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) $I_s = 10 \times 20 \times 10^{-8} \frac{1}{10^{-4}} 2\times10^{20} \frac{1.6\times10^{-19}\times18}{10^{17}} = 0.115\ fA.$

$$\beta_F = \frac{1}{\frac{1.8}{18}\frac{10^{17}}{10^{19}}\frac{1}{1} + \frac{(10-4)^2}{2\times150\times10^{-9}\times18}} = \frac{1}{\frac{1}{1000}+\frac{1}{540}} = 351$$

(b) $I_C = 0.115\times10^{-15}\times\exp(700/26) = 56.8\ \mu A$

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

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

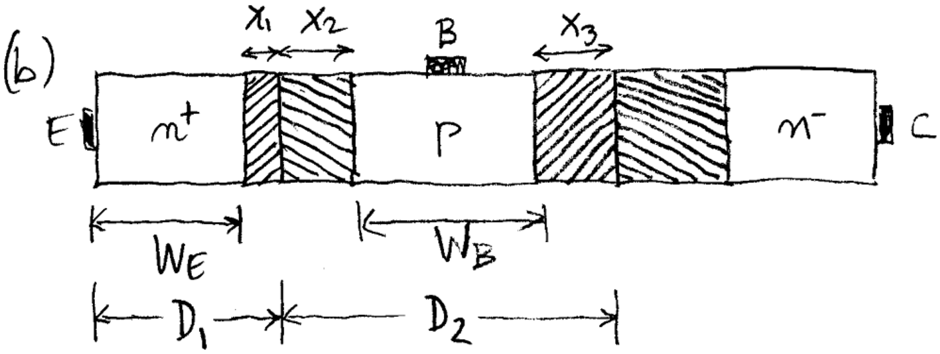
2.3 (a) $\beta_F = 250 \Rightarrow 1/(1/x + 1/y) = 250$; $i_{BE} = i_{BB} \Rightarrow$

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

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

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

(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) $I_s = (25\times10^{-4})(50\times10^{-4})\frac{1}{10^{-4}}\times2\times10^{20}\frac{1.6\times10^{-19}}{10^{17}}8 = 0.32\ fA.$

$$\beta_F = \frac{1}{\frac{3}{8}\frac{10^{17}}{10^{19}}\frac{1}{1}+\frac{(10^{-4})^2}{2\times100\times10^{-9}\times8}} = \frac{1}{\frac{1}{267}+\frac{1}{160}} = 100$$

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

$$\beta_F = \frac{1}{K_2W_B + K_3W_B^2} \Rightarrow \beta_F = \frac{1}{\frac{0.5}{267}+\frac{0.5^2}{160}} = \frac{1}{\frac{1}{533}+\frac{1}{640}} = 291.$$

(c) $I_S = 0.32\ fA$ (unchanged).

$$\beta_F = \frac{1}{K_3/W_E + 1/160} = \frac{1}{\frac{1}{267\times2}+\frac{1}{160}} = 123.$$

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) $I_E \cong \frac{4-0.7}{3.3} = 1\ mA$; $V_{EB} = 0.026 \ln\frac{10^{-3}}{4\times10^{-15}} = 0.682V$;

$I_E = \frac{4-0.682}{3.3} = 1.005\ mA$

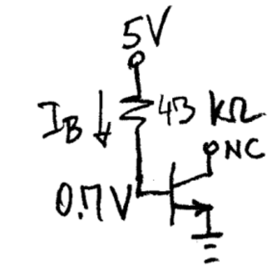
$\beta_F = \frac{1}{0.002+0.004} = 167 \Rightarrow I_B = \frac{1.005}{167+1} \cong 6\mu A$

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

(b) $I_{EB} = 0.002\times0.999 \cong 2\mu A$; $I_{BB} \cong 4\mu A$.

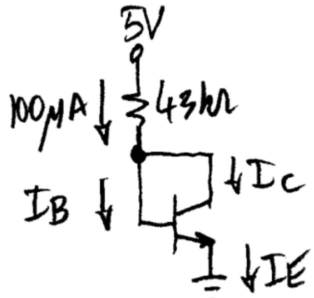
(c) $I_C = 0$; $I_B = I_E \cong 1mA$.

2.6



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

About 1 μA of holes diffusing from B to E, and 99 μA of electrons diffusing from E to B.

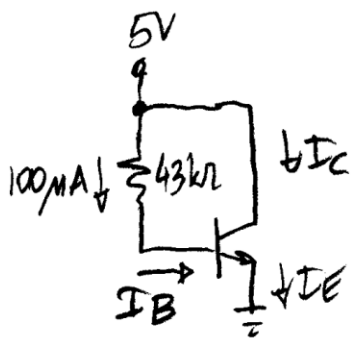


$I_E = 100\,\mu A$ (~1 μA holes from B to E, and ~99 μA electrons from E to C).

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

$\Rightarrow I_B \cong 1\,\mu A$ (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 $V_B = -5 - 0.8 = -5.8\,V$; $I_E = I_L = 500\,\mu A$;

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

2.8

(a) $i_{O1} = \frac{1}{100} = 10\ mA$; $i_{O2} = 0$; $v_I = v_O + v_{BE1} = 1 + 0.026 \ln[(10\times10^{-3})/(10\times10^{-15})] = 1.72\ V$; $i_I = 10/151 = 66.2\ \mu A$.

(b) $i_{O1} = 0$; $i_{O2} = 10\ mA$; $v_I = v_O - v_{EB2} = -1 - 0.026 \times \ln[(10\times10^{-3})/(20\times10^{-15})] = -1.70\ V$; $i_{I2} = 10/101 \cong 9.9\ \mu A$.

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

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

2.9

(a) $i_{C2} \cong i_{E2} = v_O/R_L = 1/8 = 125\ mA$; $i_I = \frac{125}{101\times51} \cong 24\ \mu A$; $i_{C1} = 100\times24 = 2.43\ mA$.

$v_I = 1 + 0.026\left[\ln\frac{2.43\times10^{-3}}{10\times10^{-15}} + \ln\frac{125\times10^{-3}}{10^{-12}}\right] = 1 + 1.346 = 2.346\ V.$

(b) $i_{C2} \cong \frac{4}{8} = 500\ mA\ (= 2\times2\times125\ mA)$; $i_I \cong 97\ \mu A$;

$v_I = 4 + 1.346 + 2(18+18)\times10^{-3} = 5.418\ V$

(c) $i_{C2} = 2A\ (= 16\times125\ mA)$; $i_I \cong 0.388\ mA$.

$v_I = 16 + 1.346 + 2(18+18+18+18)\times10^{-3} = 17.490\ V.$

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

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

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

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

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

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

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

(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) $500\times10^{-6} = 2\times10^{-15} e^{V_{EB}/26}(1+\frac{4}{50}) \Rightarrow V_{EB} \cong 680$ mV.

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

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

(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 μA, we'd have to decrease V_{EB} by $30\times2 = 60$ mV, or 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 $I_C = 10\times500 = 5$ mA.

2.13 (a) $I_B = \frac{5-0.7}{300} = 14.\overline{3}\,\mu A$; $I_C = \beta_F I_B = 120 \times 14.\overline{3}$
$= 1.720$ 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) $I_B = \frac{5-0.7}{30} = 0.14\overline{3}$ mA; $I'_C = \beta_R I_B = 2 \times 0.14\overline{3} =$
$0.28\overline{6}$ V; $V_E = 5 - 10 \times 0.28\overline{6} = 2.1\overline{3}$ V.

2.14 (a) $I_C = \frac{5-1}{2} = 2$ mA; $I_B = \frac{5-0.71}{300} = 14.3\,\mu A$
$\Rightarrow \beta_F = 2/0.0143 \cong 140$.
$I_S = I_C / e^{V_{BE}/V_T} = 2 \times 10^{-3}/\exp(700/26) = 2.76$ 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;
$\beta_R = 0.3/0.14\overline{3} \cong 2$.

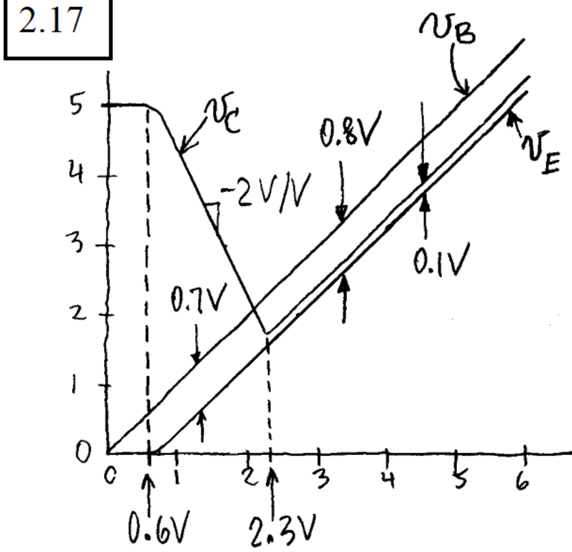
2.15

(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

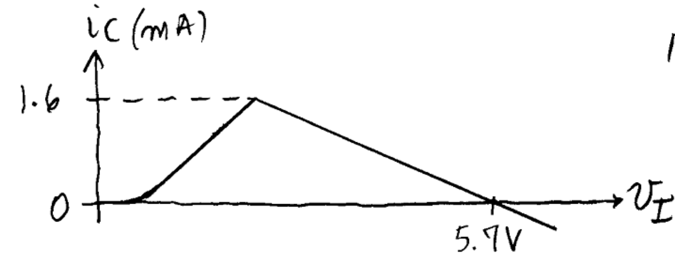
(a) $V_{BC} = 0 \Rightarrow I_C = (10.7-0.7)/10 = 1.000\ mA$;
$\beta_F = 1000/8 = 125$.
(b) $V_{BC} = -10\ V \Rightarrow x_p = 20nm\sqrt{1-\frac{-10}{0.8}} = 73.5\ nm$.
$W_B = 500 - 73.5 = 426.5\ nm$. $I_C = 1mA\frac{500}{426.5} = 1.172\ mA$
(c) $r_o = \frac{\Delta V_C}{\Delta I_C} = \frac{10}{0.172} = 58\ k\Omega = \frac{V_A}{I_C} \Rightarrow V_A \cong 60\ V$.

