ESE 319 MT1 2010 Review

1)--> Physical operation of a BJT (layout, why currents are related, npn vs. pnp).
2)Cover the Eber's Mole Model for forward and reverse active configurations. (large signal model)
3)Cover the various resistances in the small signal model e.g. r(e), r(pi), r(o) etc.
4)Design of PNP transistor circuits.
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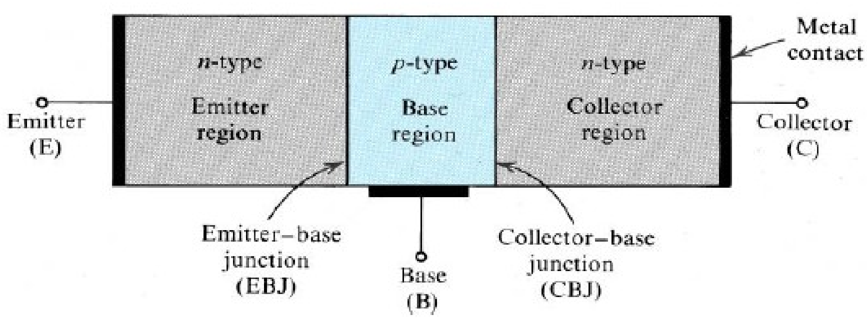
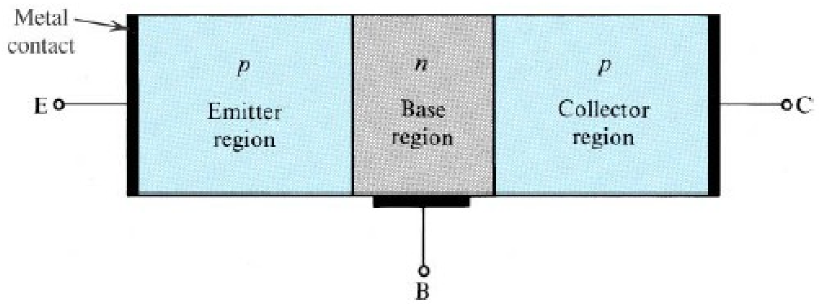
6)CC & CB Amplifier Configurations

BJT Physical Configuration

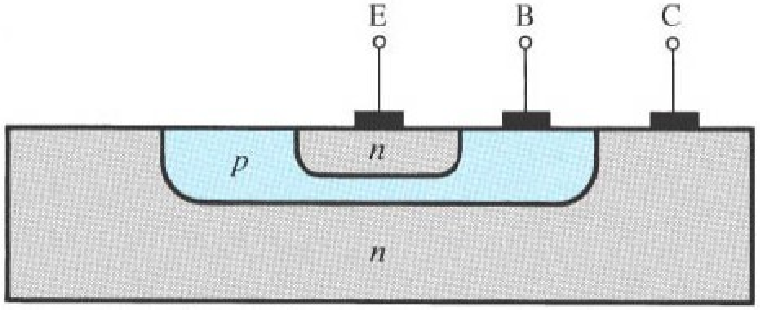
NPN



PNP

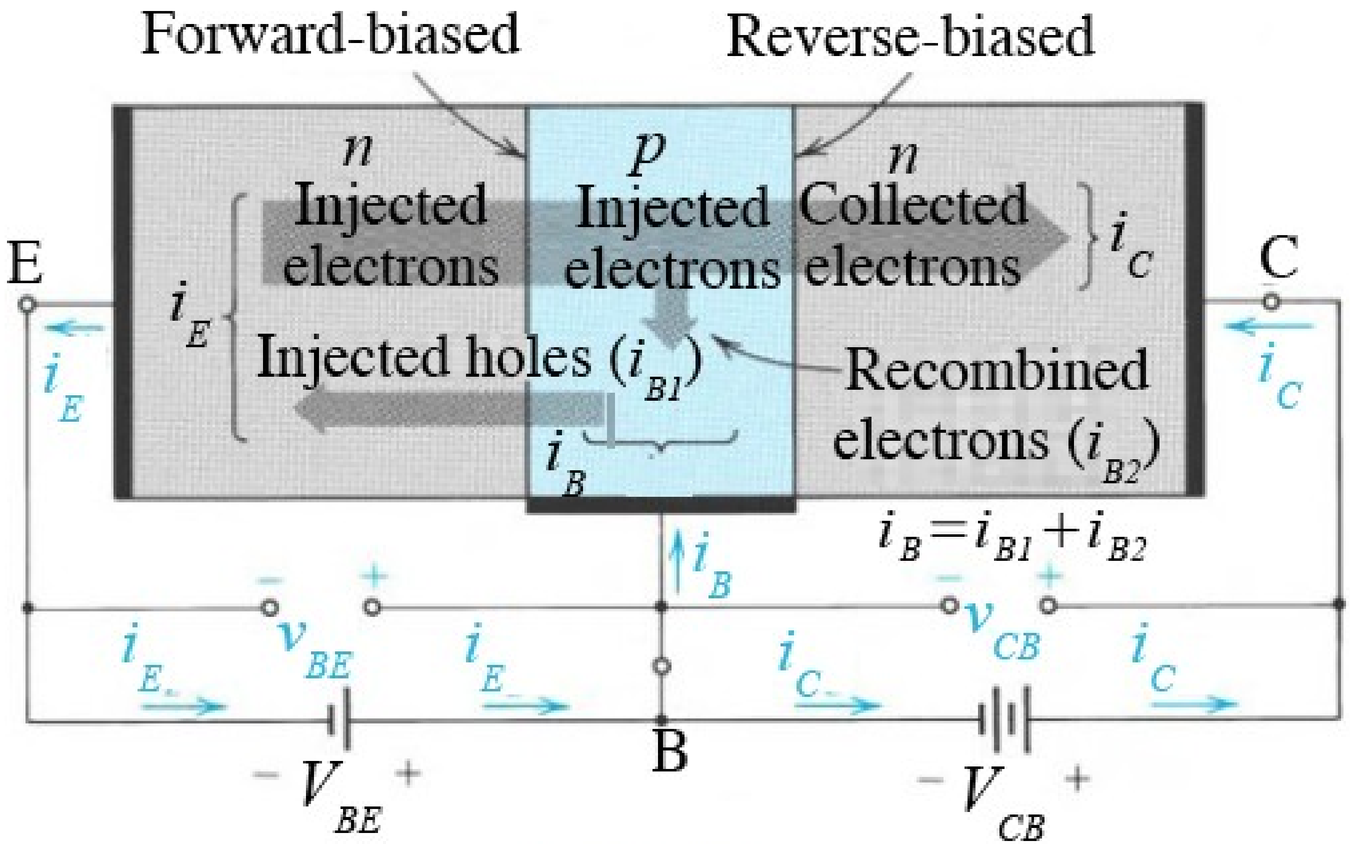


Closer to actual layout



Each transistor looks like two back-to-back diodes, but each behaves much differently!

