Probs. sugeridos: 16-21 y 23

14.16 Consider the circuit of Fig. 14.9 with a 5-V supply, $R = 4\ \text{k}\Omega$, $R_C = 2\ \text{k}\Omega$, $V_{BE} = 0.7$ V, V_{CEsat} $(Q_3) \simeq 0.2$ V, $\beta_F = 20$, and $\beta_R = 0.1$. What input current flows with input high (≥ 1.4 V)? with input low (at 0.2 V)? What is the value of V_{OH} with no load? For what fan-out of similar circuits does V_{OH} decrease by 2 V?

14.17 Consider the circuit of Fig. 14.9 with $V_{CC} = 3$ V, $R = 3\ \text{k}\Omega$, and $R_C = 1\ \text{k}\Omega$, as the input rises slowly from 0 V. If V_{CEsat} of Q_1 is 0.1 V, and if Q_3 turns on when its V_{BE} reaches 0.6 V, at what value of input voltage does Q_3 begin to conduct? This is a good estimate of V_{IL}.

***14.18** A variant of the T^2L gate shown in Fig. 14.19 is being considered in which all resistances are tripled. For input high, estimate all node voltages and branch currents with $\beta_F = 30$, $\beta_R = 0.01$, $V_{BE} = 0.7$ V, and a load of $1\ \text{k}\Omega$ connected to the 5-V supply.

***14.19** Repeat the analysis of the circuit suggested in Problem 14.18 with input low (at +0.2 V) and a resistor of $1\ \text{k}\Omega$ connected from the output to ground.

***14.20** Two TTL gates of the type described in Problem 14.18, one with input high and one with input low, have their outputs accidentally joined. What output voltage results? What current flows in the short circuit?

***14.21** A transistor for which $\beta_F = 50$ and $\beta_R = 5$ is used for Q_3 in Fig. 14.20. For a base current of 2.5 mA, what is V_{CEsat} for $i_L = 0$, 1, 10, and 100 mA? Estimate R_{CEsat} at 0.5, 5, and 50 mA.

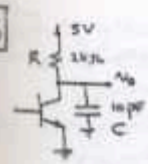
14.22 Consider the output circuit of the gate in Fig. 14.22. What is the output voltage when a current of 2 mA is extracted? What is the (small-signal) output resistance at this current level? Use $\beta = 50$.

14.23 Consider the output circuit of the gate in Fig. 14.22. For $\beta = \infty$ and $V_{CEsat} = 0.2$ V, at what output current does Q_4 saturate? For $\beta = 20$, at what current does saturation occur?

14.24 If the output of the circuit in Fig. 14.22 is short-circuited to ground, what current flows? Assume high β, $V_{CEsat} = 0.2$ V, and $V_{BE} = V_D = 0.7$ V. What is the minimum value of β for which your analysis holds?

chapter ↓

15



14

$\beta_f = 10,\ \beta_F = 50$

$I_{C_{sat}} = \frac{5-0.2}{2k\Omega} = 2.4mA$

Base current = 2.4/10 = 0.24mA

For falltime (on turnon) : $I_C = 50 \times 0.24 = 12mA$

$v_O = 5 - (2k\Omega)(12mA)(1-e^{-t/RC}) = -19 + 24e^{-t/RC}$

Now, $v_O = 0.2 + 0.1(5-0.2) = 0.68V$, when

$0.68 = -19 + 24e^{-t/RC}$, or $e^{-t/RC} = \frac{19.68}{24} = 0.82$

or $-t/RC = -0.198$, or $t = 0.198RC$

That is, $t_f = 0.198 \times 2\times10^3 \times 10\times10^{-12} = \underline{\underline{3.97\ ns}}$

For rise time (on turnoff):

$v_O = 0.2 + (5-0.2)(1-e^{-t/RC}) = 5 - 4.8e^{-t/RC}$

Now, v_O reaches $0.2 + 0.1(5-0.2) = 0.68V$, when

$0.68 = 5 - 4.8e^{-t/RC}$, or $t = -20\times10^{-9}\ln\frac{5-.68}{4.8} = 2.1$ ns

and reaches $5-0.1(5-0.2) = 4.52$, when

$4.52 = 5 - 4.8e^{-t/RC}$, or $t = -20\times10^{-9}\ln\frac{0.48}{4.8} = 46.0$ ns