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



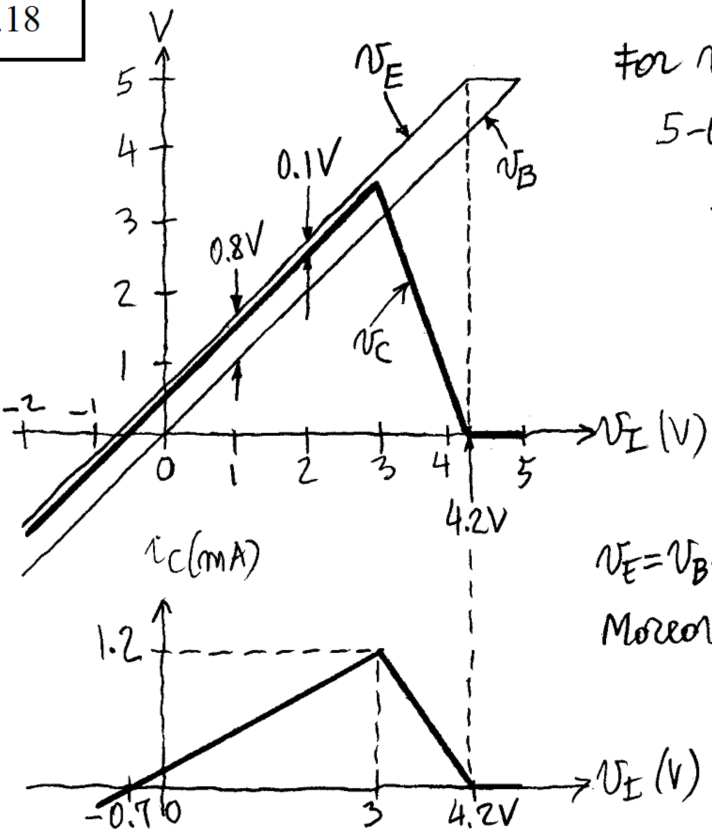
$v_C = V_S + \frac{R_C}{R_E} V_{BE(on)} - \frac{R_C}{R_E} v_I$. Clearly, the plot of v_C v.s. v_I has a slope of $-R_C/R_E = -2\,V/V$.

③ The BJT reaches the EOS when $\frac{v_E}{1} \cong \frac{5-(v_E+0.2)}{2}$, 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 $v_I > V_S - V_{EB(eoc)} = 5 - 0.8 = 4.2\text{V}$, BJT = CO $\Rightarrow v_C = 0$, $i_C = 0$. Lowering v_I below 4.2V turns BJT on, initially FA, where we have

$v_E = v_B + V_{EB(on)} = v_I + 0.8\text{V}$. 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 $(3\text{V})/(3\text{k}\Omega) = 1$ mA/V. Once v_C comes within 0.1V 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 $v_I = 2.975 \cong 3\text{V}$. At this point, $i_C = \frac{v_C}{3} \cong \frac{3}{3}(4.2 - 3) = 1.2\text{mA}$. Lowering v_I below 3V drives the BJT more and more into saturation, and $v_C = v_E - 0.1 = v_I + 0.8 - 0.1 = v_I + 0.7\text{V}$, $i_C = v_C/R_C = (v_I + 0.7\text{V})/(3\text{k}\Omega)$. 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 $v_I < -0.7\text{V}$.

2.19 [V, mA, kΩ].

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:

$i_E = \frac{v_S - 0.7}{1}$; $i_B = \frac{i_E}{\beta_F + 1} = \frac{v_S - 0.7}{101 \times 1}$; $i_C = \alpha_F i_E = \frac{100}{101}\frac{v_S - 0.7}{1} \cong$

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

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

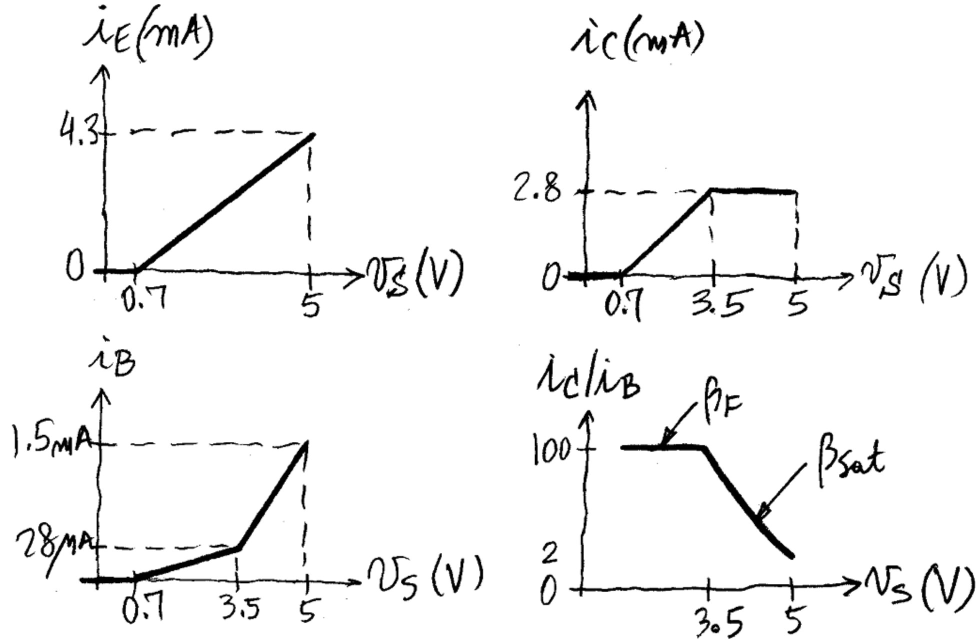
$I_{C(EOS)} = \frac{0.6 - (-5)}{2} = 2.8mA$, $V_{S(EOS)} = 0.7 + 1 \times I_{E(EOS)} \cong$

$0.7 + 1 \times I_{C(EOS)} = 0.7 + 2.8 = 3.5V$; $I_{B(EOS)} = \frac{2.8}{100} = 28\mu A$.

(4) For $v_S > 3.5V$, BJT = Sat: $i_C = I_{C(EOS)} = 2.8mA$,

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

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



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

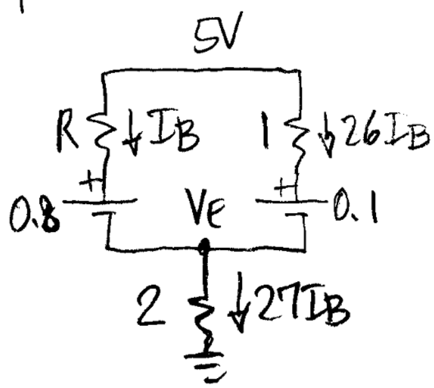
$\Rightarrow 3 = (3\beta_F + 2) I_B$, $4.3 = (302 + 2\beta_F) I_B \Rightarrow$

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

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

$\Rightarrow I_E \cong (5 - 0.2)/3 = 1.6\ mA$; $V_E = 2 \times 1.6 = 3.2\ V$; $V_B = 3.2 + 0.7 = 3.9\ V$; $I_B = 1.6/131 = 12.2\ \mu A$; $R_B = (5 - 3.9)/0.0122 = 90\ k\Omega$.

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



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

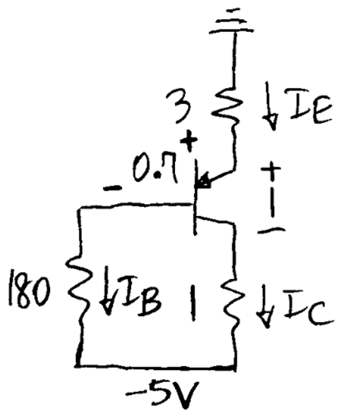
$5 = 1 \times 26 I_B + 0.1 + 54 I_B \Rightarrow I_B = 61.25\ \mu A$.

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

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

2.21

(a) [V, kΩ, mA].



KVL: $5 = 3I_E + 1 + 1I_C$, or

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

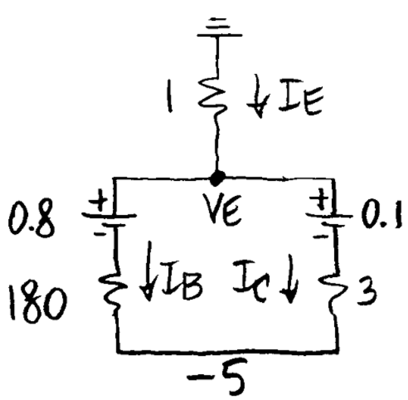
KVL: $5 = 3I_E + 0.7 + 180I_B$, or

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

Take the ratio of the two eqns:

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

(b) Swapping R_E and R_C causes the BJT to saturate.



$$\text{KCL: } \frac{0-V_E}{1} = \frac{V_E-0.8-(-5)}{180} + \frac{V_E-0.1+5}{3}$$

$\Rightarrow V_E = -1.237\text{ V}$. $I_E = 1.237\text{ mA}$;

$I_C = 1.221\text{ mA}$; $I_B = 16.5\ \mu\text{A}$.

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

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

In FA, $5 = 0.7 + 20 I_B + 3(1+150) I_B \Rightarrow I_B = 9.\overline{09}\ \mu A$;

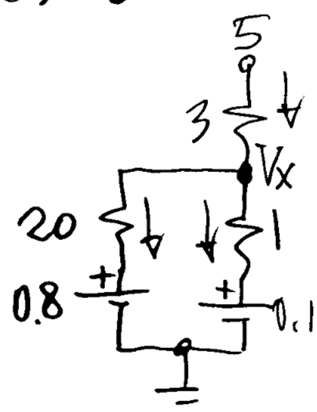
$I_C = 150 \times 9.\overline{09} = 1.\overline{36}\ mA$; $I_E = 1.3\overline{72}\ mA$; KVL:

$V_C = 0.7 + 20 \times 0.00\overline{909} - R_3 \times 1.\overline{36} = 0.8\overline{81} - R_3 \times 1.\overline{36}$.

$V_{C(min)} = V_{CE(EOS)} = 0.2V \Rightarrow 0.2 = 0.8\overline{81} - R_{3(max)} \times 1.\overline{36} \Rightarrow$

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

(b) $R_3 = 2 \times 0.5 = 1\ k\Omega \Rightarrow$ BJT = Sat $\Rightarrow V_{CE} = 0.1V$, $V_{BE} = 0.8V$.



$$\frac{5 - V_X}{3} = \frac{V_X - 0.8}{20} + \frac{V_X - 0.1}{1} \Rightarrow V_X = 1.306\,V.$$

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

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

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

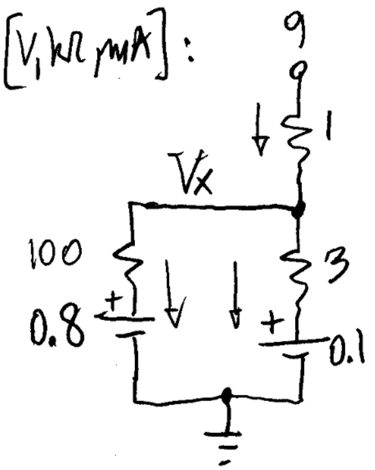
2.23 (a) Assume FA, and check. By inspection, $I_{R_2} = I_B + I_C = (\beta_F + 1) I_B = 151 I_B$. KVL:

$9 = 20(151 I_B) + 100 I_B + 0.7 \Rightarrow I_B = 2.66\ \mu A$, $I_C = 150 I_B = 0.399\ mA$, $I_E = 151 I_B = 0.402\ mA$. By KVL again,

$V_{CE} = V_C = V_S - R_2 I_E - R_3 I_C = 9 - 20 \times 0.402 - 1 \times 0.399 = 0.567V > 0.2V \Rightarrow$ FA!

