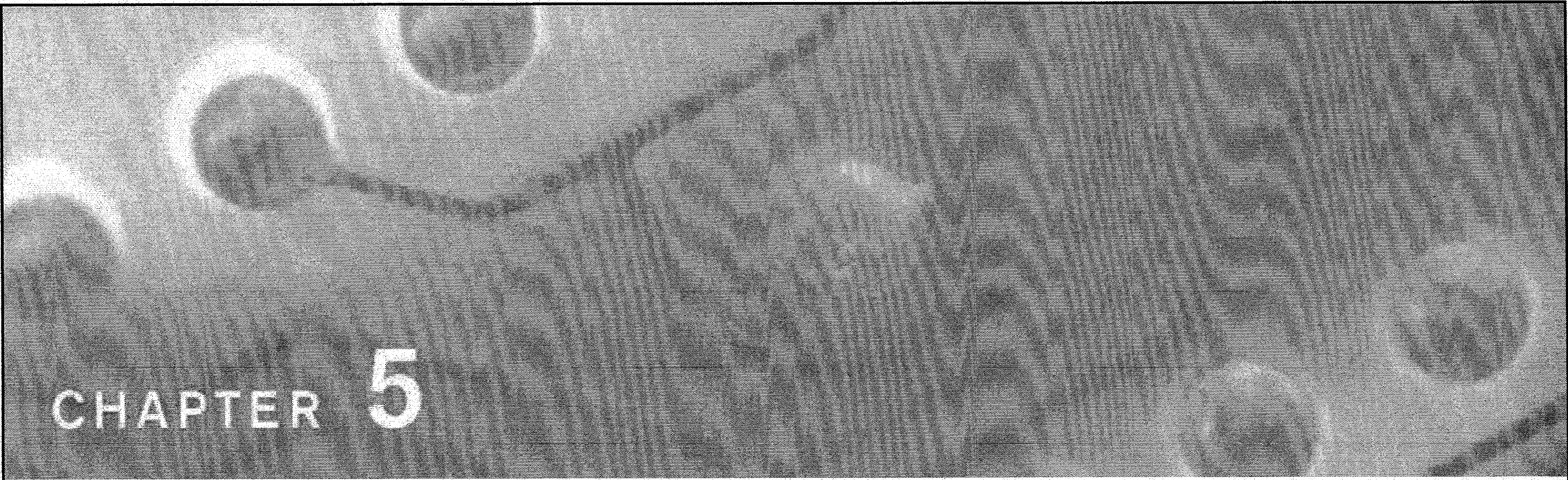
ECE321 Electronics I
Fall 2006

Professor James E. Morris

Lecture 14

14th November, 2006

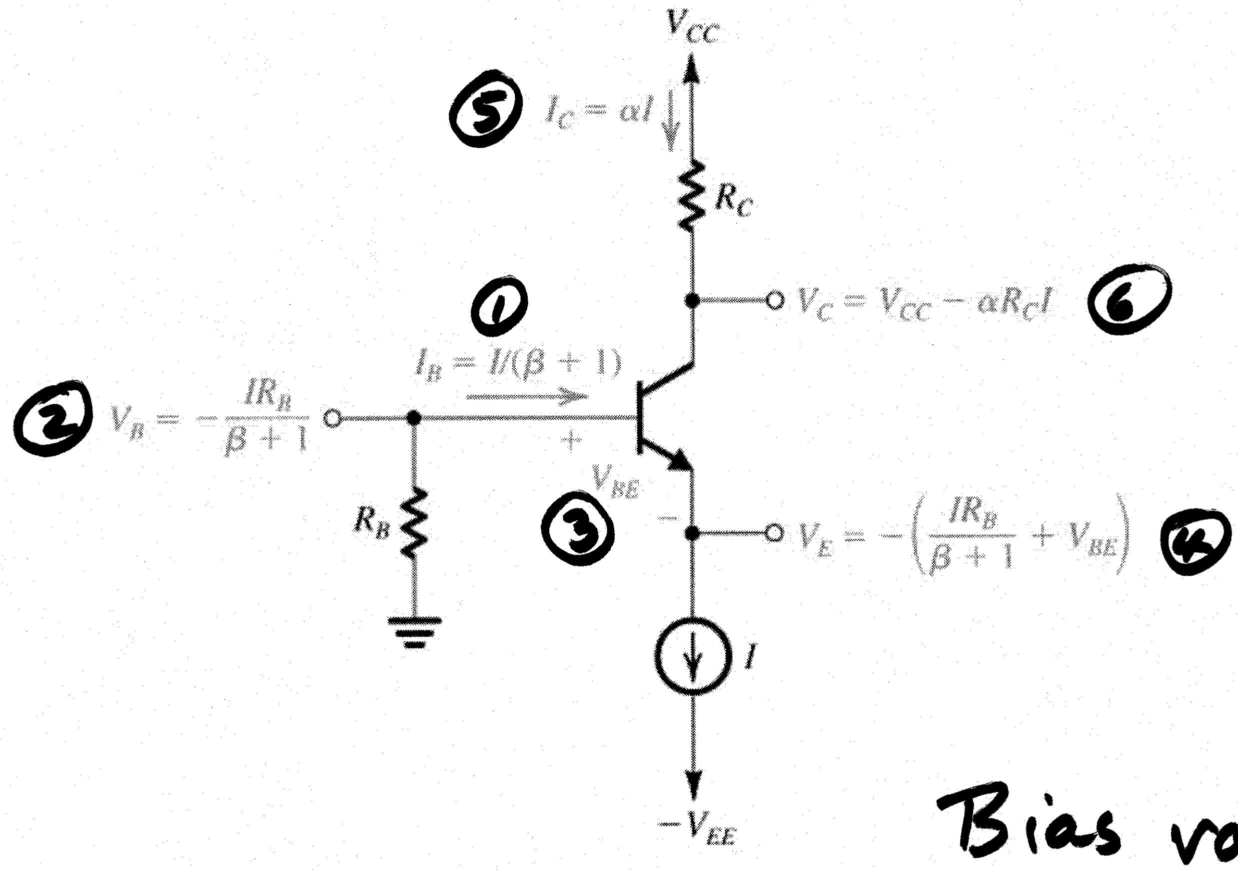


Bipolar Junction Transistors (BJTs)

5.7 Single Stage Amplifiers: CE, CB, & CC

General Configuration:

Assume:-
2 supplies + ground
Emitter current source



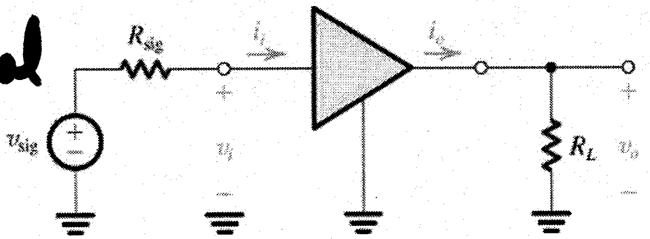
Bias values

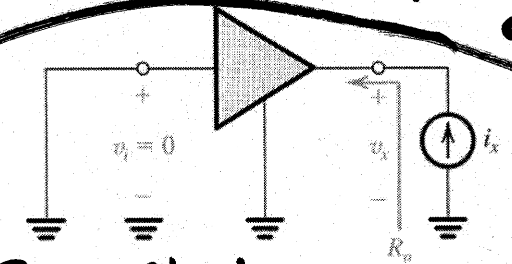
Figure 5.59 Basic structure of the circuit used to realize single-stage, discrete-circuit BJT amplifier configurations.

Exercise 5.41

Table 5.5 Compare Section 1·5 Unilateral amplifiers, extend to "non-unilateral amplifiers"

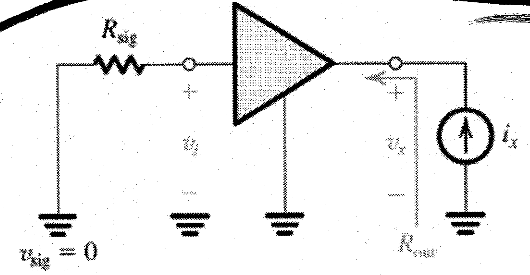
General Circuit



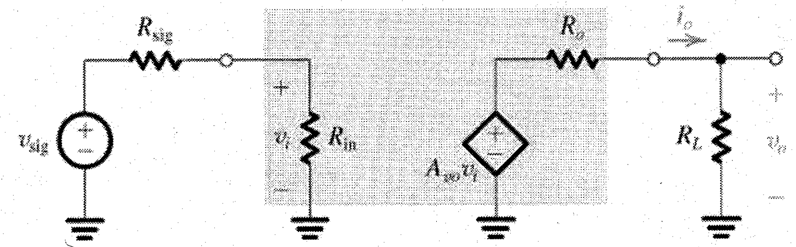


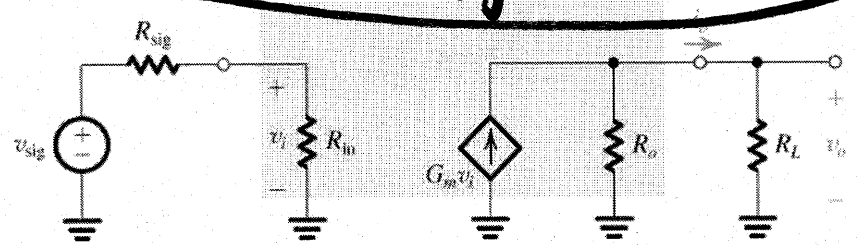
$R_o = \frac{v_x}{i_x}\Big|_{v_i=0}$ for "amplifier proper"