That, $t_r = 46.0 - 2.1 = \underline{\underline{43.9\ ns}}$

---

16 For input high: $I_{B1} = \frac{5-0.7-0.7}{4k\Omega} = 0.9mA$

and $I_{in} = \beta_R I_{B1} = 0.1(0.9) = \underline{\underline{90\mu A}}$

$V_{OL} \simeq 0.2V$, but more precisely:

$I_{B3} = 0.9 + 0.09 = 0.99mA$; $I_{C3} \simeq \frac{5-0.2}{2k\Omega} = 2.4mA$

∴ $\beta_f = 2.4/0.99 = 2.42$

Thus $V_{OL} = V_{CE sat} = V_T \ln\left(\frac{1+(2.42+1)/0.1}{1-2.42/50}\right) = \underline{923mV}$

14

For input low: $I_{in} = I_{E1} = I_{B1} = \frac{5-0.7-0.2}{4k\Omega} = \underline{\underline{1.025}}mA$

V_{OH}, with no load, is $\underline{\underline{5V}}$

For a fanout of N, decrease in output

is $N\times90\times10^{-6}\times2\times10^{3} = 180N\times10^{-3}$

For a 2V drop, $2 = 180N\times10^{-3} \to N = \frac{2000}{180} = 11.1$

Thus a fanout of $\underline{\underline{11}}$ causes about 2V output drop.

---

17 $V_{IL} \simeq 0.6V - 0.1V = \underline{\underline{0.5V}}$

---

18 All resistors in Fig 14.19 are tripled.

For v_I high:

See $V_{B3} = \underline{\underline{0.7V}} = V_{E2}$; $V_{B2} = \underline{\underline{1.4V}} = V_{C1}$; $V_{B1} = \underline{\underline{2.1V}}$.

For V_{C2}: $V_{C2} \simeq V_{E2} = 0.7V$

$I_{C2} \simeq \frac{5-0.7}{3(1.6)} = \underline{\underline{0.897mA}}$

$I_{B2} \simeq \frac{5-2.1}{3(4)} = \underline{\underline{0.242mA}}$

∴ $\beta_{F(2)} = \frac{0.897}{0.242} = 3.71$

$V_{CE2sat} = 25\ln\left(\frac{1+(3.71+1)/0.01}{1-3.71/30}\right)$

$= 25\ln 539 = 157mV$

∴ $V_{C2} = V_{E2} + 0.16 = \underline{\underline{0.86V}}$

$I_{C2} = \frac{5-0.86}{3(1.6)} = \underline{\underline{0.863mA}}$

$V_{B4} = \underline{\underline{0.86V}}$; $V_{E4} \geq 0.86 - 0.70 = \underline{\underline{0.16}}$

14

$I_{E2} = 0.863 + 0.242 = \underline{\underline{1.105mA}}$

$I_{B3} = 1.105 - 0.7/3k = \underline{\underline{0.872mA}}$

Now, for $V_{out} \simeq 0.2V$, $I_{C3} = \frac{5-0.2}{1k\Omega} = \underline{\underline{4.8mA}}$

$\beta_{f(3)} = \frac{4.8}{0.872} = 5.52$

∴ $V_{CE3_{sat}} = 25\ln\left(\frac{1+(5.52+1)/.01}{1-5.52/30}\right) \doteq 167mV$

ie $V_{C3} = V_O = \underline{\underline{0.17V}}$

and $V_{C4} = \underline{\underline{+5V}}$, $I_{in} = 0.725\times.01 = \underline{\underline{7.25\mu A}}$.

