1. The figure shows a current mirror. The transistors are identical.

(a) If the base currents and the Early effect can be neglected, use the equations

\[ I_1 = I_S e^{V_{BE1}/V_T} \]
\[ I_2 = I_S e^{V_{BE2}/V_T} \]
\[ V_{BE1} + I_1 R_1 = V_{BE2} + I_2 R_2 \]

to show that

\[ I_1 \exp \left( \frac{I_1 R_1}{V_T} \right) = I_2 \exp \left( \frac{I_2 R_2}{V_T} \right) \]

(b) If \( I_1 = 1 \text{ mA} \), \( R_1 = 1.2 \text{ kΩ} \), and \( V_T = 25 \text{ mV} \), solve for \( R_2 \) for \( I_2 = 20 \mu\text{A} \). Answer: \( R_2 = 64.89 \text{ kΩ} \).

2. The figure shows a current mirror.
(a) If the transistors are identical and the Early effect can be neglected, label all currents in the unlabeled branches in terms of \( I_O \).
(b) Write a KCL equation at the collector of \( Q_1 \) and use it to solve for \( I_O \).
(c) What is the minimum \( \beta \) for \( I_O \geq 0.99 I_{REF} \)? Answer: \( \beta \geq 198 \).
(d) What is the small-signal output resistance \( r_{out} \)? Answer: \( r_{out} = r_{02} \).
(e) Explain how the Early effect can cause \( I_O \) to be greater than \( I_{REF} \).

3. The figure shows a current mirror with base current compensation.
(a) If the transistors are identical and the Early effect can be neglected, label all currents in the unlabeled branches in terms of \( I_O \).
(b) Write a KCL equation at the collector of \( Q_1 \) and use it to show that \( I_O \) is given by

\[ I_O = \frac{I_{REF}}{2} \frac{1 + \frac{2}{\beta (1 + \beta)}}{1 + \frac{1}{\beta (1 + \beta)}} \]
(c) What is the minimum $\beta$ for $I_O \geq 0.99I_{REF}$? Answer: $\beta \geq 13.58$.
(d) What is the small-signal output resistance $r_{out}$? Answer: $r_{out} = r_{02}$.
(e) Explain how the Early effect can cause $I_O$ to be greater than $I_{REF}$.

4. The figure shows a Wilson current mirror
   (a) If the transistors are identical and the Early effect can be neglected, label all currents in the unlabeled branches in terms of $I_O$. Hint, express $I_{E3}$ in terms of $I_O$ and use the results of problem 2 to show that $I_{C1}$ is given by in terms of $I_{E3}$
   
   $I_{C1} = \frac{I_O/\alpha}{1 + \frac{2}{\beta}}$

   (b) Write a KCL equation at the collector of $Q_1$ and use it to show that $I_O$ is given by
   
   $I_O = \frac{I_{REF}}{\frac{1}{\alpha} + \frac{2}{\beta} + \frac{1}{\beta}}$

   (c) What is the minimum $\beta$ for $I_O \geq 0.99I_{REF}$? Answer: $\beta \geq 13.12$.
   (d) Explain how a positive feedback effect causes the small-signal output resistance to be greater than $r_{03}$.

5. The figure shows a transconductance op amp. (a) It is desired to obtain an output current given by $i_o = 0.02(v_{11} - v_{12})$. If $V_T = 0.025 \, \text{V}$, what must be the value of $I_{ABC}$? Answer: $I_{ABC} = 1 \, \text{mA}$.
6. The transconductance op amp of problem 5 is to be connected to a current-to-voltage converter as shown below.

(a) The maximum peak value of $v_i$ is ±5 V. Specify the values of $R_1$ and $R_2$ which will prevent the voltage applied to the + terminal of the op amp from exceeding 40 mV. The source resistance seen looking out of the + terminal is to be 100Ω. Answers: $R_1 = 12.5 \, \text{k}\Omega$ and $R_2 = 101 \, \Omega$.

(b) For $I_{ABC}$ given by the value found in problem 5, calculate the value of $R_F$ for $v_o = 8$ V when $v_i = 5$ V. Assume $C_F$ is an open circuit. Answer: $R_F = 10 \, \text{k}\Omega$.

(c) Sketch and label the waveform for $v_o$ if $v_i(t) = 5 \sin (20000\pi t)$ and $I_{ABC} = 1 \times 10^{-3} [1 + 0.5 \sin (2000\pi t)]$. The waveform can easily be displayed with Mathcad, Matlab, or Excel.