Ex: 12.1 Using Eq. (12.2), we obtain

$V_{ICM\,\min} = -V_{SS} + V_{tn} + V_{OV3} - |V_{tp}|$

$= -1.65 + 0.5 + 0.3 - 0.5$

$= -1.35$ V

Using Eq. (12.3), we get

$V_{ICM\,\max} = V_{DD} - |V_{OV3}| - |V_{tp}| - |V_{OV1}|$

$= 1.65 - 0.3 - 0.5 - 0.3$

$= +0.55$ V

Thus,

$-1.35 \text{ V} \le V_{ICM} \le +0.55$ V

Using Eq. (12.5), we obtain

$-V_{SS} + V_{OV6} \le v_O \le V_{DD} - |V_{OV7}|$

Thus

$-1.65 + 0.5 \le v_O \le 1.65 - 0.5$

$\Rightarrow -1.15 \text{ V} \le v_O \le +1.15$ V

Ex: 12.2 For all devices, we have

$|V_A| = 20$ V

Using Eq. (12.13), we get

$$A_1 = -\frac{2}{|V_{OV1}|} \Bigg/ \left[\frac{1}{|V_{A2}|} + \frac{1}{V_{A4}}\right]$$

$$= -\frac{2}{0.2} \Bigg/ \frac{2}{20} = -100 \text{ V/V}$$

Using Eq. (12.20), we obtain

$$A_2 = -\frac{2}{|V_{OV6}|} \Bigg/ \left[\frac{1}{V_{A6}} + \frac{1}{|V_{A7}|}\right]$$

$$= -\frac{2}{0.5} \Bigg/ \frac{2}{20} = -40 \text{ V/V}$$

$A = A_1 A_2$

$= -100 \times -40 = 4000$ V/V

$$r_{o6} = r_{o7} = \frac{|V_A|}{0.5 \text{ mA}} = \frac{20}{0.5} = 40 \text{ k}\Omega$$

$R_o = r_{o6} \parallel r_{o7} = 40 \parallel 40 = 20 \text{ k}\Omega$

Ex: 12.3 The feedback is of the voltage sampling type (i.e., the connection at the output is a shunt one), thus

$$R_{\text{out}} = R_{of} = \frac{R_o}{1 + A\beta}$$

where

$R_o = r_{o6} \parallel r_{o7}$

$A = g_{m1}(r_{o2} \parallel r_{o4}) g_{m6}(r_{o6} \parallel r_{o7})$

$\beta = 1$

Thus,

$$R_{\text{out}} = \frac{r_{o6} \parallel r_{o7}}{1 + g_{m1}(r_{o2} \parallel r_{o4}) g_{m6}(r_{o6} \parallel r_{o7})}$$

Usually,

$A \gg 1$

Thus,

$$R_{\text{out}} \simeq \frac{1}{g_{m6}[g_{m1}(r_{o2} \parallel r_{o4})]}$$

Ex: 12.4 Using Eq. (12.36), we get

$$f_t = \frac{G_{m1}}{2\pi C_C}$$

$$\Rightarrow C_C = \frac{G_{m1}}{2\pi f_t}$$

$$= \frac{0.3 \times 10^{-3}}{2\pi \times 10 \times 10^6}$$

$= 4.8$ pF

From Eq. (12.31), we have

$$f_Z = \frac{G_{m2}}{2\pi C_C}$$

$$= \frac{0.6 \times 10^{-3}}{2\pi \times 4.8 \times 10^{-12}}$$

$\simeq 20$ MHz

From Eq. (12.35), we have

$$f_{P2} = \frac{G_{m2}}{2\pi C_2}$$

$$= \frac{0.6 \times 10^{-3}}{2\pi \times 2 \times 10^{-12}} = 48 \text{ MHz}$$

Thus, f_t is lower than f_Z and f_{P2}.

Ex: 12.5 (a) Using Eq. (12.36), we have

$$f_t = \frac{G_{m1}}{2\pi C_C}$$

$$\Rightarrow C_C = \frac{G_{m1}}{2\pi f_t}$$

$$= \frac{1 \times 10^{-3}}{2\pi \times 100 \times 10^6}$$

$= 1.6$ pF

$A_0 = G_{m1}(r_{o2} \parallel r_{o4}) G_{m2}(r_{o6} \parallel r_{o7})$

$= 1(100 \parallel 100) \times 2(40 \parallel 40)$

$= 50 \times 2 \times 20 = 2000$ V/V

$$f_{3dB} = \frac{f_t}{A_0} = \frac{100 \times 10^6}{2000} = 50 \text{ kHz}$$

(b) From Eq. (12.34), we have

$R = \frac{1}{G_{m2}} = \frac{1}{2 \times 10^{-3}} = 500\ \Omega$

(c) From Eq. (12.35), we have

$f_{P2} = \frac{G_{m2}}{2\pi C_2}$

$= \frac{2 \times 10^{-3}}{2\pi \times 1 \times 10^{-12}} = 318\text{ MHz}$

$\phi_{P2} = -\tan^{-1}\frac{f_t}{f_{P2}}$

$= -\tan^{-1}\frac{100}{318}$

$= -17.4°$

$\text{PM} = 90 - 17.4 = 72.6°$

Ex: 12.6 Using Eq. (12.47), we obtain

$\text{SR} = V_{OV1}\omega_t$

$= 0.2 \times 2\pi \times 100 \times 10^6$

$= 126\text{ V}/\mu\text{s}$

Using Eq. (12.45),

$\text{SR} = \frac{I}{C_C}$

$\Rightarrow I = 126 \times 10^6 \times 1.6 \times 10^{-12}$

$= 200\ \mu\text{A}$

Ex: 12.7

$R_B = \frac{2}{\sqrt{2\mu_n C_{ox}(W/L)_{12}I_{\text{REF}}}}\left(\sqrt{\frac{(W/L)_{12}}{(W/L)_{13}}} - 1\right)$

$=$

$\frac{2}{\sqrt{2 \times 90 \times 10^{-6} \times 80 \times 10 \times 10^{-6}}}\left(\sqrt{\frac{80}{20}} - 1\right)$

$= 5.27\text{ k}\Omega$

Using Eq. (12.61), we obtain

$g_{m12} = \frac{2}{R_B}\left(\sqrt{\frac{(W/L)_{12}}{(W/L)_{13}}} - 1\right)$

$= \frac{2}{5.27}\left(\sqrt{\frac{80}{20}} - 1\right)$

$= 0.379\text{ mA/V}$

Ex: 12.8 From Example 8.6, Q_8 has

$\left(\frac{W}{L}\right)_8 = \frac{40}{0.8}$

$g_{m8} = 0.6\text{ mA/V}$

$g_{m13} = g_{m8} = 0.6\text{ mA/V}$

$g_{m12} = \sqrt{2\mu_n C_{ox}(W/L)_{12}I_{\text{REF}}}$

$= \sqrt{2\mu_n C_{ox} \times 4(W/L)_{13}I_{\text{REF}}}$

$= 2g_{m13} = 1.2\text{ mA/V}$

Now,

$R_B = \frac{2}{\sqrt{2\mu_n C_{ox}(W/L)_{12}I_{\text{REF}}}}\left(\sqrt{\frac{(W/L)_{12}}{(W/L)_{13}}} - 1\right)$

$= \frac{2}{1.2 \times 10^{-3}}(\sqrt{4} - 1)$

$= 1.67\text{ k}\Omega$

From Example 8.6, we have

$V_{DD} = V_{SS} = 2.5\text{ V}$

$I_{\text{REF}} = 90\ \mu\text{A}$

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

$|V_{tp}| = 0.8\text{ V}$

$|V_{OV8}| = 0.3\text{ V}$

$I_{\text{REF}}R_B = 0.09 \times 1.67$

$= 150\text{ mV}$

Since

$g_{m13} = \frac{2I_{\text{REF}}}{V_{OV13}}$

$0.6 = \frac{2 \times 0.09}{V_{OV13}}$

$\Rightarrow V_{OV13} = 0.3\text{ V}$

$V_{GS13} = 0.3 + 0.7 = 1\text{ V}$

$V_{G13} = -V_{SS} + V_{GS13}$

$= -2.5 + 1 = -1.5\text{ V}$

$V_{GS11} = V_{GS13} = 1\text{ V}$

$V_{G11} = V_{G13} + V_{GS11}$

$= -1.5 + 1 = -0.5\text{ V}$

$V_{SG8} = |V_{tp}| + |V_{OV8}|$

$= 0.8 + 0.3 = 1.1\text{ V}$

$V_{G8} = V_{DD} - V_{SG8}$

$= 2.5 - 1.1 = +1.4\text{ V}$

Ex: 12.9 Total bias current $= 300\ \mu\text{A} = 2I_B$

$\Rightarrow I_B = 150\ \mu\text{A}$

$I_B = I_{D1} + I_{D3}$

$150 = I_{D1} + 0.25I_{D1}$

$\Rightarrow I_{D1} = 120\ \mu\text{A}$

$I = I_{D1} + I_{D2}$

$= 120 + 120 = 240\ \mu\text{A}$

$I_{D3,4} = 0.25 I_{D1,2} = 0.25 \times 120$

$= 30\ \mu\text{A}$

Ex: 12.10 Using Eq. (12.64), we get

$V_{ICM\max} = V_{DD} - |V_{OV9}| + V_{tn}$

$= 1.65 - 0.3 + 0.5 = +1.85\text{ V}$

Using Eq. (12.65), we obtain

$V_{ICM\min} = -V_{SS} + V_{OV11} + V_{OV1} + V_{tn}$

$V_{ICM\min} = -1.65 + 0.3 + 0.3 + 0.5$

$= -0.55\text{ V}$

Thus,

$-0.55\text{ V} \le V_{ICM} \le +1.85\text{ V}$

Using Eq. (12.68), we get

$V_{O\max} = V_{DD} - |V_{OV10}| - |V_{OV4}|$

$= 1.65 - 0.3 - 0.3 = +1.05\text{ V}$

Using Eq. (12.69), we obtain

$V_{O\min} = -V_{SS} + V_{OV7} + V_{OV5} + V_{tn}$

$= -1.65 + 0.3 + 0.3 + 0.5$

$= -0.55\text{ V}$

Thus,

$-0.55\text{ V} \le v_O \le +1.05\text{ V}$

Ex: 12.11 $G_m = g_{m1} = g_{m2}$

$$G_m = \frac{2(I/2)}{V_{OV1}} = \frac{I}{V_{OV1}}$$

$$= \frac{0.24}{0.2} = 1.2\text{ mA/V}$$

$$r_{o2} = \frac{|V_A|}{I/2} = \frac{20}{0.12} = 166.7\text{ k}\Omega$$

$$r_{o4} = \frac{|V_A|}{I_{D4}} = \frac{|V_A|}{I_B - \dfrac{I}{2}} = \frac{20}{0.150 - 0.120}$$

$$= \frac{20}{0.03} = 666.7\text{ k}\Omega$$

$$r_{o10} = \frac{|V_A|}{I_B}$$

$$= \frac{20}{0.15} = 133.3\text{ k}\Omega$$

$$g_{m4} = \frac{2I_{D4}}{|V_{OV}|} = \frac{2 \times 0.03}{0.2} = 0.3\text{ mA/V}$$

$R_{o4} = (g_{m4} r_{o4})(r_{o2} \parallel r_{o10})$

$= (0.3 \times 666.7)(166.7 \parallel 133.3)$

$= 14.8\text{ M}\Omega$

$$g_{m6} = \frac{2I_{D6}}{V_{OV}} = \frac{2 \times 0.03}{0.2} = 0.3\text{ mA/V}$$

$$r_{o6} = r_{o8} = \frac{|V_A|}{I_{D6,8}} = \frac{20}{0.03} = 666.7\text{ k}\Omega$$

$R_{o6} = g_{m6} r_{o6} r_{o8}$

$= 0.3 \times 666.7 \times 666.7 = 133.3\text{ M}\Omega$

$R_o = R_{o4} \parallel R_{o6}$

$= 14.8 \parallel 133.3 = 13.3\text{ M}\Omega$

$A_v = G_m R_o = 1.2 \times 13.3 \times 10^3 = 16{,}000\text{ V/V}$

Ex: 12.12 (a) The NMOS input stage operates over the following input common-mode range:

$-V_{SS} + 2V_{OV} + V_{tn} \le V_{ICM} \le V_{DD} - |V_{OV}| + V_{tn}$

that is,

$(-2.5 + 0.6 + 0.7) \le V_{ICM} \le (2.5 - 0.3 + 0.7)$

$-1.2\text{ V} \le V_{ICM} \le +2.9\text{ V}$

(b) The PMOS input stage operates over the following input common-mode range:

$-V_{SS} + V_{OV} - |V_{tp}| \le V_{ICM} \le V_{DD} - 2|V_{OV}| - |V_{tp}|$

that is,

$(-2.5 + 0.3 - 0.7) \le V_{ICM} \le (2.5 - 0.6 - 0.7)$

$-2.9\text{ V} \le V_{ICM} \le +1.2\text{ V}$

(c) The overlap range is

$-1.2\text{ V} \le V_{ICM} \le +1.2\text{ V}$

(d) The input common-mode range is

$-2.9\text{ V} \le V_{ICM} \le +2.9\text{ V}$

Ex: 12.13 Denote the (W/L) of the transistors in the wide-swing mirror by $(W/L)_M$. Transistor Q_4 has

$$(W/L)_5 = \frac{1}{4}(W/L)_M$$

$$I_{\text{REF}} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_5 V_{OV5}^2$$

$$= \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_M \times \frac{1}{4}V_{OV5}^2$$

$$= \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_M (V_{OV5}/2)^2$$

Thus,

$$\frac{V_{OV5}}{2} = V_{OV}$$

where V_{OV} is the overdrive voltage for each of the mirror transistors. Thus,

$$V_5 = V_{tn} + 2V_{OV}$$

which is the value of V_{BIAS} needed in the circuit of Fig. 12.13(b).

Ex: 12.14 At $I_C = 0.1$ mA,

$$V_{BE} = 25 \ln \frac{0.1 \times 10^{-3}}{10^{-14}}$$

$$= 575.6 \text{ V}$$

$$g_m = \frac{I_C}{V_T} = \frac{0.1 \text{ mA}}{0.025 \text{ V}} = 4 \text{ mA/V}$$

$$r_e \simeq \frac{1}{g_m} = 250\ \Omega$$

$$r_\pi = \frac{\beta}{g_m} = \frac{200}{4} = 50 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{125 \text{ V}}{0.1 \text{ mA}} = 1.25 \text{ M}\Omega$$

Ex: 12.15 $V_T \ \ln \dfrac{I_{\text{REF}}}{I_{C10}} = I_{C10}R_4$

$$25 \ln \frac{730}{I_{C10}} = 5I_{C10} \qquad (1)$$

where I_{C10} is in μA, and both sides of Eq. (1) are in mV. Using iteration:

I_C (μA)	LHS of Eq. (1) (mV)	RHS of Eq. (1) (mV)
100	49.5	500
50	67	250
20	89.9	100
19	91.2	95
18	92.6	90

Thus,

$$I_{C10} \simeq 19 \text{ μA}$$

Ex: 12.16 Refer to Fig. 12.15. At node X,

$$I_{C10} = \frac{2I}{1 + \dfrac{2}{\beta_P}} + \frac{2I}{\beta_P}$$

$$I_{C10} = 2I \left[\frac{\beta_P + 1 + \dfrac{2}{\beta_P}}{\beta_P \left(1 + \dfrac{2}{\beta_P}\right)} \right]$$

$$\simeq 2I \frac{\beta_P + 1}{\beta_P + 2}$$

$$\simeq 2I$$

Thus,

$$I = \frac{I_{C10}}{2} = 9.5 \text{ μA}$$

resulting in

$$I_{C1} = I_{C2} = I_{C3} = I_{C4} = 9.5 \text{ μA}$$

Ex: 12.17 Figure 1 on next page shows the determination of the loop gain of the feedback circuit that stabilizes the bias currents of the first stage of the 741 op amp. Note that since I_{C10} is assumed to be constant, we have shown its incremental value at node X to be zero. Observe that this circuit shows only incremental quantities. The analysis shown provides the returned current signal as

$$I_r = -I_t \ \frac{\beta_P}{1 + \dfrac{2}{\beta_P}}$$

For $\beta_P \gg 1$, we have

$$I_r \simeq -\beta_P I_t$$

and the loop gain $A\beta$ is

$$A\beta \equiv -\frac{I_r}{I_t} = \beta_P$$

Ex: 12.18 $V_{BE6} = V_T \ \ln \dfrac{I_{C6}}{I_S}$

$$= 25 \ln \frac{9.5 \times 10^{-6}}{10^{-14}} = 517 \text{ mV}$$

$$V_{R3} = V_{BE6} + IR_2$$

$$= 517 + 9.5 \times 10^{-6} \times 1 = 526.5 \text{ mV}$$

$$I_{C7} \simeq I_{E7} \simeq \frac{V_{R3}}{R_3}$$

$$= \frac{526.5}{50} = 10.5 \text{ μA}$$

Ex: 12.19 $I_B = \dfrac{1}{2}(I_{B1} + I_{B2})$

$$= \frac{1}{2}\left(\frac{I}{\beta_N + 1} + \frac{I}{\beta_N + 1}\right)$$

$$= \frac{I}{\beta_N + 1} \simeq \frac{I}{\beta_N}$$

$$= \frac{9.5}{200} = 47.5 \text{ nA}$$

$$I_{OS} = 0.1 \times I_B = 4.75 \text{ nA}$$

Ex: 12.20

$$V_{C1} = V_{CC} - V_{EB8} = 15 - 0.6 = 14.4 \text{ V}$$

Q_1 and Q_2 saturate when V_{ICM} exceeds V_{C1} by 0.3 V. Thus,

$$V_{ICM\,\text{max}} = +14.7 \text{ V}$$

This figure belongs to Exercise 12.17.