Physical Operation of Forward Active NPN BJT



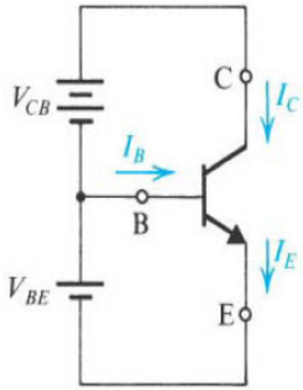
$$i_E = i_C + i_B$$

Forward Active => $i_C = \alpha_F i_E \quad i_C = \beta_F i_B$

NPN BJT Modes of Operation

$i_E = i_C + i_B$

$v_{CE} = v_{CB} + v_{BE}$



Forward-Active Mode

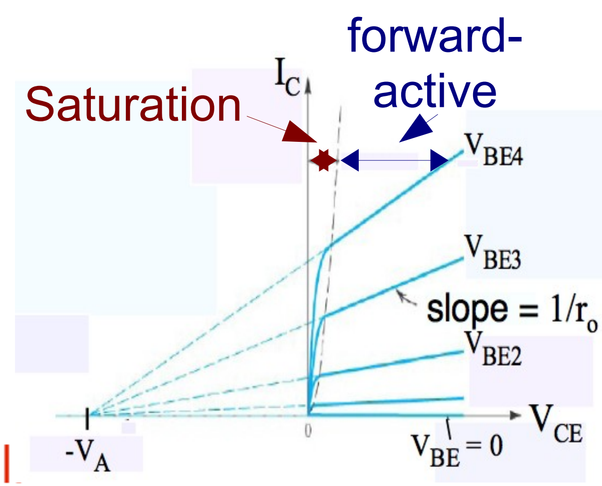
EBJ forward bias ($V_{BE} > 0$)

CBJ reverse bias ($V_{BC} < 0$)

Mode	V_{BE}	V_{BC}
Forward-Active	> 0	< 0
Reverse-Active	< 0	> 0
Cutoff	< 0	< 0
Saturation	> 0	> 0

$V_{BC} = -V_{CB}$

← Not Useful (Reverse-Active)



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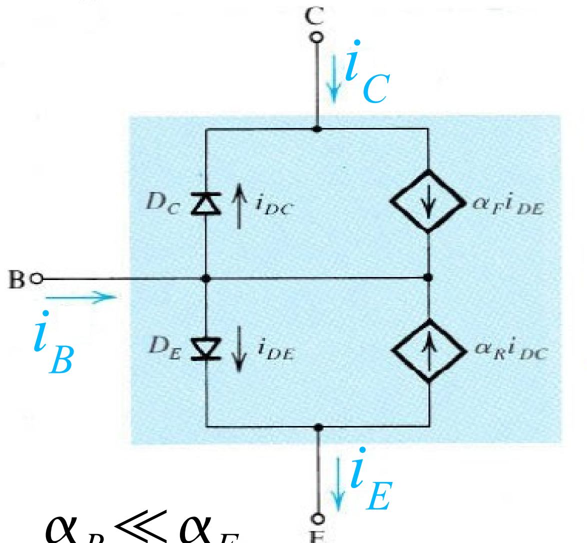
The Ebers-Moll Large Signal Model

The E-M model combines the FWD & RVRS Active equivalent circuits:



$\alpha_R \ll \alpha_F$

Note that the lower left diode and the upper right *controlled current source* form the forward-active mode model, while the upper left diode and the lower right source represent the reverse-active mode model.

$$i_C = \alpha_F i_{DE} - i_{DC}$$

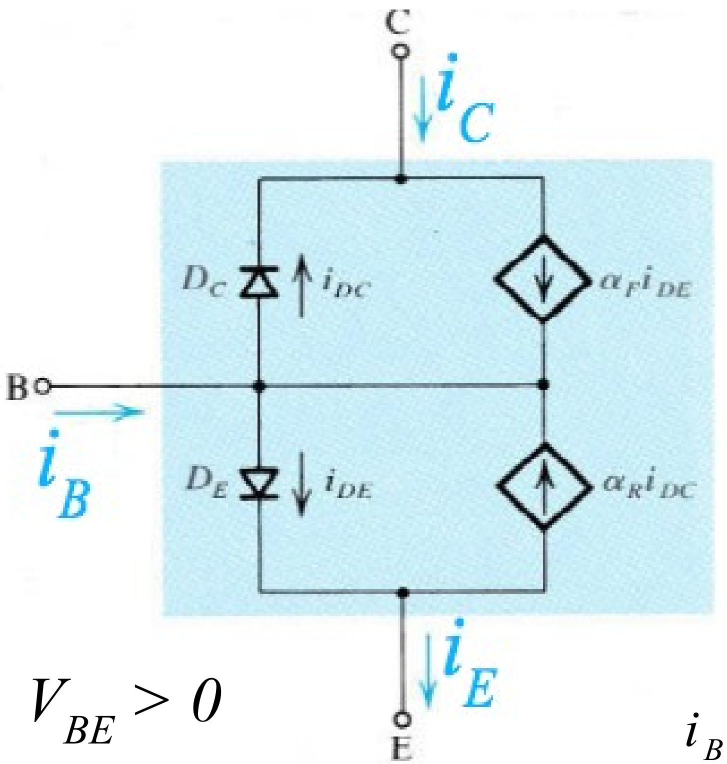
$$i_E = i_{DE} - \alpha_R i_{DC}$$

$$i_B = (1-\alpha_F) i_{DE} + (1-\alpha_R) i_{DC}$$

$$i_{DE} = \frac{I_S}{\alpha_F}\left(e^{\frac{v_{BE}}{V_T}} - 1\right)$$

$$i_{DC} = \frac{I_S}{\alpha_R}\left(e^{\frac{v_{BC}}{V_T}} - 1\right)$$

Ebers-Moll Mode in Forward-Active Mode



$V_{BE} > 0$

$V_{BC} < 0$

$$i_C = \alpha_F i_{DE} - i_{DC}$$
$$i_E = i_{DE} - \alpha_R i_{DC}$$
$$i_B = (1-\alpha_F) i_{DE} + (1-\alpha_R) i_{DC}$$

$$i_{DE} = \frac{I_S}{\alpha_F}\left(e^{\frac{v_{BE}}{V_T}} - 1\right)$$
$$\ll 1$$
$$i_{DC} = \frac{I_S}{\alpha_R}\left(e^{\frac{v_{BC}}{V_T}} - 1\right)$$

$$i_C = I_S e^{\frac{v_{BE}}{V_T}} + I_S\left(\frac{1}{\alpha_R} - 1\right)$$

$$i_E = \frac{I_S}{\alpha_F} e^{\frac{v_{BE}}{V_T}} + I_S\left(1 - \frac{1}{\alpha_F}\right)$$

$$i_B = \frac{1-\alpha_F}{\alpha_F} I_S\left(e^{\frac{v_{BE}}{V_T}} - 1\right) - \frac{1-\alpha_R}{\alpha_R} I_S = \frac{1}{\beta_F} e^{\frac{v_{BE}}{V_T}} - I_S\left(\frac{1}{\beta_F} + \frac{1}{\beta_R}\right)$$

Conclusions

- Ebers-Moll model is accurate large signal model.
- Used for all operation modes.
- includes bias + ac.
- Too complex for pencil-and-paper computations for most applications, e.g. nonlinear.
- Has been used in computer simulation, e.g. SPICE.

