Solutions to *The Art of Electronics 3rd Edition*

July 16, 2023

Contents

Solutions for Chapter 2

Exercise 2.1

In order to solve this problem, many assumptions must be made. Different people may assume slightly different values for parameters. This is OK. What is important is making good assumptions and checking our conclusions to make sure they are reasonable.

To solve for the current in the LED, let us assume we know the LED is red, so it follows the red LED curve from Figure 2.8 in the book. Let us also assume the transistor is acting like a closed switch, so the collector voltage of Q1 is close to 0 V. Let us also assume the LED is ON, so it's voltage is approximately $V_{\text{LED}} = 2\,\text{V}$. From the preceding assumptions, we can calculate that the LED current is

$$I_{\text{LED}} = \frac{3.3\,\text{V} - 2\,\text{V}}{330\,\Omega} = \frac{1.3\,\text{V}}{330\,\Omega} \approx 3.94\,\text{mA}$$

If we use Figure 2.8 (from the textbook) to check our numbers, we see that a current of 3.94 mA roughly correlates to an LED voltage of $V_{\text{LED}} = 1.7\,\text{V}$. We will run the same calculation again to reduce our error.

$$I^*_{\text{LED}} = \frac{3.3\,\text{V} - 1.7\,\text{V}}{330\,\Omega} = \frac{1.6\,\text{V}}{330\,\Omega} \approx \boxed{4.85\,\text{mA}}$$

In order to determine the minimum current gain required from our transistor, we must calculate the base current. Let us assume we know the base-emitter voltage $V_{\text{BE}} = 0.6\,\text{V}$. Therefore

$$I_{\text{B}} = \frac{3.3\,\text{V} - 0.6\,\text{V}}{10\,\text{k}\Omega} = 270\,\mu\text{A}$$

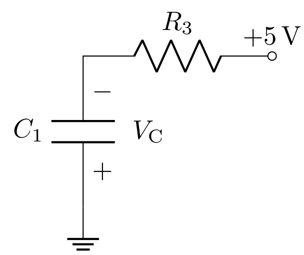
So the minimum current gain must be

$$\beta_{\min} = \frac{I^*_{\text{LED}}}{I_{\text{B}}} \approx \frac{4.85\,\text{mA}}{270\,\mu\text{A}} \approx \boxed{18.0}$$

Exercise 2.2

When Q_1 goes is in saturation, the base voltage of Q_2 equals the opposite of the voltage on the capacitor C_1 at $t = 0\,\text{s}$, $V_0 = 4.4\,\text{V}$ and Q_2 is then cutoff. V_{out} will be equal to 5 V until Q_2 is brought in saturation again. This happens when its base voltage gets higher or equal to the Q_2 threshold voltage (0.6 V). As soon as Q_1 is brought in saturation, C_1 starts to discharge into the resistor R_3 and the equivalent circuit, valid until Q_2 is cutoff, is then:

Figure 1.1: Equivalent C_1 discharging circuit.



The time evolution of the voltage across the capacitor C_1 is given by:

$$V_C(t) = (V_0 - V_\infty)\, e^{-\frac{t}{R_3 C_1}} + V_\infty$$

where V_∞ is the steady-state voltage on the capacitor C_1 end equals $-5\,\mathrm{V}$. Given the considerations above, we have that $V_C(t = T_{\mathrm{pulse}}) = -0.6\,\mathrm{V}$. Solving for t gives:

$$T_{\mathrm{pulse}} = -R_3 C_1 \ln\left(\frac{-0.6\,\mathrm{V} - V_\infty}{V_0 - V_\infty}\right) = \boxed{0.76 R_3 C_1 = 76\,\mu\mathrm{s}}$$

Exercise 2.3

The output voltage is now influenced by R_5 that goes in series with R_4, and by the V_{BE} of Q_3 which is equal to 0.6 V when the transistor is in saturation. Therefore:

$$V_{\mathrm{out}} = \frac{R_5}{R_5 + R_4}\,(5\,\mathrm{V} - 0.6\,\mathrm{V}) + 0.6\,\mathrm{V} = \boxed{4.79\,\mathrm{V}}$$

The minimum value of β of Q_3 can be obtained looking at the maximum value of the current flowing through the collector of Q_3, $I_c^{Q_3}$. As soon as Q_1 goes in saturation, the capacitor C_1 starts to discharge and its current is given by $C_1 dV_C/dt$. With reference to the variables introduced in the previous exercise (2.2):

