Ex: 11.1 To allow for v_O to reach $-V_{CC} + V_{CE\text{sat}} = -15 + 0.2 = -14.8$ V, with Q_1 just cutting off (i.e. $i_{E1} = 0$),

$$I = \frac{14.8 \text{ V}}{R_L} = \frac{14.8}{1 \text{ k}\Omega} = 14.8 \text{ mA}$$

The value of R can now be found from

$$I = \frac{V_R}{R} = \frac{V_{CC} - V_D}{R}$$

$$14.8 = \frac{15 - 0.7}{R}$$

$$\Rightarrow R = \frac{14.3}{14.8} = 0.97 \text{ k}\Omega$$

The resulting output signal swing will be -14.8 V to $+14.8$ V. The minimum current in $Q_1 = 0$. The maximum current in $Q_1 = 14.8 + 14.8 = 29.6$ mA

Ex: 11.2 At $v_O = -10$ V, we have

$$i_L = \frac{-10}{1} = -10 \text{ mA}$$

$$i_{E1} = I + i_L = 14.8 - 10 = 4.8 \text{ mA}$$

$$v_{BE1} = 0.6 + 0.025 \ln\left(\frac{4.8}{1}\right)$$

$$= 0.64 \text{ V}$$

$$v_I = v_O + v_{BE1}$$

$$= -10 + 0.64 = -9.36 \text{ V}$$

At $v_O = 0$ V, we have

$$i_L = 0 \text{ mA}$$

$$i_{E1} = I = 14.8 \text{ mA}$$

$$v_{BE1} = 0.6 + 0.025 \ln\left(\frac{14.8}{1}\right)$$

$$= 0.67 \text{ V}$$

$$v_I = v_O + v_{BE1}$$

$$= 0 + 0.67 = 0.67 \text{ V}$$

At $v_O = 10$ V

$$i_L = \frac{10}{1} = 10 \text{ mA}$$

$$i_{E1} = I + i_L = 14.8 + 10 = 24.8 \text{ mA}$$

$$v_{BE1} = 0.6 + 0.025 \ln\left(\frac{24.8}{1}\right)$$

$$= 0.68 \text{ V}$$

$$v_I = v_O + v_{BE1}$$

$$= 10 + 0.68 = 10.68 \text{ V}$$

At $v_O = -10$ V, we have

$$i_{E1} = 4.8 \text{ mA}$$

$$r_{e1} = \frac{25 \text{ mV}}{4.8 \text{ mA}} = 5.2 \ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + r_{e1}} = \frac{1}{1 + 0.0052} = 0.995 \text{ V/V}$$

At $v_O = 0$ V,

$$i_{E1} = 14.8 \text{ mA}$$

$$r_{e1} = \frac{25 \text{ mV}}{14.8 \text{ mA}} = 1.7 \ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + r_{e1}} = \frac{1}{1 + 0.0017} = 0.998 \text{ V/V}$$

At $v_O = +10$ V,

$$i_{E1} = 24.8 \text{ mA}$$

$$r_{e1} = \frac{25 \text{ mV}}{24.8 \text{ mA}} = 1.0 \ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + r_{e1}} = \frac{1}{1 + 0.001} = 0.999 \text{ V/V}$$

Ex: 11.3

a. $P_L = \dfrac{\left(\hat{V}_o/\sqrt{2}\right)^2}{R_L} = \dfrac{\left(8/\sqrt{2}\right)^2}{100} = 0.32$ W

$$P_S = 2V_{CC} \times I = 2 \times 10 \times 100 \times 10^{-3}$$

$$= 2 \text{ W}$$

$$\text{Efficiency } \eta = \frac{P_L}{P_S} \times 100$$

$$= \frac{0.32}{2} \times 100$$

$$= 16\%$$

Ex: 11.4 (a) $P_L = \dfrac{1}{2}\dfrac{\hat{V}_o^2}{R_L}$

$$= \frac{1}{2}\frac{(4.5)^2}{4} = 2.53 \text{ W}$$

(b) $P_{S+} = P_{S-} = V_{CC} \times \dfrac{1}{\pi}\dfrac{\hat{V}_o}{R_L}$

$$= 6 \times \frac{1}{\pi} \times \frac{4.5}{4} = 2.15 \text{ W}$$

(c) $\eta = \dfrac{P_L}{P_S} \times 100 = \dfrac{2.53}{2 \times 2.15} \times 100$

$$= 59\%$$

(d) Peak input currents $= \dfrac{1}{\beta + 1}\dfrac{\hat{V}_o}{R_L}$

$$= \frac{1}{51} \times \frac{4.5}{4}$$

$$= 22.1 \text{ mA}$$

(e) Using Eq. (11.22), we obtain

$$P_{DN\max} = P_{DP\max} = \frac{V_{CC}^2}{\pi^2 R_L}$$

$$= \frac{6^2}{\pi^2 \times 4} = 0.91 \text{ W}$$

Ex: 11.5 (a) The quiescent power dissipated in each transistor $= I_Q \times V_{CC}$

Total power dissipated in the two transistors

$= 2I_Q \times V_{CC}$

$= 2 \times 2 \times 10^{-3} \times 15$

$= 60$ mW

(b) I_Q is increased to 10 mA

At $v_O = 0$, we have $i_N = i_P = 10$ mA

From Eq. (11.31), we obtain

$$R_{\text{out}} = \frac{V_T}{i_P + i_N} = \frac{25}{10+10} = 1.25\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{\text{out}}} = \frac{100}{100+1.25}$$

$$\frac{v_o}{v_i} = 0.988 \text{ at } v_O = 0 \text{ V}$$

At $v_O = 10$ V, we have

$$i_L = \frac{10\text{ V}}{100\ \Omega} = 0.1\text{ A} = 100\text{ mA}$$

Use Eq. (11.27) to calculate i_N:

$$i_N^2 - i_N i_L - I_Q^2 = 0$$

$$i_N^2 - 100\, i_N - 10^2 = 0$$

$$\Rightarrow i_N = 101.0\ \text{mA}$$

Using Eq. (11.26), we obtain

$$i_P = \frac{I_Q^2}{i_N} \simeq 1\text{ mA}$$

$$R_{\text{out}} = \frac{V_T}{i_N + i_P} = \frac{25}{101.0+1} \simeq 0.2451\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{\text{out}}} = \frac{100}{100+0.2451} \simeq 1$$

$$\%\text{ change} = \frac{1-0.988}{1} \times 100 = 1.2\%$$

In Example 11.3, $I_Q = 2$ mA, and for $v_O = 0$

$$R_{\text{out}} = \frac{V_T}{i_N + i_P} = \frac{25}{2+2} = 6.25\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{\text{out}}} = \frac{100}{100+6.25} = 0.94$$

$v_O = 10$ V

$$i_L = \frac{10\text{ V}}{100\ \Omega} = 100\text{ mA}$$

Again calculate i_N (for $I_Q = 2$ mA) using Eq. (11.27) ($i_N = 100.04$ mA):

$$i_P = \frac{I_Q^2}{I_N} = \frac{2^2}{100.04} = 0.04\text{ mA}$$

$$R_{\text{out}} = \frac{V_T}{i_N + i_P} = \frac{25}{100.04+0.04} = 0.25\ \Omega$$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{\text{out}}} \simeq 1$$

$$\%\text{ Change} = \frac{1-0.94}{1} \times 100 = 6\%$$

For $I_Q = 10$ mA, change is 1.2%

For $I_Q = 2$ mA, change is 6%

(c) The quiesent power dissipated in each transistor $= I_Q \times V_{CC}$

Total power dissipated $= 2 \times 10 \times 10^{-3} \times 15$

$= 300$ mW

Ex: 11.6 From Example 11.4, we have $V_{CC} = 15$ V,
$R_L = 100\ \Omega$

Q_N and Q_P matched and $I_S = 10^{-13}$ A and $\beta = 50$, $I_{\text{Bias}} = 3$ mA

For $v_O = 10$ V, we have $i_L = \dfrac{10}{100} = 0.1$ A

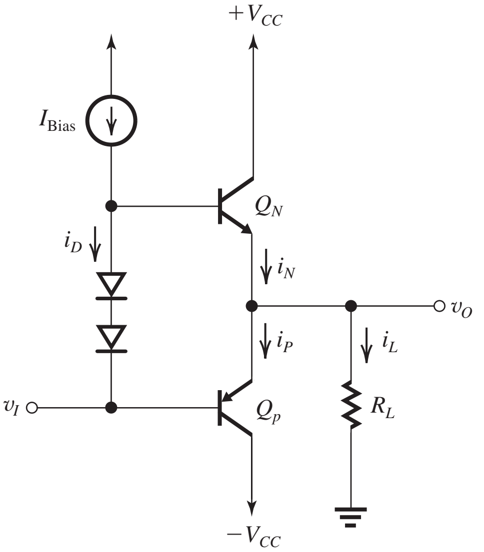
As a first approximation, $i_N \simeq 0.1$ A,

$$i_P = 0,\ i_{BN} \simeq \frac{0.1\text{ A}}{50+1} \simeq 2\text{ mA}$$

$$i_D = I_{\text{Bias}} - i_{BN} = 3 - 2 = 1\text{ mA}$$

$$V_{BB} = 2V_T \ln\left(\frac{10^{-3}}{\frac{1}{3} \times 10^{-13}}\right) \quad (1)$$

This $\frac{1}{3}$ is because biasing diodes have $\frac{1}{3}$ area of the output devices.



But $V_{BB} = V_{BEN} + V_{BEP}$

$= V_T \ln\left(\frac{i_N}{I_S}\right) + V_T \ln\left(\frac{i_N - i_L}{I_S}\right)$

$= V_T \ln\left[\frac{i_N\ (i_N - i_L)}{I_S^2}\right]$ (2)

Equating Eqs. 1 and 2, we obtain

$$2V_T \ln\left(\frac{10^{-3}}{\frac{1}{3} \times 10^{-13}}\right) = V_T \ln\left[\frac{i_N (i_N - i_L)}{I_S^2}\right]$$

$$\left(\frac{10^{-3}}{\frac{1}{3} \times 10^{-13}}\right)^2 = \frac{i_N\ (i_N - 0.1)}{\left(10^{-13}\right)^2}$$

$i_N (i_N - 0.1) = 9 \times 10^{-6}$

If i_N is in mA, then

$i_N (i_N - 100) = 9$

$i_N^2 - 100\ i_N - 9 = 0$

$\Rightarrow i_N = 100.1$ mA

$i_P = i_N - i_L = 0.1$ mA

For $v_O = -10$ V and $i_L = \frac{-10}{100} = -0.1$ A

$= -100$ mA:

As a first approximation assume $i_P \cong 100$ mA,

$i_N \simeq 0$. Since $i_N = 0$, current through diodes $= 3$ mA

$$\therefore V_{BB} = 2V_T \ln\left(\frac{3 \times 10^{-3}}{\frac{1}{3} \times 10^{-13}}\right) \quad (3)$$

But $V_{BB} = V_T \ln\left(\frac{i_N}{10^{-13}}\right) + V_T \ln\left(\frac{i_P}{10^{-13}}\right)$

$= V_T \ln\left(\frac{i_P + i_L}{10^{-13}}\right) + V_T \ln\left(\frac{i_P}{10^{-13}}\right)$ (4)

Here $i_L = -0.1$ A

Equating Eqs. (3) and (4), we obtain

$$2V_T \ln\left(\frac{3 \times 10^{-3}}{\frac{1}{3} \times 10^{-13}}\right) =$$

$$V_T \ln\left(\frac{i_P - 0.1}{10^{-13}}\right) + V_T \ln\left(\frac{i_P}{10^{-13}}\right)$$

$$\left(\frac{3 \times 10^{-3}}{\frac{1}{3} \times 10^{-13}}\right)^2 = \frac{i_P\ (i_P - 0.1)}{\left(10^{-13}\right)^2}$$

$i_P (i_P - 0.1) = 81 \times 10^{-6}$

Expressing currents in mA, we have

$i_P\ (i_P - 100) = 81$

$i_P^2 - 100\ i_P - 81 = 0$

$\Rightarrow i_P = 100.8$ mA

$i_N = i_P + i_L = 0.8$ mA

Ex: 11.7 $\Delta I_C = g_m \times 2$ mV/°C $\times 5$ °C, mA

where g_m is in mA / mV

$g_m = \frac{10 \text{ mA}}{25 \text{ mV}} = 0.4$ mA/mV

Thus, $\Delta I_C = 0.4 \times 2 \times 5 = 4$ mA

Ex: 11.8 Refer to Fig. 11.15.

(a) To obtain a terminal voltage of 1.2 V, and since β_1 is very large, it follows that $V_{R1} = V_{R2} = 0.6$ V.

Thus $I_{C1} = 1$ mA

$I_R = \frac{1.2 \text{ V}}{R_1 + R_2} = \frac{1.2}{2.4} = 0.5$ mA

Thus, $I = I_{C1} + I_R = 1.5$ mA

(b) For $\Delta V_{BB} = +50$ mV:

$V_{BB} = 1.25$ V $\ I_R = \frac{1.25}{2.4} = 0.52$ mA

$V_{BE} = \frac{1.25}{2} = 0.625$ V

$I_{C1} = 1 \times e^{\Delta V_{BE}/V_T} = e^{0.025/0.025}$

$= 2.72$ mA

$I = 2.72 + 0.52 = 3.24$ mA

For $\Delta V_{BB} = +100$ mV, we have

$V_{BB} = 1.3$ V, $\quad I_R = \frac{1.3}{2.4} = 0.54$ mA

$V_{BE} = \frac{1.3}{2} = 0.65$ V

$I_{C1} = 1 \times e^{\Delta V_{BE}/V_T} = 1 \times e^{0.05/0.025}$

$= 7.39$ mA

$I = 7.39 + 0.54 = 7.93$ mA

For $\Delta V_{BB} = +200$ mV:

$V_{BB} = 1.4$ V, $\quad I_R = \frac{1.4}{2.4} = 0.58$ mA

$V_{BE} = 0.7$ V

$I_{C1} = 1 \times e^{0.1/0.025} = 54.60$ mA

$I = 54.60 + 0.58 = 55.18$ mA

For $\Delta V_{BB} = -50$ mV:

$V_{BB} = 1.15$ V, $\quad I_R = \frac{1.15}{2.4} = 0.48$ mA

$V_{BE} = \frac{1.15}{2}$

$= 0.575$

$I_{C1} = 1 \times e^{-0.025/0.025} = 0.37$ mA

$I = 0.48 + 0.37 = 0.85$ mA

For $\Delta V_{BB} = -100$ mV:

$V_{BB} = 1.1$ V $\quad I_R = \frac{1.1}{2.4} = 0.46$ mA

$V_{BE} = 0.55$ V

$I_{C1} = 1 \times e^{-0.05/0.025} = 0.13$ mA

$I = 0.46 + 0.13 = 0.59$ mA

For $\Delta V_{BB} = -200$ mV:

$V_{BB} = 1.0$ V $\ I_R = \frac{1}{2.4} = 0.417$ mA

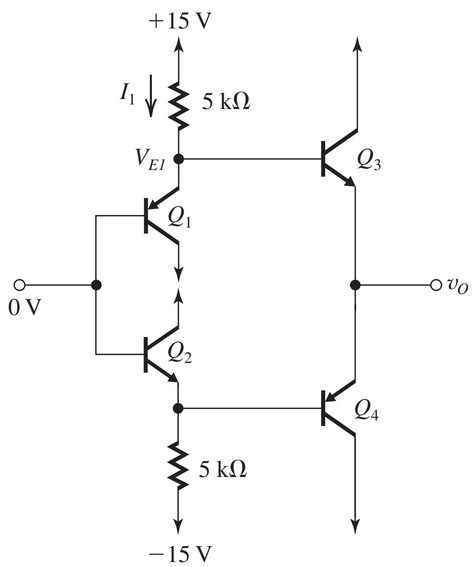
$V_{BE} = 0.5$ V

$I_{C1} = 1 \times e^{-0.1/0.025} = 0.018$ mA

$I = 0.43$ mA

Ex: 11.9 (a) From symmetry we see that all transistors will conduct equal currents and have equal V_{BE}'s. Thus,

$v_O = 0$ V



If $V_{BE} \simeq 0.7$ V, then

$V_{E1} = 0.7$ V and $I_1 = \frac{15 - 0.7}{5} = 2.86$ mA

If we neglect I_{B3}, then

$I_{C1} \simeq 2.86$ mA

At this current, $|V_{BE}|$ is given by

$|V_{BE}| = 0.025 \ln\left(\frac{2.86 \times 10^{-3}}{3.3 \times 10^{-14}}\right) \simeq 0.63$ V

Thus $V_{E1} = 0.63$ V and $I_1 = 2.87$ mA

No more iterations are required and

$i_{C1} = i_{C2} = i_{C3} = i_{C4} \simeq 2.87$ mA

(b) For $v_I = +10$ V:

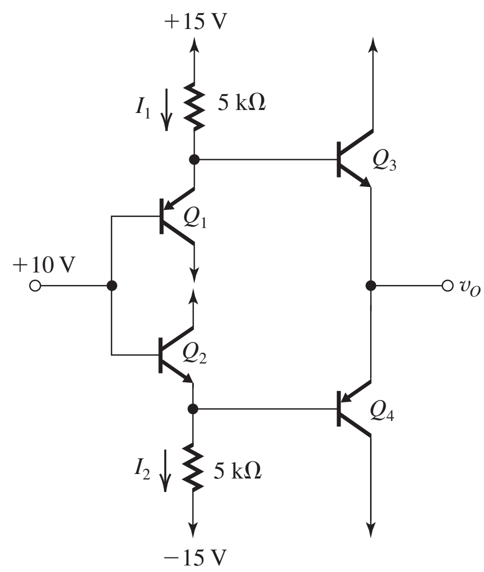
To start the iterations, let $V_{BE1} \simeq 0.7$ V

Thus,

$V_{E1} = 10.7$ V

and

$I_1 = \frac{15 - 10.7}{5} = 0.86$ mA



Neglecting I_{B3}, we obtain

$I_{C1} \simeq I_{E1} \simeq I_1 = 0.86$ mA

But at this current

$|V_{BE1}| = V_T \ln\left(\frac{I_{C1}}{I_S}\right)$

$= 0.025 \ln\left(\frac{0.86 \times 10^{-3}}{3.3 \times 10^{-14}}\right)$

$= 0.6$ V

Thus, $V_{E1} = +10.6$ V and $I_1 = 0.88$ mA. No further iterations are required and $I_{C1} \simeq 0.88$ mA.

