Solutions to *The Art of Electronics 3rd Edition*

June 25, 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 $V_{\mathrm{LED}} = 2\,\mathrm{V}$. From the preceding assumptions, we can calculate that the LED current is

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

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 $V_{\mathrm{LED}} = 1.7\,\mathrm{V}$. We will run the same calculation again to reduce our error.

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

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 $V_{\mathrm{BE}} = 0.6\,\mathrm{V}$. Therefore

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

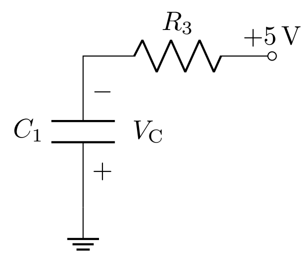
So the minimum current gain must be

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

Exercise 2.2

When Q_1 goes is brought in saturation, the base voltage of Q_2 equals the opposite of the voltage on the capacitor C_1 at $t = 0\,\mathrm{s}$, $V_0 = 4.4\,\mathrm{V}$ 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:

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

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, $I_\mathrm{c}^{\mathrm{Q}_3}$. As soon as Q_1 goes in saturation, the capacitor C_1 starts to discharge and its current is given by $C_1 dV_\mathrm{C}/dt$. With reference to the variables introduced in the previous exercise (2.2):

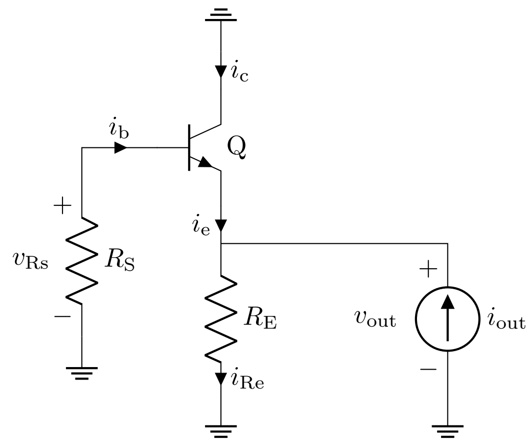
$$I_\mathrm{c}^{\mathrm{Q}_3}(t) = \frac{5\,\mathrm{V}}{R_2} - I_{\mathrm{C}_1}(t) = \frac{5\,\mathrm{V}}{R_2} + C_1 \frac{1}{R_3 C_1}\,(V_0 - V_\infty)\, e^{-\frac{t}{R_3 C_1}}$$

Therefore:

$$\beta_\mathrm{min} = \frac{I_\mathrm{c}^{\mathrm{Q}_3}(t)|_\mathrm{max}}{I_\mathrm{b}^{\mathrm{Q}_3}} = \frac{I_\mathrm{c}^{\mathrm{Q}_3}(t = 0\,\mathrm{s})}{I_\mathrm{b}^{\mathrm{Q}_3}} = \boxed{27}$$

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:

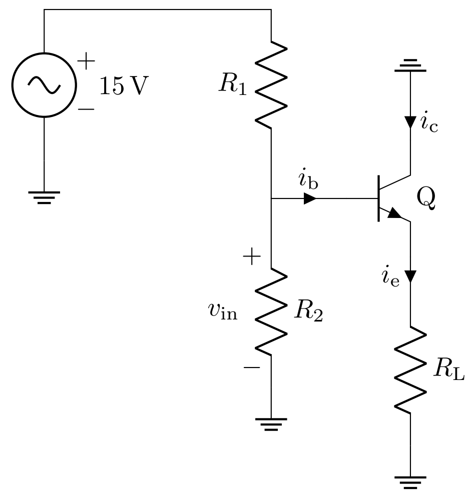
$$R_{out} = \frac{v_{out}}{i_{out}} = \frac{R_E R_S}{R_S + (\beta + 1) R_E}$$

If $R_E >> R_S$:

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

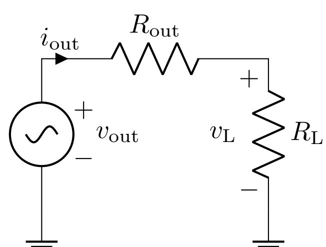
Exercise 2.5

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 **TODO: write solution**

Exercise 2.7 **TODO: write solution**

Exercise 2.8 **TODO: write solution**

Exercise 2.9 **TODO: write solution**

Exercise 2.10 **TODO: write solution**

Exercise 2.11 **TODO: write solution**

Exercise 2.12 **TODO: write solution**

Exercise 2.13 **TODO: write solution**

Exercise 2.14 **TODO: write solution**

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Exercise 2.29 **TODO: write solution**

Exercise 2.30 **TODO: write solution**