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Small Signal Analysis – Origin of r_π, r_e & r_o

$$i_C = I_C + i_c = I_S e^{\frac{v_{BE}}{V_T}} = I_S e^{\frac{V_{BE}+v_{be}}{V_T}} = \boxed{I_S e^{\frac{V_{BE}}{V_T}}} e^{\frac{v_{be}}{V_T}}$$

I_C

$$i_C = I_C e^{\frac{v_{be}}{V_T}}$$

And using the first two terms of the Taylor series expansion:

$$i_C \approx I_C \left(1 + \frac{1}{V_T} v_{be}\right) = I_C + \frac{I_C}{V_T} v_{be} = I_C + i_c$$

We define *transconductance* and *incremental (or ac) current as*:

bias current → $$g_m = \frac{I_C}{V_T}$$

$$i_c = g_m v_{be}$$ ← VCCS

Origin of r_π, r_e & r_o cont.

$$i_B = I_B + i_b = \frac{1}{\beta} i_C = \frac{1}{\beta}(I_C + i_c)$$

$$i_B = \frac{1}{\beta} i_C = \frac{1}{\beta} I_C + \frac{1}{\beta}\left(\frac{I_C}{V_T}\right) v_{be}$$

Define the *incremental base current* and *base resistance*:

$$i_b = \left(\frac{1}{\beta}\right) i_c = \frac{1}{\beta}\left(\frac{I_C}{V_T}\right) v_{be} = \frac{1}{r_\pi} v_{be}$$

Note:

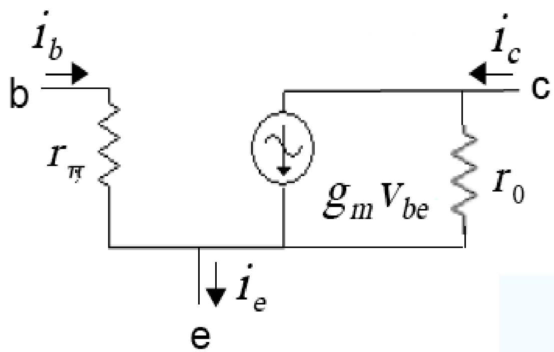
$$i_e = (\beta+1) i_b = (\beta+1)\frac{v_{be}}{r_\pi} = \frac{v_{be}}{r_e}$$

$$r_\pi = \beta \frac{V_T}{I_C} = \frac{\beta}{g_m}$$

bias current → I_C

$$r_e = \frac{r_\pi}{\beta+1}$$

Origin of r_π, r_e & r_o cont.

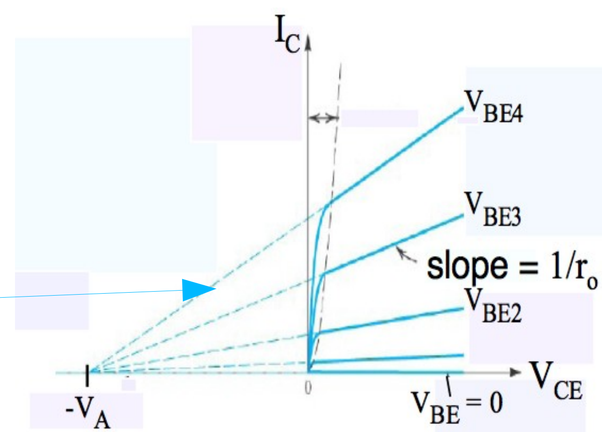


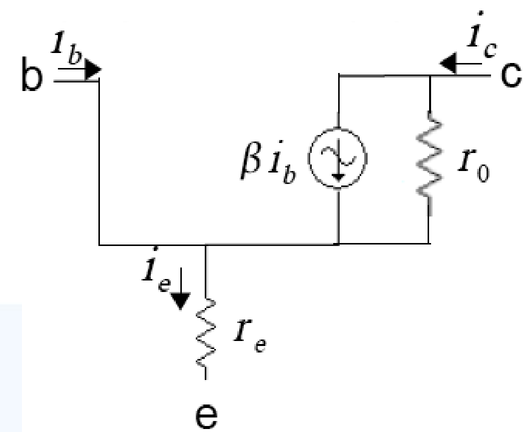
$$i_c = g_m v_{be} + \frac{v_{ce}}{r_0}$$

$$g_m = \frac{I_C}{V_T} \qquad r_0 = \frac{V_A}{I_C}$$

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

$$r_\pi = \frac{V_T}{I_B} = \frac{\beta}{g_m}$$





$$i_c = \beta i_b + \frac{v_{ce}}{r_0}$$

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

$$i_e = \frac{v_{be}}{r_e}$$

$$r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m} = \frac{r_\pi}{\beta+1}$$

Conclusions

- Resistors g_m, r_π, r_e, r_o are equivalent circuit model parameters, not parasitic resistances.
- Resistor r_x, the ohmic base resistance, is a parasitic resistance.
- $I_S e^{\frac{v_{BE}}{V_t}}$ term from Ebers-Moll model linearized by limiting the ac signal amplitude.