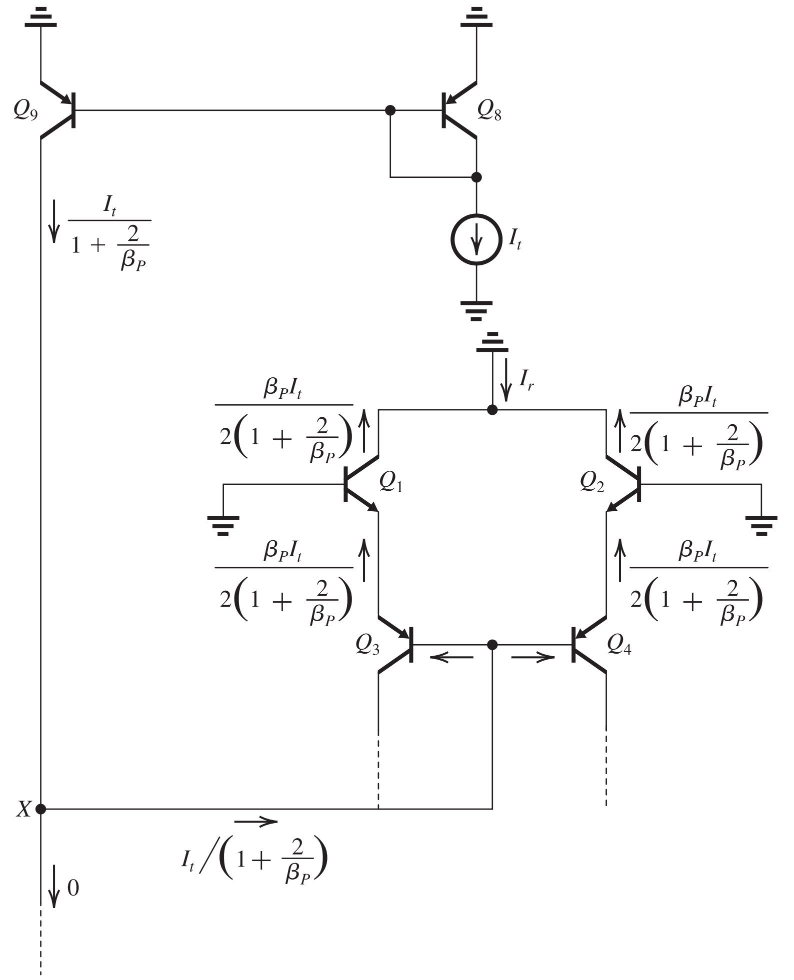

Figure 1

$V_{C5} \simeq -V_{EE} + V_{BE5} + V_{BE7}$

$= -15 + 0.6 + 0.6 = -13.8$ V

Q_3 (and Q_4) saturate when

$V_{B3} = V_{C5} - 0.3$

$= -13.8 - 0.3 = -14.1$ V

But,

$V_{B3} = V_{ICM} - V_{BE1} - V_{EB3}$

$= V_{ICM} - 1.2$ V

Thus,

$V_{ICM\,\text{min}} = V_{B3} + 1.2$ V

$= -14.1 + 1.2 = -12.9$ V

Thus,

$-12.9 \text{ V} \leq V_{ICM} \leq +14.7$ V

Ex: 12.21 $I_{C13B} = 0.75 I_{C12}$

$= 0.75 \times 0.73 = 0.55$ mA

$= 550\ \mu$A

$I_{C17} = I_{C13B} = 550\ \mu$A

$$V_{BE17} = V_T \ln \frac{I_{C17}}{I_S}$$

$$= 25 \ln \frac{550 \times 10^{-6}}{10^{-14}}$$

$= 618$ mV

$V_{R9} = V_{BE17} + I_{E17} R_8$

$\simeq 618 + 550 \times 0.1$

$= 673$ mV

$$I_{R9} = \frac{673}{50} = 13.46\ \mu\text{A}$$

$I_{B17} = \frac{550}{201} = 2.74\ \mu A$

$I_{E16} = I_{R9} + I_{B17} = 16.30\ \mu A$

$I_{C16} = \frac{200}{201} \times 16.3 = 16.2\ \mu A$

$I_{B16} = \frac{16.2}{200} = 0.08\ \mu A$

Ex: 12.22 The two diode-connected transistors will carry a bias current of $0.25 I_{REF} = 180\ \mu A$. Since the output transistors have three times the values of I_S as that of the diode-connected transistors, the bias current in the output transistors will be

$= 3 \times 180 = 540\ \mu A$

Ex: 12.23 $r_e = \frac{V_T}{I_E} \simeq \frac{25\text{ mV}}{9.5\ \mu A} = 2.63\ k\Omega$

$g_{m1} \simeq \frac{1}{r_e} = 0.38\text{ mA/V}$

$G_{m1} = \frac{1}{2} g_{m1} = 0.19\text{ mA/V}$

$R_{id} = (\beta_N + 1) \times 4r_e$

$= 201 \times 4 \times 2.63$

$= 2.1\ M\Omega$

Ex: 12.24 refer to Fig. 12.19.

(a) $v_{b6} = i_{e6}(r_{e6} + R_2)$

$= i_e(r_{e6} + R_2)$

$r_{e6} = \frac{V_T}{I_{E6}} \simeq \frac{25\text{ mV}}{9.5\ \mu A} = 2.63\ k\Omega$

$v_{b6} = i_e(2.63 + 1) = 3.63\ k\Omega \times i_e$

(b) $i_{e7} = i_{R3} + i_{b5} + i_{b6}$

$= \frac{v_{b6}}{R_3} + \frac{2\alpha i_e}{\beta_N}$

$= \frac{3.63}{50} i_e + \frac{2}{201} i_e$

$= 0.08 i_e$

(c) $i_{b7} = \frac{i_{e7}}{\beta_N + 1} = \frac{0.08}{201} i_e = 0.0004 i_e$

(d) $v_{b7} = i_{e7} r_{e7} + v_{b6}$

$v_{b7} = 0.08 \times 2.63 i_e + 3.63 i_e$

$= 3.84\ k\Omega \times i_e$

(e) $R_{in} = \frac{v_{b7}}{\alpha i_e} \simeq 3.84\ k\Omega$

Ex: 12.25 $r_{o4} = \frac{|V_{Ap}|}{I} = \frac{50\text{ V}}{9.5\ \mu A} = 5.26\ M\Omega$

$g_{m4} = 0.38\text{ mA/V}$

$r_{e2} = 2.63\ k\Omega$

$r_{\pi 4} = \frac{\beta_P}{g_{m4}} = \frac{50}{0.38} = 131.6\ k\Omega$

$R_{o4} = r_{o4}[1 + g_{m4}(r_{e2} \parallel r_{\pi 4})]$

$= 5.26[1 + 0.38(2.63 \parallel 131.6)]$

$= 10.4\ M\Omega$

(The answer in the book was obtained by neglecting $r_{\pi 4}$.)

$r_{o6} = \frac{V_{An}}{I} = \frac{125\text{ V}}{9.5\ \mu A} = 13.16\ M\Omega$

$g_{m6} = 0.38\text{ mA/V}$

$R_6 = 1\ k\Omega$

$r_{\pi 6} = \frac{200}{0.38} = 526.3\ k\Omega$

$R_{o6} = r_{o6}[1 + g_{m6}(R_2 \parallel r_{\pi 6})]$

$= 13.16[1 + 0.38(1 \parallel 526.3)]$

$= 18.2\ M\Omega$

$R_{o1} = R_{o9} \parallel R_{o6}$

$= 10.4 \parallel 18.2 = 6.62\ M\Omega$

Ex: 12.26 $|A_{vo}| = G_{m1} R_{o1}$

Using G_{m1} given in the answer to Exercise 12.23,

$G_{m1} = 0.19\text{ mA/V}$

and R_{o1} given in the answer to Exercise 12.25,

$R_{o1} = 6.7\ M\Omega$

we obtain

$|A_{vo}| = G_{m1} R_{o1}$

$= 0.19 \times 6.7 = 1273\text{ V/V}$

Ex: 12.27 Refer to Fig. 12.22, which shows the current mirror with an imbalance between $R_1 = R$ and $R_2 = R + \triangle R$. Observe that the imbalance causes an error in the mirror transfer ratio of

$\epsilon_m = \frac{\triangle I}{I}$

where $\frac{\triangle I}{I}$ is given by Eq. (12.94). Thus,

$\epsilon_m = \frac{\triangle R}{R + \triangle R + r_e}$

where $r_e = r_{e5} = r_{e6}$,

$$\epsilon_m = \frac{\triangle R}{R + \triangle R + r_{e5}} \qquad \text{Q.E.D.}$$

For $R = 1$ kΩ, $\frac{\triangle R}{R} = 0.02$ and $r_{e5} = 2.63$ kΩ,

$$\epsilon_m = \frac{0.02}{1 + 0.02 + 2.63} = 5.5 \times 10^{-3}$$

Ex: 12.28

$$R_{o9} = r_{o9} = \frac{|V_{Ap}|}{I_{C9}} = \frac{50\text{ V}}{19\ \mu\text{A}} = 2.63\text{ M}\Omega$$

$$R_{o10} = r_{o10}[1 + g_{m10}(R_4 \parallel r_{\pi 10})]$$

where

$$r_{o10} = \frac{V_{An}}{I_{C10}} = \frac{125\text{ V}}{19\ \mu\text{A}} = 6.58\text{ M}\Omega$$

$$g_{m10} = \frac{I_{C10}}{V_T} = \frac{19\ \mu\text{A}}{0.025\text{ V}} = 0.76\text{ mA/V}$$

$$R_4 = 5\text{ k}\Omega$$

$$r_{\pi 10} = \frac{\beta_N}{g_{m10}} = \frac{200}{0.76} = 263.2\text{ k}\Omega$$

$$R_{o10} = 6.58[1 + 0.76(5 \parallel 263.2)]$$

$$= 31.1\text{ M}\Omega$$

$$R_o = R_{o9} \parallel R_{o10}$$

$$= 2.63 \parallel 31.1 = 2.43\text{ M}\Omega$$

Ex: 12.29 Using Eq. (12.100), we obtain

$$G_{mcm} = \frac{\epsilon_m}{2R_o}$$

$$= \frac{5.5 \times 10^{-3}}{2 \times 2.43 \times 10^6} = 1.13 \times 10^{-6}\text{ mA/V}$$

$$\text{CMRR} = \frac{G_{m1}}{G_{mcm}} = \frac{0.19}{1.13 \times 10^{-6}} = 1.68 \times 10^5$$

or 104.5 dB

Without common-mode feedback, the CMRR is reduced by a factor equal to β_P. Equivalently,

$$\text{CMRR} = 104.5 - 20\log\beta_P$$

$$= 104.5 - 20\log 50$$

$$= 70.5\text{ dB}$$

Ex: 12.30 $r_{e16} = \frac{V_T}{I_{E16}} \simeq \frac{25\text{ mV}}{16.2\text{ mA}} = 1.54\text{ k}\Omega$

$$r_{e17} = \frac{V_T}{I_{E17}} \simeq \frac{25\text{ mV}}{0.55\text{ mA}} = 45.5\ \Omega$$

Using Eq. (12.103), we obtain

$$R_{i2} =$$

$$(200 + 1)\{1.54 + [50 \parallel (200 + 1)(0.0455 + 0.1)]\}$$

$$\simeq 4\text{ M}\Omega$$

Ex: 12.31 Using Eq. (12.104), we get

$$i_{c17} = \frac{\alpha}{r_{e17} + R_8} v_{b17}$$

$$= \frac{200}{201}\,\frac{1}{0.0455 + 0.1} v_{b17} = 6.85 v_{b17} \qquad (1)$$

Using Eq. (12.106), we obtain

$$R_{i17} = 201(0.0455 + 0.1) = 29.25\text{ k}\Omega$$

Using Eq. (12.105), we get

$$v_{b17} = v_{i2}\frac{50 \parallel 29.25}{(50 \parallel 29.25) + 1.54} = 0.92 v_{i2} \qquad (2)$$

Combining Eqs. (1) and (2), we obtain

$$i_{c17} = 6.32 v_{b17}$$

Thus,

$$G_{m2} = 6.32\text{ mA/V}$$

This value is somewhat lower than the value generally published for G_{m2}, namely

$$G_{m2} = 6.5\text{ mA/V}$$

To conform with published literature, we shall use the latter value in future calculations.

Ex: 12.32 $R_{o13B} = r_{o13B} = \frac{|V_{Ap}|}{I_{C13B}}$

$$= \frac{50}{0.55} = 90.9\text{ k}\Omega$$

$$R_{o17} = r_{o17}[1 + g_{m17}(R_8 \parallel r_{\pi 17})]$$

where

$$r_{o17} = \frac{125}{0.55} = 227.3\text{ k}\Omega$$

$$g_{m17} = \frac{0.55}{0.025} = 22\text{ mA/V}$$

$$R_8 = 0.1\text{ k}\Omega$$

$$r_{\pi 17} = \frac{200}{22} = 9.09\text{ k}\Omega$$

$$R_{o17} = 227.3[1 + 22(0.1 \parallel 9.09)]$$

$$= 722\text{ k}\Omega$$

$$R_{o2} = R_{o13B} \parallel R_{o17}$$

$$= 90.9 \parallel 722 \simeq 81\text{ k}\Omega$$

Ex: 12.33 Open-circuit voltage gain $= -G_{m2}R_{o2}$

$$= -6.5 \times 81 = -526.5\text{ V/V}$$

Ex: 12.34 $r_{e23} = \frac{V_T}{I_{E23}}$

$$\simeq \frac{25\text{ mV}}{0.18\text{ mA}} = 138.9\ \Omega$$

$$R_{o23} = \frac{R_{o2}}{\beta_{23}+1} + r_{e23}$$

$$= \frac{81}{50+1} + 0.139$$

$$= 1.73\ \text{k}\Omega$$

$$r_{e20} = \frac{V_T}{I_{E20}}$$

$$= \frac{25\ \text{mV}}{5\ \text{mA}} = 5\ \Omega$$

$$R_{\text{out}} = r_{e20} + \frac{R_{o23}}{\beta_{20}+1}$$

$$= 5 + \frac{1730}{50+1} = 39\ \Omega$$

Total output resistance $= R_{\text{out}} + R_7$

$$= 39 + 27 = 66\ \Omega$$

Ex: 12.35

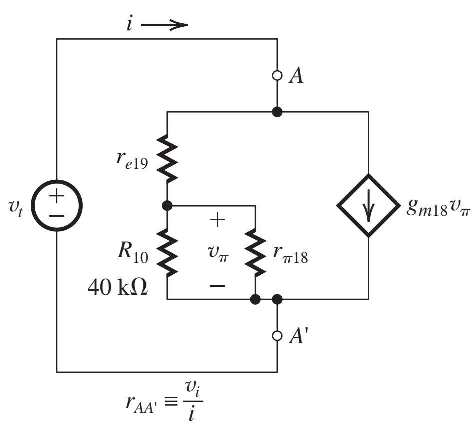

Figure 1 shows the equivalent circuit model of the circuit in Fig. E12.35. Note that the diode-connected transistors Q_{19} is replaced with r_{e19},

$$r_{e19} = \frac{V_T}{I_{E19}}$$

$$\simeq \frac{25\ \text{mA}}{16\ \mu\text{A}} = 1.56\ \text{k}\Omega$$

Transistor Q_{18} is replaced with its hybrid-π model,

$$g_{m18} = \frac{I_{C18}}{V_T} = \frac{0.165\ \text{mA}}{0.025\ \text{V}}$$

$$= 6.6\ \text{mA/V}$$

$$r_{\pi 18} = \frac{\beta_N}{g_{m18}} = \frac{200}{6.6} = 30.3\ \text{k}\Omega$$

Now,

$$v_\pi = v_t \frac{R_{10} \parallel r_\pi}{(R_{10} \parallel r_\pi) + r_{e19}}$$

$$= v_t \frac{40 \parallel 30.3}{(40 \parallel 30.3) + 1.56} = 0.917 v_t$$

$$i = \frac{v_t}{(40 \parallel 30.3) + 1.56} + g_{m18} \times 0.917 v_t$$

$$= 6.11 \times 10^{-3} v_t$$

$$r'_{AA} \equiv \frac{v_t}{i} \simeq 163\ \Omega$$

Ex: 12.36 For $v_O = 10\ \sin\omega t$

$$\frac{dv_O}{dt} = \omega \times 10\ \cos\omega t$$

$$SR = \left.\frac{dv_O}{dt}\right|_{\max} = \omega_M \times 10 = 2\pi f_M \times 10$$

$$f_M = \frac{SR}{20\pi} = \frac{0.63 \times 10^6}{20\pi} = 10\ \text{kHz}$$

Ex: 12.37 $I_{S2} = 2I_{S1}$

Using Eq. (12.127), we obtain

$$I = \frac{V_T}{R_2} \ln\frac{I_{S2}}{I_{S1}}$$

$$0.01 = \frac{0.025}{R_2} \ln 2$$

$$\Rightarrow R_2 = 1.73\ \text{k}\Omega$$

$$R_3 = R_4 = \frac{0.2\ \text{V}}{0.01\ \text{mA}} = 20\ \text{k}\Omega$$

Ex: 12.38 To obtain $I_8 = 10\ \mu$A, transistor Q_8 must have the same (ratio = 1) emitter area as Q_3, and

$$R_8 = R_3 = 20\ \text{k}\Omega$$

To obtain $I_9 = 20\ \mu$A, Q_9 must have an EBJ area twice (ratio = 2) that of Q_3 and

$$R_9 = \frac{1}{2} R_3 = 10\ \text{k}\Omega$$

To obtain $I_{10} = 5\ \mu$A, Q_{10} must have an EBJ area half (ratio = 0.5) that of Q_3 and

$$R_{10} = 2R_3 = 40\ \text{k}\Omega$$

Ex: 12.39 Refer to the circuit in Fig. 12.42.

(a) Current gain from v_{IP} to output $= (\beta_1 + 1)(\beta_2 + 1)\beta_P$

$$\simeq \beta_1\beta_2\beta_P = \beta_N\beta_P^2$$

Current gain from v_{IN} to output $= (\beta_3 + 1)\beta_N$

$$\simeq \beta_3\beta_N = \beta_N^2$$

(b) For $i_L = +10$ mA,

current needed at v_{IP} input

$$= \frac{10}{\beta_N\beta_P^2} = \frac{10}{40 \times 10^2} = 2.5\ \mu\text{A}$$

For $i_L = -10$ mA,

current needed at v_{IN} input $= \frac{10}{\beta_N^2} = \frac{10}{40^2}$

$= 6.25\ \mu$A

Ex: 12.40 $I_Q = 0.4$ mA, $I = 10\ \mu$A,

$\frac{I_{SN}}{I_{S10}} = 10, \ \frac{I_{S7}}{I_{S11}} = 2$

Using Eq. (12.136), we obtain

$$0.4 \times 10^3 = 2\left(\frac{I_{\text{REF}}^2}{10}\right) \times 10 \times 2$$

where I_{REF} is in μA. Thus,

$I_{\text{REF}} = 10\ \mu$A

For $i_L = -10$ mA, then

$i_P = 10 + i_N$

Using Eq. (12.137), we get

$$\frac{i_N(10 + i_N)}{i_N + 10 + i_N} = 0.2$$

$\Rightarrow i_N^2 - 9.6 i_N + 2 = 0$

$\Rightarrow i_N = 0.2$ mA

$i_P = 10.2$ mA

12.1 Using Eq. (12.2), we get

$$V_{ICM\,\text{min}} = -V_{SS} + V_{tn} + V_{OV3} - |V_{tp}|$$

$$= -1 + 0.4 + 0.2 - 0.4 = -0.8 \text{ V}$$

Using Eq. (12.3), we obtain

$$V_{ICM\,\text{max}} = V_{DD} - |V_{OV5}| - |V_{tp}| - |V_{OV1}|$$

$$= 1 - 0.2 - 0.4 - 0.2 = +0.2 \text{ V}$$

Thus,

$$-0.8 \text{ V} \leq V_{ICM} \leq +0.2 \text{ V}$$

Using Eq. (12.5), we get

$$-V_{SS} + V_{OV6} \leq v_O \leq V_{DD} - |V_{OV7}|$$

Thus,

$$-0.8 \text{ V} \leq v_O \leq +0.8 \text{ V}$$

12.2 For NMOS devices, we have

$$V_A = 25 \times 0.3 = 7.5 \text{ V}$$

For PMOS devices,

$$|V_A| = 20 \times 0.3 = 6 \text{ V}$$

Using Eq. (12.13),

$$A_1 = -\frac{2}{|V_{OV1}|} \Big/ \left[\frac{1}{|V_{A2}|} + \frac{1}{V_{A4}}\right]$$

$$= -\frac{2}{0.15} \Big/ \left(\frac{1}{6} + \frac{1}{7.5}\right)$$

$$= -44.4 \text{ V/V}$$

Using Eq. (12.20), we obtain

$$A_2 = -\frac{2}{V_{OV6}} \Big/ \left[\frac{1}{V_{A6}} + \frac{1}{|V_{A7}|}\right]$$

$$= -\frac{2}{0.2} \Big/ \left[\frac{1}{7.5} + \frac{1}{6}\right]$$

$$= -33.3 \text{ V/V}$$

$$A = A_1 A_2 = 1478.5 \text{ V/V}$$

$$r_{o6} = \frac{7.5}{0.3} = 25 \text{ k}\Omega$$

$$r_{o7} = \frac{6}{0.3} = 20 \text{ k}\Omega$$

$$R_o = r_{o6} \parallel r_{o7} = 11.1 \text{ k}\Omega$$

For a unity-gain voltage amplifier using this op amp, we have

$$R_{\text{out}} = R_{of} = \frac{R_o}{1 + A\beta}$$

$$= \frac{11.1 \text{ k}\Omega}{1 + 1481.5 \times 1}$$

$$= 7.5 \text{ }\Omega$$

12.3 For the op amp to not have a systematic offset voltage, the condition in Eq. (12.1) must be satisfied, that is,

$$\frac{(W/L)_6}{(W/L)_4} = 2\frac{(W/L)_7}{(W/L)_5}$$

$$\frac{W/0.3}{6/0.3} = 2\frac{45/0.3}{30/0.3}$$

$$\Rightarrow W = 18 \text{ }\mu\text{m}$$

Refer to Fig. 12.1:

$$I_{D8} = I_{\text{REF}} = 40 \text{ }\mu\text{A}$$

$$I = I_{D5} = I_{\text{REF}}\frac{W_5}{W_8} = 40 \times \frac{30}{6} = 200 \text{ }\mu\text{A}$$

$$I_{D7} = I_{\text{REF}}\frac{W_7}{W_8} = 40 \times \frac{45}{6} = 300 \text{ }\mu\text{A}$$

$$I_{D6} = 300 \text{ }\mu\text{A}$$

$$I_{D1} = I_{D2} = I_{D3} = I_{D4} = \frac{I}{2} = 100 \text{ }\mu\text{A}$$

The overdrive voltage at which each transistor is operating is determined from

$$I_D = \frac{1}{2}\mu C_{ox}\frac{W}{L}V_{OV}^2$$

Then V_{GS} is found from

$$|V_{GS}| = |V_t| + |V_{OV}|$$

The transconductance at which each transistor is operating is obtained from

$$g_m = \frac{2I_D}{V_{OV}}$$

The output resistance of each transistor is found from

$$r_o = \frac{|V_A|}{I_D}$$

$$A_1 = -g_{m1,2}(r_{o2} \parallel r_{o4})$$

$$= -1.33(150 \parallel 150) = -100 \text{ V/V}$$

$$A_2 = -g_{m6}(r_{o6} \parallel r_{o7})$$

$$= -3.16(50 \parallel 50) = -79 \text{ V/V}$$

$$A = A_1 A_2 = 7900 \text{ V/V}$$

Using Eq. (12.2), we obtain

$$V_{ICM\,\text{min}} = -V_{SS} + V_{tn} + V_{OV3} - |V_{tp}|$$

$$V_{ICM\,\text{min}} = -1 + 0.45 + 0.19 - 0.45$$

$$= -0.81 \text{ V}$$

Using Eq. (12.3), we get

$$V_{ICM\,\text{max}} = V_{DD} - |V_{OV5}| - |V_{tp}| - |V_{OV1}|$$

$$= 1 - 0.24 - 0.45 - 0.15$$

$$= +0.16 \text{ V}$$

The results are summarized in the following table:

	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8
I_D (μA)	100	100	100	100	200	300	300	40
$\lvert V_{OV}\rvert$ (V)	0.15	0.15	0.19	0.19	0.24	0.19	0.24	0.24
$\lvert V_{GS}\rvert$ (V)	0.6	0.6	0.64	0.64	0.69	0.64	0.69	0.69
g_m (mA/V)	1.33	1.33	1.05	1.05	1.67	3.16	2.5	0.33
r_o (kΩ)	150	150	150	150	75	50	50	375

Thus,

$-0.8\text{ V} \le V_{ICM} \le +0.16\text{ V}$

Using Eq. (12.5), we obtain

$-V_{SS} + V_{OV6} \le v_O \le V_{DD} - |V_{OV7}|$

Thus,

$-1 + 0.19 \le v_O \le 1 - 0.24$

$-0.81\text{ V} \le v_O \le 0.76\text{ V}$

12.4 For all transistors, we have

$|V_A| = 20 \times 0.3 = 6\text{ V}$

Using Eq. (12.13), we get

$$A_1 = -\frac{2}{|V_{OV}|}\bigg/\frac{2}{|V_A|} = -\frac{6}{|V_{OV}|}$$

Using Eq. (12.20), we obtain

$$A_2 = -\frac{2}{|V_{OV}|}\bigg/\frac{2}{|V_A|} = -\frac{6}{|V_{OV}|}$$

$$A = A_1A_2 = \frac{36}{|V_{OV}|^2}$$

$$1600 = \frac{36}{|V_{OV}|^2}$$

$\Rightarrow |V_{OV}| = 0.15\text{ V}$

12.5 From Eq. (12.24), we have

$\text{CMRR} = [g_{m1}(r_{o2} \parallel r_{o4})]\,[2g_{m3}R_{SS}]$

where

$$g_{m1} = \frac{I}{|V_{OV}|}$$

$$r_{o2} = r_{o4} = |V_A|/(I/2) = \frac{2|V_A|}{I}$$

$$g_{m3} = \frac{I}{|V_{OV}|}$$

$$R_{SS} = r_{o5} = \frac{|V_A|}{I}$$

Thus,

$$\text{CMRR} = \frac{I}{|V_{OV}|} \times \frac{1}{2} \times \frac{2|V_A|}{I} \times 2 \times \frac{I}{|V_{OV}|} \times \frac{|V_A|}{I}$$

$$= 2\frac{|V_A|^2}{|V_{OV}|^2}$$

For CMRR = 72 dB = 4000, we have

$$4000 = 2 \times \frac{|V_A|^2}{0.15^2}$$

$\Rightarrow |V_A| = 6.7\text{ V}$

Since $|V_A| = |V_A'|L$, we have

$6.7 = 15L$

$\Rightarrow L = 0.45\ \mu\text{m}$

$$A_{\hat{v}} = \left|\frac{V_A}{V_{OV}}\right|^2 = \left(\frac{6.7}{0.15}\right)^2 = 2000\text{ V/V}$$

12.6 From Eq. (12.36), we obtain

$$f_t = \frac{G_{m1}}{2\pi C_C}$$

Thus,

$$C_C = \frac{G_{m1}}{2\pi f_t} = \frac{0.8 \times 10^{-3}}{2\pi \times 120 \times 10^6} = 1.06\text{ pF}$$

From Eq. (12.35), we get

$$f_{P2} = \frac{G_{m2}}{2\pi C_2}$$

$$= \frac{2.4 \times 10^{-3}}{2\pi \times 1.2 \times 10^{-12}} = 318.3\text{ MHz}$$

From Eq. (12.31), we get

$$f_Z = \frac{G_{m2}}{2\pi C_C}$$

$$= \frac{2.4 \times 10^{-3}}{2\pi \times 1.06 \times 10^{-12}} = 360\text{ MHz}$$

12.7 (a) $A = G_{m1}R_1G_{m2}R_2$

$= 1 \times 100 \times 2 \times 50 = 10{,}000\text{ V/V}$

(b) Without C_C connected:

$$\omega_{P1} = \frac{1}{C_1R_1} = \frac{1}{0.1 \times 10^{-12} \times 100 \times 10^3}$$

$= 10^8$ rad/s

This figure belongs to Problem 12.7, part (b).

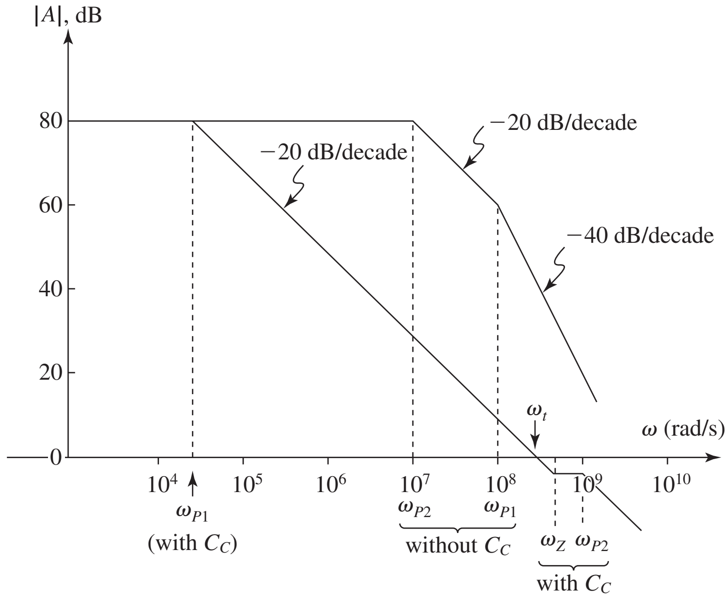

Figure 1

$$\omega_{P2} = \frac{1}{C_2R_2} = \frac{1}{2 \times 10^{-12} \times 50 \times 10^3}$$

$$= 10^7 \text{ rad/s}$$

Figure 1 shows a Bode plot for the gain magnitude.

(c) With C_C connected:

Using Eq. (12.35), we obtain

$$\omega_{P2} = \frac{G_{m2}}{C_2}$$

$$= \frac{2 \times 10^{-3}}{2 \times 10^{-12}} = 10^9 \text{ rad/s}$$

For ω_t two octaves below ω_{P2}, we have

$$\omega_t = \frac{10^9}{4} \text{ rad/s}$$

Using Eq. (12.36), we get

$$\omega_t = \frac{G_{m2}}{C_C}$$

Thus,

$$\frac{10^9}{4} = \frac{1 \times 10^{-3}}{C_C}$$

$$\Rightarrow C_C = 4 \text{ pF}$$

Now using Eq. (12.34), we obtain

$$\omega_{P1} = \frac{1}{R_1C_CG_{m2}R_2}$$

$$= \frac{1}{100 \times 10^3 \times 4 \times 10^{-12} \times 2 \times 10^{-3} \times 50 \times 10^3}$$

$$= \frac{10^5}{4} \text{ rad/s} = 25{,}000 \text{ rad/s}$$

Using Eq. (12.31), we get

$$\omega_Z = \frac{G_{m2}}{C_C}$$

$$= \frac{2 \times 10^{-3}}{4 \times 10^{-12}} = \frac{10^9}{2} \text{ rad/s} = 5 \times 10^8 \text{ rad/s}$$

The Bode plot for the gain magnitude with C_C connected is shown in Fig. 1.

12.8 $G_{m1} = 0.3$ mA/V

$G_{m2} = 0.6$ mA/V

$r_{o2} = r_{o4} = 222$ kΩ

$r_{o6} = r_{o7} = 111$ kΩ

$C_2 = 1$ pF

(a) $A = G_{m1}(r_{o2} \parallel r_{o4})G_{m2}(r_{o6} \parallel r_{o7})$

$= 0.3(222 \parallel 222) \times 0.6(111 \parallel 111)$

$= 33.3 \times 33.3 = 1109$ V/V

(b) $f_{P2} = \dfrac{G_{m2}}{2\pi C_2}$

$$= \frac{0.6 \times 10^{-3}}{2\pi \times 1 \times 10^{-12}} = 95.5 \text{ MHz}$$

(c) $R = \dfrac{1}{G_{m2}} = \dfrac{1}{0.6 \times 10^{-3}} = 1.67\ \text{k}\Omega$

(d) Phase margin $= 180 - 90 - \tan^{-1}\left(\dfrac{f_t}{f_{P2}}\right)$

$$80^\circ = 90 - \tan^{-1}\left(\frac{f_t}{f_{P2}}\right)$$

$$f_t = f_{P2}\tan 10^\circ$$

$$= 95.5 \times 0.176 = 16.8\ \text{MHz}$$

Using Eq. (12.36), we obtain

$$C_C = \frac{G_{m1}}{2\pi f_t} = \frac{0.3 \times 10^{-3}}{2\pi \times 16.8 \times 10^6} = 2.84\ \text{pF}$$

The dominant pole will be at a frequency

$$f_{P1} = \frac{f_t}{\text{DC Gain}} = \frac{16.8 \times 10^6}{1109}$$

$$= 15.1\ \text{kHz}$$

(e) Since

$$f_t = \frac{G_{m1}}{2\pi C_C}$$

to double f_t, C_C must be reduced by a factor of 2,

$$C_C = \frac{2.84}{2} = 1.42\ \text{pF}$$

At the new $f_t = 2 \times 16.8 = 33.6$ MHz, we have

$$\phi_{P2} = -\tan^{-1}\frac{f_t}{f_{P2}}$$

$$= -\tan^{-1}\left(\frac{33.6}{95.5}\right) = -19.4^\circ$$

To reduce this phase lag to -10°, we need to change R so that the zero moves to the negative real axis and introduces a phase lead of 9.4°. Thus,

$$\tan^{-1}\frac{f_t}{f_Z} = 9.4^\circ$$

$$f_Z = \frac{f_t}{\tan 9.4} = \frac{33.6}{0.166} = 203\ \text{MHz}$$

$$f_Z = \frac{1}{2\pi C_C\left(R - \dfrac{1}{G_{m2}}\right)}$$

$$\Rightarrow R - \frac{1}{G_{m2}} = \frac{1}{2\pi \times 203 \times 10^6 \times 1.42 \times 10^{-12}}$$

$$= 552\ \Omega$$

$$R = 1670 + 552 = 2222\ \Omega$$

$$= 2.22\ \text{k}\Omega$$

12.9 (a) Using Eq. (12.36), we get

$$f_t = \frac{G_{m1}}{2\pi C_C}$$

$$C_C = \frac{G_{m1}}{2\pi f_t}$$

$$= \frac{1 \times 10^{-3}}{2\pi \times 100 \times 10^6} = 1.59\ \text{pF}$$

(b) $f_{P2} = \dfrac{G_{m2}}{2\pi C_2}$

$$= \frac{2 \times 10^{-3}}{2\pi \times 1 \times 10^{-12}} = 318\ \text{MHz}$$

$$f_Z = \frac{G_{m2}}{2\pi C_C} = \frac{2 \times 10^{-3}}{2\pi \times 1 \times 1.59 \times 10^{-12}}$$

$$= 200\ \text{MHz}$$

To obtain f_{P1}, we need to know the dc gain of the op amp, A_0, then

$$f_{P1} = \frac{f_t}{A_0}$$

The value of A_0 is not specified in the problem statement!

(c) $\phi_{P2} = -\tan^{-1}\left(\dfrac{f_t}{f_{P2}}\right)$

$$= -\tan^{-1}\left(\frac{100}{318}\right) = -17.5^\circ$$

$$\phi_Z = -\tan^{-1}\left(\frac{f_t}{f_Z}\right)$$

$$\phi_Z = -\tan^{-1}\left(\frac{100}{200}\right) = -26.6^\circ$$

$$\phi_{\text{total}} = 90^\circ + 17.5 + 26.6 = 134^\circ$$

Phase margin $= 180 - 134 = 46^\circ$

(d) From Eq. (12.44), for

$$f_Z = \infty$$

we select

$$R = \frac{1}{G_{m2}} = \frac{1}{2} = 0.5\ \text{k}\Omega = 500\ \Omega$$

Phase margin $= 180^\circ - (90^\circ + 17.5^\circ) = 72.5^\circ$

(e) To obtain a phase margin of 85°, we need the left-half plane zero to provide at f_t a phase angle of $85^\circ - 72.5^\circ = 12.5^\circ$. Thus,

$$12.5^\circ = \tan^{-1}\left(\frac{f_t}{f_Z}\right)$$

$$f_Z = \frac{f_t}{\tan 12.5^\circ} = \frac{100}{\tan 12.5^\circ} = 451\ \text{MHz}$$

From Eq. (12.44), we have

$$-f_Z = \frac{1}{2\pi C_C\left(\dfrac{1}{G_{m2}} - R\right)}$$

$$\Rightarrow R = 722\ \Omega$$

12.10 Using Eq. (12.46), we obtain

$SR = 2\pi f_t V_{OV1,2}$

$= 2\pi \times 100 \times 10^6 \times 0.2$

$= 125.6\ V/\mu s$

Using Eq. (12.45),

$$SR = \frac{I}{C_C}$$

$$\Rightarrow C_C = \frac{I}{SR} = \frac{100 \times 10^{-6}}{125.6 \times 10^6}$$

$= 0.8\ pF$

12.11 $G_{m1} = 1$ mA, $G_{m2} = 5$ mA/V

(a) Using Eq. (12.36), we obtain

$$f_t = \frac{G_{m1}}{2\pi C_C}$$

$$\Rightarrow C_C = \frac{G_{m1}}{2\pi f_t} = \frac{1 \times 10^{-3}}{2\pi \times 80 \times 10^6}$$

$= 2$ pF

(b) Phase margin =

$$90^\circ - \tan^{-1}\left(\frac{f_t}{f_{P2}}\right) - \tan^{-1}\left(\frac{f_t}{f_Z}\right)$$

where

$$f_{P2} = \frac{G_{m2}}{2\pi C_2}$$

and

$$f_Z = \frac{G_{m2}}{2\pi C_C}$$

For a PM of 70°, we have

$$\tan^{-1}\left(\frac{f_t}{f_{P2}}\right) + \tan^{-1}\left(\frac{f_t}{f_Z}\right) = 20^\circ$$

But,

$$f_Z = \frac{5 \times 10^{-3}}{2\pi \times 2 \times 10^{-12}} = 398\ \text{MHz}$$

and

$$\tan^{-1}\left(\frac{f_t}{f_Z}\right) = \tan^{-1}\left(\frac{80}{398}\right) = 11.4^\circ$$

Thus,

$$\tan^{-1}\left(\frac{f_t}{f_{P2}}\right) = 20 - 11.4^\circ = 8.6^\circ$$

$$\frac{f_t}{f_{P2}} = \tan 8.6^\circ$$

$$\Rightarrow f_{P2} = \frac{80}{\tan 8.6^\circ} = 529\ \text{MHz}$$

$$\frac{G_{m2}}{2\pi C_2} = 529 \times 10^6$$

$$C_2 = \frac{5 \times 10^{-3}}{2\pi \times 529 \times 10^6} = 1.51\ \text{pF}$$

This is the maximum value that C_2 can have; if C_2 is larger, then f_{P2} will be lower; and the phase it introduces at f_t will increase, causing the phase margin to drop below 70°.

12.12 $C_2 = 0.7$ pF.

For a phase margin of 72°, the phase due to f_{P2} at f_t must be 18°; thus,

$$\frac{f_t}{f_{P2}} = \tan 18^\circ$$

$$\Rightarrow f_{P2} = \frac{100}{\tan 18^\circ} = 307.8\ \text{MHz}$$

But

$$f_{P2} = \frac{G_{m2}}{2\pi C_2}$$

$\Rightarrow G_{m2} = 2\pi f_{P2} C_2$

$= 2\pi \times 307.8 \times 10^6 \times 0.7 \times 10^{-12}$

$= 1.35$ mA/V

Thus,

$g_{m6} = 1.35$ mA/V

For the transmission zero to be at ∞,

$$R = \frac{1}{G_{m2}} = \frac{1}{1.35 \times 10^{-3}} = 739\ \Omega$$

$SR = 2\pi f_t |V_{OV1,2}|$

$= 2\pi \times 100 \times 10^6 \times 0.15$

$= 94.2\ V/\mu s$

$$SR = \frac{I}{C_C}$$

$$\Rightarrow C_C = \frac{I}{SR} = \frac{100 \times 10^{-6}}{94.2 \times 10^6} = 1.06\ \text{pF}$$

12.13 SR = 60 V/μs, $f_t = 60$ MHz

(a) Using Eq. (12.46), we obtain

$SR = 2\pi f_t |V_{OV1}|$

$$\Rightarrow |V_{OV1}| = \frac{60 \times 10^6}{2\pi \times 60 \times 10^6} = 0.16\ \text{V}$$

(b) Using Eq. (12.45), we get

$$SR = \frac{I}{C_C}$$

$$\Rightarrow C_C = \frac{I}{SR} = \frac{120 \times 10^{-6}}{60 \times 10^6} = 2\ \text{pF}$$

(c) For Q_1 and Q_2, we have

$$I_{D1,2} = \frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_{1,2} |V_{OV1,2}|^2$$

$$60 = \frac{1}{2} \times 60 \times \left(\frac{W}{L}\right)_{1,2} \times 0.16^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = 78.1$$

12.14 $G_{m1} = 0.8$ mA/V, $G_{m2} = 2$ mA/V

(a) Using Eq. (12.36), we obtain

$$f_t = \frac{g_{m1}}{2\pi C_C}$$

$$\Rightarrow C_C = \frac{G_{m1}}{2\pi f_t} = \frac{0.8 \times 10^{-3}}{2\pi \times 100 \times 10^6} = 1.27 \text{ pF}$$

(b) Phase margin =

$$90° - \tan^{-1}\left(\frac{f_t}{f_{P2}}\right) - \tan^{-1}\left(\frac{f_t}{f_Z}\right)$$

$$60° = 90 - \tan^{-1}\left(\frac{f_t}{f_{P2}}\right) - \tan^{-1}\left(\frac{f_t}{f_Z}\right)$$