(b) Assume saturation, and check. KCL:

[V, kΩ, mA]:



$$\frac{9 - V_x}{1} = \frac{V_x - 0.1}{3} + \frac{V_x - 0.8}{100} \Rightarrow V_x = 6.73V.$$

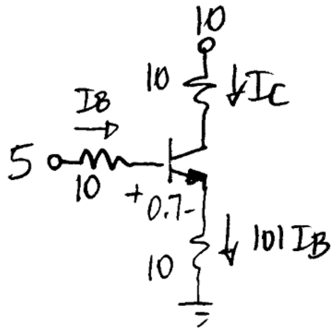
$$I_B = \frac{6.73 - 0.8}{100} = 59.3\ \mu A$$

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

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

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

2.24 (a) [V, mA, kΩ]. Assume FA. KVL:



$5 = 10I_B + 0.7 + 10(101 I_B) \Rightarrow I_B = 4.2\,\mu A$

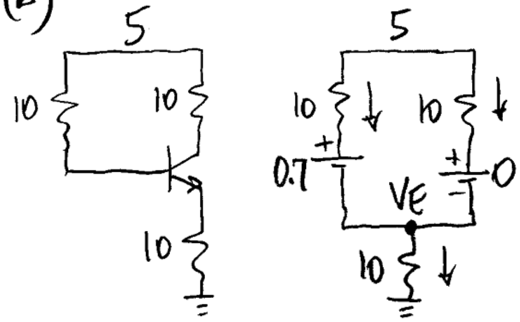
$I_C = 0.422\,mA$; $I_E = 0.426\,mA$

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

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

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

(b)



Now BJT is saturated.

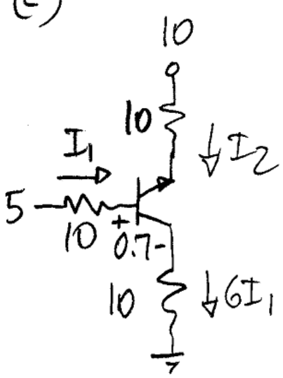
KCL:

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

$\Rightarrow V_E = 3.1\,V.$

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

(c) Reverse active mode. KVL:



$5 = 10I_1 + 0.7 + 6I_1 \Rightarrow I_1 = 61.4\,\mu A$

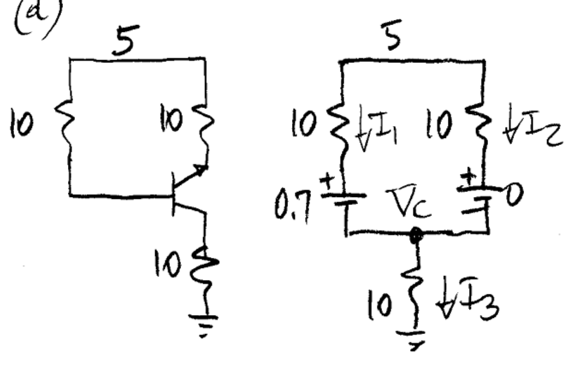
$I_2 = 5I_1 = 307\,\mu A$; $6I_1 = 369\,\mu A$.

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

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

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

(d)



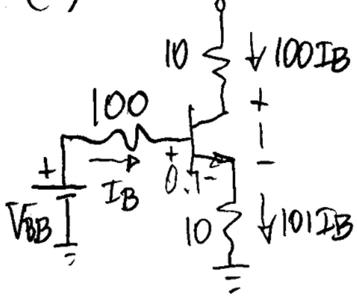
BJT is in reverse-mode saturation. Equivalent circuit is similar to (b).

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

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

2.25 $[\text{V}, \text{mA}, \text{k}\Omega]$.

(a)



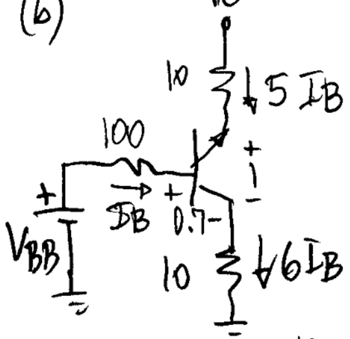
KVL: $10 = 10(100 I_B) + 1 + 10(101 I_B)$

$\Rightarrow I_B = 4.478\ \mu A$;

$V_E = 10 \times 101 I_B = 4.522\ V$; $V_B = V_E + 0.7 V$

$= 5.22\ V$; $V_{BB} = V_B + 100 I_B = 5.67\ V$.

(b)



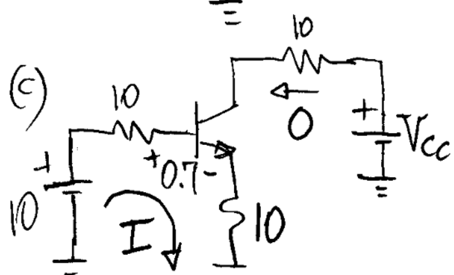
KVL: $10 = 10(5I_B) + 1 + 10(6I_B)$

$\Rightarrow I_B = 81.\overline{81}\ \mu A$

$V_C = 10 \times 6 I_B = 4.91\ V$; $V_B = 5.61\ V$

$V_{BB} = 5.61 + 100 \times 0.0\overline{81} = 13.8\ V$.

(c)



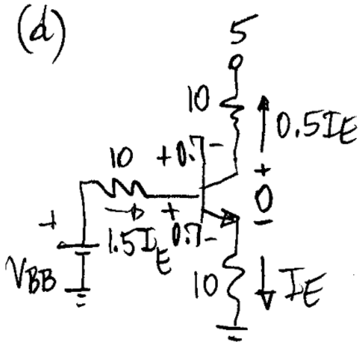
$I_C = 0 \Rightarrow I_B = I_E = I$. KVL:

$10 = 10I + 0.7 + 10I \Rightarrow I = 0.465\ mA$

$\Rightarrow V_E = 4.65\ V$, $V_B = 5.35\ V$.

For $I_C = 0$, $V_{CC} \cong V_B - 0.65 = 4.7\ V$.

(d)



$I_B = 1.5 I_E \Rightarrow I_C = -0.5 I_E$ (out of collector)

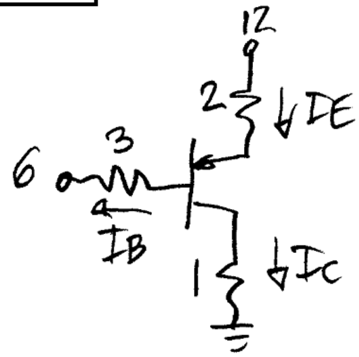
$\Rightarrow \beta_{sat} = (-0.5 I_E)/(1.5 I_B) = -\frac{1}{3} < \beta_F \Rightarrow$ sat.

$\Rightarrow V_{BC} = V_{BE} = 0.7\ V \Rightarrow 10 I_E = 5 + 10(0.5 I_E)$

$\Rightarrow I_E = 1\ mA \Rightarrow V_{BB} = 10(1.5 \times 1) + 0.7 +$

$10(1) = 25.7\ V$.

2.26 (a) [V, mA, kΩ].



Assume FA: KVL:

$$12 = 2 \times 151 I_B + 0.7 + 3 I_B + 6$$

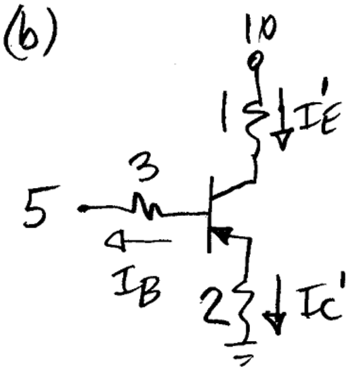
$\Rightarrow I_B = 17.4\ \mu A$, $I_C = 2.61$ mA,

$I_E = 2.62$ mA, $V_B = 6.052$ V,

$V_E = 6.752$ V, $V_C = 2.607$ V

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

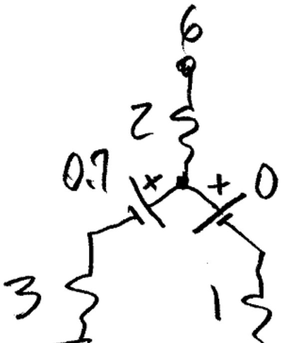
$I_E' = 5 \times 0.5375 = 2.6875$ mA

$V_B = 5 + 3 \times 0.5375 = 6.6125$ V; $V_C = 6.6125 + 0.7 = 7.3125$ V;

$V_E = 2 \times 2.15 = 4.3$V. $7.3125 - 4.3 > 0.1 \Rightarrow$ 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

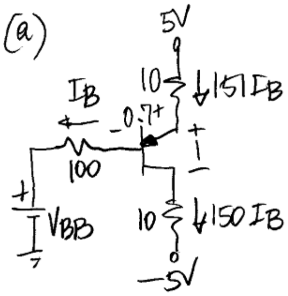
$V_B = 1.0\overline{36}$ V

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

$\Rightarrow$ Sat!

2.27 $[V, mA, k\Omega]$.

(a)



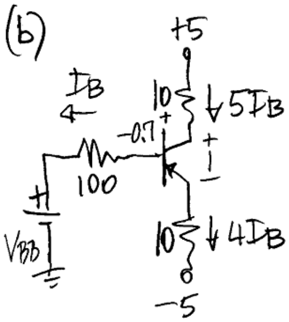
KVL: $5-(-5)=10(151I_B)+1+10(150I_B)$

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

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

$= -0.514$ V.

(b)



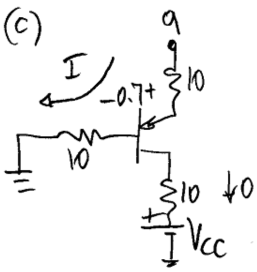
$10 = 10(5I_B)+1+10(4I_B)$

$\Rightarrow I_B = 0.1$ mA

$V_{BB} = 5-10(5\times0.1)-0.7-100\times0.1$

$= -10.7$V

(c)



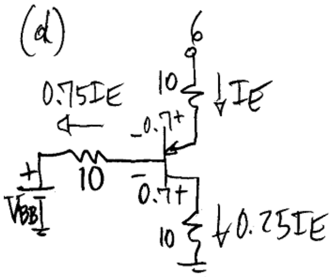
$I_C = 0 \Rightarrow I_B = I_E = I$. KVL:

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

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

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

(d)



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

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

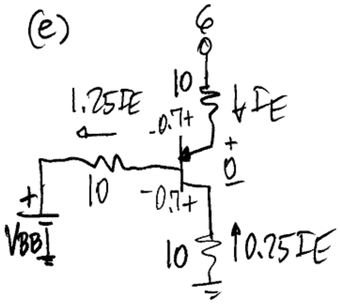
$\frac{1}{3} < 150 \Rightarrow$ saturation $\Rightarrow V_{EC} = 0$

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

$I_E = 0.48$ mA. KVL:

$V_{BB} = 6-10(0.48)-0.7-10(0.75\times0.48) = -3.1$V.

