The Art of Electronics, 3rd Edition - Solutions

This is an ongoing project with solutions to problems in *The Art of Electronics, 3rd edition* by Paul Horowitz and Winfield Hill. There is no guarantee for the correctness of the solutions and any suggestions for improvement are more that welcome.

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1 Foundations

Exercise 1.30

V_{out} is the voltage at the output of the impedance voltage divider. We know that $Z_R = R$ and $Z_C = \frac{1}{j\omega C}$. So we have

$$V_{\text{out}} = \frac{Z_C}{Z_R + Z_C} V_{\text{in}} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} V_{\text{in}} = \frac{1}{1 + j\omega RC} V_{\text{in}}$$

The magnitude of this expression follows:

$$|V_{\text{out}}| = \sqrt{V_{\text{out}} V_{\text{out}}^*} = \frac{1}{\sqrt{1 + \omega^2 R^2 C^2}} V_{\text{in}}$$

where V_{out}^* is the complex conjugate of V_{out}.

Exercise 1.37

The Norton equivalent circuit can be found by measuring I_{short} and V_{open}:

$$I_{\text{Norton}} = I_{\text{short}} = \frac{10\text{V}}{10\text{k}\Omega} = \boxed{\mathbf{1}\text{mA}}$$

and since $V_{\text{open}} = 5\text{V}$, we have

$$R_{\text{Norton}} = \frac{5\text{V}}{1\text{mA}} = \boxed{\mathbf{5}\text{k}\boldsymbol{\Omega}}$$

2 Bipolar Transistors

Exercise 2.1

We assume a forward voltage for the LED of 1.5V. Then for I_{LED} we have

$$I_{LED} = \frac{V_R}{R} = \frac{3.3\text{V} - 1.5\text{V}}{330\Omega} \approx \boxed{\mathbf{5.5}\text{mA}}$$

To estimate the β_{min} we need the current entering the base

$$I_B = \frac{3.3\text{V} - 0.6\text{V}}{10\text{k}\Omega} = 0.27\text{mA}$$

Thus

$$\beta_{min} \geq \frac{I_{LED}}{I_B} = \boxed{\mathbf{20}}$$

Exercise 2.2

NOTE: According to the errata 0.63 should be replaced by 0.76 and 63μsec by 76μsec.

Starting from the hint that the capacitor charges from -4.4V towards $+5$V, we would result to a total 9.4V for a full charge. However, the V_{BE} of Q_2 is clipping the charging process at only 5V of the total (from -4.4V to 0.6V). Thus, the capacitor will be 53% charged at the end.
Solving the voltage equation for a charging capacitor gives us

$$V_C(t) = V_f * (1 - e^{-\frac{t}{RC}})$$

set $V_C(t_1) = 0.53 * V_f$

$$0.53 = 1 - e^{-\frac{t_1}{R_3C_1}}$$

$$\Rightarrow$$

$$t_1 = -R_3C_1 * ln(0.47) \approx \boxed{\mathbf{0.76 * R_3C_1}}$$

Exercise 2.3

The output voltage is reduced due to the $R_4 - R_5$ voltage divider

$$V_{\text{out}} = \frac{R_5}{R_4 + R_5} * (V_{CC} - 0.6\text{V}) \approx \boxed{\mathbf{4.18}\text{V}}$$

To estimate the minimum β_3, we need first to find the maximum (worst-case) collector current for which Q_3 should still be in saturation. For this we can assume a 0V drop across C and Q_3 while the current travels through the parallel connected resistors $R_2||R_3$.

$$I_{C_3,max} = \frac{V_{CC}}{R_2||R_3} = 5.5\text{mA}$$

$$\Rightarrow \beta_{3,min} = \frac{I_{C_3,max}}{I_{B_3}} = \frac{5.5\text{mA}}{\frac{(4.18\text{V}-0.6\text{V})}{20\text{k}\Omega}} \approx \boxed{\mathbf{31}}$$

Exercise 2.4

By using KCL and the fact that the transistor is in the active region we get

$$i_E = i_C + i_B = (\beta + 1) * i_B = (\beta + 1)\frac{v_B}{Z_{source}}$$

For small signals $Z_{\text{out}} = \frac{v_E}{i_E} = \frac{v_B}{i_E}$. Thus:

$$\boxed{\mathbf{Z}_{\text{out}} = \frac{\mathbf{v_B}}{(\beta + \mathbf{1})\frac{\mathbf{v_B}}{\mathbf{Z_{source}}}} = \frac{\mathbf{Z_{source}}}{\beta + \mathbf{1}}} \qquad \textit{q.e.d.}$$

Note: In practice one will often see $Z_{\text{out}} \approx \frac{Z_{source}}{\beta}$. When $\beta \approx 100$ the "+1" part is often being ignored to simplify calculations.