CH. 2 – PROBLEM SOLUTIONS   (UPDATED DECEMBER 16, 2013)

2.1 Two conditions are necessary for successful BJT operation: (a) the emitter must be doped much more heavily than the base; (b) the emitter and collector must be separated by a thin contiguous base.

In the case of two discrete diodes, it is not known a priori whether (a) is met; (b) is certainly not met, as the two anodes are not contiguous; the holes injected from the emitter-acting anode would rather recombine with the electrons supplied by the "base" wire, than progress towards the collector-acting anode.

In the case of two half-BJTs, condition (a) is met, but condition (b) still isn't, as the two base regions, though thin, are not contiguous, but separated by interconnecting wires. The electrons supplied by those wires will recombine with the holes injected by the emitter, resulting in virtually zero collector current. Thus, $\beta_F \cong 0 / I_B = 0$.

2.2

(a) $I_s = 10 \times 20 \times 10^{-8} \dfrac{1}{10^{-4}} \; 2 \times 10^{20} \; \dfrac{1.6 \times 10^{-19} \times 18}{10^{17}} = 0.115 \, fA.$

$\beta_F = \cfrac{1}{\dfrac{1.8}{18} \dfrac{10^{17}}{10^{19}} \dfrac{1}{1} + \dfrac{(10^{-4})^2}{2 \times 150 \times 10^{-9} \times 18}} = \cfrac{1}{\dfrac{1}{1000} + \dfrac{1}{540}} = 351$

(b) $I_C = 0.115 \times 10^{-15} \times \exp(700/26) = 56.8 \, \mu A$

$I_B = I_C / \beta_F = 56.8 / 351 = 162 \, nA.$

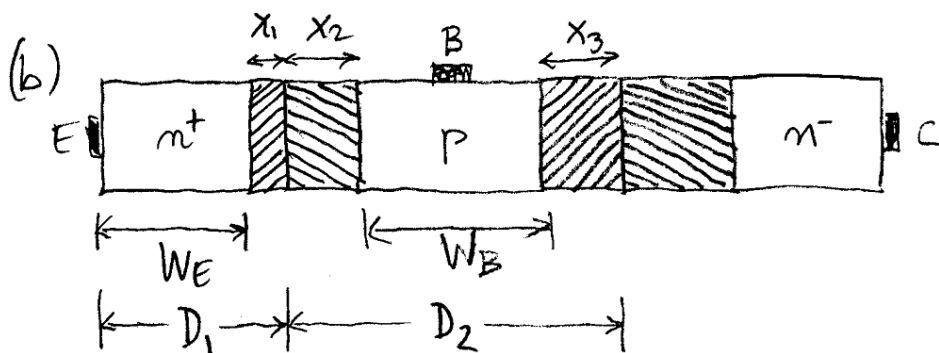(c) $I_{BE} = 56.8/1000 = 57 \, nA \; ; \; I_{BB} = 56.8/540 = 105 \, nA.$

2.3

(a) $\beta_F = 250 \Rightarrow 1/(1/x + 1/y) = 250$; $i_{BE} = i_{BB} \Rightarrow$

$x = y$; $1/(1/x + 1/x) = 250 \Rightarrow x = 500$

$$\frac{1}{500} = \frac{W_B^2}{2\tau_n D_n} = \frac{W_B^2}{2 \times 150 \times 10^{-9} \times 18} \Rightarrow W_B = 1.039 \mu m$$

$$\frac{1}{500} = \frac{D_p N_{AB} W_B}{D_n N_{DE} W_E} = \frac{1.8 \times 10^{17} \times 1.039 \, 10^{-4}}{18 \times 10^{19} \times W_E} \Rightarrow W_E = 0.520 \mu m.$$

(b)

$$\phi_e = 26 \ln \frac{10^{17} \times 10^{19}}{2 \times 10^{20}} = 940 \, mV; \quad \phi_c = 700 mV$$

$$x_{20} = \sqrt{\frac{2\varepsilon_{si}\phi_e}{q N_{AB}} \frac{N_{DE}}{N_{AB} + N_{DE}}} = \sqrt{\frac{2 \times 10^{-12} \times 0.94}{1.6 \times 10^{-19} \times 10^{17}} \frac{10^{19}}{10^{17} + 10^{19}}} = 108 nm$$

$$x_{10} = \frac{N_{AB}}{N_{DE}} x_{20} = \frac{108}{100} \cong 1.1 nm$$

$$x_{30} = \sqrt{\frac{2 \times 10^{-12} \times 0.7}{1.6 \times 10^{-19} \times 10^{17}} \frac{10^{15}}{10^{17} + 10^{15}}} = 9.4 nm$$

$$D_1 = W_E + x_1 = 520 nm + (1.1 nm)\sqrt{1 - \frac{0.7}{0.94}} \cong 520 nm.$$

$$D_2 = W_B + x_2 + x_3 = 1.039 nm + (108 nm)\sqrt{1 - \frac{0.7}{0.94}} +$$

$$+ (9.4 nm)\sqrt{1 - \frac{-2}{0.7}} \cong 1.039 + 55 + 18 = 1.112 nm.$$

2.4

(a) $I_s = (25 \times 10^{-4})(50 \times 10^{-4}) \frac{1}{10^{-4}} \times 2 \times 10^{20} \frac{1.6 \times 10^{-19}}{10^{17}} 8 = 0.32 \, fA.$

$$\beta_F = \cfrac{1}{\frac{3}{8} \frac{10^{17}}{10^{19}} \frac{1}{1} + \frac{(10^{-4})^2}{2 \times 100 \times 10^{-9} \times 8}} = \cfrac{1}{\frac{1}{267} + \frac{1}{160}} = 100$$

(b) $I_s = \frac{K_1}{W_B} \Rightarrow I_s$ doubles to $0.64 \, fA.$

$$\beta_F = \cfrac{1}{K_2 W_B + K_3 W_B^2} \Rightarrow \beta_F = \cfrac{1}{\frac{0.5}{267} + \frac{0.5^2}{160}} = \cfrac{1}{\frac{1}{533} + \frac{1}{640}} = 291.$$

(c) $I_s = 0.32 \, fA$ (unchanged).

$$\beta_F = \cfrac{1}{K_3/W_E + 1/160} = \cfrac{1}{\frac{1}{267 \times 2} + \frac{1}{160}} = 123.$$

W_B affects both I_s and β_F, and halving it will double I_s and increase β_F by more than a factor of 2. W_E affects only β_F, and doubling it will halve the B-E diffusion component of I_B, thus increasing β_F.

2.5

(a) $I_E \cong \frac{4 - 0.7}{3.3} = 1 \, mA$; $V_{EB} = 0.026 \ln \frac{10^{-3}}{4 \times 10^{-15}} = 0.682 V;$

$I_E = \frac{4 - 0.682}{3.3} = 1.005 \, mA$
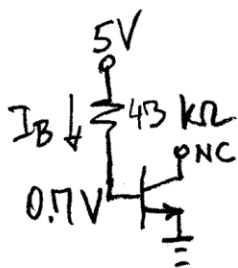
$\beta_F = \frac{1}{0.002 + 0.004} = 167 \Rightarrow I_B = \frac{1.005}{167 + 1} \cong 6 \, \mu A$

$I_C = I_E - I_B = 1.005 - 0.006 = 0.999 \, mA.$

(b) $I_{EB} = 0.002 \times 0.999 \cong 2 \, \mu A$; $I_{BB} \cong 4 \, \mu A.$

(c) $I_C = 0$; $I_B = I_E \cong 1 \, mA.$

2.6

$I_B = \frac{5-0.7}{43} = 100\,\mu A = I_E . \quad I_C = 0$

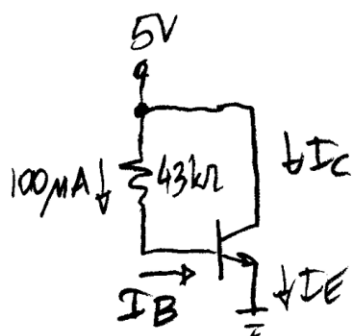About $1\,\mu A$ of holes diffusing from B to E, and $99\,\mu A$ of electrons diffusing from E to B.
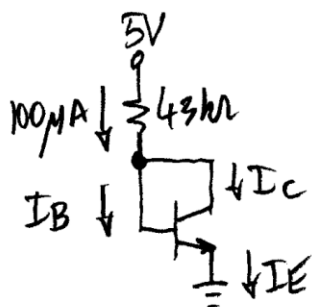
$I_E = 100\,\mu A$ ($\sim 1\,\mu A$ holes from B to E, and $\sim 99\,\mu A$ electrons from E to C).

$I_C + I_B = 100\,I_B + I_B = 100\,\mu A$

$\Rightarrow I_B \cong 1\,\mu A$ (holes from B to E plus holes recombining with el.ons within B).

$I_C \cong 99\,\mu A$ (electrons from E to B to C).

$I_B = 100\,\mu A$ (holes from B to E plus holes recombining with el.ns within B).

$I_C = \beta_F I_B = 100 \times 0.1 = 10\,mA$ (electrons from E to B). $I_E = I_B + I_C = 10.1\,mA$ (mostly electrons from E to C).

2.7

$V_B = -5 - 0.8 = -5.8\,V;\quad I_E = I_L = 500\,\mu A;$

$I_B = I_E / (\beta_F + 1) = 500/81 = 6.17\,mA;\quad I_C = I_E - I_B \cong 494\,mA.$

2.8

(a) $i_{O1} = \frac{1}{100} = 10\,\text{mA}$; $i_{O2} = 0$; $v_I = v_O + v_{BE1} =$
$1 + 0.026\,\ell n\left[(10 \times 10^{-3})/(10 \times 10^{-15})\right] = 1.72\,\text{V}$; $i_I = 10/151 = 66.2\,\mu\text{A}$.

(b) $i_{O1} = 0$; $i_{O2} = 10\,\text{mA}$; $v_I = v_O - v_{EB2} = -1 - 0.026 \times$
$\ell n\left[(10 \times 10^{-3})/(20 \times 10^{-15})\right] = -1.70\,\text{V}$; $i_{I2} = 10/101 \cong 9.9\,\mu\text{A}$.

(c) $i_{O1} = 50\,\text{mA}$; $i_{I1} = 0.33\,\text{mA}$; $v_I - 5 + 0.76 = 5.76\,\text{V}$

(d) $i_{O2} = 80\,\text{mA}$; $i_{I2} = 0.792\,\text{mA}$; $v_I = -8 - 0.75 = -8.75\,\text{V}$.

2.9

(a) $i_{C2} \cong i_{E2} = v_O/R_L = 1/8 = 125\,\text{mA}$; $i_I = \frac{125}{101 \times 51}$
$\cong 24\,\mu\text{A}$; $i_{C1} = 100 \times 24 = 2.43\,\text{mA}$.
$v_I = 1 + 0.026\left[\ell n\,\frac{2.43 \times 10^{-3}}{10 \times 10^{-15}} + \ell n\,\frac{125 \times 10^{-3}}{10^{-12}}\right] = 1 + 1.346 = 2.346\,\text{V}$.

(b) $i_{C2} \cong \frac{4}{8} = 500\,\text{mA}$ $(= 2 \times 2 \times 125\,\text{mA})$; $i_I \cong 97\,\mu\text{A}$;
$v_I = 4 + 1.346 + 2(18 + 18) \times 10^{-3} = 5.418\,\text{V}$

(c) $i_{C2} = 2\text{A}$ $(= 16 \times 125\,\text{mA})$; $i_I \cong 0.388\,\text{mA}$.
$v_I = 16 + 1.346 + 2(18 + 18 + 18 + 18) \times 10^{-3} = 17.490\,\text{V}$.

2.10   (a) $i_{C2} \cong i_{E2} = 1/4 = 250 \, mA$; $i_I = \frac{250}{101 \times 41} \cong 60.4 \, \mu A$;

$i_{C1} = 100 \times 60.4 = 6.04 \, mA$.

$v_I = -1 - 0.026 \left[\ln \frac{6.04 \times 10^{-3}}{5 \times 10^{-15}} + 1.5 \ln \frac{250 \times 10^{-3}}{100 \times 10^{-12}} \right] =$

$= -1 - (0.723 + 0.844) = -2.567 \, V.$

(b) $i_{C2} \cong i_{E2} = 5/4 = 1.25 \, A \, (= 250 \times 10/2 \, mA)$;

$i_I = 60.4 \times 10/2 = 302 \, \mu A$;

$v_I = -1V - \left[(723 + 60 - 18) mV + (844 + 1.5 \times 60 - 1.5 \times 18) \right] mV$

$= -1 - (0.765 + 0.907) = -2.672 \, V.$

2.11   (a) $1 \times 10^{-3} = 10^{-5} e^{V_{BE}/26mV} \left(1 + \frac{5}{75} \right) \Rightarrow V_{BE} \cong 717 \, mV.$

(b) $I_C = (1.0 \, mA) \times \left[(1 + 12/75)/(1 + 5/75) \right] = 1.0875 \, mA$

$I_C = (1.0 \, mA) \times \left[(1 + 1/75)/(1 + 5/75) \right] = 0.95 \, mA.$

(c) $\Delta T = -25 °C \Rightarrow \Delta V_{BE} = -2(-25) = +50 \, mV \Rightarrow$

$V_{BE} = 717 + 50 = 767 \, mV.$

$I_C = 0.2 \, mA = (1 \, mA) \times (2/10) \Rightarrow \Delta V_{BE} = +18 - 60 = -42 \, mV$;

$\Delta T = 50 - 25 = +25 \, mV \Rightarrow \Delta V_{BE} = -2(25) = -50 \, mV$;

$\Delta V_{(net)} = -42 - 50 = -92 \, mV$; $V_{BE} = 717 - 92 = 625 \, mV.$

$\Delta V_{(net)} = 18 + 18 - 2(40 - 25) = 6 \, mV$; $V_{BE} = 723 \, mV.$

2.12

(a) $500 \times 10^{-6} = 2 \times 10^{-15} e^{V_{EB}/26}\left(1 + \frac{4}{60}\right) \Rightarrow V_{EB} \cong 680\,mV.$

(b) $I_C = (500\,\mu A) \times \left[(1 + 1/50)/(1 + \frac{4}{50})\right] \cong 472\,\mu A.$

$I_C = (500\,\mu A)\left[(1 + 8/50)/(1 + 4/50)\right] = 537\,\mu A.$

(c) $200\,\mu A = 500\,\mu A \times 2/10 \Rightarrow \Delta V_{EB} = +18 - 60 = -42\,mV;$
$\Delta T = 75 - 25 = 50\,°C; \ \Delta V_{EB} = (-2\,mV)50 = -100\,mV; \ \Delta V_{EB}\,(tot)$
$= -42 - 100 = -142\,mV; \ V_{EB} = 680 - 142 = 538\,mV.$

(d) $\Delta T = 55 - 25 = 30\,°C.$ If we were to keep I_C constant at $500\,\mu A$, we'd have to decrease V_{EB} by $30 \times 2 = 60$ mV, n lower it to $680 - 60 = 620\,mV.$ We are instead keeping it constant at a value 60 mV higher, indicating a 10-fold increase in I_C, so $I_C = 10 \times 500 = 5\,mA.$

2.13 (a) $I_B = \dfrac{5-0.7}{300} = 14.\overline{3}\,\mu A$; $I_C = \beta_F I_B = 120 \times 14.\overline{3}$

$= 1.720\,mA$; $V_C = V_S - R_2 I_C = 5 - 2 \times 1.720 = 1.56\,V$.

(b) Shorting out R_2 changes V_{CE} from $1.56\,V$ to $5\,V$.

Since $I_C = k(1 + V_{CE}/V_A)$, we have

$1.720 = k(1 + 1.56/100)$, $I_C = k(1 + 5/100)$

$I_C/1.720 = (1 + 5/100)/(1 + 1.56/100) \Rightarrow I_C = 1.778\,mA$.

(c) $I_B = \dfrac{5-0.7}{30} = 0.14\overline{3}\,mA$; $I'_C = \beta_R I_B = 2 \times 0.143 =$

$0.28\overline{6}\,V$; $V_E = 5 - 10 \times 0.28\overline{6} = 2.1\overline{3}\,V$.

2.14 (a) $I_C = \dfrac{5-1}{2} = 2\,mA$; $I_B = \dfrac{5-0.71}{300} = 14.3\,\mu A$

$\Rightarrow \beta_F = 2/0.0143 \cong 140$.

$I_S = I_C/e^{V_{BE}/V_T} = 2 \times 10^{-3}/\exp(700/26) = 2.76\,fA$.

(b) $V_{CE1} = 1\,V$, $I_{C1} = 2\,mA$; $V_{CE2} = 2.950\,V$, $I_{C2} = (5-2.950)/1 = 2.05\,mA$

$2.05/2 = (1 + 2.950/V_A)/(1 + 1.0/V_A) \Rightarrow V_A = 77\,V$.

(c) $I'_C = (5-2)/10 = 0.3\,mA$; $I_B \cong (5-0.7)/30 = 0.14\overline{3}\,mA$;

$\beta_R = 0.3/0.14\overline{3} \cong 2$.

2.15

(a) $I_B = \frac{6-0.69}{470} = 11.3\,\mu A$; $I_C = \frac{6-1}{3} = \frac{5}{3}\,mA$;

$\beta_F = (5/3)/0.0113 = 147.5$. $(5/3) \times 10^{-3} = I_s e^{690/26} \Rightarrow$

$I_s \cong 5\,fA$. (b) $V_A/I_C = \Delta V_C/\Delta I_C \Rightarrow V_A = \frac{5-0}{0.1 \times 5/3}\,\frac{5}{3} = 50\,V$.

(c) $I'_C = 3.5/10 = 0.35\,mA$; $I_B \cong \frac{6-0.7}{20}\,0.265$; $\beta_R =$

$0.35/0.265 = 1.3$.