(e)



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

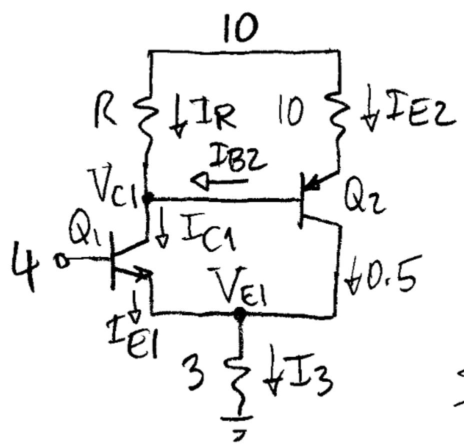
$= -0.2 < 150 \Rightarrow$ saturation $\Rightarrow$

$V_{EC} = 0$. KVL:

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

$V_{BB} = 6-10(0.8)-0.7-10(1.25\times0.8) = -12.7$ V.

2.28 $[\mathrm{V}, \mathrm{mA}, \mathrm{k}\Omega]$. Assume $Q_1 = Q_2 = \mathrm{FA}$. $I_{E2} = \frac{51}{50} 0.5 = 0.51\ \mathrm{mA}$.



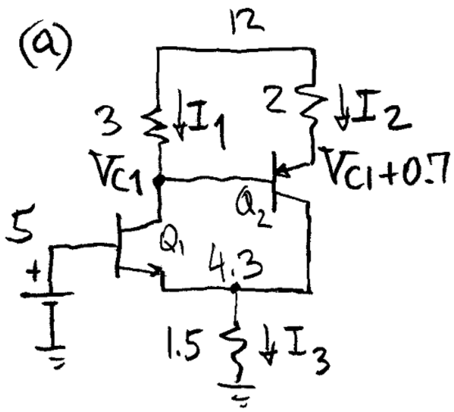
KVL: $V_{E2} = 10 - 10 \times 0.51 = 4.9\ \mathrm{V}$. KVL: $V_{B2} = 4.9 - 0.7 = 4.2\ \mathrm{V} = V_{C1}$. KCL: $I_{E1} = I_3 - I_{C2} = \frac{4-0.7}{3} - 0.5 = 0.6\ \mathrm{mA}$. $I_{C1} = \frac{55}{56} 0.6 = \frac{33}{56}\ \mathrm{mA}$. KCL: $I_R = I_{C1} - I_{B2} = \frac{33}{56} - \frac{0.5}{50} = \frac{811}{1400}\ \mathrm{mA}$.

Ohm: $R = \frac{10 - 4.2}{811/1400} = \mathbf{10.0\ k\Omega}$. Check: $V_{CE1} = 4.2 - (4 - 0.7) > 0.2\ \mathrm{V}$ $\Rightarrow Q_1 = \mathrm{FA}$. $V_{EC2} = 4.9 - (4 - 0.7) > 0.2\ \mathrm{V} \Rightarrow Q_2 = \mathrm{FA}$.

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

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

(a)

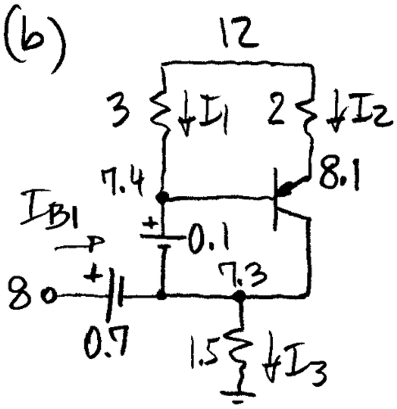


$I_3 = I_{E1} + I_{C2} \cong I_1 + I_2$, or

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

$\Rightarrow V_{C1} = 8.14\text{V} \Rightarrow I_{C1} \cong I_1 = \frac{12 - 8.14}{3} \cong 1.29$ mA; $I_{C2} \cong I_2 = \frac{12 - (8.14 + 0.7)}{2} \cong 1.58$ mA; $V_{CE1} = 8.14 - 4.3 = 3.84$ V ($\gg 0.1$V $\Rightarrow$ Sat); $V_{EC2} = (8.14 + 0.7) - 4.3 = 4.54$ V ($\gg 0.1$V $\Rightarrow$ Sat). Consequently, $Q_1 = Q_1(1.29\text{mA}, 3.84\text{V})$, $Q_2 = Q_2(1.58\text{mA}, 4.54\text{V})$.

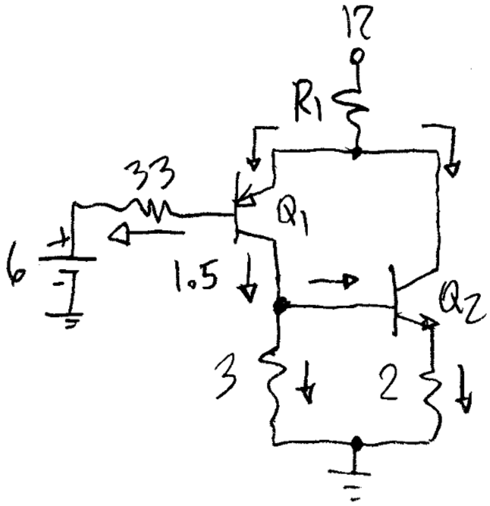
(b)



Assume $Q_1 =$ Sat, $Q_2 =$ FA, and check. $V_{E1} = V_{C2} = 8 - 0.7 = 7.3$V; $I_3 = 7.3/1.5 = 4.87$mA; $V_{C1} = V_{B2} = 7.3 + 0.1 = 7.4$V; $V_{E2} = V_{B2} + 0.7 = 8.1$ V. $I_1 = (12 - 7.4)/3 = 1.53$mA; $I_2 = (12 - 8.1)/2 = 1.95$ mA. $Q_2 = Q_2(1.95\text{mA}, 0.8\text{V})$, FA. KCL:

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

2.30 (a) [V, mA, kΩ]: KCL: $15 = I_{3k\Omega} + I_{B2} = I_{3k\Omega} + I_{E2}/(\beta_2+1)$



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

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

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

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

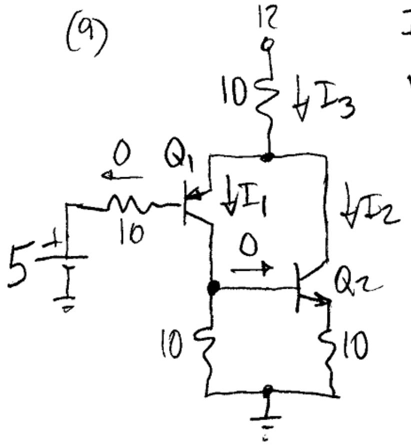
$$I_{R1} = I_{E1} + I_{C2} = 3.34 \text{ mA}$$

$I_{B1} = I_{C1}/\beta_1 = 1.5/50 = 0.03$ mA; $V_{B1} = 6 + 33\times 0.03 = 6.99$ V;
$V_{E1} = V_{B1} + 0.7 = 7.69$ V. $R_1 = (12-7.69)/3.34 \cong 1.3$ kΩ.
Check: $V_{EC1} = (12 - 1.3\times 3.34) - 4.39 \cong 3.3V >> 0.1V \Rightarrow$ FA.
$V_{CE2} = (12 - 1.3\times 3.34) - (4.39-0.7) \cong 4V >> 0.1V \Rightarrow$ FA.

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

2.31 [V, mA, kΩ]. Assume $Q_1 = Q_2 = FA$, and check.

(a)



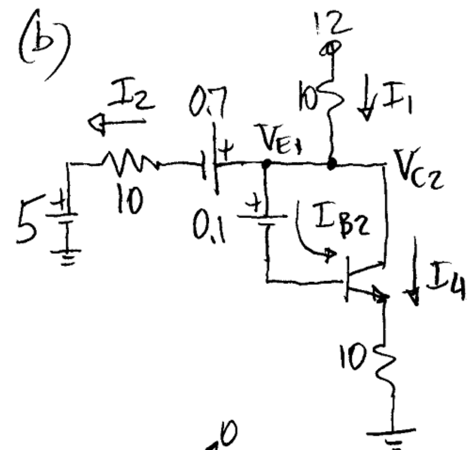
Ignoring I_{B1} and I_{B2}, we have, by KVL, $V_{C2} = V_{E1} = V_{B1} + 0.7 \cong 5 + 0.7 = 5.7\text{V}$. Ω: $I_3 = (12 - 5.7)/10 = 0.63\text{ mA}$. KCL: $I_3 = I_1 + I_2 \Rightarrow 0.63 \cong \frac{V_{C1}}{10} + \frac{V_{C1} - 0.7}{10}$

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

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

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

(b)



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

$I_1 = I_2 + \cancel{I_{B2}}^{\,0} + I_4 \cong I_2 + I_4$, or

$\frac{12 - V_x}{10} = \frac{(V_x - 0.7) - 5}{10} + \frac{(V_x - 0.1) - 0.7}{10} \Rightarrow V_x = 6.1\bar{6}\text{ V}$.

$I_{B1} = I_2 = \frac{(6.1\bar{6} - 0.7) - 5}{10} = 0.04\bar{6}\text{ mA}$; $I_{C2} \cong I_4 = \frac{(6.1\bar{6} - 0.1) - 0.7}{10} = 0.53\bar{6}\text{ mA}$. $I_{C1} = I_{B2} = I_{C2}/\beta_{F2}$. Assuming $\beta_{F2} > 100$, we have $I_{C1} < 0.53\bar{6}/100 = 5.3\bar{6}\,\mu\text{A} \Rightarrow \beta_{sat1} < 5.3\bar{6}/46.\bar{6} \approx 0.1 \Rightarrow Q_1$ = Sat. Thus, $Q_1 = Q_1(<5.3\bar{6}\,\mu\text{A}, 0.1\text{V})$, and $Q_2 = Q_2(0.53\bar{6}\text{mA}, 0.8\text{ V})$.

2.32 [V, mA, kΩ]. 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 $= V_{C1}$.