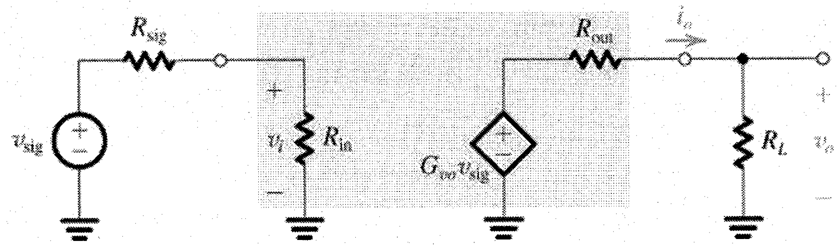
Compare



$R_{out} = \frac{v_x}{i_x}\Big|_{v_{sig}=0}$ includes R_{sig}







Define: $R_i = v_i/i_i$, $A_v = v_o/v_i$, $A_i = i_o/i_i$
"Overall" voltage gain $g_v = v_o/v_{sig}$

Table 5.5

Unilateral → R_i, A_v, R_o fixed (R_i, R_o for "amplifier proper")
Non-unilateral → R_{in}, R_{out}, A_v may depend on R_s, R_L etc due to internal f.b.
(R_{in}, R_{out} "actual" values, including R_s, R_L)

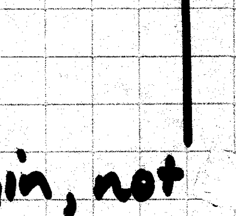
	Amplifier Proper	General	No-load Open Circuit o/p	Short Circuit Output
Input Resistance	$R_i = v_i / i_i \big\|_{R_L=\infty}$	$R_{in} = \frac{v_i}{i_i}$	$R_i = \frac{v_i}{i_i} \big\|_{R_L=\infty}$	
Voltage Gain	$A_v = v_o / v_i$	$A_v = v_o / v_i$	$A_{vo} = \frac{v_o}{v_i} \big\|_{R_L=\infty}$	N/A
Current Gain	$A_i = i_o / i_i$	$A_i = i_o / i_i$	N/A	$A_{is} = \frac{i_o}{i_i} \big\|_{R_L=0}$
Output Resistance	$R_o = \frac{v_x}{i_x} \big\|_{v_i=0}$	$R_{out} = \frac{v_x}{i_x} \big\|_{v_{sig}=0}$		
Overall Voltage Gain	N/A	* $G_v = v_o / v_{sig}$	* $G_{vo} = \frac{v_o}{v_{sig}} \big\|_{R_L=\infty}$	N/A
Transconductance				$G_m = \frac{i_o}{v_i} \big\|_{R_L=0}$

* Note: G here is a voltage gain, not conductance units.

Small signal: $v_i / v_{sig} = R_{in} / (R_{in} + R_{sig})$

$A_v = A_{vo} R_L / (R_L + R_o)$

$A_{vo} = G_m R_o$



$i_o = G_m v_i$

$v_o = i_o R_o$

$G_v = G_{vo} R_L / (R_L + R_{out})$

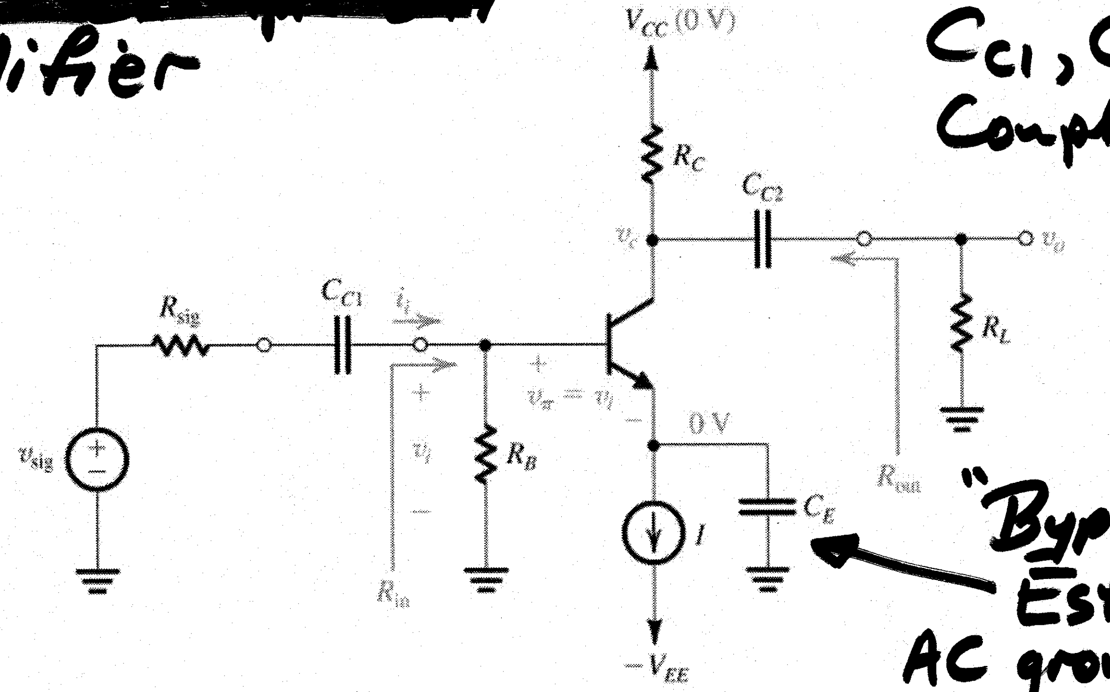
$G_{vo} = A_{vo} R_i / (R_i + R_{sig})$

Exercise 5.42

[redacted]

CE Amplifier

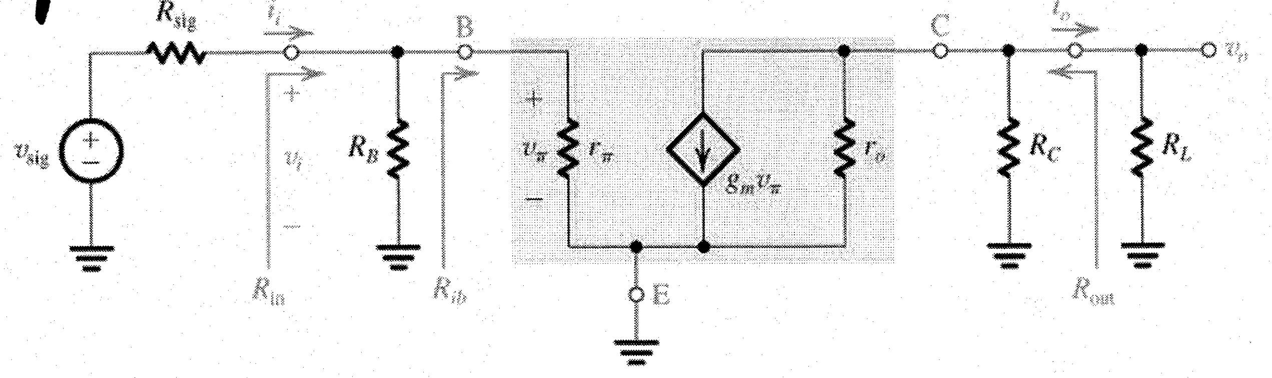
C_{C1}, C_{C2}
Coupling capacitors



"Bypass" capacitor
Establishes
AC ground for Emitter

(a)

Hybrid-π equivalent circuit.



(b)

Figure 5.60 **(a)** A common-emitter amplifier using the structure of Fig. 5.59. **(b)** Equivalent circuit obtained by replacing the transistor with its hybrid-π model.

$$R_{in} = v_i/i_i = R_B \| R_{ib} = R_B \| r_\pi \approx r_\pi \text{ for } R_B \gg r_\pi$$

$$\& \; v_i = v_{sig} \frac{R_{in}}{R_{in} + R_{sig}} = \frac{R_B \| r_\pi}{(R_B \| r_\pi) + R_{sig}} \approx \frac{r_\pi}{r_\pi + R_{sig}}$$

$= v_\pi$

Text mis-print

$$v_o = -g_m v_\pi (r_o \| R_C \| R_L) \quad \therefore A_v = -g_m (r_o \| R_C \| R_L)$$

$$\text{and } A_{vo} \xrightarrow[R_L = \infty]{} -g_m (r_o \| R_C)$$

Typically $r_o \gg R_C$, so $A_{vo} \rightarrow -g_m R_C$ & $A_v \rightarrow -g_m (R_C \| R_L)$

For R_{out}, set $v_{sig} = 0$, $\therefore v_\pi = 0$ $\therefore R_{out} = R_C \| r_o \approx R_C$

& $R_o = R_{out}$ here

[Note $A_v = A_{vo} \frac{R_L}{R_L + R_o} = -g_m R_o \frac{R_L}{R_L + R_o} = -g_m (R_L \| R_o) = -g_m (R_L \| R_C \| r_o)$

Checks with direct result above]