2.16

(a) $V_{BC} = 0 \Rightarrow I_C = (10.7-0.7)/10 = 1.000\,mA$;

$\beta_F = 1000/8 = 125$.

(b) $V_{BC} = -10\,V \Rightarrow x_p = 20nm\sqrt{1 - \frac{-10}{0.8}} = 73.5\,\mu m$.

$W_B = 500 - 73.5 = 426.5\,nm$. $I_C = 1mA\frac{500}{426.5} = 1.172\,mA$

(c) $r_o = \frac{\Delta V_C}{\Delta I_C} = \frac{10}{0.172} = 58\,k\Omega = \frac{V_A}{I_C} \Rightarrow V_A \cong 60\,V$.

2.17
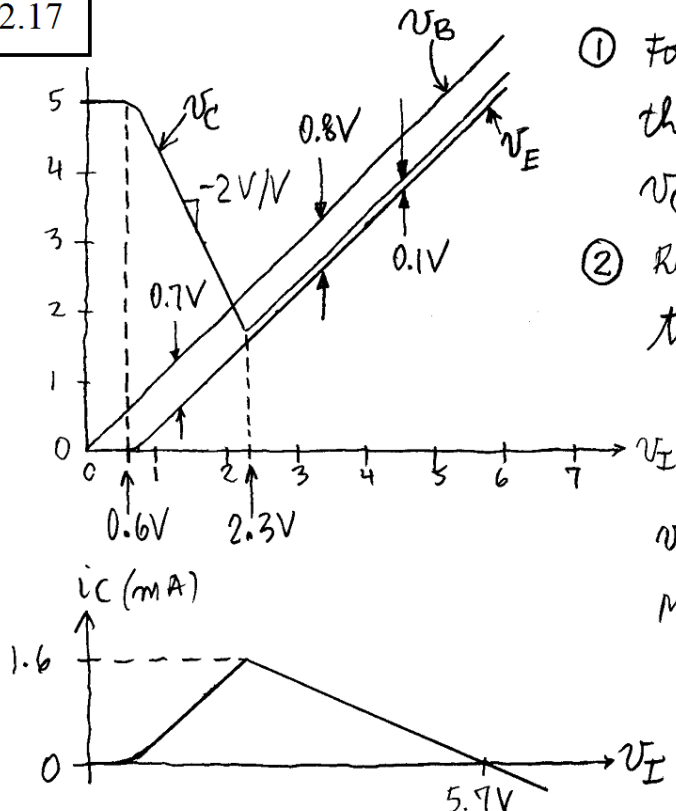
① For $v_I < V_{BE(EOC)} = 0.6V$, the BJT is in cutoff; $v_C = V_S = 5V$, $i_C = 0$.

② Raising v_I above 0.6V turns the BJT on. Initially, it is in FA, where

$v_E = v_B - V_{BE(on)} = v_I - 0.7V$.

Moreover, $v_C = V_S - R_C i_C$

$\cong V_S - R_C i_E = V_S - R_C \times \dfrac{v_I - V_{BE(on)}}{R_E}$, or

$v_C = V_S + \dfrac{R_C}{R_E} V_{BE(on)} - \dfrac{R_C}{R_E} v_I$. Clearly, the plot of v_C v.s. v_I has a slope of $-R_C/R_E = -2\ V/V$.

③ The BJT reaches the EOS when $\dfrac{v_E}{1} \cong \dfrac{5 - (v_E + 0.2)}{2}$, or $v_E = 1.6V$. At this point, $v_C = v_E + 0.2 = 1.8V$, and $v_B = 1.6 + 0.7 = 2.3V = v_I$. Also, $i_C = (5 - 1.8)/2 = 1.6\ mA$

④ As we keep increasing v_I, the BJ saturates, and $v_E = v_I - 0.8V$, $v_C = v_E + 0.1 = v_I - 0.7V$, and $i_C = (5 - v_C)/2 = [5 - (v_I - 0.7)]/2 = (5.7 - v_I)/2$. Clearly, i_C now decreases with v_I.

⑤ As v_I reaches 5.7V, i_C drops to zero. For $v_I > 5.7V$, i_C becomes negative. The B-C junction is forward biased, and i_C flows out of the collector!

2.18
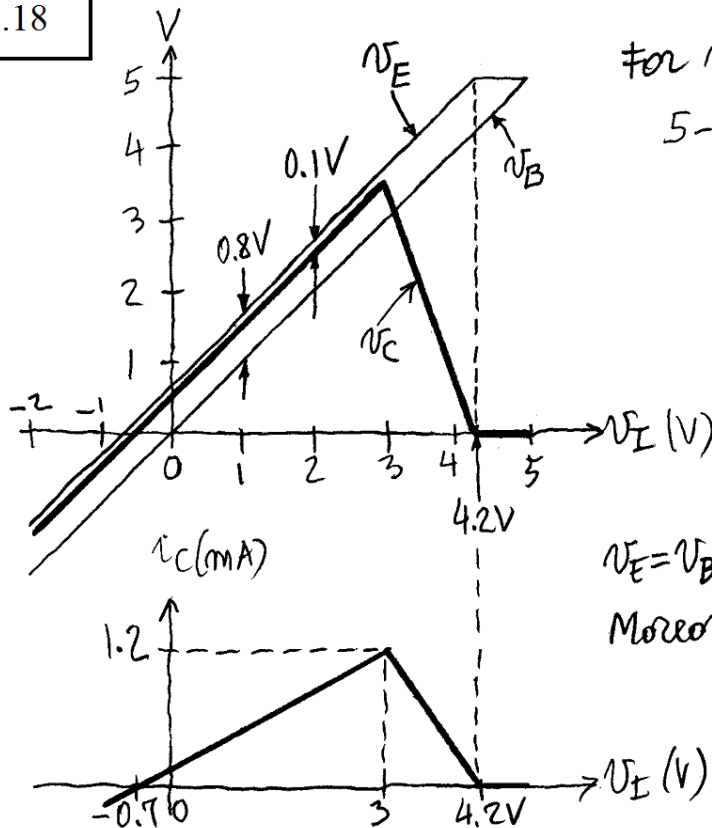
for $v_I > V_S - V_{EB(EOC)} = 5 - 0.8 = 4.2V$, BJT = CO

$\Rightarrow v_C = 0$, $i_C = 0$.

Lowering v_I below 4.2V turns BJT on, initially FA, where we have

$v_E = v_B + V_{EB(on)} = v_I + 0.8V$.

Moreover, $v_C = R_C i_C \cong R_C i_E$

$= R_C \dfrac{V_S - v_E}{R_E}$

$= \dfrac{3}{1}(5 - v_I - 0.8)$

or $v_C = 3(4.2 - v_I)$. Clearly, as v_I is lowered below 4.2V, v_C increases at the rate of +3 V/V, and i_C increases at the rate of $(3V)/(3k\Omega) = 1 mA/V$. Once v_C comes within 0.1 V of v_E, the BJT reaches the EOS. Imposing $v_C = v_E - 0.1$, or $3(4.2 - v_I) = (v_I + 0.8) - 0.1$, we find that the BJT reaches the EOS for $v_I = 2.975 \approx 3V$. At this point, $i_C = \dfrac{v_C}{3} \cong \dfrac{3}{3}(4.2 - 3) = 1.2 mA$. Lowering v_I below 3V drives the BJT more and more into saturation, and $v_C = v_E - 0.1 = v_I + 0.8 - 0.1 = v_I + 0.7V$, $i_C = v_C/R_C = (v_I + 0.7V)/(3k\Omega)$. Once v_I is lowered to $-0.7V$, i_C becomes 0, and turns negative (i.e. flowing into the FB B-C junction) for $v_I < -0.7V$.

2.19 $[V, mA, k\Omega]$.

1. $v_S < 0.7V \Rightarrow BJT = CO \Rightarrow i_C = i_B = 0, v_C = -5V.$

2. $v_S > 0.7V \Rightarrow BJT = ON$, initially FA:

$$i_E = \frac{v_S - 0.7}{1}; \quad i_B = \frac{i_E}{\beta_F + 1} = \frac{v_S - 0.7}{10(x1)}; \quad i_C = \alpha_F i_E = \frac{100}{101} \frac{v_S - 0.7}{1} \cong$$

$$i_E = \frac{v_S - 0.7}{1}; \quad v_C = -5 + 2\left(\frac{v_S - 0.7}{1}\right).$$

(3) When v_C reaches $v_{EB} - v_{EC}(EOS) = 0.7 - 0.1 = 0.6V$, BJT reaches EOS. At this point,

$$I_C(EOS) = \frac{0.6 - (-5)}{2} = 2.8 mA, \quad V_S(EOS) = 0.7 + 1 \times I_E(EOS) \cong$$

$$0.7 + 1 \times I_C(EOS) = 0.7 + 2.8 = 3.5V; \quad I_B(EOS) = \frac{2.8}{100} = 28\mu A.$$

(4) For $v_S > 3.5V$, BJT = Sat: $i_C = I_C(EOS) = 2.8 mA$,

$$v_E = \frac{v_S - 0.7}{1}, \quad i_B = i_E - i_C = \frac{v_S - 0.7}{1} - 2.8 = (v_S - 3.5) mA.$$

$$\frac{i_C}{i_B} = \frac{2.8}{v_S - 3.5}. \quad \text{For } v_S = 5V, \quad \frac{i_C}{i_B} = \frac{2.8}{1.5} = 1.8\overline{6}.$$

2.20 (a)
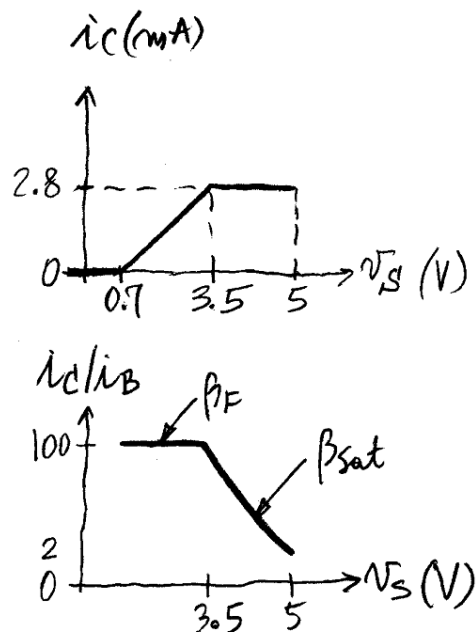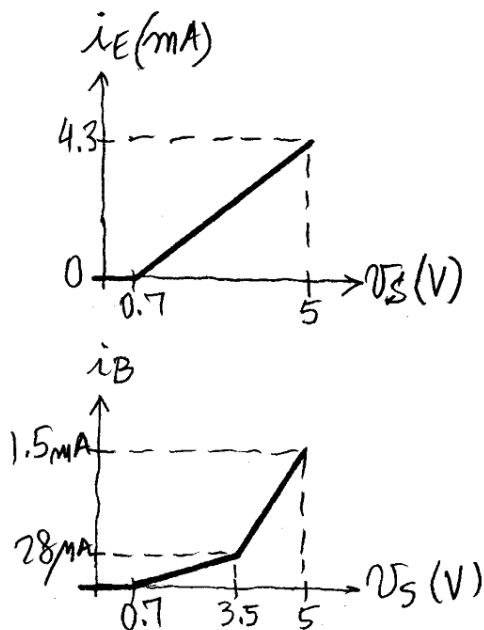
KVL: $V_{CC} = R_C I_C + V_{CE} + R_E I_E \Rightarrow 5 = 1\beta_F I_B + 2 + 2(\beta_F + 1) I_B$;

KVL: $V_{CC} = R_B I_B + V_{BE(on)} + R_E I_E \Rightarrow 5 = 300 I_B + 0.7 + 2(\beta_F + 1) I_B$;

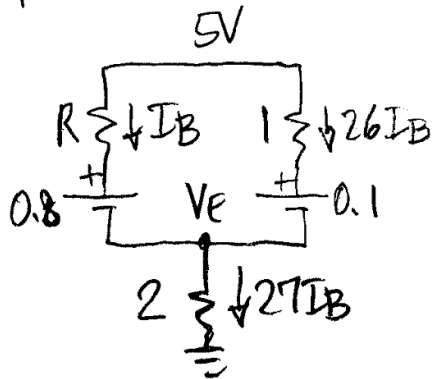$\Rightarrow 3 = (3\beta_F + 2) I_B$, $\quad 4.3 = (302 + 2\beta_F) I_B \Rightarrow$

$$\frac{3}{4.3} = \frac{3\beta_F + 2}{302 + 2\beta_F} \Rightarrow \beta_F = 130.$$

(b) KVL: $5 = 1 I_C + 0.2 + 2 I_E \simeq \alpha_F I_E + 0.2 + 2 I_E \simeq 0.2 + 3 I_E$

$\Rightarrow I_E \simeq (5 - 0.2)/3 = 1.6 \, mA$; $V_E = 2 \times 1.6 = 3.2 V$; $V_B = 3.2 + 0.7 =$

$3.9 V$; $I_B = 1.6/131 = 12.2 \mu A$; $R_B = (5 - 3.9)/0.0122 = 90 \, k\Omega$.

(c) $\beta_{sat} = 130/5 = 26 \Rightarrow I_C = 26 I_B$; $I_E = 27 I_B$.

$V_E = 2 \times 27 I_B = 54 I_B$.

$5 = 1 \times 26 I_B + 0.1 + 54 I_B \Rightarrow I_B = 61.25 \mu A$.

$V_B = 54 \times 0.062125 + 0.8 = 3.4075 V$.

$R = (5 - 3.4075)/0.06125 = 14.6 \, k\Omega$.

2.21

(a) $[V, k\Omega, mA]$. KVL: $5 = 3I_E + 1 + 1I_C$, or

$$4 = 3(\beta_F+1)I_B + \beta_F I_B = (4\beta_F+3)I_B$$

KVL: $5 = 3I_E + 0.7 + 180I_B$, or

$$4.3 = 3(\beta_F+1)I_B + 180I_B = (3\beta_F+183)I_B$$

Take the ratio of the two eqns:

$$\frac{4}{4.3} = \frac{4\beta_F+3}{3\beta_F+183} \Rightarrow \boxed{\beta_F = 138}$$

(b) Swapping R_E and R_C causes the BJT to saturate.
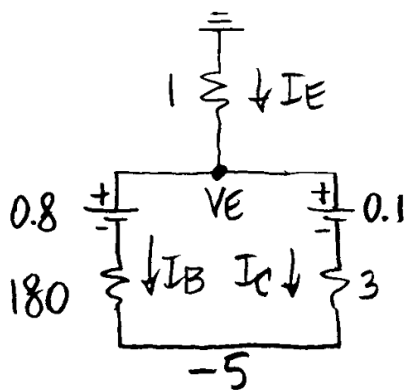
$$KCL: \frac{0-V_E}{1} = \frac{V_E-0.8-(-5)}{180} + \frac{V_E-0.1+5}{3}$$

$$\Rightarrow V_E = -1.237V. \quad I_E = 1.237 mA;$$

$$I_C = 1.221 mA; \quad I_B = 16.5\,\mu A.$$

$$\beta_{sat} = \frac{1.221}{0.0165} = 74 < 138 (=\beta_F).$$

2.22

(a) KVL: $V_5 = V_{BE(on)} + R_1 I_B + R_2(I_B + I_C)$.

In FA, $5 = 0.7 + 20 I_B + 3(1+150) I_B \Rightarrow I_B = 9.0\overline{9}\ \mu A$;

$I_C = 150 \times 9.0\overline{9} = 1.\overline{36}\ mA$; $I_E = 1.3\overline{72}\ mA$; KVL:

$V_C = 0.7 + 20 \times 0.0090\overline{9} - R_3 \times 1.\overline{36} = 0.88\overline{1} - R_3 \times 1.\overline{36}$.

$V_{C(min)} = V_{CE(EOS)} = 0.2V \Rightarrow 0.2 = 0.88\overline{1} - R_{3(max)} \times 1.\overline{36} \Rightarrow$

$0 \leq R_3 \leq 0.5\ k\Omega$.

(b) $R_3 = 2 \times 0.5 = 1\ k\Omega \Rightarrow BJT = Sat \Rightarrow V_{CE} = 0.1V, V_{BE} = 0.8V$.
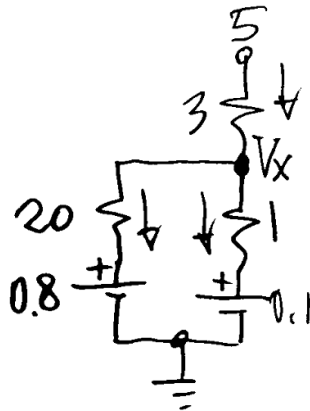
$\dfrac{5 - V_x}{3} = \dfrac{V_x - 0.8}{20} + \dfrac{V_x - 0.1}{1} \Rightarrow V_x = 1.306\ V$.

$\Rightarrow I_B = 25.3\ \mu A, \quad I_C = 1.206\ mA,$

$\beta_{sat} = 1.206 / 0.0253 \cong 48$.

(c) $I_C = 0 \Rightarrow \beta_{sat} = 0 / I_B = 0$.