$I_{B2} = 6.\overline{72}/100 = 67.\overline{27}$ μA

$I_{C1} = (15 - 6.0\overline{27})/30 + 67.\overline{27} \times 10^{-3} = 0.36\overline{63}$ mA. Assume Q_1 = FA.

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

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

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

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

$R_3 = 3.9/0.37 = 10.5$ kΩ

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

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

$$I_{B1} = \frac{5-0.7}{110+101\times 18} = 2.23\ mA$$

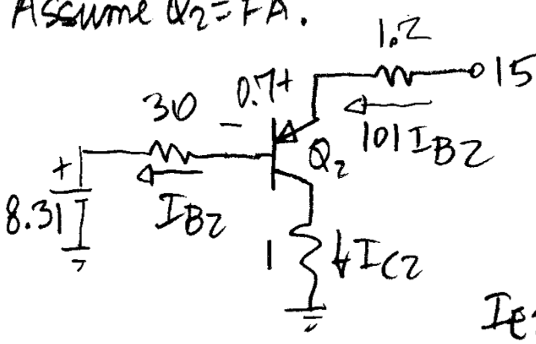
$V_{B1} = 5 - 110\times 2.23\times 10^{-3} = 4.75V$; $V_{E1} = 4.05V$

$I_{C1} = 100\times 2.23 = 0.223\ mA$

$V_{C1} = 15 - 30\times 0.223 = 8.31\ V$

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

Assume $Q_2 = FA$.



$$I_{B2} = \frac{15-8.31-0.7}{30+101\times 1.2} \cong 39.6\ \mu A.$$

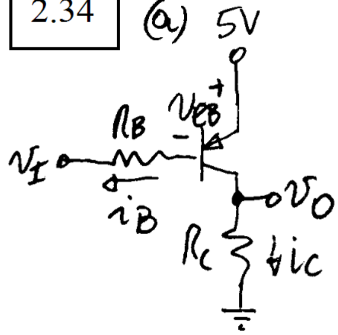
$V_{B2} = 8.31 + 30\times 39.6\times 10^{-3} = 9.5V$

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

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

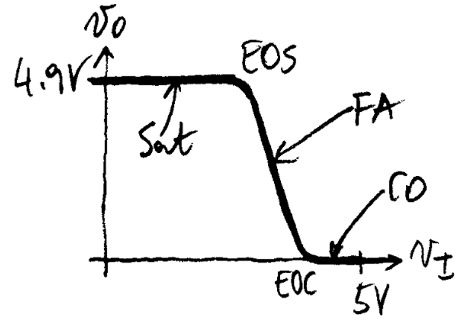
$V_{C2} = 1\times 3.96 \cong 4V$. $V_{EC2} = 10.2 - 4 \gg 0.2 \Rightarrow Q_2 = FA.$

2.34 (a)



For $v_I > V_{CC} - V_{EB(EOC)} \cong 5 - 0.6 = 4.4\,\text{V}$, 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 $v_O = V_{CC} - V_{EC(sat)} = 5 - 0.1 = 4.9\,\text{V}$.

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

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

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

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

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

(b) $v_I = 10^4\left(\frac{5-v_O}{10^3}\right)/100 + \left(1+\frac{10}{5}\right) 0.026 \ln \frac{5-v_O}{10^3 \times 2\times10^{-15}}$

$$v_I = \frac{5-v_O}{10} + 0.078 \ln \frac{5-v_O}{2\times10^{-12}}.$$

(c) $V_I = \frac{5-2.5}{10} + 0.078 \ln \frac{5-2.5}{2\times10^{-12}} = 0.25 + 2.173 = 2.423\text{ V}$

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

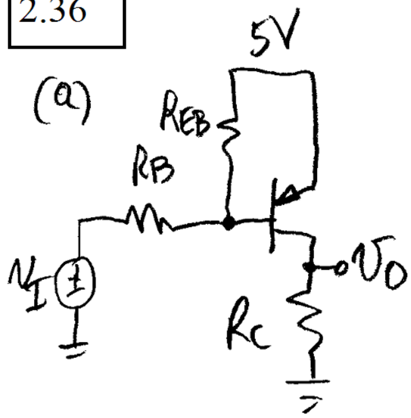
(d) $\frac{dv_I}{dv_I} = \frac{1}{10}\frac{dv_O}{dv_I} + 0.078 \frac{2\times10^{-12}}{5-v_O}\left(-\frac{1}{2\times10^{-12}}\frac{dv_O}{dv_I}\right) \Rightarrow$

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

@ $v_O = 2.5\text{ V}$, $a = -7.62$ 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 $2.5 = 5 - 10^4 \dfrac{2.5}{80 \times 10^3} - \left(1 + \dfrac{10^4}{R_{EB}}\right) \times$

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

(b) $v_I = 5 - 10 \dfrac{v_O}{80 \times 1} - 3 \times 0.026 \ln v_O/(10^3 \times 10^{-15})$, or

$v_I = 5 - \frac{1}{8} v_O - 0.078 \ln(10^{12} v_O)$. Differentiate wrt v_I:

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

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

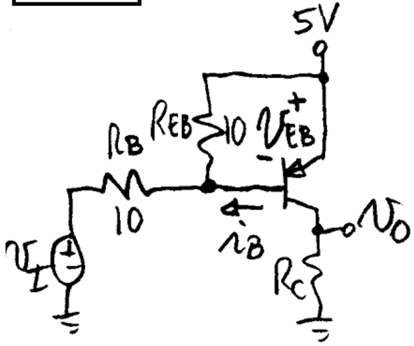
For $v_O = 2.5$ V, gain $= \dfrac{1}{0.078/2.5 - 1/8} = -10.7$ V/V

2.37

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

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

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



(b) $i_B = i_C/\beta_F = \frac{v_O}{R_C\beta_F} = \frac{v_O}{2\times10^3\times125} = \frac{v_O}{25\times10^4}$

$$v_I = 5 - 10^4\frac{v_O}{25\times10^4} - 2\times0.026\ \ln\frac{v_O/(2\times10^3)}{5\times10^{-15}}$$

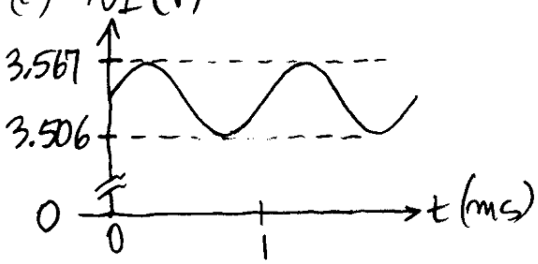
$\Rightarrow v_I = 5 - \frac{v_O}{25} - 0.052\ln(10^{11}v_O)$.

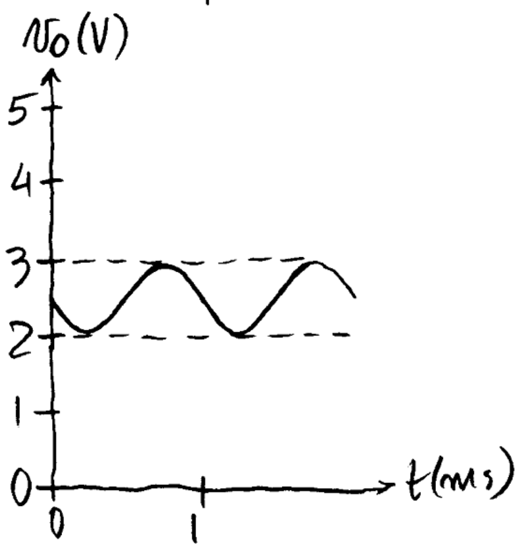
$v_{I1} = 5 - \frac{2}{25} - 0.052\ln(10^{11}\times2) = 3.567\text{ V}$

$v_{I2} = 5 - \frac{3}{25} - 0.052\ln(10^{11}\times3) = 3.506\text{ V}$

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

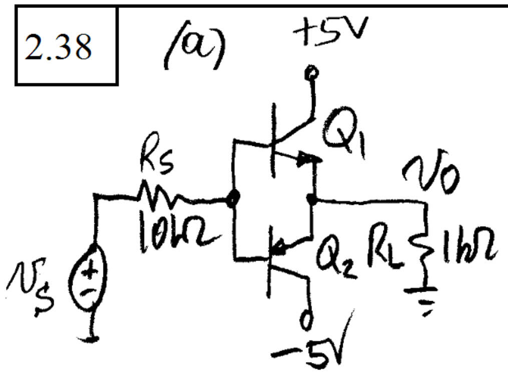
(c) v_I (V)





2.38

(a)



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

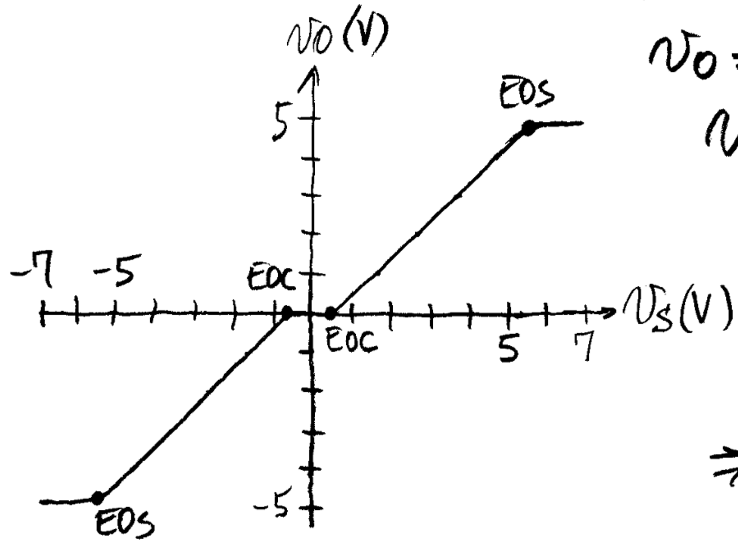
$v_I = 4.8 + 0.7 + R_S i_B$

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

$= 5.55V$.