Overall source → load $G_v = \frac{v_i}{v_{sig}} A_v = -\frac{R_B \| r_\pi}{R_{sig} + R_B \| r_\pi} g_m (r_o \| R_C \| R_L)$

$$\xrightarrow[R_B \gg r_\pi]{} -\frac{r_\pi}{R_{sig} + r_\pi} g_m (r_o \| R_C \| R_L) \xrightarrow[R_{sig} \ll r_\pi]{} -g_m (r_o \| R_C \| R_L)$$

(Cont'd)

Note $G_v \approx \dfrac{-g_m r_\pi}{r_\pi + R_{sig}}(r_o \| R_L \| R_C) \approx -\beta \dfrac{(R_L \| R_C \| r_o)}{r_\pi + R_{sig}}$

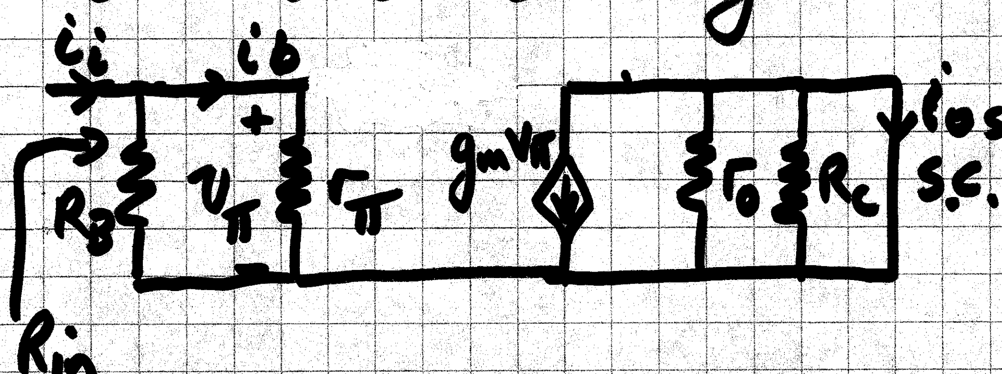
$\xrightarrow[R_{sig} \gg r_\pi]{} -\beta \dfrac{(R_L \| R_C \| r_o)}{R_{sig}}$ Very dependent on β

Signal source looks like a current source; defines i_b

$\xrightarrow[R_{sig} \ll r_\pi]{} -\beta \dfrac{(R_L \| R_C \| r_o)}{r_\pi} = -g_m (R_L \| R_C \| r_o)$

Voltage source and $v_\pi \approx v_{sig}$

Short circuit current gain



$i_{osc} = -g_m v_\pi = -g_m r_\pi i_b = -g_m R_{in} i_i$

$\therefore A_{is} = \dfrac{i_{osc}}{i_i} = -g_m (R_B \| r_\pi)$

$\approx -g_m r_\pi$ for $r_\pi \gg R_B$

$= -\beta$

CE Amplifier with R_E (Emitter "degenerated")

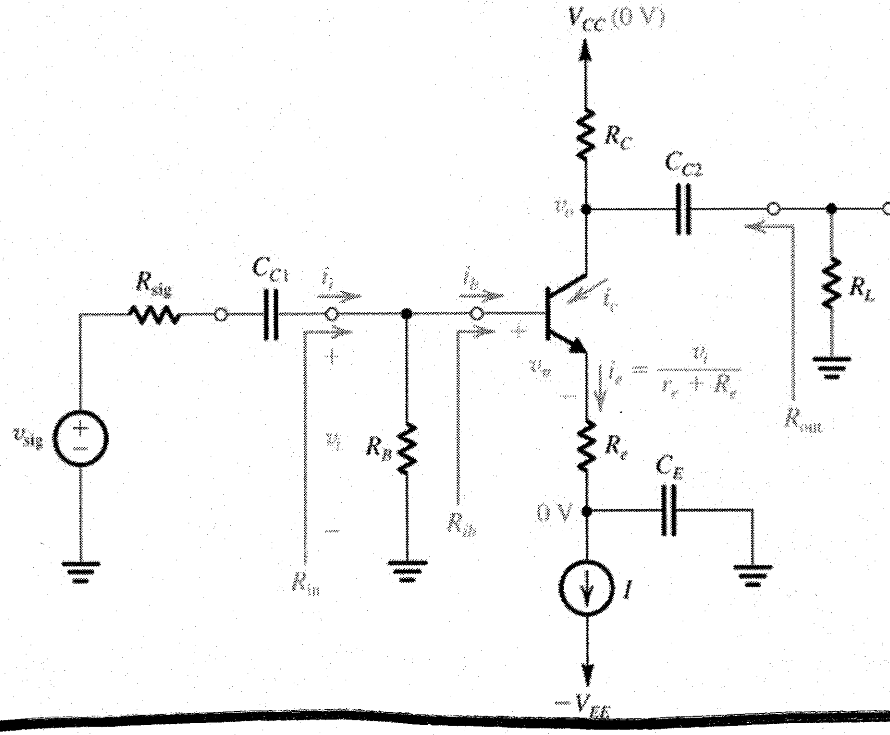
Example of Use of T-equivalent circuit

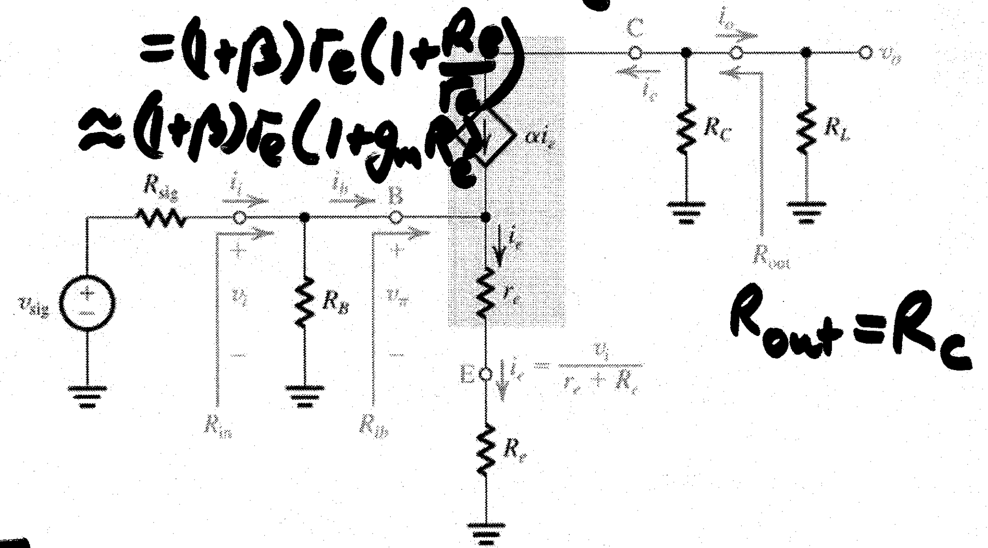
$R_{ib} = v_b / i_b = \dfrac{i_e(r_e + R_E)}{i_b}$

$= (1+\beta)(r_e + R_E)$

$= (1+\beta) r_e (1 + \dfrac{R_E}{r_e})$

$\approx (1+\beta) r_e (1 + g_m R_E)$





$R_{out} = R_C$

- R_{in} incr $\times (1 + g_m R_e)$
- A_{vi} reduced $\times (1 + g_m R_e)^{-1}$
- A_{vo} " " "
- A_v less dependent on β
- Improved frequency response (see later)

Figure 5.61 **(a)** A common-emitter amplifier with an emitter resistance R_e. **(b)** Equivalent circuit obtained by replacing the transistor with its T model.

$A_v = v_o/v_i = -i_c(R_C \| R_L)/v_i$

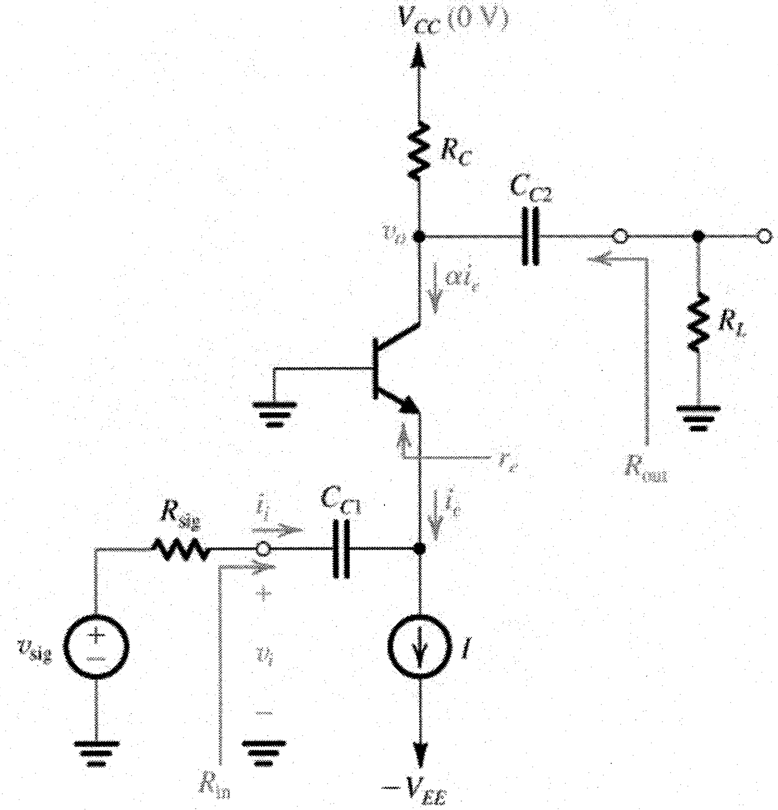
$= \dfrac{-\alpha\, i_e (R_C \| R_L)}{i_e (r_e + R_e)} \approx \dfrac{-R_C \| R_L}{r_e + R_e}$

