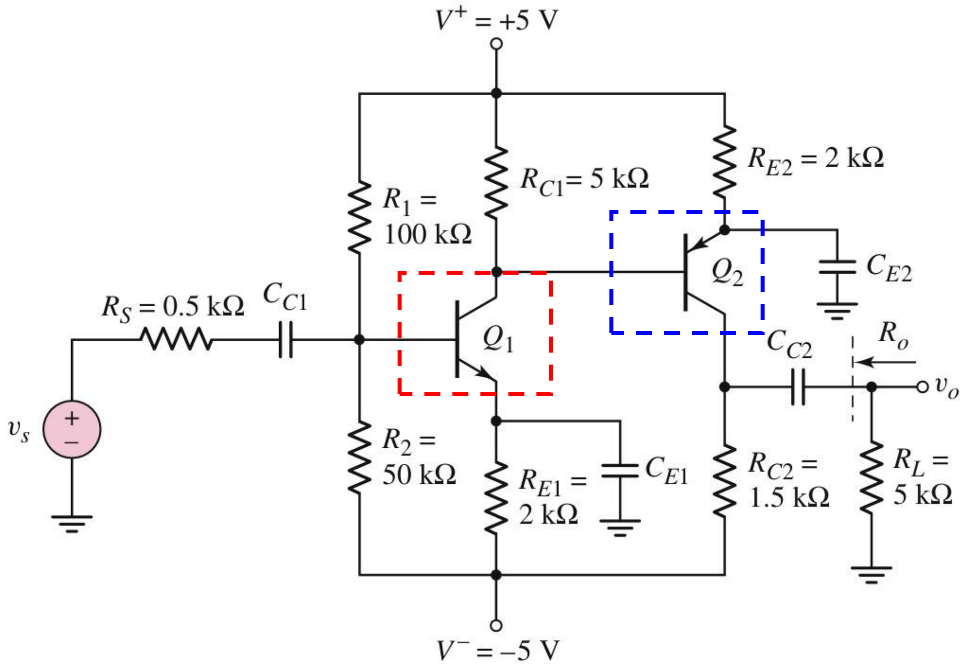


$$R_i = R_1 \| R_2 \| r_{\pi 1}$$

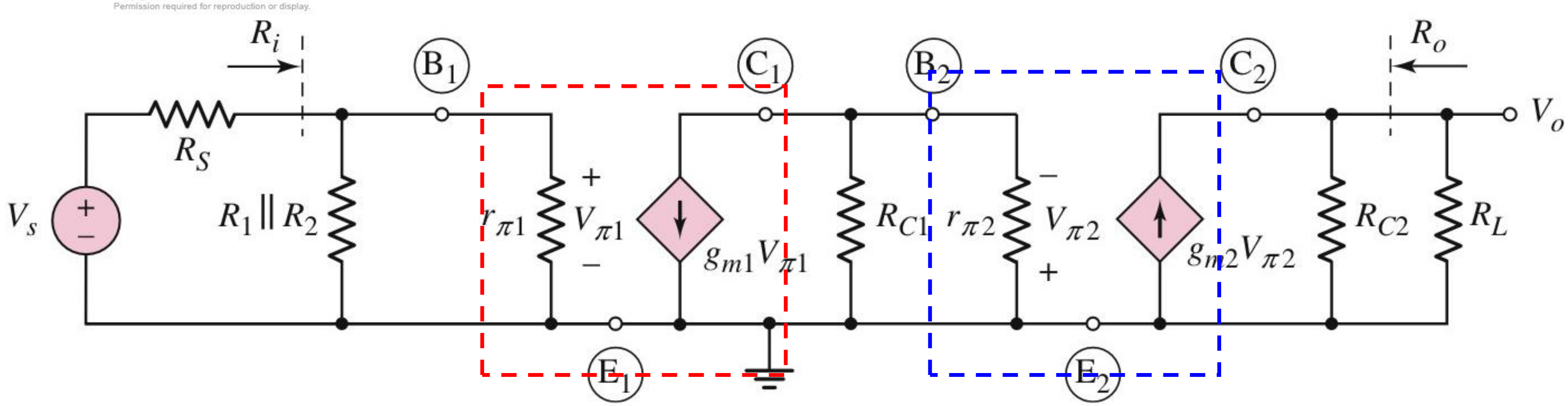
$$R_o = R_{c2}$$

6.9 Multistage Amplifiers

6.9.1 Multistage Analysis: Cascade Configuration