$v_I > 5.55V \Rightarrow Q_1 = Sat$

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



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

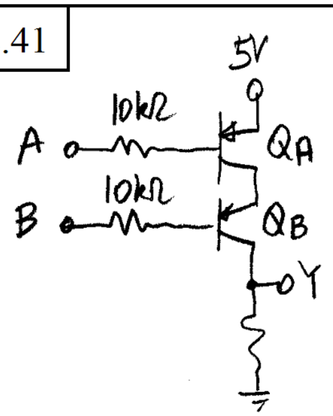
2.40 (a)

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

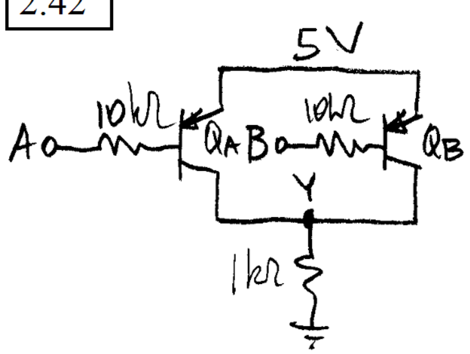
$$\beta_{FB} \geq \left[\frac{5-2(0.1)}{1} + \frac{5-(0.8+0.1)}{10}\right] \Big/ \left[\frac{5-0.8}{10}\right] = 11.$$

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

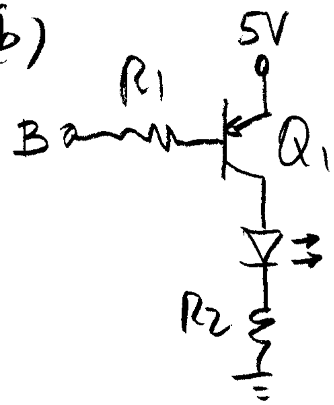
(a) $R_2 = (5-1.5-0.1)/10 = 0.34\ k\Omega$ (use $330\ \Omega$).

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

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

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

(b)

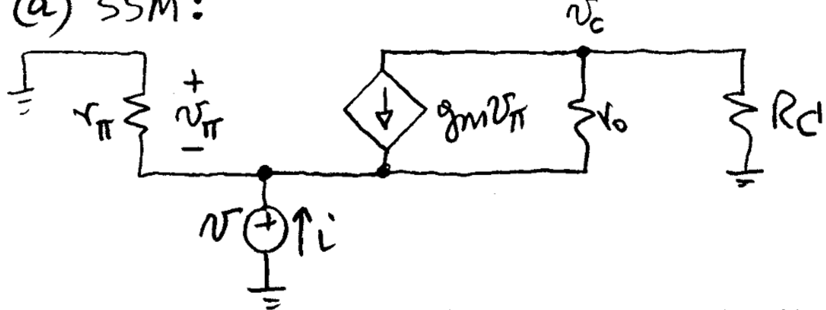


$B = L = 0V \Rightarrow Q_1 = Sat \Rightarrow$ LED glows.

$B = H = 5V \Rightarrow Q_1 = CO \Rightarrow$ 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: $i + \frac{v_\pi}{r_\pi} + g_m v_\pi + \frac{v_c - v}{r_o} = 0$, or

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

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

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

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

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

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

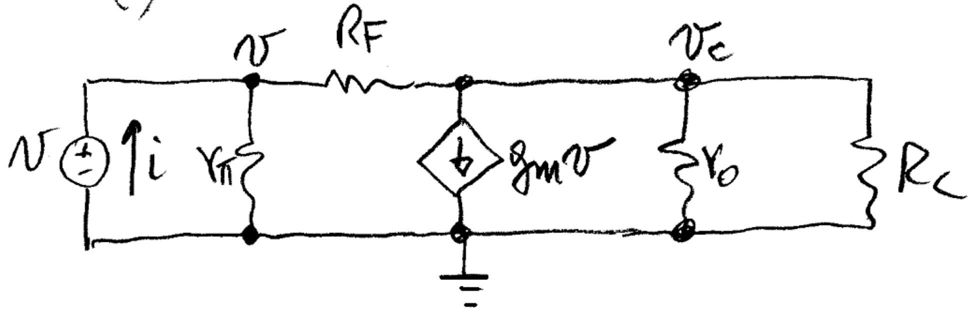
(b) $r_e = \frac{100}{101} \times \frac{26}{1} \cong 26\ \Omega$, $r_o = \frac{100}{1} = 100\ \text{k}\Omega$

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

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

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

2.45 (a)



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

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

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

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

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

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

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

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

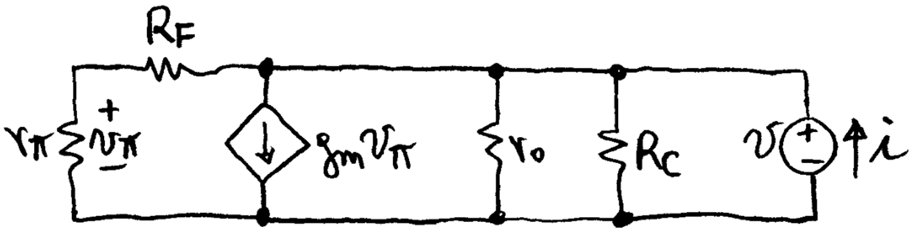
$$R_i = 2.6 /\!/ \frac{10 + (1 /\!/ 100)}{1 + (1 /\!/ 100)10^3/26} = 2.6 /\!/ 0.281 = 254\ \Omega.$$

(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: $i = \dfrac{v}{r_o /\!/ R_C} + g_m v_\pi + \dfrac{v}{R_F + r_\pi}$. 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,

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

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

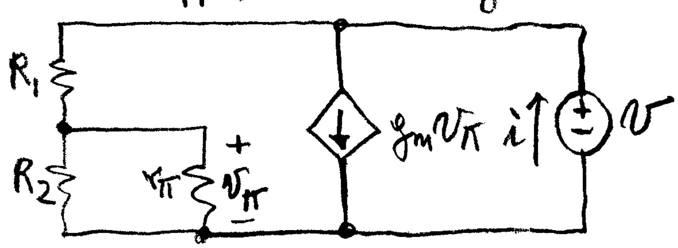
(b) $r_e \cong 26\,\Omega$, $r_o = 100\text{ k}\Omega$, $R_o = 10^5 /\!/ 10^3 /\!/ \left(26 + \dfrac{10^4}{101} \right) \cong 111\,\Omega$.

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

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

2.47

Apply test voltage v:



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

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

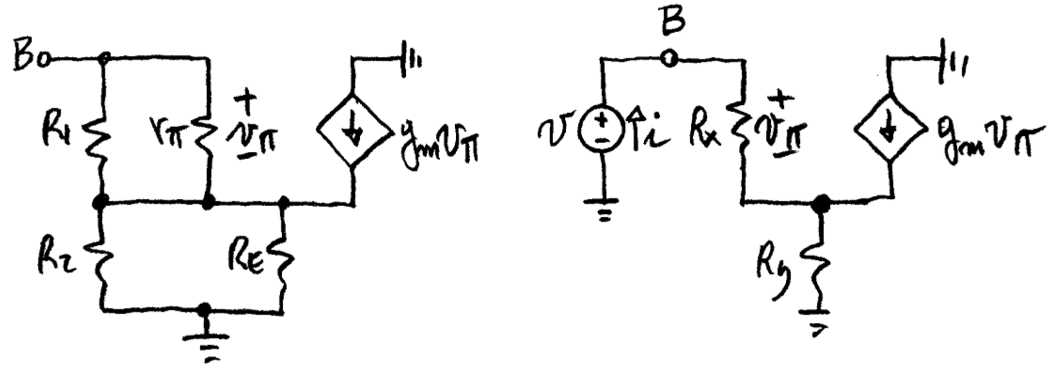
$= \dfrac{g_m (R_2 /\!/ r_\pi) + 1}{R_1 + (R_2 /\!/ r_\pi)} v$

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

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) $V_E = (2/3)9 = 6V$, $V_C = (1/3)9 = 3V$; $R_E = R_C = 3/2 = 1.5 k\Omega$. 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) $R_{BB} = 18 // 24 = 10.3 k\Omega$, $V_{BB} = 9 \times 24/(18 + 24) = 5.14 V$

$$I_C \cong \frac{V_{EE} - V_{BB} - V_{EB(on)}}{R_{BB}/\beta_F + R_E}.$$

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

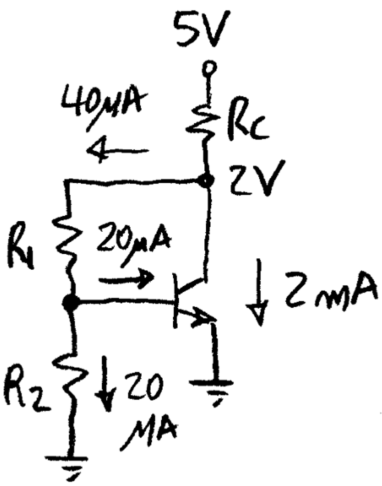
$$I_C(\max) = \frac{9 - 5.14(0.95) - 0.7}{(10.3 \times 0.95)/150 + 1.5(0.95)} \approx 2.3 mA$$

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

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

2.50

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



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

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

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

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

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

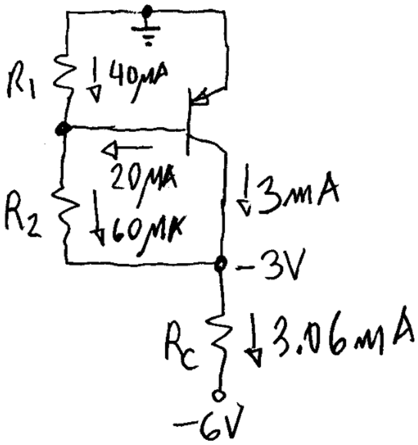
$I_C = \dfrac{5-V_C}{R_C} - \left(I_B + \dfrac{0.7}{36}\right) = \dfrac{5-1.34-33I_B}{1.5} - I_B - \dfrac{0.7}{36}$

$= 2.42 - 23 I_B = 2.42 - 23 I_C/\beta_F$. 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, $V_{CE} = V_C = 1.34 + 33 I_C/\beta_F \cong 2.44V, 1.99V, 1.90V$, 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 $18\,k\Omega$). $I_{R_2} = I_{R_1} + I_B = 3I_B = 60\mu A$; $R_2 = [-0.7-(-3)]/0.06 = 38.3\,k\Omega$ (use $39\,k\Omega$). $I_{R_C} = I_C + I_{R_2} = 3 + 0.06 = 3.06\,mA$; $R_C = [-3-(-6)]/3.06 = 0.98\,k\Omega$ (use $1\,k\Omega$).



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

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

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

$$I_C = 3.7\bar{4} - 40 I_B = 3.7\bar{4} - \frac{40}{\beta_F} I_C \Rightarrow I_C = 3.7\bar{4}\Big/\left(1 + \frac{40}{\beta_F}\right).$$

$I_C(\text{min}) = \frac{3.7\bar{4}}{1+40/75} = 2.44\,mA$; $I_C(\text{nom}) = \frac{3.7\bar{4}}{1+40/150} = 2.96\,mA$; $I_C(\text{max}) = \frac{3.7\bar{4}}{1+40/250} = 3.23\,mA$. Correspondingly,

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

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

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

(c) $\Delta V_R = (26\ mV)\ln(1000/123) = 54.5\ mV$; $R = 54.5/0.123$
$= 443\ \Omega$.