To find I_{C2}, we use an identical procedure:

$V_{BE2} \simeq 0.7$ V

$V_{E2} = 10 - 0.7 = +9.3$ V

$I_2 = \frac{9.3 - (-15)}{5} = 4.86$ mA

$V_{BE2} = 0.025 \ln\left(\frac{4.86 \times 10^{-3}}{3.3 \times 10^{-14}}\right)$

$= 0.643$ V

$V_{E2} = 10 - .643 = +9.357$

$I_2 = 4.87$ mA

$I_{C2} \simeq 4.87$ mA

Finally,

$I_{C3} = I_{C4} = 3.3 \times 10^{-14}\ \mathrm{e}^{V_{BE}/V_T}$

where

$V_{BE} = \frac{V_{E1} - V_{E2}}{2} = 0.62$ V

Thus, $I_{C3} = I_{C4} = 1.95$ mA

The symmetry of the circuit enables us to find the values for $v_I = -10$ V as follows:

$I_{C1} = 4.87$ mA $I_{C2} = 0.88$ mA

$I_{C3} = I_{C4} = 1.95$ mA

For $v_I = +10$ V, we have $v_O = V_{E1} - V_{BE3}$

$= 10.6 - 0.62 = +9.98$ V

For $v_I = -10$ V, we have $v_O = V_{E1} - V_{BE3}$

$= -9.357 - 0.62 = -9.98$ V

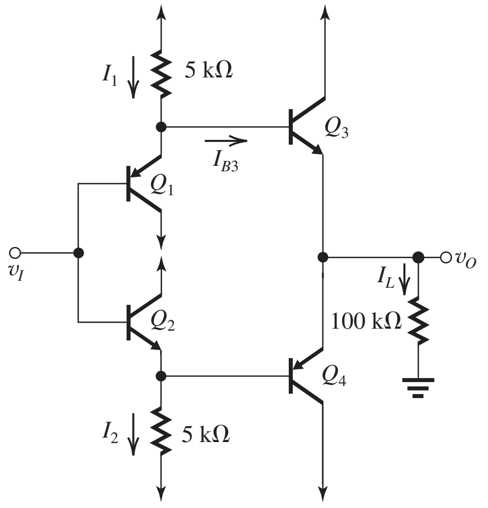
(c) For $v_I = +10$ V, we have

$v_O \simeq 10$ V

$I_L \simeq 100$ mA

$I_{C3} \simeq 100$ mA

$I_{B3} = \frac{100}{201} \simeq 0.5$ mA



Assuming that $|V_{BE1}|$ has not changed much from 0.6 V, then

$V_{E1} \simeq 10.6$ V

$I_1 = \frac{15 - 10.6}{5} = 0.88$ mA

$I_{E1} = I_1 - I_{B3} = 0.88 - 0.5 = 0.38$ mA

$I_{C1} \simeq 0.38$ mA

$|V_{BE1}| = 0.025 \ln\left(\frac{0.38 \times 10^{-3}}{3.3 \times 10^{-14}}\right)$

$= 0.58$ V

$V_{E1} = 10.58$ V

$I_1 = \frac{15 - 10.58}{5} = 0.88$ mA

Thus, $I_{C1} \simeq 0.38$ mA

Now for Q_2 we have

$V_{BE2} = 0.643$ V

$V_{E2} = 10 - 0.643 = 9.357$

$I_2 = 4.87$ mA

$I_{B4} \simeq 0$

$I_{C2} \simeq 4.87$ mA (as in (b))

Assuming that $I_{C3} \simeq 100$ mA, we have

$V_{BE3} = 0.025 \ln\left(\frac{100 \times 10^{-3}}{3.3 \times 10^{-14}}\right)$

$= 0.72$ V

Thus, $v_O = V_{E1} - V_{BE3}$

$= 10.58 - 0.72 = +9.86$ V

$|V_{BE4}| = v_O - V_{E2}$

$9.86 - 9.36 = 0.5$ V

Thus, $I_{C4} = 3.3 \times 10^{-14} e^{0.5/0.025}$

$\simeq 0.02$ mA

From symmetry we find the values for the case

$v_I = -10$ V as:

$I_{C1} = 4.87$ mA, $\quad I_{C2} = 0.38$ mA

$I_{C3} = 0.02$ mA, $\quad I_{C4} = 100$ mA

$v_O = -9.86$ V.

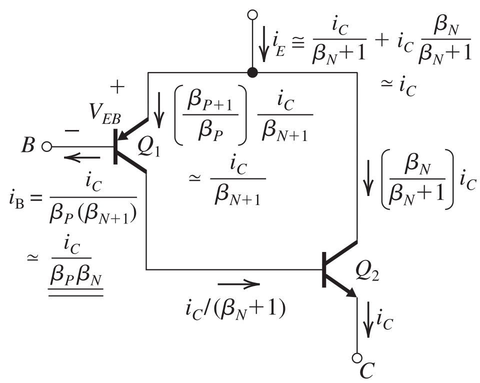
Ex: 11.10 For Q_1:

$i_{C1} = I_{SP} e^{v_{EB}/V_T}$

$\frac{i_C}{\beta_N + 1} = I_{SP} e^{v_{EB}/V_T}$

$i_C \simeq \beta_N I_{SP} e^{v_{EB}/V_T}$

Thus, effective scale current $= \beta_N I_{SP}$



(b) Effective current gain $\equiv \dfrac{i_C}{i_B} = \beta_P \beta_N$

$= 20 \times 50 = 1000$

$100 \times 10^{-3} = 50 \times 10^{-14}\ e^{v_{EB}/0.025}$

$v_{EB} = 0.025 \ln\left(2 \times 10^{11}\right)$

$= 0.651$ V

Ex: 11.11 See Figure 11.21

When $V_{BE5} = 150 \times 10^{-3} \times R_{E1}$, then $I_{CS} = I_{\text{Bias}}$

$= 2$ mA

$$V_{BE5} = V_T \ln\left(\frac{I_{C5}}{I_S}\right)$$

$$= 25 \times 10^{-3} \ln\left(\frac{2 \times 10^{-3}}{10^{-14}}\right)$$

$= 0.651$ V

$150 \times 10^{-3}\ R_{E1} = 0.651$

$R_{E1} = 4.34\ \Omega$

If peak output current = 100 mA

$V_{BE5} = R_{E1} \times 100 \text{ mA} = 4.34 \times 100 \times 10^{-3}$

$= 0.434$ V

$i_{C5} = I_S e^{V_{BE5}/V_T}$

$= 10^{-14} e^{0.434/25\times 10^{-3}}$

$\simeq 0.35\ \mu$A

Ex: 11.12 Using Eq. (11.43), we obtain

$$I_Q = I_{\text{Bias}} \frac{(W/L)_n}{(W/L)_1}$$

$$1 = 0.2\ \frac{(W/L)_n}{(W/L)_P}$$

$$\frac{(W/L)_n}{(W/L)_1} = 5$$

$$Q_1\colon I_{\text{Bias}} = \frac{1}{2} k_n' \left(\frac{W}{L}\right)_1 (V_{GS} - V_{tn})^2$$

$$0.2 = \frac{1}{2} \times 0.250 \left(\frac{W}{L}\right)_1 (0.2)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_1 = 40$$

$$Q_2\colon I_{\text{Bias}} = \frac{1}{2} k_P' \left(\frac{W}{L}\right)_2 (V_{GS} - |V_t|)^2$$

$$0.2 = \frac{1}{2} \times 0.100 \times \left(\frac{W}{L}\right)_2 \times (0.2)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_2 = 100$$

$$Q_N\colon I_Q = \frac{1}{2} k_n' \left(\frac{W}{L}\right)_N (V_{GS} - V_t)^2$$

$$1 = \frac{1}{2} \times 0.250 \times \left(\frac{W}{L}\right)_n 0.2^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_n = 200$$

$$Q_P\colon I_Q = \frac{1}{2} k_p' \left(\frac{W}{L}\right)_p (V_{GS} - |V_t|)^2$$

$$1 = \frac{1}{2} \times 0.100 \times \left(\frac{W}{L}\right)_p \times 0.2^2$$

$$\left(\frac{W}{L}\right)_p = 500$$

Now $V_{GG} = V_{\text{GS1}} + V_{\text{GS2}}$

$= (V_{\text{ov1}} + V_t) + (V_{\text{ov2}} + |V_t|)$

$= (0.2 + 0.5) + (0.2 + 0.5)$

$= 1.4$ V

Ex: 11.13 $I_N = i_{L\max} = 10$ mA

$$\therefore\ 10 = \frac{1}{2} k_n' \left(\frac{W}{L}\right)_n V_{OV}^2$$

$$10 = \frac{1}{2} \times 0.250 \times 200 \times V_{OV}^2$$

$\Rightarrow V_{OV} = 0.63$ V

Using equation 11.46, we obtain

$v_{O\max} = V_{DD} - V_{OV}|_{\text{Bias}} - V_{tn} - V_{OVN}$

$= 2.5 - 0.2 - 0.5 - 0.63$

$= 1.17$ V

Ex: 11.14 New values of W/L are

$$\left(\frac{W}{L}\right)_P = \frac{2000}{2} = 1000$$

$$\left(\frac{W}{L}\right)_N = \frac{800}{2} = 400$$

$$I_Q = \frac{1}{2}k_p'\left(\frac{W}{L}\right)_P V_{OV}^2$$

$$1 \times 10^{-3} = \frac{1}{2} \times 0.1 \times 10^{-3} \times 1000 \times V_{OV}^2$$

$$\Rightarrow V_{OV} = 0.14 \text{ V}$$

Gain error

$$= -\frac{V_{OV}}{4\mu I_Q R_L} = -\frac{0.14}{4 \times 10 \times 1 \times 10^{-3} \times 100}$$

$$= -0.035$$

Gain error $= -0.035 \times 100 = -3.5\%$

$$g_{mn} = g_{mp} = \frac{2I_Q}{V_{OV}} = \frac{2 \times 1 \times 10^{-3}}{0.14}$$

$$= 14.14 \text{ mA/V}$$

$$R_{\text{out}} = \frac{1}{\mu\left(g_{mp} + g_{mn}\right)}$$

$$= \frac{1}{10 \times\ (14.14 + 14.14) \times 10^{-3}}$$

$$\simeq 3.5\ \Omega$$

Ex: 11.15 Total current into node $B = \dfrac{2v_i}{R_3} + \dfrac{v_o}{R_2}$

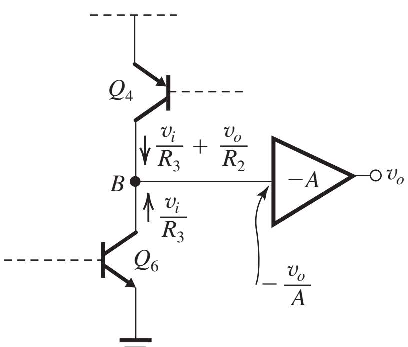
Thus

$$\left(\frac{2v_i}{R_3} + \frac{v_o}{R_2}\right)R = -\frac{v_o}{\text{A}}$$

$$\Rightarrow v_o\left(\frac{1}{A} + \frac{R}{R_2}\right) = -\frac{2R}{R_3}v_i$$

$$\frac{v_o}{v_i} = \frac{-\dfrac{2R}{R_3}}{\dfrac{1}{A} + \dfrac{R}{R_2}}$$

$$= \frac{-2R_2/R_3}{1 + (R_2/AR)} \qquad \text{Q.E.D.}$$



For $AR \gg R_2$, we have

$$\frac{v_o}{v_i} \simeq -\frac{2R_2}{R_3}$$

Ex: 11.16 From Fig. 11.31 we see that for $P_{\text{dissipation}}$ to be less than 2.9 W, a maximum supply voltage of 20V is called for. The 20-V-supply curve intersects the 3% distoration line at a point for which the output power is 4.2 W. Since

$$P_L = \frac{\left(\hat{V}_o/\sqrt{2}\right)^2}{R_L}$$

we have $\hat{V}_o = \sqrt{4.2 \times 2 \times 8} = 8.2$ V

or 16.4 V peak-to-peak

Ex: 11.17 Voltage gain $= 2$ K

where $K = \dfrac{R_4}{R_3} = 1 + \dfrac{R_2}{R_1} = 1.5$

Thus, $A_v = 3$ V/V

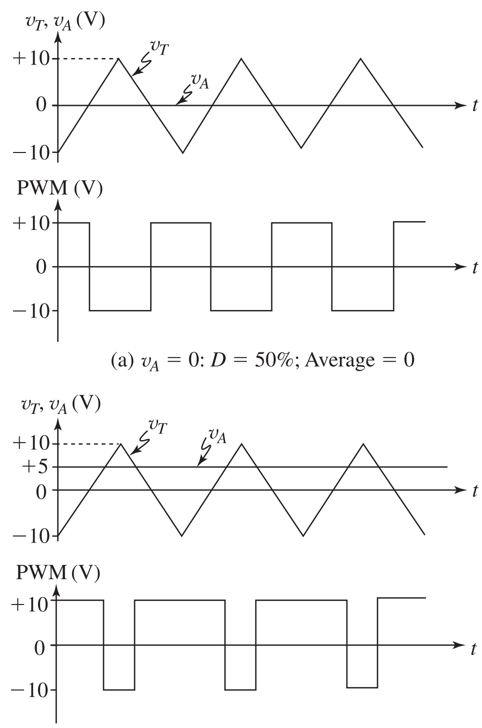
Input resistance = $R_3 = 10$ kΩ

Peak-to-Peak $v_o = 3 \times 20 = 60$ V

Peak load current $= \dfrac{30 \text{ V}}{8\ \Omega} = 3.75$ A

$$P_L = \frac{\left(30/\sqrt{2}\right)^2}{8} = 56.25 \text{ W}$$

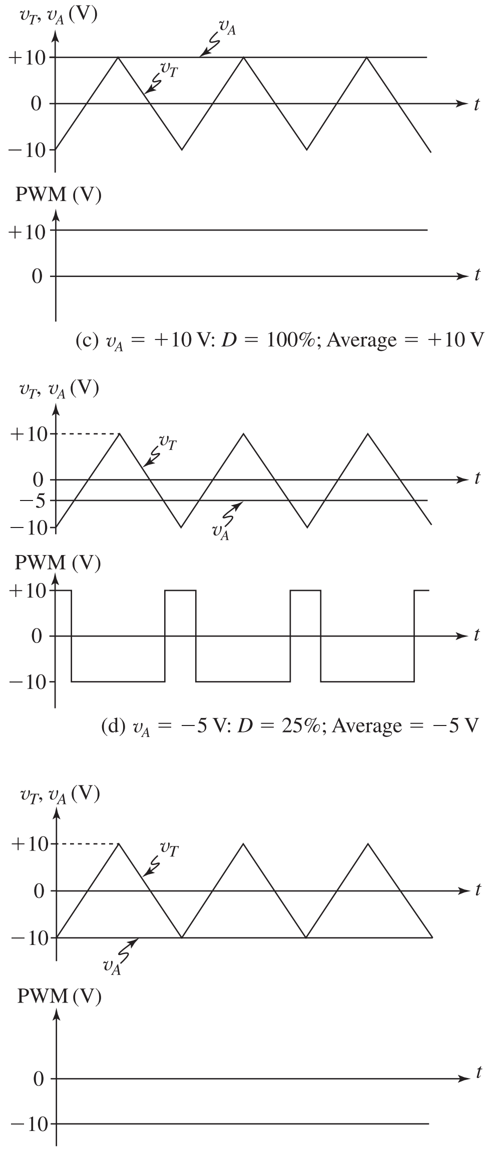
Ex: 11.18 See Fig. 1.



(a) $v_A = 0$: $D = 50\%$; Average $= 0$

(b) $v_A = +5$ V: $D = 75\%$; Average $= +5$ V

Figure 1 *continued*



(c) $v_A = +10$ V: $D = 100\%$; Average $= +10$ V

(d) $v_A = -5$ V: $D = 25\%$; Average $= -5$ V

(e) $v_A = -10$ V: $D = 0\%$; Average $= -10$ V

Figure 1

Ex: 11.19
$f_s = 10 \times$ highest frequency in audio signal

$= 10 \times 20 = 200$ kHz

Since f_s is a decade higher than f_P, the gain will have fallen by 40 dB. Thus the PWM component at f_s will be attenuated by 40 dB.

Ex: 11.20 Maximum peak amplitude $= V_{DD}$

Maximum power delivered to $R_L = \dfrac{(V_{DD}/\sqrt{2})^2}{R_L}$

$= \dfrac{V_{DD}^2}{2R_L}$

For $V_{DD} = 35$ V and $R_L = 8\ \Omega$:

Peak amplitude $= 35$ V

Maximum power $= \dfrac{35^2}{2 \times 8} = 76.6$ W

Power delivered by power supplies

$= \dfrac{P_L}{\eta} = \dfrac{76.6}{0.9} = 85.1$ W

Ex: 11.21 $T_J - T_A = \theta_{JA} P_D$

$200 - 25 = \theta_{JA} \times 50$

$\theta_{JA} = \dfrac{175}{50} = 3.5°\text{C/W}$

But, $\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA}$

$3.5 = 1.4 + 0.6 + \theta_{SA}$

$\Rightarrow \theta_{SA} = 1.5°\text{C/W}$

$T_J - T_C = \theta_{JC} \times P_D$

$T_C = T_J - u_{JC} \times P_D$

$= 200 - 1.4 \times 50$

$= 130°\text{C}$

11.1 $I = \dfrac{0 - (-V_{CC}) - V_D}{R}$

$= \dfrac{10 - 0.7}{1} = 9.3$ mA

Upper limit on $v_O = V_{CC} - V_{CE\text{sat}}$

$= 10 - 0.3 = 9.7$ V

Corresponding input $= 9.7 + 0.7 = 10.4$ V

Lower limit on $v_O = -IR_L = -9.3 \times 1$

$= -9.3$ V

Corresponding input $= -9.3 + 0.7 = -8.6$ V

If the EBJ area of Q_3 is twice as large as that of Q_2, then

$I = \dfrac{1}{2} \times 9.3 = 4.65$ mA

There will be no change in $v_{O\max}$ and in the corresponding value of v_I. However, $v_{O\min}$ will now become

$v_{O\min} = -IR_L$

$= -4.65 \times 1 = -4.65$ V

and the corresponding value of v_I will be

$v_I = -4.65 + 0.7 = -3.95$ V

If the EBJ area of Q_3 is made half as big as that of Q_2, then

$I = 4 \times 9.3 = 18.6$ mA

There will be no change in $v_{O\max}$ and in the corresponding value of v_I. However, $v_{O\min}$ will now become

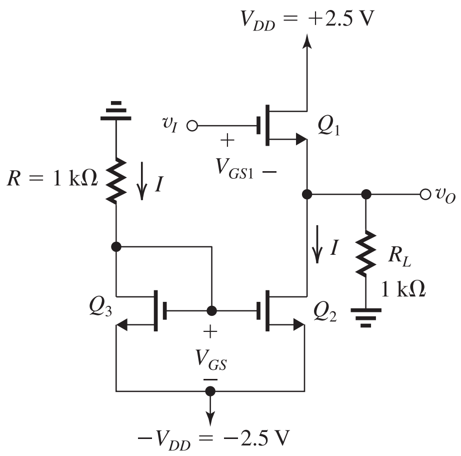
$v_{O\min} = -V_{CC} + V_{CE\text{sat}}$

$= -10 + 0.3 = -9.7$ V

and the corresponding value of v_I will be

$v_I = -9.7 + 0.7 = -9$ V

11.2 First we determine the bias current I as follows:



$I = \dfrac{1}{2}\mu_n C_{ox}\left(\dfrac{W}{L}\right)(V_{GS} - V_t)^2$

But

$V_{GS} = 2.5 - IR = 2.5 - I$

Thus

$I = \dfrac{1}{2}\mu_n C_{ox}\left(\dfrac{W}{L}\right)(2.5 - I - V_t)^2$

$= \dfrac{1}{2} \times 20(2.5 - I - 0.5)^2$

$I = 10(2 - I)^2$

$\Rightarrow I^2 - 4.1I + 4 = 0$

$I = 1.6$ mA and $V_{GS} = 0.9$ V

The upper limit on v_O is determined by Q_1 leaving the saturation region (and entering the triode region). This occurs when v_I exceeds V_{DD} by V_t volts:

$v_{I\max} = 2.5 + 0.5 = 3$ V

To obtain the corresponding value of v_O, we must find the corresponding value of V_{GS1}, as follows:

$v_O = v_I - V_{GS1}$

$i_L = \dfrac{v_O}{R_L} = \dfrac{v_I - V_{GS1}}{R_L} = \dfrac{v_I - V_{GS1}}{1}$

$i_L = 3 - V_{GS1}$

$i_{D1} = i_L + I = 3 - V_{GS1} + 1.6$

$= 4.6 - V_{GS1}$

But,

$i_{D1} = \dfrac{1}{2}\mu_n C_{ox}\left(\dfrac{W}{L}\right)(V_{GS1} - V_t)^2$

$4.6 - V_{GS1} = \dfrac{1}{2} \times 20(V_{GS1} - 0.5)^2$

$\Rightarrow V_{GS1}^2 - 0.9V_{GS1} - 0.21 = 0$

$V_{GS1} = 1.09$ V

$v_{O\max} = v_{I\max} - V_{GS1}$

$= 3 - 1.09 = +1.91$ V

The lower limit of v_O is determined either by Q_1 cutting off,

$v_O = -IR_L = -1.6 \times 1 = -1.6$ V

or by Q_2 leaving saturation,

$v_O = -V_{DD} + V_{OV2}$

where

$V_{OV2} = V_{GS2} - V_t = 0.9 - 0.5 = 0.4$ V

Thus,

$v_O = -2.5 + 0.4 = -2.1$ V

We observe that Q_1 will cut off before Q_2 leaves saturation, thus

$v_{O\min} = -1.6$ V

and the corresponding value of v_I will be

$v_{I\min} = v_{O\min} + V_t$

$= -1.6 + 0.5 = -1.1$ V

11.3 Refer to Fig. 11.2. For a load resistance of 100 Ω and v_O ranging between –5 V and +5 V, the maximum current through Q_1 is

$I + \dfrac{5}{0.1} = I + 50$, mA and the minimum current is $I - \dfrac{5}{0.1} = I - 50$, mA.