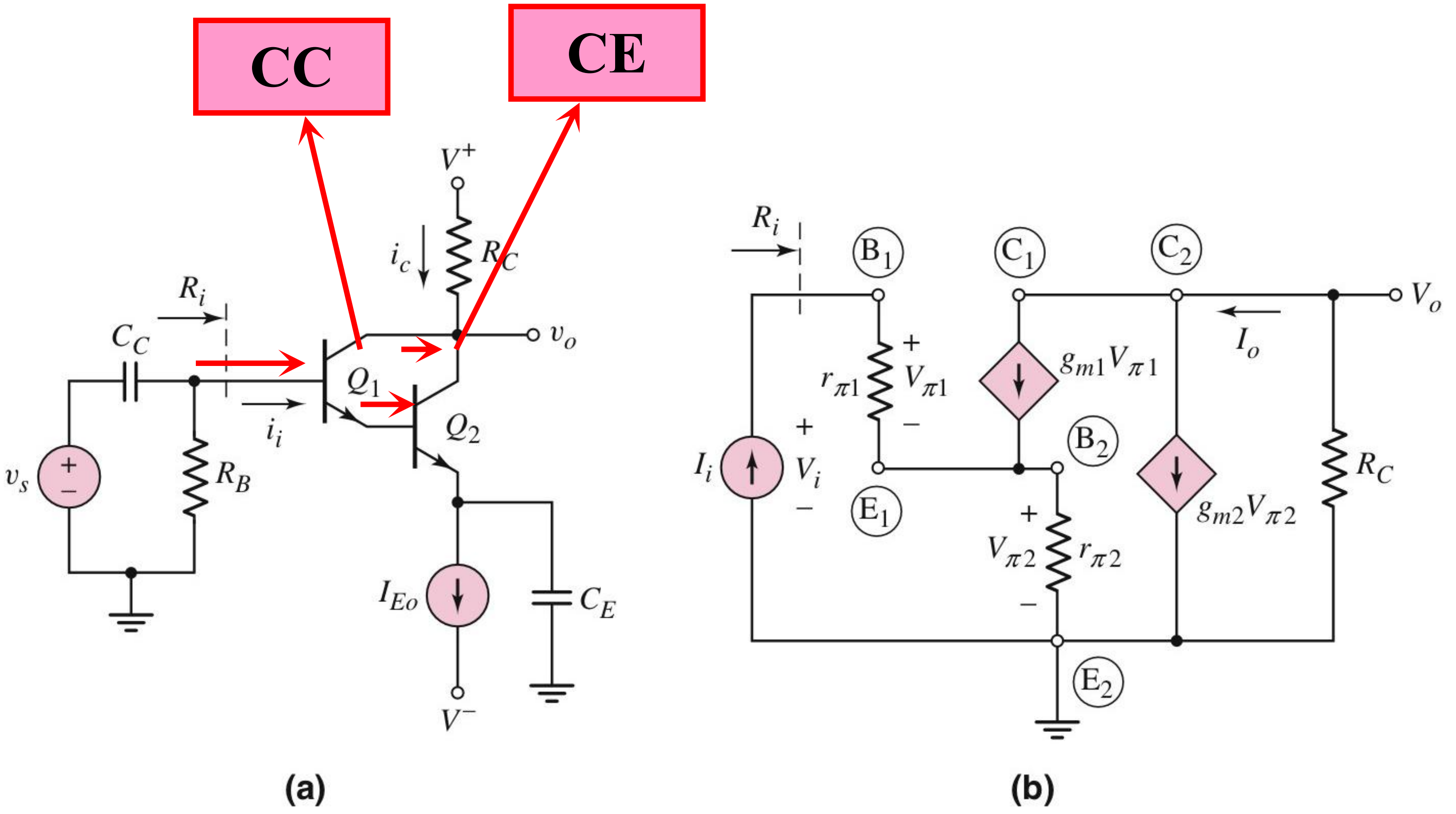


Sketch small-signal circuit



6.9 Multistage Amplifiers

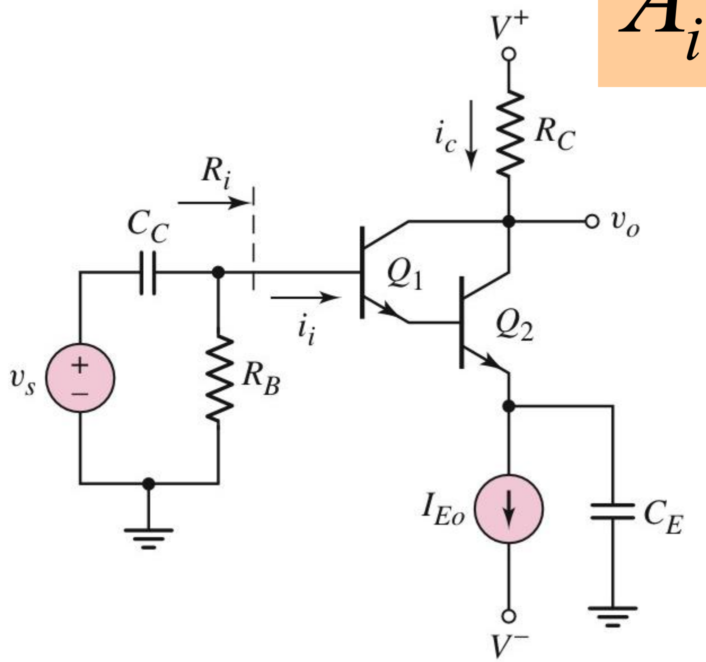
6.9.2 Multistage Circuit: Darlington Pair Configuration