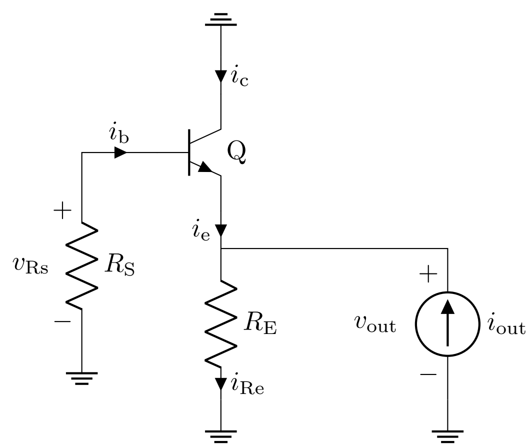
$$I_c^{Q_3}(t) = \frac{5\,\mathrm{V}}{R_2} - I_{C_1}(t) = \frac{5\,\mathrm{V}}{R_2} + C_1 \frac{1}{R_3 C_1}\,(V_0 - V_\infty)\, e^{-\frac{t}{R_3 C_1}}$$

Therefore:

$$\beta_{\min} = \frac{I_c^{Q_3}(t)|_{\max}}{I_b^{Q_3}} = \frac{I_c^{Q_3}(t = 0\,\mathrm{s})}{I_b^{Q_3}} = \boxed{27}$$

Exercise 2.4

Figure 1.2: Emitter follower circuit used for computing the output resistance



Applying the KCL on the Q transistor:

$$i_e = i_b + i_c = i_b (\beta + 1)$$

The current flowing through the emitter resistor R_E is equal to:

$$i_{Re} = i_e + i_{out} = i_b (\beta + 1) + i_{out}$$

Since for the emitter follower $v_{Rs} = v_{out}$:

$$[i_b (\beta + 1) + i_{out}] R_E = v_{out}$$

Since:

$$i_b = -\frac{v_{Rs}}{R_S} = -\frac{v_{out}}{R_S}$$

we can write:

$$\left[-\frac{v_{out}}{R_S} (\beta + 1) + i_{out}\right] R_E = v_{out}$$

Therefore:

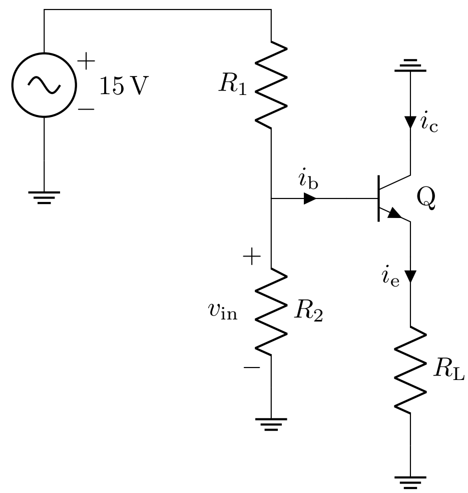
$$R_{out} = \frac{v_{out}}{i_{out}} = \frac{R_E R_S}{R_S + (\beta + 1) R_E}$$

If $R_E >> R_S/(\beta + 1)$:

$$\boxed{R_{out} \approx \frac{R_S}{(\beta + 1)}}$$

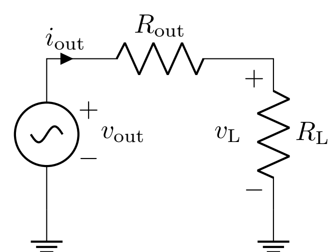
Exercise 2.5

Figure 1.3: Small signal circuit



In order to achieve a maximum voltage change of 5 % for a maximum current to the load (R_L) equal to 25 mA, we can make reference to the equivalent circuit of Figure 1.4:

Figure 1.4: Output equivalent circuit



obtaining:

$$\left.\frac{v_{out} - v_L}{v_{out}}\right|_{i_{out}=25\,\mathrm{mA}} = 0.05$$

Since

$$v_{out} - R_{out}\, i_{out} = v_L$$

and for an emitter follower $v_{out} = v_{in} = 5\,\mathrm{V}$ we can write:

$$\frac{R_{out}\, 25\,\mathrm{mA}}{5\,\mathrm{V}} = 0.05$$

obtainin the following condition on R_{out}:

$$R_{out} = \frac{0.05\, 5\,\mathrm{V}}{25\,\mathrm{mA}}$$

For the emitter follower configuration:

$$R_{\text{out}} = \frac{R_{\text{in}}}{\beta + 1}$$

and we see from the circuit of Figure 1.3 that R_{in} is given by the parallel between R_1 and R_2:

$$R_{\text{in}} = \frac{R_1\, R_2}{R_1 + R_2}$$

In order to achieve $v_{\text{in}} = 5\,\text{V}$, the following condition must be verified for the values of R_1 and R_2:

$$\frac{R_2}{R_1 + R_2} = \frac{5\,\text{V}}{15\,\text{V}}$$

Assuming $\beta = 100$, we can finally obtain:

$$\boxed{R_1 = 30\,\Omega,\; R_2 = 15\,\Omega}$$

Exercise 2.6

The minimum current flowing through the R resistor has to be at least equal to the maximum current to the load plus the minimum current to the zener:

$$I_{\text{min,R}} = \frac{20\,\text{V} - 10\,\text{V}}{R} \geq 100\,\text{mA} + 10\,\text{mA}$$