$A_{vo} \xrightarrow[R_L = \infty]{} -R_C/(r_e + R_e)$

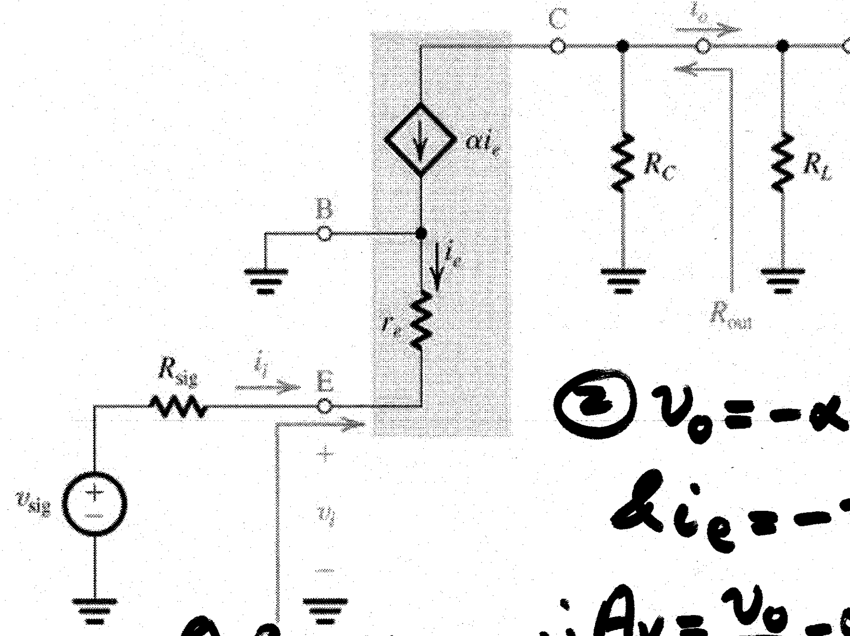
Gains decr $(1 + \frac{R_e}{r_e}) \approx 1 + g_m R_e$ & $\dfrac{v_\pi}{v_i} = \dfrac{r_e}{r_e + R_e} = \dfrac{1}{1 + R_e/r_e} \approx \dfrac{1}{1 + g_m R_e}$

Exercise 5.43
Exercise 5.44

CB Amplifier → Input to Emitter
Output from Collector
Base grounded as common/reference terminal



(a)



(b)

① $R_{in} = r_e$ i.e. small

② $v_o = -\alpha i_e (R_C \| R_L)$ & $i_e = -v_i / r_e$

$\therefore A_v = \frac{v_o}{v_i} = \frac{\alpha}{r_e}(R_C \| R_L)$

$= g_m (R_C \| R_L)$

Gives $A_{vo} \xrightarrow{R_L = \infty} g_m R_C$

Also $R_{out} = R_C$

③ $A_{is} = \frac{-\alpha i_e}{-i_e} = \alpha$

④ $v_i / v_{sig} = R_i / (R_i + R_{sig})$

$= \frac{r_e}{r_e + R_{sig}} \approx \frac{r_e}{R_{sig}}$??

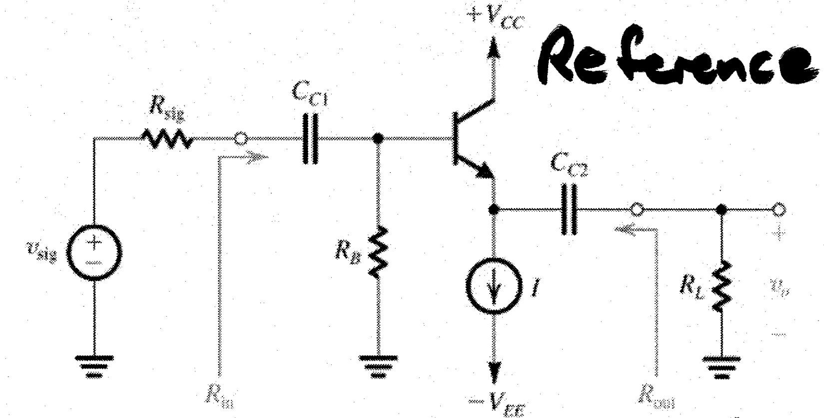
← Small too, 50 or 75Ω if coax cable

Figure 5.62 **(a)** A common-base amplifier using the structure of Fig. 5.59. **(b)** Equivalent circuit obtained by replacing the transistor with its T model.

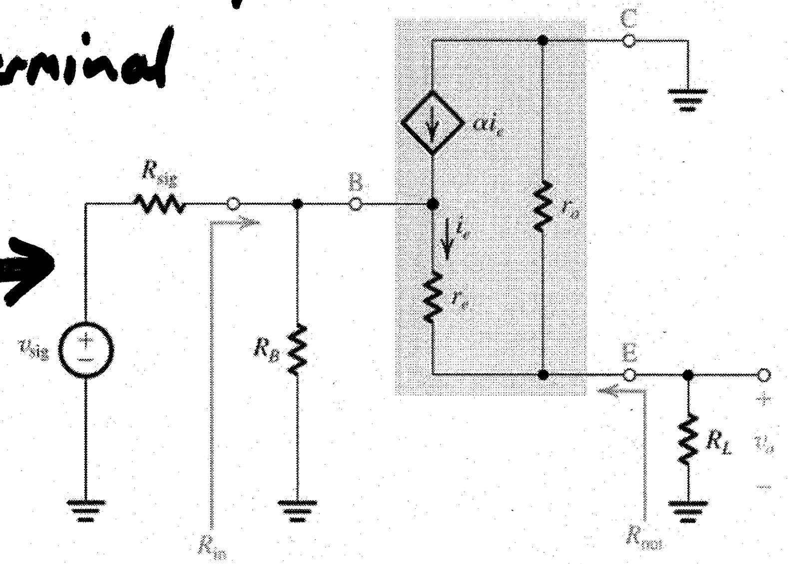
Exercise 5.45
Exercise 5.46

Common Collector (CC) Amplifier

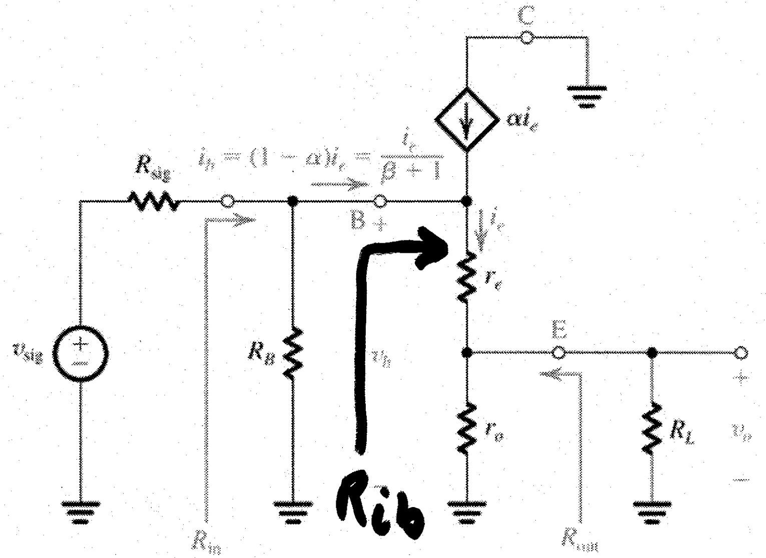
Reference terminal



Base input (a) Emitter Output



(b)