Thus,

$$\tan^{-1}\left(\frac{f_t}{f_{P2}}\right) + \tan^{-1}\left(\frac{f_t}{f_Z}\right) = 30°$$

where

$$f_{P2} = \frac{G_{m2}}{2\pi C_2}$$

$$f_Z = \frac{1}{2\pi C_C\left(\frac{1}{G_{m2}} - R\right)}$$

$$= \frac{1}{2\pi \times 1.27 \times 10^{-12}(0.5 - 0.5) \times 10^3} = \infty$$

Thus,

$$\tan^{-1}\left(\frac{f_t}{f_{P2}}\right) = 30°$$

$$f_{P2} = \frac{f_t}{\tan 30} = 173.2 \text{ MHz}$$

We now can obtain C_2 from

$$173.2 \times 10^6 = \frac{2 \times 10^{-3}}{2\pi C_2}$$

$$\Rightarrow C_2 = \frac{2 \times 10^{-3}}{2\pi \times 173.2 \times 10^6} = 1.84 \text{ pF}$$

12.15 (a) From Eq. (12.54), we have

$$\text{PSRR}^- = g_{m1}(r_{o2} \parallel r_{o4})g_{m6}r_{o6}$$

where

$$g_{m1} = \frac{2 \times \frac{I}{2}}{|V_{OV}|} = \frac{I}{|V_{OV}|}$$

$$r_{o2} = r_{o4} = \frac{|V_A|}{I/2} = \frac{2|V_A|}{I}$$

$$g_{m6} = \frac{2I_{D6}}{|V_{OV}|}$$

$$r_{o6} = \frac{|V_A|}{I_{D6}}$$

Thus,

$$\text{PSRR}^- = \frac{I}{|V_{OV}|} \times \frac{1}{2} \times \frac{2|V_A|}{I} \times \frac{2I_{D6}}{|V_{OV}|} \times \frac{|V_A|}{I_{D6}}$$

$$= 2\left|\frac{V_A}{V_{OV}}\right|^2 \qquad \text{Q.E.D.}$$

(b) A PSRR^- of 72 dB means

$$\text{PSRR}^- = 4000$$

Thus,

$$4000 = 2\frac{|V_A|^2}{0.15^2}$$

$$\Rightarrow |V_A| = 6.71 \text{ V}$$

Now,

$$|V_A| = |V_A'|L$$

$$6.71 = 15L$$

$$\Rightarrow L = 0.45\ \mu\text{m}$$

12.16 For Q_8 and Q_9, we have

$$I_{\text{REF}} = \frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_{8,9} |V_{OV8,9}|^2$$

$$225 = \frac{1}{2} \times 60 \times \frac{60}{0.5} \times |V_{OV8,9}|^2$$

$$\Rightarrow |V_{OV8,9}| = 0.25 \text{ V}$$

$$g_{m8} = g_{m9} = \frac{2I_D}{|V_{OV}|} = \frac{2 \times 0.225}{0.25}$$

$$= 1.8 \text{ mA/V}$$

For Q_{10}, Q_{11} and Q_{12}, we have

$$g_m = g_{m8} = 1.8 \text{ mA/V}$$

$$\frac{2I_{\text{REF}}}{V_{OV}} = 1.8$$

$$\Rightarrow V_{OV} = 0.25 \text{ V}$$

and

$$225 = \frac{1}{2} \times 180 \times \left(\frac{W}{L}\right) \times 0.25^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_{10} = \left(\frac{W}{L}\right)_{11} = \left(\frac{W}{L}\right)_{12} = 40$$

Using Eq. (12.61), we obtain

$$R_B = \frac{2}{g_{m12}}\left(\sqrt{\frac{(W/L)_{12}}{(W/L)_{13}}} - 1\right)$$

$$= \frac{2}{1.8 \times 10^{-3}}\left(\sqrt{4} - 1\right)$$

$$= 1.11 \text{ k}\Omega$$

Voltage drop across $R_B = I_{\text{REF}} \times 1.11$

$= 0.225 \times 1.11 = 0.25$ V

The $\left(\frac{W}{L}\right)$ ratios of Q_{10}, Q_{11} and Q_{12} are given above. For Q_{13}, we have

$$\left(\frac{W}{L}\right)_{13} = 4\left(\frac{W}{L}\right)_{12}$$

$$\Rightarrow \left(\frac{W}{L}\right)_{13} = 160$$

DC voltage at gate of Q_{12}

$= -V_{SS} + I_{\text{REF}}R_B + V_{tn} + V_{OV12}$

$= -1.5 + 0.25 + 0.5 + 0.25 = -0.5$ V

DC Voltage at gate of Q_{10}

$= V_{G12} + V_{tn} + V_{OV11}$

$= -0.5 + 0.5 + 0.25 = +0.25$ V

DC Voltage at gate of Q_8

$= V_{DD} - |V_{tp}| - |V_{OV8}|$

$= 1.5 - 0.5 - 0.25 = +0.75$ V

12.17 $2I_B \times 2 = 1$ mW

$$I_B = \frac{10^{-3}}{4} = 0.25 \text{ mA} = 250 \ \mu\text{A}$$

$I_{D1} = 4I_{D3}$

$I_{D1} + I_{D3} = I_B$

$5I_{D3} = 250 \ \mu$A

$I_{D3} = 50 \ \mu$A, $I_{D4} = 50 \ \mu$A

$I_{D1} = 200 \ \mu$A, $I_{D2} = 200 \ \mu$A

$I = 400 \ \mu$A

12.18 $V_{\text{BIAS1}} = V_{DD} - |V_{OV9}| - |V_{OV3}| - |V_{tp}|$

$= 1 - 0.15 - 0.15 - 0.4 = +0.3$ V

$V_{\text{BIAS2}} = V_{DD} - |V_{OV9}| - |V_{tp}|$

$= 1 - 0.15 - 0.4 = +0.45$ V

$V_{\text{BIAS3}} = -V_{SS} + V_{OV11} + V_{tn}$

$= -1 + 0.15 + 0.4 = -0.45$ V

$V_{ICM\max} = V_{DD} - |V_{OV9}| + V_{tn}$

$= 1 - 0.15 + 0.4 = +1.25$ V

$V_{ICM\min} = -V_{SS} + |V_{OV11}| + V_{OV1} + V_{tn}$

$= -1 + 0.15 + 0.15 + 0.4 = -0.3$ V

Thus,

$-0.3 \text{ V} \le V_{ICM} \le +1.25$ V

$v_{O\max} = V_{\text{BIAS1}} + |V_{tp}|$

$= 0.3 + 0.4 = +0.7$ V

$v_{O\min} = -V_{SS} + V_{OV7} + V_{tn} + V_{OV5}$

$= -1 + 0.15 + 0.4 + 0.15 = -0.3$ V

Thus,

$-0.3 \text{ V} \le v_O \le +0.7$ V

12.19 $I_{D1} = I_{D2} = \frac{I}{2} = 0.2$ mA

$$0.2 = \frac{1}{2} \times 0.4 \times \left(\frac{W}{L}\right)_{1,2} \times 0.04$$

$$\Rightarrow \left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = 25$$

$$I_{D3} = I_{D4} = I_B - \frac{I}{2} = 250 - 200 = 50 \ \mu\text{A}$$

$$50 = \frac{1}{2} \times 100 \times \left(\frac{W}{L}\right)_{3,4} \times 0.04$$

$$\Rightarrow \left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = 25$$

$I_{D5} = I_{D6} = I_{D7} = I_{D8} = 50 \ \mu$A

$$50 = \frac{1}{2} \times 400 \times \left(\frac{W}{L}\right)_{5-8} \times 0.04$$

$$\Rightarrow \left(\frac{W}{L}\right)_5 = \left(\frac{W}{L}\right)_6 = \left(\frac{W}{L}\right)_7 = \left(\frac{W}{L}\right)_8$$

$= 6.25$

$I_{D9} = I_{D10} = I_B = 250 \ \mu$A

$$250 = \frac{1}{2} \times 100 \times \left(\frac{W}{L}\right)_{9,10} \times 0.04$$

$$\Rightarrow \left(\frac{W}{L}\right)_9 = \left(\frac{W}{L}\right)_{10} = 125$$

$I_{D11} = I = 400 \ \mu$A

This table belongs to Problem 12.19.

Transistor	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}
W/L	25	25	25	25	6.25	6.25	6.25	6.25	125	125	50

$$400 = \frac{1}{2} \times 400 \times \left(\frac{W}{L}\right)_{11} \times 0.04$$

$$\Rightarrow \left(\frac{W}{L}\right)_{11} = 50$$

Summary: See table on previous page.

12.20 $G_m = g_{m1} = g_{m2} = \dfrac{2(I/2)}{V_{OV}}$

$$= \frac{I}{V_{OV}} = \frac{0.4}{0.2} = 2 \text{ mA/V}$$

$$I_{D4} = I_B - \frac{I}{2} = 0.25 - 0.2 = 0.05 \text{ mA}$$

$$g_{m4} = \frac{2I_{D4}}{|V_{OV}|} = \frac{2 \times 0.05}{0.2} = 0.5 \text{ mA/V}$$

$$r_{o4} = \frac{|V_A|}{I_{D4}} = \frac{10}{0.05} = 200 \text{ k}\Omega$$

$$r_{o2} = \frac{|V_A|}{I_{D2}} = \frac{|V_A|}{I/2} = \frac{10}{0.2} = 50 \text{ k}\Omega$$

$$r_{o10} = \frac{|V_A|}{I_{D10}} = \frac{|V_A|}{I_B} = \frac{10}{0.25} = 40 \text{ k}\Omega$$

$$R_{o4} = (g_{m4}r_{o4})\ (r_{o2} \parallel r_{o10})$$

$$= 0.5 \times 200\ (50 \parallel 40)$$

$$= 2.22 \text{ M}\Omega$$

$$I_{D6} = 50\ \mu\text{A} = 0.05 \text{ mA}$$

$$g_{m6} = \frac{2 \times 0.05}{0.2} = 0.5 \text{ mA/V}$$

$$r_{o6} = \frac{|V_A|}{I_{D6}} = \frac{10}{0.05} = 200 \text{ k}\Omega$$

$$r_{o8} = \frac{|V_A|}{I_{D8}} = \frac{10}{0.05} = 200 \text{ k}\Omega$$

$$R_{o6} = g_{m6}r_{o6}r_{o8}$$

$$= 0.5 \times 200 \times 200 = 20 \text{ M}\Omega$$

$$R_o = R_{o4} \parallel R_{o6}$$

$$= 2.22 \parallel 20 = 2 \text{ M}\Omega$$

$$A_v = G_m R_o$$

$$= 2 \times 2000 = 4000 \text{ V/V}$$

For the closed-loop amplifier:

$$A = A_v = 4000$$

$$\beta = \frac{C}{C + 9C} = 0.1$$

$$\frac{V_o}{V_i} = A_f = \frac{A}{1 + A\beta} = \frac{4000}{1 + 4000 \times 0.1}$$

$$= \frac{4000}{401} = 9.975 \text{ V/V}$$

$$R_{\text{out}} = R_{of} = \frac{R_o}{1 + A\beta} = \frac{2 \text{ M}\Omega}{401} \simeq 5 \text{ k}\Omega$$

12.21 $\text{SR} = \dfrac{I_B}{C_L}$

$$10 \times 10^6 = \frac{I_B}{10 \times 10^{-12}}$$

$$\Rightarrow I_B = 10^{-4} \text{ A} = 0.1 \text{ mA} = 100\ \mu\text{A}$$

$$\frac{I}{2} = 3\left(I_B - \frac{I}{2}\right)$$

$$\frac{I}{2}(1 + 3) = 3I_B = 300$$

$$I = 150\ \mu\text{A}$$

Now,

$$f_t = \frac{G_m}{2\pi C_L}$$

where

$$G_m = g_{m1,2} = \frac{2(I/2)}{V_{OV1,2}} = \frac{I}{V_{OV1,2}}$$

$$= \frac{0.15 \text{ mA}}{0.15 \text{ V}} = 1 \text{ mA/V}$$

Thus,

$$f_t = \frac{1 \times 10^{-3}}{2\pi \times 10^{-12}}$$

$$= 15.92 \text{ MHz}$$

Phase due to the two nondominant poles at f_t

$$= -2 \tan^{-1}\left(\frac{15.92}{50}\right) = -35.3^\circ$$

Thus,

Phase margin $= 90 - 35.3 = 54.7^\circ$

To increase the phase margin to 75°, the phase due to the two nondominant poles must be reduced to $90 - 75 = 15^\circ$, i.e. each should contribute 7.5°, thus we must reduce f_t to the value obtained as follows:

$$\tan^{-1}\left(\frac{f_t}{50 \text{ MHz}}\right) = 7.5^\circ$$

$$f_t = 50 \times \tan 7.5^\circ = 6.58 \text{ MHz}$$

This is achieved by increasing C_L,

$$6.58 \times 10^6 = \frac{1 \times 10^{-3}}{2\pi C_L}$$

$$\Rightarrow C_L = \frac{10^{-3}}{2\pi \times 7.92 \times 10^6} = 24.2 \text{ pF}$$

The new value of slew-rate will be

$$\text{SR} = \frac{I_B}{C_L} = \frac{0.1 \times 10^{-3}}{24.2 \times 10^{-12}} = 4.13 \text{ V}/\mu\text{s}$$

12.22 Refer to Fig. 12.9. When V_{id} is sufficiently large to cause Q_1 to cut off and Q_2 to conduct all of I, Q_3 will carry a current I_B. However, Q_4 will carry $(I_B - I)$. The current I_B in Q_3 will be mirrored in the drain of Q_6. Thus, at the output node the current available to charge C_L will be

$$I_O = I_B - (I_B - I) = I$$

and the slew rate becomes

$$\text{SR} = \frac{I}{C_L}$$

12.23 $A = 80 \text{ dB} \equiv 10^4 \text{ V/V}$

$f_t = 20 \text{ MHz}, \quad C_L = 10 \text{ pF}$

$I_B = I$

$|V_A| = 12 \text{ V}$

Refer to Figs. 12.9 and 12.10. For $I = I_B$, the dc operating currents of the 11 transistors are as follows:

$Q_1 - Q_8$: $\dfrac{I}{2}$

$Q_9,\ Q_{10}$, and Q_{11}: I

Thus, for $Q_1 - Q_8$, we have

$$g_m = \frac{I}{|V_{OV}|}$$

and

$$r_o = \frac{2|V_A|}{I}$$

while, for $Q_9 - Q_{11}$,

$$r_o = \frac{|V_A|}{I}$$

Now,

$$G_m = g_{m1,2} = \frac{I}{V_{OV}}$$

$$R_{o4} = (g_{m4}r_{o4})\ (r_{o2} \parallel r_{o10})$$

$$= \frac{I}{|V_{OV}|} \times \frac{2|V_A|}{I}\left[\frac{2|V_A|}{I} \parallel \frac{|V_A|}{I}\right]$$

$$= \frac{2|V_A|}{|V_{OV}|} \times \frac{2}{3}\frac{|V_A|}{I}$$

$$= \frac{4|V_A|^2}{3|V_{OV}|I}$$

$$R_{o6} = g_{m6}r_{o6}r_{o8}$$

$$= \frac{I}{|V_{OV}|}\ \frac{2|V_A|}{I}\ \frac{2|V_A|}{I}$$

$$= \frac{4|V_A|^2}{|V_{OV}|I}$$

$$R_o = R_{o4} \parallel R_{o6}$$

$$= \left[\frac{4}{3}\ \frac{|V_A|^2}{|V_{OV}|I}\right] \parallel \left[\frac{|V_A|^2}{|V_{OV}|I}\right]$$

$$= \frac{|V_A|^2}{|V_{OV}|I}$$

The voltage gain can now be found as

$$A = G_m R_o = g_{m1,2}R_o$$

$$= \frac{I}{|V_{OV}|}\ \frac{|V_A|^2}{|V_{OV}|I}$$

$$= \frac{|V_A|^2}{|V_{OV}|^2}$$

$$10{,}000 = \left|\frac{V_A}{V_{OV}}\right|^2$$

$$\Rightarrow \frac{|V_A|}{|V_{OV}|} = 100$$

$$\Rightarrow |V_{OV}| = \frac{12}{100} = 0.12 \text{ V}$$

To obtain $f_t = 20$ MHz, we use

$$20 \times 10^6 = \frac{g_{m1,2}}{2\pi \times 10 \times 10^{-12}}$$

$$g_{m1,2} = 2\pi \times 10 \times 10^{-12} \times 20 \times 10^6$$

$$= 1.257 \times 10^{-3} \text{ A/V}$$

Thus,

$$\frac{I}{|V_{OV}|} = 1.257 \times 10^{-3}$$

$$\Rightarrow I = 1.257 \times 0.12 \times 10^{-3}$$

$$= 0.15 \text{ mA} = 150\ \mu\text{A}$$

$$I_B = I = 150\ \mu\text{A}$$

$$\text{SR} = \frac{I_B}{C_L} = \frac{150 \times 10^{-6}}{10 \times 10^{-12}}$$

$$= 15 \text{ V}/\mu\text{s}$$

For Q_1 and Q_2, we have

$$I_D = \frac{I}{2} = 75\ \mu\text{A} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_{1,2} V_{OV}^2$$

$$75 = \frac{1}{2} \times 400 \times \left(\frac{W}{L}\right)_{1,2} \times 0.12^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = 26$$

For Q_3 and Q_4, we have

$$I_D = I_B - \frac{I}{2} = 150 - 75 = 75\ \mu\text{A}$$

Thus,

$$75 = \frac{1}{2} \times \frac{400}{2.5} \times \left(\frac{W}{L}\right)_{3,4} \times 0.12^2$$

Summary (Approximate Values):

Transistor	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}
W/L	26	26	65	65	26	26	26	26	130	130	52

$$\Rightarrow \left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = 65.1$$

For Q_5, Q_6, Q_7, and Q_8, we have

$I_D = I_B = 75\ \mu\text{A}$

$$75 = \frac{1}{2} \times 400 \times \left(\frac{W}{L}\right)_{5-8} \times 0.12^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_5 = \left(\frac{W}{L}\right)_6 = \left(\frac{W}{L}\right)_7 = \left(\frac{W}{L}\right)_8 = 26$$

For Q_9 and Q_{10}, we have

$I_D = I_B = 150\ \mu\text{A}$

$$150 = \frac{1}{2} \times \frac{400}{2.5} \times \left(\frac{W}{L}\right)_{9,10} \times 0.12^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_9 = \left(\frac{W}{L}\right)_{10} = 130.2$$

For Q_{11}, we have

$I_D = I = 150\ \mu\text{A}$

$$150 = \frac{1}{2} \times 400 \times \left(\frac{W}{L}\right)_{11} \times 0.12^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_{11} = 52$$

See table above for a summary.

12.24 (a) Refer to Fig. 12.12. For the NMOS input stage

$V_{ICM\,\max} = V_{DD} - |V_{OV}| + V_{tn}$

$= 1 - 0.15 + 0.45 = +1.3$ V

$V_{ICM\,\min} = -V_{SS} + V_{OV} + V_{OV} + V_{tn}$

$= -1 + 0.15 + 0.15 + 0.45$

$= -0.25$ V

Thus,

$-0.25\ \text{V} \le V_{ICM} \le +1.3$ V

(b) For the PMOS input stage

$V_{ICM\,\max} = V_{DD} - |V_{OV}| - |V_{tp}|$

$= 1 - 0.15 - 0.15 - 0.45$ V

$= +0.25$ V

$V_{ICM\,\min} = -V_{SS} + V_{OV} - |V_{tp}|$

$= -1 + 0.15 - 0.45$

$= -1.3$ V

Thus,

$-1.3\ \text{V} \le V_{ICM} \le +0.25$ V

(c) The overlap range is

$-0.25\ \text{V} \le V_{ICM} \le +0.25$ V

(d) $-1.3\ \text{V} \le V_{ICM} \le +1.3$ V

12.25 First we determine V_{OV}:

$$90 = \frac{1}{2} \times 400 \times 20\ V_{OV}^2$$

$\Rightarrow V_{OV} = 0.15$ V

$V_{\text{BIAS}} = V_t + 2V_{OV} = 0.45 + 2 \times 0.15$

$= 0.75$ V

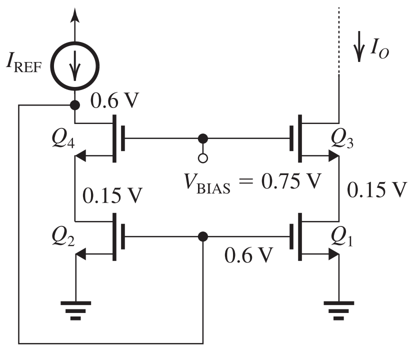

Figure 1

Figure 1 shows the voltages at the various nodes in the mirror circuit. The minimum voltage allowable at the output terminal is

$v_{O\min} = V_{\text{BIAS}} - V_{tn}$

$= 0.75 - 0.45 = 0.3$ V

which is $2V_{OV}$.

