A DC sweep of the specified MOSFET \((\text{nch } W=10\mu\text{m}, L=0.35\mu\text{m})\) provides:

<table>
<thead>
<tr>
<th>Data Point</th>
<th>(V_{GS})</th>
<th>(V_{DS})</th>
<th>(I_0)</th>
<th>(g_{m0})</th>
<th>(V_{th})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>44866.3(\mu\text{A})</td>
<td>1.6022(\mu\text{A})</td>
<td>566,mV</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>483.9163(\mu\text{A})</td>
<td>1.6615(\mu\text{A})</td>
<td>557,mV</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2.5156(\mu\text{A})</td>
<td>2.2851(\mu\text{A})</td>
<td>559,mV</td>
</tr>
</tbody>
</table>

b) Using the two points with constant \(V_{GS}\), we can find \(\lambda\) as follows:

\[
I_0 = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{th})^2 (1 + \lambda V_{DS})
\]

\[
I_{01} = X (1 + \lambda V_{031} \Rightarrow \frac{I_{01}}{I_{02}} = \frac{1 + \lambda V_{031}}{1 + \lambda V_{032}}
\]

\[
I_{01} + \lambda V_{032} I_{01} = I_{02} + \lambda V_{031} I_{02}
\]

\[
\lambda = \frac{I_{02} - I_{01}}{V_{032} I_{01} - V_{031} I_{02}} \approx 0.084 \, \text{V}^{-1}
\]

Using the two points with constant \(V_{DS}\), we can find \(V_{th}\):

\[
I_{02} = X (V_{GS2} - V_{th})^2 \Rightarrow \frac{I_{02}}{I_{03}} = \frac{(V_{GS2} - V_{th})^2}{(V_{GS3} - V_{th})^2}
\]

\[
(V_{GS3} - V_{th}) \sqrt{I_{02}} = (V_{GS2} - V_{th}) \sqrt{I_{03}}
\]

\[
V_{th} = \frac{V_{GS2} \sqrt{I_{03}} - V_{GS3} \sqrt{I_{02}}}{\sqrt{I_{03}} - \sqrt{I_{02}}} \approx 0.219 \, \text{V}
\]
16.) Continued.

Using any one of the data points and our calculated $\lambda$ and $V_{th}$, we can find $\mu_n C_{ox}$ by plugging the values into the long-channel expression for $I_0$.

$$I_0 = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{as} - V_{th})^2 (1 + \lambda V_{th})$$

$$\Rightarrow \mu_n C_{ox} = \frac{2 I_0 L}{W (V_{as} - V_{th})^2 (1 + \lambda V_{th})} \approx 4.7558 \times 10^{-5} \frac{A}{V^2}$$

(i) $g_m$ is calculated by:

$$g_m = \mu_n C_{ox} \frac{W}{L} (V_{as} - V_{th})(1 + \lambda V_{th})$$

$$= \frac{2 I_0}{V_{as} - V_{th}}$$

Relative error is:

$$\text{calculated } g_m - \text{spice } g_m \times 100\% \over \text{spice } g_m$$

<table>
<thead>
<tr>
<th>Results</th>
<th>$V_{as}$</th>
<th>$V_{th}$</th>
<th>spice $g_m$</th>
<th>calculated $g_m$</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.602m</td>
<td>1.15m</td>
<td>-28</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1.662m</td>
<td>1.24m</td>
<td>-25</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2.225m</td>
<td>2.33m</td>
<td>27</td>
<td></td>
</tr>
</tbody>
</table>
Problem 2-
Since $\lambda \neq 0 \Rightarrow r_o$ is finite. Also $\gamma \neq 0 \Rightarrow g_{mb} \neq 0$. But the bulk of all transistors are connected to source (it is not shown in picture). So $V_{BS} = 0$. As a result, we do not need to consider $g_{mb}$ at all. For all problems, a small signal model has been drawn. To find the output resistance, we only need to find the ratio of $V_X$ to $I_X$.