Therefore:

$$R \leq \frac{10\,\text{V}}{110\,\text{mA}} = \boxed{91\,\Omega}$$

It follows that the maximum power to the zener, selecting $R = 91\,\Omega$, is equal to

$$P_{\text{max,z}} = \left(\frac{25\,\text{V} - 10\,\text{V}}{91\,\Omega} - 0\,\text{A}\right) 10\,\text{V} = \boxed{1.65\,\text{W}}$$

Exercise 2.7

With reference to figure 2.21 of the book, neglecting the current entering the ase of the transistor Q, in order to have at least 10 mA flowing through the zener, the resistor R should comply with the following condition:

$$\frac{20\,\text{V} - 10\,\text{V}}{R} \geq 10\,\text{mA}$$

which results in:

$$\boxed{R \leq 1\,\text{k}\Omega}$$

In order to avoid the transistor to be saturated, we want the collector-base voltage to be always higher than zero. This translates in:

$$R_{\text{C}} < R\frac{10\,\text{mA}}{100\,\text{mA}} = 100\,\Omega$$

Selecting a conservative value of R_{C} equal to $\boxed{20\,\Omega}$, we can compute the maximum power dissipated by the zener, $P_{\text{max,z}}$ and the transistor, $P_{\text{max,Q}}$ as:

$$P_{\text{max,z}} = \left(\frac{25\,\text{V} - 10\,\text{V}}{1\,\text{k}\Omega}\right) 10\,\text{V} = \boxed{0.15\,\text{W}}$$

$$P_{\mathrm{Q}} = (25\,\mathrm{V} - 20\,\Omega I_{\mathrm{load}})\, I_{\mathrm{load}}$$

The maximum power dissipated by the transistor is obtained for a collector current equal to 625 mA which is higher than the maximum load current. Therefore, in our case, the maximum power dissipated by Q will be obtained for $I_{\mathrm{load,max}} = 100\,\mathrm{mA}$:

$$P_{\mathrm{max,Q}} = (25\,\mathrm{V} - 20\,\Omega I_{\mathrm{load,max}})\, I_{\mathrm{load,max}} = \boxed{2.3\,\mathrm{W}}$$

Comparing the results with those of the previous exercise, we notice that the power disspated by the zener diode significantly decreased but we have an additional power dissipated by the transistor which is higher than the power that the zener diode dissipated in the circuit of the previous exercise. However this power can be decreased by increasing the value of R_{C}.

Exercise 2.8

In order to keep the emitter voltage V_{E} in the half range of the dc supply, considering the quiescent current of 5 mA we have:

$$V_{\mathrm{E}} = \frac{15\,\mathrm{V} - (-15\,\mathrm{V})}{2} = 15\,\mathrm{V}$$

and the emitter resistor R_{E}:

$$R_{\mathrm{E}} = \frac{15\,\mathrm{V}}{5\,\mathrm{mA}} = \boxed{3\,\mathrm{k}\Omega}$$

Since the imput impedance to the transistor, under the assumption of a load resistance much larger than the emitter resistance, is:

$$R_{\mathrm{in}} = \beta R_{\mathrm{E}} = 300\,\mathrm{k}\Omega$$

in order to have the 3 dB point below the lowest frequency of 20 Hz, the capacitor C_1 has to be:

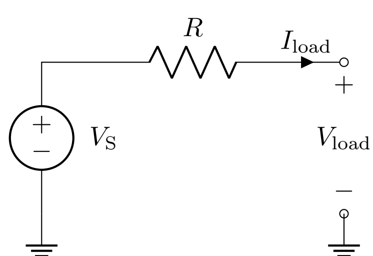
$$\frac{1}{R_{\mathrm{in}} C_1} \leq 20\,\mathrm{Hz}$$

meaning that:

$$\boxed{C_1 \geq 0.17\,\mu\mathrm{F}}$$

Exercise 2.9

Figure 1.5: Current source circuit



We want:

$$\frac{I_{\mathrm{load}}^{\mathrm{max}} - I_{\mathrm{load}}^{\mathrm{min}}}{I_{\mathrm{load}}^{\mathrm{max}}} = \frac{V_{\mathrm{S}} - 0\,\mathrm{V} - (V_{\mathrm{S}} - 10\,\mathrm{V})}{V_{\mathrm{S}} - 0\,\mathrm{V}} = 0.01$$

from which it follows:

$$\boxed{V_{\mathrm{S}} = 1\,\mathrm{kV}}$$

Exercise 2.10

With reference to Figure 1.5, we assume that I_{load} is equal to 10 mA if V_{load} is equal to 0 V, which means R_{load} is equal to $0\,\Omega$. We can therfore calculate R as:

$$R = \frac{V_S}{10\,\text{mA}} = 100\,\text{k}\Omega$$

In this case we have:

$$\boxed{P_{\text{load}} = 0\,\text{W},\ P_R = I_{\text{load}}^2 R = 10\,\text{W}}$$

If $V_{\text{load}} = 10\,\text{V}$, from the condition of the previous exercise, we have:

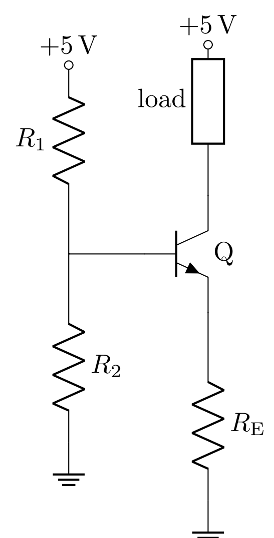
$$I_{\text{load}} = (1 - 0.01)10\,\text{mA} = 9.9\,\text{mA}$$

Therefore:

$$\boxed{P_{\text{load}} = 10\,\text{V}I_{\text{load}} = 0.1\,\text{W},\ P_R = I_{\text{load}}^2 R = 9.8\,\text{W}}$$

Exercise 2.11

Figure 1.6: Current sink



In order to have an emitter current equal to 5 mA, the following condition has to be verified:

$$\frac{R_2}{R_1 + R_2} 5\,\text{V} - 0.6\,\text{V} = R_E 5\,\text{mA}$$

Furthermore, the transistor shouldn't sensibly load the voltage divider, therefore:

$$\frac{R_1 R_2}{R_1 + R_2} << R_E \beta$$

Since we have a dc voltage of 5 V, we want the voltage on R_2 to be lower or equal to this value:

$$R_E 5\,\text{mA} + 0.6\,\text{V} \leq 5\,\text{V}$$

leading to:

$$R_{\mathrm{E}} \leq 880\,\Omega$$

A good guess value for R_{E} could be:

$$\boxed{R_{\mathrm{E}} = 200\,\Omega}$$

The base voltage will be given by:

$$V_{\mathrm{B}} = R_{\mathrm{E}} 5\,\mathrm{mA} + 0.6\,\mathrm{V} = 1.6\,\mathrm{V}$$

Selecting $\boxed{R_1 = 1\,\mathrm{k}\Omega}$ it is possible to compute R_2:

$$\boxed{R_2 = 470\,\Omega}$$

The impedance seen by the input of the transistor is equal to $320\,\Omega$ and the input impedance of the transistor, considering $\beta = 100$, is $R_{\mathrm{E}}\beta = 20\,\mathrm{k}\Omega$ with the former much lower than the latter. Finally, considering a maximum V_{CE} voltage of the transistor equal to $0.2\,\mathrm{V}$ before it saturates, we obtain the compliance voltage on the load as:

$$\boxed{V_{\mathrm{comp}} = 5\,\mathrm{V} - (0.2\,\mathrm{V} + R_{\mathrm{E}} 5\,\mathrm{mA}) = 3.8\,\mathrm{V}}$$

Exercise 2.12 TODO: write solution

Exercise 2.13 TODO: write solution

Exercise 2.14 TODO: write solution

Exercise 2.15 TODO: write solution

Exercise 2.16 TODO: write solution

Exercise 2.17 TODO: write solution

Exercise 2.18 TODO: write solution

Exercise 2.19 TODO: write solution

Exercise 2.20 TODO: write solution

Exercise 2.21 TODO: write solution

Exercise 2.22 TODO: write solution

Exercise 2.23 TODO: write solution

Exercise 2.24 TODO: write solution

Exercise 2.25 TODO: write solution

Exercise 2.26 TODO: write solution

Exercise 2.27 TODO: write solution

Exercise 2.28 TODO: write solution

Exercise 2.29 TODO: write solution

Exercise 2.30 TODO: write solution