For a current ratio of 15, we have

$$\frac{I+50}{I-50} = 15$$

$\Rightarrow I = 57.1$ mA

$$R = \frac{9.3\text{ V}}{57.1\text{ mA}} = 163\ \Omega$$

The incremental voltage gain is $A_v = \dfrac{R_L}{R_L + r_{e1}}$

For R_L = 100 Ω;

At $v_O = +5$ V, $i_{E1} = 57.1 + 50 = 107.1$ mA

$$r_{e1} = \frac{25}{107.1} = 0.233\ \Omega$$

$$A_v = \frac{100}{100 + 0.233} = 0.998\text{ V/V}$$

At $v_O = 0$ V, $i_{E1} = 57.1$ mA

$$r_{e1} = \frac{25}{57.1} = 0.438\ \Omega$$

$$A_v = \frac{100}{100.438} = 0.996\text{ V/V}$$

At $v_O = -5$ V, $i_{E1} = 57.1 - 50 = 7.1$ mA

$$r_{e1} = \frac{25}{7.1} = 3.52\ \Omega$$

$$A_v = \frac{100}{103.52} = 0.966\text{ V/V}$$

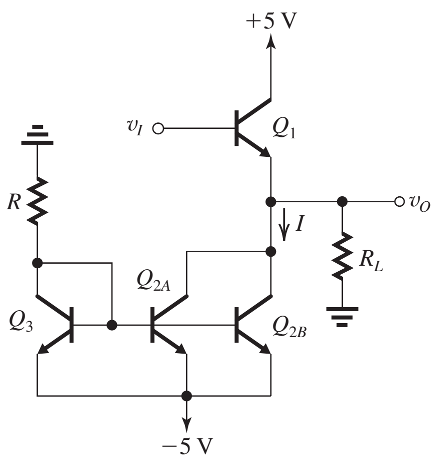
Thus the incremental gain changes by $0.998 - 0.966 = 0.032$ or about 3% over the range of v_O.

11.4 Refer to Fig. 11.2. With $V_{CC} = +5$ V, the upper limit on v_o is 4.7 V, which is greater than the required value of +3 V. To obtain a lower limit of −3 V, we select I so that

$IR_L = 3$

$\Rightarrow I = 3$ mA

Since we are provided with four devices, we can minimize the total supply current by paralleling two devices to form Q_2 as shown below.



The resulting supply current will be $3 \times \dfrac{I}{2}$ rather than $2I$ which is the value obtained in the circuit of Fig. 11.2. Then the supply current is 4.5 mA. The value of R is found from

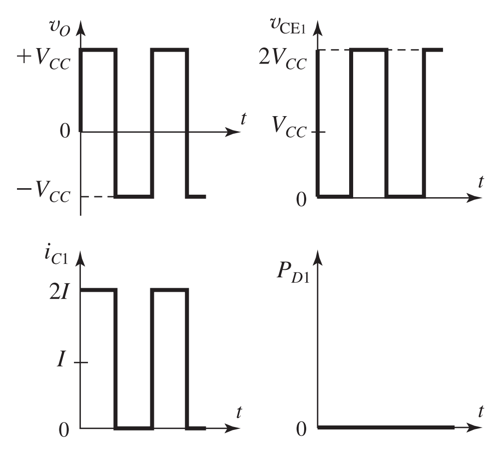
$$R = \frac{4.3\text{ V}}{1.5\text{ mA}} = 2.87\text{ k}\Omega$$

In a practical design we would select a standard value for R that results in I somewhat larger than 3 mA. Say, $R = 2.7$ kΩ. In this case $I = 3.2$ mA.

Power from negative supply $= 3 \times 1.6 \times 5$ $= 24$ mW.

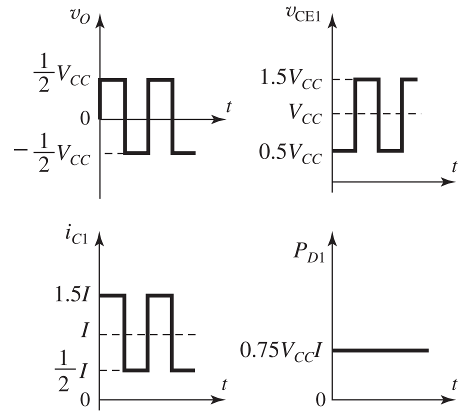
11.5 Refer to Figs. 11.2 and 11.4.

For v_O being a square wave of $\pm V_{CC}$ levels:



$P_{D1}|_{\text{average}} = 0$. For the corresponding sine wave curve [Fig. 11.4], we have $P_{D1}|_{\text{avg}} = \dfrac{1}{2}V_{CC}I$.

For v_O being a square wave of $\pm V_{CC}/2$ levels:



$$P_{D1}|_{\text{average}} = 0.75V_{CC}I$$

For a sine-wave output of $V_{CC}/2$ peak amplitude:

$$v_O = \frac{1}{2}V_{CC}\sin\theta$$

$$i_{C1} = I + \frac{\frac{1}{2}V_{CC}}{R_L}\sin\theta = I + \frac{1}{2}I\sin\theta$$

$$v_{CE1} = V_{CC} - \frac{1}{2}V_{CC}\sin\theta$$

$$P_{D1} = \left(V_{CC} - \frac{1}{2}V_{CC}\sin\theta\right)\left(I + \frac{1}{2}I\sin\theta\right)$$

$$= V_{CC}I - \frac{1}{4}V_{CC}I\sin^2\theta$$

$$= V_{CC}I - \frac{1}{4}V_{CC}I \times \frac{1}{2}(1-\cos 2\theta)$$

$$= \frac{7}{8}V_{CC}I + \frac{1}{8}V_{CC}I\cos 2\theta$$

$$P_{D1}|_{\text{average}} = \frac{7}{8}V_{CC}I$$

11.6 In all cases, the average voltage across Q_2 is equal to V_{CC}. Thus, since Q_2 conducts a constant current I, its average power dissipation is $V_{CC}I$.

11.7 The minimum required value of V_{CC} is

$$V_{CC} = \hat{V}$$

and the minimum required value of I is

$$I = \frac{\hat{V}}{R_L}$$

From Eq. (11.10),

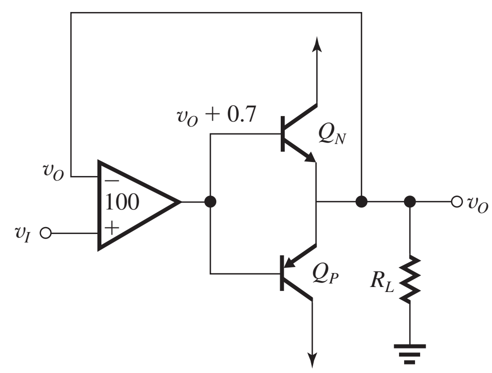
$$\eta = \frac{1}{4}\left(\frac{\hat{V}_o}{IR_L}\right)\left(\frac{\hat{V}_o}{V_{CC}}\right)$$

$$= \frac{1}{4}\left(\frac{\hat{V}}{\hat{V}}\right)\left(\frac{\hat{V}}{\hat{V}}\right) = 0.25$$

or 25%

11.8 Refer to Figs. 11.6 and 11.7. A 10% loss in peak amplitude is obtained when the amplitude of the input signal is 5 V.

11.9



With v_I sufficiently positive so that Q_N is conducting, the situation shown obtains. Then,

$$(v_I - v_O) \times 100 = v_O + 0.7$$

$$\Rightarrow v_O = \frac{1}{1.01}(v_I - 0.007)$$

This relationship applies for $v_I \geq 0.007$.

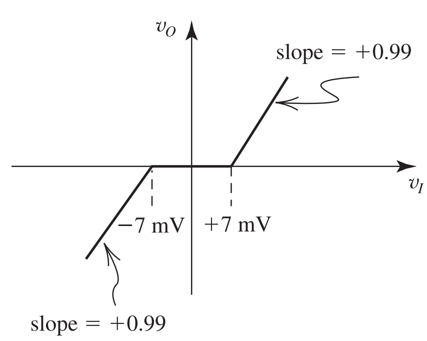
Similarly, for v_I sufficiently negative so that Q_P conducts, the voltage at the output of the amplifier becomes $v_O - 0.7$, thus

$$(v_I - v_O) \times 100 = v_O - 0.7$$

$$\Rightarrow v_O = \frac{1}{1.01}(v_I + 0.007)$$

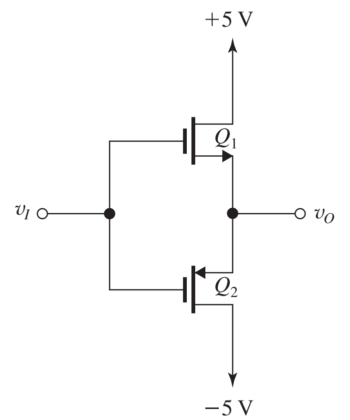
This relationship applies for $v_I \leq -0.007$.

The result is the transfer characteristic



Without the feedback arrangement, the deadband becomes ± 700 mV and the slope change a little (to nearly $+1$ V/V).

11.10



Devices have $|V_t| = 0.5$ V

$\mu C_{ox}\dfrac{W}{L} = 2\ \text{mA/V}^2$

For $R_L = \infty$, the current is normally zero, so

$V_{GS} = V_t$

$\therefore\ v_O = v_I - V_{GS1} = 5 - 0.5 = 4.5$ V

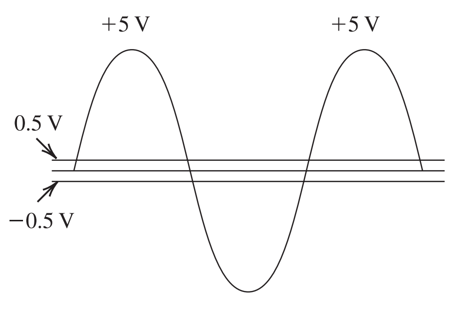
The peak output voltage will be 4.5 V

$\sin\theta = \dfrac{0.5}{5} \Rightarrow \theta = 5.74°$

Crossover interval $= 4\theta = 22.968$

$= \dfrac{22.96}{360} \times 100$

$= 6.4\%$

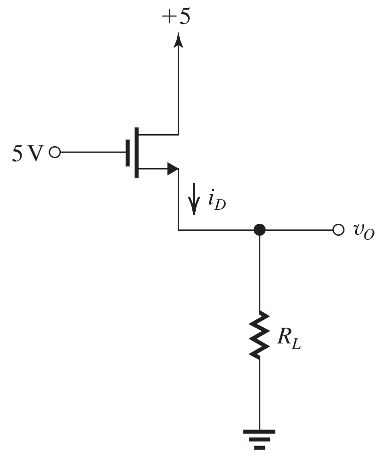


For $v_I = 5$ V, $v_O = 2.5$ V:

$\therefore\ V_{GS} = 5 - 2.5 = 2.5$ V

$i_D = \dfrac{1}{2}\mu C_{ox}\dfrac{W}{L}(V_{GS} - V_t)^2$

$= \dfrac{1}{2} \times 2 \times (2.5 - 0.5)^2$



$i_D = 4$ mA and $R_L = \dfrac{2.5\ \text{V}}{4\ \text{mA}} = 625\ \Omega$

11.11 For $V_{CC} = 10$ V and $R_L = 8\ \Omega$, the maximum sine-wave output power occurs when $\hat{V}_o = V_{CC}$ and is $P_{L\max} = \dfrac{1}{2}\dfrac{V_{CC}^2}{R_L}$

$= \dfrac{1}{2} \times \dfrac{100}{8} = 6.25$ W

Correspondingly,

$P_{S+} = P_{S-} = \dfrac{1}{\pi}\dfrac{\hat{V}_o}{R_L}V_{CC}$

$= \dfrac{1}{\pi} \times \dfrac{10}{8} \times 10 = 3.98$ W

for a total supply power of

$P_S = 2 \times 3.98 = 7.96$ W

The power conversion efficiency η is

$\eta = \dfrac{P_L}{P_S} \times 100 = \dfrac{6.25}{7.96} \times 100 = 78.5\%$

For $\hat{V}_o = 5$ V,

$P_L = \dfrac{1}{2}\dfrac{\hat{V}_o^2}{R_L} = \dfrac{1}{2} \times \dfrac{25}{8} = 1.56$ W

$P_{S+} = P_{S-} = \dfrac{1}{\pi}\dfrac{\hat{V}_o}{R_L}V_{CC}$

$= \dfrac{1}{\pi} \times \dfrac{5}{8} \times 10 = 2$ W

$P_S = 4$ W

$\eta = \dfrac{1.56}{4} \times 100 = 39\%$

Thus, the efficiency reduces to half its maximum value.

11.12 $P_L = \dfrac{1}{2}\dfrac{\hat{V}_o^2}{R_L}$

$50 = \dfrac{1}{2}\dfrac{\hat{V}_o^2}{8}$

$\Rightarrow \hat{V}_o = 28.3$ V

$V_{CC} = 28.3 + 4 = 32.3 \to 33$ V

Peak current from each supply $= \dfrac{\hat{V}_o}{R_L} = \dfrac{28.3}{8}$

$= 3.54$ A

$P_{S+} = P_{S-} = \dfrac{1}{\pi} \times 3.54 \times 33 = 37.2$ W

Thus,

$P_S = 2 \times 37.2 = 74.4$ W

$\eta = \dfrac{P_L}{P_S} = \dfrac{50}{74.4} = 67.2\%$

Using Eq. (11.22), we obtain

$P_{DN\max} = P_{DP\max} = \dfrac{V_{CC}^2}{\pi^2 R_L} = \dfrac{33^2}{\pi^2 \times 8} = 13.8$ W

11.13 $V_{CC} = 10$ V

For maximum η,

$\hat{V}_o = V_{CC} = 10$ V

The output voltage that results in maximum device dissipation is given by Eq. (11.20),

$\hat{V}_o = \dfrac{2}{\pi} V_{CC}$

$= \dfrac{2}{\pi} \times 10 = 6.37$ V

If operation is always at full output voltage, $\eta = 78.5\%$ and thus

$P_{\text{dissipation}} = (1 - \eta) P_S$

$= (1 - \eta) \dfrac{P_L}{\eta} = \dfrac{1 - 0.785}{0.785} P_L = 0.274 P_L$

$P_{\text{dissipation/device}} = \dfrac{1}{2} \times 0.274 P_L = 0.137 P_L$

For a rated device dissipation of 2 W, and using a factor of 2 safety margin,

$P_{\text{dissipation/device}} = 1$ W

$= 0.137 P_L$

$\Rightarrow P_L = 7.3$ W

$7.3 = \dfrac{1}{2} \times \dfrac{100}{R_L}$

$\Rightarrow R_L = 6.85\ \Omega$ (i.e. $R_L \geq 6.85\ \Omega$)

The corresponding output power (i.e., greatest possible output power) is 7.3 W.

If operation is allowed at $\hat{V}_o = \dfrac{1}{2} V_{CC} = 5$ V,

$\eta = \dfrac{\pi}{4} \dfrac{\hat{V}_o}{V_{CC}}$ (Eq. 11.15)

$= \dfrac{\pi}{4} \times \dfrac{1}{2} = 0.393$

$P_{\text{dissipation/device}} = \dfrac{1}{2} \dfrac{1 - \eta}{\eta} P_L = 0.772 P_L$

$1 = 0.772 P_L$

$\Rightarrow P_L = 1.3$ W

$= \dfrac{1}{2} \dfrac{5^2}{R_L}$

$\Rightarrow R_L = 9.62\ \Omega$ (i.e., $\geq 9.62\ \Omega$)

11.14 $P_L = \dfrac{\hat{V}_o^2}{R_L}$

$P_{S+} = P_{S-} = \dfrac{1}{2} \left(\dfrac{\hat{V}_o}{R_L} \right) V_{SS}$

$P_S = \dfrac{\hat{V}_o}{R_L} V_{SS}$

$\eta = \dfrac{P_L}{P_S} = \dfrac{\hat{V}_o^2 / R_L}{\hat{V}_o V_{SS} R_L} = \dfrac{\hat{V}_o}{V_{SS}}$

$\eta_{\max} = 1(100\%)$, obtained for $\hat{V}_o = V_{SS}$

$P_{L\max} = \dfrac{V_{SS}^2}{R_L}$

$P_{\text{dissipation}} = P_S - P_L$

$= \dfrac{\hat{V}_o}{R_L} V_{SS} - \dfrac{\hat{V}_o^2}{R_L}$

$\dfrac{\partial P_{\text{dissipation}}}{\partial \hat{V}_o} = \dfrac{V_{SS}}{R_L} - \dfrac{2\hat{V}_o}{R_L}$

$= 0$ for $\hat{V}_o = \dfrac{V_{SS}}{2}$

Correspondingly, $\eta = \dfrac{V_{SS}/2}{V_{SS}} = \dfrac{1}{2}$ or 50%

11.15 $V_{BB} = 2V_T \ln(I_Q / I_S)$

$= 2 \times 0.025 \ln(10^{-3} / 10^{-14})$

$= 1.266$ V

At $v_I = 0$, $i_N = i_P = I_Q = 1$ mA, we have

$r_{eN} = r_{eP} = \dfrac{25 \text{ mV}}{1 \text{ mA}} = 25\ \Omega$

$R_{\text{out}} = r_{eN} \parallel r_{eP} = 12.5\ \Omega$

$A_v = \dfrac{v_o}{v_i} = \dfrac{R_L}{R_L + R_{\text{out}}} = \dfrac{100}{100 + 12.5}$

$= 0.889$ V/V

At $v_O = 10$ V, we have

$i_L = \dfrac{10}{100} = 0.1$ A $= 100$ mA

To obtain i_N, we use Eq. (11.27):

$i_N^2 - i_L i_N - I_Q^2 = 0$

$i_N^2 - 100\, i_N - 1 = 0$

$\Rightarrow i_N = 100.01$ mA

$i_P = i_N - i_L = 0.01$ mA

$$R_{out} = \frac{V_T}{i_P + i_N} \simeq \frac{25 \text{ mV}}{100 \text{ mA}} = 0.25\ \Omega$$

$$A_v = \frac{R_L}{R_L + R_{out}} = \frac{100}{100 + 0.25} = 0.998 \text{ V/V}$$

11.16 At $i_L = 0$, we have $i_N = i_P = I_Q$ and

$$R_{out} = \frac{1}{2}\frac{V_T}{I_Q}$$

Thus,

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{out}} = \frac{100}{100 + \dfrac{12.5}{I_Q}} \qquad (1)$$

where I_Q is in mA.

