1. The circuit below represents the internal circuitry of a simple op-amp. You can neglect the base currents and use the concept of virtual ground in your analysis when appropriate. Assume all NPN's to be matched in equal size and have $V_{BE} = 0.7V$. Let $V_{CC} = -V_{EE} = 15V$.

(a) Determine each transistor's collector d.e. current and collector-emitter d.e. voltage, present when $V_{CE} = V_{BE} = 0$. Neglect the base currents. Write your results in the table shown in the next page. (25 points)

(b) Estimate the overall amplifier gain $A_{out} = rac{V_{out}}{V_{in}}$. (25 points)

(c) Find the input and output resistances, $R_{in}$ and $R_{out}$, seen between the input terminals and the output terminal, respectively. (10 points)

(d) Find the common mode rejection ratio (CMRR) assuming the differential amplifier's transistors are perfectly matched and all components ideal. Use $V_{DD} = 100V$. (10 points)

(e) Find a new value for $V_{BE}$ that would make $V_{CE}$ to be zero when $V_{in} = V_{out} = 0$. (5 points)

\[ V_{CE} = \frac{10V - \frac{3V}{2}}{3} = 0.25mA \]

\[ I_{C} = I_{C1} = I_{C2} = 0.125mA \]

\[ I_{C3} = I_{C4} = I_{C5} = 0.25mA \]

\[ V_{BE} = V_{CC} - I_{C1} \times 10k = 5V - 0.125mA \times 10k = 2.5V \]

\[ I_{C6} = \frac{2.5V - (-5V)}{1.8mA} \]

\[ V_{CE1} = V_{C2} = V_{CE2} = V_{CE3} = V_{CE4} = V_{CE5} = V_{CE6} = 2.5V \]

\[ V_{CE7} = V_{CE8} = 5V - 2.5V = 2.5V \]

\[ V_{CE9} = V_{CE10} = 0.55V - (-5V) = 5.55V \]
<table>
<thead>
<tr>
<th>Transistor</th>
<th>$I_C (mA)$</th>
<th>$V_C (V)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.125</td>
<td>2.325</td>
</tr>
<tr>
<td>2</td>
<td>0.15</td>
<td>2.325</td>
</tr>
<tr>
<td>3</td>
<td>0.20</td>
<td>4.95</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>1.95</td>
</tr>
<tr>
<td>5</td>
<td>0.75</td>
<td>3.2</td>
</tr>
<tr>
<td>6</td>
<td>0.25</td>
<td>1.95</td>
</tr>
<tr>
<td>7</td>
<td>0.25</td>
<td>4.3</td>
</tr>
<tr>
<td>8</td>
<td>0.15</td>
<td>5.55</td>
</tr>
</tbody>
</table>

(b) $A_{v1} = \frac{V_C}{I_C} = g_m R_C = \left(\frac{125mA}{25mA}\right)(27K||10K) = 3605 V/V$

$A_{v2} = \frac{1}{2} g_m R_C \quad R_C = 10K || \left[\frac{g_m}{g_m + (1+g_m)1k}\right] = 9.1K$

$A_{v3} = \frac{1}{2} \left(\frac{125mA}{25mA}\right)(9102) = 455 V/V$

$A_v = \frac{g_m (1k)}{1 + g_m (1k)} = \frac{25mA}{125mA + 125mA} = 1$

$A_h = \frac{V_{out}}{V_i} = (3.65 \times 45.5)(1) = 1660 V/V$

(c) $R_m = 2R_C = 2(100) = 2(125mA) = 0.125mA$

$R_{out} = 1K || \left[\frac{g_m + R_C}{100}\right] = 1K || 102 = \frac{92.8 ohms}{102}$

(d) $CMRR = \infty$ because 1st stage output is differential.

(e) For $V_{out} = 0, \quad V_{ref} = 0.7V$

$I_{ref} = \frac{5V - 0.7V}{10k} = 0.43mA$
2. The following sketch shows a Widlar current source connected to a load. Assume that the load is a resistor $R_{\text{LOAD}}$ and that the transistors are matched and have the same area. Assume the collector-emitter saturation voltage to be 0.7V. Use $V_{CC} = V_{EE} = 5V$.

(a) Estimate the load current, $I_{\text{LOAD}}$. (10 points)

(b) Find the value of $R_{\text{LOAD}}$ that will drive the transistor into saturation. (15 points)

![Diagram of Widlar current source with transistors and load resistor]

(a) \[I_{\text{Ref}} = \left[\frac{V_{CC} - 0.4V - (-V_{EE})}{5\text{k} \Omega}\right] = \frac{4.3V}{5\text{k} \Omega} = 1.86 \text{ mA}\]

\[I_{0} = \frac{V_{T}}{R_{\text{m}}} \ln \left( \frac{I_{\text{Ref}}}{I_{0}} \right)\]

\[I_{0} = \frac{25 \text{mV}}{500 \text{k} \Omega} \ln \left( \frac{1.86 \text{ mA}}{I_{0}} \right)\]

\[I_{0} = 5 \text{mA} \ln \left( \frac{1.86 \text{ mA}}{I_{0}} \right)\]

Successive approx. yields \[I_{0} = 1.32 \text{ mA}\]

(b) \[V_{CC} = I_{\text{OUT}} \cdot R_{\text{LOAD}} = V_{CC} \cdot 500 = (-V_{EE}) = 0\]

\[10 = I_{\text{OUT}} \cdot (R_{\text{LOAD}} + 500) = 0 \Rightarrow 10 = \frac{10V}{I_{\text{OUT}}} + \frac{10V}{132 \mu A} = 500\]

\[R_{\text{LOAD}} = 75.2 \text{k} \Omega\]
3. (BONUS) For the circuit in problem 1, find the minimum and maximum common-mode voltage that can be applied to the input without driving any transistor into cutoff or saturation. Assume \( V_{CM} = 0 \). (10 points)

\[
V_{CM} = V_{CM} = 1.625 \text{V}
\]

\[
V_{CM_{\text{max}}} = 1.625 \text{V} + 0.2 \text{V} = 2.325 \text{V}
\]

\[
V_{CM_{\text{min}}} = V_{CM_{\text{max}}} - 2 \times V_{EE} = -4.3 \text{V}
\]

\[-4.3 \text{V} \leq V_{CM} \leq 2.325 \text{V}\]