$$R_{ib} = v_b / i_b$$

$$= \frac{i_e(r_e + r_o \| R_L)}{i_e/(1+\beta)}$$

$$= (1+\beta)(r_e + r_o \| R_L)$$

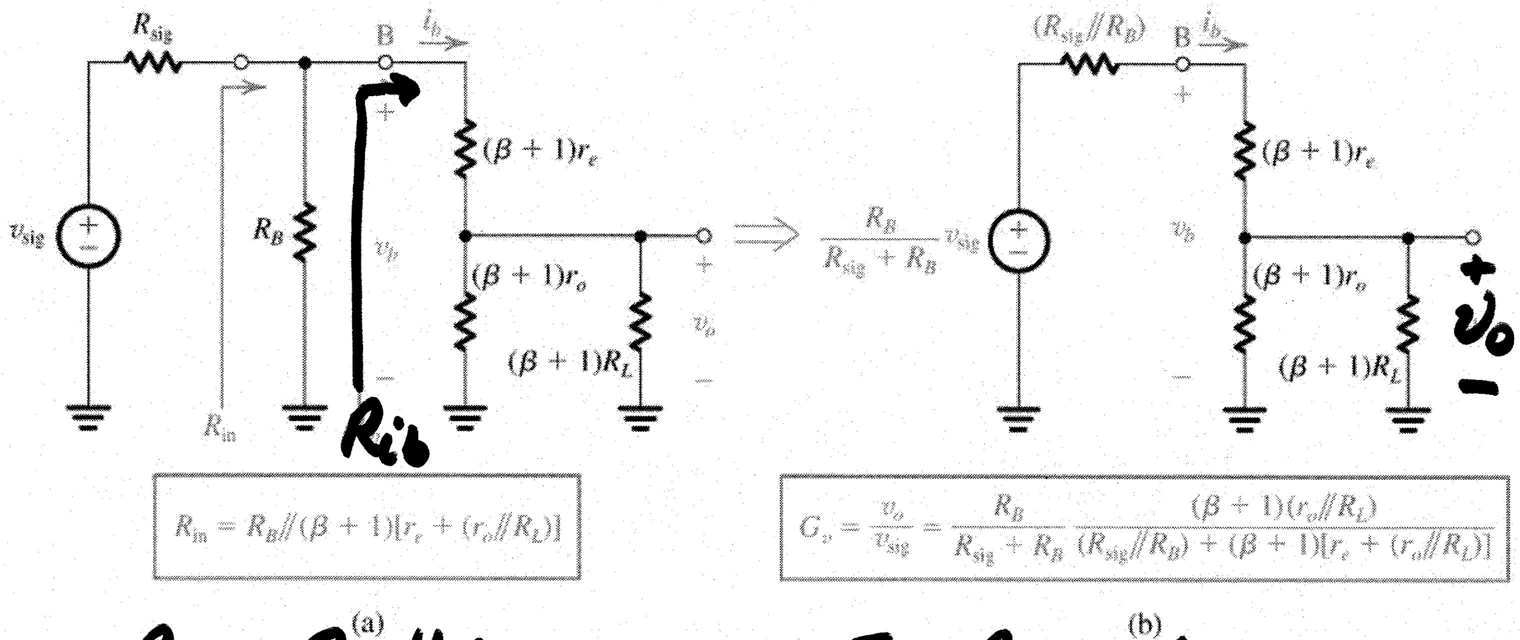
Re-draw equivalent circuit ($r_o \| R_L$)

(c)

Figure 5.63 **(a)** An emitter-follower circuit based on the structure of Fig. 5.59. **(b)** Small-signal equivalent circuit of the emitter follower with the transistor replaced by its T model augmented with r_o. **(c)** The circuit in (b) redrawn to emphasize that r_o is in parallel with R_L. This simplifies the analysis considerably.

"Reflect" emitter resistances to base circuit

Thevenin at B



$R_{in} = R_B // R_{ib}$

For $R_B \gg R_{sig}$

& $(1+\beta)(r_e + r_o // R_L) \gg (R_{sig} // R_B)$

$G_v \rightarrow (r_o // R_L)/(r_e + r_o // R_L)$

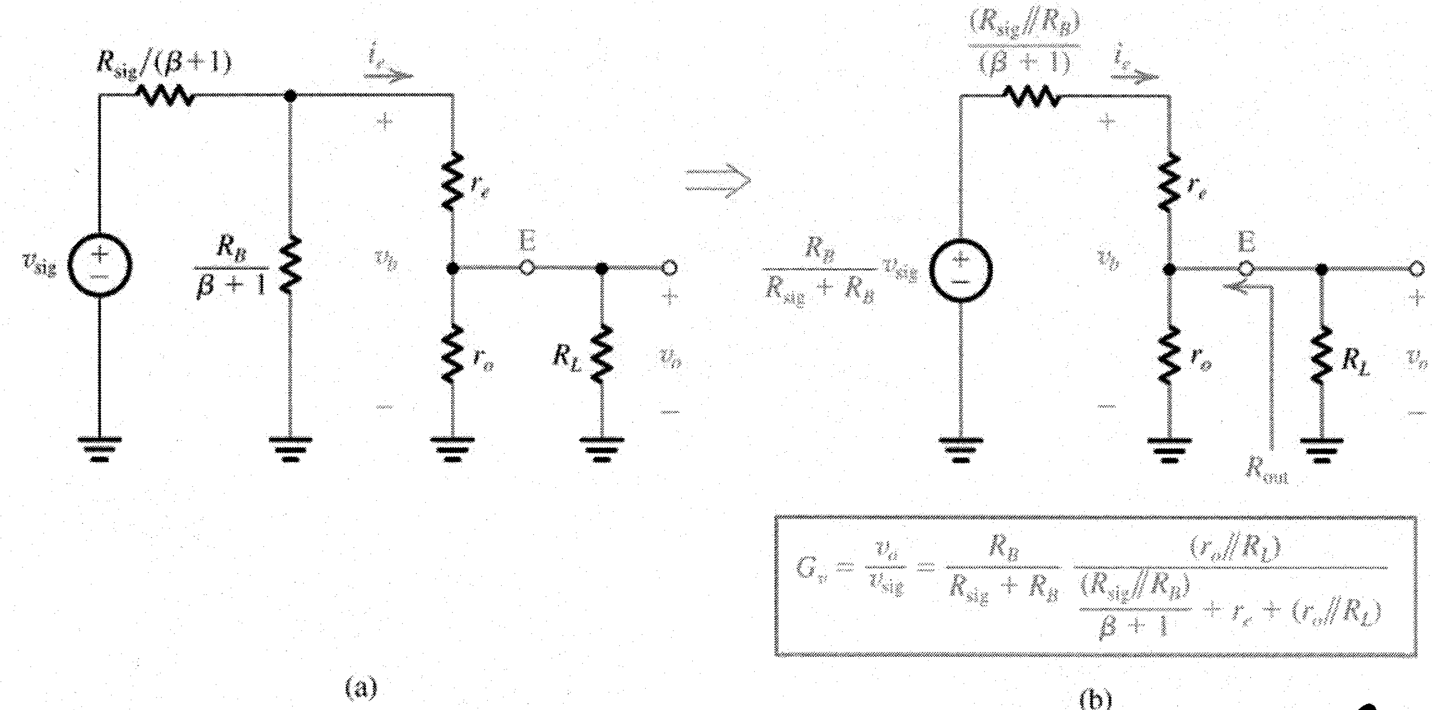
Figure 5.64 **(a)** An equivalent circuit of the emitter follower obtained from the circuit in Fig. 5.63(c) by reflecting all resistances in the emitter to the base side. **(b)** The circuit in (a) after application of Thévenin theorem to the input circuit composed of v_{sig}, R_{sig}, and R_B.

$\approx \frac{R_L}{r_e + R_L}$

"Emitter Follower"

(Compare Voltage follower) $\lessapprox 1$

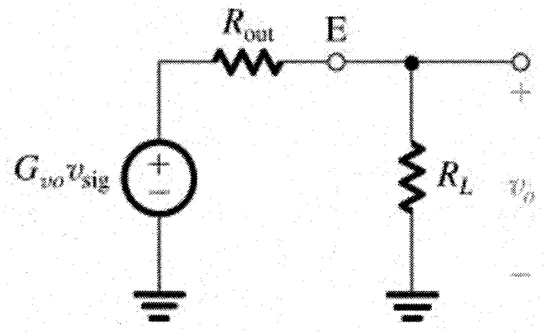
Reflect Base resistances to Emitter circuit



$$R_{out} = r_o // \left(r_e + \frac{R_{sig}//R_B}{1+\beta} \right)$$

Figure 5.65 **(a)** An alternate equivalent circuit of the emitter follower obtained by reflecting all base-circuit resistances to the emitter side. **(b)** The circuit in (a) after application of Thévenin theorem to the input circuit composed of v_{sig}, $R_{sig}/(\beta+1)$, and $R_B/(\beta+1)$.

Equivalent emitter follower (CC) output circuit



$$G_{vo} = \frac{R_B}{R_{sig} + R_B} \frac{r_o}{\frac{(R_{sig} /\!/ R_B)}{(\beta + 1)} + r_e + r_o}$$

$$R_{out} = r_o /\!/ \left(r_e + \frac{R_{sig} /\!/ R_B}{\beta + 1} \right)$$

Figure 5.66 Thévenin equivalent circuit of the output of the emitter follower of Fig. 5.63(a). This circuit can be used to find v_o and hence the overall voltage gain v_o/v_{sig} for any desired R_L.