2.23 (a) Assume FA) and check. By inspection, $I_{R_2} = I_B + I_C$
$= (\beta_F + 1) I_B = 151 I_B$. KVL:

$9 = 20(151 I_B) + 100 I_B + 0.7 \Rightarrow I_B = 2.66 \mu A, I_C = 150 I_B =$

$0.399 \, mA$, $I_E = 151 I_B = 0.402 \, mA$. By KVL again,

$V_{CE} = V_C = V_S - R_2 I_E - R_3 I_C = 9 - 20 \times 0.402 - 1 \times 0.399 = 0.567 V$

$> 0.2 V \Rightarrow FA!$

(b) Assume Saturation, and check. KCL:

$[V, k\Omega, mA]$:
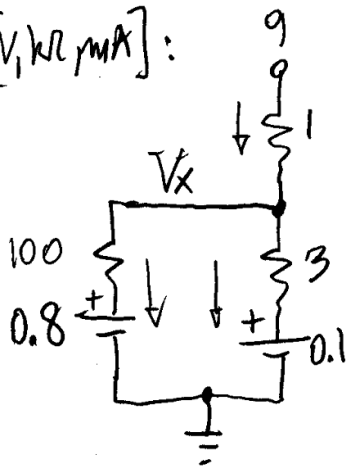
$\dfrac{9 - V_x}{1} = \dfrac{V_x - 0.1}{3} + \dfrac{V_x - 0.8}{100} \Rightarrow V_x = 6.73 V.$

$I_B = \dfrac{6.73 - 0.8}{100} = 59.3 \mu A$

$I_C = \dfrac{6.73 - 0.1}{3} = 2.221 \, mA$

$I_E = I_C + I_B = 2.28 \, mA$

$\beta_{sat} = I_C / I_B = 2.221 / 0.0593 = 37 < 150 \Rightarrow Sat!$

2.24

(a) $[V, mA, k\Omega]$. Assume FA. KVL:
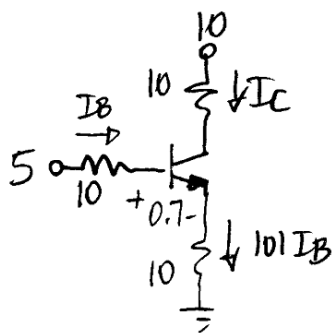
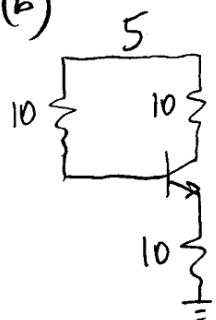$5 = 10 I_B + 0.7 + 10 (101 I_B) \Rightarrow I_B = 4.2 \mu A$

$I_C = 0.422 mA; \quad I_E = 0.426 mA$

$V_B = 5 - 10 I_B = 4.958 V; \quad V_E = 4.26 V$

$V_C = 10 - 10 \times 0.422 = 5.78 V$

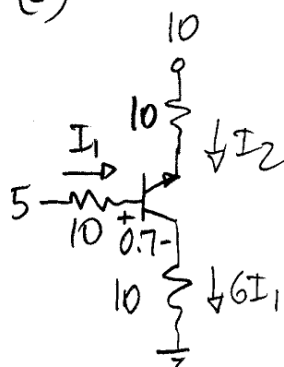$V_{CE} = 5.78 - 4.26 = 1.52 V > 0.2V \Rightarrow FA!$

(b)
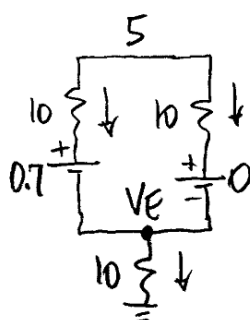
Now BJT is saturated.

KCL:

$$\frac{5 - (V_E + 0.7)}{10} + \frac{5 - V_E}{10} = \frac{V_E}{10}$$

$$\Rightarrow V_E = 3.1 V.$$

$I_E = 0.31 mA; \quad I_B = 0.12 mA; \quad I_C = 0.19 mA. \quad \beta_{sat} = \frac{0.19}{0.12} = 1.6.$

(c) Reverse active mode. KVL:
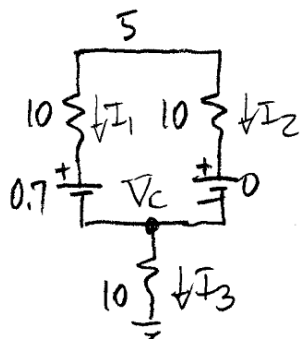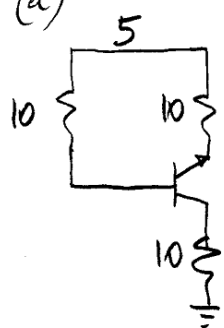
$5 = 10 I_1 + 0.7 + 6 I_1 \Rightarrow I_1 = 61.4 \mu A$

$I_2 = 5 I_1 = 307 \mu A; \quad 6 I_1 = 369 \mu A.$

$V_B = 5 - 10 I_1 = 4.39 V; \quad V_C = V_B - 0.7$

$= 3.69 V; \quad V_E = 10 - 10 I_2 = 6.93 V$

$V_{EC} = 6.93 - 3.69 > 0.2V \Rightarrow RA!$

(d)
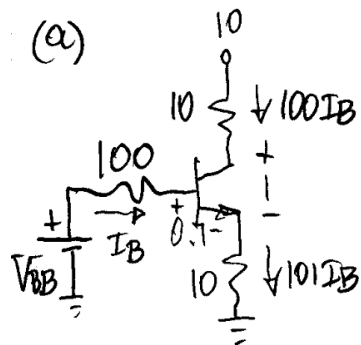
BJT is in reverse-mode saturation. Equivalent circuit is similar to (b).

$V_C = 3.1 V, \quad I_1 = 0.12 mA$

$I_2 = 0.19 mA, \quad \beta_{sat} = 0.19/0.12 = 1.6.$

2.25 $[V, mA, k\Omega]$.

(a)

$$KVL: \quad 10 = 10(100 I_B) + 1 + 10(101 I_B)$$
$$\Rightarrow I_B = 4.478 \, \mu A;$$
$$V_E = 10 \times 101 I_B = 4.522 \, V; \quad V_B = V_E + 0.7V$$
$$= 5.22 \, V; \quad V_{BB} = V_B + 100 I_B = 5.67 \, V.$$

(b)
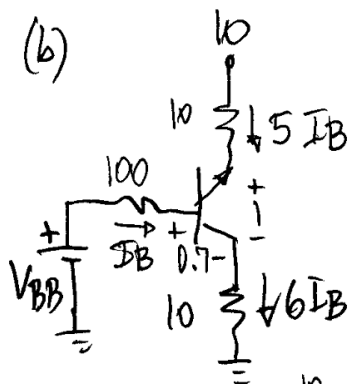
$$KVL: \quad 10 = 10(5 I_B) + 1 + 10(6 I_B)$$
$$\Rightarrow I_B = 81.\overline{81} \, \mu A$$
$$V_C = 10 \times 6 I_B = 4.91 \, V; \quad V_B = 5.61 \, V$$
$$V_{BB} = 5.61 + 100 \times 0.0\overline{81} = 13.8 \, V.$$

(c)
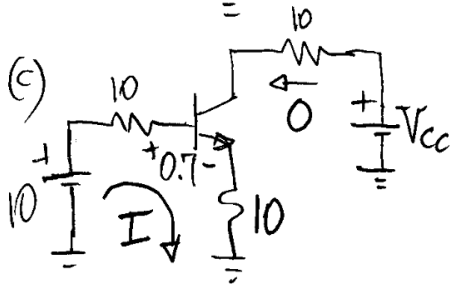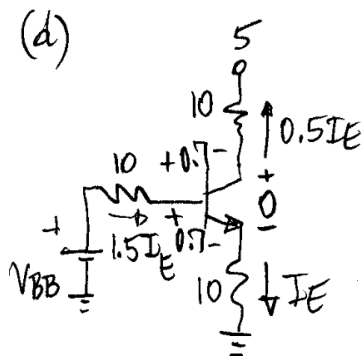
$$I_C = 0 \Rightarrow I_B = I_E = I. \quad KVL:$$
$$10 = 10 I + 0.7 + 10 I \Rightarrow I = 0.465 \, mA$$
$$\Rightarrow V_E = 4.65 V, \quad V_B = 5.35 V.$$
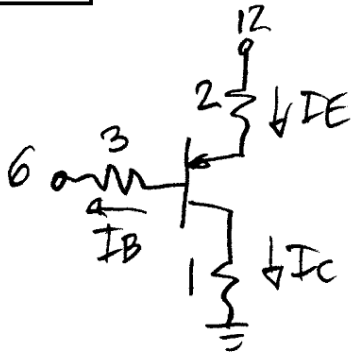$$\text{For } I_C = 0, \quad V_{CC} \approx V_B - 0.65 = 4.7 \, V.$$

(d)

$$I_B = 1.5 I_E \Rightarrow I_C = -0.5 I_E \, (\text{out of collector})$$
$$\Rightarrow \beta_{sat} = (-0.5 I_E)/(1.5 I_B) = -\frac{1}{3} < \beta_F \Rightarrow Sat.$$
$$\Rightarrow V_{BC} = V_{BE} = 0.7V \Rightarrow 10 I_E = 5 + 10(0.5 I_E)$$
$$\Rightarrow I_E = 1 mA \Rightarrow V_{BB} = 10(1.5 \times 1) + 0.7 +$$
$$10(1) = 25.7 V.$$

2.26	(a) $[V, mA, k\Omega]$.

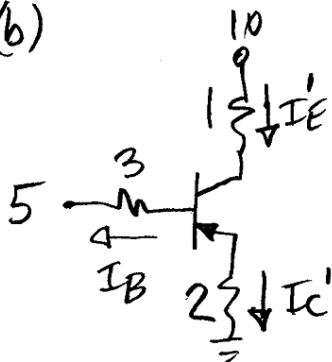Assume FA: kVL:

$$12 = 2 \times 151 I_B + 0.7 + 3 I_B + 6$$
$$\Rightarrow I_B = 17.4 \mu A, \quad I_C = 2.61 mA,$$
$$I_E = 2.62 mA, \quad V_B = 6.052 V,$$
$$V_E = 6.752 V, \quad V_C = 2.607 V$$

$$V_{EC} = 4.14 V > 0.1 V \Rightarrow FA!$$

(b)

Assume RA: kVL

$$10 = 1 \times 5 I_B + 0.7 + 3 I_B + 5$$
$$\Rightarrow I_B = 0.5375 mA$$
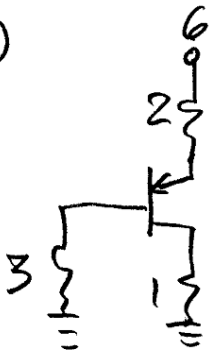$$I_C' = 4 \times 0.5375 = 2.15 mA$$
$$I_E' = 5 \times 0.5375 = 2.6875 mA$$

$$V_B = 5 + 3 \times 0.5375 = 6.6125 V; \quad V_C = 6.6125 + 0.7 = 7.3125 V;$$
$$V_E = 2 \times 2.15 = 4.3 V. \quad 7.3125 - 4.3 > 0.1 \Rightarrow RA!$$

(c)

Assume Sat: kCL:

$$\frac{6 - V_E}{2} = \frac{V_E - 0.7}{3} + \frac{V_E - 0}{1}$$
$$\Rightarrow V_E = 1.7\overline{36} V$$
$$V_C = 1.7\overline{36} V$$
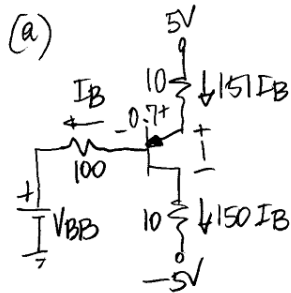$$I_C = 1.7\overline{36} mA$$
$$V_B = 1.0\overline{36} V$$

$$I_B = 1.0\overline{36}/3 = 0.3\overline{45} mA; \quad \beta_{sat} = 1.7\overline{36}/0.3\overline{45} \cong 5 < \beta_F$$
$$\Rightarrow Sat!$$

2.27 [V, mA, kΩ].

(a)

KVL: $5 - (-5) = 10(151 I_B) + 1 + 10(150 I_B)$

$\Rightarrow I_B = 2.99 \, \mu A$

$V_{BB} = 5 - 10(151 I_B) - 0.7 - 100 I_B$

$\quad\quad = -0.514 \, V.$

(b)
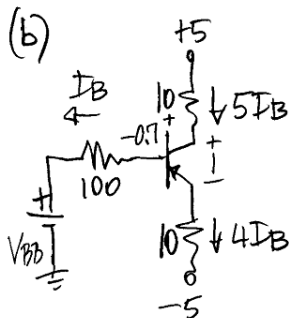
$10 = 10(5 I_B) + 1 + 10(4 I_B)$

$\Rightarrow I_B = 0.1 \, mA$

$V_{BB} = 5 - 10(5 \times 0.1) - 0.7 - 100 \times 0.1$

$\quad\quad = -10.7 \, V$

(c)
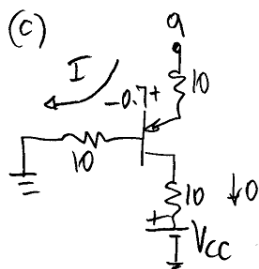
$I_C = 0 \Rightarrow I_B = I_E = I.$ KVL:

$9 = 10 I + 0.7 + 10 I \Rightarrow I = 0.415 \, mA.$

$V_B = 10 I = 4.15 V.$ For $I_C = 0$, need

$V_{CC} \cong V_B + 0.65 = 4.15 + 0.65 = 4.8 V.$
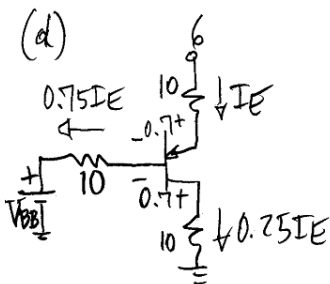
(d)

$I_B = 0.75 I_E \Rightarrow I_C = 0.25 I_E,$ by KCL.

$\beta_{sat} = I_C / I_B = (0.25 I_E)/(0.75 I_E) = \frac{1}{3}$

$\frac{1}{3} < 150 \Rightarrow$ Saturation $\Rightarrow V_{EC} = 0$

KVL: $6 = 10 I_E + 10(0.25 I_E) \Rightarrow$

$I_E = 0.48 \, mA.$ KVL:

$V_{BB} = 6 - 10(0.48) - 0.7 - 10(0.75 \times 0.48) = -3.1 \, V.$

(e)
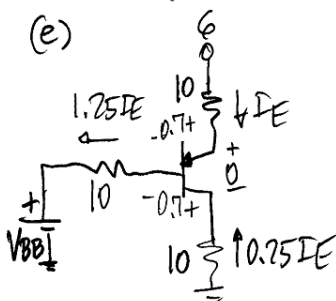
$I_B = 1.25 I_E \Rightarrow I_C = 0.75 I_E$ (into the collector). $\beta_{sat} = (-0.25 I_E)/(1.25 I_E)$

$= -0.2 < 150 \Rightarrow$ Saturation $\Rightarrow$

$V_{EC} = 0.$ KVL:

$6 + 10(0.25 I_E) = 10 I_E \Rightarrow I_E = 0.8 \, mA.$

$V_{BB} = 6 - 10(0.8) - 0.7 - 10(1.25 \times 0.8) = -12.7 \, V.$

2.28 $[V, mA, k\Omega]$. Assume $Q_1 = Q_2 = FA$. $I_{E2} = \frac{51}{50} 0.5 = 0.51$ mA.
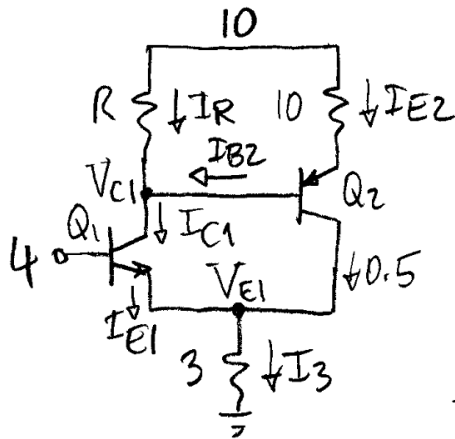
KVL: $V_{E2} = 10 - 10 \times 0.51 = 4.9$ V. KVL:

$V_{B2} = 4.9 - 0.7 = 4.2$ V $= V_{C1}$. KCL:

$I_{E1} = I_3 - I_{C2} = \frac{4 - 0.7}{3} - 0.5 = 0.6$ mA.

$I_{C1} = \frac{55}{56} 0.6 = \frac{33}{56}$ mA. KCL:
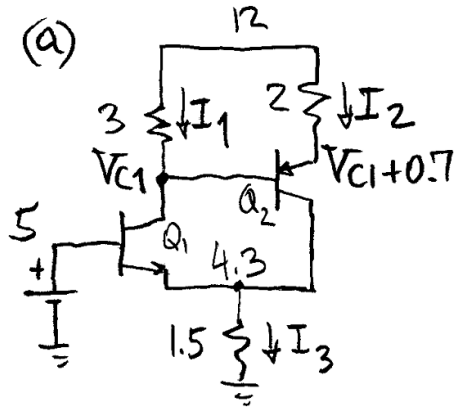
$I_R = I_{C1} - I_{B2} = \frac{33}{56} - \frac{0.5}{50} = \frac{811}{1400}$ mA.

Ohm: $R = \frac{10 - 4.2}{811/1400} = 10.0$ kΩ. Check: $V_{CE1} = 4.2 - (4 - 0.7) > 0.2$ V

$\Rightarrow Q_1 = FA$. $V_{EC2} = 4.9 - (4 - 0.7) > 0.2$ V $\Rightarrow Q_2 = FA$.

$I_{4V} = I_{B1} = I_{C1}/\beta_{F1} = (33/56)/55 = 10.7$ μA.

2.29 $[V, mA, k\Omega]$. Assume $Q_1 = Q_2 = FA$, and check. $V_{E1} = V_{C2} = 5 - 0.7 = 4.3V$. Ignoring base currents,

(a)

$I_3 = I_{E1} + I_{C2} \cong I_1 + I_2$, or

$$\frac{4.3}{1.5} = \frac{12 - V_{C1}}{3} + \frac{12 - (V_{C1} + 0.7)}{2}$$

$$\Rightarrow V_{C1} = 8.14V \Rightarrow I_{C1} \cong I_1 = \frac{12 - 8.14}{3} \cong$$

$1.29\,mA; \quad I_{C2} \cong I_2 = \frac{12 - (8.14 + 0.7)}{2} \cong$

$1.58\,mA; \quad V_{CE1} = 8.14 - 4.3 = 3.84V \;(\gg 0.1V \Rightarrow Sat); \quad V_{EC2} = (8.14 + 0.7) - 4.3 = 4.54V \;(\gg 0.1V \Rightarrow Sat)$. Consequently,

$Q_1 = Q_1(1.29\,mA, 3.84V), \quad Q_2 = Q_2(1.58\,mA, 4.54V)$.