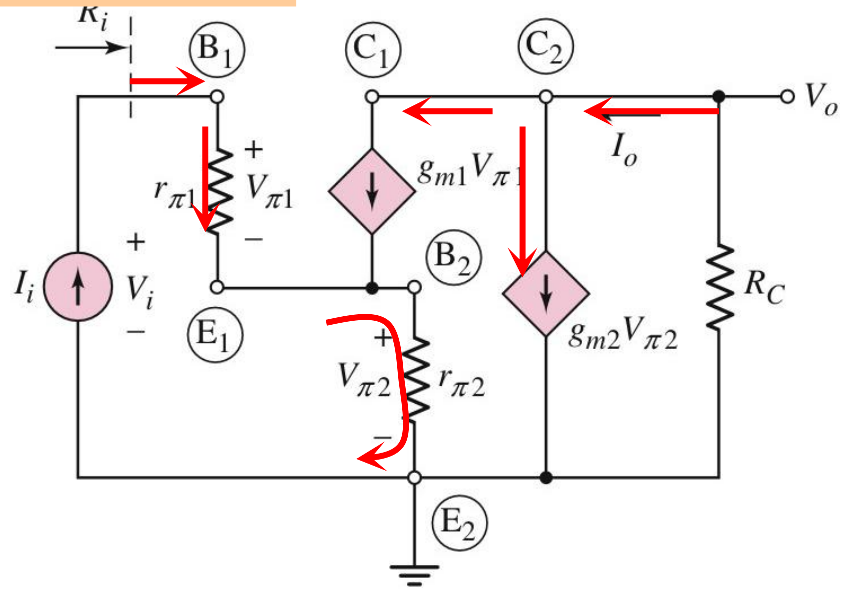


6.9 Multistage Amplifiers

6.9.2 Multistage Circuit: Darlington Pair Configuration

$$\boxed{A_i \cong \beta_1 \beta_2}$$





$$V_{\pi 1} = I_i r_{\pi 1}$$

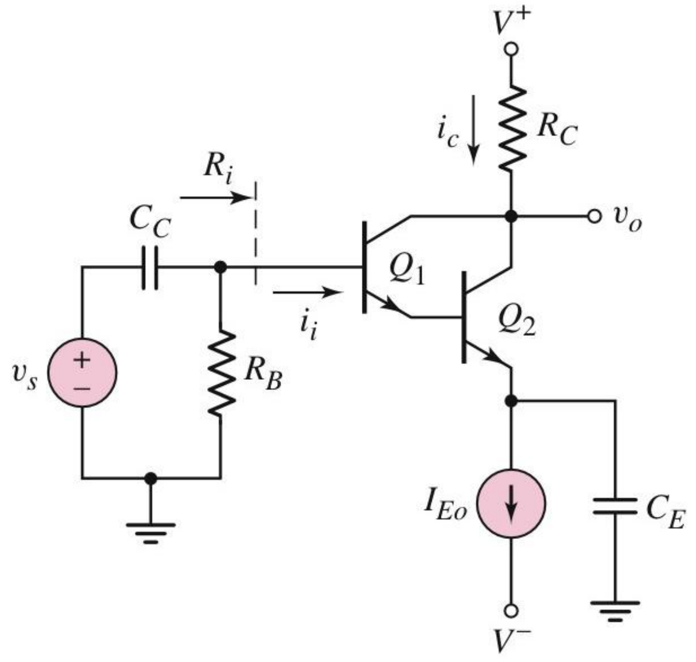
$$I_o = g_{m1}V_{\pi 1} + g_{m2}V_{\pi 2} = \beta_1 I_i + \beta_2(1+\beta_1)I_i$$

$$g_{m1}V_{\pi 1} = g_{m1}r_{\pi 1}I_i = \beta_1 I_i$$

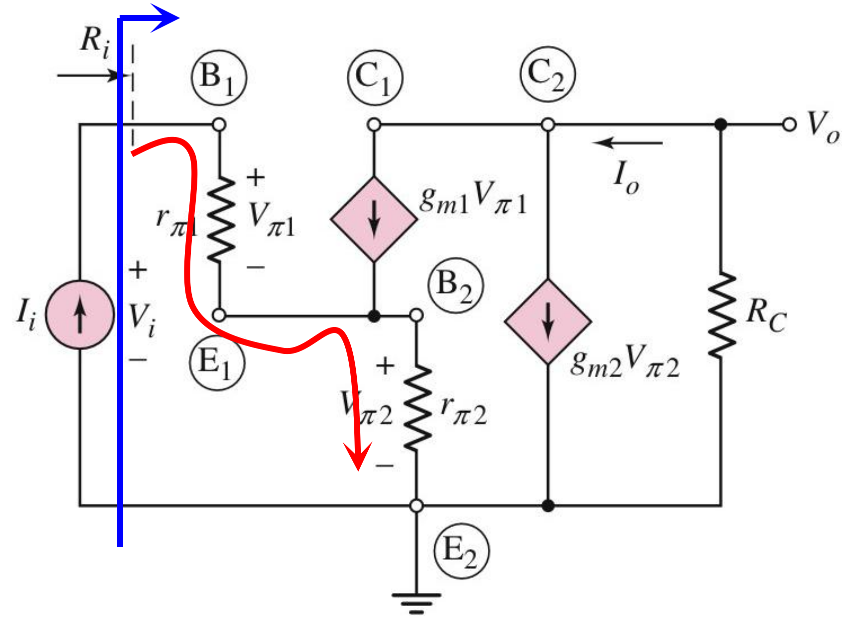
$$V_{\pi 2} = (I_i + \beta_1 I_i)r_{\pi 2} \qquad A_i = \frac{I_o}{I_i} = \beta_1 + \beta_2(1+\beta_1) \cong \beta_1\beta_2$$

6.9 Multistage Amplifiers

6.9.2 Multistage Circuit: Darlington Pair Configuration



(a)