Exercise 5.47

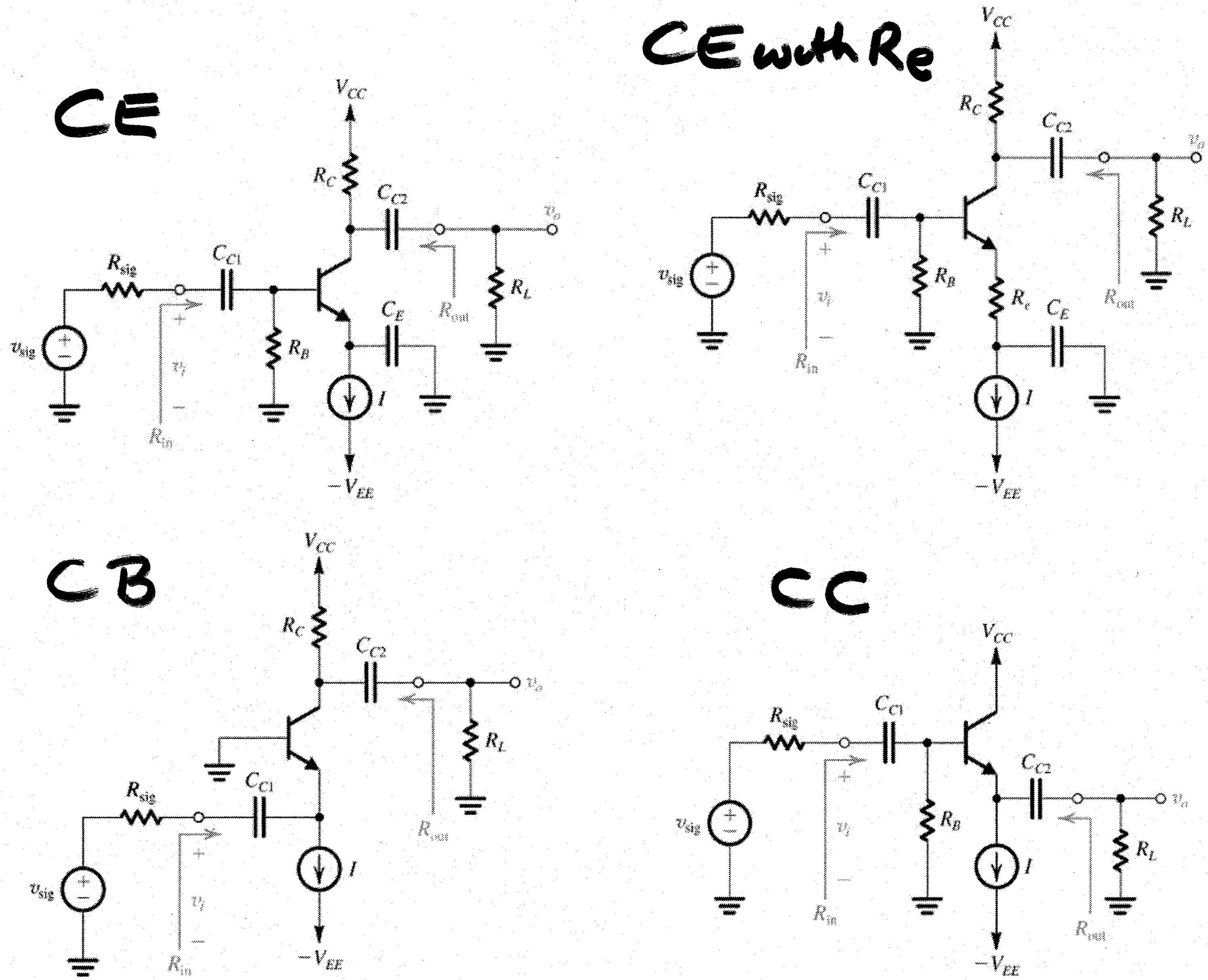

CE
V_{CC}
R_C
C_{C2}
v_o
R_{sig}
C_{C1}
C_E
R_{out}
R_L
v_{sig}
R_B
v_i
I
R_{in}
$-V_{EE}$
CE with Re
V_{CC}
R_C
C_{C2}
v_o
R_{sig}
C_{C1}
R_L
v_{sig}
R_B
v_i
R_e
C_E
R_{out}
R_{in}
I
$-V_{EE}$
CB
V_{CC}
R_C
C_{C2}
v_o
R_L
R_{sig}
C_{C1}
R_{out}
v_{sig}
v_i
I
R_{in}
$-V_{EE}$
CC
V_{CC}
R_{sig}
C_{C1}
C_{C2}
v_o
v_{sig}
v_i
R_B
I
R_L
R_{in}
R_{out}
$-V_{EE}$

Table 5.6

Ex 5.41

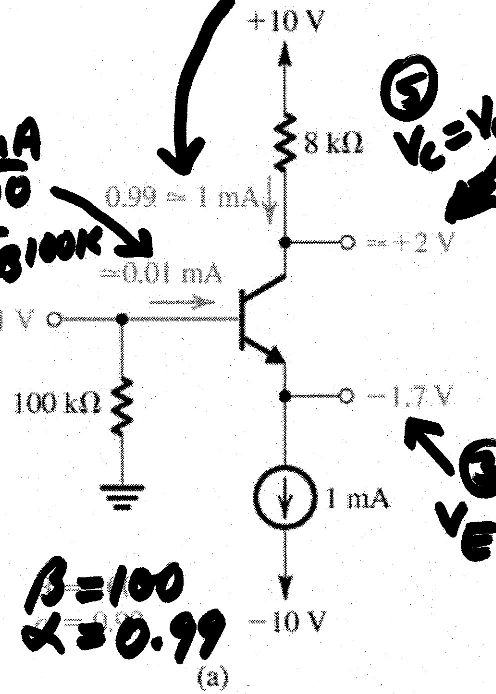
(a) DC bias values

④ $I_C = \alpha I_E$ $= .99\text{mA}$

① $I_B = \frac{1\text{mA}}{100}$

$V_B = -I_B 100K$ ⟶

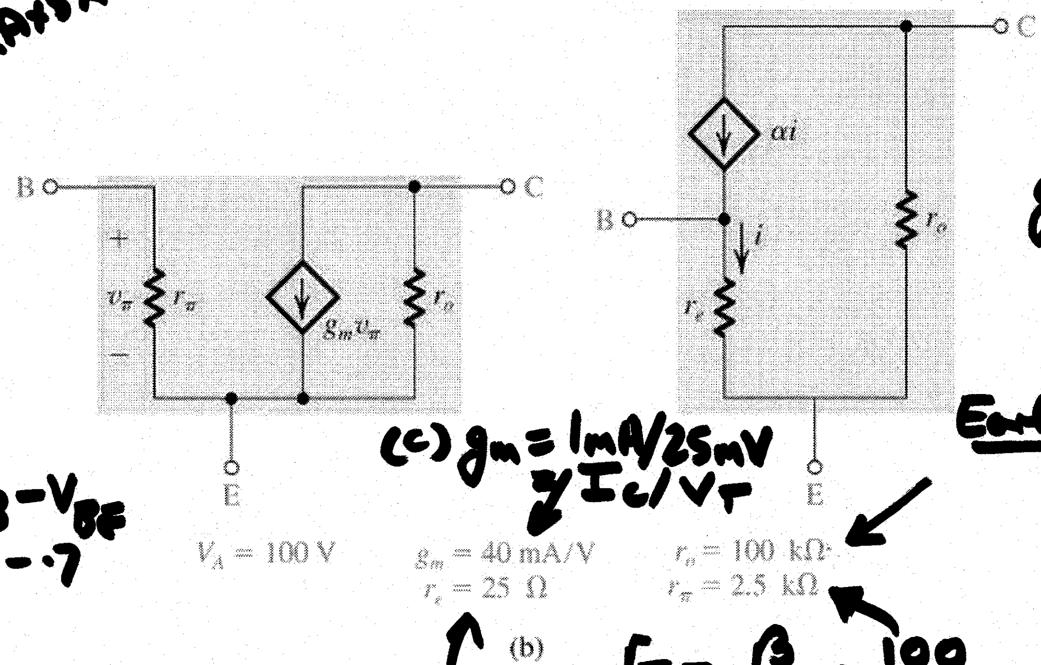
⑤ $V_C = V_{CC} - 1\text{mA} \times 8K$



③ $V_E = V_B - V_{BE}$ $= -1 - .7$

$\beta = 100$

$\therefore \alpha = 0.99$



given as 100v ⟶ $\frac{\text{Early Voltage}}{I_C}$

(c) $g_m = 1\text{mA}/25\text{mV}$ $= I_C/V_T$

$r_\pi = \frac{\beta}{g_m} = \frac{100}{1\text{mA}/25\text{mV}} = \frac{V_T}{I_B}$

$r_e = \frac{V_T}{I_E} = \frac{25\text{mA}}{1\text{mA}}$

(b) V_C can swing +2v +8v to 10v

& +2v −3.4v to −1.4v

↑ $-1.7 + V_{CE})_{SAT}$

Figure E5.41

Note: +ve swing same +8v to Vcc

If $\beta \to 50$	$I_B = .02\text{mA}$	$V_B = -2\text{v}$	$V_E = -2.7\text{v}$	V_C swing +2 to −2.4v = 4.4v
$\beta \to 200$	.005mA	−.5	−1.2v	+2 to −.8v = −2.8v

Ex 5.42 (See also Example 5.17)

Example 5.17:
Measured for

	v_i	v_o
$R_L = \infty$	9mV	90mV
$R_L = 10K$	8mV	70mV
$R_{sig} = 100K$		

Find R_{in}, G_v, R_{out} for

	R_{sig}	R_L
(a)	200K	10K
(b)	100K	20K
(c)	200K	20K

Use Example 5.17 measurement data to find:

$R_L = \infty$:

$A_{vo} = v_o/v_i\,\big]_{R_L=\infty} = 90\text{mV}/9\text{mV} = 10$ — indep of R_{sig}, R_L

$G_{vo} = v_o/v_{sig}\,\big]_{R_L=\infty} = 90\text{mV}/10\text{mV} = 9$ — depends on R_{sig}

$R_i = R_{in}\,\big]_{R_L=\infty} \Rightarrow G_{vo} = \dfrac{R_i}{R_i + R_{sig}} A_{vo} \quad \therefore R_i = R_{sig}\left(\dfrac{A_{vo}}{G_{vo}} - 1\right)^{-1}$