(b)
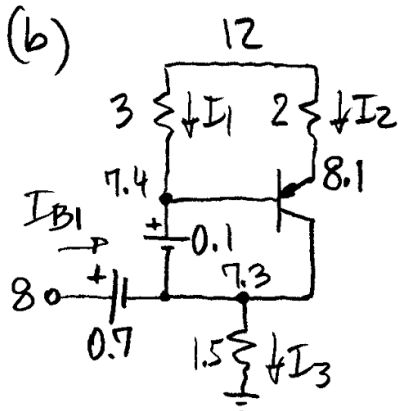
Assume $Q_1 = Sat$, $Q_2 = FA$, and check.

$V_{E1} = V_{C2} = 8 - 0.7 = 7.3V; \quad I_3 = 7.3/1.5 = 4.87\,mA; \quad V_{C1} = V_{B2} = 7.3 + 0.1 = 7.4V; \quad V_{E2} = V_{B2} + 0.7 = 8.1V. \quad I_1 = (12 - 7.4)/3 = 1.53\,mA; \quad I_2 = (12 - 8.1)/2 = 1.95\,mA.$

$Q_2 = Q_2(1.95\,mA, 0.8V), \quad FA. \quad KCL:$

$I_{B1} = I_3 - (I_1 + I_2) = 4.87 - (1.53 + 1.95) = 1.38\,mA. \quad I_{C1}/I_{B1} \cong I_1/I_{B1} = 1.53/1.38 = 1.1 \Rightarrow Q_1 = Sat, \text{ and } Q_1 = (1.53\,mA, 0.1V).$

2.30

(a) $[V, mA, k\Omega]$: KCL: $I_5 = I_{3k\Omega} + I_{B2} = I_{3k\Omega} + I_{E2}/(\beta_2 + 1)$

$$15 = \frac{V_{C1}}{3} + \frac{1}{50+1}\frac{V_{C1}-0.7}{2} \Rightarrow V_{C1} = 4.39\,V.$$

$$I_{E2} = \frac{4.39 - 0.7}{2} = 1.85\,mA$$

$$I_{C2} = \frac{50}{51}I_{E2} = 1.81\,mA$$

$$I_{E1} = \frac{51}{50}I_{C1} = \frac{51}{50}1.5 = 1.53\,mA$$

$$I_{R1} = I_{E1} + I_{C2} = 3.34\,mA$$
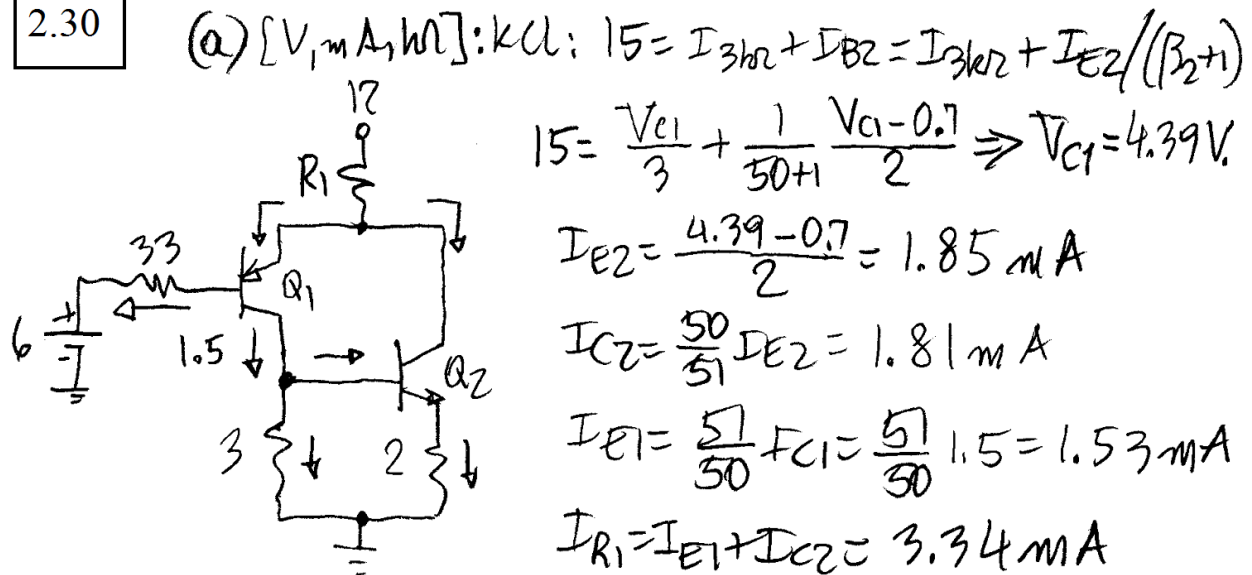
$I_{B1} = I_{C1}/\beta_1 = 1.5/50 = 0.03\,mA;$ $V_{B1} = 6 + 33\times0.03 = 6.99\,V;$
$V_{E1} = V_{B1} + 0.7 = 7.69\,V.$ $R_1 = (12 - 7.69)/3.34 \cong 1.3\,k\Omega.$
check: $V_{EC1} = (12 - 1.3\times3.34) - 4.39 \cong 3.3\,V \gg 0.1V \Rightarrow FA.$
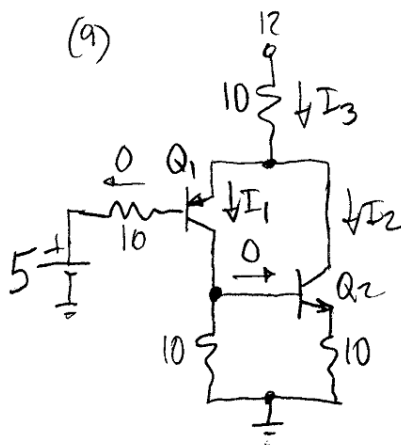$V_{CE2} = (12 - 1.3\times3.34) - (4.39 - 0.7) \cong 4\,V \gg 0.1V \Rightarrow FA.$

(b) The base currents can be ignored, except when
calculating the voltage drop across R_2. Thus,
$V_{C1} \cong 3\times1.5 = 4.5V;$ $I_{E2} \cong (4.5 - 0.7)/2 = 1.9\,mA;$ $I_{R1} \cong$
$1.5 + 1.9 = 3.4\,mA;$ $R_1 = (12 - 7.69)/3.4 = 1.27\,k\Omega \cong 1.3\,k\Omega.$

2.31 $[V, mA, k\Omega]$. Assume $Q_1 = Q_2 = FA$, and check.

(a)

Ignoring I_{B1} and I_{B2}, we have, by KVL,
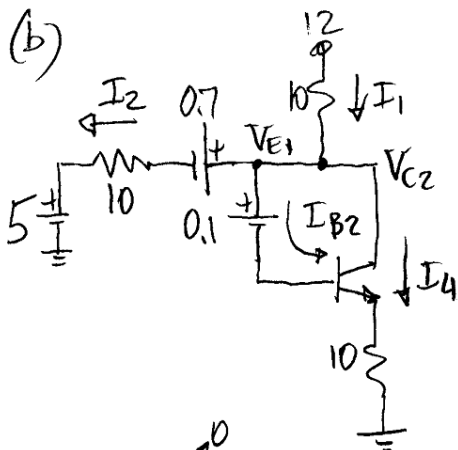
$V_{C2} = V_{E1} = V_{B1} + 0.7 \cong 5 + 0.7 = 5.7V$. Ω:

$I_3 = (12 - 5.7)/10 = 0.63 \, mA$. KCL:

$I_3 = I_1 + I_2 \Rightarrow 0.63 \cong \dfrac{V_{C1}}{10} + \dfrac{V_{C1} - 0.7}{10}$

$\Rightarrow V_{B2} = V_{C1} = 3.5V \Rightarrow I_{C1} = \dfrac{3.5}{10} = 0.35 \, mA$.

$I_{C2} = 0.63 - 0.35 = 0.28 \, mA$.

$V_{EC1} = 5.7 - 3.5 = 2.2V \gg 0.1V \Rightarrow FA$; $V_{CE2} = 5.7 - (3.5 - 0.7) = 2.9V \gg 0.1V \Rightarrow FA$. Thus, $Q_1 = Q_1(0.35 mA, 2.2V)$; $Q_2 = Q_2(0.28 mA, 2.9V)$.

(b)

With R_3 out of the way, $I_{C1} = I_{B2} =$ very small, so we expect $I_{C1}/I_{B1} \ll \beta_{F1} \Rightarrow$ sat. Thus, assume $Q_1 =$ sat. By inspection, $V_{CE2} = 0.7 + 0.1 = 0.8V > 0.1V \Rightarrow Q_2 = FA$. Let $V_x = V_{E1} = V_{C2}$. KCL:

$I_1 = I_2 + I_{B2} + I_4 \cong I_2 + I_4$, or

$\dfrac{12 - V_x}{10} = \dfrac{(V_x - 0.7) - 5}{10} + \dfrac{(V_x - 0.1) - 0.7}{10} \Rightarrow V_x = 6.1\overline{6} \, V.$

$I_{B1} = I_2 = \dfrac{(6.1\overline{6} - 0.7) - 5}{10} = 0.04\overline{6} \, mA$; $I_{C2} \cong I_4 = \dfrac{(6.1\overline{6} - 0.1) - 0.7}{10}$

$= 0.53\overline{6} \, mA$. $I_{C1} = I_{B2} = I_{C2}/\beta_{F2}$. Assuming $\beta_{F2} > 100$, we have $I_{C1} < 0.53\overline{6}/100 = 5.3\overline{6} \mu A \Rightarrow \beta_{sat1} < 5.3\overline{6}/46.6 \approx 0.1 \Rightarrow Q_1 =$ sat. Thus, $Q_1 = Q_1(<5.3\overline{6}\mu A, 0.1V)$, and $Q_2 = Q_2(0.53\overline{6} mA, 0.8V)$.

2.32 $[V, mA, k\Omega]$. Use KVL, KCL, Ohm's law repeatedly.

$V_{CC} = R_4 I_{C2} + V_{EC2}(EOS) + R_5 I_2 \cong (R_4 + R_5) I_{C2} + V_{EC2}(EOS) \Rightarrow$

$15 \cong 2.2 I_{C2} + 0.2 \Rightarrow I_{C2} = 6.\overline{72} \, mA.$

$V_{E2} = 1 \times 6.\overline{72} = 6.\overline{72} \, V \; ; \; V_{B2} = 6.\overline{72} - 0.7 = 6.0\overline{27} \, V = V_{C1}.$

$I_{B2} = 6.\overline{72}/100 = 67.\overline{27} \, \mu A$

$I_{C1} = (15 - 6.0\overline{27})/30 + 62.\overline{27} \times 10^{-3} = 0.36\overline{63} \mu A.$ Assume $Q_1 = FA.$

$I_{B1} = 0.36\overline{63}/100 = 3.66 \mu A$

$V_{B1} = V_1 - R_1 I_{B1} = 5 - 110 \times 3.66 \times 10^{-3} \cong 4.6 \, V$

$V_{E1} = 4.6 - 0.7 = 3.9 \, V$

$I_{E1} \cong I_{C1} = 0.37 \, mA$

$R_3 = 3.9/0.37 = 10.5 \, k\Omega$

$V_{CE1} = 6.0\overline{27} - 3.9 \gg 0.2 \Rightarrow Q_1 = FA.$

2.33 Consider Q_1 first, and assume FA. KVL, KCL, Ω:

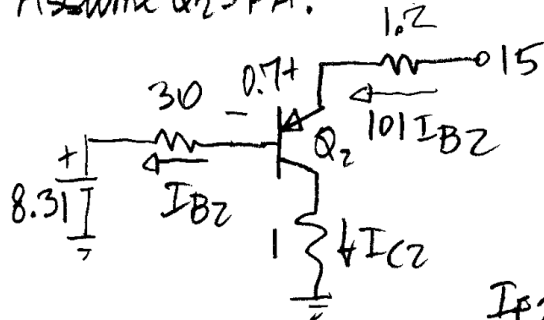$$I_{B1} = \frac{5-0.7}{110+101\times18} = 2.23 \text{ mA}$$

$$V_{B1} = 5 - 110\times2.23\times10^{-3} = 4.75V \; ; \; V_{E1} = 4.05V$$

$$I_{C1} = 100\times2.23 = 0.223 \text{ mA}$$

$$V_{C1} = 15 - 30\times0.223 = 8.31 V$$

$$V_{CE1} = 8.31 - 4.05 \gg 0.2 \Rightarrow Q_1 = FA. \text{ Equivalent Cht:}$$

Assume $Q_2 = FA$.
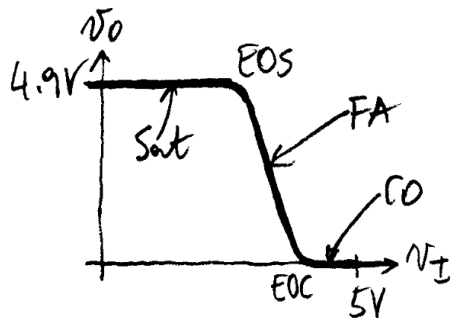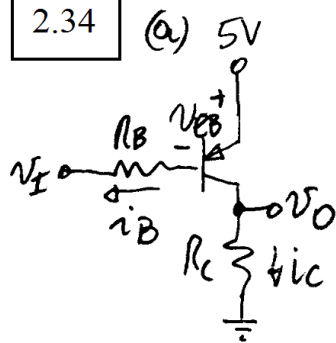

$$I_{B2} = \frac{15-8.31-0.7}{30+101\times1.2} \cong 39.6 \,\mu A.$$

$$V_{B2} = 8.31 + 30\times39.6\times10^{-3} = 9.5V$$

$$V_{E2} = 9.5 + 0.7 = 10.2 V$$

$$I_{E2} \cong I_{C2} = 100\,I_{B2} = 3.96 \text{ mA}$$

$$V_{C2} = 1\times3.96 \cong 4V. \quad V_{EC2} = 10.2 - 4 \gg 0.2 \Rightarrow Q_2 = FA.$$

2.34

(a)

For $v_I > V_{CC} - V_{EB(EOC)} \cong 5 - 0.6 = 4.4V$, the BJT is in cutoff. Lowering v_I below 4.4V drives the BJT in FA:

$$v_I = V_{CC} - v_{EB} - R_B i_B$$

$$= V_{CC} - V_T \ln \frac{v_O/R_C}{I_S} - R_B \frac{v_O/R_C}{\beta_F}$$

$$= 5 - 0.026 \ln \frac{v_O}{10^3 \times 10^{-15}} - \frac{10}{1} \frac{v_O}{80}, \text{ or}$$

$$v_I = 5 - \frac{v_O}{8} - 0.026 \ln (10^{12} v_O).$$

The EOS is reached when $v_O = V_{CC} - V_{EC}(\text{sat}) = 5 - 0.1 = 4.9 V$.

This occurs for $v_I = 5 - \frac{4.9}{8} - 0.026 \ln (10^{12} \times 4.9) = 3.628V.$

(b) $v_I = 5 - \frac{4}{8} - 0.026 \ln (10^{12} \times 4) = 3.746 V$

(c) $\frac{dv_I}{dv_I} = -\frac{1}{8} \frac{dv_O}{dv_I} - 0.026 \frac{1}{10^{12} v_O} 10^{12} \frac{dv_O}{dv_I}$, or

$1 = -\frac{a}{8} - 0.026 \frac{a}{v_O} \Rightarrow a = \frac{-8 v_O}{v_O - 0.208}; \ a \Big|_{v_O = 4V} = -8.44 \ V/V.$

Ch. 2 – Problem solutions –

2.35 (a) KVL: $v_I = R_B i_{R_B} + v_{BE} = R_B\left(i_B + \frac{v_{BE}}{R_{BE}}\right) + v_{BE} = R_B i_B + \left(1 + R_B/R_{BE}\right) v_{BE}.$

(b) $v_I = 10^4\left(\frac{5 - v_O}{10^3}\right)\Big/100 + \left(1 + \frac{10}{5}\right) 0.026 \ln \frac{5 - v_O}{10^3 \times 2\times 10^{-15}}$

$v_I = \frac{5 - v_O}{10} + 0.078 \ln \frac{5 - v_O}{2\times 10^{-12}}.$

(c) $V_I = \frac{5 - 2.5}{10} + 0.078 \ln \frac{5 - 2.5}{2\times 10^{-12}} = 0.25 + 2.173 = 2.423\,V$

(shifted to the right by about $2 V_{BE}$'s).

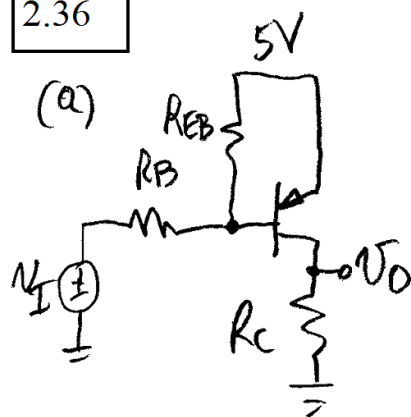(d) $\frac{dv_I}{dv_I} = \frac{1}{10}\frac{dv_O}{dv_I} + 0.078 \frac{2\times 10^{-12}}{5 - v_O}\left(-\frac{1}{2\times 10^{-12}}\frac{dv_O}{dv_I}\right) \Rightarrow$

$1 = -\frac{a}{10} - 0.078\frac{a}{5 - v_O} \Rightarrow a = -10\frac{5 - v_O}{5.78 - v_O}.$

@ $v_O = 2.5\,V$, $a = -7.62\,V/V$. In the example, $a = -9.06\,V/V$. Reduced gain stems from the presence of R_{BE}, which forms an input voltage divider with R_B.