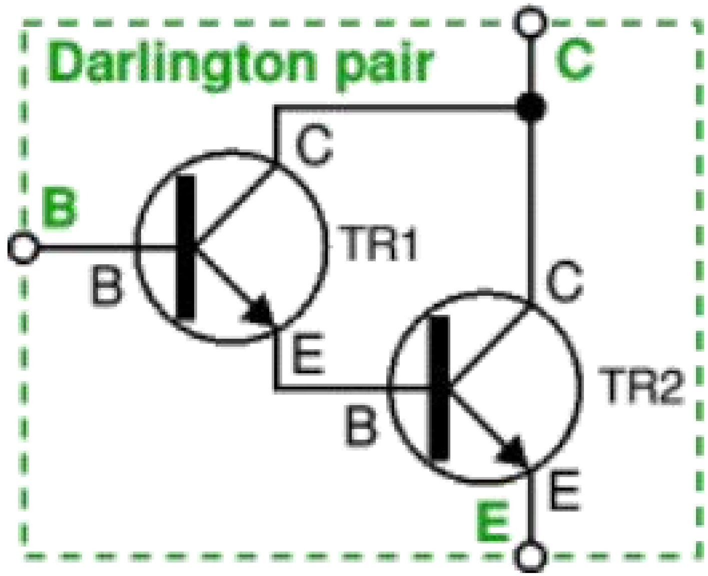
(b)

$$V_i = V_{\pi 1} + V_{\pi 2} = I_i r_{\pi 1} + I_i(1+\beta_1)r_{\pi 2}$$

$$R_i = r_{\pi 1} + (1+\beta_1)r_{\pi 2}$$

6.9 Multistage Amplifiers

6.9.2 Multistage Circuit: Darlington Pair Configuration

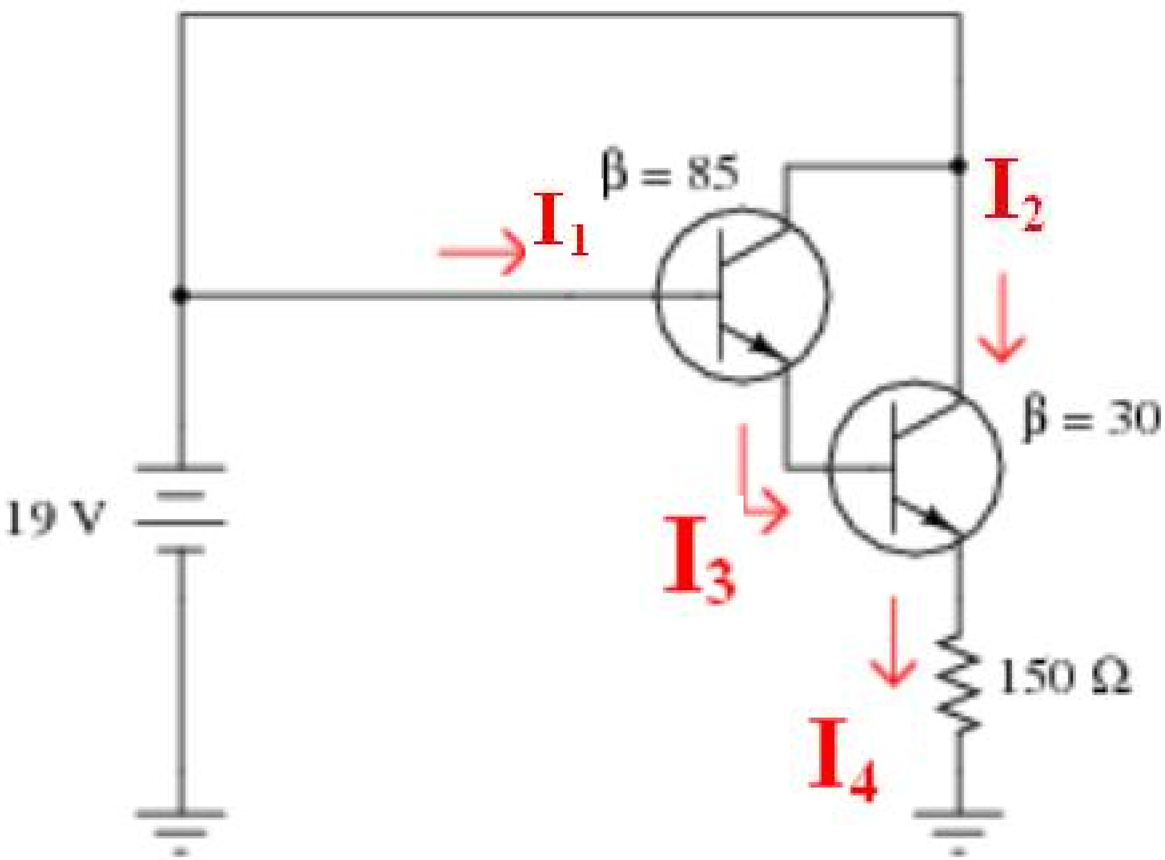


A Darlington pair behaves like a single transistor with a very high current gain

6.9 Multistage Amplifiers

6.9.2 Multistage Circuit: Darlington Pair Configuration

Calculate all labeled currents in this Darlington pair circuit, for all transistors, assuming V_{BE}=0.7 V



- $I_1 = 44.01\ \mu A$
- $I_2 = 113.5\ mA$
- $I_3 = 3.785\ mA$
- $I_4 = 117.3\ mA$