$= 100K\,(10/9 - 1)^{-1}$

$= 900K$

independs of R_{sig}, R_L

Ex 5.42 (cont'd)

$R_L = 10K\Omega \left\{ \begin{array}{l} A_v = 70mV/8mV = 8.75 \\ G_v = 70mV/10mV = 7 \end{array} \right.$

And $A_v = A_{vo} \dfrac{R_L}{R_L + R_o}$ gives $R_o = R_L (A_{vo} - A_v)/A_v$

$= R_L (A_{vo}/A_v - 1)$

$= 10K (10/8.75 - 1)$

$= 1.43 K\Omega$

& $R_o = v_x/i_x \Big]_{v_i = 0}$ is independent of R_{sig}

$G_v = G_{vo} \dfrac{R_L}{R_L + R_{out}}$

gives $R_{out} = R_L (G_{vo}/G_v - 1) = 10K (9/7 - 1) = 2.86 K\Omega$

& $R_{out} = v_x/i_x \Big]_{v_{sig} = 0}$

Also $v_i/v_{sig} = \dfrac{R_{in}}{R_{in} + R_{sig}}$ i.e. for $R_{sig} = 100K$, $R_L = 10K$: $\dfrac{8mV}{10mV} = \dfrac{R_{in}}{R_{in} + 100K}$

gives $R_{in} \Big)_{10K, 100K} = \dfrac{0.8 \times 100K}{.2} = 400K$

Ex 5.42 (cont'd)

(a) $R_{sig} = 200K$ $R_L = 10K$ (b) $R_{sig} = 100K$ $R_L = 20K$ (c) $R_{sig} = 200K$ $R_L = 20K$

(a)

R_{in} independent of R_{sig}

$\therefore R_{in} = 400K$, as for 5.17

$$G_v = \frac{R_{in}}{R_{in}+R_{sig}} \cdot A_{vo} \cdot \frac{R_L}{R_L+R_o}$$

$$= \frac{400}{400+200} \cdot 10 \cdot \frac{10}{10+1.43}$$

$$= 5.83$$

& $$G_{vo} = \frac{R_i}{R_i+R_{sig}} A_{vo}$$

$$= \frac{900}{900+200} \cdot 10 = 8.18$$

$$R_{out} = R_L\,(G_{vo}/G_v - 1)$$
$$= 10K\,(8.18/5.83 - 1)$$
$$= 4.03\,K\Omega$$

(b)

R_{out} independent of R_L

$\therefore R_{out} = 2.86\,K\Omega$ as for 5.17

$$G_{vo} = G_{vo} \frac{R_L}{R_L+R_{out}}$$

$$= 9\ \frac{20}{20+2.86} = 7.87$$

& $$G_v = \frac{R_{in}}{R_{in}+R_{sig}} A_{vo} \frac{R_L}{R_L+R_o}$$

$$7.87 = \frac{R_{in}}{R_{in}+100K}\, 10\, \frac{20}{20+1.43}$$

gives $R_{in} = 538\,k\Omega$

(c)

$R_{in} = 538\,K\Omega$ as for (b)

$R_{out} = 4.03\,K\Omega$ as for (a)

$G_{vo} = 8.18$ as for (a)

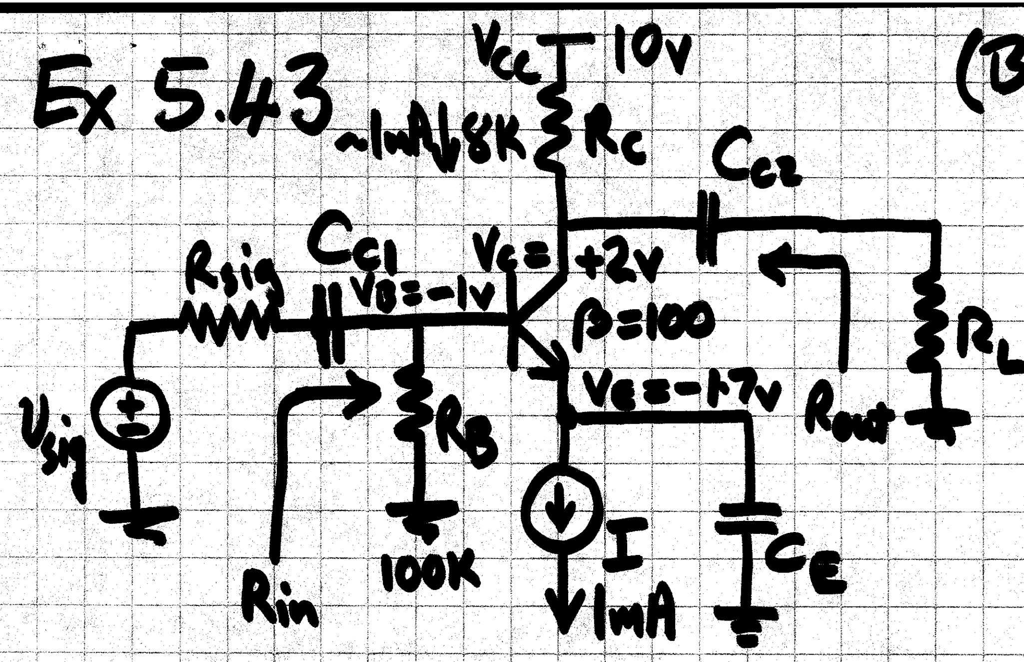
$$\therefore G_v = G_{vo} \frac{R_L}{R_L+R_{out}}$$

$$= 8.18\ \frac{20}{20+4.03}$$

$$= 6.8$$

Ex 5.43

(Bias as for Ex 5.41)



$R_{in} = r_\pi // R_B \approx r_\pi$

$= 2.5K // 100K$

$= 2.44K$

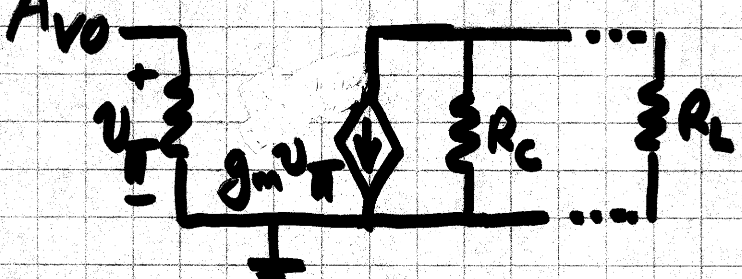
including R_B

$= \frac{V_T}{I_B}$

$= \frac{25mV}{1mA/101}$

$\approx 2.5K\Omega$

neglecting R_B



$g_m = \frac{I_C}{V_T} = \frac{1mA}{25mV} = 40 \times 10^{-3} A/V$

$\therefore A_{vo} = -g_m R_C = -40 \times 10^{-3} \times 8 \times 10^3 = -320$

or with r_o $A_{vo} \rightarrow -g_m (R_C // r_o)$

$= -296$

[Ex 5.41: $V_A = 100v$ $\therefore r_o \approx 100K$]

$A_{is} = \frac{-g_m v_\pi}{v_\pi / (r_\pi // R_B)} = -g_m (r_\pi // R_B) \approx -g_m r_\pi = -40 \times 10^{-3} \times 2.5K$

$= -100$

$= -40 \times 10^{-3} \frac{2.5 \times 10^2}{102.5} K$

$= -97.5$

$R_{out} = r_o // R_C \approx R_C = 8K$

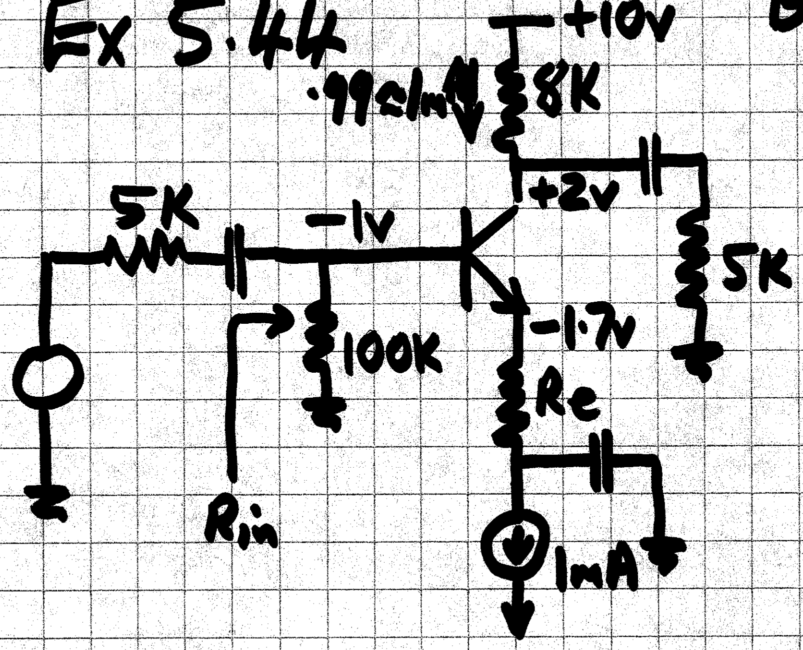
$= \frac{800K}{108} = 7.4K$

For $R_L = 5K$ $A_v = \frac{5K}{5K + 7.4K}(-296)$

$= -119.4$

For $R_{sig} = 5K$ $G_v = \frac{5K}{5K + 2.44K}(-119.4) = -39.15$

Ex 5.44



BJT: $\beta = 100 \quad V_A = 100v$

Find R_e for $R_{in} = 20K$

$R_{in} = 100K \,\|\, (1+\beta)(r_e + R_e) = 20K$

$\therefore (1+\beta)(R_e + r_e) = 25K$

$R_e + r_e \approx 250$

$r_e = \dfrac{V_T}{I_E} = 25\Omega \quad \therefore R_e = 225\Omega$

$A_{vo} = -\dfrac{8K}{250\Omega} = -32$

$R_{OUT} = R_C = 8K$

$A_v = -\dfrac{R_L \| R_C}{R_e + r_e} = \dfrac{-8K \| 5K}{250} = \dfrac{-3.077K}{250} = -12.308$