2.36

(a)

$$v_I = 5 - v_{EB} - R_B\left(i_B + \frac{v_{EB}}{R_{EB}}\right)$$

$$= 5 - R_B i_B - \left(1 + \frac{R_B}{R_{EB}}\right)v_{EB}, \quad i_B = \frac{i_C}{80} = \frac{v_O}{80 \times 10^3}.$$

Impose $2.5 = 5 - 10^4 \dfrac{2.5}{80 \times 10^3} - \left(1 + \dfrac{10^4}{R_{EB}}\right) \times$

$\times\ 0.026 \ln \dfrac{2.5/10^3}{10^{-15}} \Rightarrow R_{EB} \cong 5\,k\Omega.$

(b) $v_I = 5 - 10\dfrac{v_O}{80 \times 1} - 3 \times 0.026 \ln v_O/(10^3 \times 10^{-15})$, or
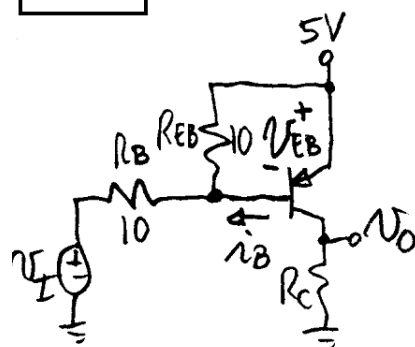
$v_I = 5 - \dfrac{1}{8}v_O - 0.078 \ln(10^{12}v_O)$. Differentiate wrt v_I:

$$1 = -\frac{1}{8}\frac{dv_O}{dv_I} - 0.078\left[\frac{1}{10^{12}v_O} \times 10^{12}\frac{dv_O}{dv_I}\right]$$

$$1 = -\frac{1}{8}\frac{dv_O}{dv_I} - \frac{0.078}{v_O}\frac{dv_O}{dv_I} \Rightarrow \frac{dv_O}{dv_I} = \frac{1}{0.078/v_O - 1/8}.$$

For $v_O = 2.5V$, gain $= \dfrac{1}{0.078/2.5 - 1/8} = -10.7\ V/V$

2.37

(a) $[V, mA, k\Omega]$. $v_I = V_{CC} - v_{EB} - R_B\left(i_B + \dfrac{v_{EB}}{R_{EB}}\right)$

$$= V_{CC} - R_B i_B - \left(1 + R_B/R_{EB}\right)v_{EB}$$

$$= 5 - 10^4 i_B - 2 v_{EB}.$$

(b) $i_B = i_C/\beta_F = \dfrac{v_O}{R_C \beta_F} = \dfrac{v_O}{2\times10^3 \times 125} = \dfrac{v_O}{25\times10^4}$

$$v_I = 5 - 10^4 \dfrac{v_O}{25\times10^4} - 2\times 0.026 \ln \dfrac{v_O/(2\times10^3)}{5\times10^{-15}}$$

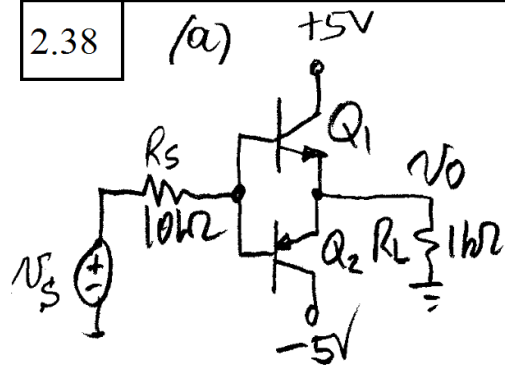$$\Rightarrow v_I = 5 - \dfrac{v_O}{25} - 0.052 \ln(10^{11} v_O).$$

$$v_{I1} = 5 - \dfrac{2}{25} - 0.052 \ln(10^{11}\times 2) = 3.567 \text{ V}$$

$$v_{I2} = 5 - \dfrac{3}{25} - 0.052 \ln(10^{11}\times 3) = 3.506 \text{ V}$$

$$a = (3-2)/(3.506-3.567) = (1\,V)/(-61\,mV) \cong -16.4 \text{ V/V}.$$

(c) $v_I (V)$

$v_O (V)$

2.38 (a)

+5V

R_S 10kΩ

Q_1

V_O

Q_2 R_L 1kΩ

V_S

−5V
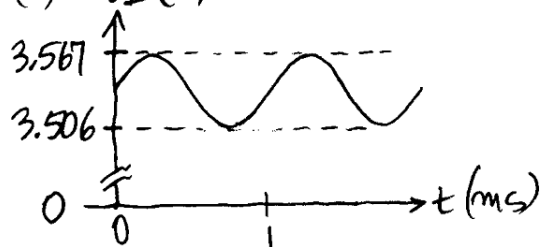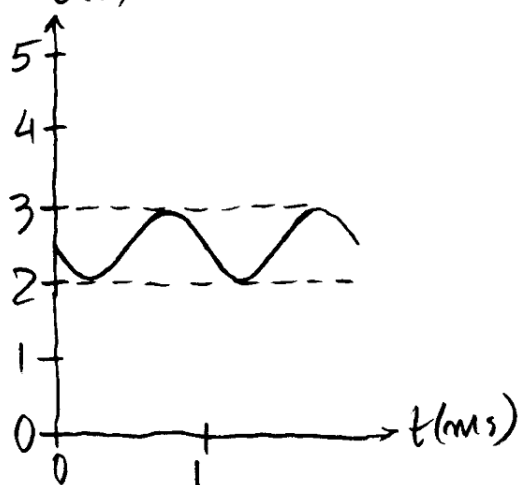
VTC is symmetric, so investigate the case $V_I \geq 0$. [V, mA, kΩ].

$0 \leq V_I < 0.6 \Rightarrow Q_1 = CO$.

$V_I = 0.6V \Rightarrow Q_1 = EOC$.

$0 < V_O < 5 - 0.2 = 4.8V \Rightarrow Q_1 = FA$.

$V_O = 4.8V \Rightarrow Q_1 = EOS$, and

$V_I = 4.8 + 0.7 + R_S i_B$

$= 5.5 + 10 \times \frac{1}{100} \frac{4.8}{1}$

$= 5.55V$.

$V_I > 5.55V \Rightarrow Q_1 = Sat$

$\Rightarrow V_O = 5 - 0.1 = 4.9V$.

$V_O(V)$

EOS

5

−7 −5 EOC

EOC 5 7 $V_S(V)$

−5

EOS
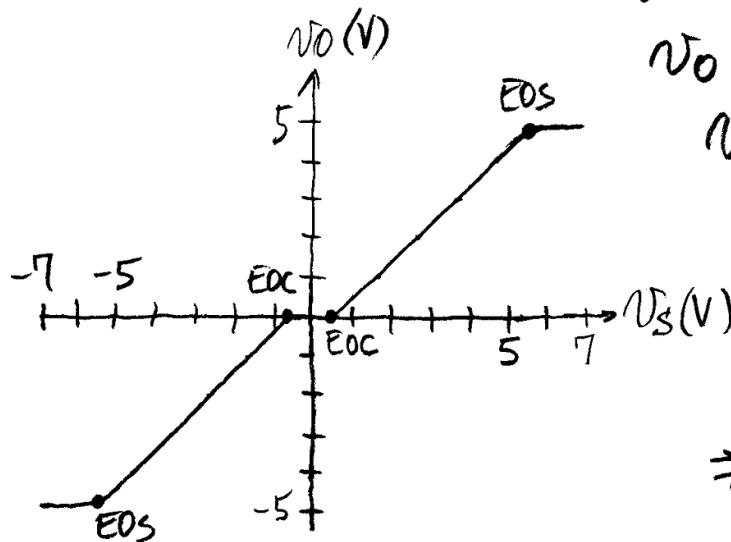
(b) $V_O = 2.5V \Rightarrow V_I = \pm\left(2.5 + 0.7 + 10\frac{2.5/1}{100}\right) = \pm 3.45V$.

2.39 (a)

A	B	Q_A	Q_B	Y
L	L	CO	CO	H
L	H	CO	Sat	L
H	L	Sat	CO	L
H	H	Sat	Sat	L

(b) $\beta_{F(min)} > \left(\frac{5-0.1}{1}\right)\Big/\left(\frac{5-0.8}{10}\right) \cong 12$

2.40

(a)

A	B	Q_A	Q_B	Y
L	L	co	co	H
L	H	co	co	H
H	L	co	co	H
H	H	Sat	sat	L

(b) $\beta_{FA} \geq \left[\dfrac{5-2(0.1)}{1}\right] / \left[\dfrac{5-(0.8+0.1)}{10}\right] = 11.7$

$\beta_{FB} \geq \left[\dfrac{5-2(0.1)}{1} + \dfrac{5-(0.8+0.1)}{10}\right] / \left[\dfrac{5-0.8}{10}\right] = 11 .$

2.41
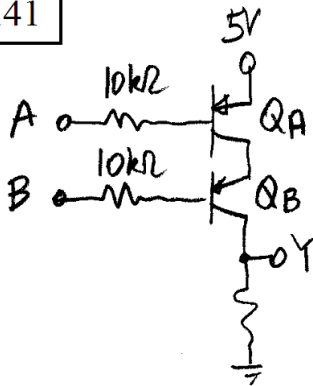
A	B	Q_A	Q_B	Y
L	L	Sat	Sat	H
L	H	co	co	L
H	L	co	co	L
H	H	co	co	L

2.42
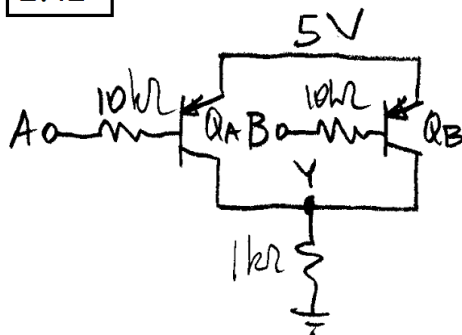
A	B	Q_A	Q_B	Y
L	L	Sat	Sat	H
L	H	Sat	co	H
H	L	co	Sat	H
H	H	co	co	L

2.43

(a) $R_2 = (5 - 1.5 - 0.1)/10 = 0.34\ k\Omega$ (use $330\ \Omega$).

$I_D = (5 - 1.5 - 0.1)/0.33 = 10.3\ mA$

$I_B(min) = 10.3/50 = 0.206\ mA$.

$R_1 \leq (5 - 0.8)/0.206 = 20\ k\Omega$

(b)
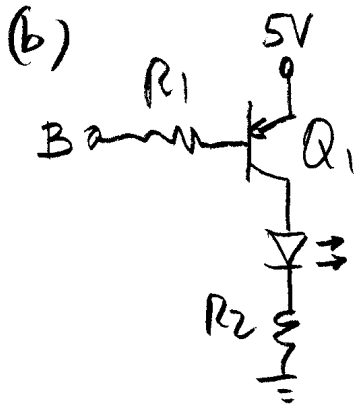
$B = L = 0V \Rightarrow Q_1 = Sat \Rightarrow$ LED glows.
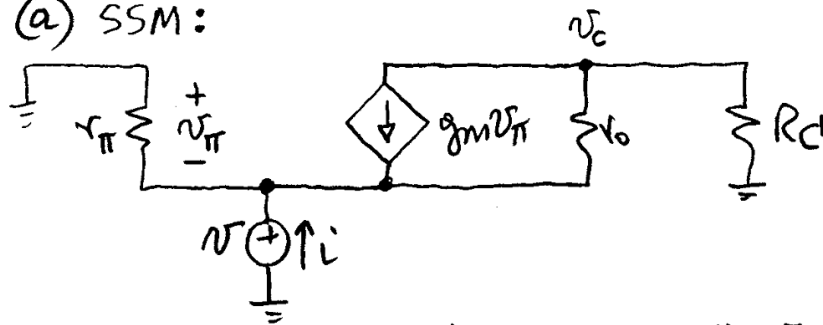
$B = H = 5V \Rightarrow Q_1 = CO \Rightarrow$ LED is dark.

Assuming the same parameters as the BJT of part (a), use $R_1 = 20\ k\Omega$, $R_2 = 330\ \Omega$.

2.44 **(a)** SSM:

KVL: $v_\pi = -v$. KCL: $i + \dfrac{v_\pi}{r_\pi} + g_m v_\pi + \dfrac{v_c - v}{r_0} = 0$, or

$i - \dfrac{v}{r_\pi} - g_m v + \dfrac{v_c - v}{r_0} = 0$. Supernode: $i = \dfrac{v}{r_\pi} + \dfrac{v_c}{R_C}$, or

$v_c = R_C \left(i - \dfrac{v}{r_\pi} \right)$. Eliminating v_c gives

$i \left(1 + \dfrac{R_C}{r_0} \right) = v \left(\dfrac{1}{r_\pi} + g_m + \dfrac{1}{r_0} + \dfrac{R_C}{r_\pi} \dfrac{1}{r_0} \right) = v \left(\dfrac{1}{r_e} + \dfrac{1}{r_0} + \dfrac{R_C}{r_\pi} \dfrac{1}{r_0} \right)$

$R_e = \dfrac{v}{i} = r_e \dfrac{r_0 + R_C}{r_0 + r_e + (r_0/r_\pi) R_C}$. Considering that $r_e \ll r_0$

and $\dfrac{r_e}{r_\pi} = \left(\dfrac{\beta_0}{\beta_0 + 1} \dfrac{1}{g_m} \right) / \left(\dfrac{\beta_0}{g_m} \right) = \dfrac{1}{\beta_0 + 1}$, we get

$R_e \cong r_e \dfrac{r_0 + R_C}{r_0 + R_C/(\beta_0 + 1)} = r_e \dfrac{1 + R_C/r_0}{1 + R_C/[(\beta_0 + 1) r_0]}$

(b) $r_e = \dfrac{100}{101} \times \dfrac{26}{1} \cong 26\,\Omega$, $r_0 = \dfrac{100}{1} = 100\,k\Omega$

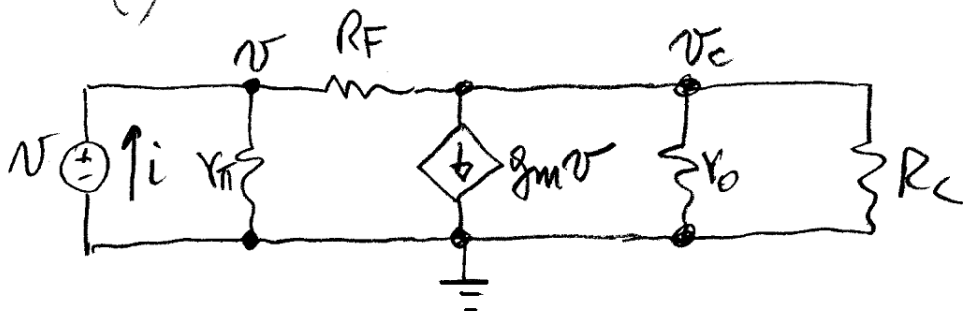$R_e \cong 26 \dfrac{1 + 10/100}{1 + 10/[101 \times 100]} \cong 28\,\Omega$.

(c) $R_e \to r_e = 26\,\Omega$.

(d) $R_e \to r_e \dfrac{R_C/r_0}{R_C/[(\beta_0 + 1) r_0]} = r_e (\beta_0 + 1) = r_\pi = 2.6\,k\Omega$.

2.45   (a)

$$i = \frac{v}{r_\pi} + \frac{v - v_c}{R_F};$$

$$\frac{v - v_c}{R_F} = g_m v + \frac{v_c}{r_o // R_C} \Rightarrow v\left(\frac{1}{R_F} - g_m\right) = \frac{v_c}{R_F // R_C // r_o} \Rightarrow$$

$$v_c = \frac{R_F \times (R_C // r_o)}{R_F + (R_C // r_o)} \frac{1 - g_m R_F}{R_F} v = \frac{R_C // r_o}{R_F + (R_C // r_o)} (1 - g_m R_F) v;$$

$$i = \frac{v}{r_\pi} + \frac{1}{R_F}\left[1 - \frac{R_C // r_o}{R_F + (R_C // r_o)} (1 - g_m R_F)\right] v$$

$$= v\left[\frac{1}{r_\pi} + \frac{1}{R_F} \frac{R_F + (R_C // r_o) - (R_C // r_o) + g_m R_F (R_C // r_o)}{R_F + (R_C // r_o)}\right]$$

$$= v\left[\frac{1}{r_\pi} + \frac{1 + g_m (R_C // r_o)}{R_F + (R_C // r_o)}\right]$$

$$R_i = \frac{v}{i} = \left(\frac{1}{r_\pi} + \frac{1 + g_m (R_C // r_o)}{R_F + (R_C // r_o)}\right)^{-1} = r_\pi // \frac{R_F + (R_C // r_o)}{1 + g_m (R_C // r_o)}$$

(b) $r_\pi = 100(26/1) = 2.6\ k\Omega,\ r_o = 100/1 = 100\ k\Omega,\ g_m = 1/(26\ \Omega)$

$$R_i = 2.6 // \frac{10 + (1 // 100)}{1 + (1 // 100)10^3/26} = 2.6 // 0.281 = 254\ \Omega.$$

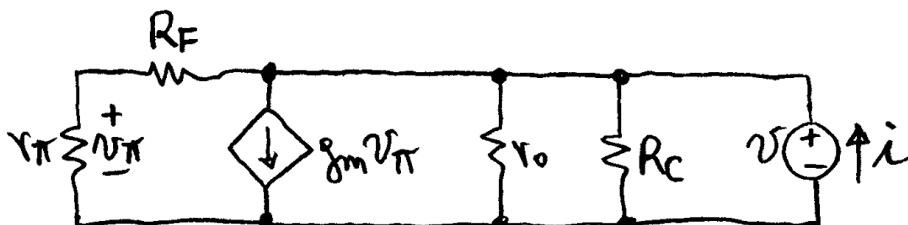(c) $R_F \to 0$ and $R_C \to \infty \Rightarrow$ BJT is diode-connected,

and $R_i = r_\pi // \left[\frac{r_o}{1 + g_m r_o}\right] \to r_\pi // \frac{1}{g_m} = r_e \cong 26\ \Omega.$

(d) $R_F \to \infty \Rightarrow R_i \to r_\pi // \infty = r_\pi.$

2.46 (a) SSM:

KCL: $i = \dfrac{v}{r_0 // R_C} + g_m v_\pi + \dfrac{v}{R_F + r_\pi}$. V.D.: $v_\pi = \dfrac{r_\pi}{R_F + r_\pi} v$.