6.9.3 Multistage Circuit: Cascode Configuration

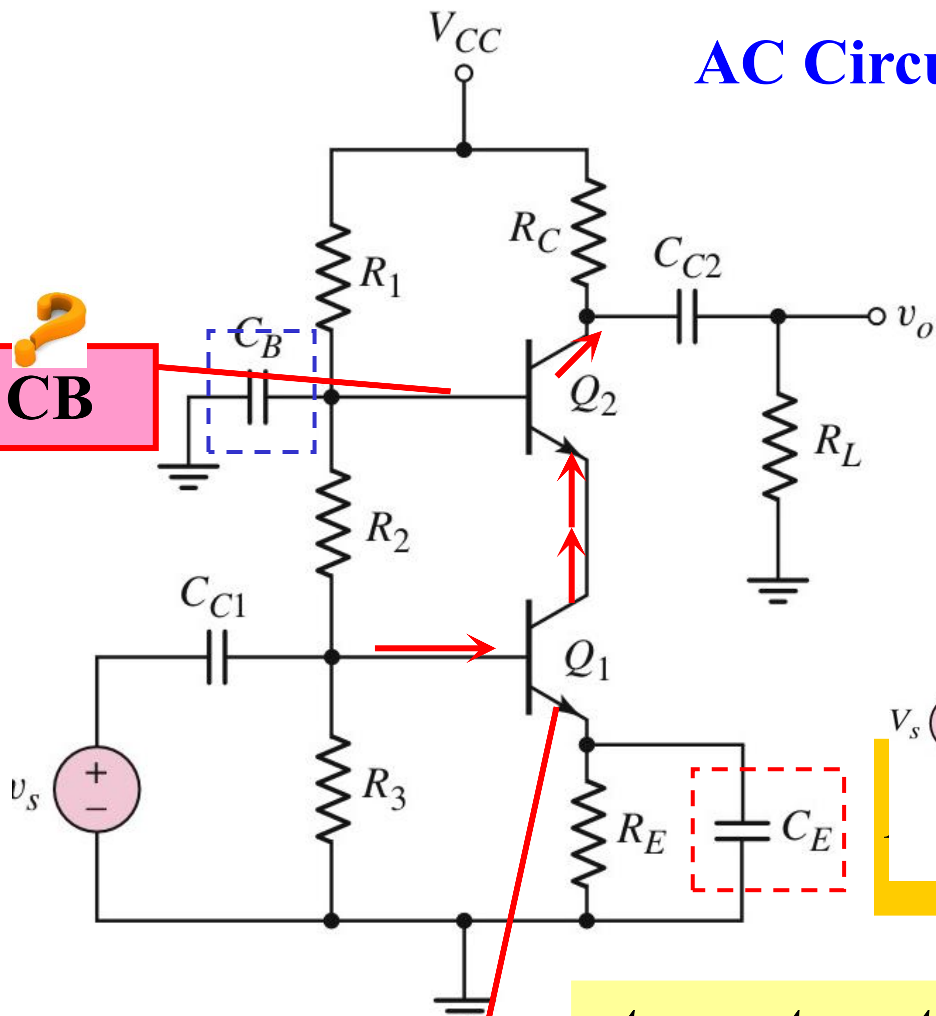
AC Circuit

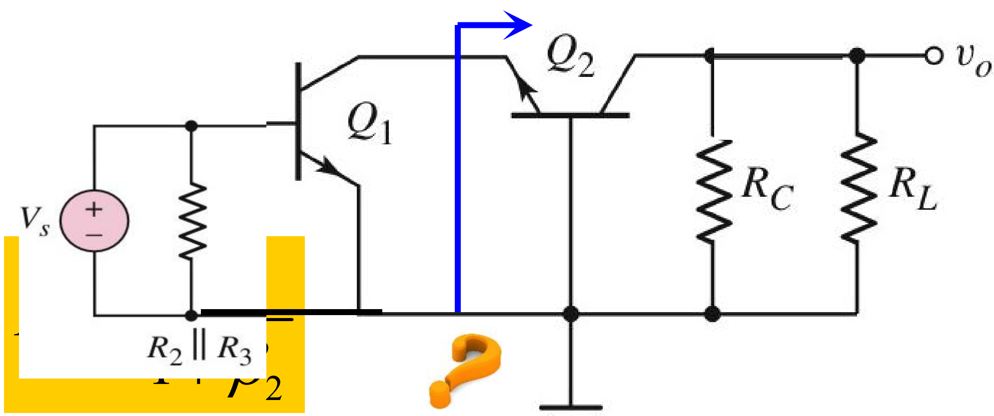
$$A_{V1}=\frac{V_{O1}}{V_I}=-g_{m1}(R_C//R_{L1})$$