---

19 all resistors in Fig 14.19 tripled

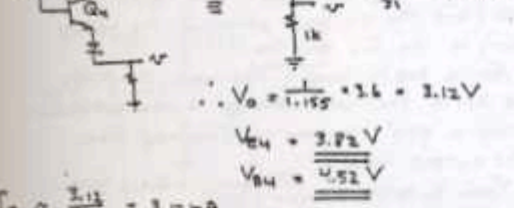
For v_I low (0.2V):

See $V_{E1} = \underline{\underline{0.2V}}$, $V_{B1} = \underline{\underline{0.9V}}$, $I_{B1} = \frac{5-0.9}{3(4)} = \underline{\underline{0.342mA}}$

Also $I_{C1} \simeq \underline{\underline{0}}$, $\beta_{F1} = 0$, $V_{CE_{sat}} = 25\ln\left(\frac{1+(0+1)/.01}{1-0/30}\right) = 115mV$

∴ $V_{C1} = 0.200 + 0.115 = \underline{\underline{0.32}}V = V_{B2}$

and $V_{E2} = \underline{\underline{0V}}$



∴ $V_O = \frac{1}{1.155}\times3.6 = 3.12V$

$V_{E4} = \underline{\underline{3.82V}}$

$V_{B4} = \underline{\underline{4.52V}}$

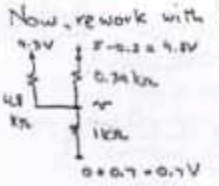
$I_{E4} \simeq \frac{3.12}{1k\Omega} = 3.12mA$

$V_{C4} = 5 - 0.390(3.12) = 3.78V$, Note saturated!

(next)

Now, rework with $V_{CE4} = 0.2V$ (say), since Q_4 sat.

14



See $\frac{4.3-v}{4.8} + \frac{4.8-v}{0.39} = \frac{v-0.7}{1}$

or $0.896 - 0.208v + 12.31 - 2.564v = v - 0.7$

ie $3.772v = 13.91$

$v = \frac{13.91}{3.772} = 3.69V$

That is, $V_{E4} = \underline{\underline{3.69V}}$, $V_{C4} = 3.69 + 0.2 = \underline{\underline{3.89V}}$,

$V_{B4} = 3.69 + 0.7 = \underline{\underline{4.39V}}$, $V_O = 3.69 - 0.7 = \underline{\underline{2.99V}}$,

$I_{E4} = 2.99V/1k\Omega = \underline{\underline{2.99mA}}$, $I_{C4} = \frac{5-3.89}{0.39} = \underline{\underline{2.85mA}}$,

$I_{B4} = \frac{5-4.39}{4.8k\Omega} = 0.13mA$.

Now, for Q_4: $\beta_F = \frac{2.85}{0.13} = 21.92$

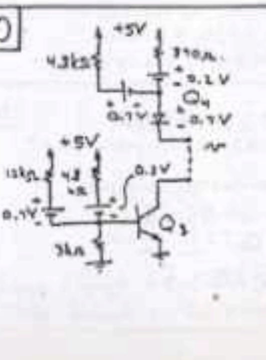
$V_{CE4sat} = 25\ln\left(\frac{1+(21.92+1)/.01}{1-21.92/30}\right) = 25\ln\frac{2293}{.269} = \underline{226mV}$

which slightly exceeds the 200mV originally assumed.

Thus V_O is lower by about $\frac{1k\Omega}{0.39k\Omega+1k\Omega}\times(226-200) \simeq 19$ mV

ie $V_O \simeq 2.99 - .02 = \underline{\underline{2.97V}}$

20



Assume that $V_{CE_{sat}} = 0.2V$ in general, and that Q_4 saturates:

$I_{B3} = \frac{5-1.4}{12} + \frac{5-0.9}{4.8} - \frac{0.7}{3}$

$= 0.3 + 0.854 - 0.233$

$= \underline{0.921\ mA}$

$I_{C3} \leq 30(0.921) = 27.6\ mA$

$I_{E4} = \frac{5-1.4-v}{4.8} + \frac{5-0.9-v}{0.39}$

$= 0.75 - 0.208v + 10.51 - 2.564v = 11.26 - 2.77v$

Now, $27.6 > 11.26 - 2.77v$ for $v \geq 0$.