$\therefore \quad g_m v_\pi = \dfrac{g_m r_\pi}{R_F + r_\pi} v = \dfrac{g_m \beta_0 / g_m}{R_F + r_\pi} v = \dfrac{\beta_0}{R_F + r_\pi} v$. Thus,

$i = \dfrac{v}{r_0 // R_C} + \dfrac{\beta_0 + 1}{R_F + r_\pi} v$; $R_o = \dfrac{v}{i} = (r_0 // R_C) // \dfrac{R_F + r_\pi}{\beta_0 + 1}$. But,

$\dfrac{r_\pi}{\beta_0 + 1} = \dfrac{\beta_0}{\beta_0 + 1} \dfrac{1}{g_m} = r_e$. So, $R_o = r_0 // R_C // \left(r_e + \dfrac{R_F}{\beta_0 + 1} \right)$.

(b) $r_e \cong 26\,\Omega$, $r_0 = 100\,k\Omega$, $R_o = 10^5 // 10^3 // \left(26 + \dfrac{10^4}{101} \right) \cong 111\,\Omega$.

(c) $(R_F \to 0, R_C \to \infty) \Rightarrow R_o = r_0 // r_e \cong r_e$ (BJT = diode).

(d) With the base at ac ground, $v_\pi \to 0$ and $g_m v_\pi \to 0$. By inspection, $R_o = R_F // r_0 // R_C$.

2.47 Apply test voltage v:
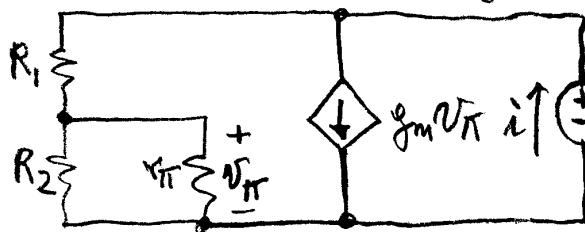
$v_\pi = \dfrac{R_2 // r_\pi}{R_1 + (R_2 // r_\pi)} v$

$i = g_m v_\pi + \dfrac{v}{R_1 + (R_2 // r_\pi)}$

$\quad = \dfrac{g_m (R_2 // r_\pi) + 1}{R_1 + (R_2 // r_\pi)} v$

$R = \dfrac{v}{i} = \dfrac{R_1 + (R_2 // r_\pi)}{1 + g_m (R_2 // r_\pi)} = \dfrac{[12 + (15 // 10)] 10^3}{1 + (15 // 10) 10^3 / 50} = \dfrac{18\,000}{121} = 149\,\Omega$.

2.48 (a) By inspection, $R_i = (R_1 + R_2) // R_b$. Using Eq. (53a),

$$R_i = (R_1 + R_2) // [r_\pi + (\beta_0 + 1) R_E]$$

(b)
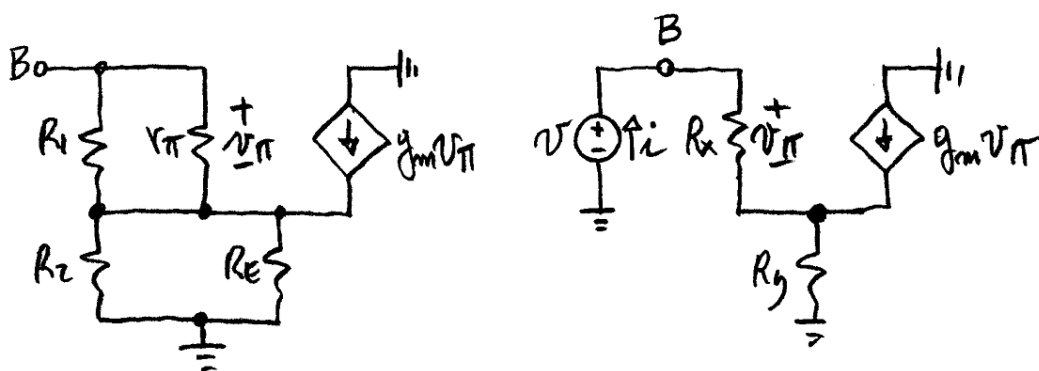
With the switch closed, we get the circuit at the left. This, in turn, is equivalent to that at the right, provided we let $R_x = R_1 // r_\pi$ and $R_y = R_2 // R_E$. Applying a test voltage, as shown, we get, by KCL & KVL,

$$\frac{v_\pi}{R_x} + g_m v_\pi = \frac{v - v_\pi}{R_y}.$$ But, $v_\pi = R_x i$. Eliminating v_π, collecting, and taking the ratio $R_i = \frac{v}{i}$ gives

$$R_i = R_x + (1 + g_m R_x) R_y.$$

(c) $g_m = 1/(26\Omega)$, $r_\pi = 2.6 k\Omega$. For case (a) we get

$$R_i = (10 + 10) // (2.6 + 101 \times 10) = 19.6 k\Omega \ (\cong R_1 + R_2).$$ For case (b) we get $R_x = 10 // 2.6 = 2.06 k\Omega$, $R_y = 10 // 10 = 5 k\Omega$;

$$R_i = 2.06 + \left(1 + \frac{5000}{26}\right) 5 = 969 k\Omega \ (\cong g_m R_x R_y).$$ This is much higher than (a)! The bootstrapping technique raises the input resistance dramatically!

2.49

(a) $V_E = (2/3)9 = 6V$, $V_C = (1/3)9 = 3V$; $R_E = R_C = 3/2 = 1.5k\Omega$. Let $\beta_F = 100$. Then, $I_B = (2mA)/100 = 20 \mu A$. Impose $I_{R_1} = 10 I_B = 0.2 mA$. Assuming $V_{EB}(on) = 0.7 V$, we have $V_B = 9 - (6 - 0.7) = 5.3V$; $R_1 = (9 - 5.3)/0.2 = 18.5 k\Omega$ (use $18 k\Omega$) and $R_2 = 5.3/(0.2 + 0.02) = 24 k\Omega$.

(b) $R_{BB} = 18//24 = 10.3 k\Omega$, $V_{BB} = 9 \times 24/(18 + 24) = 5.14 V$
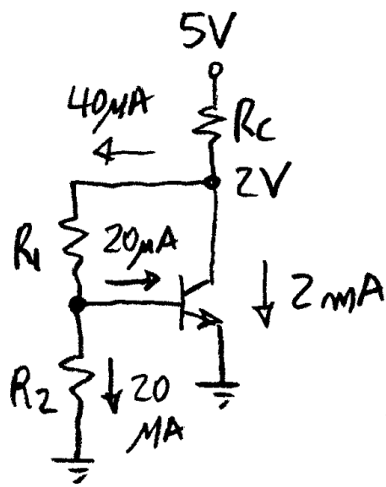
$$I_C \cong \frac{V_{EE} - V_{BB} - V_{EB}(on)}{R_{BB}/\beta_F + R_E} .$$

$$I_C(nominal) = \frac{9 - 5.14 - 0.7}{10.3/100 + 1.5} = 1.97 mA$$

$$I_C(max) = \frac{9 - 5.14(0.95) - 0.7}{(10.3 \times 0.95)/150 + 1.5(0.95)} \cong 2.3 mA$$

$$I_C(min) = \frac{9 - 5.14(1.05) - 0.7}{(10.3 \times 1.05)/75 + 1.5(1.05)} \cong 1.7 mA$$

$(\pm 0.3/2 = \pm 15\%$ variation in $I_C)$.

2.50

(a) $I_B = 2mA/100 = 20\mu A = I_{R_2}$.

5V

40μA

R_C

2V

R_1 20μA

↓2mA

R_2 ↓20 MA

$R_2 = 0.7/0.02 = 35 k\Omega$ (use 36 kΩ)

$R_1 = \dfrac{2-0.7}{0.02} = 32.5 k\Omega$ (use 33 kΩ)

$R_C = \dfrac{5-2}{2+0.04} = 1.47 k\Omega$ (use 1.5 kΩ).

(b) $V_C = V_{BE} + R_1\left(I_B + \dfrac{V_{BE}}{R_2}\right)$;

$V_C = 0.7 + 33(I_B + 0.7/36) = 1.34\,V + (33k\Omega)I_B$.

$I_C = \dfrac{5-V_C}{R_C} - \left(I_B + \dfrac{0.7}{36}\right) = \dfrac{5-1.34-33I_B}{1.5} - I_B - \dfrac{0.7}{36}$
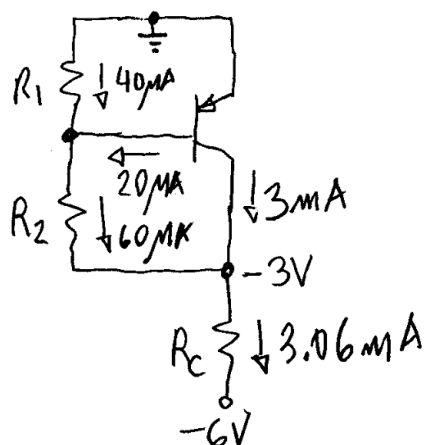
$= 2.42 - 23 I_B = 2.42 - 23 I_C/\beta_F$. Solving for I_C,

$I_C = \dfrac{2.42}{1+23/\beta_F}$. For $\beta_F = 50, 100, 200$, we get $I_C \cong 1.66\,mA,$

$1.97\,mA, 2.17\,mA$. **Not bad!** Moreover, $V_{CE} = V_C =$

$1.34 + 33I_C/\beta_F \cong 2.44V, 1.99V, 1.90V$, all near the

intended value of 2V.

| 2.51 |

(a) $I_B = 3/150 = 20\mu A$; $I_{R_1} = 40\mu A$; $R_1 = 0.7/0.04 = 17.5 k\Omega$ (Use 18 kΩ). $I_{R_2} = I_{R_1} + I_B = 3I_B = 60\mu A$; $R_2 = [0.7 - (-3)]/0.06 = 38.3 k\Omega$ (use 39 kΩ). $I_{R_C} = I_C + I_{R_2} = 3 + 0.06 = 3.06 mA$; $R_C = [-3 - (-6)]/3.06 = 0.98 k\Omega$ (use 1 kΩ).

$R_1 \downarrow 40\mu A$
$20\mu A \leftarrow$
$R_2 \downarrow 60\mu A$ $\quad \downarrow 3 mA$
$-3V$
$R_C \downarrow 3.06 mA$
$-6V$

(b) $V_C = -0.7 - R_2\left(I_B + \frac{0.7}{R_1}\right) = -0.7 - 39\left(I_B + \frac{0.7}{18}\right) \Rightarrow$

$V_{EC} = 0 - V_C = 2.217 + 39 I_B$. $\quad I_C = I_{R_C} - I_{R_2}$, or

$I_C = \frac{6 - V_{EC}}{R_C} - \left(I_B + \frac{0.7}{R_1}\right) = \frac{6 - 2.217 - 39 I_B}{1} - I_B - \frac{0.7}{18}$, or

$I_C = 3.74 - 40 I_B = 3.74 - \frac{40}{\beta_F} I_C \Rightarrow I_C = 3.74/\left(1 + \frac{40}{\beta_F}\right)$.

$I_{C(min)} = \frac{3.74}{1 + 40/75} = 2.44 mA$; $I_{C(nom)} = \frac{3.74}{1 + 40/150} = 2.96$

mA ; $I_{C(max)} = \frac{3.74}{1 + 40/250} = 3.23 mA$. Correspondingly,

$V_{EC}(max) = 2.217 + 39(2.44/75) = 3.49 V$;

$V_{EC}(nom) = 2.99 V$, $V_{EC}(min) = 2.72 V$.

2.52 (a) $I_{C2} = I_{C1} = (5 - 0.7)/4.3 = 1.0 \ mA$

(b) $I_{C2} = I_{C1} \exp(\Delta V_{BE}/V_T) = 1.0 \exp(2/26) = 1.080 \ mA$

(c) $I_{C2} = I_{C1} \exp(2 \times 5/26) = 1.469 \ mA$

(d) $V_{BE1} = 700 - 2 \times 10 = 680 \ mV;$

$I_{C1} = (5 - 0.68)/4.3 = (4.32/4.3) \ mA;$

$I_{C2} = \frac{4.32}{4.3} \exp(-2 \times 10/26) = 0.466 \ mA,$

(e) Now we must have $T(Q_1) > T(Q_2)$, such that

$T(Q_1) - T(Q_2) = \frac{26}{2} \ln \frac{1.0}{0.75} = 3.74 \ °C.$

2.53 $I_{C1} = (5 - 0.7)/4.3 = 1.0 \ mA$

(a) $I_{C2} = 0.4 \ mA = (1 \ mA/10) \times 2 \times 2.$ By the rule of thumb,

$V_{BE2} = 700 - 60 + 18 + 18 = 700 - 24 \ mV \Rightarrow \Delta V_R = 24 \ mV;$

$R = \Delta V_R / I_R = 24/0.4 = 60 \ \Omega$

(b) $\Delta V_R = 60 + 18 = 78 \ mV; \quad R = 78/0.05 = 1560 \ \Omega.$

(c) $\Delta V_R = (26 \ mV) \ln(1000/123) = 54.5 \ mV; \quad R = 54.5/0.123$

$= 443 \ \Omega.$

2.54

(a) $V_{BE1} = (26\,mV)\ln \dfrac{(6-0.7)/10^4}{2\times 10^{-15}} \cong 684\,mV$

$V_{BE2} = 0.026\ln \dfrac{0.684 - V_{BE2}}{10^3 \times 2\times 10^{-15}}$; start out with $V_{BE2} = 0.6\,V$.

$V_{BE2} = 0.026\ln \dfrac{0.684 - 0.6}{2\times 10^{-12}} = 0.636\,V$

$V_{BE2} = 0.026\ln \dfrac{0.684 - 0.636}{2\times 10^{-12}} = 0.620\,V$

Iterate further, and end with $V_{BE2} = 626\,mV$.

$I_{C2} = (0.684 - 0.626)/10^3 \cong 58\,\mu A$.
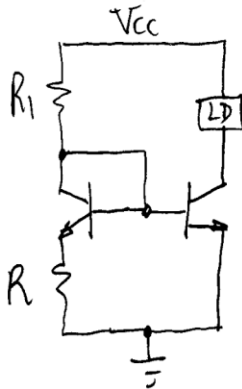
(c) With $V_{CC} = 6V$, $I_{C1} = (6 - 0.684)/10 = 0.5316$;

$(1/2)I_{C1} = 0.5316/2 = 0.2658$; Rule of Thumb:

$V_{BE1} = 684 - 18 = 0.666\,V$; $V_{CC} = 0.666 + 10 \times 0.2658 =$

$3.324\,V$. Reiterate as before, and find

$V_{BE2} = 0.026\ln \dfrac{0.666 - V_{BE2}}{2\times 10^{-12}} \Rightarrow V_{BE2} = 620\,mV \Rightarrow$

$I_{C2} = (0.666 - 0.620)/10^3 = 46\,\mu A$. While I_{C1} has

dropped to $\frac{1}{2}$ its initial value, I_{C2} has dropped

from $58\,\mu A$ to $46\,\mu A$. **Not** $1/2$, as I_{C2} is not

linearly proportional to I_{C1}.

2.55

(a) $I_S = 2fA \Rightarrow V_{BE} = 700\,mV$ @ $I_C = 1mA$.

$I_{C1} = 0.5mA \Rightarrow V_{BE1} = 700 - 18 = 682\,mV$

$I_{C2} = 2mA \Rightarrow V_{BE2} = 700 + 18 = 718\,mV$

∴ $R = (718 - 682)/0.5 = 72\,\Omega$.

$R_1 = (5 - 0.718)/0.5 = 8.564\,k\Omega$.

(b) $I_{C1} = 1mA \Rightarrow V_{BE1} = 700mV$; $V_R = 72 \times 1 = 72\,mV$.

$V_{BE2} = 700 + 72 = 772\,mV = (700 + 4 \times 18)mV \Rightarrow I_{C2} = 1 \times 2^4 =$

16 mA. Thus, while I_{C1} has doubled once, I_{C2} has

doubled four times!

2.56   (a) $R_1 = (12 - 5.6)/3 = 2.1\,k\Omega$ (use $2.0\,k\Omega$).

$R_2 = (5.6 - 0.7)/2 = 2.45\,k\Omega$ (use $2.4\,k\Omega$).

$g_m = 2/26 = 1/(13\Omega)$; $r_\pi = 100 \times 13 = 1.3\,k\Omega$; $r_0 = \frac{75}{2} \cong 37\,k\Omega$.

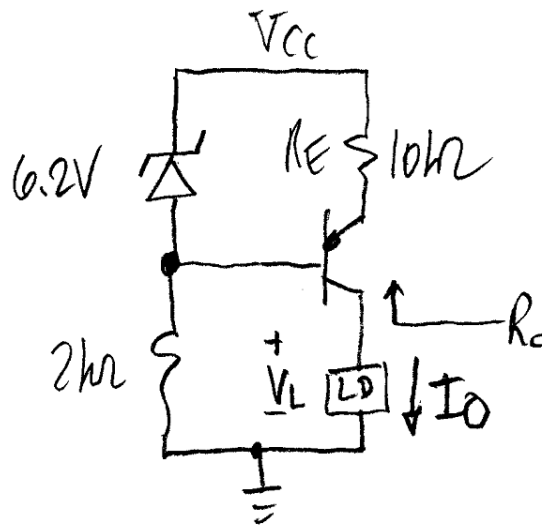$R_c = r_0 [1 + g_m(R_2 // r_\pi)] = 37[1 + (2400 // 1300)/13] \cong 2.5\,M\Omega$.