$$=-g_{m1}R_{i2}=-g_{m1}\frac{r_{\pi 2}}{1+\beta_2}$$

$$A_{V2}=g_{m2}(R_C//R_L)$$

CB

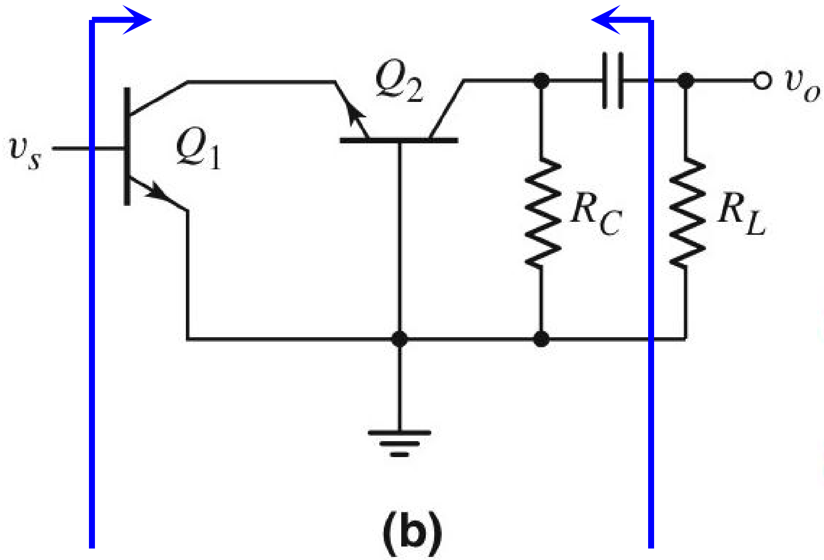




CE

$$A_V=A_{V1}\bullet A_{V2}=-g_{m1}\frac{r_{\pi 2}}{1+\beta_2}\bullet g_{m2}(R_C//R_L)$$

6.9.3 Multistage Circuit: Cascode Configuration



$$g_{m2}\left(\frac{r_{\pi 2}}{1+\beta_2}\right) = \frac{\beta_2}{1+\beta_2} \cong 1$$

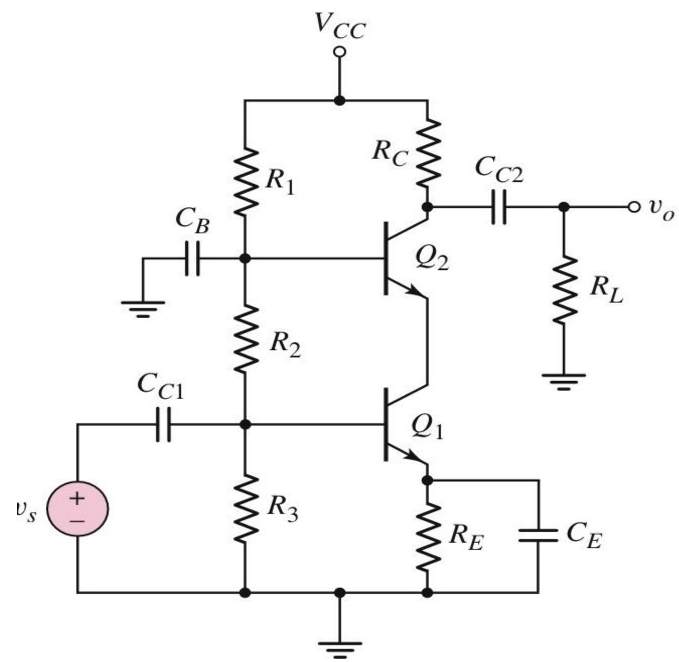
$$A_v \cong -g_{m1}(R_C \| R_L)$$

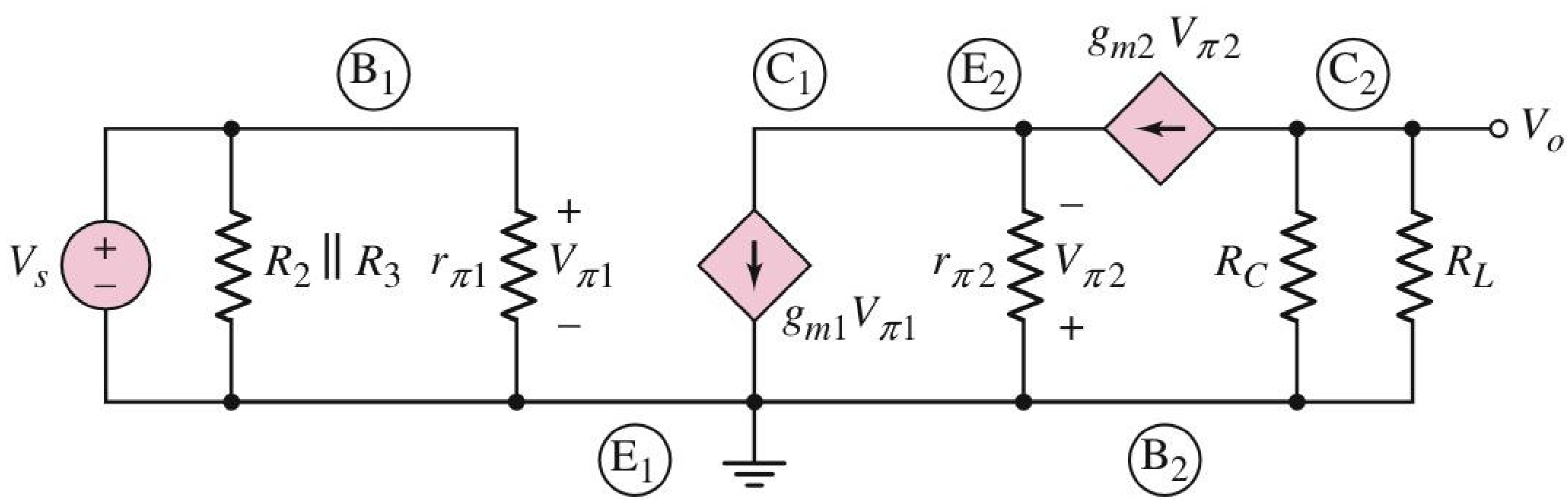
$$A_V = A_{V1} \bullet A_{V2} = -g_{m1}\frac{r_{\pi 2}}{1+\beta_2} \bullet g_{m2}(R_C // R_L)$$