For $i_L = 50$ mA, we have

$i_N \simeq 50$ mA and $i_P \simeq 0$

Thus,

$$R_{out} \simeq r_{eN} = \frac{V_T}{i_N} = \frac{25 \text{ mV}}{50 \text{ mA}} = 0.5\ \Omega$$

$$\frac{v_o}{v_i} = \frac{100}{100 + 0.5} = 0.995 \text{ V/V}$$

To limit the variation to 5%, we use

$$\left.\frac{v_o}{v_i}\right|_{i_L=0} = 0.995 - 0.05 = 0.945 \text{ V/V}$$

Substituting this value in Eq. (1) yields

$I_Q = 2.15$ mA

11.17 $A_v = \dfrac{R_L}{R_L + R_{out}}$ and $R_{out} = \dfrac{r_e}{2} = \dfrac{V_I}{2I_Q}$

Now $A_v \geq\ 0.97$ for $R_L \geq 100\ \Omega$

$$\therefore 0.97 = \frac{100}{100 + R_{out}}$$

$\Rightarrow R_{out} \simeq 3\ \Omega$

$$R_{out} = 3 = \frac{V_T}{2I_Q}$$

$$I_Q = \frac{V_T}{6} = \frac{25 \times 10^{-3}}{6} = 4.17 \text{ mA}$$

$$V_{BB} = 2V_{BE} = 2\left[0.7 + V_T \ln\left(\frac{4.17}{100}\right)\right]$$

$= 1.24$ V

11.18 The current i_I can be obtained as

$$i_I = \frac{i_N}{\beta_N + 1} - \frac{i_p}{\beta_P + 1} = \frac{i_L}{\beta + 1}$$

where $\beta_N = \beta_P = \beta = 49$

Using values of v_I from the table, one can evaluate R_{in} as

$$R_{in} = \frac{v_I}{i_I}$$

Using the resistance reflection rule

$R_{in} \simeq (\beta + 1)R_L = 50 \times 100$

$= 5000\ \Omega$

For large input signal, the two values of R_{in} are somewhat the same. For the small values of v_I, the calculated value in the table is larger.

This table belongs to Problem 11.18.

v_O (V)	i_L (mA)	i_N (mA)	i_P (mA)	v_{BEN} (V)	v_{EBP} (V)	v_i (V)	v_O/v_I (V/V)	R_{out} (Ω)	v_o/v_i (V/V)	i_I (mA)	R_{in} (Ω)
+10.0	100	100.04	0.04	0.691	0.495	10.1	0.99	0.25	1.00	2	5050
+5.0	50	50.08	0.08	0.673	0.513	5.08	0.98	0.50	1.00	1	5080
+1.0	10	10.39	0.39	0.634	0.552	1.041	0.96	2.32	0.98	0.2	5205
+0.5	5	5.70	0.70	0.619	0.567	0.526	0.95	4.03	0.96	0.1	5260
+0.2	2	3.24	1.24	0.605	0.581	0.212	0.94	5.58	0.95	0.04	5300
+0.1	1	2.56	1.56	0.599	0.587	0.106	0.94	6.07	0.94	0.02	5300
0	0	2	2	0.593	0.593	0	–	6.25	0.94	0	
–0.1	–1	1.56	2.56	0.587	0.599	–0.106	0.94	6.07	0.94	–0.02	5300
–0.2	–2	1.24	3.24	0.581	0.605	–0.212	0.94	5.58	0.95	–0.04	5300
–0.5	–5	0.70	5.70	0.567	0.619	–0.526	0.95	4.03	0.96	–0.1	5260
–1.0	–10	0.39	10.39	0.552	0.634	–1.041	0.96	2.32	0.98	–0.2	5205
–5.0	–50	0.08	50.08	0.513	0.673	–5.08	0.98	0.50	1.00	–1	5080
–10.0	–100	0.04	100.04	0.495	0.691	–10.1	0.99	0.25	1.00	–2	5050

11.19 $\frac{v_o}{v_i} = \frac{R_L}{R_L + R_{out}}$ and

$R_{out} = \frac{V_T}{i_P + i_N} = \frac{V_T}{I_Q + I_Q}$ at $v_O = 0$

(a) $\epsilon = 1 - \left.\frac{v_o}{v_1}\right|_{v_O=0}$

$= 1 - \frac{R_L}{R_L + R_{out}} = 1 - \frac{R_L}{R_L + \frac{V_T}{2I_Q}} =$

$\frac{V_T/2I_Q}{R_L + (V_T/2I_Q)}$

$$\epsilon = \frac{V_T/2I_Q}{R_L + (V_T/2I_Q)} = \frac{V_T}{2R_L I_Q + V_T}$$

If $2I_Q R_L \gg V_T$, then we have

$\epsilon \simeq \frac{V_T}{2I_Q R_L}$ Q.E.D.

(b) Quiescent power dissipation $= 2V_{CC}I_Q = P_D$

(c) $\epsilon \times$ Quiescent power dissipation $=$

$\frac{V_T}{2I_Q R_L} \times 2V_{CC}I_Q = V_T \times \left(\frac{V_{CC}}{R_L}\right)$

$\therefore \epsilon P_D = V_T\left(\frac{V_{CC}}{R_L}\right)$

(d) $\epsilon P_D = V_T \frac{V_{CC}}{R_L} = 25 \times 10^{-3} \times \frac{10}{100}$

$= 2.5$ mW

$P_D = \frac{2.5 \times 10^{-3}}{\epsilon}$

ϵ	P_D (mW)	I_Q (mA)
0.05	50	2.5
0.02	125	6.25
0.01	250	12.5

11.20 $I_Q = 1$ mA

For output of –1 V, we have

$i_L = -\frac{1}{100} = -10$ mA

Using Eq. (11.27), we obtain

$i_N^2 - i_L i_N - I_Q^2 = 0$

$i_N^2 + 10i_N - 1 = 0$

$i_N = 0.1$mA

$i_P = 10.1$mA

Thus v_{EBP} increases by $V_T \ln\frac{10.1}{1} = 0.06$ V

and the input step must be –1.06 V.

Largest possible positive output from 6 to 10, i.e., 4 V

Largest negative output from 6 to 0, i.e., 6 V

11.21 $R_{out} = r_e/2 = 8\ \Omega$

$\Rightarrow r_e = 16\ \Omega$

$I_Q = \frac{V_T}{r_e} = \frac{25}{16} = 1.56$ mA

Thus, $n = \frac{1.56}{0.2} = 7.8$

11.22 $I_Q \simeq I_{BIAS} = 1$ mA, neglecting the base current of Q_N. More precisely,

$I_Q = I_{BIAS} - \frac{I_Q}{\beta + 1}$

$\Rightarrow I_Q = \frac{I_{BIAS}}{1 + \frac{1}{\beta + 1}} \simeq 0.98 \times 1 = 0.98$ mA

The largest positive output is obtained when all of I_{BIAS} flows into the base of Q_N, resulting in

$v_O = (\beta_N + 1)I_{BIAS}R_L$

$= 51 \times 1 \times 100\ \Omega = 5.1$ V

The largest possible negative output voltage is limited by the saturation of Q_P to

$-10 + V_{ECsat} = -10$ V

To achieve a maximum positive output of 10 V without changing I_{BIAS}, β_N must be

$10 = (\beta_N + 1) \times 1 \times 10^{-3} \times 100\ \Omega$

$\Rightarrow \beta_N = 99$

Alternatively, if β_N is held at 50, I_{BIAS} must be increased so that

$10 = 51 \times I_{BIAS} \times 10^{-3} \times 100\ \Omega$

$\Rightarrow I_{BIAS} = 1.96$ mA

for which

$I_Q = \frac{I_{BIAS}}{1 + \frac{1}{\beta + 1}} = 1.92$ mA

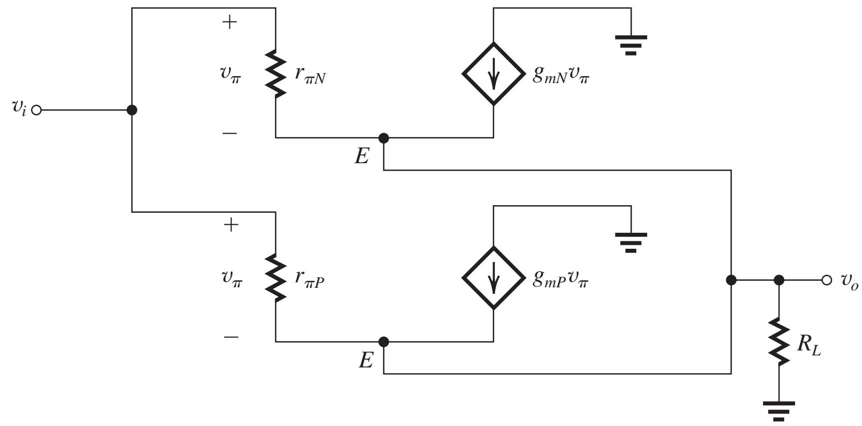
11.23 Figure 1(a) shows the small-signal equivalent circuit of the class AB circuit in Fig. 11.14. Here, each of Q_N and Q_P has been replaced with its hybrid-π model, and the small resistances of the diodes have been neglected. As well, we have not included r_o of each of Q_N and Q_P.

The circuit in Fig. 1(a) can be simplified to that in Fig. 1(b) where

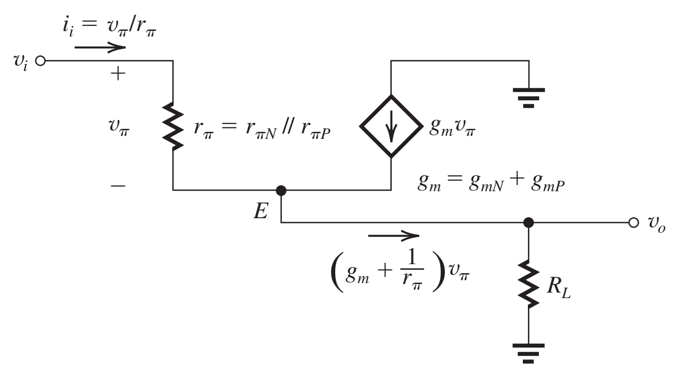
$$r_\pi = r_{\pi N} \parallel r_{\pi P} \quad (1)$$

$$g_m = g_{mN} + g_{mP} \quad (2)$$

This figure belongs to Problem 11.23.



(a)



(b)

Figure 1

Since $g_m \simeq \dfrac{1}{r_e}$, then from (2) we obtain

$$\frac{1}{r_e} = \frac{1}{r_{eN}} + \frac{1}{r_{eP}}$$

or, equivalently,

$$r_e = r_{eN} \parallel r_{eP} \tag{3}$$

We observe that the circuit in Fig. 1(b) is the equivalent circuit of an emitter follower with the small-signal parameters r_π, g_m, and r_e given in Eqs. (1), (2), and (3). Furthermore, its β is given by

$$\beta = g_m r_\pi = (g_{mN} + g_{mP})(r_{\pi N} \parallel r_{\pi P}) \tag{4}$$

For the circuit in Fig. 1(b), we can write

$$v_i = v_\pi + v_o \tag{5}$$

$$v_o = \left(g_m + \frac{1}{r_\pi}\right)v_\pi R_L \tag{6}$$

Equations (5) and (6) can be used to obtain the incremental (or small-signal) gain,

$$\frac{v_o}{v_i} = \frac{\left(g_m + \dfrac{1}{r_\pi}\right)R_L}{\left(g_m + \dfrac{1}{r_\pi}\right)R_L + 1}$$

But,

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

Thus,

$$\frac{v_o}{v_i} = \frac{R_L/r_e}{R_L/r_e + 1}$$

$$\Rightarrow \frac{v_o}{v_i} = \frac{R_L}{R_L + r_e} = \frac{R_L}{R_L + (r_{eN} \parallel r_{eP})} \quad \text{Q.E.D.} \tag{7}$$

The input resistance is found as follows:

$$R_{\text{in}} = \frac{v_i}{i_i} = \frac{v_i}{v_\pi/r_\pi}$$

Substituting for v_i from (5) together with utilizing (7) gives

$$R_{\text{in}} = \frac{v_\pi\left[1 + \left(g_m + \frac{1}{r_\pi}\right)R_L\right]}{v_\pi/r_\pi}$$

$$= r_\pi + (g_m r_\pi + 1)R_L$$

$$= r_\pi + (\beta + 1)R_L$$

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

$$\simeq \beta[R_L + (r_{eN} \parallel r_{eP})] \qquad \text{Q.E.D.} \qquad (8)$$

11.24 Refer to Fig. P11.24. Neglecting the small resistances of D_1 and D_2, we can write for the voltage gain of the CE amplifier transistor Q_3,

$$\frac{v_{c3}}{v_i} = -g_{m3}R_{\text{in}} \qquad (1)$$

where R_{in} is the input resistance of the class AB circuit, given in the statement of Problem 11.23 as

$$R_{\text{in}} \simeq \beta[R_L + (r_{eN} \parallel r_{eP})] \qquad (2)$$

where

$$\beta = (g_{mN} + g_{mP})(r_{\pi N} \parallel r_{\pi P}) \qquad (3)$$

The voltage gain of the class AB circuit is given in the statement of Problem 11.23 as

$$\frac{v_o}{v_{c3}} = \frac{R_L}{R_L + (r_{eN} \parallel r_{eP})} \qquad (4)$$

Now, we can combine (1), (2), and (4) to obtain the voltage gain of the circuit in Fig. P11.24 as

$$\frac{v_o}{v_i} = -g_{m3}\beta[R_L + (r_{eN} \parallel r_{eP})]\frac{R_L}{R_L + (r_{eN} \parallel r_{eP})}$$

$$\Rightarrow \frac{v_o}{v_i} = -g_{m3}\beta R_L$$

where β is given by Eq. (3).

11.25 At 20°C, $I_Q = 1\text{mA} = I_S e^{(0.6/0.025)}$

$\Rightarrow I_S$ (at 20°C) $= 3.78 \times 10^{-11}$ mA

At 70°C, $I_S = 3.78 \times 10^{-11}(1.14)^{50}$

$= 2.64 \times 10^{-8}$ mA

At 70°C, $V_T = 25\dfrac{273 + 70}{273 + 20} = 29.3$ mV

Thus, I_Q (at 70°C) $= 2.64 \times 10^{-8} e^{0.6/0.0293}$

$= 20.7$ mA

Additional current $= 20.7 - 1 = 19.7$ mA

Additional power $= 2 \times 20 \times 19.7 = 788$ mW

Additional temperature rise $= 10 \times 0.788 = 7.9$°C,

At 77.9°C:

$$V_T = \frac{25}{293}(273 + 77.9) = 29.9 \text{ mV}$$

$$I_Q = 3.78 \times 10^{-11} \times (1.14)^{57.9} e^{(0.6/0.0299)}$$

$$= 37.6 \text{ mA}$$

etc., etc.

11.26 (a) $V_{BE} = 0.7$ V at 1 mA

At 0.5 mA,

$$V_{BE} = 0.7 + 0.025 \ln\frac{0.5}{1} = 0.683 \text{ V}$$

Thus, $R_1 = \dfrac{0.683}{0.5} = 1.365$ kΩ

and $R_2 = 1.365$ kΩ

$V_{BB} = 2V_{BE} = 1.365$ V

(b) For $I_{\text{bias}} = 2$ mA, I_C increases to nearly 1.5 mA for which

$$V_{BE} = 0.7 + 0.025 \ln\frac{1.5}{1} = 0.710 \text{ V}$$

Note that $I_R = \dfrac{0.710}{1.365} = 0.52$ mA is very nearly equal to the assumed value of 0.50 mA, thus no further iterations are required.

$V_{BB} = 2V_{BE} = 1.420$ V

(c) For $I_{\text{bias}} = 10$ mA, assume that I_R remains constant at 0.5 mA, thus $I_{C1} = 9.5$ mA

and $V_{BE} = 0.7 + 0.025 \ln\dfrac{9.5}{1} = 0.756$ V

at which

$$I_R = \frac{0.755}{1.365} = 0.554 \text{ mA}$$

Thus,

$I_{C1} = 10 - 0.554 = 9.45$ mA

and $V_{BE} = 0.7 + 0.025 \ln\dfrac{9.45}{1} = 0.756$ V

Thus, $V_{BB} = 2 \times 0.756 = 1.512$ V

(d) Now for $\beta = 100$,

$$I_{R1} = \frac{0.756}{1.365} = 0.554 \text{ mA}$$

$$I_{R2} = 0.554 + \frac{9.45}{101} = 0.648 \text{ mA}$$

$I_C = 10 - 0.648 = 9.352$ mA

Thus, $V_{BE} = 0.7 + 0.025 \ln\dfrac{9.352}{1} = 0.756$ V

$V_{BB} = 0.756 + I_{R2}R_2$

$= 0.756 + 0.648 \times 1.365$

$= 1.641$ V

This figure belongs to Problem 11.27.