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Amplifier Design with PNP Transistors

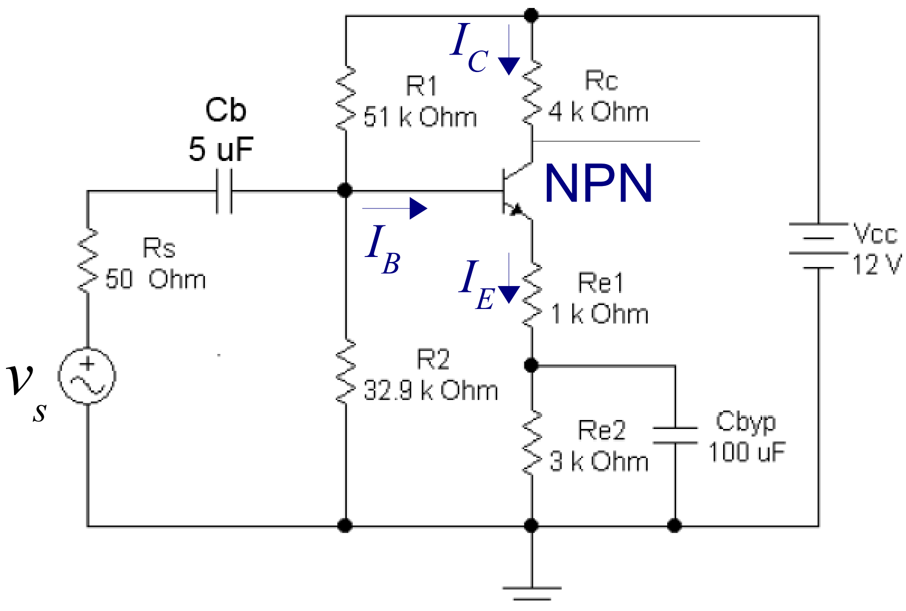
Bipolar process are optimized for NPN performance:

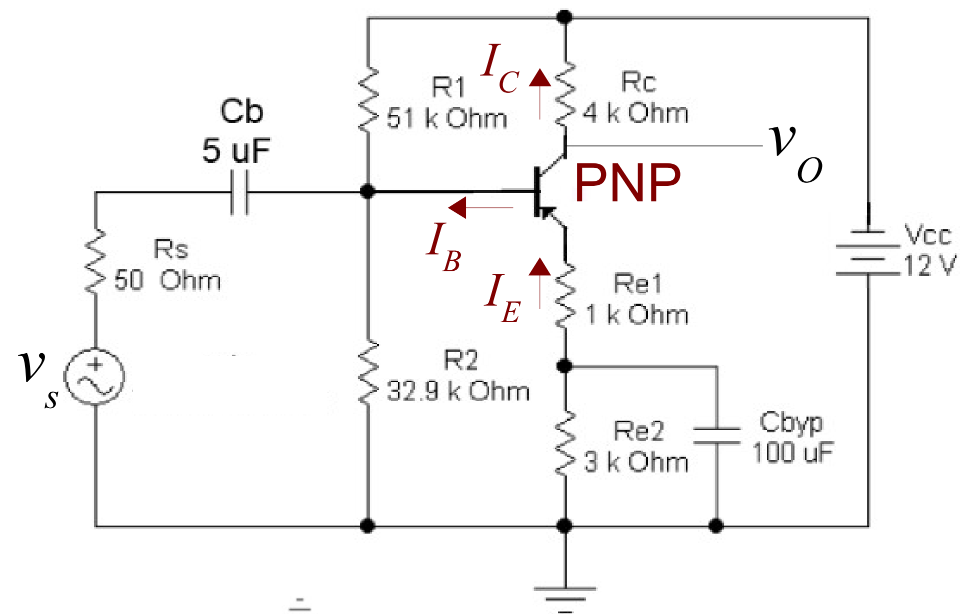
a. PNP have lower β than NPN transistors.
b. PNP have lower f_T than NPN transistors.

Example: Intersil CA3096 NPN & PNP array (Data Sheet)
NPN: $h_{fe} = \beta = 390, f_T = 280\ Mhz\ (I_C = 1mA)$
PNP: $h_{fe} = \beta = 47, f_T < 10\ Mhz\ (I_C = 1mA)$

c. NPN transistors are typically used where high gain and f_T are needed, e.g. amplifier transistor
d. PNP transistors are used where gain and f_T are not as needed, e.g. current sources and active loads.
e. When NPNs and PNPs are used together, two power supplies are needed.

NPN vs. PNP CE Design

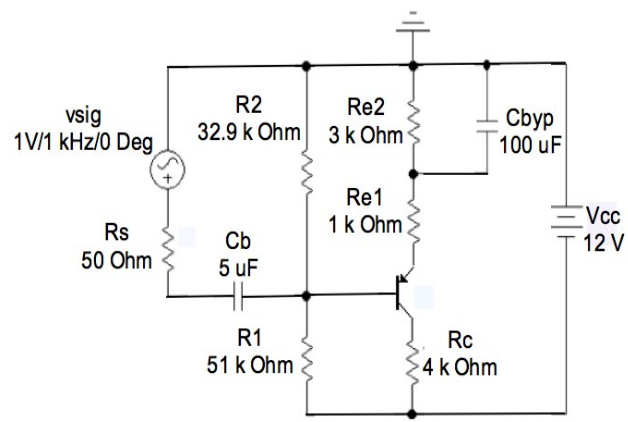




Forward Active:

$V_{BE} > 0\,V$

$V_{BC} < 0\,V$

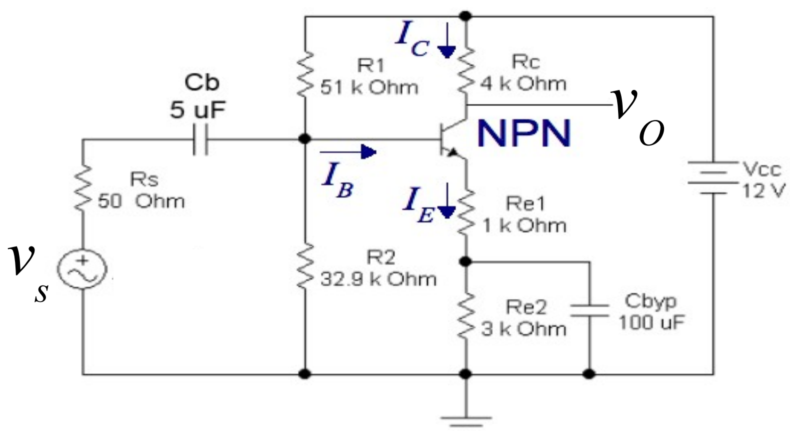


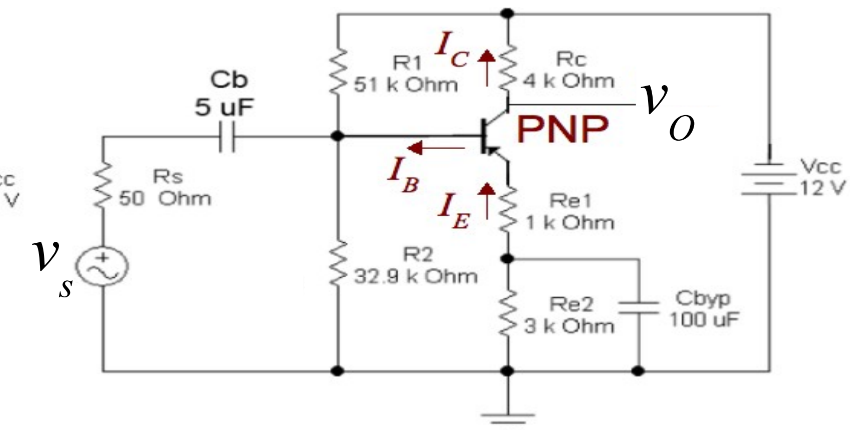
Forward Active:

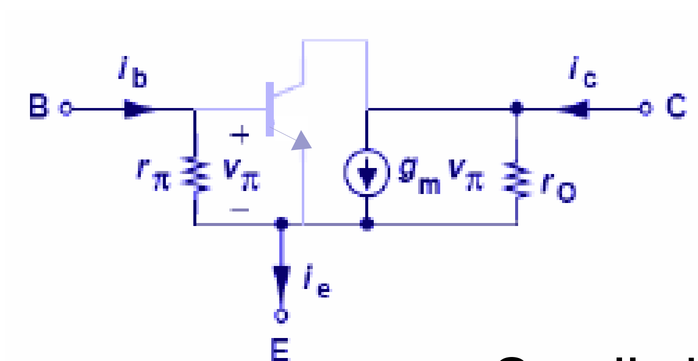
$V_{EB} > 0\,V$

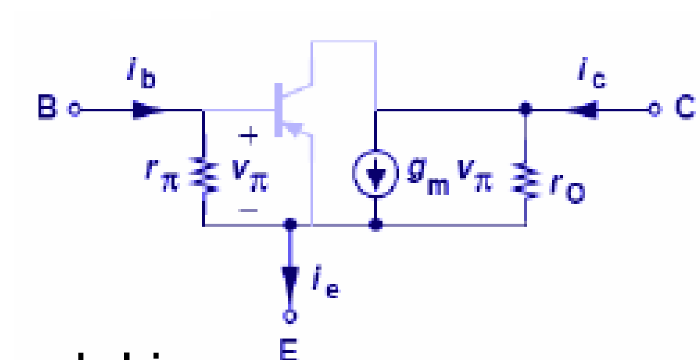
$V_{CB} < 0\,V$

NPN and PNP Small Signal Models









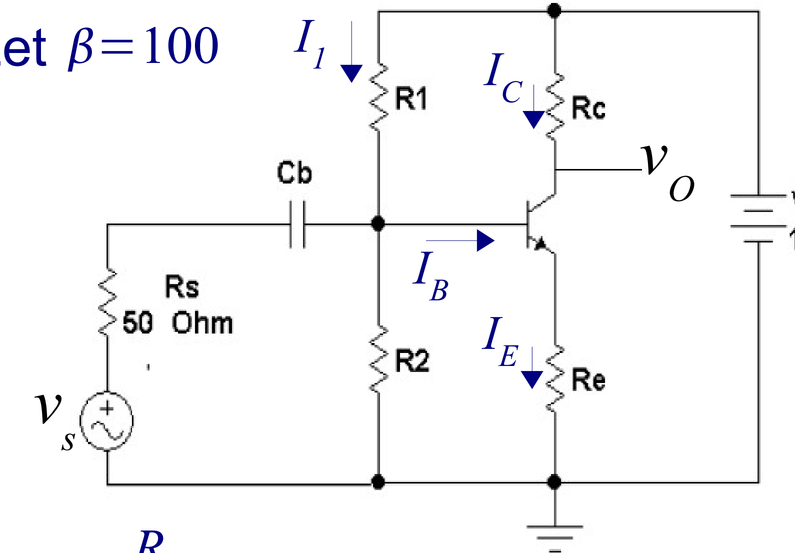
NPN: dc and ac currents in same direction

Small signal model is identical for NPN and PNP transistors!

PNP: dc and ac currents in opposite direction due to vsig polarity

NPN vs. PNP CE Design cont.

Let $\beta = 100$



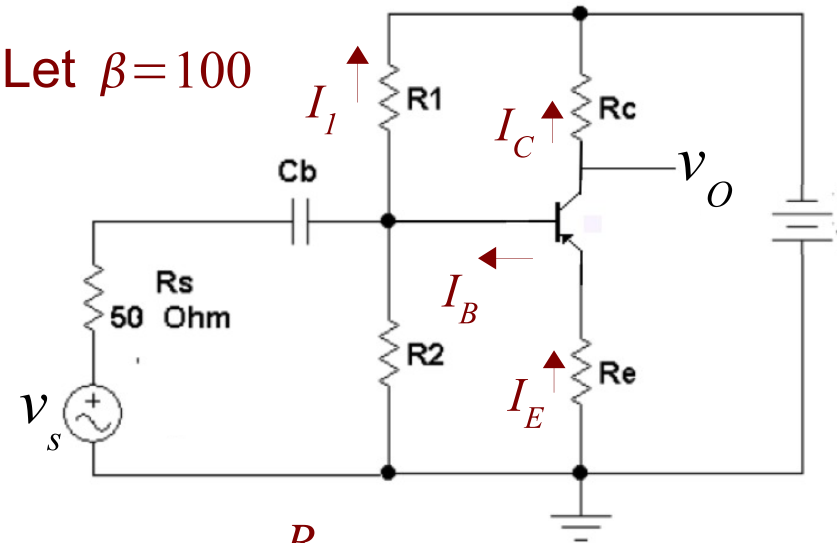
$$V_B = \frac{R_2}{R_2 + R_1} V_{CC} \qquad R_B = R_1 \| R_2$$

$$I_C = \frac{V_{CC} - V_C}{R_C}$$

$$I_C = \beta I_B = \frac{\beta (V_B - V_{BE})}{R_B + (\beta + 1) R_E}$$

$$V_E = V_B - V_{BE} = I_E R_E$$

Let $\beta = 100$



$$V_B = \frac{-R_2}{R_2 + R_1} |V_{CC}| < 0 \qquad R_B = R_1 \| R_2$$

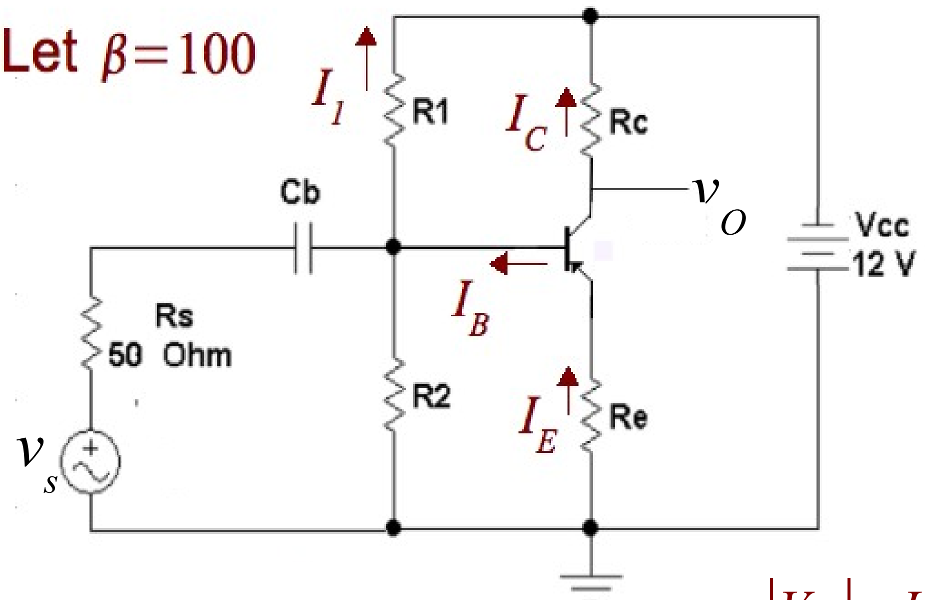
$$I_C = \frac{V_C - (-|V_{CC}|)}{R_C} = \frac{V_C + |V_{CC}|}{R_C} \Rightarrow V_C < 0$$