The output resistance is

$R_o \simeq g_{m3} r_{o3} r_{o1}$

where

$$r_{o1} = r_{o3} = \frac{V_A}{I_D} = \frac{10}{0.09} = 111.1\ \text{k}\Omega$$

$$g_{m3} = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.09}{0.15} = 1.2\ \text{mA/V}$$

$R_o = 1.2 \times 111.1 \times 111.1 = 14.8\ \text{M}\Omega$

12.26 Since Q_3 is operating in the common-gate configuration and since the resistance in its drain is low, the input resistance at its source is $1/g_{m3}$. This resistance appears in parallel with r_{o1} which is much larger. Thus, the total resistance at this node is $\simeq 1/g_{m3}$ and since the total capacitance is C_P, the pole introduced will have a frequency

$$f_P \simeq \frac{1}{2\pi C_P/g_{m3}} = \frac{g_{m3}}{2\pi C_P} \qquad \text{Q.E.D.}$$

Now,

$$f_t = \frac{g_{m1}}{2\pi C_L}$$

where $g_{m1} = g_{m3}$ because all transistors are operating at the same values of I_D and $|V_{OV}|$.

For a phase margin of 80° the phase at f_t introduced by the pole at f_P must be only 10°,

$$\tan^{-1}\left(\frac{f_t}{f_P}\right) = 10°$$

$$f_P = \frac{f_t}{\tan 10°} = \frac{f_t}{0.176}$$

$$\frac{g_{m3}}{2\pi C_P} = \frac{g_{m1}}{2\pi C_L \times 0.176}$$

$$\Rightarrow C_P = 0.176 C_L$$

This is the largest value that C_P can have.

12.27 For each transistor we use

$$V_{BE} = V_T \ln \frac{I_C}{I_S}$$

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

$$g_m = \frac{I_C}{V_T} = \frac{I_C}{0.025\text{ V}}$$

$$r_e \simeq \frac{1}{g_m}$$

$$r_\pi = \beta/g_m = 200/g_m$$

$$r_o = V_A/I_C = 125/I_C$$

We obtain the following results:

	Q_1	Q_2	Q_5	Q_6	Q_{16}	Q_{17}
I_C (μA)	9.5	9.5	9.5	9.5	16.2	550
V_{BE} (mV)	517	517	517	517	530	618
g_m (mA/V)	0.38	0.38	0.38	0.38	0.65	22
r_e (kΩ)	2.63	2.63	2.63	2.63	1.54	0.045
r_π (kΩ)	526	526	526	526	308	9.1
r_o (MΩ)	13.2	13.2	13.2	13.2	7.72	0.227

12.28 $V_{BE1} = V_T \ln \dfrac{I_1}{I_{S1}}$

$$V_{BE2} = V_T \ln \frac{I_1}{I_{S2}}$$

$$V_{BE3} = V_T \ln \frac{I_3}{I_{S3}}$$

$$V_{BE4} = V_T \ln \frac{I_3}{I_{S4}}$$

$$V_{BE3} + V_{BE4} = V_{BE1} + V_{BE2}$$

$$V_T \ln \frac{I_3}{I_{S3}} + V_T \ln \frac{I_3}{I_{S4}} = V_T \ln \frac{I_1}{I_{S1}} + V_T \ln \frac{I_1}{I_{S2}}$$

$$V_T \ln \frac{I_3^2}{I_{S3}I_{S4}} = V_T \ln \frac{I_1^2}{I_{S1}I_{S2}}$$

$$\Rightarrow \frac{I_3^2}{I_{S3}I_{S4}} = \frac{I_1^2}{I_{S1}I_{S2}}$$

$$\Rightarrow I_3 = I_1 \sqrt{\frac{I_{S3}I_{S4}}{I_{S1}I_{S2}}} \qquad \text{Q.E.D.}$$

$$150 = I_1\sqrt{3 \times 3} = 3I_1$$

$$\Rightarrow I_1 = 50\ \mu\text{A}$$

12.29 For the A and B devices, we have

$$V_{EB} = V_T \ln \frac{0.73 \times 10^{-3}}{10^{-14}}$$

$$= 625\text{ mV}$$

For the A device, we have

$$g_{mA} = \frac{I_{CA}}{V_T} = \frac{0.25 \times 0.73}{0.025} = 7.3\text{ mA/V}$$

$$r_{eA} \simeq \frac{1}{g_{mA}} = 137\ \Omega$$

$$r_{\pi A} = \frac{\beta}{g_{mA}} = \frac{50}{7.3} = 6.85\text{ k}\Omega$$

$$r_{oA} = \frac{|V_A|}{I_{CA}} = \frac{50}{0.18} = 278\text{ k}\Omega$$

For the B device, we have

$$g_{mB} = \frac{I_{CB}}{V_T} = \frac{0.75 \times 0.73}{0.025} = 21.9\text{ mA/V}$$

$$r_{eB} \simeq \frac{1}{g_{mB}} = 46\ \Omega$$

$$r_{\pi B} = \frac{\beta}{g_{mB}} = \frac{50}{21.9} = 2.28\text{ k}\Omega$$

$$r_{oB} = \frac{|V_A|}{I_{CB}} = \frac{50}{0.55} = 90.9\text{ k}\Omega$$

12.30 $V_{SG1} = |V_{tp}| + |V_{OV1}|$

$$V_{GS2} = V_{tn} + V_{OV2}$$

$$V_{GS3} = V_{tn} + V_{OV3}$$

$V_{SG4} = |V_{tp}| + |V_{OV4}|$

But,

$V_{SG1} + V_{GS2} = V_{GS3} + V_{SG4}$

$\Rightarrow |V_{OV1}| + V_{OV2} = V_{OV3} + |V_{OV4}|$

Since

$|V_{OV1}| = \sqrt{2I_1/k_1}$

$V_{OV2} = \sqrt{2I_1/k_2}$

$V_{OV3} = \sqrt{2I_3/k_3}$

$|V_{OV4}| = \sqrt{2I_3/k_4}$

then

$$\sqrt{2I_1}\left(\frac{1}{\sqrt{k_1}} + \frac{1}{\sqrt{k_2}}\right) = \sqrt{2I_3}\left(\frac{1}{\sqrt{k_3}} + \frac{1}{\sqrt{k_4}}\right)$$

$$\Rightarrow I_3 = I_1\left[\frac{\frac{1}{\sqrt{k_1}} + \frac{1}{\sqrt{k_2}}}{\frac{1}{\sqrt{k_3}} + \frac{1}{\sqrt{k_4}}}\right]^2$$

For $k_1 = k_2$ and $k_3 = k_4 = 16\,k_1$, we have

$$I_3 = I_1\left[\frac{2/\sqrt{k_1}}{2/\sqrt{k_3}}\right]^2 = 16\,I_1$$

For $I_3 = 1.6$ mA, we have

$I_1 = 0.1$ mA

12.31 Differential input breakdown voltage

$= 0.6 + 0.6 + 50 + 7$

$= 58.2$ V

where we have assumed that a forward conducting transistor exhibits $|V_{BE}| = 0.6$ V.

12.32

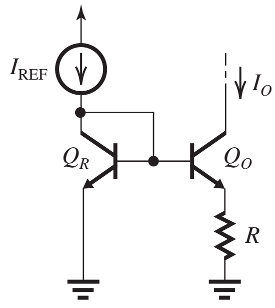

Figure 1

Refer to Fig. 1,

$I_{REF} = 0.3$ mA, $I_O = 10$ μA

$$V_{BER} = V_T \ln\frac{I_{REF}}{I_S}$$

$$= 25\ln\left(\frac{0.3\times10^{-3}}{10^{-14}}\right) = 603 \text{ mV}$$

$$V_{BEO} = V_T \ln\frac{I_O}{I_S}$$

$$= 25\ln\left(\frac{10\times10^{-6}}{10^{-14}}\right)$$

$= 518$ mV

$V_{BER} - V_{BEO} = 603 - 518 = 85$ mV

$$R = \frac{85 \text{ mV}}{10\ \mu\text{A}} = 8.5\ \text{k}\Omega$$

12.33 Refer to Fig. 12.15.

(a) A node equation at X yields

$$\frac{2I}{1+2/\beta_P} + \frac{2I}{\beta_P} = I_{C10}$$

$$2I\ \frac{\beta_P + 1 + \frac{2}{\beta_P}}{\beta_P\left(1+\frac{2}{\beta_P}\right)} = I_{C10}$$

$$I = \frac{I_{C10}}{2}\left[\frac{\beta_P(\beta_P+2)}{\beta_P^2+\beta_P+2}\right]$$

For $\beta_P = 50$, we have

$$I = \frac{I_{C10}}{2}\times 1.019$$

For $\beta_P = 20$, we have

$$I = \frac{I_{C10}}{2}\times 1.043$$

Thus, I increases by $\frac{I_{C10}}{2}\times 0.024$, which is 2.4%.

(b)

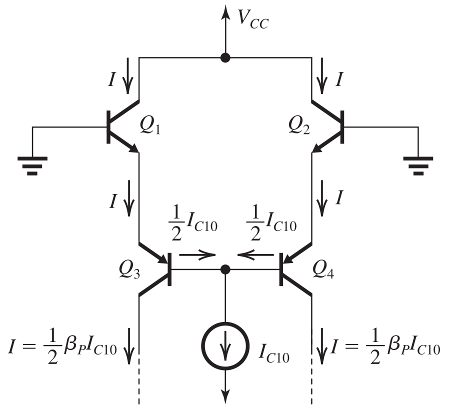

Figure 1

Figure 1 shows the suggested alternative design. As shown, here

$$I \simeq \frac{1}{2}\beta_P I_{C10}$$

For $\beta_P = 50$, we have

$I = 25I_{C10}$

For $\beta_P = 20$, we have

$I = 10I_{C10}$

Thus, I changes by $-15I_{C10}$, which is -60% change! This is a result of the absence of the desensitivity effect of negative feedback.

12.34 Refer to Fig. 12.15.

For $I_{S9} = 2I_{S8}$, the collector current of Q_9 will be

$$I_{C9} = \frac{4I}{1 + \frac{2}{\beta_P}}$$

If β_P is large, a node equation at X yields

$4I \simeq I_{C10}$

$$\Rightarrow I = \frac{1}{4}I_{C10} = \frac{19}{4} = 4.75\ \mu\text{A}$$

To establish $I_{C1} = I_{C2} = 9.5\ \mu$A, we need to redesign the Widlar source to provide

$I_{C10} = 38\ \mu$A. From Eq. (12.86), we obtain

$$V_T\ \ln\frac{I_{\text{REF}}}{I_{C10}} = I_{C10}R_4$$

$$25 \times \ln\frac{730}{38} = 38R_4$$

$\Rightarrow R_4 = 1.94\ \text{k}\Omega$

12.35 Refer to Fig. 12.15. For β_P large, a node equation at X yields

$I_{C9} \simeq I_{C10}$

If the ratio of the area of Q_9 to that of Q_8 is n, then

$I_{C9} = n \times 2I$

Thus,

$2nI = I_{C10}$

For $I = 10\ \mu$A and $I_{C10} = 40\ \mu$A, we have

$n = 2$

12.36 Figure 1 shows the circuit when R_3 is adjusted so that $I_{C5} = I_{C6} = I_{C7}$. Denoting the new value of these three currents I_1, we obtain the various currents indicated in Fig. 1. Now, at the input node X, we have

$$I_1\left(1 + \frac{1}{\beta_N}\right) = 9.5\ \mu\text{A}$$

$$\Rightarrow I_1 = \frac{9.5}{1 + (1/200)} = 9.45\ \mu\text{A}$$

At this collector current, we have

$$V_{BE} = 25\ \ln\frac{9.45 \times 10^{-6}}{10^{-14}} = 516.7\ \mu\text{A}$$

The voltage drop across R_3 becomes

$$V_{R3} = V_{BE5} + I_1\left(1 + \frac{1}{\beta_N}\right)R_1$$

$= 516.7 + 9.5 \times 1$

$= 526.2$ mV

The value of R_3 can now be found as

$$R_3 = \frac{V_{R3}}{I_1\left(1 - \frac{1}{\beta_N}\right)} = \frac{526.2}{9.45\left(1 - \frac{1}{200}\right)}$$

$= 56\ \text{k}\Omega$

12.37 Refer to the circuit in Fig. 12.16. The current in Q_5 remains equal to

$I = 9.5\ \mu$A

This figure belongs to Problem 12.36.

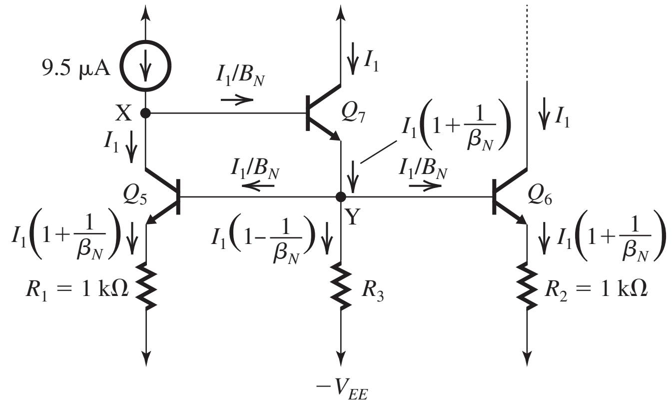

Figure 1

The voltage between the base of Q_5 and $-V_{EE}$ is

$= V_{BE5} + IR_1$

$= 25 \ln\left(\frac{9.5 \times 10^{-6}}{10^{-14}}\right) + 9.5 \times 1$

$= 517 + 9.5 = 526.5$ mV

With R_2 shorted, this voltage appears across the BE junction of Q_6. Thus,

$I_{C6} = I_S\, e^{V_{BE6}/V_T}$

$= 10^{-14}\, e^{526.5/25}$

$= 14\ \mu\text{A}$

12.38 $2I = 19\ \mu\text{A}$

Assuming

$I_{C1} = I_{C2} = I = 9.5\ \mu\text{A}$

then

$I_{B1} = \frac{9.5}{150} = 63.3$ nA

$I_{B2} = \frac{9.5}{220} = 43.2$ nA

$I_B = \frac{1}{2}(I_{B1} + I_{B2}) = 53.3$ nA

$I_{OS} = |I_{B1} - I_{B2}| = 20.1$ nA

12.39 Refer to Fig. 12.14 and to Exercise 12.21. From the answers to Exercise 12.21, we find that

$V_{BE17} = 618$ mV

$I_{E17} \simeq I_{C17} = 550\ \mu\text{A}$

$I_{B17} = \frac{550}{200} = 2.75\ \mu\text{A}$

Voltage across $R_9 = V_{BE17} + I_{E17}\, R_8$

$= 618 + 550 \times 0.1$

$= 673$ mV

$I_{E16} = I_{B17} + \frac{V_{R9}}{R_9}$

For $I_{C16} = 9.5\ \mu\text{A}$, we have

$I_{E16} = 9.5 + \frac{9.5}{200} = 9.55\ \mu\text{A}$

Thus,

$9.55 = 2.75 + \frac{673\ (\text{mV})}{R_9\ (\text{k}\Omega)}$

$\Rightarrow R_9 = 98.9\ \text{k}\Omega$

12.40 $V_{C1} = V_{CC} - V_{EB8} = 5 - 0.6 = 4.4$ V

Q_1 and Q_2 saturate when V_{ICM} exceeds V_{C1} by 0.4 V. Thus,

$V_{ICM\,\max} = +4.8$ V

$V_{C5} \simeq -V_{EE} + V_{BE5} + V_{BE7}$

$= -5 + 0.6 + 0.6 = -3.8$ V

Q_3 and Q_4 saturate when

$V_{B3} = V_{C5} - 0.4 = -4.2$ V

But,

$V_{B3} = V_{ICM} - V_{BE1} - V_{EB3}$

$= V_{ICM} - 1.2$

Thus,

$V_{ICM\,\min} = V_{B3} + 1.2$

$= -4.2 + 1.2 = -3.0$ V

Thus,

$-3\text{ V} \le V_{ICM} \le +4.8$ V

12.41 $I_{C18} + I_{C19} = 0.25 \times 0.73 = 180\ \mu\text{A}$

Require

$I_{C18} = I_{C19} = 90\ \mu\text{A}$

$V_{BE18} = 25 \ln \frac{90 \times 10^{-6}}{10^{-14}}$

$= 573$ mV

Current through $R_{10} = I_{C19} + I_{B19} - I_{B18}$

$\simeq I_{C19} = 90\ \mu\text{A}$

$R_{10} = \frac{573}{90} = 6.4\ \text{k}\Omega$

$V_{BB} = V_{BE18} + V_{BE19}$

$= 2 \times 0.573 = 1.146$ V

Since V_{BB} appears across the series combination of Q_{14} and Q_{20}, we can write

$V_{BB} = V_T \ln \frac{I_{C14}}{I_{S14}} + V_T \ln \frac{I_{C20}}{I_{S20}}$

Substituting $V_{BB} = 1.146$ V,
$I_{S14} = I_{S20} = 3 \times 10^{-14}$, we obtain for the equal currents I_{C14} and I_{C20}

$$1.146 = 2 \times 0.025 \ln \frac{I_{C14}}{3 \times 10^{-14}}$$

$$\Rightarrow I_{C14} = I_{C20} = 270\ \mu\text{A}$$

12.42

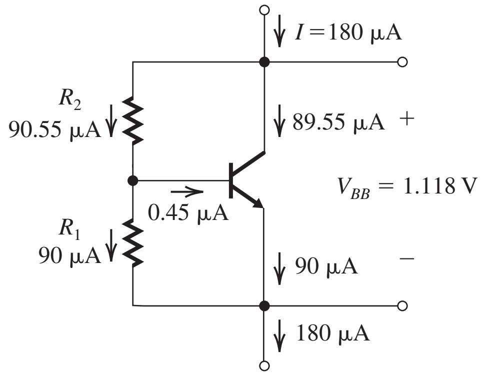

Figure 1

Refer to Fig. 1.