(b) An increase in V_L decreases V_{CE} and thus decreases

I_O. The change is such that $\Delta I_O / \Delta V_L = -\frac{1}{R_c} \cong -\frac{1}{2.5 \times 10^6} =$

$-0.4\,\mu A/V$. An increase in $|\Delta V_{EE}|$ increases both

V_Z and V_{CE}, according to

$\Delta V_Z = \frac{r_z}{R_1 + r_z} |\Delta V_{EE}| = \frac{15}{2000 + 15}|\Delta V_{EE}| \cong \frac{|\Delta V_{EE}|}{134}$, $\Delta V_{CE} = |\Delta V_{EE}|$.

$\Delta I_O = \frac{\Delta V_Z}{R_2} + \frac{\Delta V_{CE}}{R_c} = \frac{|\Delta V_{EE}|}{134 \times 2.4 \times 10^3} + \frac{|\Delta V_{EE}|}{2.5 \times 10^6} = (3.1 + 0.4)10^{-6}|\Delta V_{EE}|$.

∴ $\frac{\Delta I_O}{|\Delta V_{EE}|} = 3.5\,\mu A/V$.

2.57

An increase in V_L decreases V_{EC} and thus decreases I_0.

$$\frac{\Delta I_0}{\Delta V_L} = -\frac{1}{R_c} = -\frac{1}{r_o\left[1+g_m(R_E//r_\pi)\right]}$$

$$r_o = \frac{100}{0.55} \; ; \; g_m = \frac{0.55}{26} \; ; \; r_\pi \doteq 100\frac{26}{0.55} \; ; \; R_c = 12.5\,M\Omega$$

$$\frac{\Delta I_0}{\Delta V_L} = -\frac{1}{12.5\times10^{+6}}\frac{V}{A} \cong -80\,nA/V.$$

An increase in V_{cc} increases V_Z as well as V_{EC}

$$\Delta V_Z = \frac{20}{2000+20}\Delta V_{cc} = \frac{\Delta V_{cc}}{101} \Rightarrow \Delta I_{01} = \frac{\Delta V_Z}{10k\Omega} = \frac{\Delta V_{cc}}{101\times10^4}$$

$$\cong \frac{\Delta V_{cc}}{1\,M\Omega} \; ; \; \Delta I_{02} \cong \frac{\Delta V_{cc}}{12.5\,M\Omega} \; ;$$

$$\Delta I_0 = \Delta I_{01} + \Delta I_{02} = \Delta V_{cc}\left(\frac{1}{1M\Omega}+\frac{1}{12.5M\Omega}\right) = \frac{\Delta V_{cc}}{930\,k\Omega}$$

$$\frac{\Delta I_0}{\Delta V_{cc}} = \frac{1}{930\,k\Omega} \cong 1.1\,\mu A/V.$$

2.58

(a) $I_B = \dfrac{10-0.7}{33+151 \times 8.2} = 7.32\,\mu A$; $I_C = 1.097\,mA$;

$V_B = 33 \times 7.32 \times 10^{-3} = 0.241\ V$

$V_E = V_B + V_{EB(on)} = 0.241 + 0.7 = 0.941\ V$

$V_C = -10 + 4.7 \times 1.097 = -4.842\ V.$

$g_m = \dfrac{1.097}{26} = \dfrac{1}{23.7\,\Omega}$; $r_\pi = 3.55\,k\Omega$; $r_o = 45.5\,k\Omega.$

$R_i = 33 // 3.55 = 3.2\,k\Omega$; $R_o = 4.7 // 45.5 = 4.26\,k\Omega$;

$\dfrac{v_o}{v_{sig}} = \dfrac{3.2}{0.3+3.2}\left(-\dfrac{4260}{23.7}\right)\dfrac{12}{4.26+12} = -121\ V/V.$

(b) $v_B = V_B + v_b = 0.241V + \dfrac{3.2}{0.3+3.2}(5mV)\cos\omega t$

$\qquad = 0.241\ V + (4.57\ mV)\cos\omega t$;

$v_C = V_C + v_c = -4.842V - 121(5mV)\cos\omega t$;

$\qquad = -4.842V + (0.605\ V)\cos(\omega t - 180°)$;

$v_O = 0 + (0.605V)\cos(\omega t - 180°)$;

$v_E = 0.941V + 0.$

2.59
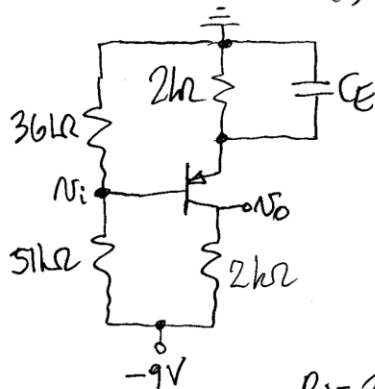
(a) $V_{BB} = \dfrac{36}{36+51}(-9) = -3.72\,V$

$R_B = 36//51 = 21\,k\Omega$

$I_C = 150\,\dfrac{3.72-0.7}{21+151\times 2} = 1.4\,mA$

$g_m = \dfrac{1}{18.5\,\Omega}$, $r_\pi = 2.78\,k\Omega$, $r_o = 43\,k\Omega$

$R_i = 36//51//2.78 \cong 2.5\,k\Omega$, $R_o = 2//43 = 2.46\,k\Omega$,

$V_o/V_i = -g_m R_o = -2.46/0.0185 \cong -133\ V/V$.

(b) $R_{eq} = r_e + R_{BB}/(\beta_o+1) = 18.5 + 21{,}000/151 \cong 160\,\Omega$.

$C_E \gg 1/(7\pi \times 160 \times 10^3) \cong 1\,\mu F$. Use $C_E = 10\,\mu F$.

2.60

$[V, mA, k\Omega]$. KVL: $10 = 3.9\,I_E + 68\,I_E/121 + 0.7 \Rightarrow$

$I_E = 2.08\,mA \Rightarrow I_C = 2.07\,mA \Rightarrow g_m = 1/(12.6\,\Omega)$, $r_\pi \cong$

$1.5\,k\Omega$, $r_o \cong 48\,k\Omega$, $R_C//r_o = 3.9//48 = 3.6\,k\Omega$

$R_i = r_\pi // \dfrac{R_F + (R_C//r_o)}{1 + g_m(R_C//r_o)} = 1.5 // \dfrac{68+3.6}{1+3600/12.6} \cong 214\,\Omega$

$R_o \cong R_C//r_o // \left[\dfrac{1}{g_m} + \dfrac{R_F}{\beta_o+1} \right] = 3600 // \left[12.6 + \dfrac{68{,}000}{121} \right] = 495\,\Omega$
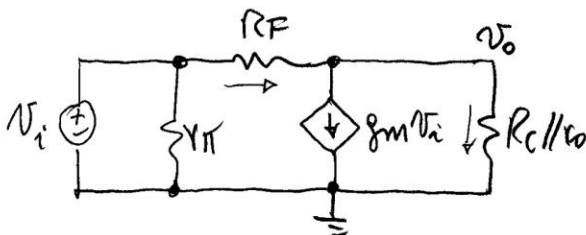
KCL:

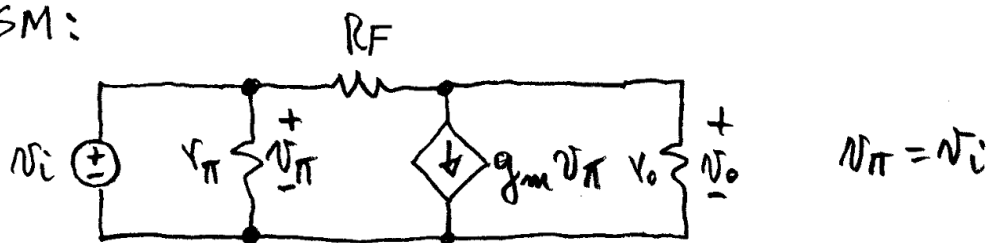$\dfrac{V_i - V_o}{R_F} = g_m V_i + \dfrac{V_o}{R_C//r_o}$

$\Rightarrow \left(\dfrac{1}{R_F} - g_m \right) V_i = V_o \left(\dfrac{1}{R_F} + \dfrac{1}{R_C//r_o} \right) = \dfrac{V_o}{R_F//R_C//r_o}$

$\dfrac{V_o}{V_i} = -\left(g_m - \dfrac{1}{R_F} \right)(R_F//R_C//r_o) = -\left(\dfrac{1}{12.6} - \dfrac{1}{68000} \right)(6800//3600) = -271\ V/V$.

2.61

(a) $I_E = I_{BIAS} = 1 \, mA$; $I_C = \alpha_F I_E = 0.99 \, mA$;

$I_B = I_E/(\beta_F + 1) = (1/101) \, mA$; $V_C = V_{BE} + R_F I_B = 0.7 + 100/101$

$\cong 1.7 \, V$. $r_o = 100/0.99 = 101 \, k\Omega$; $g_m = 0.99/26 \cong 1/(26.3 \, \Omega)$.

SSM:

$V_\pi = V_i$

KCL: $\dfrac{V_i - V_o}{R_B} = g_m V_i + \dfrac{V_o}{r_o}$; $V_i \left(\dfrac{1}{R_B} - g_m \right) = \dfrac{V_o}{R_F} + \dfrac{V_o}{r_o} = \dfrac{V_o}{R_F /\!/ r_o}$;

$\dfrac{V_o}{V_i} = -g_m \left(R_F /\!/ r_o \right) \left(1 - \dfrac{1}{g_m R_F} \right) = -\dfrac{0.99}{26} \left(100 /\!/ 101 \right) 10^3 \left(1 - \dfrac{1}{10^5/26.3} \right)$

$= -1913 \, V/V$.
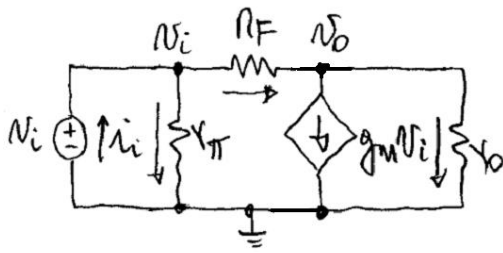
(b) g_m doubles to $2 \times 0.99/26$, and r_o halves to $50.5 \, k\Omega$.

From (a), it is apparent that $V_o/V_i \cong -g_m (R_F /\!/ r_o)$, so

$\dfrac{V_o}{V_i} = -\dfrac{1.98}{26} \left(100 /\!/ 50.5 \right) 10^3 = -2555 \, V/V$. Because of the

presence of R_F, which remains unchanged, the doubling

of g_m prevails over the halving of r_o, so the gain

magnitude increases.

2.62

(a) $I_C = 1 \text{mA} \Rightarrow g_m = 1/(26\Omega), \; r_\pi = 2.6k\Omega, \; r_o = 100 \, k\Omega.$

KCL: $i_i = \dfrac{v_i}{r_\pi} + \dfrac{v_i - v_o}{R_F} = \dfrac{v_i}{r_\pi // R_F} - \dfrac{v_o}{R_F}.$

KCL: $\dfrac{v_i - v_o}{R_F} = g_m v_i + \dfrac{v_o}{r_o} \Rightarrow$

$\dfrac{1 - g_m R_F}{R_F} v_i = \dfrac{v_o}{R_F // r_o} \Rightarrow$

$v_o = \dfrac{1 - g_m R_F}{R_F} \cdot \dfrac{R_F r_o}{R_F + r_o} v_i = \dfrac{1 - g_m R_F}{1 + R_F / r_o} v_i \Rightarrow i_i = \dfrac{v_i}{r_\pi // R_F} - \dfrac{1 - g_m R_F}{R_F (1 + R_F / v_o)} v_i$

$R_i = \dfrac{v_i}{i_i} = r_\pi // R_F // \dfrac{R_F (1 + R_F / r_o)}{g_m R_F - 1} = 2.6 // 100 // \dfrac{100 (1 + 100/100)}{100 / 0.026 - 1} \cong 52 \, \Omega.$

If $R_L = 100 k\Omega$, replace r_o with $r_o // R_L = 100 // 100 = 50 k\Omega$. Then,

$R_i = 2.6 // 100 // \dfrac{100 (1 + 100/50)}{100 / 0.026 - 1} \cong 76 \, \Omega.$ R_i is dominated by

the third term, roughly representing R_F divided by the gain $|v_o / v_i|$ (Miller effect). Loading the amplifier reduces the gain and thus increases R_i.
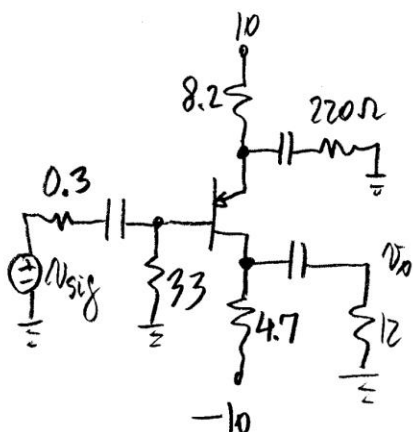
(b)
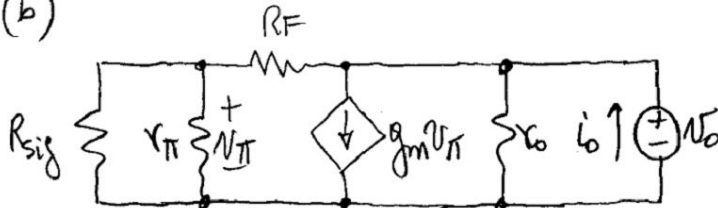
$i_o = \dfrac{v_o}{r_o} + \dfrac{v_o}{R_F + (R_{sig} // r_\pi)} + g_m \dfrac{R_{sig} // r_\pi}{R_F + (R_{sig} // r_\pi)} v_o = v_o \left[\dfrac{1}{r_o} + \dfrac{1 + g_m (R_{sig} // r_\pi)}{R_F + (R_{sig} // r_\pi)} \right]$

$R_o = \dfrac{v_o}{i_o} = r_o // \dfrac{R_F + (R_{sig} // r_\pi)}{1 + g_m (R_{sig} // r_\pi)}$. $R_o (R_{sig} = 0) = r_o // R_F = 50 \, k\Omega.$

$R_o (R_{sig} = 1 k\Omega) = 100 // \dfrac{100 + 1 // 2.6}{1 + (1 // 2.6) / 0.026} \cong 3.4 \, k\Omega$

With $R_{sig} \neq 0$, $v_\pi \neq 0$ and $g_m v_\pi \neq 0$, so i_o increases, reducing R_o. In the limit $R_{sig} \to \infty$, we get $R_o \to 1 k\Omega.$

2.63

$[V, mA, k\Omega]$:   DC analysis:

$$I_B = \frac{10-0.7}{33+126 \times 8.2} = 8.72 \mu A$$

$$I_C = 125 \times 8.72 = 1.09 \ mA$$

$$g_m = \frac{1.09}{26} = \frac{1}{23.8 \Omega}$$

$$r_\pi = 125 \times 23.8 = 2.98 \ k\Omega$$

$$R_i = R_B // R_b = 33 // \left[2.98 + (125+1)(8.2 // 0.22) \right] = 15.9 \ k\Omega$$

$$R_o \cong 8.2 \ k\Omega$$

$$\frac{v_o}{v_{sig}} = \frac{15.9}{0.3+15.9} \left(- \frac{1/23.8}{1+(1/23.8)(8200 // 220)} \, 8200 \right) \frac{12}{8.2+12}$$

$$= -17.2 \ V/V$$

2.64

(a) $I_C = 125 \dfrac{12-0.7}{100+126 \times 15} = 0.71 \ mA$; $g_m = 0.71/26 \cong$

$1/(37 \Omega)$; $r_\pi = 125 \times 37 \cong 4.6 \ k\Omega$.

$R_i = (100 \ k\Omega) // R_b = 100 // \left[4.6 + 126(15 // 0.1) \right] = 14.6 \ k\Omega$; $R_o = 10 k\Omega$.

$$\frac{v_o}{v_i} = - \frac{g_m}{1+g_m(15//0.1)10^3} R_o = - \frac{10,000/37}{1+99.3/37} = -74 \ V/V.$$

(b) $R_{eq} = 100 \Omega + 15 k\Omega // R_e = 100 + \left[15,000 // \left(37 + \dfrac{10^5}{126} \right) \right]$

$\qquad = 887 \Omega$. $C > 1/(6.28 \times 887 \times 100) = 1.8 \mu F$.

Use $20 \mu F$.

(c) Without C, the gain drops to $\dfrac{v_o}{v_i} \cong - \dfrac{10 \ k\Omega}{15 \ k\Omega} = -0.67 \ V/V$.

2.65

(a) $R_{BB} = 30//15 = 10 k\Omega$, $V_{BB} = [15/(30+15)]9 = 3V$.

$I_C = 100 \dfrac{3-0.7}{10+101\times2.2} = 0.99\,mA$; $g_m = \dfrac{1}{26\Omega}$; $r_\pi = 2.6 k\Omega$.