$$R_i = R_2 \| R_3 \| r_{\pi 1}$$

$$R_o = R_c$$

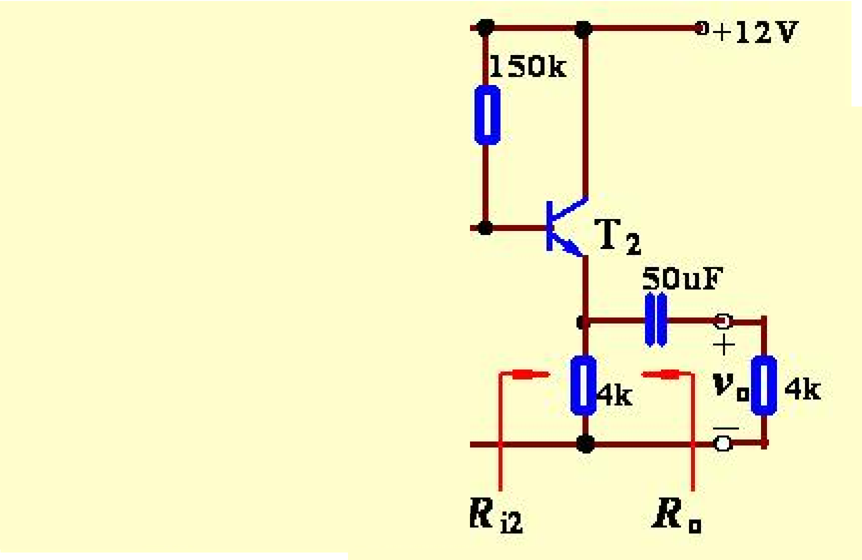
6.9.3 Multistage Circuit: Cascode Configuration





Example 2

Find $A_v = \dfrac{V_o}{V_i}$, β=50.



Sol:

(1) Find the Q-point values

$$I_{B1} = \frac{V_{CC} - V_{BE}}{R_{B1}} \approx 40\mu A$$

$$I_{C1} = \beta \cdot I_{B1} = 2mA$$

$$I_{B2} = \frac{V_{CC} - V_{BE}}{R_{B2} + (1+\beta)R_E} \approx 34.3\mu A$$

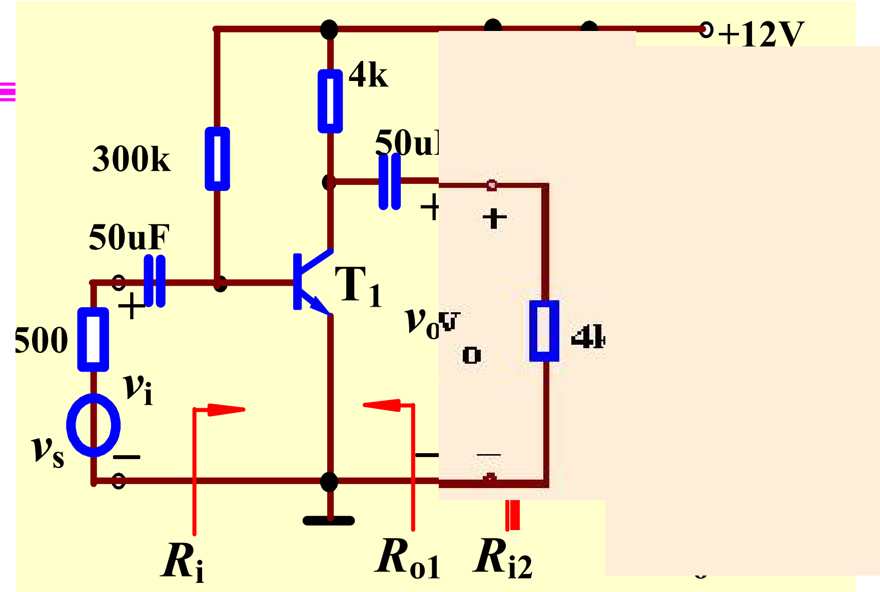
$$I_{C2} = \beta \cdot I_{B2} = 1.7mA$$

(2) Determine small-signal parameters

$$r_{\pi 1} = \frac{26(mV)}{I_{B1}(mA)} = 650\Omega$$

$$r_{\pi 2} = \frac{26(mV)}{I_{B2}(mA)} = 758\Omega$$

2. Multistage Amplifiers



(3) Find voltage gain

$$R_{i2} = R_{B2}//[r_{\pi2} + (1+\beta)(R_{E2}//R_L)]$$
$$= 61\text{k}\Omega$$

$$A_{v1} = \frac{V_{o1}}{V_i} = -\frac{\beta \cdot (R_{C1} // R_{i2})}{r_{\pi1}} = -217.5$$

$$\dot{A}_{v2} = \frac{V_o}{V_{i2}} \approx 1 \qquad A_v = \frac{V_o}{V_i} = \frac{V_{o1}}{V_i} \cdot \frac{V_o}{V_{o1}} = A_{v1} \cdot A_{v2} = -217.5$$