Thus Q_3 must also saturate, and $v = \underline{0.2V} = V_O$, and the short-circuit current $= 11.26 - 2.77(0.2) = \underline{10.7\text{ mA}}$

More precisely, for $\beta_F = \frac{10.7}{0.921} = 11.62$

⋮ $V_{CEsat} = V_T \ln\left(\frac{1+(11.62+1)/51}{1-11.62/50}\right)$

$= 25\ln\left(\frac{1.363}{.413}\right) = 191\text{ mV}$

$\therefore V_O = \underline{0.19V}$

---

21 $\underline{\text{For } i_L = 0}$, $\beta_F = 0$, and

$V_{CEsat} = 25\ln\left(\frac{1+(0+1)/5}{1-0/50}\right) = 25\ln 1.2 = \underline{4.56\text{ mV}}$

$\underline{\text{For } i_L = 1\text{ mA}}$, $\beta_F = 1/2.5 = 0.4$, and

$V_{CEsat} = 25\ln\left(\frac{1+(0.4+1)/5}{1-0.4/50}\right) = 25\ln\frac{1.28}{.992} = \underline{6.37\text{ mV}}$

$\underline{\text{For } i_L = 10\text{ mA}}$, $\beta_F = 10/2.5 = 4$, and

$V_{CEsat} = 25\ln\left(\frac{1+(4+1)/5}{1-4/50}\right) = 25\ln\frac{2}{0.92} = \underline{19.4\text{ mV}}$

$\underline{\text{For } i_L = 100\text{ mA}}$, $\beta_F = 100/2.5 = 40$, and

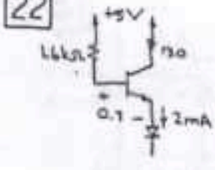
$V_{CEsat} = 25\ln\left(\frac{1+(40+1)/5}{1-40/50}\right) = 25\ln\frac{9.2}{0.2} = \underline{95.4\text{ mV}}$

$\underline{\text{At } 0.5\text{ mA}}$: $R_{CEsat} = \frac{6.37-4.56}{0.5} = \underline{3.62\,\Omega}$

$\underline{\text{At } 5.0\text{ mA}}$: $R_{CEsat} = \frac{19.4-6.4}{5} = \underline{2.60\,\Omega}$

$\underline{\text{At } 50\text{ mA}}$: $R_{CEsat} = \frac{9.54-6.4}{50} = \underline{1.78\,\Omega}$

22



Assume linear operation:

$V_B = 5 - 1.6 \times \frac{2}{51} = 4.94\text{ V}$

$V_C = 5 - 0.13 \times 2 = 4.74\text{ V}$

$V_E = 4.94 - 0.7 = 4.24\text{ V}$

$V_O = 4.24 - 0.7 = \underline{3.54\text{ V}}$

Assume $n = 1$ for the diode (ie it is a diode-connected transistor), and $r_d = r_e = \frac{25\text{ mV}}{2\text{ mA}}$

$\therefore R_{out} = \frac{25}{2} + \frac{25}{2} + \frac{1600}{51} = 12.5 + 12.5 + 31.4$

$= \underline{56.4\,\Omega}$

---

23 $\underline{\text{For } \beta = \infty}$, saturation occurs when the drop across 130 Ω is $0.7 - 0.2 = 0.5V$, ie for $I = 0.5/0.130 = \underline{3.85\text{ mA}}$

$\underline{\text{For } \beta = 20}$, and output I,

$I/21 \times 1.6 + 0.7 - 0.2 = 20/21\, I(0.13)$

$1.6I + 10.5 = 2.6I$

$I = \underline{10.5\text{ mA}}$.

---

24 For high β, short-circuit current is

$(5 - 0.2 - 0.7 - 0)/130\,\Omega = \underline{31.5\text{ mA}}$

Now, for the output at 0V, $I_{B4} = \frac{5-0.7-0.7}{1.6\text{ k}\Omega} = 2.25\text{ mA}$

Thus β for which saturation occurs is $> \frac{31.5}{2.25} = 14$

That is, the minimum β for 31.5 mA is $\underline{14}$

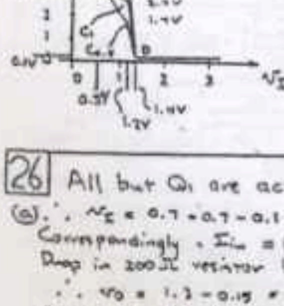
---

25 The value of R_2 affects the output voltage for $v_I = 1.2V$ (point C of Fig 14.23).

For $R_2 = 1\text{ k}\Omega$, $v_O = \underline{2.7V}$

For $R_2 = 0.5\text{ k}\Omega$, v_O falls twice as much, ie by $2(3.7 - 2.7) = 2V$ to $3.7 - 2.7 = \underline{1.7V}$