$$I_C = \beta I_B = \frac{\beta (|V_B| - V_{EB})}{R_B + (\beta + 1) R_E}$$

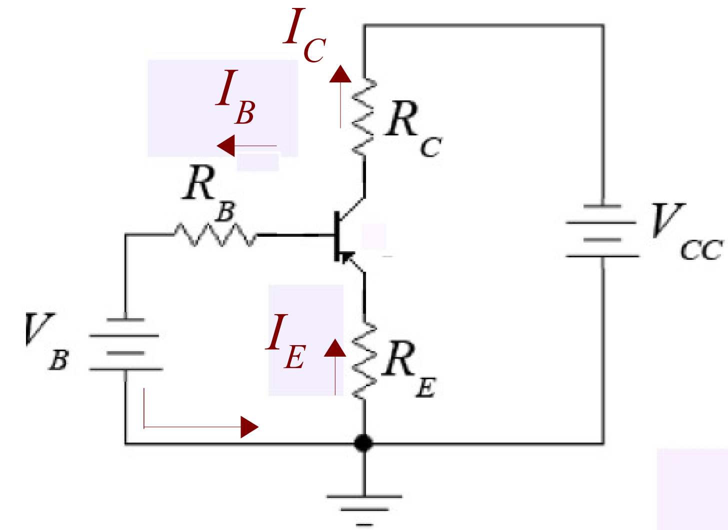
$$V_E = V_{EB} - |V_B| = I_E R_E < 0$$

Base DC Thevenin Equivalent Circuit

Let $\beta=100$



=>



$$|V_B|=I_B R_B+V_{EB}+I_E R_E=(R_B+(\beta+1)R_E)I_B+V_{EB}$$

$$I_B=\frac{|V_B|-V_{EB}}{R_B+(\beta+1)R_E}$$

$$I_C=\beta I_B=\frac{\beta(|V_B|-V_{EB})}{R_B+(\beta+1)R_E}$$

NPN vs. PNP CE Design Conclusions

- DC Bias design same for both NPN & PNP.
- Be careful!
- PNP DC I & V are inverse of NPN DC I & V.
- PNP DC supply voltage V_{CC} polarity is inverse of NPN.
- AC design the same for both NPN & PNP.
- Small signal models are identical.
- Be careful!
- PNP ac current directions are inverse of DC current directions.

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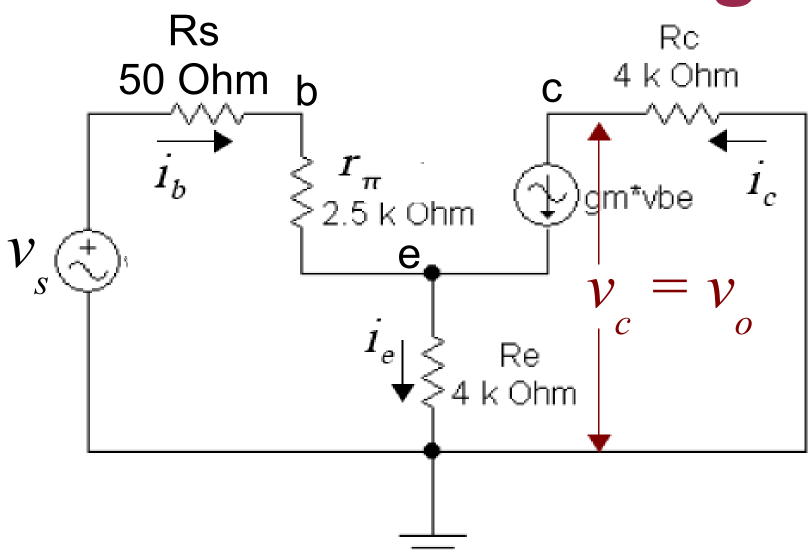
AC Small-Signal CE Voltage Gain