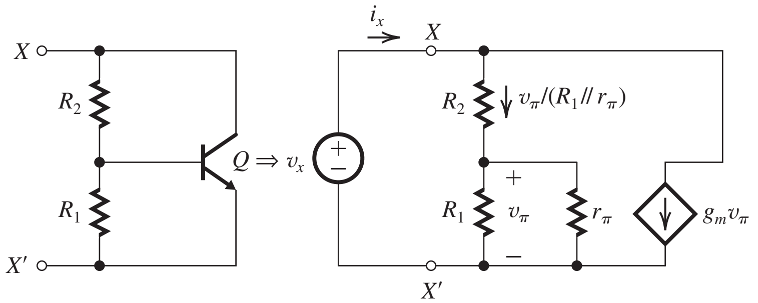


Figure 1

11.27 Figure 1 shows the V_{BE} multiplier together with its small-signal equivalent circuit prepared for determining the incremental terminal resistance r,

$$r \equiv \frac{v_x}{i_x}$$

Now,

$$i_x = g_m v_\pi + \frac{v_\pi}{R_1 \parallel r_\pi} \qquad (1)$$

$$v_x = v_\pi + \frac{v_\pi}{R_1 \parallel r_\pi} R_2 \qquad (2)$$

Dividing (2) by (1) gives

$$r = \frac{1 + R_2/(R_1 \parallel r_\pi)}{g_m + \dfrac{1}{R_1 \parallel r_\pi}}$$

$$= \frac{R_2 + (R_1 \parallel r_\pi)}{1 + g_m(R_1 \parallel r_\pi)}$$

For $R_1 = R_2 = 1.2\text{ k}\Omega$, $I_C = 1\text{ mA}$, and $\beta = 100$, we have

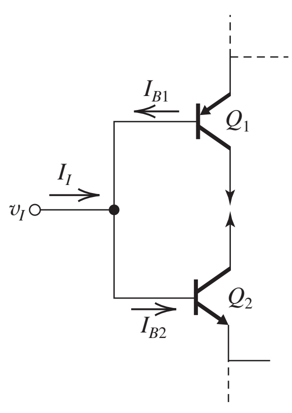
$$g_m = 40\text{ mA/V}$$

$$r_\pi = \frac{100}{40} = 2.5\text{ k}\Omega$$

Thus,

$$r = \frac{1.2 + (1.2 \parallel 2.5)}{1 + 40(1.2 \parallel 2.5)} = 60.2\ \Omega$$

11.28 (a) For $R_L = \infty$:



At $v_I = 0$ V, we have

$$I_{B1} = I_{B2} = \frac{2.87}{200}$$

$$I_I = I_{B2} - I_{B1} = 0$$

At $v_I = +10$ V, we have

$$I_{B1} = \frac{0.88}{200}\text{ mA} = 4.4\ \mu\text{A}$$

$$I_{B2} = \frac{4.87}{200}\text{ mA} = 24.4\ \mu\text{A}$$

$$I_I = I_{B2} - I_{B1} = 20\ \mu\text{A}$$

At $v_I = -10$ V, we have

$$I_{B1} = \frac{4.87}{200}\text{ mA} = 24.4\ \mu\text{A}$$

$$I_{B2} = \frac{0.88}{200}\text{ mA} = 4.4\ \mu\text{A}$$

$$I_I = I_{B2} - I_{B1} = -20\ \mu\text{A}$$

(b) For $R_L = 100\ \Omega$:

At $v_I = 0$ V, we have $I_I = 0$

At $v_I = +10$ V, we have

$$I_{B1} = \frac{0.38}{200} = 1.9\ \mu\text{A}$$

$$I_{B2} = \frac{4.87}{200} = 24.4\ \mu\text{A}$$

$$I_I = I_{B2} - I_{B1} = 22.5\ \mu\text{A}$$

At $v_I = -10$ V, we have $I_I = -22.5\ \mu\text{A}$

11.29 Circuit operating near $v_I = 0$ and is fed with a signal source having zero resistance.

The resistance looking as shown by the arrow X is

$= R_1 \parallel r_{e1}$

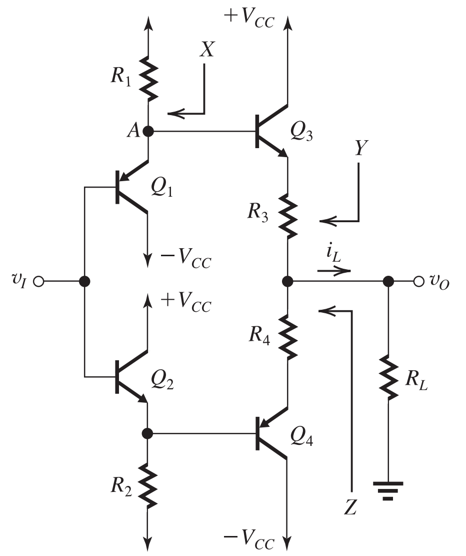
This resistance is reflected from base to the emitter of Q_3 as $(R_1 \parallel r_{e1})/(\beta_3 + 1)$.

The resistance seen by arrow Y, from the upper half of the circuit

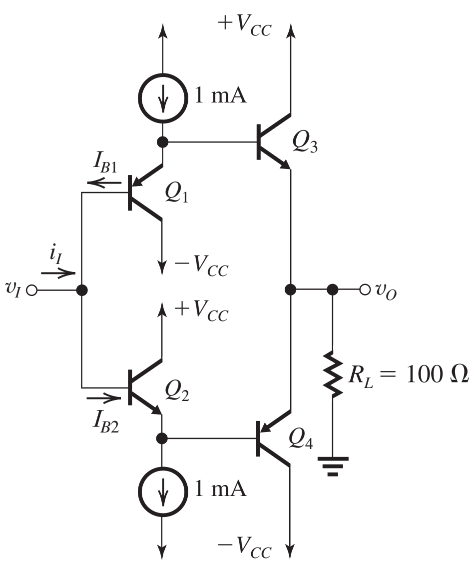
$= R_3 + r_{e3} + (R_1 \parallel r_{e1})/(\beta_3 + 1)$

A similar resistance is seen by the arrow Z and both of these resistances (seen by arrows Y and arrow Z) are in parallel, therefore

$$R_{\text{out}} = \frac{1}{2}\left[R_3 + r_{e3} + (R_1 \parallel r_{e1}) / \left(\beta_3 + 1\right)\right]$$



11.30



(a) $v_I = 0$ and transistors have $\beta = 100$.

$v_O = 0\,\text{V}$

$I_Q = I_{E3} = I_{E4} = I_{E1} = I_{E2} \simeq 1\text{ mA}$

More precisely, $\dfrac{I_{E3}}{\beta + 1} + I_{E1} = 1\text{ mA}$

thus,

$I_Q\left(\dfrac{1}{(\beta + 1)} + 1\right) = 1$

$\Rightarrow I_Q \simeq 0.99\text{ mA}$

Input bias current is zero because $I_{B1} = I_{B2}$.

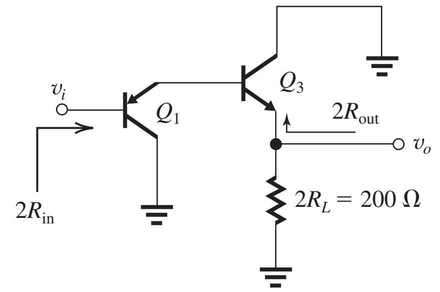
(b) From the equivalent half circuit, we have

$2R_{\text{in}} = \left(\beta_1 + 1\right)\left[r_{e1} + \left(\beta_3 + 1\right)(r_{e3} + 2R_L)\right]$

$r_{e1} = r_{e3} = \dfrac{V_T}{I_E} = \dfrac{25}{1} = 25\ \Omega$

$2R_{\text{in}} = (100 + 1)[25 + (100 + 1)(25 + 2 \times 100)]$

$\Rightarrow R_{\text{in}} = 1.15\text{ M}\Omega$



$$A_v = \frac{v_o}{v_i} = \frac{2R_L}{2R_L + r_{e3} + \dfrac{r_{e1}}{\beta_3 + 1}}$$

$$= \frac{200}{200 + 25 + \dfrac{25}{101}}$$

$\simeq 0.89\text{ V/V}$

$2R_{\text{out}} = r_{e3} + \dfrac{r_{e1}}{\beta + 1}$

$= 25 + \dfrac{25}{101}$

$R_{\text{out}} = 12.6\ \Omega$

11.31 See figure on the next page.

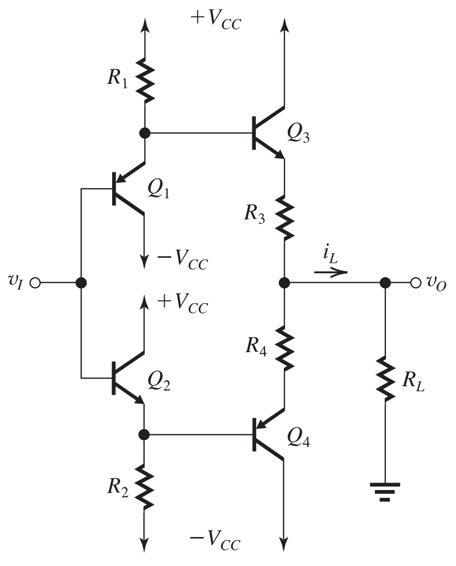
At $v_I = 5$ V, we have

$V_{E1} = +5.7$ V

$I_{R1} = \dfrac{V_{CC} - V_{E1}}{R_1} = \dfrac{10 - 5.7}{R_1} = \dfrac{4.3}{R_1}$

To allow for $I_{B3} = 10$ mA if needed while reducing I_{E1} by no more than half, then I_{R1} must be $2 \times 10 = 20$ mA. Thus,

$R_1 = \dfrac{V_{R1}}{I_{R1}} = \dfrac{4.3}{20} = 0.215\text{ k}\Omega = 215\ \Omega$



Similarly,

$R_2 = 0.215\text{ k}\Omega = 215\ \Omega$

Next, we determine the values of R_3 and R_4: At $v_I = 0$, assume $V_{EB1} = 0.7$. Then

$V_{E1} = 0.7\text{ V}$

$I_{R1} = \dfrac{10 - 0.7}{0.215} = 43.3\text{ mA}$

$V_{EB1} = 0.7 + 0.025 \times \ln\left(\dfrac{43.3}{10}\right)$

$= 0.737\text{ V}$

$V_{E1} = 0.737\text{ V}$

Meanwhile Q_3 will be conducting $I_Q = 40\text{ mA}$. Since $I_{S3} = 3I_{S1}$ then Q_3 has $V_{BE} = 0.7\text{ V}$ at $I_C = 30\text{ mA}$. At 40 mA,

$V_{BE3} = 0.7 + 0.025 \times \ln\left(\dfrac{40}{30}\right)$

$= 0.707\text{ V}$

For $v_O = 0$,

$V_{E1} - V_{BE3} - I_{E3}R_3 = 0$

$0.737 - 0.707 - 40R_3 = 0$

$\Rightarrow R_3 = 0.75\ \Omega$

Similarly,

$R_4 = 0.75\ \Omega$

$R_{\text{out}} = \dfrac{1}{2}\left[R_3 + r_{e3} + \dfrac{R_1 \parallel r_{e1}}{\beta_3 + 1}\right]$

where

$r_{e3} = \dfrac{25\text{ mV}}{40\text{ mA}} = 0.625\ \Omega$

$r_{e1} = \dfrac{25\text{ mV}}{20\text{ mA}} = 1.25\ \Omega$

$R_{\text{out}} = \dfrac{1}{2}\left[0.75 + 0.625 + \dfrac{215 \parallel 1.25}{51}\right]$

$R_{\text{out}} = 0.7\ \Omega$

Next, consider the situation when

$v_I = +1\text{ V}$ and $R_L = 2\ \Omega$

Let $v_O \simeq 1\text{ V}$, then

$i_L = \dfrac{1\text{ V}}{2\ \Omega} = 0.5\text{ A} = 500\text{ mA}$

Now if we assume that $i_{E4} \simeq 0$, then

$i_{E3} = i_L = 500\text{ mA}$

$V_{BE3} = 0.7 + 0.025\ \ln\dfrac{500}{30}$

$= 0.770\text{ V}$

$i_{B3} = \dfrac{500}{51} \simeq 10\text{ mA}$

Assuming that $V_{EB1} \simeq 0.7\text{ V}$, then

$v_{E1} = 1 + 0.7 = 1.7\text{ V}$

$i_{R1} = \dfrac{10 - 1.7}{0.215} = 38.6\text{ mA}$

$i_{E1} = i_{R1} - i_{B2} = 38.6 - 10 = 28.6\text{ mA}$

$V_{EB1} = 0.7 + 0.025\ \ln\dfrac{28.6}{10}$

$= 0.726\text{ V}$

$V_{E1} = 1.726\text{ V}$

$i_L = \dfrac{V_{E1} - V_{BE3}}{R_3 + R_L}$

$= \dfrac{1.726 - 0.770}{0.75 + 2}$

$= 0.348\text{ A}$

$v_O = i_L R_L$

$= 0.348 \times 2 = 0.695\text{ V}$

Let's check that i_{E4} is zero. The voltage at the base of Q_4 is

$V_{B4} = 1 - V_{BE2}$

$\simeq 1 - 0.74 = 0.26\text{ V}$

The voltage across R_4 and V_{EB4} is

$= v_O - 0.26 = 0.695 - 0.26 = 0.435\text{ V}$

which is sufficiently small to keep Q_4 cutoff, verifying our assumption that $i_{E4} \simeq 0$.

Let's now do more iterations to refine our estimate of v_O:

$i_L = 0.35\text{ A}$

$$i_{B3} = \frac{0.35}{51} \simeq 7 \text{ mA}$$

$$i_{E1} = \frac{10 - 1 - 0.726}{0.215} - 7 = 31.5 \text{ mA}$$

$$V_{EB1} = 0.7 + 0.025 \ln\left(\frac{31.5}{10}\right)$$

$$= 0.729 \text{ V}$$

$$V_{E1} = 1 + 0.729 = 1.729 \text{ V}$$

$$i_{E3} = i_L = 350 \text{ mA}$$

$$V_{BE3} = 0.7 + 0.025 \ln\left(\frac{350}{30}\right)$$

$$= 0.761 \text{ V}$$

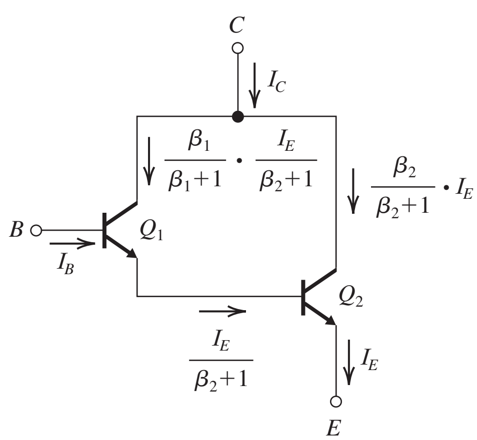
$$i_L = \frac{V_{E1} - V_{BE3}}{R_3 + R_2}$$

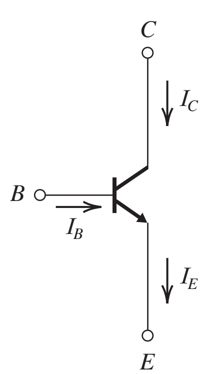
$$= \frac{1.729 - 0.761}{0.75 + 2} = 0.352 \text{ A}$$

$$v_O = i_L R_L$$

$$= 0.352 \times 2 = 0.704 \text{ V}$$

11.32





(a) For the composite transistor, we have

$$\beta = \frac{I_C}{I_B}$$

Refer to the diagram.

$$I_B = \frac{1}{\beta_1 + 1} \frac{I_E}{\beta_2 + 1}$$

$$I_C = \frac{\beta_1}{(\beta_1 + 1)(\beta_2 + 1)} I_E + \frac{\beta_2}{(\beta_2 + 1)} I_E$$

$$= \frac{\beta_1 + \beta_2 (\beta_1 + 1)}{(\beta_1 + 1)(\beta_2 + 1)} \cdot I_E$$

For the composite transistor, β is given by

$$\beta = \frac{I_C}{I_B} = \frac{\frac{\beta_1 + \beta_2 (\beta_1 + 1)}{(\beta_1 + 1)(\beta_2 + 1)} \times I_E}{\frac{1}{(\beta_1 + 1)(\beta_2 + 1)} \cdot I_E}$$

$$= \beta_1 + \beta_2 (\beta_1 + 1)$$

$$\simeq \beta_1 \beta_2 \text{ since } \beta_1 \gg 1 \text{ and } \beta_2 \gg 1$$

(b) Refer to the diagram.

Operating current of Q_2

$$= I_{C2} = \frac{\beta_2}{\beta_2 + 1} I_E = \frac{\beta_2}{\beta_2 + 1} \times \frac{\beta + 1}{\beta} I_C$$

where $\beta = \beta_1 \beta_2$

$$\simeq I_C \text{ since } \beta_2 \gg 1 \text{ and } \beta \gg 1$$

Operating current of Q_1

$$= I_{C1} = \frac{\beta_1}{(\beta_1 + 1)(\beta_2 + 1)} I_E$$

$$= \frac{\beta_1}{(\beta_1 + 1)(\beta_2 + 1)} \cdot \frac{\beta + 1}{\beta} I_C$$

$$\simeq \frac{I_C}{\beta_2} \text{ since } \beta \gg 1,\ \beta_2 \gg \text{ and } \beta_1 \gg 1.$$

(c) Again refer to the diagram and part (b).

$$V_{BE} = V_{BE2} + V_{BE1} = V_T \text{ In}\left(\frac{I_{C2}}{I_S}\right) + V_T \text{ In}\left(\frac{I_{C1}}{I_S}\right)$$

From part (b), $I_{C2} \simeq I_C$ and $I_{CI} \simeq \frac{I_C}{\beta_2}$

$$\therefore V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right) + V_T \ln\left(\frac{1}{\beta_2} \frac{I_C}{I_S}\right)$$

$$= V_T \ln\left(\frac{I_C}{I_S}\right) + V_T \ln\left(\frac{I_C}{I_S}\right) + V_T \ln\left(\frac{1}{\beta_2}\right)$$

$$V_{BE} = 2V_T \ln\left(\frac{I_C}{I_S}\right) - V_T \ln(\beta_2)$$

(d) $r_{\pi\text{eq}} = (\beta_1 + 1)\left[r_{e1} + (\beta_2 + 1) r_{e2}\right]$

Here, $r_{e2} = \frac{V_T}{I_{E2}} \simeq \frac{V_T}{I_{C2}} \simeq \frac{V_T}{I_C}$

$$r_{e1} = \frac{V_T}{I_{E2}} \simeq \frac{V_T}{I_{C1}} \simeq \frac{V_T}{I_C/\beta_2} = \beta_2 r_{e2}$$

$$r_{\pi eq} \simeq (\beta_1 + 1)\,[\beta_2 r_{e2} + \beta_2 r_{e2}]$$

$$= 2(\beta_1 + 1)\,\beta_2 r_{e2}$$

$$\cong 2\beta_1\beta_2 r_{e2}$$

$$= 2\beta_1\beta_2 \frac{V_T}{I_C}$$

(e) To find g_{meq}, apply a signal v_{be} and find the corresponding current i_c:

$$i_c = i_{c1} + i_{c2} = g_{m1}v_{be1} + g_{m2}v_{be2}$$

$$= g_{m1}v_{be}\frac{r_{e1}}{r_{e1} + (\beta_2+1)\,r_{e2}}$$

$$+ g_{m2}\frac{(\beta_2+1)\,r_{e2}}{r_{e1} + (\beta_2+1)\,r_{e2}} \cdot v_{be}$$

$$\simeq v_{be}\frac{1}{\beta_2 r_{e2} + (\beta_2+1)\,r_{e2}}$$

$$+ \frac{\beta_2}{\beta_2 r_{e2} + (\beta_2+1)\,r_{e2}} \cdot v_{be}$$

$\because g_m r_e \simeq 1,$

$$i_c \simeq v_{bc}\frac{1}{2\beta_2 r_{e2}} + v_{be}\frac{\beta_2}{2\beta_2 r_{e2}}$$

$$\simeq v_{bc}\frac{(\beta_2+1)}{2\beta_2 r_{e2}}$$

$$\simeq v_{bc}\frac{1}{2r_{e2}}$$

$$g_{meq} = \frac{i_c}{v_{be}} = \frac{1}{2r_{e2}}$$

$$= \frac{1}{2}\frac{I_C}{V_T}$$

11.33 (a)

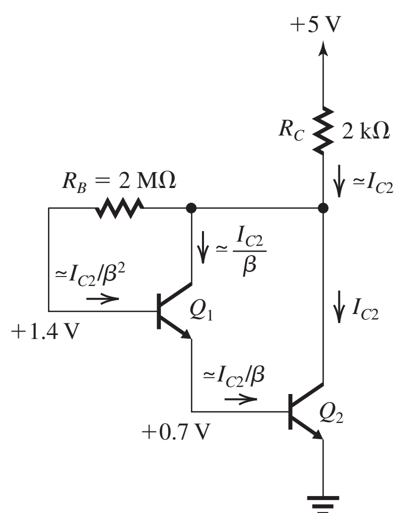


Figure 1

From Figure 1 we can write

$$5 = I_{C2}R_C + \frac{I_{C2}}{\beta^2}R_B + 1.4$$

$$\Rightarrow I_{C2} = \frac{5 - 1.4}{R_C + \dfrac{R_B}{\beta^2}}$$

$$= \frac{3.6}{2 + \dfrac{2000}{10,000}} = 1.64 \text{ mA}$$

$$I_{C1} \simeq \frac{I_{C2}}{\beta} = \frac{1.64}{100} = 0.0164 \text{ mA}$$

(b)