$$I_E = I_{R1} = \frac{180}{2} = 90\ \mu\text{A}$$

$$I_B = \frac{90}{201} = 0.45\ \mu\text{A}$$

$$I_C = \frac{\beta_N}{\beta_N + 1} I_E$$

$$= \frac{200}{201} \times 90 = 89.55\ \mu\text{A}$$

$$V_{BE} = V_T \ln \frac{I_C}{I_S}$$

$$= 25 \ln \frac{89.55 \times 10^{-6}}{10^{-14}}$$

$$= 573\ \text{mV}$$

$$R_1 = \frac{573\ \text{mV}}{90\ \mu\text{A}} = 6.37\ \text{k}\Omega$$

$$I_{R2} = I_{R1} + I_B = 90 + 0.45 = 90.45\ \mu\text{A}$$

$$V_{R2} = V_{BB} - V_{R1} = 1.118 - 0.573$$

$$= 0.545\ \text{V}$$

$$R_2 = \frac{545\ \text{mV}}{90.45\ \mu\text{A}} = 6.03\ \text{k}\Omega$$

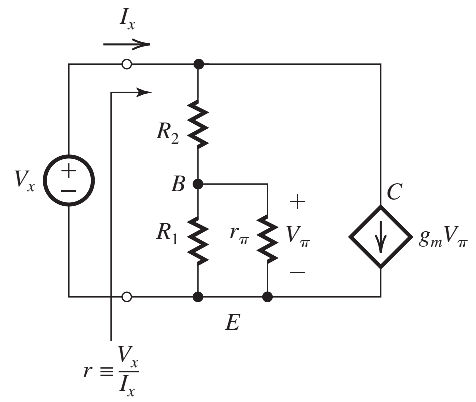

Figure 2

To determine the incremental resistance between the two terminals of the V_{BE} multiplier, we replace the transistor with its hybrid-π model, as shown in Fig. 2. Here

$$g_m = \frac{I_C}{V_T} = \frac{89.55\ \mu\text{A}}{25\ \text{mV}} = 3.6\ \text{mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{200}{3.6} = 55.6\ \text{k}\Omega$$

$$R_1 \parallel r_\pi = 6.37 \parallel 55.6 = 5.7\ \text{k}\Omega$$

$$V_\pi = V_x \frac{R_1 \parallel r_\pi}{(R_1 \parallel r_\pi) + R_2}$$

$$= V_x \frac{5.7}{5.7 + 6.03} = 0.49\ V_x$$

$$I_x = \frac{V_x}{5.7 + 6.03} + g_m \times 0.49\ V_x$$

$$= V_x(0.085 + 1.764)$$

$$r \equiv \frac{V_x}{I_x} = \frac{1}{0.085 + 1.764} = 0.541\ \text{k}\Omega$$

$$= 541\ \Omega$$

12.43 Refer to Fig. 12.14 and Table 12.1. The current I_{CC} drawn from V_{CC} can be found as follows:

$$I_{CC} = I_{E12} + I_{E13} + I_{C14} + I_{E9} + I_{E8} + I_{C7} + I_{C16}$$

Assuming β_P and $\beta_N \gg 1$,

$$I_{CC} = 730 + 730 + 154 + 19 + 19 + 10.5$$
$$+ 16.2$$

$$= 1678.7\ \mu\text{A} = 1.68\ \text{mA}$$

$$P_D = I_{CC}(V_{CC} + V_{EE})$$

$$= 1.68(15 + 15) = 50.4\ \text{mW}$$

12.44

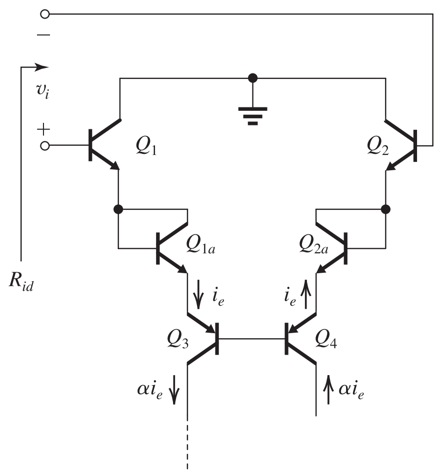

Figure 1

Figure 1 shows the input stage with the two extra diode-connected transistors Q_{1a} and Q_{2a}. Since these devices are simply in series with $Q_1 - Q_4$, they will have the same dc bias current, namely 9.5 μA. Thus, each of Q_{1a} and Q_{2a} will have an incremental resistance equal to r_e of each of Q_1 to Q_4,

$$r_e = \frac{25\text{ mV}}{9.5\ \mu\text{A}} = 2.63\text{ k}\Omega$$

The input differential resistance R_{id} now becomes

$$R_{id} = (\beta_N + 1) \times 6r_e$$

$$= 201 \times 6 \times 2.63$$

$$= 3.2\text{ M}\Omega$$

The effective transconductance of the input stage, G_{m1}, now becomes

$$G_{m1} \equiv \frac{2\alpha i_e}{v_{id}}$$

$$= \frac{2\alpha i_e}{6 i_e r_e} = \frac{1}{3} g_{m1}$$

$$= \frac{1}{3}\,\frac{9.5\ \mu\text{A}}{25\text{ mV}} = 0.13\text{ mA/V}$$

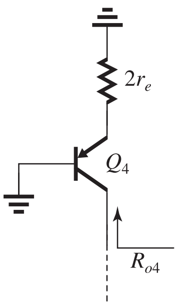

Figure 2

To find R_{o4}, refer to the circuit in Fig. 2.

$$R_{o4} = r_{o4}[1 + g_{m4}(2\, r_e \parallel r_{\pi 4})]$$

where

$$r_{o4} = \frac{50\text{ V}}{9.5\ \mu\text{A}} = 5.26\text{ M}\Omega$$

$$g_{m4} = 0.38\text{ mA/V}$$

$$r_{\pi 4} = \frac{50}{0.38} = 131.6\text{ k}\Omega$$

$$R_{o4} = 5.26[1 + 0.38(5.26 \parallel 131.6)]$$

$$= 15.4\text{ M}\Omega$$

$$R_{o1} = R_{o4} \parallel R_{o6}$$

$$= 15.4 \parallel 18.2 = 8.33\text{ M}\Omega$$

Open-circuit voltage gain $= G_{m1}R_{o1}$

$$= 0.13 \times 8.33 \times 10^3 = 1083\text{ V/V}$$

Comparison

	Original Design	**Modified Design**
R_{id} (kΩ)	2.1	3.2
G_{m1} (mA/V)	0.19	0.13
R_{o4} (MΩ)	10.5	15.4
R_{o1} (MΩ)	6.7	8.3
$\lvert A_{vo}\rvert$ (V/V)	1273	1083

Thus the input resistance increases but the gain decreases: The additional diodes introduce negative feedback in the input stage; same effect as adding a resistance in the emitter of a common-emitter amplifier.

12.45 From Fig. 12.20(b) and Eq. (12.91), we get

$$R_{o6} = r_{o6}[1 + g_{m6}(R_2 \parallel r_{\pi 6})]$$

where

$$r_{o6} = \frac{125\text{ V}}{9.5\ \mu\text{A}} = 13.6\text{ M}\Omega$$

$$g_{m6} = \frac{9.5\ \mu\text{A}}{25\text{ mV}} = 0.38\text{ mA/V}$$

$$r_{\pi 6} = \frac{200}{0.38} = 526.3\text{ k}\Omega$$

$$\frac{R_{o6}(\text{modified})}{R_{o6}(\text{original})} = \frac{1 + 0.38(R_2' \parallel 526.3)}{1 + 0.38(1 \parallel 526.3)}$$

$$2 \simeq \frac{1 + 0.38\, R_2'}{1 + 0.38}$$

$$\Rightarrow R_2' = 4.63\text{ k}\Omega$$

Thus, R_2 must be increased by a factor of 4.63.

12.46 Refer to Fig. 12.19.

(a) $v_{b6} = i_{e6}(r_{e6} + R_2)$

$= i_e(r_{e6} + R_2)$

where

$$r_{e6} = \frac{25\text{ mV}}{9.5\ \mu\text{A}} = 2.63\text{ k}\Omega$$

$v_{b6} = i_e(2.63 + 2) = 4.63\text{ k}\Omega \times i_e$

(b) $i_{e7} = i_{R3} + i_{b5} + i_{b6}$

$$= \frac{v_{b6}}{R_3} + \frac{2\alpha i_e}{\beta}$$

$$= \frac{4.63}{50} i_e + \frac{2}{201} i_e$$

$= 0.1 i_e$

(c) $i_{b7} = \dfrac{i_{e7}}{\beta_N + 1} = \dfrac{0.1}{201} i_e = 0.0005 i_e$

(d) $v_{b7} = i_{e7} r_{e7} + v_{b6}$

$= 0.1 \times 2.38 i_e + 4.63 i_e$

$= 4.89 i_e$

(e) $R_{\text{in}} \equiv \dfrac{v_{b7}}{\alpha i_e} \simeq 4.9\text{ k}\Omega$

12.47 Output current of first stage $= (1 - 0.8)I$

$= 0.2I$

$$V_{OS} = \frac{0.2I}{G_{m1}}$$

where

$$G_{m1} = \frac{1}{2} g_{m1} = \frac{1}{2} \frac{I}{V_T}$$

Thus,

$$V_{OS} = \frac{0.2I}{0.5I/V_T}$$

$= 0.4 \times V_T = 10\text{ mV}$

12.48 Refer to Fig. 12.22 which shows the situation when $R_1 = R$ and $R_2 = R + \triangle R$. The result of this mismatch is an output current $\triangle I$ given by Eq. (12.94):

$$\triangle I = I \frac{\triangle R}{R + \triangle R + r_e} \tag{1}$$

If we have an input offset voltage V_{OS}, this offset results in an output current $\triangle I$ given by

$$\triangle I = G_{m1} V_{OS} \tag{2}$$

The offset can be nulled by introducing a mismatch $\triangle R$ that results in an equal magnitude and opposite polarity output current. The required $\triangle R$ can be found by equating (1) and (2), thus

$$I \frac{\triangle R}{R + \triangle R + r_e} = G_{m1} V_{OS}$$

Substituting for G_{m1} by

$$G_{m1} = \frac{1}{2} g_{m1} = \frac{1}{2} \frac{I}{V_T}$$

we obtain

$$I \frac{\triangle R}{R + \triangle R + r_e} = \frac{1}{2} \frac{I}{V_T} V_{OS}$$

$$\Rightarrow \frac{\triangle R}{R} = \frac{V_{OS}}{2V_T} \frac{1 + r_e/R}{1 - V_{OS}/2V_T} \qquad \text{Q.E.D.}$$

(b) For $V_{OS} = 3$ mV and recalling that

$$r_e = \frac{25\text{ mV}}{9.5\ \mu\text{A}} = 2.63\text{ k}\Omega \text{ and } R = 1\text{ k}\Omega$$

then

$$\frac{\triangle R}{R} = \frac{3}{2 \times 25} \frac{1 + (2.63/1)}{1 - (3/50)}$$

$$\frac{\triangle R}{R} = 0.23$$

or 23%

For $V_{OS} = -3$ mV, we have

$$\frac{\triangle R}{R} = -0.205 \text{ or } -20.5\%$$

(c) The maximum offset voltage than can be trimmed this way corresponds to R_2 completely shorted, that is, $\triangle R = -R$, thus

$$-1 = \frac{V_{OS}}{2V_T} \frac{1 + 2.63}{1 - \dfrac{V_{OS}}{2V_T}}$$

$$\Rightarrow V_{OS} = -\frac{2V_T}{2.63} = -19\text{ mV}$$

12.49

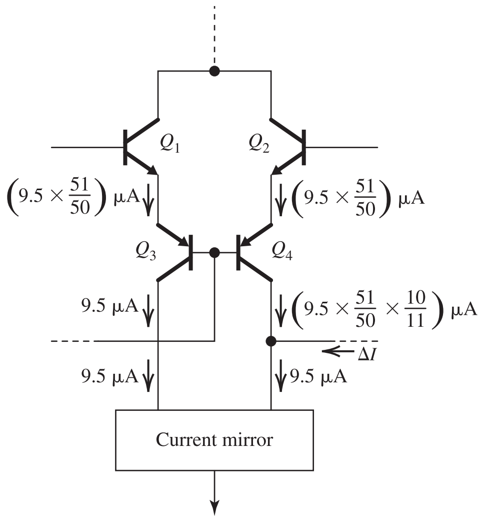

Figure 1

Figure 1 (see preceding page) shows the analysis when the β of Q_4 is reduced to 10. The output current of the mirror is

$\triangle I = 0.691\ \mu A$

which corresponds to an input offset voltage of

$$V_{OS} = \frac{\triangle I}{G_{m1}}, \text{ where } G_{m1} = \frac{1}{2}g_{m1} = 0.19 \text{ mA/V}$$

Thus,

$$V_{OS} = \frac{0.691}{0.19} = 3.6 \text{ mV}$$

12.50 From Eq. (12.102) we have

$\text{CMRR} = g_{m1}(R_{o9} \parallel R_{o10})/\epsilon_m$

where

$g_{m1} = 0.38$ mA/V

$R_{o9} = 2.63$ MΩ

$R_{o10} = 31.1$ MΩ

$\epsilon_m = 1 - 0.995 = 0.005$

Thus,

$\text{CMRR} = 0.38(2.63 \parallel 31.3) \times 10^3/0.005$

$= 1.84 \times 10^5$

or 105.3 dB

12.51 Refer to Fig. 12.19.

(a) If R_1 is short-circuited, the incremental transfer ratio of the mirror can be found as follows:

$i_{e5}r_{e5} = i_{e6}(r_{e6} + R_2)$

Thus,

$$\frac{i_{c6}}{i_{c5}} = \frac{i_{e6}}{i_{e5}} = \frac{r_{e5}}{r_{e5} + R_2} = \frac{2.63}{2.63 + 1}$$

$= 0.72$

Thus, the output current of the mirror becomes

$i_o = 1.72\alpha i_e$

rather than $2\alpha i_e$. Thus, the gain of the 741 will be reduced by a factor of $\frac{1.72}{2} = 0.86$.

(b) If R_2 is short-circuited, then

$i_{e5}(r_{e5} + R_1) = i_{e6}r_{e6}$

$$\Rightarrow \frac{i_{c6}}{i_{c5}} = \frac{i_{e6}}{i_{e5}} = \frac{r_{e5} + R_1}{r_{e6}}$$

$$= \frac{2.63 + 1}{2.63} = 1.38$$

Thus, i_o of the mirror becomes

$i_o = 2.38\alpha i_e$

with the result that the gain of the 741 increases by a factor of $\frac{2.38}{2} = 1.19$.

(c) If both R_1 and R_2 are shorted, the gain remains unchanged.

12.52 Please note that an error occurred in the first printing of the text: Q_9 is biased at 19 µA. With a resistance R in the emitter of Q_9, R_{o9} becomes

$R_{o9} = r_{o9}[1 + g_{m9}(R \parallel r_{\pi 9})]$

where

$$r_{o9} = \frac{|V_{Ap}|}{I_{C9}} = \frac{50 \text{ V}}{19\ \mu\text{A}} = 2.63 \text{ M}\Omega$$

$$g_{m9} = \frac{I_{C9}}{V_T} = \frac{19\ \mu\text{A}}{0.025 \text{ V}} = 0.76 \text{ mA/V}$$

$$r_{\pi 9} = \frac{\beta_P}{g_{m9}} = \frac{50}{0.76} = 65.8 \text{ k}\Omega$$

Thus, to obtain $R_{o9} = R_{o10} = 31.1$ MΩ, we use

$31.1 = 2.63[1 + 0.76(R \parallel 65.8)]$

$\Rightarrow R = 18.2$ kΩ

Thus, R_o to the left of node Y becomes

$R_o = 31.1 \text{ M}\Omega \parallel 31.1 \text{ M}\Omega = 15.55 \text{ M}\Omega$

12.53

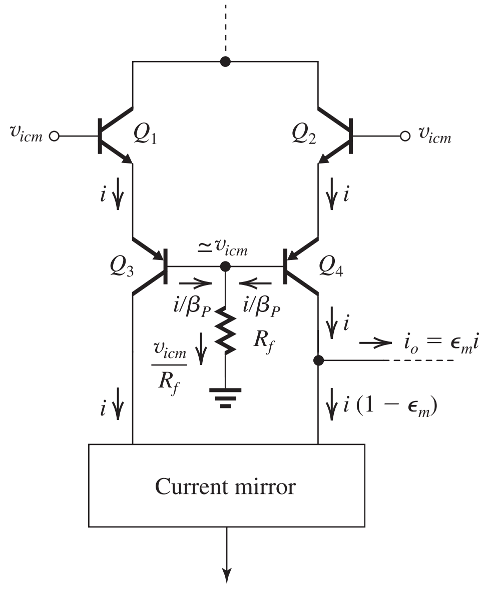

Figure 1

Figure 1 (see previous page) shows the input stage with the approach suggested for determining G_{mcm}. Here

$$R_f = R_o(1 + A\beta) = R_o(1 + \beta_P) \simeq \beta_P R_o$$

A node equation at the common bases of the Q_3 and Q_4 yields

$$\frac{2i}{\beta_P} = \frac{v_{icm}}{R_f}$$

$$\Rightarrow i = \frac{\beta_P}{2R_f} v_{icm}$$

$$= \frac{\beta_P}{2\beta_P R_o} v_{icm}$$

$$= \frac{v_{icm}}{2R_o}$$

Thus,

$$i_o = \epsilon_m i = \frac{\epsilon_m}{2R_o} v_{icm}$$

and

$$G_{mcm} \equiv \frac{i_o}{v_{icm}} = \frac{\epsilon_m}{2R_o}$$

which is the same result [Eq. (12.100)] obtained by the alternative approach of Example 12.5.

12.54 Refer to the results of Exercise 12.32. We need to raise r_{o13B} from 90.9 kΩ to 722 kΩ by inserting a resistance R_{13B} in the emitter of Q_{13B}. Since

$$R_{o13B} = r_{o13B}[1 + g_{m13B}(R_{13B} \parallel r_{\pi 13B}]$$

where

$$r_{o13B} = 90.9 \text{ k}\Omega$$

$$g_{m13B} = \frac{0.55 \text{ mA}}{0.025 \text{ V}} = 22 \text{ mA/V}$$

$$r_{\pi 13B} = \frac{\beta_P}{g_{m13B}} = \frac{50}{22} = 2.27 \text{ k}\Omega$$

Thus,

$$722 = 90.9[1 + 22(R_{13B} \parallel 2.27)]$$

$$\Rightarrow R_{13B} = 366 \ \Omega$$

The resistors in the emitters of Q_{13A} and Q_{12} must be of values that will result in

$$I_{E13B}R_{13B} = I_{E12}R_{12} = I_{E13A}R_{13A}$$

Thus,

$$R_{13A} = \frac{I_{E13B}}{I_{E13A}} R_{13B}$$

$$= \frac{I_{C13B}}{I_{C13A}} R_{13B}$$

$$= \frac{550}{180} \times 366 = 1.12 \text{ k}\Omega$$

$$R_{12} = \frac{I_{E13B}}{I_{E12}} R_{13B}$$

$$= \frac{I_{C13B}}{I_{C12}} R_{13B}$$

$$= \frac{550}{730} \times 366 = 275 \ \Omega$$

12.55 Using Eq. (12.110), we obtain

$$v_{O\max} = V_{CC} - |V_{CE\text{sat}}| - V_{BE14}$$

$$= 5 - 0.2 - 0.6 = +4.2 \text{ V}$$

Using Eq. (12.111), we get

$$v_{O\min} = -V_{EE} + |V_{CE\text{sat}}| + V_{EB23} + V_{BE20}$$

$$= -5 + 0.2 + 0.6 + 0.6 = -3.6 \text{ V}$$

Thus,

$$-3.6 \text{ V} \le v_O \le +4.2 \text{ V}$$

12.56 Refer to Fig. P12.56.

$$R_{\text{out}} = r_{e14} + \frac{r_{AA} + r_{e23} + [R_{o2}/(\beta_P + 1)]}{\beta_{14} + 1}$$

where

$$r_{e14} = \frac{25 \text{ mV}}{5 \text{ mA}} = 5 \ \Omega$$

$$r_{AA} = 163 \ \Omega$$

$$r_{e23} = \frac{25 \text{ mV}}{0.18 \text{ mA}} = 139 \ \Omega$$

$$R_{o2} = 81 \text{ k}\Omega$$

$$\beta_P = 50$$

$$\beta_{14} = 200$$

Thus

$$R_{\text{out}} = 5 + \frac{163 + 139 + (81000/51)}{201}$$

$$= 14.4 \ \Omega$$

12.57 Refer to Fig. 12.25 and Example 12.6 with Q_{23} having its emitter and base shorted together. In such a situation the input resistance of the output stage becomes

$$R_{\text{in3}} = (\beta_{20}R_L) \parallel (r_{o13A} + r_{AA}) \qquad (1)$$

where we have assumed the situation with v_O negative and Q_{20} supplying the load current.

In Eq. (1),

$\beta_{20} = 50$

$R_L = 2\ \text{k}\Omega$

$$r_{o13A} = \frac{|V_{Ap}|}{I_{C13A}} = \frac{50}{0.18} = 280\ \text{k}\Omega$$

and r_{AA} is the incremental resistance of the $Q_{18} - Q_{19}$ bias network; very small ($\simeq 160\ \Omega$). Thus,

$R_{\text{in}3} \simeq (50 \times 2) \parallel 280$

$= 74\ \text{k}\Omega$

The gain of the second stage becomes

$$A_2 = \frac{v_{i3}}{v_{i2}} = -G_{m2}R_{o2}\ \frac{R_{\text{in}3}}{R_{\text{in}3} + R_{o2}}$$

$$= -6.5 \times 81 \times \frac{74}{74 + 81}$$

$= -215.4$ V/V

Compare to the value with Q_{23} included (-515 V/V).