2.54 (a) $V_{BE1} = (26\,mV)\ln\frac{(6-0.7)/10^4}{2\times10^{-15}} \cong 684\,mV$

$V_{BE2} = 0.026\ln\frac{0.684 - V_{BE2}}{10^3\times2\times10^{-15}}$; start out with $V_{BE2} = 0.6V$.

$V_{BE2} = 0.026\ln\frac{0.684-0.6}{2\times10^{-12}} = 0.636\ V$

$V_{BE2} = 0.026\ln\frac{0.684-0.636}{2\times10^{-12}} = 0.620\ V$

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:

$V_{BE1} = 684-18 = 0.666\ V$; $V_{CC} = 0.666 + 10\times0.2658 =$

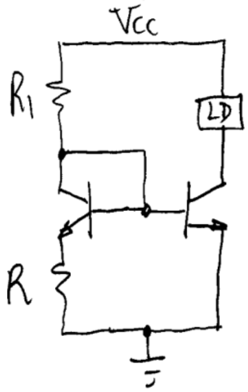
$3.324\ V$. Reiterate as before, and find

$V_{BE2} = 0.026\ln\frac{0.666-V_{BE2}}{2\times10^{-12}} \Rightarrow V_{BE2} = 620\,mV \Rightarrow$

$I_{C2} = (0.666-0.620)/10^3 = 46\,\mu A$. While I_{C1} has droped to $\frac{1}{2}$ its initial value, I_{C2} has droped from 58 μA to 46μA. <u>Not</u> 1/2, as I_{C2} is not linearly proportional to I_{C1}.

2.55

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



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

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

$\therefore R = (718 - 682)/0.5 = 72\ \Omega$.

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

(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 $2.4\ k\Omega$).

$g_m = 2/26 = 1/(13\Omega)$; $r_\pi = 100 \times 13 = 1.3 k\Omega$; $r_o = \frac{75}{2} \cong 37\ k\Omega$.
$R_c = r_o[1 + g_m(R_2 // r_\pi)] = 37[1 + (2400//1300)/13] \cong 2.5\ M\Omega$.

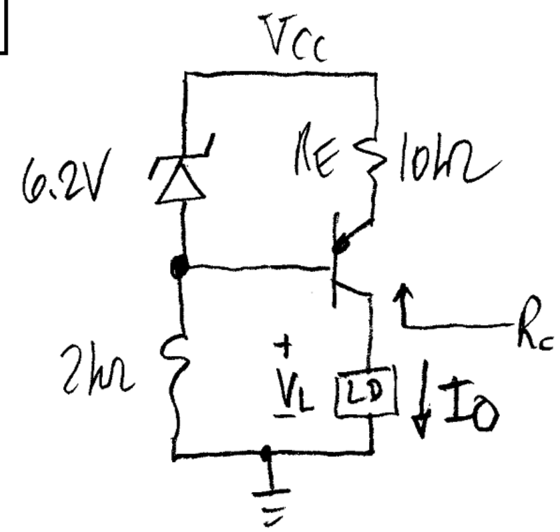
(b) An increase in V_L decreases V_{CE} and thus decreases I_O. The change is such that $\Delta I_O/\Delta V_L = -\frac{1}{R_c} \cong -\frac{1}{2.5\times 10^6} =$ $-0.4\mu A/V$. An increase in $|\Delta V_{EE}|$ increases both V_Z and V_{CE}, according to

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

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

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

2.57



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

$$\frac{\Delta I_O}{\Delta V_L} = -\frac{1}{R_C} = -\frac{1}{r_o\left[1+g_m(R_E \| r_\pi)\right]}$$

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

$$\frac{\Delta I_O}{\Delta V_L} = -\frac{1}{12.5\times 10^{+6}}\,\frac{V}{A} \cong -80\ nA/V.$$

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

$$\Delta V_Z = \frac{20}{2000+20}\Delta V_{CC} = \frac{\Delta V_{CC}}{101} \Rightarrow \Delta I_{O1} = \frac{\Delta V_Z}{10k\Omega} = \frac{\Delta V_{CC}}{101\times 10^4}$$

$$\cong \frac{\Delta V_{CC}}{1M\Omega}\ ;\ \Delta I_{O2} \cong \frac{\Delta V_{CC}}{12.5M\Omega}\ ;$$

$$\Delta I_O = \Delta I_{O1} + \Delta I_{O2} = \Delta V_{CC}\left(\frac{1}{1M\Omega} + \frac{1}{12.5M\Omega}\right) = \frac{\Delta V_{CC}}{930\ k\Omega}$$

$$\frac{\Delta I_O}{\Delta V_{CC}} = \frac{1}{930\ k\Omega} \cong 1.1\ \mu A/V.$$

2.58

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

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

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

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

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

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

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

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

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

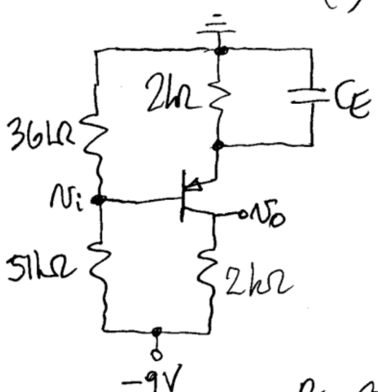
$v_C = V_C + v_c = -4.842V - 121(5mV)\cos\omega t;$

$= -4.842V + (0.605\ V)\cos(\omega t - 180^\circ);$

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

$v_E = 0.941V + 0.$

2.59



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

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

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

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

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

$v_o/v_i = -g_m R_o = -2.46/0.0185 \cong -133\ V/V.$

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

$C_E \gg 1/(2\pi \times 160 \times 10^3) \cong 1\ \mu F$. Use $C_E = 10\ \mu F$.

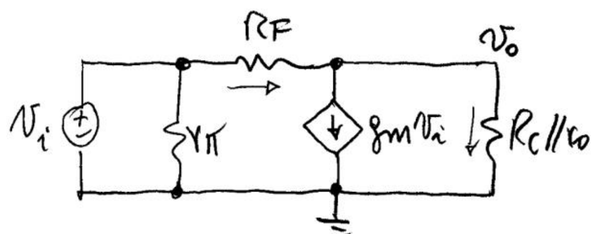
2.60 [V, mA, kΩ]. KVL: $10 = 3.9 I_E + 68 I_E/121 + 0.7 \Rightarrow$

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

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

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

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



KCL:

$$\frac{v_i - v_o}{R_F} = g_m v_i + \frac{v_o}{R_C//r_o}$$

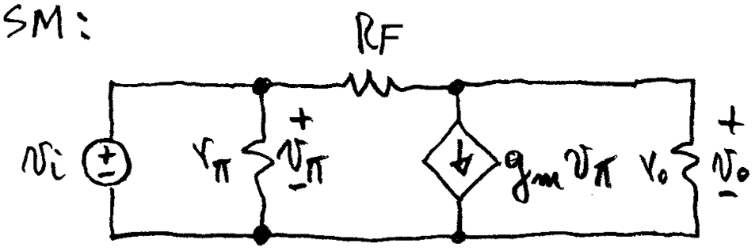
$$\Rightarrow \left(\frac{1}{R_F} - g_m\right) v_i = v_o\left(\frac{1}{R_F} + \frac{1}{R_C//r_o}\right) = \frac{v_o}{R_F//R_C//r_o}$$

$$\frac{v_o}{v_i} = -\left(g_m - \frac{1}{R_F}\right)(R_F//R_C//r_o) = -\left(\frac{1}{12.6} - \frac{1}{68000}\right)(6800//3600) = -271\ V/V.$$

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:



$v_\pi = v_i$

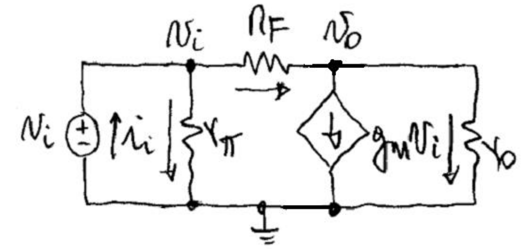
KCL: $\dfrac{v_i - v_o}{R_B} = g_m v_i + \dfrac{v_o}{r_o}$; $v_i\left(\dfrac{1}{R_B} - g_m\right) = \dfrac{v_o}{R_F} + \dfrac{v_o}{r_o} = \dfrac{v_o}{R_F /\!/ r_o}$;

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

$= -1913\ V/V$.

(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
$\dfrac{v_o}{v_i} = -\dfrac{1.98}{26}(100/\!/50.5)10^3 = -2555\ V/V$. 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) $I_C = 1\text{mA} \Rightarrow g_m = 1/(26\,\Omega)$, $r_\pi = 2.6\,\text{k}\Omega$, $r_o = 100\,\text{k}\Omega$.



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

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

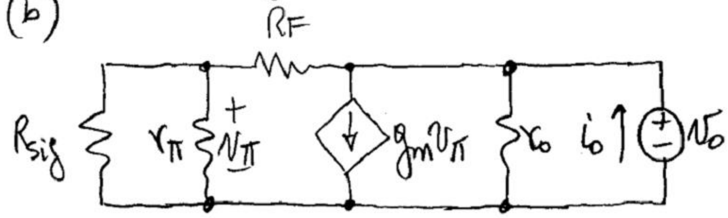
$$v_o = \frac{1 - g_m R_F}{\cancel{R_F}} \frac{\cancel{R_F} r_o}{R_F + r_o} v_i = \frac{1 - g_m R_F}{1 + R_F/r_o} v_i \Rightarrow i_i = \frac{v_i}{r_\pi /\!/ R_F} - \frac{1 - g_m R_F}{R_F(1 + R_F/r_o)} v_i$$

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

If $R_L = 100\,\text{k}\Omega$, replace r_o with $r_o /\!/ R_L = 100/\!/100 = 50\,\text{k}\Omega$. 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)



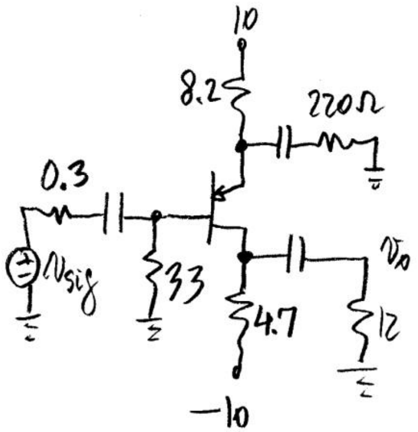
$$i_o = \frac{v_o}{r_o} + \frac{v_o}{R_F + (R_{sig} /\!/ r_\pi)} + g_m \frac{R_{sig} /\!/ r_\pi}{R_F + (R_{sig} /\!/ r_\pi)} v_o = v_o \left[\frac{1}{r_o} + \frac{1 + g_m(R_{sig} /\!/ r_\pi)}{R_F + (R_{sig} /\!/ r_\pi)} \right]$$

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

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

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 $R_o \to 1\,\text{k}\Omega$.