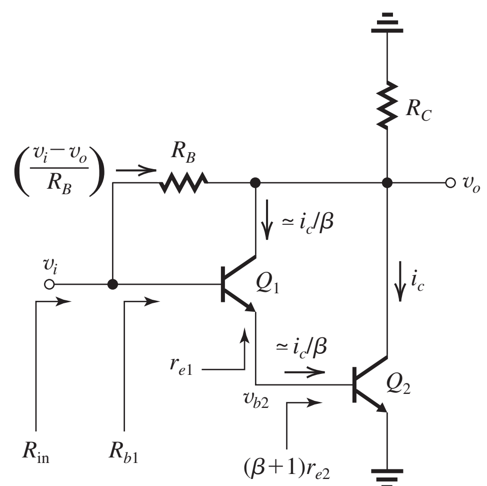


Figure 2

$$v_{b2} = v_i\frac{(\beta+1)r_{e2}}{(\beta+1)r_{e2} + r_{e1}}$$

where

$$r_{e2} = \frac{V_T}{I_{E2}} \simeq \frac{V_T}{I_{C2}} = \frac{25 \text{ mV}}{1.64 \text{ mA}} = 15.2\ \Omega$$

$$r_{e1} = \frac{V_T}{I_{E1}} \simeq \frac{V_T}{I_{C1}} = \frac{25 \text{ mV}}{0.0164 \text{ mA}} = 1.52\ \Omega$$

$$v_{b2} = v_i\frac{101 \times 15.2}{101 \times 15.2 + 1520} = 0.5v_i$$

$$i_c = g_{m2}v_{b2}$$

$$= g_{m2} \times 0.5v_i$$

where

$$g_{m2} = \frac{I_{C2}}{V_T} = \frac{1.64}{0.025} = 65.6 \text{ mA/V}$$

$$i_c = 65.6 \times 0.5v_i = 32.8v_i$$

Writing a node equation at the output provides

$$\frac{v_o}{R_C} + i_c + \frac{i_c}{\beta} + \frac{v_o - v_i}{R_B} = 0$$

Substituting $i_c = 32.8v_i$, we obtain

$$v_o\left(\frac{1}{R_C}+\frac{1}{R_B}\right) = -v_i\left[\left(1+\frac{1}{\beta}\right)32.8-\frac{1}{R_B}\right]$$

$$A_v \equiv \frac{v_o}{v_i} = -\frac{\left(1+\frac{1}{\beta}\right)32.8-\frac{1}{R_B}}{\frac{1}{R_C}+\frac{1}{R_B}}$$

$$= -\frac{1.01\times 32.8-(1/2000)}{\frac{1}{2}+\frac{1}{2000}}$$

$$= -66.2 \text{ V/V}$$

(c) $R_{b1} = (\beta+1)[r_{e1}+(\beta+1)r_{e2}]$

$$= 101[1.52+101\times 0.0152]$$

$$= 318.7 \text{ k}\Omega$$

The component of R_{in} arising from R_B can be found as

$$R_{i2} = \frac{v_i}{(v_i-v_o)/R_B}$$

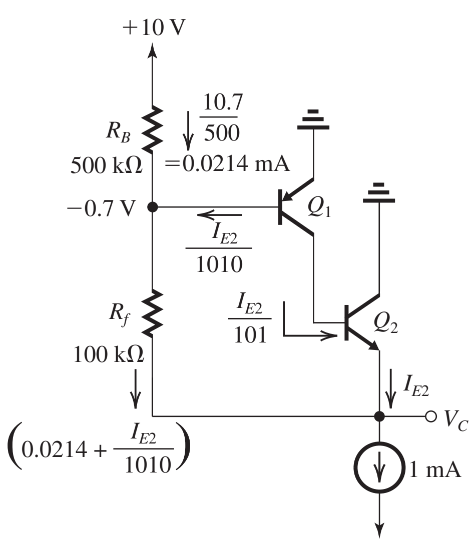
$$= \frac{R_B}{1-(v_o/v_i)} = \frac{2000}{1-(-66.2)} = 29.8 \text{ k}\Omega$$

Thus

$$R_{\text{in}} = R_{ib} \parallel R_{i2}$$

$$= 318.7 \parallel 29.8 = 27.2 \text{ k}\Omega$$

11.34 (a) DC Analysis:



$$1 \text{ mA} = 0.0214+\frac{I_{E2}}{1010}+I_{E2}$$

$$\Rightarrow I_{E2} = 0.978 \text{ mA}$$

$$I_{C2} = 0.99\times 0.978 = 0.97 \text{ mA}$$

$$I_{C1} = \frac{0.978}{101} = 9.7\ \mu\text{A}$$

$$V_C = -0.7-100\left(0.0214+\frac{0.978}{1010}\right)$$

$$= -2.94 \text{ V}$$

(b) Small-signal parameters:

$$g_{m1} = \frac{9.7\times 10^{-6}}{25\times 10^{-3}} = 0.388 \text{ mA/V}$$

$$r_{\pi 1} = \frac{\beta_1}{g_{m1}} = 25.77 \text{ k}\Omega$$

$$r_{o1} = \frac{|V_A|}{I_{C1}} = \frac{100}{9.7\ \mu\text{A}} = 10.31 \text{ M}\Omega$$

$$g_{m2} = \frac{0.97\times 10^{-3}}{25\times 10^{-3}} = 38.8 \text{ mA/V}$$

$$r_{\pi 2} = \frac{\beta_2}{g_{m2}} = 2.58 \text{ k}\Omega$$

$$r_{o2} = |V_A|/I_{C2} = 103.1 \text{ k}\Omega$$

Node equation at b_2:

$$g_{m1}v_{\pi 1}+\frac{v_{b2}}{r_{o1}}+\frac{v_{\pi 2}}{r_{\pi 2}} = 0$$

But $v_{b2} = v_o + v_{p2}$, then

$$g_{m1}v_{\pi 1}+\frac{v_o+v_{\pi 2}}{r_{o1}}+\frac{v_{\pi 2}}{r_{\pi 2}} = 0$$

$$\Rightarrow v_{\pi 2}\left(\frac{1}{r_{\pi 2}}+\frac{1}{r_{o1}}\right) = -\left(\frac{v_o}{r_{o1}}+g_{m1}v_{\pi 1}\right)$$

$$\text{or, } v_{\pi 2} = -\frac{\frac{v_o}{r_{o1}}+g_{m1}v_{\pi 1}}{\frac{1}{r_{\pi 2}}+\frac{1}{r_{o1}}}$$

Node equation at output:

$$\frac{v_o}{r_{o2}}+\frac{v_o-\ v_{\pi 1}}{R_f} = g_{m2}v_{\pi 2}+\frac{1}{r_{\pi 2}}v_{\pi 2}$$

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

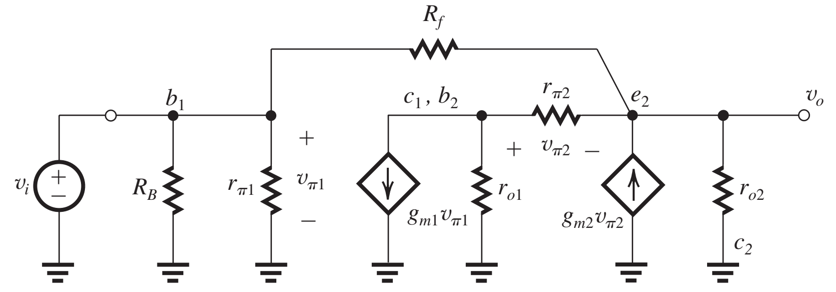
$$= -\frac{\left(g_{m2}+\frac{1}{r_{\pi 2}}\right)\left[\frac{v_o}{r_{o1}}+g_{m1}v_{\pi 1}\right]}{\frac{1}{r_{\pi 2}}+\frac{1}{r_{o1}}}$$

Substituting $v_{\pi 1} = v_i$ and collecting terms, we obtain

$$v_o\left[\frac{1}{r_{o2}}+\frac{1}{R_f}+\frac{\left(g_{m2}+\frac{1}{r_{\pi 2}}\right)}{r_{o1}\left(\frac{1}{r_{\pi 2}}+\frac{1}{r_{o1}}\right)}\right]$$

$$= -v_i\left[\frac{g_{m1}\left(g_{m2}+\frac{1}{r_{\pi 2}}\right)}{\frac{1}{r_{\pi 2}}+\frac{1}{r_{o2}}}-\frac{1}{R_f}\right]$$

This figure belongs to Exercise 11.34, part (b).



$$\frac{v_o}{v_i} = -\frac{\dfrac{g_{m1}\left(g_{m2}+\dfrac{1}{r_{\pi2}}\right)}{\dfrac{1}{r_{\pi2}}+\dfrac{1}{r_{o2}}} - \dfrac{1}{R_f}}{\dfrac{1}{r_{o2}}+\dfrac{1}{R_f}+\dfrac{\left(g_{m2}+\dfrac{1}{r_{\pi2}}\right)}{r_{o1}\left(\dfrac{1}{r_{\pi2}}+\dfrac{1}{r_{o1}}\right)}}$$

Since $r_{\pi2} \ll r_{o1}$, we have

$$\frac{v_o}{v_i} \simeq -\frac{g_{m1}\,(g_{m2}r_{\pi2}+1) - \dfrac{1}{R_f}}{\dfrac{1}{r_{o2}}+\dfrac{1}{R_f}+\dfrac{1}{r_{o1}}\,(g_{m2}r_{\pi2}+1)}$$

$$= -\frac{g_{m1}\,(\beta_2+1) - \dfrac{1}{R_f}}{\left(\dfrac{1}{r_{o2}}+\dfrac{1}{R_f}\right)+\dfrac{1}{r_{o1}}\,(\beta_2+1)}$$

Since $\dfrac{1}{R_f} \ll g_{m1}\,(\beta_2+1)$, we have

$$\frac{v_o}{v_i} \simeq -\frac{g_{m1}\,(\beta_2+1)}{\left(\dfrac{1}{r_{o2}}+\dfrac{1}{R_f}\right)+\dfrac{1}{r_{o1}}\,(\beta_2+1)}$$

Substituting $\beta_2 = \beta_N$ and noting that $\beta_N \gg 1$, we obtain

$$\frac{v_o}{v_i} \simeq -g_{m1}\frac{1}{\dfrac{1}{\beta_N}\left(\dfrac{1}{r_{o2}}+\dfrac{1}{R_f}\right)+\dfrac{1}{r_{o1}}}$$

$$= -g_{m1}\left[r_{o1} \parallel \beta_N\,(r_{o2} \parallel R_f)\right] \qquad \text{Q.E.D.}$$

(c)

$$\frac{v_o}{v_i} = -0.388\left[10.31\times10^3 \parallel 100\,(103.1 \parallel 100)\right]$$

$$= -1320 \text{ V/V}$$

$$R_{\text{in}} = R_B \parallel r_{\pi1} \parallel \left[v_i \Big/ \left(\frac{v_i - v_o}{R_f}\right)\right]$$

$$= 500 \parallel 25.77 \parallel \left[\frac{R_f}{1-\dfrac{v_o}{v_i}}\right]$$

$$= 500 \parallel 25.77 \parallel \frac{100}{1+1320}$$

$$= 500 \parallel 25.77 \parallel 0.0757$$

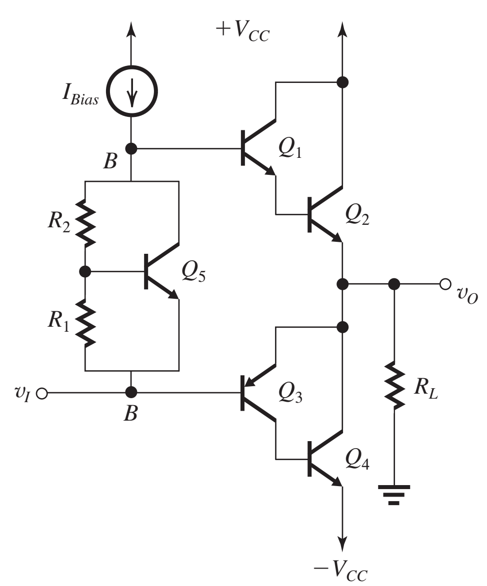
$$= 75.5\ \Omega$$

11.35 First consider the situation in the quiescent state and find V_{BB}.

$I_{Q2} = I_{Q4} = 2$ mA

$$V_{BE2} = V_{BE4} = 0.7 + 0.025\ \ln\left(\frac{2}{10}\right)$$

$= 0.660$ V



For Q_1 and Q_3, we have

$$I_C = \frac{2}{\beta} = \frac{2}{100} = 0.02 \text{ mA}$$

$$V_{BE1} = |V_{BE3}| = 0.7 + 0.025\ \ln\left(\frac{0.02}{1}\right)$$

$= 0.602$ V

$$I_{B1} = \frac{0.02 \text{ mA}}{\beta} = \frac{0.02}{100} = 0.2\ \mu\text{A}$$

$I_{\text{Bias}} = 100 \times$ Base current in B_1

$= 100 \times 0.2 = 20\ \mu A$

$I_{R1,R2} = \frac{1}{10} \times 20\ \mu A = 2\ \mu A$

and $I_{C5} = 20 - 2 = 18\ \mu A$

$V_{BE5} = 0.7 + 0.025 \ln\left(\frac{18\ \mu}{1\ m}\right) \simeq 0.600$ V

$V_{BB} = V_{BE1} + V_{BE2} + |V_{BE3}|$

$= 0.602 + 0.660 + 0.602$

$= 1.864$ V

$R_1 + R_2 = \frac{1.864}{2\ \mu A} = 932\ k\Omega$

$R_1 = \frac{0.600}{2\ \mu A} = 300\ k\Omega$

$R_2 = 932 - 300 = 632\ k\Omega$

Now find v_I for $v_O = 10$ V and $R_L = 1\ k\Omega$.

Q_2 is conducting most of the current and Q_4 conducting a negligible current.

$\therefore\ I_{C2} \simeq I_L = \frac{10\ V}{1\ k\Omega} = 10$ mA

$\therefore$ The current through each of Q_1 and Q_2 increases by a factor of $\frac{10}{2} = 5$

Thus $V_{BE2} = 0.66 + 0.025 \ln 5 = 0.700$ V

$V_{BE1} = 0.602 + 0.025 \ln 5 = 0.642$ V

and $I_{B1} = 5 \times 0.2\ \mu A = 1\ \mu A$

$\therefore$ The current through the multiplier is $I_{\text{Bias}} - 1 = 20 - 1 = 19\ \mu A$. Assuming most of the decrease occurs in I_{C5}, we obtain

$\therefore\ I_{C5} = 18 - 1 = 17\ \mu A$

$V_{BE5} = 0.7 + 0.025 \ln\left(\frac{17\ \mu A}{1\ \mu A}\right) = 0.598$ V

$\therefore V_{BB1}$, the voltage across the multiplier is

$V_{BB} = 0.598 \times \frac{932}{300} = 1.858$ V

It follows that V_{EB3} becomes

$V_{EB3} = 1.858 - 0.700 - 0.642 = 0.516$ V

i.e. V_{EB3} has decreased by $0.600 - 0.516 = 0.084$ V

Correspondinly, I_{C3} will decrease by a factor of $e^{\frac{-0.084}{0.025}} = 0.035$.

$\therefore\ I_{C4}$ becomes $0.035 \times 2 = 0.07$ mA

This value is close to zero, no iteration required.

$\therefore v_I = 10 + 0.7 + 0.642 - 1.858$

$v_I = 9.484$ V

Now find v_I for $v_O = -10$ V and $R_L = 1\ k\Omega$.

$i_L = \frac{-10}{1\ k\Omega} = -10$ mA

Assume that current through Q_2 is almost zero.

$\therefore I_{C4} \simeq 10$ mA

The current through Q_4 increases by a factor of 5 (relative to the quiescent value).

$\therefore$ The current through Q_3 must also increase by the same factor. Thus $|V_{BE3}| = 0.602 + 0.025 \ln 5 = 0.642$ V

$|V_{BE3}|$ has increased by $0.642 - 0.602 = 0.04$ V. Since Q_1 and Q_2 are almost cut off, all of the I_{Bias} now flows through the V_{BE} multiplier. That is an increase of $0.2\ \mu$. Assuming that most of the increase occurs in I_{C5}, V_{BE5} becomes

$V_{BE5} = 0.7 + 0.025 \ln\left(\frac{18.2\ \mu A}{1\ mA}\right) \simeq 0.600$ V

The voltage V_{BE5} remains almost constant, and the voltage across the multiplier will remain almost constant. Thus the increase in $|V_{EB3}|$ will result in an equal decrease in $|V_{BE1}| + |V_{BE2}|$, i.e.

$V_{BE1} + V_{BE2} = 0.660 + 0.602 - 0.04$

The current through each of Q_1 and Q_2 decreases by the same factor, let it be m; then

$0.025 \ln m + 0.025 \ln m = -0.04$ V

$\Rightarrow m = 0.45$

Thus $I_{C2} = 0.45 \times 2 = 0.9$ mA

Now do iteration

$I_{C4} = 10.9$

I_{C4} has increased by a factor of $\frac{10.9}{2} = 5.45$

$\therefore |V_{BE3}| = 0.602 + 0.025 \ln 5.45$

$= 0.644$

$v_I = v_O + |V_{EB3}|$

$v_I \cong -10.644$ V

11.36 (a) Refer to the circuit in Fig. P11.36. While D_1 is conducting, the voltage at the emitter of Q_3 is $(V_{CC1} - V_D)$. For Q_3 to turn on, the voltage at its base must be at least equal to $V_{CC1} = 35$ V. This will occur when v_I reaches the value

$v_I = V_{CC1} - V_{Z1} - V_{BB}$

$= 35 - 3.3 - 1.2 = 30.5$ V

This is the positive threshold at which Q_3 is turned on.

(b) The power dissipated in the circuit is given by Eq. (11.19):

$$P_D = \frac{2}{\pi}\frac{\hat{V}_o}{R_L}V_{CC} - \frac{1}{2}\frac{\hat{V}_o^2}{R_L}$$

For 95% of the time, $\hat{V}_o = 30$ V, $V_{CC} = 35$ V,

$$P_D = \frac{1}{R_L}\left[\frac{2}{\pi} \times 30 \times 35 - \frac{1}{2} \times 30^2\right]$$

$$= \frac{218.5}{R_L}$$

For 5% of the time, $\hat{V}_o = 65$ V, $V_{CC} = 70$ V,

$$P_D = \frac{1}{R_L}\left[\frac{2}{\pi} \times 65 \times 70 - \frac{1}{2} \times 65^2\right]$$

$$= \frac{784.1}{R_L}$$

Thus, the total power dissipation is

$$P_D = \frac{218.5}{R_L} \times 0.95 + \frac{784.1}{R_L} \times 0.05$$

$$= \frac{246.8}{R_L} \qquad (1)$$

This should be compared to the power dissipation of a class AB output stage operated from ±70 V. Here,

P_D (for 95% of the time)

$$= \frac{1}{R_L}\left[\frac{2}{\pi} \times 30 \times 70 - \frac{1}{2} \times 30^2\right]$$

$$= \frac{886.9}{R_L}$$

P_D (for 5% of the time)

$$= \frac{1}{R_L}\left[\frac{2}{\pi} \times 65 \times 70 - \frac{1}{2} \times 65^2\right]$$

$$= \frac{784.1}{R_L}$$

$$\text{Total dissipation} = \frac{886.9}{R_L} \times 0.95 + \frac{784.1}{R_L} \times 0.05$$

$$= \frac{881.8}{R_L} \qquad (2)$$

The results in (1) and (2) indicate that using the Class G circuit in Fig. P11.36 results in a reduction in P_D by a factor of 3.6!