(4) Determine input and output resistances

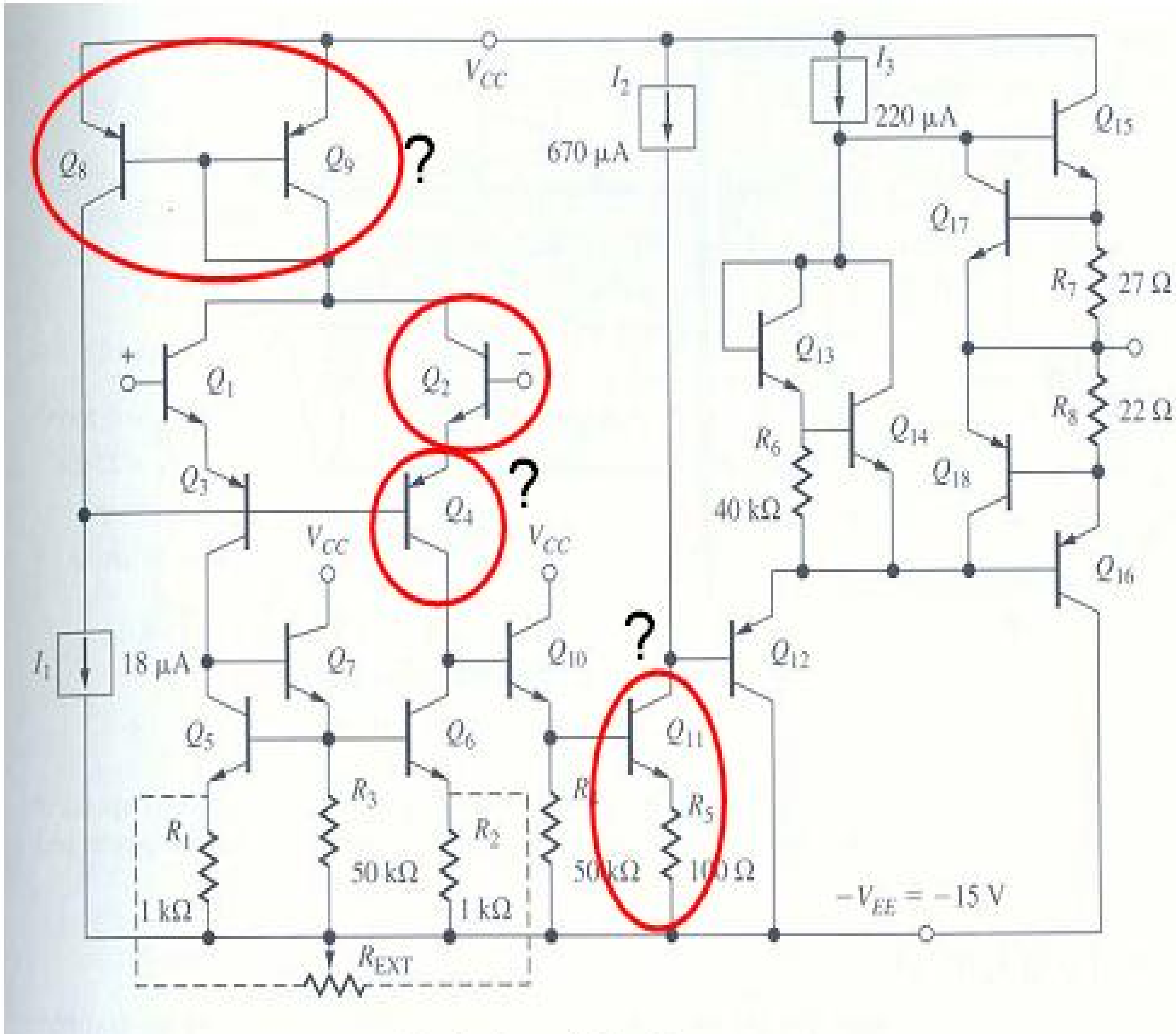
$$\dot{A}_V = -115.87$$

$$R_i = R_{B1} // r_{\pi1} \approx r_{\pi1} = 650\Omega$$

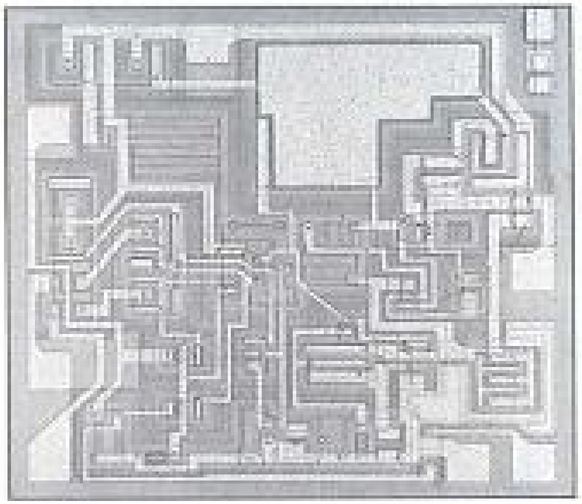
$$R_o = R_{E2} // \frac{(R_S // R_B) + r_{\pi2}}{1+\beta} = R_{E2} // \frac{(R_{o1} // R_{B2}) + r_{\pi2}}{1+\beta}$$

$$= 4\text{k} // \frac{(4\text{k} // 150\text{k}) + 0.758\text{k}}{1+50} \approx 95\Omega$$

More Complicated Amplifier …



Circuit schematic for µA741 op amp


uA741 Die Photograph (Courtesy of Fairchild Semiconductor)