$$v_{be} = i_b r_\pi = \frac{r_\pi}{R_S + r_\pi + (\beta+1) R_E} v_s$$

$$i_c = g_m v_{be} = \frac{g_m r_\pi}{R_S + r_\pi + (\beta+1) R_E} v_s$$

$$v_o = -R_C i_c = \frac{-\beta R_C}{R_S + r_\pi + (\beta+1) R_E} v_s$$

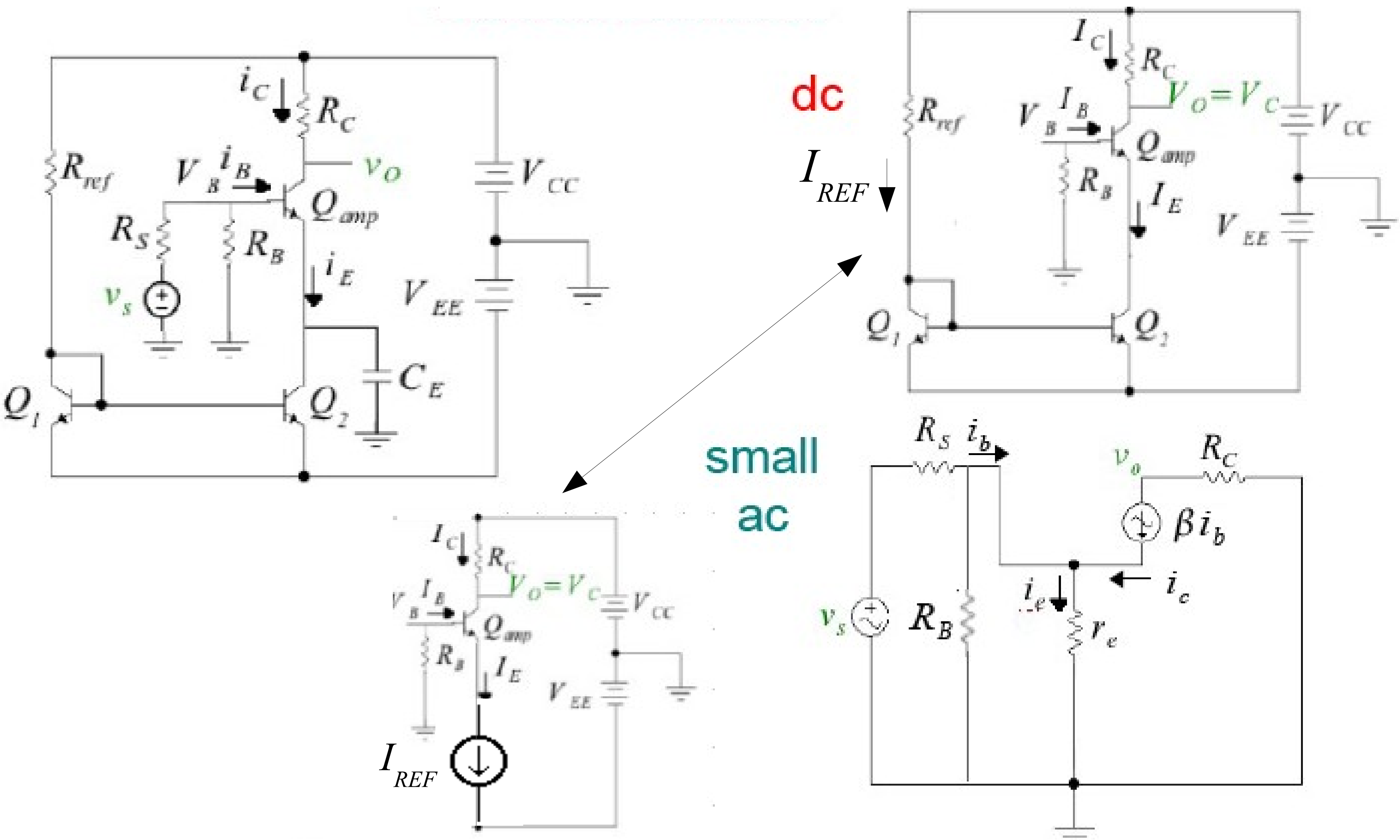
$$g_m r_\pi = \frac{I_C}{V_T} \beta \frac{V_T}{I_C} = \beta$$

$$\beta \approx 100$$

$$v_s = i_b (R_S + r_\pi) + i_b (\beta+1) R_E$$

If $\beta R_E \gg R_S + r_\pi$, $\beta \gg 1$ $\Rightarrow v_o \approx \frac{-\beta R_C}{(\beta+1) R_E} v_s$

$$A_v = \frac{v_o}{v_s} \approx \frac{-R_C}{R_E}$$


dc
small
ac
i_C
R_C
v_O
R_{ref}
V_B
i_B
Q_{amp}
V_{CC}
R_S
R_B
i_E
v_s
V_{EE}
Q_1
Q_2
C_E
I_C
$V_O = V_C$
I_B
I_{REF}
I_E
i_b
v_o
βi_b
i_e
i_c
r_e

Conclusions

- Approximations are encouraged when conditions are satisfied, i.e.

$$\left.\begin{array}{l}\beta R_E \gg R_S + r_\pi \\ \beta \gg 1\end{array}\right] \Rightarrow A_v = \frac{v_o}{v_s} \approx \frac{-R_C}{R_E}$$

- If $R_E = 0$:

$$v_o = -R_C i_c = \frac{-\beta R_C}{R_S + r_\pi + (\beta+1) R_E} v_s$$

If $r_\pi >> R_S$ => $A_V = \frac{v_o}{v_s} \approx -\frac{\beta}{r_\pi} R_C = -g_m R_C$

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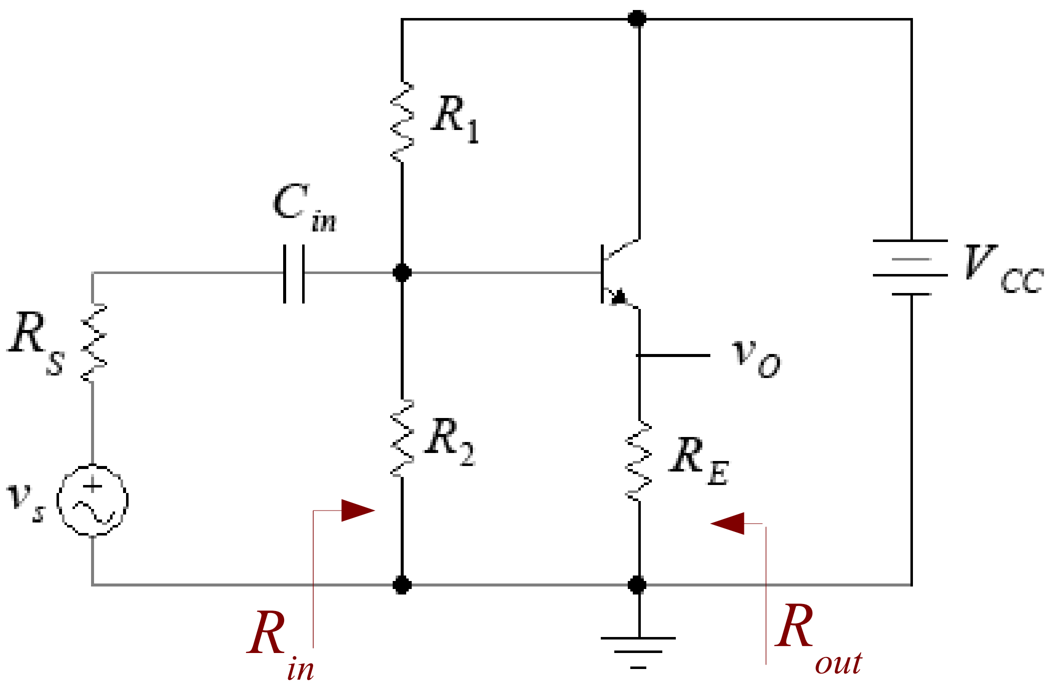
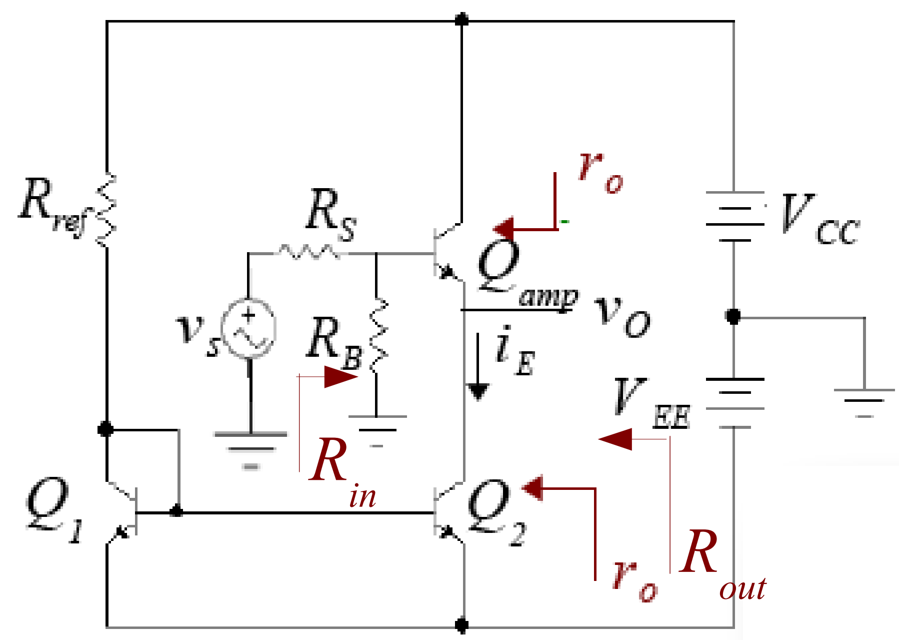
CC Amplifier