11.37 Refer to Exercise 11.11 and Fig. 11.21.

$$2 \times 10^{-3} = 10^{-14} e^{V_{BE}/V_T}$$

$$\Rightarrow V_{BE} = 0.650 \text{ V}$$

$$R_{E1} = \frac{0.650 \text{ V}}{100 \text{ mA}} = 6.5\ \Omega$$

From a normal peak output current of 75 mA, we get

$$V_{BE} = 6.5 \times 75 = 487.5 \text{ mV}$$

$$I_{C5} = 10^{-14} \times e^{487.5/25} = 2.9\ \mu\text{A}$$

11.38 Refer to Fig. P11.38.

$$2 \times 10^{-3} = 10^{-14} e^{V_{EB5}/V_T}$$

$$V_{EB5} = 0.025 \ln(2 \times 10^{11})$$

$$= 0.650 \text{ V}$$

$$R = \frac{0.650 \text{ V}}{100 \text{ mA}} = 6.5\ \Omega$$

For a normal peak output current of 75 mA, we have

$$V_{EB5} = 6.5 \times 75 = 487.5 \text{ mV}$$

$$I_{C5} = 10^{-14} \times e^{487.5/25}$$

$$= 2.9\ \mu\text{A}$$

11.39 Refer to Fig. 11.22.

At 125°C, we have

$$V_Z = 6.8 + (125 - 25) \times 2 = 7.0 \text{ V}$$

Since $I_{C2} = 200\ \mu$A, then

$$V_{BE1} = 0.7 + 0.025 \ln\left(\frac{200}{100}\right) - 2 \text{ mV} \times 100$$

$$= 0.517 \text{ V}$$

Similarly, for Q_2 to conduct 200 μA, we need

$$V_{BE2} = 0.517 \text{ V}$$

Now, the voltage across R_1 and R_2 is

$$V_{(R_1+R_2)} = V_Z - V_{BE1}$$

$$= 7 - 0.517 = 6.483 \text{ V}$$

The voltage across R_2 is equal to V_{BE1}, thus

$$R_2 = \frac{0.517}{0.2 \text{ mA}} = 2.59 \text{ k}\Omega$$

The voltage across R_1 is given by $6.487 - 0.517 = 5.966$ V. Thus,

$$R_1 = \frac{5.966 \text{ V}}{0.2 \text{ mA}} = 29.8 \text{ k}\Omega$$

Now, at 25°C, we have

$$V_Z = 6.8 \text{ V}$$

Assume $V_{BE1} = 0.7$ V, then

$$V_{(R_1+R_2)} = 6.8 - 0.7 = 6.1 \text{ V}$$

$$I_{(R_1+R_2)} = \frac{6.1}{2.59 + 29.8} = 0.188\ \mu\text{A}$$

Thus

$$V_{BE1} = 0.7 + 0.025 \ln \frac{188}{100} = 0.716 \text{ V}$$

$$V_{(R_1+R_2)} = 6.8 - 0.716 = 6.084$$

$$V_{BE2} = 6.084 \times \frac{R_2}{R_1 + R_2}$$

$$= 6.084 \times \frac{2.59}{2.59 + 29.8} = 0.486 \text{ V}$$

Thus,

$$I_{C2} = 100\, e^{(486-700)/25} = 0.019\ \mu\text{A}$$

11.40 (a) Refer to the circuit in Fig. 11.23.

$$R_{\text{out}} = R_{on} \parallel R_{op}$$

where

$$R_{on} = \frac{1}{g_{mn}} \parallel r_{on} \simeq 1/g_{mn}$$

$$R_{op} = \frac{1}{g_{mp}} \parallel r_{op} \simeq 1/g_{mp}$$

$$R_{\text{out}} = R_{on} \parallel R_{op} \simeq \frac{1}{g_{mn}} \parallel \frac{1}{g_{mp}}$$

Thus,

$$R_{\text{out}} \simeq \frac{1}{g_{mn} + g_{mp}} \qquad \text{Q.E.D.}$$

For matched devices, we have

$$g_{mn} = g_{mp} = g_m$$

$$R_{\text{out}} = \frac{1}{2g_m} \qquad \text{Q.E.D.}$$

(b) $R_{\text{out}} = 20\ \Omega$

$$\frac{1}{2g_m} = 20$$

$$\Rightarrow g_m = \frac{1}{40} \text{ A/V} = 25 \text{ mA/V}$$

But,

$$g_m = k'(W/L)V_{OV}$$

$$25 = 200V_{OV}$$

$$\Rightarrow V_{OV} = \frac{25}{200} = 0.125 \text{ V}$$

$$V_{GG} = 2V_{GS}$$

$$= 2(|V_t| + |V_{OV}|)$$

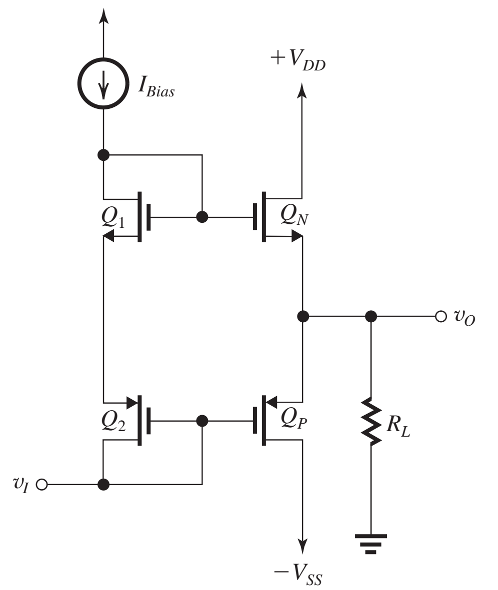
$$= 2(0.5 + 0.125)$$

$$= 2 \times 0.625 = 1.25 \text{ V}$$

$$I_Q = \frac{1}{2}k'\left(\frac{W}{L}\right)V_{OV}^2$$

$$= \frac{1}{2} \times 200 \times 0.125^2 = 1.56 \text{ mA}$$

11.41



(a) Equation (11.43)

$$I_Q = I_{\text{Bias}} \frac{(W/L)_n}{(W/L)_1}$$

$$1 = 0.1 \frac{(W/L)_n}{(W/L)_1}$$

$$\frac{(W/L)_n}{(W/L)_1} = 10$$

$$Q_1\text{: } I_{\text{Bias}} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_1 V_{OV}^2$$

$$0.1 = \frac{1}{2} \times 0.250 \times \left(\frac{W}{L}\right)_1 \times (0.15)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_1 = 35.6$$

$$Q_2\text{: } 0.1 = \frac{1}{2} \times 0.100 \times \left(\frac{W}{L}\right)_2 \times (0.15)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_2 = 88.9$$

$$Q_N\text{: } 1 = \frac{1}{2} \times 0.250 \times \left(\frac{W}{L}\right)_N \times (0.15)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_N = 356$$

$$Q_P\text{: } 1 = \frac{1}{2} \times 0.100 \times \left(\frac{W}{L}\right)_P \times (0.15)^2$$

$$\left(\frac{W}{L}\right)_P = 889$$

(b) From the circuit we get $v_I = v_O - V_{SGP}$

Since $v_O = 0$, we have

$v_I = -V_{SGP}$

$V_{SGP} = |V_{OV}| + |V_t|$

$= 0.15 + 0.45$

$= 0.6$ V

$\therefore\ v_I = -V_{SGP} = -0.6$ V

(c) Using Eq. (11.46), we obtain

$v_{O\max} = V_{DD} - V_{OV}|_{\text{Bias}} - V_{GSN}$

To find V_{GSN}, use the equations

$$i_{DN\max} = \frac{1}{2}k_n' \frac{W}{L}(V_{GSN} - V_t)^2$$

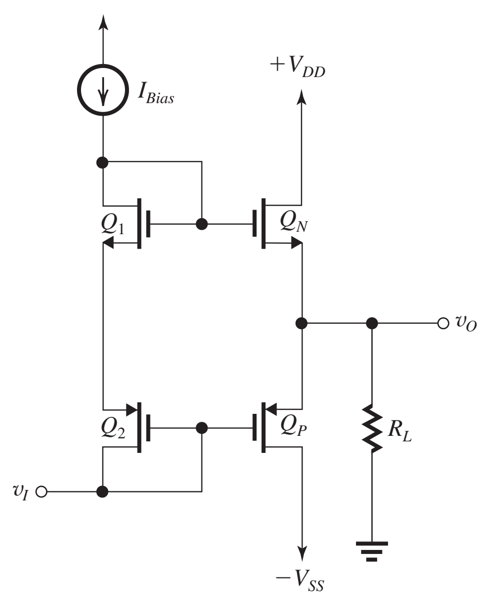
$$10 = \frac{1}{2} \times 0.250 \times 356\,(V_{GSN} - V_t)^2$$

$\Rightarrow V_{GSN} - V_t = 0.47$ V

$V_{GSN} = V_t + 0.47 = 0.45 + 0.47 \simeq 0.92$ V

$\therefore\ v_{O\max} = 2.5 - 0.2 - 0.92 = 1.38$ V

11.42



(a) under quiescent condition

$$\text{Voltage gain} = \frac{v_o}{v_i} = \frac{R_L}{R_L + R_{\text{out}}}$$

As shown in problem 11.40, for matched transistors we have

$$R_{\text{out}} = \frac{1}{2g_m}$$

Substituting for R_{out} above, we obtain for $\frac{v_o}{v_i}$

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + \frac{1}{2g_m}} \qquad \text{Q.E.D.}$$

(b) Voltage gain $= 0.98 = \dfrac{R_L}{R_L + \frac{1}{2g_m}}$

$$0.98 = \frac{1000}{1000 + \frac{1}{2g_m}}$$

$\Rightarrow g_m = 24.5$ mA/V

For Q_1, we have $I_{Bias} = I_D$.

$$\therefore 0.2 = \frac{1}{2}k_1 V_{OV}^2$$

$$0.2 = \frac{1}{2} \times 20 \times V_{OV}^2$$

$\Rightarrow V_{OV} = 0.14$ V

For Q_N, we have

$g_m = k_n V_{OV}$

$24.5 = k_n \times 0.14$

$k_n = 173$ mA/V^2

$$n = \frac{k_n}{k_1} = \frac{173}{20}$$

$= 8.66$

and $I_Q = nI_{\text{bias}}$

$= 8.66 \times 0.2$

$= 1.73$ mA

11.43 Refer to Fig. 11.24. Consider the situation when Q_N is conducting the maximum current of 20 mA,

$$20 = \frac{1}{2}k_n v_{OVN}^2$$

$$= \frac{1}{2} \times 200 v_{OVN}^2$$

$\Rightarrow v_{OVN} = 0.45$ V

Thus,

$v_{O\min} = -V_{SS} + v_{OVN}$

$= -2.5 + 0.45 = -2.05$ V

Because Q_N and Q_P are matched, a similar situation pertains when Q_P is supplying maximum current, and

$v_{O\max} = +2.05$ V

Thus, the output voltage swing realized is ± 2.05 V.

11.44 From Eq. (11.57), we obtain

$R_{\text{out}} = 1/\mu(g_{mp} + g_{mn})$

where

$$g_{mp} = g_{mn} = \frac{2I_Q}{|V_{OV}|} = \frac{2 \times 2}{0.2} = 20 \text{ mA/V}$$

$$R_{\text{out}} = \frac{1}{5(20+20)} = \frac{1}{200} \text{ k}\Omega = 5\ \Omega$$

11.45 (a) From Eq. (11.68), we obtain

$$|\text{Gain error}| = \frac{1}{2\mu g_m R_L} \qquad (1)$$

From Eq. (11.57), we get

$$R_{\text{out}} = \frac{1}{\mu(g_{mn} + g_{mp})}$$

For $g_{mn} = g_{mp} = g_m$, we have

$$R_{\text{out}} = \frac{1}{2\mu g_m} \qquad (2)$$

Combining (1) and (2) yields

$$|\text{Gain error}| = \frac{R_{\text{out}}}{R_L} \qquad \text{Q.E.D.}$$

(b) For $R_L = 100\ \Omega$ and $|\text{Gain error}| = 3\%$,

$R_{\text{out}} = 0.03 \times 100 = 3\ \Omega$

But,

$$R_{\text{out}} = \frac{1}{2\mu g_m}$$

$$3 = \frac{1}{2 \times 5 \times g_m}$$

$$\Rightarrow g_m = \frac{1}{30} = 33.3 \text{ mA/V}$$

Using

$$g_m = \frac{2I_Q}{V_{OV}}$$

we obtain

$$33.3 = \frac{2 \times 2.5}{V_{OV}}$$

$$\Rightarrow V_{OV} = \frac{5}{33.3} = 0.15 \text{ V}$$

11.46 i_{DP} and i_{DN} are given by Eqs. (11.61) and (11.62) as

$$i_{DP} = I_Q\left(1 - \mu\frac{v_O - v_I}{V_{OV}}\right)^2 \qquad (1)$$

$$i_{DN} = I_Q\left(1 + \mu\frac{v_O - v_I}{V_{OV}}\right)^2 \qquad (2)$$

Equation (1) shows that Q_P turns off and $i_{DP} = 0$ when

$$\mu\frac{v_O - v_I}{V_{OV}} = 1$$

Substituting this into Eq. (2) gives

$i_{DN} = I_Q(1+1)^2 = 4I_Q$

Since $i_L = -i_{DN}$, we have

$v_O = i_L R_L = -4I_Q R_L \qquad$ Q.E.D.

Similarly, Eq. (2) shows that Q_N turns off and $i_{DN} = 0$ when

$$\mu\frac{v_O - v_I}{V_{OV}} = -1$$

substituting this into Eq. (1) gives

$i_{DP} = I_Q(1+1)^2 = 4I_Q$

Since in this case $i_L = i_{DP}$, then

$v_O = i_L R_L = 4I_Q R_L \qquad$ Q.E.D.

Thus, one of the two transistors turns off when $|i_L|$ reaches $4I_Q$.

11.47 (a) $I_Q = \frac{1}{2}k'\frac{W}{L}V_{OV}^2$

$$1.5 = \frac{1}{2} \times 0.1\left(\frac{W}{L}\right)_P (0.15)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_P = 1333.3$$

$$\left(\frac{W}{L}\right)_N = \frac{(W/L)_P}{k_n'/k_p'}$$

$$\left(\frac{W}{L}\right)_N = \frac{1333.3}{2.5} = 533.3$$

(b) $g_m = \dfrac{2I_Q}{V_{OV}} = \dfrac{2 \times 1.5}{0.15} = 20$ mA/V

$$R_{\text{out}} = \frac{1}{2\mu g_m} \text{ (where } g_{mn} = g_{mp} = g_m)$$

$$2.5 = \frac{1}{2\mu \times 20 \times 10^{-3}}$$

$$\Rightarrow \mu = 10 \text{ V/V}$$

(c) Gain error $= -\dfrac{1}{2\mu g_m R_L}$

$$= -\frac{1}{2 \times 10 \times 20 \times 10^{-3} \times 50} = -0.05$$

or -5%

(d) In the quiescent state the dc voltage at the output of each amplifier must be of the value that causes the current in Q_N and Q_P to be I_Q. Thus, for the Q_P amplifier the output voltage is

$$V_{DD} - V_{SG} = V_{DD} - |V_{tp}| - |V_{OV}|$$

$$= 2.5 - 0.5 - 0.15 = 1.85 \text{ V}$$

Similarly, the voltage at the output of the Q_N amplifier must be

$$-V_{SS} + V_{GS} = -2.5 + 0.5 + 0.15$$

$$= -1.85 \text{ V}$$

(e) Q_P will be supplying all the load current when Q_N cuts off. From Eq. (11.62) we see that Q_N cuts off when

$$\mu \frac{v_O - v_I}{V_{OV}} = -1$$

Substituting this in Eq. (11.61), we find the current i_{DP} to be

$$i_{DP} = I_Q(1+1)^2 = 4I_Q$$

Since in this situation

$$i_L = i_{DP}$$

then

$$i_L = 4I_Q$$

and

$$v_O = 4I_Q R_L$$

$$= 4 \times 1.5 \times 10^{-3} \times 50 = 0.3 \text{ V}$$

Similarly, when $v_O = -0.3$ V, Q_P will cut off and all the current ($4I_Q = 6$ mA) will be supplied by Q_N.

(f) The situation at $v_O = v_{O\max}$ is illustrated in Fig. 1. Analysis of this circuit provides

$$i_{DP} = \frac{1}{2} \times k_n' \left(\frac{W}{L}\right)_n [2.5 - (v_{O\max} - 0.5) - 0.5]^2$$

$$\frac{v_{O\max}}{R_L} = \frac{1}{2} \times 0.25 \times 533.3(2.5 - v_{O\max})^2$$

$$\Rightarrow v_{O\max} = 1.77 \text{ V}$$

Similarly,

$$v_{O\min} = -1.77 \text{ V}$$

11.48 (a) From the circuit in Fig. P11.48 we see that

$$V_{B1} - V_{B4} = \left(1 + \frac{R_3}{R_4}\right)V_{BE6} + \left(1 + \frac{R_1}{R_2}\right)V_{BE5}$$

and

$$V_{GG} = (V_{B1} - V_{B4}) - (V_{BE1} + V_{BE2} + V_{EB3} + V_{EB4})$$

Thus

$$V_{GG} = \left(1 + \frac{R_3}{R_4}\right)V_{BE6} + \left(1 + \frac{R_1}{R_2}\right)V_{BE5} - 4V_{BE} \qquad \text{Q.E.D.} \qquad (1)$$

where V_{BE} denotes the magnitude of the base-emitter voltage of each of $Q_1 - Q_4$.

(b) From the circuit diagram we see that as the output transistors heat up, Q_6 also heats up. Thus in Eq. (1) only V_{BE6} changes with the temperature of the output stage, thus V_{GG} changes with temperature according to

$$\frac{\partial V_{GG}}{\partial T} = \left(1 + \frac{R_3}{R_4}\right)\frac{\partial V_{BE6}}{\partial T} \qquad \text{Q.E.D.} \qquad (2)$$

(c) To stabilize the operation of Q_N and Q_P as temperature changes, we arrange that

$$\frac{\partial V_{GG}}{\partial T} = \frac{\partial (V_{tN} + |V_{tP}|)}{\partial T}$$

$$= -3 - 3 = -6 \text{ mV/°C} \qquad (3)$$

From Eq. (2), we obtain

$$\frac{\partial V_{GG}}{\partial T} = \left(1 + \frac{R_3}{R_4}\right)\frac{\partial V_{BE6}}{\partial T}$$

$$= \left(1 + \frac{R_3}{R_4}\right) \times -2$$

$$= -2\left(1 + \frac{R_3}{R_4}\right) \text{ mV/°C} \qquad (4)$$

This figure belongs to Problem 11.47, part (f).