12.58

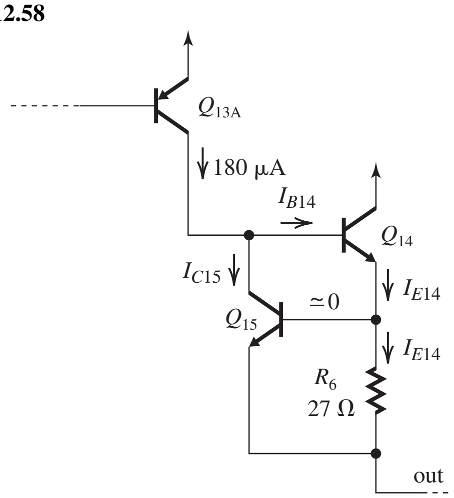

Figure 1

Refer to Fig. 1.

Iteration #1:

$I_{C15} = 180\ \mu\text{A}$

$$V_{BE15} = 25\ \ln\frac{180 \times 10^{-6}}{10^{-14}} = 590\ \text{mV}$$

$$I_{E14} = \frac{V_{BE15}}{R_6} = \frac{590\ \text{mV}}{27\ \Omega} = 21.85\ \text{mA}$$

$$I_{B14} = \frac{I_{E14}}{\beta_N + 1} = \frac{21.85}{201} = 108.7\ \mu\text{A}$$

Iteration #2:

$I_{C15} = 180 - I_{B14} = 180 - 108.7 = 71.3\ \mu\text{A}$

$$V_{BE15} = 25\ \ln\frac{71.3 \times 10^{-6}}{10^{-14}} = 567.2\ \text{mV}$$

$$I_{E14} = \frac{567.2}{27} = 21\ \text{mA}$$

$$I_{B14} = \frac{21\ \text{mA}}{201} = 104.5\ \mu\text{A}$$

Iteration #3:

$I_{C15} = 180 - 104.5 = 75.5\ \mu\text{A}$

$$V_{BE15} = 25\ \ln\frac{75.5 \times 10^{-6}}{10^{-14}} = 568.6$$

$$I_{E14} = \frac{568.6}{27} = 21.06\ \text{mA}$$

which is very close to the value found in Iteration #2; thus, no further iterations are necessary and

$I_{E14} \simeq 21\ \text{mA}$

12.59 Refer to Fig. 12.14.

Maximum current available from input stage $= 19\ \mu\text{A}$

$I_{C22} = 19\ \mu\text{A}$

$$V_{BE22} = 25\ \ln\frac{19 \times 10^{-6}}{10^{-14}}$$

$= 534$ mV

$V_{BE24} = 534$ mV

$I_{C24} = 19\ \mu\text{A}$

$$I_{R11} = \frac{534\ \text{mV}}{50\ \text{k}\Omega} = 10.7\ \mu\text{A}$$

$I_{C21} = I_{C24} + I_{R11}$

$= 19 + 10.7 = 29.7\ \mu\text{A}$

$$V_{EB21} = 25\ \ln\frac{29.7 \times 10^{-6}}{10^{-14}}$$

$= 545.3$ mV

$$I_{R7} = \frac{545.3}{27} = 20.2\ \text{mA}$$

This is the maximum current that the 741 can sink. To reduce this current limit to 10 mA, we need to double the value of R_7.

12.60 The factor 0.97 is simply

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

Thus, for $R_L = \infty$,

$A_0 = 243,147/0.97 = 250,667$ V/V

This is the open-circuit voltage gain. The output resistance is found from

$$\frac{2}{2 + R_{out}} = 0.97$$

$\Rightarrow R_{out} = 62\ \Omega$

The gain with $R_L = 500\ \Omega$ is

$$A_0 = 250,667 \times \frac{500}{500 + 62}$$

$= 223,013$ V/V

12.61 If the phase margin is 80°, the phase due to the second pole f_{P2} at the unity gain frequency f_t must be 10°. Thus,

$$\tan^{-1} \frac{f_t}{f_{P2}} = 10°$$

Since $f_t = 1$ MHz,

$$f_{P2} = \frac{1 \text{ MHz}}{\tan 10°} = 5.67 \text{ MHz}$$

12.62 The phase introduced at $f_t = 1$ MHz by each of the coincident second and third poles must be 5°. Thus, $f_{P2} = f_{P3}$ can be obtained from

$$\tan^{-1} \frac{f_t}{f_{P2}} = 5°$$

$$\Rightarrow f_{P2} = f_{P3} = \frac{1 \text{ MHz}}{\tan 5°} = 11.4 \text{ MHz}$$

12.63 $f_P = \dfrac{f_t}{A_0} = \dfrac{5 \text{ MHz}}{10^6} = 5$ Hz

But,

$$f_P = \frac{1}{2\pi CR}$$

where

$C = (1 + |A|)C_C$

$= (1 + 1000) \times 50$

$= 50.05$ nF

$$5 = \frac{1}{2\pi \times 50.05 \times 10^{-9} \times R}$$

$\Rightarrow R = 636$ kΩ

12.64

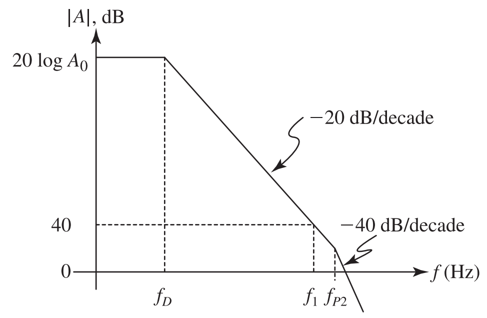

Figure 1

For a phase margin of 85° with a closed loop gain of 100, the phase at f_1 due to the pole at 5 MHz must be at most 5°; thus,

$$\tan^{-1} \frac{f_1}{5 \text{ MHz}} = 5°$$

$\Rightarrow f_1 = 5 \times \tan 5° = 437$ kHz

Thus, the new dominant pole must be at f_D,

$$f_D \times \frac{A_0}{100} = 437$$

$$f_D \times \frac{243,147}{100} = 437$$

$\Rightarrow f_D = 180$ Hz

To find the required value of C_C, we use Eq. (12.116) to determine C_{in}:

$C_{in} = C_C(1 + |A_2|)$

$= C_C \times 516$

Then,

$$f_D = \frac{1}{2\pi C_{in} R_t}$$

where

$R_t = 2.5$ MΩ

$$180 = \frac{1}{2\pi \times 516 C_C \times 2.5 \times 10^6}$$

$\Rightarrow C_C = 0.7$ pF

12.65 DC gain $A_0 = G_{m1}R$

$= 2 \times 10^{-3} \times 2 \times 10^7$

$= 4 \times 10^4$ V/V

$20 \log A_0 = 92$ dB

$$f_P = \frac{1}{2\pi C_C R}$$

$$= \frac{1}{2\pi \times 100 \times 10^{-12} \times 2 \times 10^7}$$

$$= 79.6 \text{ Hz} \simeq 80 \text{ Hz}$$

$$f_t = A_0 f_P = 4 \times 10^4 \times 80$$

$$= 3.2 \text{ MHz}$$

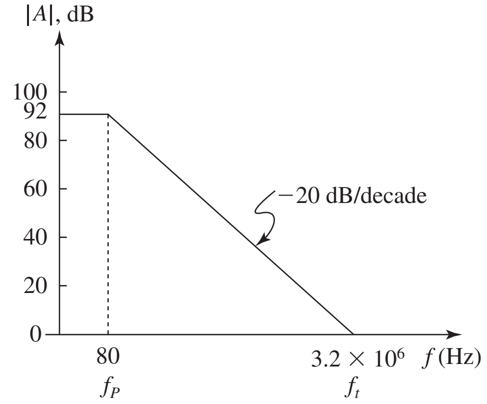

Figure 1

Figure 1 shows a sketch of the Bode plot for the magnitude of the open-loop gain of the op amp.

$$SR = \frac{I}{C_C}$$

But,

$$G_{m1} = \frac{I}{2V_T}$$

Thus,

$$I = 2V_T G_{m1}$$

and

$$SR = 2V_T \frac{G_{m1}}{C_C}$$

$$= 2 \times 25 \times 10^{-3} \times \frac{2 \times 10^{-3}}{100 \times 10^{-12}}$$

$$= 1 \text{ V}/\mu\text{s}$$

12.66 For a sine-wave output, we have

$$v_O = \hat{V}_o \sin \omega t$$

$$\frac{dv_O}{dt} = \omega \hat{V}_o \cos \omega t$$

$$\left.\frac{dv_O}{dt}\right|_{\max} = \omega \hat{V}_o$$

$$10 \times 10^6 = \omega_M \times 10$$

$$\omega_M = 10^6 \text{ rad/s}$$

$$f_M = \frac{10^6}{2\pi} = 159.2 \text{ kHz}$$

If the topology is similar to that of the 741, then we can use Eq. (12.126),

$$SR = 4V_T \omega_t$$

$$\Rightarrow \omega_t = \frac{SR}{4V_T} = \frac{10 \times 10^6}{4 \times 25 \times 10^{-3}}$$

$$= 10^8 \text{ rad/s}$$

$$f_t = \frac{10^8}{2\pi} = 15.9 \text{ MHz}$$

12.67 Including a resistance R_E in the emitter of each of Q_3 and Q_4 cause G_{m1} to become

$$G_{m1} = \frac{2}{4r_e + 2R_E}$$

$$= \frac{1}{2r_e + R_E}$$

where r_e is the emitter resistance of each of $Q_1 - Q_4$,

$$r_e = \frac{V_T}{I}$$

Thus,

$$G_{m1} = \frac{I}{2V_T + IR_E} \quad (1)$$

The slew rate is still given by (12.125),

$$SR = \frac{2I}{C_C} \quad (2)$$

Also, the model in Fig. 12.30 still applies; thus,

$$\omega_t = \frac{G_{m1}}{C_C} \quad (3)$$

Equations (1)–(3) can be combined to obtain

$$SR = \frac{2I}{C_C} = \frac{2G_{m1}(2V_T + IR_E)}{C_C}$$

$$= 2\omega_t(2V_T + IR_E)$$

$$= 4(V_T + IR_E/2)\omega_t \qquad \text{Q.E.D.}$$

Since for the 741

$$SR = 4V_T \omega_t$$

to double SR while keeping ω_t unchanged, we select

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

If we also keep I unchanged, then

$$R_E = \frac{2V_T}{I} = \frac{2 \times 25 \times 10^{-3}}{9.5 \times 10^{-6}}$$

$= 5.26\ \text{k}\Omega$

From Eq. (1), the new value of G_{m1} is

$$G_{m1} = \frac{I}{2V_T + IR_E}$$

$$= \frac{I}{2V_T + 2V_T} = \frac{I}{4V_T}$$

$= 0.095$ mA/V

which is half the original value. From Eq. (3), we see that C_C will have to be one half the original value, thus

$C_C = 15$ pF

This result could have been obtained also from $SR = I/C_C$; doubling SR with I unchanged requires halving C_C. Now, with G_{m1} half the original value, the dc gain also will be half the original value,

$$A_0 = \frac{1}{2} \times 243,147 = 121,573 \text{ V/V}$$

or 101.7 dB

Finally, since

$$f_P = \frac{f_t}{A_0}$$

halving A_0 with f_t unchanged means f_P is doubled,

$f_P = 8.2$ Hz

This is a result of C_C in Eq. (12.116) being is halved and thus f_P in Eq. (12.118) is doubled.

12.68 (a) Refer to Fig. P12.68.

$I_{C1} = I_{C2} = I_{C3} = I_{C4} = 0.05$ mA

$I_{C5} = 1$ mA

$I_{C7} = I_{C6} = I_{C5} = 1$ mA

(b) For Q_1 and Q_2, we have

$$g_m = \frac{0.05 \text{ mA}}{0.025 \text{ V}} = 2 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{2} = 50\ \text{k}\Omega$$

$R_{id} = 2r_\pi = 100\ \text{k}\Omega$

(c) Figure 1 shows the small-signal analysis where

$$i_e = \frac{v_i}{2r_{e1,2}}$$

$$v_o = (\beta + 2)\beta\alpha i_e R_L$$

$$A_v = \frac{v_o}{v_i} = \frac{(\beta + 2)\beta\alpha R_L}{2r_{e1,2}}$$

$$A_v \simeq \frac{1}{2}\beta^2 \frac{R_L}{r_{e1,2}}$$

where

$$r_{e1,2} = \frac{25 \text{ mV}}{0.05 \text{ mA}} = 0.5\ \text{k}\Omega$$

This figure belongs to Problem 12.68, part (c).

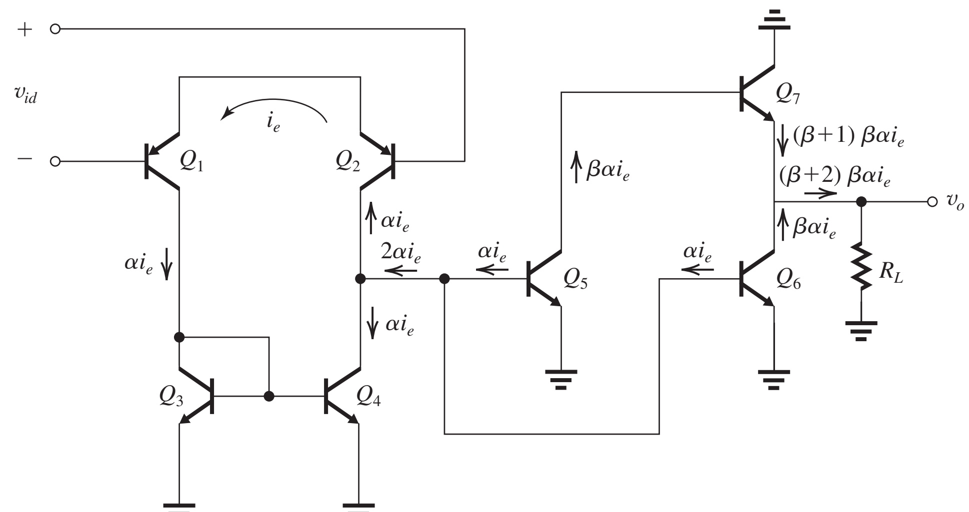

Figure 1

$$A_v = \frac{1}{2}100^2 \times \frac{5}{0.5} = 5 \times 10^4 \text{ V/V}$$

or 94 dB

(d)

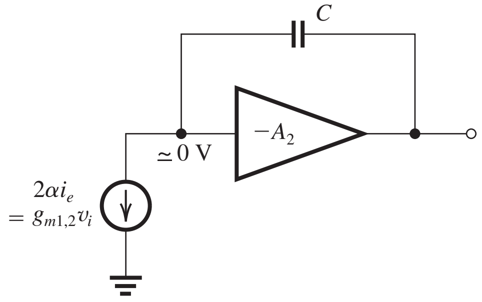

Figure 2

Replacing the second stage with an amplifier having a large negative gain, we obtain the equivalent circuit shown in Fig. 2. From this equivalent circuit we see that the gain is approximately given by

$$A(s) = \frac{g_{m1,2}}{sC}$$

Thus, the unity gain frequency ω_t is given by

$$\omega_t = \frac{g_{m1,2}}{C}$$

and the 3-dB frequency ω_P is

$$\omega_P = \frac{\omega_t}{A_0} = \frac{g_{m1,2}}{A_0 C}$$

$$f_P = \frac{g_{m1,2}}{2\pi A_0 C}$$

For $f_P = 100$ Hz and substituting $g_{m1,2} = 2$ mA/V and $A_0 = 5 \times 10^4$, we find

$$C = \frac{2 \times 10^{-3}}{2\pi \times 100 \times 5 \times 10^4}$$

$$= 63.7 \text{ pF}$$

12.69 $I = 5\ \mu\text{A}$

$$\frac{I_{S2}}{I_{S1}} = 4$$

Using Eq. (12.127), we obtain

$$I = \frac{V_T}{R_2} \ln\left(\frac{I_{S2}}{I_{S1}}\right)$$

$$5 \times 10^{-3} = \frac{0.025}{R_2} \ln 4$$

$$\Rightarrow R_2 = 6.93 \text{ k}\Omega$$

$$R_3 = R_4 = \frac{0.15 \text{ V}}{0.005 \text{ mA}} = 30 \text{ k}\Omega$$

12.70 For $I_5 = 10\ \mu\text{A} = I$, then

$$\frac{Q_5 \text{ emitter area}}{Q_1 \text{ emitter area}} = 1$$

For $I_6 = 40\ \mu\text{A} = 4I$, then

$$\frac{Q_6 \text{ emitter area}}{Q_1 \text{ emitter area}} = 4$$

If we connect a resistance R_6 in the emitter of Q_6, then I_6 changes to a new value determined as follows:

$$V_{BE6} + I_6 R_6 = V_{BE1}$$

$$I_6 R_6 = V_{BE1} - V_{BE6}$$

$$= V_T \ln\frac{I}{I_{S1}} - V_T \ln\frac{I_6}{I_{S6}}$$

But I_6 is to be equal to I, thus

$$IR_6 = V_T \ln\frac{I_{S6}}{I_{S1}}$$

$$R_6 = \frac{V_T}{I} \ln 4$$

$$\Rightarrow R_6 = \frac{0.025}{0.01} \ln 4 = 3.47 \text{ k}\Omega$$

If the V_{BIAS1} line has a low incremental resistance to ground, then

$$R_{o5} = r_{o5} = \frac{V_{An}}{I_5} = \frac{30 \text{ V}}{10\ \mu\text{A}} = 3 \text{ M}\Omega$$

$$R_{o6} = r_{o6} + (R_6 \parallel r_{\pi 6})(1 + g_{m6} r_{o6})$$

where

$$r_{o6} = \frac{30 \text{ V}}{10\ \mu\text{A}} = 3 \text{ M}\Omega$$

$$g_{m6} = \frac{10\ \mu\text{A}}{0.025 \text{ V}} = 0.4 \text{ mA/V}$$

$$r_{\pi 6} = \frac{\beta_N}{g_{m6}} = \frac{40}{0.4} = 100 \text{ k}\Omega$$

$$R_{o6} = 3 + (3.47 \parallel 100) \times 10^{-3}(1 + 1200)$$

$$R_{o6} = 3 + 4 = 7 \text{ M}\Omega$$

Thus, increasing the BEJ area by a factor of 4 and adding a resistance R_6 to restore the current to the desired value of 10 μA increases the output resistance by a factor of about 2.5!

12.71 (a) The bias current I of the differential pair is given by Eq. (12.127),

$$I = \frac{V_T}{R_5} \ln\left(\frac{I_{S5}}{I_{S1}}\right) \qquad (1)$$

The voltage gain of the differential pair is given by

$$A_d = g_m R_C$$

where g_m is the transconduuctance of each of the two transistors in the differential pair,

$$g_m = \frac{I/2}{V_T} = \frac{I}{2V_T}$$

Thus,

$$A_d = \frac{IR_C}{2V_T} \qquad (3)$$

Substituting for I from Eq. (1) into Eq. (3), we obtain

$$A_d = \frac{1}{2}\frac{R_C}{R_5}\ln\left(\frac{I_{S5}}{I_{S2}}\right) \qquad (4)$$

which indicates that A_d will be independent of temperature!

(b) $I = 20\ \mu\text{A}$, $A_d = 10$ V/V, $\dfrac{I_{S5}}{I_{S1}} = 4$

Using Eq. (1), we obtain

$$20 \times 10^{-3} = \frac{0.025}{R_5} \ln 4$$

$$\Rightarrow R_5 = 1.73\ \text{k}\Omega$$

Using Eq. (4), we get

$$10 = \frac{1}{2}\frac{R_C}{1.73} \ln 4$$

$$\Rightarrow R_C = 25\ \text{k}\Omega$$

12.72 (a) Refer to Fig. 12.35(a).

$$V_{ICM\,\text{min}} = V_{C1} - 0.6$$

$$= 0.7 - 0.6 = 0.1\ \text{V}$$

$$V_{ICM\,\text{max}} = V_{CC} - 0.1 - 0.7$$

$$= 3 - 0.8 = 2.2\ \text{V}$$

Thus,

$$0.1\ \text{V} \le V_{ICM} \le 2.2\ \text{V}$$

(b)

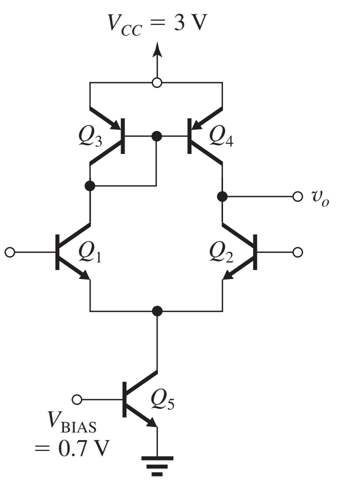

Figure 1

Figure 1 shows the complementary circuit to that in Fig. 12.33(a).