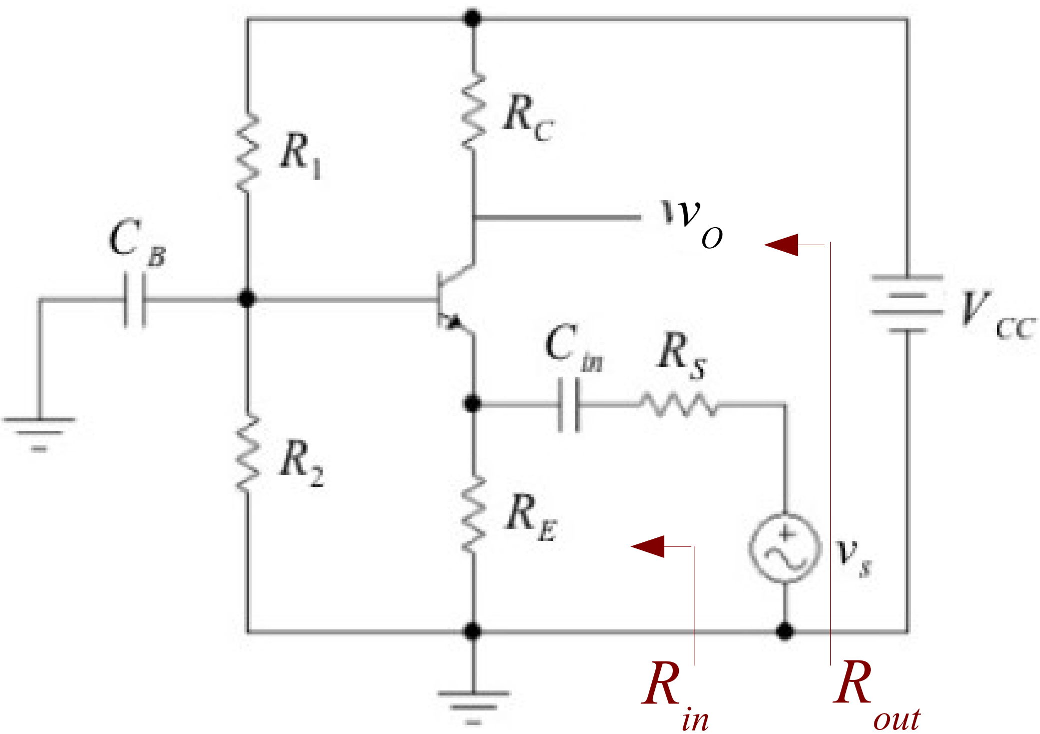


Voltage Bias Design

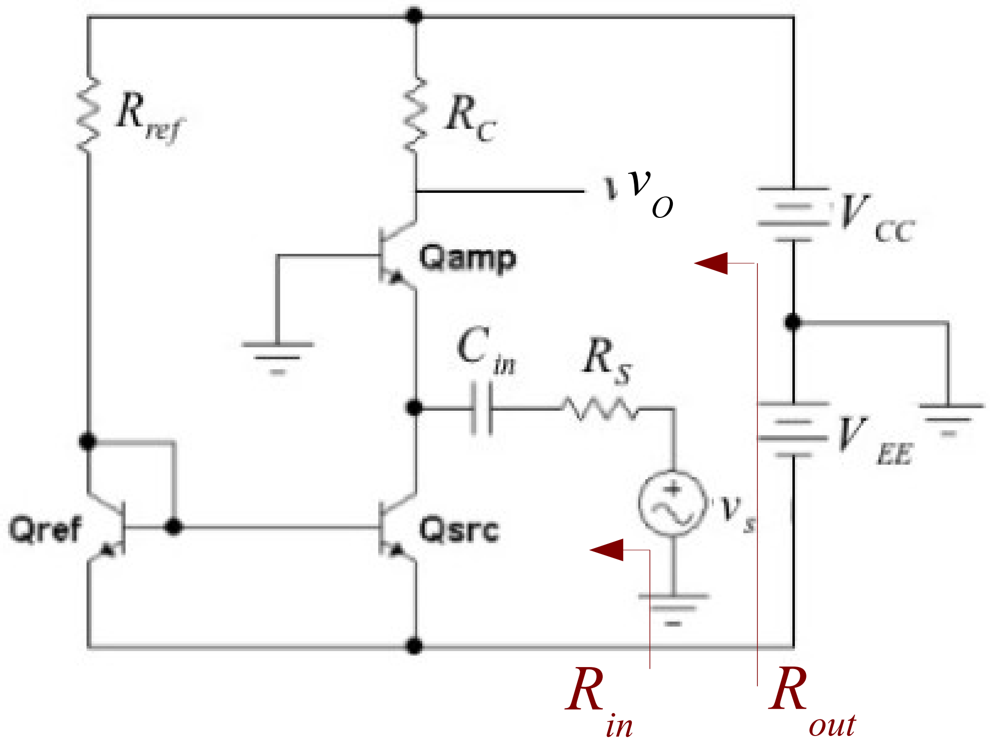


Current Bias Design

CB Amplifier



Voltage Bias Design



Current Bias Design

Conclusions

	CE Amplifier	CC Amplifier	CB Amplifier
Voltage Gain (A_V)	moderate ($-R_C/R_E$)	low (about 1)	high
Current Gain (A_I)	moderate (β)	moderate ($\beta + 1$)	low (about 1)
Input Resistance	high ($R_B \| \| \beta R_E$)	high ($R_B \| \| \beta R_E$)	low ($r_e \| \| R_E$)
Output Resistance	high ($R_C \| \| r_o$)	low (r_e)	high ($R_C \| \| r_o$)
		VCVS	CCCS

**All parameters for ac small signal.