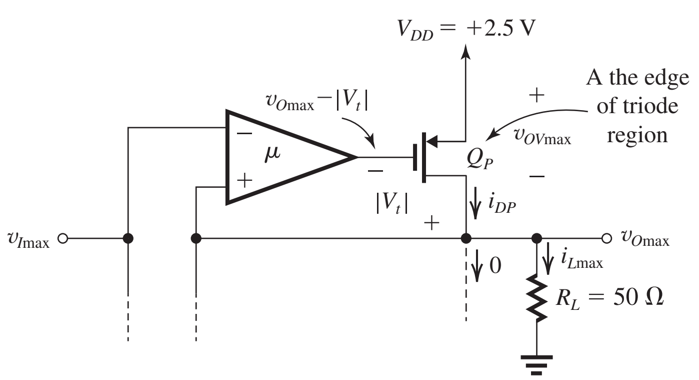


Figure 1

From Eqs. (3) and (4), we obtain

$$1+\frac{R_3}{R_4}=3$$

$$\Rightarrow \frac{R_3}{R_4}=2$$

(d) $I_{DN}=I_{DP}=100$ mA

$$100=\frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_N V_{OVN}^2$$

$$100=\frac{1}{2}\times 2\times 10^3\times V_{OVN}^2$$

$$\Rightarrow V_{OVN}=0.316\text{ V}$$

Similarly,

$$|V_{OVP}|=0.316\text{ V}$$

Thus,

$$V_{GSN}=|V_{GSP}|=0.316+3=3.316\text{ V}$$

and

$$V_{GG}=2\times 3.316=6.632\text{ V}$$

To establish a quiescent current of 20 mA in the driver stage, we use

$$R=\frac{V_{GG}}{20}=\frac{6.632}{20}=0.3316\text{ k}\Omega$$

$$\simeq 332\ \Omega$$

$$V_{B1}-V_{B4}=V_{GG}+4V_{BE}$$

$$=6.632+4\times 0.7=9.432\text{ V}$$

Thus,

$$\left(1+\frac{R_3}{R_4}\right)V_{BE6}+\left(1+\frac{R_1}{R_2}\right)V_{BE5}=9.432\text{ V}$$

$$(1+2)\times 0.7+\left(1+\frac{R_1}{R_2}\right)\times 0.7=9.432$$

$$\Rightarrow \frac{R_1}{R_2}=9.47$$

11.49 Refer to the circuit of Fig. 11.29.

Resistors R_2 and R_3 control the gain,

$$A_v=-\frac{2R_2}{R_3}$$

Resistor R_3 controls the gain alone. Resistor R_2 affects both the gain and the dc output level. To see the later point, equate I_3 and I_4 from Eqs. (11.69) and (11.70) to obtain

$$\frac{V_S-3V_{EB}}{R_1}=\frac{V_O-2V_{EB}}{R_2}$$

$$\Rightarrow V_O=2V_{EB}+\frac{R_2}{R_1}V_S-\frac{3R_2}{R_1}V_{EB}$$

$$=\frac{R_2}{R_1}V_S+\left(2-\frac{3R_2}{R_1}\right)V_{EB}$$

For $V_O\simeq\frac{2}{3}V_S$, select $\frac{R_2}{R_1}=\frac{2}{3}$

$$R_2=\frac{2R_1}{3}=\frac{100}{3}=33.3\text{ k}\Omega$$

To keep the gain unchanged, we must change R_3 so that

$$\frac{2R_2}{R_3}=50$$

$$R_3=\frac{2\times(100/3)}{50}=\frac{4}{3}=1.33\text{ k}\Omega$$

11.50 Refer to Fig. 11.29 with $V_S=22$ V.

$$V_{B1}\simeq 0$$

$$V_{E1}\simeq 0.7\text{ V}$$

$$V_{E3}\simeq 1.4\text{ V}$$

$$V_{C10}=22-0.7=21.3\text{ V}$$

$$I_{E3}=\frac{21.3-1.4}{50}\simeq 0.4\text{ mA}$$

$$I_{E1}=I_{B3}=\frac{I_{E3}}{\beta_P+1}=\frac{0.4}{21}=19\ \mu\text{A}$$

$$I_{B1}=\frac{I_{E1}}{\beta_P+1}=\frac{19}{21}=0.9\ \mu\text{A}$$

$$V_{B1}=I_{B1}\times R_4=0.9\times 10^{-3}\times 150=0.136\text{ V}$$

We can use this value to obtain I_{E1}:

$$V_{E1}=0.836\text{ V}$$

$$V_{E3}=1.536\text{ V}$$

$$I_{E3}=\frac{21.3-1.536}{50}\simeq 0.4\text{ mA}$$

(almost no change)

$$I_{E1}\simeq 19\ \mu\text{A}$$

$$I_{E4}=I_{E3}=0.4\text{ mA}$$

$$I_{E2}=I_{E1}=19\ \mu\text{A}$$

$$I_{E5}\simeq I_{C3}=0.4\times\frac{20}{21}=0.38\text{ mA}$$

$$I_{E6}=I_{E5}=0.38\text{ mA}$$

$$I_{R1}=I_{R2}\simeq 0.4\text{ mA}$$

$$V_O=V_{E4}+I_{R2}R_2$$

$$=V_{E3}+I_{R2}R_2$$

$$=1.536+0.4\times 25$$

$$=11.54\text{ V}$$

11.51 Refer to Fig. 11.31. To limit P_D to 2 W, we need to limit the supply voltage to

$V_S = 16$ V

The $V_S = 16$ V graph intersects the THD = 3% line at $P_L = 2.7$ W, which is the maximum possible load power. Thus,

$$\frac{(\hat{V}_o/\sqrt{2})^2}{R_L} = 2.7$$

$$\hat{V}_o = \sqrt{2.7 \times 8 \times 2} = 6.57 \text{ V}$$

which means that an approximately 13-V peak-to-peak sinusoid is needed.

11.52 Figure 1 shows the currents in the circuit for the case where v_I is positive and assuming an op amp with very high gain (hence the 0 V between its two input terminals) and all β's are very high. The result is that

$$i_O = \frac{v_I}{R}$$

If v_I is negative, the current through R reverses direction and is thus supplied by Q_2 and then mirrored to the output by the mirror $Q_5 - Q_6$, resulting in $i_O = v_I/R$ but reversed in direction.

Consider next the effect of finite transistor β. For the case in Fig. 1, we have

$$i_{E1} = \frac{v_I}{R}$$

$$i_{C1} = \alpha_1 i_{E1} = \frac{\beta}{\beta+1}\left(\frac{v_I}{R}\right)$$

$$i_{C4} = i_{C1}\frac{1}{1+\dfrac{2}{\beta}}$$

Thus,

$$i_O = \frac{\beta}{\beta+1}\,\frac{\beta}{\beta+2}\,\frac{v_I}{R}$$

$$= \frac{100}{101} \times \frac{100}{102} \times \frac{v_I}{R}$$

$$\simeq 0.97\frac{v_I}{R}$$

11.53 Refer to Fig. 11.32.

$\text{Gain} = 2K = 8$

$K = 4$

$$\frac{R_4}{R_3} = K = 4$$

$\Rightarrow R_4 = 40\text{ k}\Omega$

$$1 + \frac{R_2}{R_1} = 4$$

$$\frac{R_2}{R_1} = 3$$

$\Rightarrow R_2 = 30\text{ k}\Omega$

This figure belongs to Problem 11.52.

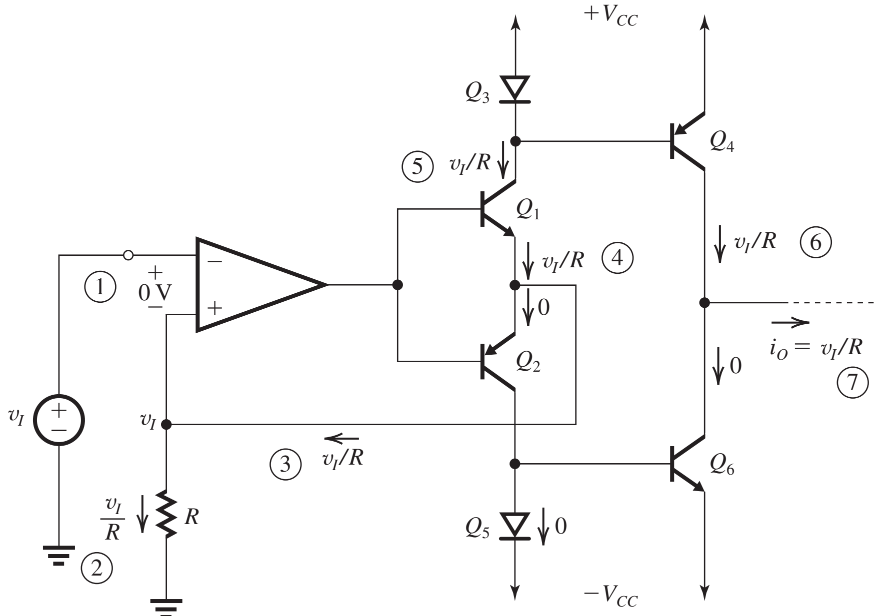


Figure 1

11.54 The analysis is shown in Fig. 1 (below), from which the gain is found as

$$\frac{v_O}{v_I} = 1 + \frac{R_2 + R_3}{R_1}$$

The largest sinusoid that can be provided across R_L will have a peak amplitude of $2 \times 13 = 26$ V. To ensure that the signals v_{O1} and v_{O2} are complementary, then

$$1 + \frac{R_2}{R_1} = \frac{R_3}{R_1}$$

Selecting $R_1 = 1$ kΩ, we obtain

$$1 + R_2 = R_3 \qquad (1)$$

and to obtain a gain of 8 V/V we write

$$1 + \frac{R_2 + R_3}{R_1} = 8$$

$$1 + R_2 + R_3 = 8 \qquad (2)$$

Solving (1) and (2) simultaneously gives

$$2(1 + R_2) = 8$$

$$\Rightarrow R_2 = 3 \text{ k}\Omega$$

$$R_3 = 4 \text{ k}\Omega$$

11.55 See figure on the next page.

11.56
Average $= +10 \times 0.65 - 10 \times 0.35 = +3$ V

If duty cycle changed to 0.35, the average becomes

$= +10 \times 0.35 - 10 \times 0.65 = -3$ V

11.57 (a) Maximum peak voltage across $R = V_{DD}$

Maximum power supplied to load

$$= \frac{(V_{DD}/\sqrt{2})^2}{R} = \frac{V_{DD}^2}{2R}$$

(b) Power loss $= 4 f_s C V_{DD}^2$

$$\eta = \frac{P_L}{P_L + P_{\text{loss}}}$$

$$= \frac{V_{DD}^2/2R}{(V_{DD}^2/2R) + 4 f_s C V_{DD}^2}$$

$$= \frac{1}{1 + 8 f_s CR}$$

For $f_s = 250$ kHz, $C = 1000$ pf and $R = 16\ \Omega$

$$\eta = \frac{1}{1 + 8 \times 250 \times 10^3 \times 1000 \times 10^{-12} \times 16}$$

$= 97\%$

11.58

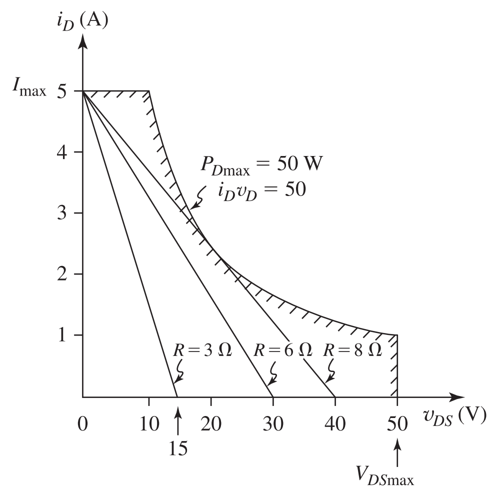


Figure 1

(a) Figure 1 shows the SOA boundaries.

(b) For the CS configuration in Fig. P11.58,

$$V_{DS} = V_{DD} - RI_D \qquad (1)$$

This figure belongs to Problem 11.54.

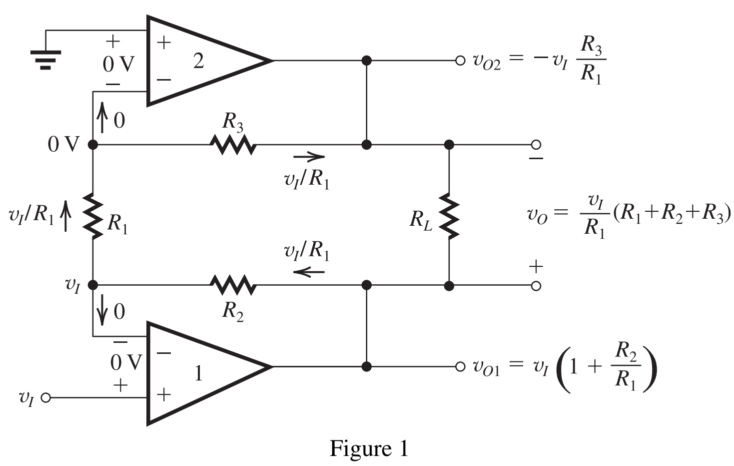
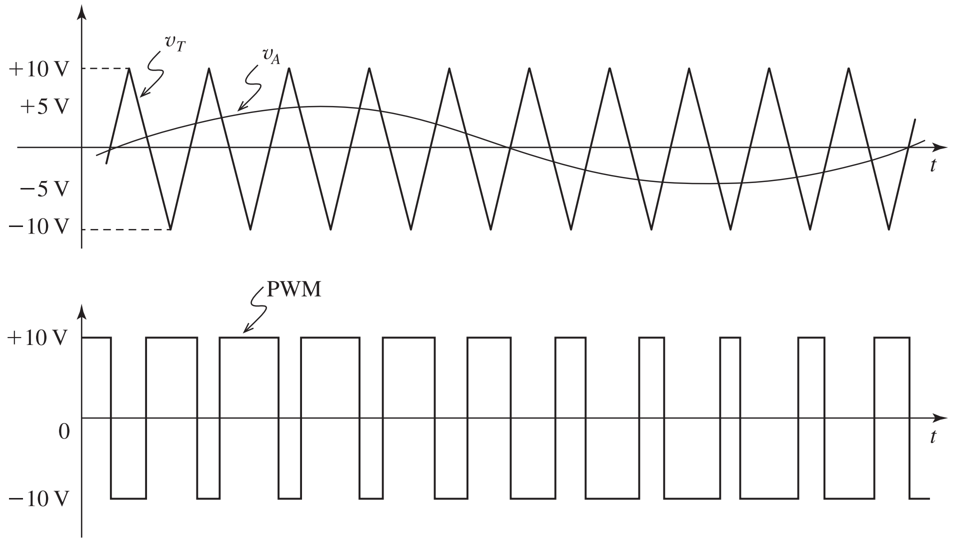


Figure 1

This figure belongs to Problem 11.55.



We see that maximum V_{DS} occurs when $I_D = 0$ and the resulting maximum V_{DS} is

$$V_{DS\max} = V_{DD}$$

Writing (1) in the alternative form

$$I_D = \frac{V_{DD} - V_{DS}}{R} \qquad (2)$$

shows that maximum I_D is obtained when $V_{DS} = 0$ and the resulting maximum I_D is

$$I_{D\max} = \frac{V_{DD}}{R}$$

The power dissipation in the transistor is given by

$$P_D = V_{DS} I_D$$

$$= (V_{DD} - RI_D) I_D$$

P_D will be maximum when

$$\frac{\partial P_D}{\partial I_D} = 0$$

that is,

$$V_{DD} - 2RI_D = 0$$

$$\Rightarrow RI_D = \frac{V_{DD}}{2}$$

or

$$V_{DS} = \frac{V_{DD}}{2}$$

The corresponding $P_{D\max}$ is

$$P_{D\max} = V_{DS} I_D$$

$$= \frac{V_{DD}}{2} \frac{V_{DD}}{2R}$$

$$= \frac{V_{DD}^2}{4R}$$

(c) For $V_{DD} = 40$ V, $v_{DS\max} = 40$ V. Now, since V_{DS} and I_D are related by the linear relationship in (1) or (2), the straight line representing this relationship on the $i_D - v_{DS}$ plane must pass by the point $v_{DS} = 40$ V and $i_D = 0$. Now we are searching for the straight line with maximum slope that clears the hyperbola and intersects the vertical axis at 5 A or less. For this case, this straight line is the one joining the points (40, 0) and (0, 5). It is a tangent to the hyperbola at $v_{DS} = \frac{V_{DD}}{2} = 20$ V, which is the point of maximum power dissipation. For this straight line

$$R = \frac{40 \text{ V}}{5 \text{ A}} = 8\ \Omega$$

$$I_{D\max} = 5 \text{ A}$$

$$P_{D\max} = \frac{V_{DD}^2}{4R} = \frac{40^2}{4 \times 8} = 50 \text{ W}$$

(d) For $V_{DD} = 30$ V: Following a process similar to that in (c), we find

$$R = \frac{30 \text{ V}}{5 \text{ A}} = 6\ \Omega$$

$$I_{D\max} = 5 \text{ A}$$

$$P_{D\max} = \frac{30^2}{4 \times 6} = 37.5 \text{ W}$$

The locus of the operating point is shown in Fig. 1.

(e) For $V_{DD} = 15$ V, we have

$$R = \frac{15 \text{ V}}{5 \text{ A}} = 3\ \Omega$$

$$I_{D\max} = 5 \text{ A}$$

$$P_{D\max} = \frac{15^2}{4 \times 3} = 18.75 \text{ W}$$

The locus of the operating point is shown in Fig. 1.

11.59 Power rating $= \dfrac{130-30}{2.5} = 40$ W

$I_{Cav} \le \dfrac{40}{20} = 2.0$ A

11.60 (a) $\theta_{JA} = \dfrac{T_{J\max} - T_{A0}}{P_{D0}}$

$= \dfrac{100-25}{2} = 37.5°\text{C/W}$

(b) At $T_A = 50°$C, we have

$P_{D\max} = \dfrac{T_{J\max} - T_A}{\theta_{JA}}$

$= \dfrac{100-50}{37.5} = 1.33$ W

(c) $T_J = 25° + 37.5 \times 1 = 62.5°$C

11.61 $T_J \le 50 + 3 \times 20 = 110°$C

$V_{BE} = 800 - 2 \times \ (110-25) = 630$ mV

$= 0.63$ V

11.62 $\theta_{JC} = \dfrac{T_J - T_C}{P_D} = \dfrac{180° - 30°}{50} = 3°\text{C/W}$

$T_J - T_S = \theta_{JS} P_D$

$180° - T_S = (\theta_{JC} + \theta_{CS}) P_D$

$\Rightarrow T_S = 180 - (3 + 0.6) \times 30 = 72°$

$T_S - T_A = \theta_{SA} P_D$

$72 - 27 = \theta_{SA} \times 30$

$\Rightarrow \theta_{SA} = 1.5°\text{C/W}$

Required heat-sink length $= \dfrac{6°\text{C/W/cm}}{1.5°\text{C/W}}$

$= 4$ cm

11.63 $T_C - T_A = \theta_{CA} P_D$

$= (\theta_{CS} + \theta_{SA})\, P_D$

$\Rightarrow P_D = \dfrac{T_C - T_A}{\theta_{CS} + \theta_{SA}} = \dfrac{97-25}{0.5+0.1} = 120$ W

$T_J - T_C = \theta_{JC} P_D$

$150 - 97 = \theta_{JC} \times 120$

$\Rightarrow \theta_{JC} = 0.44°\text{C/W}$