2.63 [V, mA, kΩ]: DC analysis:



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

$$I_C = 125\times 8.72 = 1.09\text{ mA}$$

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

$$r_\pi = 125\times 23.8 = 2.98\text{ k}\Omega$$

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

$$R_o \cong 8.2\text{ k}\Omega$$

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

$$= -17.2\text{ V/V}$$

2.64 (a) $I_C = 125\,\dfrac{12-0.7}{100+126\times 15} = 0.71\text{ mA};\ g_m = 0.71/26 \cong 1/(37\,\Omega);\ r_\pi = 125\times 37 \cong 4.6\text{ k}\Omega.$

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

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

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

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

Use $20\,\mu F$.

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

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

$$I_C = 100\,\frac{3-0.7}{10+101\times 2.2} = 0.99\,mA;\ g_m = \frac{1}{26\,\Omega};\ r_\pi = 2.6\,k\Omega.$$

$R_i = 10 // [2.6 + 101\times 0.2] \cong 7\,k\Omega$; $R_o \cong 2.7\,k\Omega$

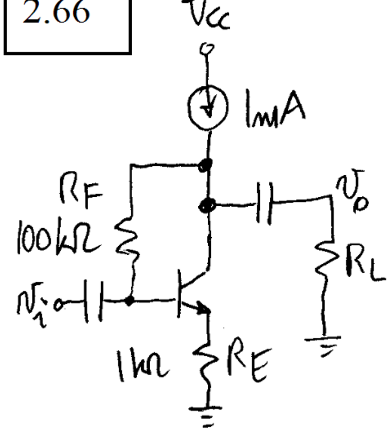
$$\frac{v_o}{v_i} = -\frac{1/26}{1+200/26}\,2700 = -11.9\ V/V$$

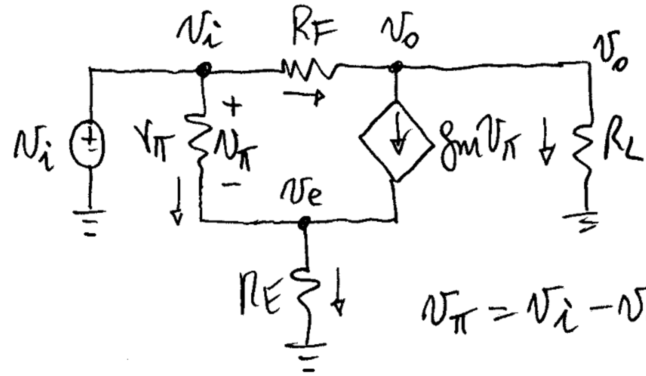
(b) $R_{eq3} = 2{,}000 // \left[200 + 26 + \frac{10{,}000}{101}\right] \cong 280\,\Omega$

$C_3 \gg 1/(2\pi\times 10^3\times 280) = 0.57\,\mu F$. Use $C_3 = 10\,\mu F$.

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

2.66





$$v_\pi = v_i - v_e$$

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

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

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

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

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

But, $g_m r_e \cong 1$, so

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

For $R_E \gg r_e$, we can approximate

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

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

$R_c = r_{o1}[1 + g_{m1}(r_{\pi 1} // R_E // r_{e2})] \cong r_o[1 + g_m r_e] \cong 2 r_o$;

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

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

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

$R_i \cong 2 r_\pi = 13.8\ k\Omega$; $R_c \cong 2 \times 133 = 267\ k\Omega$; $R_o = R_c // R_C =$ $267 // 10 = 9.64\ k\Omega$; $\dfrac{v_o}{v_{sig}} = -\dfrac{1}{2}\,\dfrac{9640}{34.7} \cong -140\ V/V$.

2.68 $\frac{v_o}{v_{sig}} = \frac{1}{1+\frac{R_{sig}+r_\pi}{(\beta_0+1)(R_L // r_o)}} \cong \frac{1}{1+\frac{R_{sig}+r_\pi}{(\beta_0+1)R_L}}$

where we are assuming $r_o >> R_L$.

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

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

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

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

$$\frac{v_o}{v_{sig}} = \frac{1}{1+\frac{20{,}000+7755}{151\times 1200}} = 0.867\text{ V/V}.$$

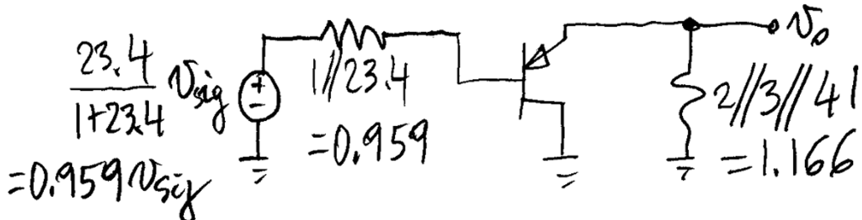
2.69

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

$I_C = 125\,\frac{7.1-0.7}{27.8+126\times 3} = 1.97\,mA$; $r_e \cong \frac{26}{1.97} = 13.2\,\Omega$; $r_\pi =$
$125 \times 13.2 = 1.65\,k\Omega$; $r_o = 80/1.97 = 40.6\,k\Omega \cong 41\,k\Omega$

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

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



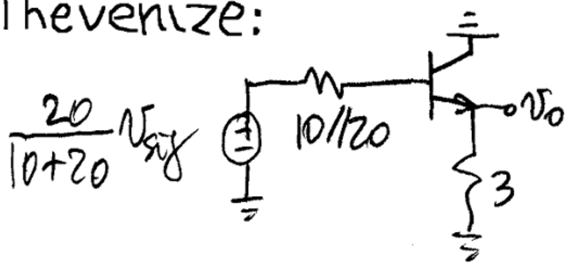
$$\frac{v_o}{v_{sig}} = 0.959\,\frac{1}{1 + \frac{1.65 + 0.959}{126 \times 1.166}} = 0.942\,V/V.$$

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:



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

$$\frac{v_o}{v_{sig}} = 0.649\ V/V$$

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

$$R_i = r_{\pi(eq)} + (\beta_0+1)R_{E(eq)} = 1.4 + 101\times 2.3 = 234\,k\Omega$$

$$R_o = R_{E(eq)} // \left(r_e + \frac{R_{sig}}{\beta_0+1}\right) = 2{,}300 // \left(15.7 + \frac{10{,}000}{101}\right) = 110\,\Omega$$

$$\frac{v_o}{v_{sig}} = \frac{1}{1 + \frac{r_{\pi(eq)} + R_{sig}}{(\beta_0+1)R_{e(eq)}}} = \frac{1}{1 + \frac{1.4 + 10}{101\times 2.3}} = 0.953\ V.$$

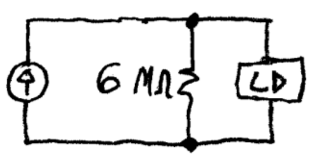
Bootstrapping increases R_i significantly, thus reducing input loading and making gain closer to unity.

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

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

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

$v_e = (496.8\,mV)\cos\omega t$; $i_o = \alpha_0 i_e \cong i_e = v_e/R$

(115.5 $\mu A \cos\omega t$) 

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

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

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

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

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

$r_{\pi1} = r_{\pi2} = 100\,(26/1.13) = 2.3\,k\Omega$

$R_i = r_{\pi1} + (\beta_{01}+1)(R_{E1}//R_{b2})$, $R_{b2} = r_{\pi2} + (\beta_{02}+1)(R_{E2}//R_L)$

$R_0 = R_{E2}//R_{e2}$, $R_{e2} = r_{e2} + \frac{R_{E1}//r_{e1}}{\beta_{01}+1}$.

$R_{b2} = 2.3 + 101\,(10//20) = 676\,k\Omega$

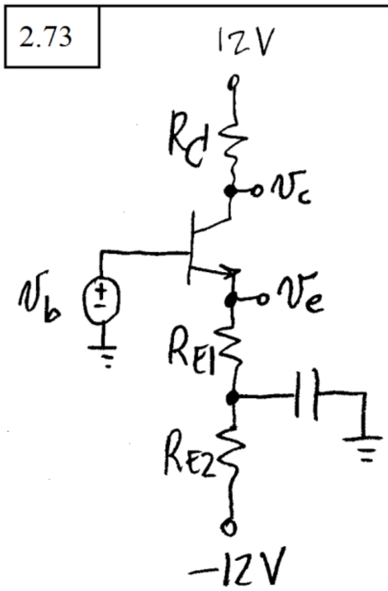
$R_i = 2.3 + 101\,(10//676) \cong 1\,M\Omega$

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

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

$\cong 0.9965\,V/V$.

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 $R_{E1} = R_C = 6.2\,k\Omega$.

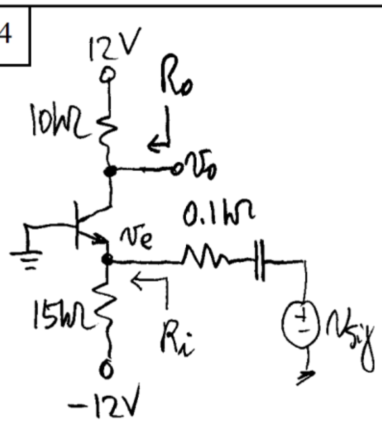
Also, to ensure $I_C = 1\,mA$, we need $R_{E1} + R_{E2} = (12-0.7)/1$, or

$R_{E2} = 11.3 - 6.2 = 5.1\,k\Omega$, 5%.

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

$$C > \frac{1}{2\pi \times 2.8 \times 10^3 \times 10^4} = 5.7\,nF.\ \text{Use } C = 0.1\,\mu F.$$

2.74



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

$$r_e = \frac{26}{0.753} \cong 35\,\Omega.\quad R_o \cong 10\,k\Omega.$$

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

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

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

2.75 $R_2 = \frac{10-0.7}{2} = 4.65\ \text{k}\Omega$ (use $4.7\ \text{k}\Omega$);

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

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

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

2.76 (a) $R_i = R_1 // R_{e1}$, $R_{e1} = r_{e1} + \frac{r_{e2} // R_2}{\beta_{01}+1} \cong r_{e1}$;

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

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

$\cong 2.35\ \text{M}\Omega$. $v_i = \frac{R_i}{R_{sig}+R_i} v_{sig} = \frac{26}{1000+26} v_{sig} = \frac{v_{sig}}{39.5}$.

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

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

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

$v_o = R_L i_o = R_L \alpha_0 i_i \cong R_L (v_{sig}/R_{sig}) \Rightarrow v_o/v_{sig} \cong R_L/R_{sig} = 5$ V/V.