For $R_2 = 2.0\text{ k}\Omega$, v_O falls by half as much, by $0.5V$, to $\underline{3.2V}$



Apparently $R_2 = 2.0\text{ k}\Omega$ gives the best transfer characteristic, being sharper (but is slow).

---

26 All but Q_1 are active with $V_{BE} = 0.7V$

ⓐ $\therefore v_I = 0.7 + 0.7 - 0.1 = 1.3V$

Correspondingly, $I_{in} = (5 - 0.7 - 1.3)/4 = 0.75\text{ mA}$

Drop in 200 Ω resistor is $(0.200)(0.75) = 0.15V$

$\therefore v_O = 1.3 - 0.15 = 1.15V$

Correspondingly, $V_{B4} = 1.15V + 0.7 + 0.7 = 2.55V$

and $I_{R_1} = (5 - 2.55)/1.6k = 1.53\text{ mA}$

Apparently Q_4 and Q_3 will be conducting a similar current, I in the collector of Q_3, and $I - 0.75$ in the emitter of Q_4:

ie $\left(\left(1.53 - \frac{I+0.75}{51}\right)\frac{51}{50} - \frac{0.7}{1}\right)50 = I$

or $(1.576 - I/50 - 0.7)50 = I$

$(0.876 - I/50)50 = I$, $43.8 - I = I$,

$2I = 43.8$, $I = 21.89\text{ mA}$

$\underline{\text{Check}}$ saturation of Q_4:

$V_{C4} = 5 - 0.13(21.89 - 0.75)\,50/51 = 2.31\text{ V}$

while $V_{B4} = 2.55V$.

Thus $V_{BC4} = 2.55 - 2.31 = 0.24$ shows Q_4 to be active!

$\underline{\text{Overall}}$: $V_{C3} = \underline{1.15V}$, $V_{E1} = \underline{1.30V}$, $V_{B1} = \underline{2.0V}$, $V_{C1} = \underline{1.4V}$, $V_{E2} = \underline{0.7V}$, $V_{E4} = \underline{1.85V}$, $V_{B4} = \underline{2.55V}$, $V_{C4} = \underline{2.31V}$, $I_{E3} = \underline{22.3\text{ mA}}$, $I_{E4} = \underline{21.1\text{ mA}}$, $I_{E2} = \underline{1.14\text{ mA}}$, $I_{E1} = \underline{0.75\text{ mA}}$.

ⓑ For Q_2, $r_{e2} = \frac{25}{1.14} = 21.9\,\Omega$, $r_{\pi 2} = 1.12\text{ k}\Omega$

Q_3, $r_{e3} = \frac{25}{22.3} = 1.12\,\Omega$, $r_{\pi 3} = 57.2\,\Omega$

Q_4, $r_{e4} = \frac{25}{21.1} = 1.18\,\Omega$, $r_{\pi 4} = 60.4\,\Omega$

$\underline{\text{For gain}}$: There are two paths to the output, one via Q_3 and one via Q_4, in which output currents, and gains, add. The highest-gain path (and the one most affecting the voltage gain) is via Q_2 and Q_4.

Thus, for a 200 Ω load (the input, to which the 200 Ω feedback resistor is connected, being a zero-ohm source); working from the output back:

Gain B_4 to $v_O = \frac{200}{200 + 2(1.18)} = 0.988\text{ V/V}$

$R_{in4} = 51(200 + 2(1.18)) = 10.3\text{ k}\Omega$

Gain B_2 to $B_4 = \left(-\frac{50}{51}(10.3 \,\|\, 1.6)\right)/(21.9 + 1k/51)$

$= -17.8\text{ V/V}$

Thus overall gain is about $-0.99(17.8) \simeq \underline{-17.6\text{ V/V}}$