Here,

$$0.8\ \text{V} \le V_{ICM} \le 2.9\ \text{V}$$

12.73 Refer to Fig. 12.35(b).

$$V_{ICM\,\text{max}} = V_{CC} - 0.1 - 0.7 = 3 - 0.8$$

$$= +2.2\ \text{V}$$

$$V_{ICM\,\text{min}} = \frac{1}{2}I_{RC} - 0.6$$

$$= \frac{1}{2} \times 0.02 \times 25 - 0.6$$

$$= -0.35\ \text{V}$$

Thus,

$$-0.35\ \text{V} \le V_{ICM} \le +2.2\ \text{V}$$

$$A_v = g_m R_C$$

where

$$g_m = \frac{I_C}{V_T} = \frac{10 \times 10^{-6}}{25 \times 10^{-3}} = 0.4\ \text{mA/V}$$

$$A_v = 0.4 \times 25 = 10\ \text{V/V}$$

12.74 $g_m = \dfrac{I/2}{V_T} = \dfrac{20\ \mu\text{A}}{25\ \text{mV}} = 0.8$ mA/V

For $A_d = 10$ V/V, we have

$$10 = g_m R_C$$

$$\Rightarrow R_C = 12.5\ \text{k}\Omega$$

$$\frac{I}{2}R_C = 20 \times 10^{-3} \times 12.5 = 0.25 \text{ V}$$

$$V_{ICM\min} = 0.8 \text{ V}$$

$$V_{ICM\max} = V_{CC} - \frac{I}{2}R_C + 0.6$$

$$= 3 - 0.25 + 0.6 = 3.35 \text{ V}$$

Thus,

$$0.8 \text{ V} \leq V_{ICM} \leq 3.35 \text{ V}$$

$$R_{id} = 2r_\pi = 2\frac{\beta_N}{g_m}$$

$$= 2\frac{40}{0.8} = 100 \text{ k}\Omega$$

To increase R_{id} by a factor of 4, g_m and hence I must be reduced by a factor of 4, thus I_{C6} becomes

$$I_{C6} = 10 \text{ µA}$$

To keep the gain and the permissable range of V_{ICM} unchanged, R_C must be increased by a factor of 4, thus R_C becomes

$$R_C = 50 \text{ k}\Omega$$

12.75 Refer to Fig. 12.38, which shows the differential half-circuit of the differential amplifier of Fig. 12.37.

$$R_{id} = 2r_{\pi 1} = 2\frac{\beta_P}{g_{m1}}$$

where

$$g_{m1} = \frac{I_{C1}}{V_T} = \frac{4 \times 10^{-6}}{25 \times 10^{-3}} = 0.16 \text{ mA/V}$$

Thus,

$$R_{id} = \frac{2 \times 10}{0.16} = 125 \text{ k}\Omega$$

The short-circuit transconductance G_{m1} can be found from Fig. 12.38(b):

$$G_{m1} = \frac{i_o}{v_{id}/2}$$

At node X we have four resistances to ground:

$$r_{o1} = \frac{|V_{Ap}|}{I_{C1}} = \frac{20 \text{ V}}{4 \text{ µA}} = 5 \text{ M}\Omega$$

$$R_7 = 22 \text{ k}\Omega$$

$$r_{o7} = \frac{|V_{An}|}{I_{C7}} = \frac{30 \text{ V}}{8 \text{ µA}} = 3.75 \text{ M}\Omega$$

$$r_{e7} \simeq \frac{1}{g_{m7}} = \frac{V_T}{I_{C7}} = \frac{25 \text{ mV}}{8 \text{ µA}} = 3.125 \text{ k}\Omega$$

Obviously, r_{o1} and r_{o7} are much larger than r_{e7} and R_7. Then, the portion of $g_{m1}(v_{id}/2)$ that flows into the emitter proper of Q_7 can be found from

$$i_{e7} \simeq g_{m1}\left(\frac{V_{id}}{2}\right)\frac{R_7}{R_7 + r_{e7}}$$

$$= g_{m1}\left(\frac{V_{id}}{2}\right)\frac{22}{22 + 3.125}$$

$$= 0.876 g_{m1}\left(\frac{V_{id}}{2}\right)$$

Thus,

$$G_{m1} \equiv \frac{i_o}{V_{id}/2} = \frac{\alpha i_{e7}}{V_{id}/2}$$

$$= 0.876 g_{m1} = 0.137 \text{ mA/V}$$

The total resistance between the output node and ground for the circuit in Fig. 12.38(a) is

$$R = R_{o9} \parallel R_{o7} \parallel (R_L/2)$$

The resistances R_{o9} is the output resistance of Q_9, which has an emitter-degeneration resistance R_9. Thus,

$$R_{o9} = r_{o9} + (R_9 \parallel r_{\pi 9})(1 + g_{m9} r_{o9})$$

where

$$r_{o9} = \frac{|V_{Ap}|}{I_{C9}} = \frac{20 \text{ V}}{8 \text{ µA}} = 2.5 \text{ M}\Omega$$

$$g_{m9} = \frac{I_{C9}}{V_T} = \frac{8 \text{ µA}}{25 \text{ mV}} = 0.32 \text{ mA/V}$$

$$r_{\pi 9} = \frac{\beta_P}{g_{m9}} = \frac{10}{0.32} = 31.25 \text{ k}\Omega$$

Thus,

$$R_{o9} = 12.5 + (33 \parallel 31.25)$$

$$\times 10^{-3}(1 + 0.32 \times 2.5 \times 10^3)$$

$$= 15.3 \text{ M}\Omega$$

The resistance R_{o7} is the output resistance of Q_7, which has an emitter-degeneration resistance $(R_7 \parallel r_{o1}) \simeq R_7$. Thus,

$$R_{o7} = r_{o7} + (R_7 \parallel r_{\pi 7})(1 + g_{m7} r_{o7})$$

where

$$r_{o7} = \frac{|V_{An}|}{I_{C7}} = \frac{30 \text{ V}}{8 \text{ µA}} = 3.75 \text{ M}\Omega$$

$$g_{m7} = \frac{I_{C7}}{V_T} = \frac{8 \text{ µA}}{25 \text{ mV}} = 0.32 \text{ mA/V}$$

$$r_{\pi 7} = \frac{\beta_N}{g_{m7}} = \frac{40}{0.32} = 125 \text{ k}\Omega$$

Thus,

$$R_{o7} = 3.75 + (22 \parallel 125) \times 10^{-3}(1 + 0.32 \times 3.75 \times 10^3)$$

$$= 26.2 \text{ M}\Omega$$

$$\frac{R_L}{2} = \frac{1.5}{2} = 0.75 \text{ M}\Omega$$

The load resistance R can now be found as

$$R = 15.3 \parallel 26.2 \parallel 0.75 = 0.696 \text{ M}\Omega$$

Finally, we can find the voltage gain as

$$A_v = \frac{v_{od}/2}{v_{id}/2} = G_{m1}R$$

$$= 0.137 \times 0.696 \times 10^3 = 95.4 \text{ V/V}$$

12.76 $I_{C1} = I$

$$I_{C7} = I_{C9} = 2I$$

From Fig. 12.37 we see that the current through R_7 is approximately $(I_{C1} + I_{C7})$, that is, $3I$. Thus,

$$R_7 = \frac{0.2}{3I}$$

Since Q_3 and Q_4 are cut off, the current through R_9 is equal to I_{E9} or approximately I_{C9}, thus

$$R_9 = \frac{0.3}{2I}$$

To determine the short-circuit transconductance G_{m1}, refer to Fig. 12.38(b).

$$g_{m1} = \frac{I_{C1}}{V_T} = \frac{I}{V_T}$$

$$G_{m1} = \frac{i_o}{v_{id}/2}$$

At node X we have four resistances in parallel, namely, r_{o1}, R_7, r_{o7}, and r_{e7}:

$$r_{o1} = \frac{|V_{Ap}|}{I_{C1}} = \frac{20}{I}$$

$$R_7 = \frac{0.2}{3I} = \frac{0.067}{I}$$

$$r_{o7} = \frac{V_{An}}{I_{C7}} = \frac{30}{2I} = \frac{15}{I}$$

$$r_{e7} \simeq \frac{V_T}{I_{C7}} = \frac{0.025}{2I} = \frac{0.0125}{I}$$

Thus, r_{o1} and r_{o7} are much greater than r_{e7} and R_7, and the portion of $g_{m1}\left(\frac{v_{id}}{2}\right)$ that flows into the emitter proper of Q_7 is given by

$$i_{e7} \simeq g_{m1}\left(\frac{v_{id}}{2}\right)\frac{R_7}{R_7 + r_{e7}}$$

$$= \left(\frac{I}{V_T}\right)\left(\frac{v_{id}}{2}\right)\frac{0.067}{0.067 + 0.0125}$$

$$= 0.84\left(\frac{I}{V_T}\right)\left(\frac{v_{id}}{2}\right)$$

The output short-circuit current i_o will be

$$i_o \simeq i_{e7} = 0.84\left(\frac{I}{V_T}\right)\left(\frac{v_{id}}{2}\right)$$

Thus,

$$G_{m1} = 0.84\frac{I}{V_T} \simeq 33.6I$$

To obtain the output resistance R,

$$R = R_{o9} \parallel R_{o7}$$

we determine R_{o9} as follows:

$$R_{o9} = r_{o9} + (R_9 \parallel r_{\pi 9})(1 + g_{m9}r_{o9})$$

where

$$r_{o9} = \frac{|V_{Ap}|}{I_{C9}} = \frac{20}{2I} = \frac{10}{I}$$

$$g_{m9} = \frac{I_{C9}}{V_T} = \frac{2I}{0.025} = 80I$$

$$g_{m9}r_{o9} = 800$$

$$r_{\pi 9} = \frac{\beta_P}{g_{m9}} = \frac{10}{80I} = \frac{0.125}{I}$$

Thus,

$$R_{o9} = \frac{10}{I} + \left(\frac{0.15}{I} \parallel \frac{0.125}{I}\right) \times 801$$

$$= \frac{64.6}{I}$$

We next determine R_{o7} as follows:

$$R_{o7} = r_{o7} + (R_7 \parallel r_{\pi 7})(1 + g_{m7}r_{o7})$$

where

$$r_{o7} = \frac{15}{I}$$

$$R_7 = \frac{0.067}{I}$$

$$g_{m7} = \frac{I_{C7}}{V_T} = \frac{2I}{V_T}$$

$$g_{m7}r_{o7} = 1200$$

$$r_{\pi 7} = \frac{\beta_N}{g_{m7}} = \frac{40}{2I/V_T} = \frac{0.5}{I}$$

Thus,

$$R_{o7} = \frac{15}{I} + \left(\frac{0.067}{I} \parallel \frac{0.5}{I}\right) \times 1201$$

$$= \frac{86}{I}$$

We now can determine the output resistance R as

$$R = R_{o9} \parallel R_{o7} = \frac{64.6}{I} \parallel \frac{86}{I} = \frac{36.9}{I}$$

The open-circuit voltage gain can be obtained as

$$A_{vo} = G_{m1}R$$

$$= 0.84\left(\frac{I}{V_T}\right)\left(\frac{36.9}{I}\right)$$

$$= 1240 \text{ V/V}$$

With a load resistance R_L, we have

$$A_v = A_{vo}\frac{R_L}{R_L + R}$$

$$= 1240\frac{R_L}{R_L + \dfrac{36.9}{I}}$$

$$= 1240\frac{IR_L}{IR_L + 36.9}$$

For $R_L = 1\text{ M}\Omega$ and I in μA, we have

$$A_v = 1240\frac{I}{I + 36.9}$$

From this equation we can obtain

$$I = \frac{36.9}{\dfrac{1240}{A_v} - 1}$$

Thus, for $A_v = 150$ V/V, the required value of I is

$$I = \frac{36.9}{\dfrac{1240}{150} - 1} = 5.1\ \mu\text{A}$$

and for $A_v = 300$ V/V, we require

$$I = \frac{36.9}{\dfrac{1240}{300} - 1} = 11.8\ \mu\text{A}$$

12.77 (a) Refer to Fig. 12.39. Break the loop at the input of the CMF circuit and apply a common-mode input signal $\triangle V_{CM}$. The CMF circuit will respond by causing a change $\triangle V_B$ in its output voltage that can be found from its transfer characteristic as

$$\triangle V_B = \triangle V_{CM}$$

Now, a change $\triangle V_B$ in the base voltage of Q_7 and Q_8 results in

$$\triangle I_{E8} = \triangle I_{E7} = \frac{\triangle V_B}{r_{e7} + R_7}$$

The corresponding change in the collector voltages of Q_7 and Q_8 will be

$$\triangle v_{O2} = \triangle v_{O1} = -\triangle I_{C7}R_o$$

Now,

$$\triangle I_{C7} \simeq \triangle I_{E7}$$

and

$$R_o = R_{o7} \parallel R_{o9}$$

thus

$$\triangle v_{O1} = -\frac{\triangle V_B}{r_{e7} + R_7}(R_{o7} \parallel R_{o9})$$

This is the returned voltage, thus

$$A\beta \equiv -\frac{\triangle v_{O1}}{\triangle V_{CM}}$$

$$= \frac{R_{o7} \parallel R_{o9}}{r_{e7} + R_7} \qquad \text{Q.E.D.} \qquad (1)$$

(b) From Example 12.8, we have

$$R_{o7} = 23\text{ M}\Omega,\ R_{o9} = 12.9\text{ M}\Omega,$$

$$r_{e7} \simeq \frac{V_T}{I_{C7}} = \frac{25\text{ mV}}{10\mu\text{A}} = 2.5\text{ k}\Omega,$$

$$R_7 = 20\text{ k}\Omega$$

thus

$$A\beta = \frac{(23 \parallel 12.9) \times 10^3}{2.5 + 20}$$

$$= 367.3$$

For a change $\triangle I = 0.3\ \mu$A, the corresponding change in V_{CM} without feedback is

$$\triangle V_{CM} = \triangle I(R_{o7} \parallel R_{o9})$$

The negative feedback reduces this change by the amount of negative feedback $1 + A\beta \simeq A\beta$, thus the actual $\triangle V_{CM}$ becomes

$$\triangle V_{CM} \simeq \frac{\triangle I(R_{o7} \parallel R_{o9})}{A\beta}$$

Substituting for $A\beta$ from Eq. (1), we obtain

$$\triangle V_{CM} = \triangle I(r_{e7} + R_7)$$

$$= 0.3 \times 10^{-6}(2.5 + 20)$$

$$= 6.75\text{ mV}$$

which is identical to the value found in Example 12.8.

12.78 (a) v_O can range to within 0.1 V (the saturation voltage) of ground and V_{CC}, thus

$0.1 \text{ V} \le v_O \le 2.9 \text{ V}$

(b) For $i_L = 0$, the output resistance is

$R_o = r_{oN} \parallel r_{oP}$

where

$$r_{oN} = \frac{V_{An}}{I_Q} = \frac{30 \text{ V}}{0.6 \text{ mA}} = 50 \text{ k}\Omega$$

$$r_{oP} = \frac{|V_{Ap}|}{I_Q} = \frac{20 \text{ V}}{0.6 \text{ mA}} = 33.3 \text{ k}\Omega$$

Thus,

$R_o = 50 \parallel 33.3 = 20 \text{ k}\Omega$

(c) $R_{\text{out}} = R_{of} = \dfrac{R_o}{1 + A\beta}$

$$= \frac{20 \text{ k}\Omega}{1 + 10^5} \simeq 0.2 \text{ }\Omega$$

(d) For $i_L = 12$ mA, we have

$$i_N = \frac{I_Q}{2} = 0.3 \text{ mA}$$

$i_P = 12 + 0.3 = 12.3$ mA

$$r_{oN} = \frac{30 \text{ V}}{0.3 \text{ mA}} = 100 \text{ k}\Omega$$

$$r_{oP} = \frac{20 \text{ V}}{12.3} = 1.63 \text{ k}\Omega$$

$R_o = 100 \parallel 1.63 = 1.6 \text{ k}\Omega$

(e) For $i_L = -12$ mA, we have

$i_P = 0.3$ mA

$i_N = 12.3$ mA

$$r_{oN} = \frac{30 \text{ V}}{12.3 \text{ mA}} = 2.44 \text{ k}\Omega$$

$$r_{oP} = \frac{20 \text{ V}}{0.3 \text{ mA}} = 66.7 \text{ k}\Omega$$

$R_o = 2.44 \parallel 66.7 = 2.4 \text{ k}\Omega$

12.79 Refer to Fig. 12.43.

$$v_{B7} = v_{BEN} = V_T \ln\left(\frac{i_N}{I_{SN}}\right) \qquad (1)$$

$$i_4 = \frac{v_{EBP} - v_{EB4}}{R_4} \qquad (2)$$

$v_{B6} = v_{BE5} + i_5 R_5$

But,

$i_5 = i_4$ and $R_5 = R_4$

thus

$v_{B6} = v_{BE5} + i_4 R_4$

Using Eq. (2), we obtain

$v_{B6} = v_{BE5} + v_{EBP} - v_{EB4}$

$= (v_{BE5} - v_{EB4}) + v_{EBP}$

$$= V_T \ln\left(\frac{I_{S4}}{I_{S5}}\right) + V_T \ln\left(\frac{i_P}{I_{SP}}\right)$$

$$= V_T \ln\left(\frac{I_{S4}\, i_P}{I_{S5}\, I_{SP}}\right) \qquad (3)$$

Now, using the given relationship

$$\frac{I_{SP}}{I_{S4}} = \frac{I_{SN}}{I_{S5}}$$

in Eq. (3), we get

$$v_{B6} = V_T \ln\left(\frac{i_P}{I_{SN}}\right) \qquad (4)$$

Using Eqs. (1) and (4), we obtain

$$v_{B6} - v_{B7} = V_T \ln\left(\frac{i_P}{i_N}\right)$$

This is the differential voltage input for the differential amplifier $Q_6 - Q_7$. Thus,

$$i_{C6} = \frac{I}{1 + e^{(v_{B6} - v_{B7})/V_T}}$$

$$= \frac{I}{1 + \dfrac{i_P}{i_N}}$$

$$= \frac{i_N}{i_P + i_N} I \qquad \text{Q.E.D.}$$

Similarly,

$$i_{C7} = \frac{I}{1 + e^{(v_{B7} - v_{B6})/V_T}}$$

$$= \frac{I}{1 + \dfrac{i_N}{i_P}}$$

$$= \frac{i_P}{i_P + i_N} I \qquad \text{Q.E.D.}$$

12.80 $v_E = v_{EB7} + v_{BEN}$

Since Q_7 conducts a current i_{C7} given by Eq. (12.131),

$$i_{C7} = I \frac{i_P}{i_P + i_N}$$

and Q_N conducts a current i_N, then

$$v_E = V_T \ln\left(\frac{I\ i_P}{i_P + i_N}\ \frac{1}{I_{S7}}\right) + V_T \ln\left(\frac{i_N}{I_{SN}}\right)$$

$$= V_T \ln\left[\frac{i_P\ i_N}{i_P + i_N}\ \frac{I}{I_{SN}\ I_{S7}}\right] \qquad \text{Q.E.D.}$$

12.81 $I_Q = 0.6 \text{ mA} = 600\ \mu\text{A}$

$I = 12\ \mu\text{A}$

$$\frac{I_{SN}}{I_{S10}} = 8$$

$$\frac{I_{S7}}{I_{S11}} = 4$$

Using Eq. (12.136), we have

$$600 = 2\left(\frac{I_{\text{REF}}^2}{12}\right) \times 8 \times 4$$

$\Rightarrow I_{\text{REF}} = 10.6\ \mu\text{A}$

The minimum current in each transistor is about 0.3 mA.