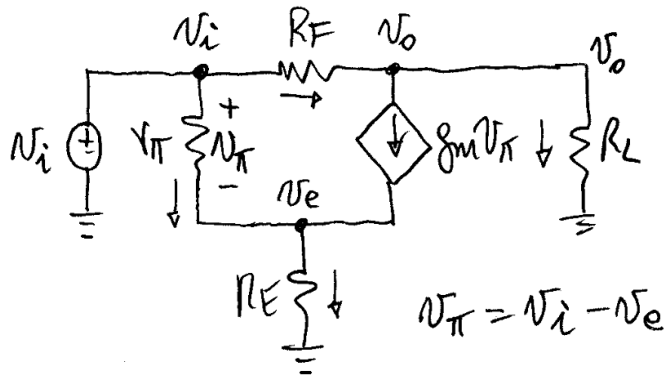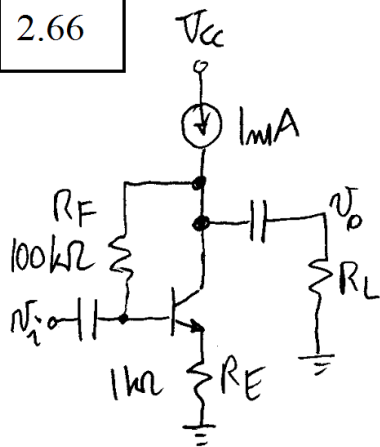$R_i = 10//[2.6+101\times0.2] \cong 7 k\Omega$; $R_o \cong 2.7 k\Omega$

$\dfrac{v_o}{v_i} = -\dfrac{1/26}{1+200/26} 2700 = -11.9 \ V/V$

(b) $R_{eq3} = 2,000//\left[200+26+\dfrac{10,000}{101}\right] \cong 280\Omega$

$C_3 >> 1/(2\pi\times10^3\times280) = 0.57\,\mu F$. Use $C_3 = 10\,\mu F$.

(c) $\dfrac{v_o}{v_i} \cong -\dfrac{2.7}{2+0.2} = -1.2 \ V/V$, quite low!

2.66

$$I_c = \alpha I_E = \frac{150}{151} 1 \approx 1mA, \quad g_m = \frac{1}{26.2\,\Omega}, \quad r_\pi = 39.3\,k\Omega.$$

KCL @ v_e:
$$\frac{v_i - v_e}{r_\pi} + g_m(v_i - v_e) = \frac{v_e}{R_E} \Rightarrow v_e = \frac{1}{1 + r_e/R_E} v_i$$

KCL @ v_o:
$$\frac{v_i - v_o}{R_F} = g_m(v_i - v_e) + \frac{v_o}{R_L} \Rightarrow$$

$$v_i\left(\frac{1}{R_F} - g_m + \frac{g_m}{1 + r_e/R_E}\right) = v_o\left(\frac{1}{R_F} + \frac{1}{R_L}\right) = \frac{v_o}{R_F \| R_L}$$

$$\frac{v_o}{v_i} = \frac{R_F R_L}{R_F + R_L} \frac{1}{R_F}\left[1 - g_m R_F\left(1 - \frac{1}{1 + r_e/R_E}\right)\right] = \frac{R_L}{R_F + R_L}\left[1 - g_m R_F \frac{r_e}{R_E + r_e}\right]$$

But, $g_m r_e \cong 1$, so

$$\frac{v_o}{v_i} = \frac{1}{1 + R_F/R_L}\left(1 - \frac{R_F}{R_E + r_e}\right) = \frac{1}{1 + 100/100}\left(1 - \frac{100}{1 + 0.026}\right) \cong -48 \; V/V.$$

For $R_E \gg r_e$, we can approximate

$$\frac{v_o}{v_i} \rightarrow \left(1 - \frac{R_F}{R_E}\right)\frac{1}{1 + R_F/R_L} = -\frac{99}{2} \; V/V.$$

2.67

(a) $R_i = r_{\pi 1} + (\beta_{01} + 1)(R_E // r_{e2}) \cong r_\pi + (\beta_0 + 1) r_e = 2 r_\pi$;

$R_C = r_{01}\left[1 + g_{m1}(r_{\pi 1} // R_E // r_{e2})\right] \cong r_0\left[1 + g_m r_e\right] \cong 2 r_0$;

$R_0 = R_d // R_c \cong R_c$; $\dfrac{v_0}{v_{sig}} = -\dfrac{g_{m1} R_0}{1 + g_{m1}(R_E // r_{e2})} \cong -\dfrac{g_m R_0}{2}$.

(b) $I_{C1} \cong I_{E1} = \dfrac{1}{2}\dfrac{12-0.7}{7.5} \cong 0.75\, mA$

$g_m = \dfrac{0.75}{26} = \dfrac{1}{34.7\, \Omega}$, $r_0 = \dfrac{100}{0.75} = 133\, k\Omega$; $r_\pi = 200 \times 34.7 = 6.9\, k\Omega$

$R_i \cong 2 r_\pi = 13.8\, k\Omega$; $R_c \cong 2 \times 133 = 267\, k\Omega$; $R_0 = R_c // R_C =$

$267 // 10 = 9.64\, k\Omega$; $\dfrac{v_0}{v_{sig}} = -\dfrac{1}{2}\dfrac{9640}{34.7} \cong -140\, V/V$.

2.68

$$\frac{v_o}{v_{sig}} = \cfrac{1}{1 + \cfrac{R_{sig} + r_\pi}{(\beta_0+1)(R_L//r_0)}} \cong \cfrac{1}{1 + \cfrac{R_{sig} + r_\pi}{(\beta_0+1)R_L}}$$

where we are assuming $r_0 \gg R_L$.

$$0.853 = \cfrac{1}{1 + \cfrac{0 + r_\pi}{(\beta_0+1)300}} = \cfrac{1}{1 + r_e/300} \Rightarrow r_e = 51.7 \ \Omega$$

$$\Rightarrow I_C \cong V_T/r_e = 26/51.7 \cong 0.5 \ mA.$$

$$0.718 = \cfrac{1}{1 + \cfrac{R_{sig} + r_\pi}{(\beta_0+1)R_L}} = \cfrac{1}{1 + \cfrac{10^4}{(\beta_0+1)300} + \cfrac{r_e}{300}} = \cfrac{1}{1 + \cfrac{33.3}{\beta_0+1} + \cfrac{51.7}{300}}$$

$$\Rightarrow \beta_0 = 150 \ ; \ r_\pi = 151 \times 51.7 = 7.75 \ k\Omega.$$

$$\frac{v_o}{v_{sig}} = \cfrac{1}{1 + \cfrac{20000 + 7755}{151 \times 1200}} = 0.867 \ V/V.$$

2.69

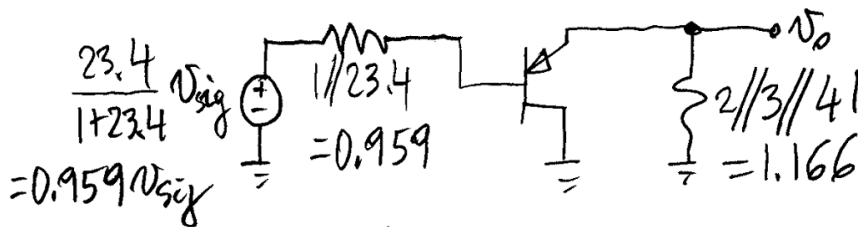$$V_{BB} = \frac{68}{68+47}(-12) = -7.1V; \quad R_{BB} = 68//47 = 27.8 \, k\Omega.$$

$$I_C = 125 \frac{7.1-0.7}{27.8+126\times3} = 1.97 \, mA; \quad r_e \cong \frac{26}{1.97} = 13.2 \, \Omega; \quad r_\pi =$$

$$125 \times 13.2 = 1.65 \, k\Omega; \quad r_o = 80/1.97 = 40.6 \, k\Omega \cong 41 \, k\Omega$$

$$R_i = R_{BB} // [r_\pi + (\beta_o+1)(R_E//R_L//r_o)] = 27.8 // [1.65 + 126(3//2//41)] = 23.4 \, k\Omega$$

$$R_o = R_E // r_o // [r_e + \frac{R_{sig}//R_{BB}}{\beta_o+1}] = 3//41//[0.0132 + \frac{1//27.8}{126}] = 20.7 \, \Omega.$$

$$\frac{23.4}{1+23.4} V_{sig}$$

$$= 0.959 \, V_{sig}$$

$$1//23.4 = 0.959$$

$$2//3//41 = 1.166$$

$$\frac{V_o}{V_{sig}} = 0.959 \frac{1}{1+\frac{1.65+0.959}{126\times1.166}} = 0.942 \, V/V.$$

2.70

(a) $I_C = 100 \dfrac{6-0.7}{20+101\times 3} = 1.64 \, mA$, $r_e = 15.7 \, \Omega$,

$r_\pi \cong 1.6 \, k\Omega$. $R_i = 20 // (1.6 + 101\times 3) \cong 19 \, k\Omega$

$R_o = 3,000 // [15.7 + (10,000 // 20,000)/101] \cong 80 \, \Omega$.

Thévenize:
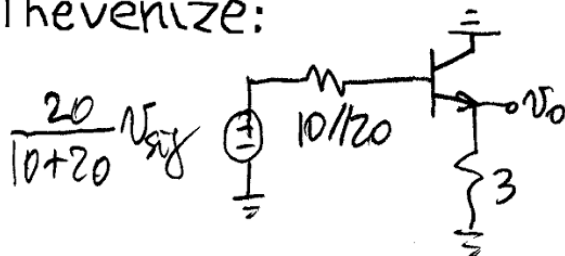
$$\dfrac{v_o}{\frac{2}{3} v_{sig}} = \dfrac{1}{1 + \dfrac{1.6 + (10 // 20)}{101 \times 3}}$$

$$\dfrac{v_o}{v_{sig}} = 0.649 \; V/V$$

(b) With C_2 in place, the upper 10-$k\Omega$ resistance is placed in parallel with r_π, giving $r_{\pi(eq)} = 10 // 1.6 \cong 1.4 \, k\Omega$; the lower 10-$k\Omega$ resistance is placed in parallel with R_E, giving $R_{E(eq)} = 10 // 3 = 2.3 \, k\Omega$. We now have

$R_i = r_{\pi(eq)} + (\beta_o + 1) R_{E(eq)} = 1.4 + 101 \times 2.3 = 234 \, k\Omega$

$R_o = R_{E(eq)} // \left(r_e + \dfrac{R_{sig}}{\beta_o + 1} \right) = 2,300 // \left(15.7 + \dfrac{10,000}{101} \right) = 110 \, \Omega$

$$\dfrac{v_o}{v_{sig}} = \dfrac{1}{1 + \dfrac{r_{\pi(eq)} + R_{sig}}{(\beta_o + 1) R_{E(eq)}}} = \dfrac{1}{1 + \dfrac{1.4 + 10}{101 \times 2.3}} = 0.953 \; V.$$

Bootstrapping increases R_i significantly, thus reducing input loading and making gain closer to unity.

2.71 $I_C = (5-0.7)/4.3 = 4.3\,mA$; $r_e \cong 26\,\Omega = 1/g_m$;

$r_o = 75/1 = 75\,k\Omega$; $r_\pi = 150 \times 26 = 3.9\,k\Omega$

$v_e = \dfrac{R//r_o}{r_e + (R//r_o)} \quad v_i = \dfrac{4.3//75}{0.026 + (4.3//75)}(0.5)\cos\omega t$

$v_e = (496.8\,mV)\cos\omega t$; $i_o = \alpha_o i_e \cong i_e = v_e/R$

$i_o = (115.5\,\mu A)\cos\omega t$

$(115.5\,\mu A\cos\omega t)$ $6\,M\Omega$ LD

$R_o = r_o\left[1 + g_m(R_E//r_\pi)\right]$

$R_o \cong 75\,k\Omega\left[1 + (4,300//3,900)/26\right] \cong 6\,M\Omega$

2.72 $I_{C1} = I_{C2} \cong \dfrac{12-0.7}{10} = 1.13\,mA$;

$r_{e1} = r_{e2} = 0.99\,(26/1.13) = 22.8\,\Omega$;

$r_{\pi 1} = r_{\pi 2} = 100\,(26/1.13) = 2.3\,k\Omega$

$R_i = r_{\pi 1} + (\beta_{o1}+1)(R_{E1}//R_{b2})$, $R_{b2} = r_{\pi 2} + (\beta_{o2}+1)(R_{E2}//R_L)$

$R_o = R_{E2}//R_{e2}$, $R_{e2} = r_{e2} + \dfrac{R_{E1}//r_{e1}}{\beta_{o1}+1}$.
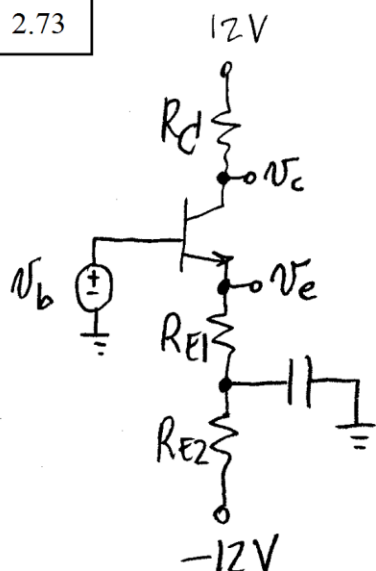
$R_{b2} = 2.3 + 101\,(10//20) = 676\,k\Omega$

$R_i = 2.3 + 101\,(10//676) \cong 1\,M\Omega$

$R_{e2} = 22.8 + \dfrac{10^4//22.8}{101} \cong 23\,\Omega$; $R_o = 10^4//23 \cong 23\,\Omega$.

$\dfrac{v_o}{v_i} = \dfrac{v_o}{v_{e1}} \times \dfrac{v_{e1}}{v_i} \cong \dfrac{R_L}{R_o + R_L} \times \dfrac{R_{E1}}{r_{e1} + R_{E1}} \cong \dfrac{20,000}{23 + 20,000} \times \dfrac{10,000}{23 + 10,000}$

$\cong 0.9965\ V/V.$

2.73

Impose $I_C = 1 mA$, $V_C = 6 V$.
$\Rightarrow R_C = 6 k\Omega$ (use $6.2 k\Omega$, 5%)

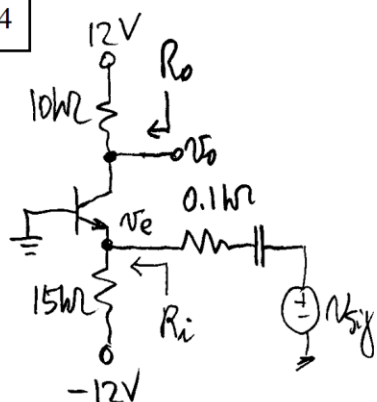We know that $v_e / v_b \cong 1$ V/V, so to achieve $v_c / v_b \cong -1$ V/V we need $R_{E1} = R_C = 6.2 k\Omega$.

Also, to ensure $I_C = 1 mA$, we need $R_{E1} + R_{E2} = (12 - 0.7)/1$, or $R_{E2} = 11.3 - 6.2 = 5.1 k\Omega$, 5%.

$R_{eq} = R_{E2} // (R_{E1} + r_e) = 5.1 // (6.2 + 0.026) = 2.8 k\Omega.$

$C > \dfrac{1}{2\pi \times 2.8 \times 10^3 \times 10^4} = 5.7 mF.$ Use $C = 0.1 \mu F.$

2.74

$I_C \cong I_E = \dfrac{12 - 0.7}{15} = 0.753 mA$

$r_e = \dfrac{26}{0.753} \cong 35 \Omega.$ $R_o \cong 10 k\Omega.$

$R_i = 35 // (15 k\Omega) \cong 35 \Omega.$

$v_e = \dfrac{0.035}{0.035 + 0.1} v_{sig} = 0.26 v_{sig}.$

$v_o = g_m v_e R_o = \dfrac{1}{35} (0.26 v_{sig}) 10,000 = 74 v_{sig}.$ $v_o / v_{sig} = 74$ V/V.

2.75

$$R_2 = \frac{10-0.7}{2} = 4.65 \, k\Omega \; (\text{use } 4.7 \, k\Omega);$$

$$r_e \simeq \frac{26}{2} = 13 \, \Omega, \; R_1 = \frac{10-5}{2} = 2.5 \, k\Omega \; (\text{use } 2.4 \, k\Omega).$$

$$10 = \frac{R_1}{r_e + R_2 // R_3} = \frac{2,400}{13 + (4,700 // R_3)} \Rightarrow 4700 // R_3 = 227 \, \Omega \Rightarrow$$

$$\frac{1}{4700} + \frac{1}{R_3} = \frac{1}{127} \Rightarrow R_3 = 238 \, \Omega \; (\text{use } 240 \, \Omega).$$

2.76

(a) $R_i = R_1 // R_{e1}, \; R_{e1} = r_{e1} + \frac{r_{e2} // R_2}{\beta_{o1} + 1} \simeq r_{e1};$

$$r_{e1} = \frac{V_T}{I_{C1}} \simeq \frac{26}{10/10} = 26 \, \Omega; \; R_i = 10,000 // 26 \simeq 26 \, \Omega.$$

$$R_o \simeq r_{o1}\left[1 + g_{m1}\left(R_{sig} // R_1 // r_{\pi 1}\right)\right] = \frac{80}{1}\left[1 + \frac{1 // 10 // (150 \times 0.026)}{0.026}\right]$$

$$\simeq 2.35 \, M\Omega. \; v_i = \frac{R_i}{R_{sig} + R_i} v_{sig} = \frac{26}{1000 + 26} v_{sig} = \frac{v_{sig}}{39.5}.$$

$$i_o = g_m v_i = \frac{1}{26} \frac{v_{sig}}{39.5} = \frac{v_{sig}}{1026 \, \Omega}.$$

(b) $v_o = (R_L // R_o) i_o \simeq R_L i_o = \frac{5000}{1026} v_{sig} \Rightarrow \frac{v_o}{v_{sig}} = 4.87 \; V/V.$

(c) As long as $R_{sig} \gg R_i$ and $R_L \ll R_o$, we have

$$v_o = R_L i_o = R_L \alpha_o i_i \simeq R_L(v_{sig}/R_{sig}) \Rightarrow v_o/v_{sig} \simeq R_L/R_{sig} = 5 \; V/V.$$