$G_v = \dfrac{R_{in}}{R_{in} + R_{sig}} A_v = \dfrac{-20}{20+5} 12.31 = -9.84$

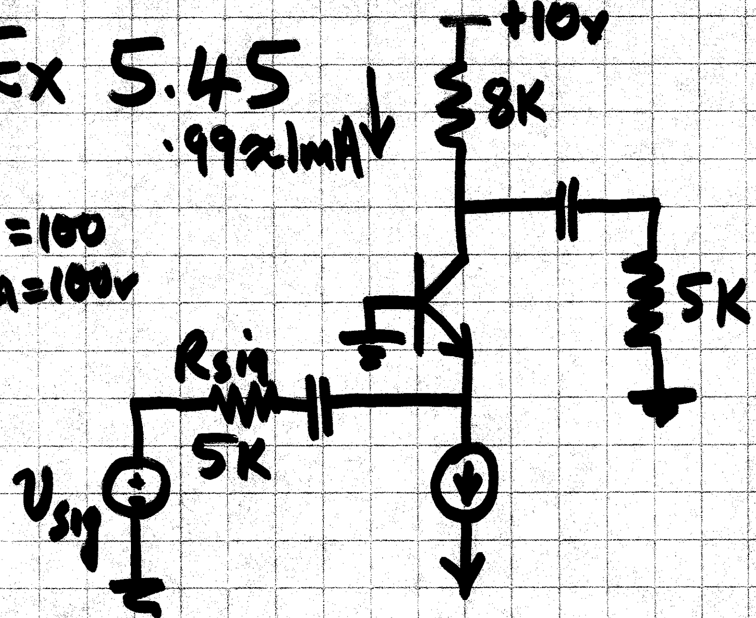
$A_{is} = -\alpha \dfrac{R_B \| R_{ib}}{r_e + R_e} \approx -.99 \dfrac{20K}{250\Omega} = -.99 \times 80 = -79.2$

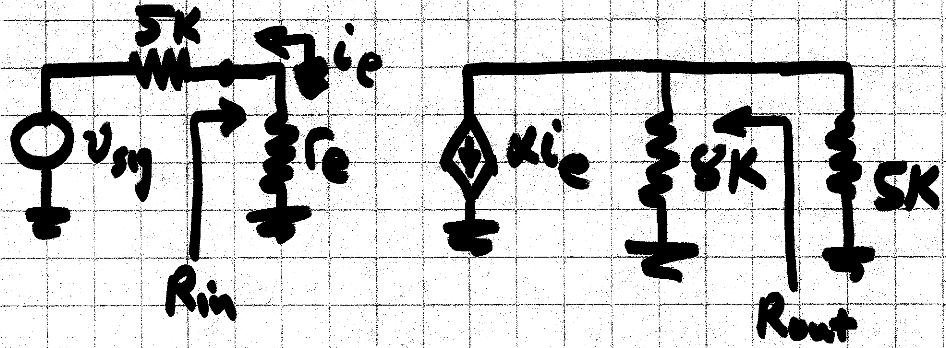
For max $v_\pi = 5mV$ Max $V_{sig} = \dfrac{5K + 20K}{20K} 5mV \dfrac{250}{25} = 62.5mV$ with R_e

$\Rightarrow \dfrac{5K + 2.5K}{2.5K} 5mV = 15mV$ without R_e

Ex 5.45

$\beta = 100$
$V_A = 100v$





$$R_{in} = r_e = \frac{V_T}{I_E} = \frac{25mV}{1mA} = 25\Omega$$

$$A_{vo} = -\frac{\alpha i_e \, 8K}{-i_e r_e} = +0.99\frac{8K}{25}$$

$$\approx 320$$

$$R_o = 8K$$

$$A_v = -\frac{\alpha i_e (8K \| 5K)}{-i_e r_e} \approx \frac{3.077K}{25}$$

$$= 123.08$$

$$v_i / v_s = \frac{25}{5K + 25} \approx 5\times10^{-3}$$

$$G_v = 5\times10^{-3} A_v = .6155$$

For $G_v \rightarrow 39$, need $123 \times \frac{25}{R_s + 25} = 39$ i.e. $R_s = 53.8\Omega$

D5.46 Design CB amplifier for $R_s = 50\,\Omega$ (coax)

$G_v = 100$

For matching, need $r_e = 50\,\Omega$

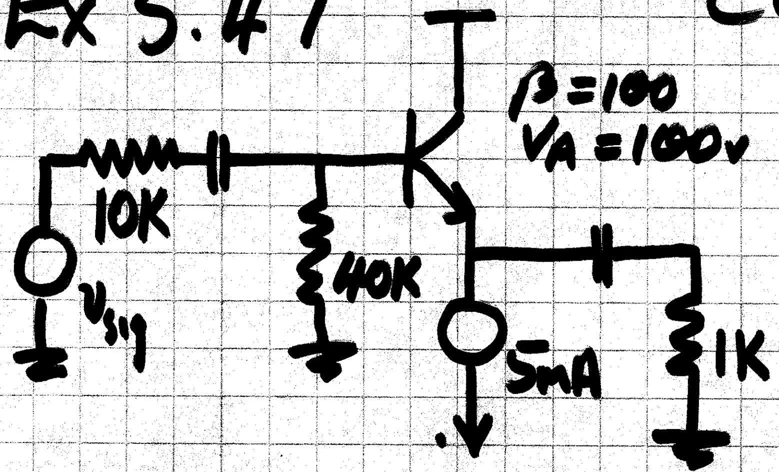
$$\therefore \frac{V_T}{I_E} = 50\,\Omega \;,\; I_E = \frac{25\,mV}{50\,\Omega} = 0.5\,mA$$

$$\therefore G_v = \frac{50}{50+50} \frac{R_c}{50} = 100 \quad (\alpha \approx 1)$$

$$\therefore R_c = 100 \times 100\,\Omega = 10\,K\Omega$$

Ex 5.47

CC – Emitter Follower



$R_{ib} = (1+\beta)(r_e + R_L \| r_o)$

$= 101 \times 955$

$= 96.5\,K\Omega$

$r_e = \frac{V_T}{I_E} = \frac{25m}{5mA}$

$= 5\,\Omega$

$r_o = \frac{100v}{5mA}$

$= 20\,K$

$20K \| 1K$

$= \frac{20 \times 1}{21} K$

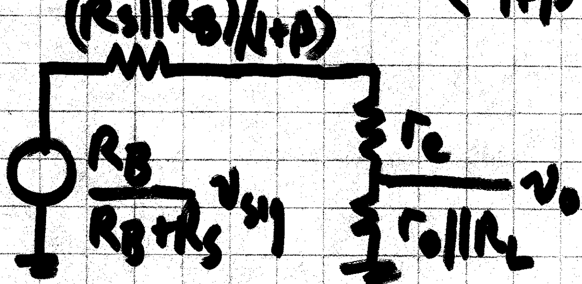
$= .95K$

$R_{in} = \frac{40K \times 96.5K}{136.5K}$

$= 2.83K$

$G_v = \frac{R_B}{R_B + R_s} \cdot \frac{r_o \| R_L}{r_e + r_o \| R_L}$

$\uparrow + \left(\frac{R_s \| R_B}{1+\beta}\right)$



$= 0.8 \quad \frac{.95K}{\frac{8K}{101} + 5 + .95K}$

$= .8 \quad \frac{950}{955 + 80} = \frac{760.0}{1035}$

$= 0.734$

$G_{vo} = .8 \quad \frac{20K}{5\Omega + 20K} \approx 0.8$

$R_{out} = r_e + \frac{10K \| 40K}{101} = 5\Omega + \frac{8K}{101} = 80\Omega - .8\Omega + 5\Omega = 84.2\Omega$

Ex 5.47 continued

Max v_o before cutoff? $5mA \times 1K // r_o = 4.75v$

$\approx 5v$

If $v_{be} = 10mV\,pk \longrightarrow v_o =$

$= (1K // r_o) \frac{10mV}{r_e} = \frac{950}{5} \times 10mV$

$= 1.9\ v$

If $R_L \to 2K$, $G_v \longrightarrow G_{vo} \frac{2K}{2K + R_{out}} = 0.8 \frac{2000}{2084}$

$= 0.77$

If $R_L \to 500$, $G_v \longrightarrow 0.8 \frac{500}{584} = 0.685$

Assignment #7

**D5.99

5.112

5.116

*5.135

5.143