(d) In this problem, R1 has no effect in the circuit operation from the small signal view. Since gate of transistors are open in the mid-band frequencies and $I_{G1}=I_{G2}=0$, there is no voltage drop across R1. So $V_{R1}=0$ and we can replace it with a wire.

$$I_X = \frac{V_X}{r_{o1}} + \frac{V_X}{r_{o2}} + (g_{m1} + g_{m2})V_X \Rightarrow R_{OUT} = \frac{V_X}{I_X} = r_{o1} \parallel r_{o2} \parallel \frac{1}{g_{m1}} \parallel \frac{1}{g_{m2}}$$
Note (1): A diode-connected transistor seen from the drain terminal is equivalent to 
\[ r_o \parallel \frac{1}{g_m} \].

(e) The gates of both transistors are connected to a constant voltage. Therefore, from the small signal viewpoint they are both grounded. As shown in the small signal model (Fig. 5), we can ignore the dependent current sources, as they have no effect.

Note (2): A MOSFET biased as a current source (a constant voltage at its gate) can be replaced by \( r_o \).

(f) This circuit is the combination of circuits shown in Fig.2 and Fig.4. So using note (1) and note (2), we can conclude that the output resistance is \( r_{o1} \parallel r_{o2} \parallel \frac{1}{g_{m2}} \).
\[ I_X = \frac{V_X}{r_{o1}} + \frac{V_X}{r_{o2}} + g_{m2}V_X \Rightarrow R_{OUT} = \frac{V_X}{I_X} = r_{o1} \parallel r_{o2} \parallel \frac{1}{g_{m2}} \]

**Problem 3**- For each of the following problems, we ignore the bulk effect \((g_{mb}=0)\). However, we have to consider \(r_o\) as \(\lambda \neq 0\). Also, we try to use the results we found before. Instead of drawing the small signal model, we substitute the diode-connected, or current source transistors with their equivalent resistors we found in the previous problem (wherever possible).

(b) This is a common-source amplifier with source degeneration. The equivalent circuit of Fig. 8 has been shown in Fig. 9 where:
\[ R_S = r_{o1} \parallel \frac{1}{g_{m1}} \quad \text{and} \quad R_D = r_{o3} \parallel \frac{1}{g_{m3}} \]

According to the textbook (page 67), the voltage gain \((A_V)\) of this type of amplifier is:
\[ A_V = -G_m R_{out} \]

where:
\[ G_m = \frac{g_{m}r_o}{R_S + (1 + g_m R_S)r_o} \quad \text{and} \quad R_{OUT} = R_D \parallel [(1 + g_{m}r_o)R_S + r_o] \]

Therefore the voltage gain is:
\[ A_V = -\frac{g_{m2}r_{o2}}{R_S + (1 + g_{m2} R_S)r_o2} \cdot R_D \parallel [(1 + g_{m2}r_{o2})R_S + r_{o2}] \]

(c) This circuit is a source follower or common-drain amplifier. Again for simplicity, the circuit has been drawn in Fig. 11 with \(R_S\) and \(R_D\) instead of the actual transistors. From note (1) we can see that:
\[ R_S = r_{o1} \parallel \frac{1}{g_{m1}} \quad \text{and} \quad R_D = r_{o3} \parallel \frac{1}{g_{m3}}. \]

The small signal model of the circuit is drawn in Fig. 12. We can find the voltage gain by writing two node equations at the output terminal and node A:

\[
V_{\text{out}} = -\frac{V_A}{R_D} \cdot R_S \quad \Rightarrow \quad V_A = -\frac{V_{\text{out}}}{R_S} \cdot R_D
\]

\[
V_{gs} = V_{in} - V_{out}
\]

\[
g_m V_{in} = V_{out} \left( g_m + \frac{1}{R_S + R_D} \right) \quad \Rightarrow \quad A_V = \frac{V_{out}}{V_{in}} = \frac{g_m R_S r_o}{1 + g_m r_o) R_S + R_D + r_o}
\]

Figure 10: Problem 3.c

Figure 11: Source follower amplifier (common-drain)

Figure 12: Small signal model of Fig. 11
(d) This problem is similar to 3.b except that diode connected transistors have been replaced by current sources. So we use note (2) to find the equivalent resistors for M3 and M1:

\[ R_S = r_{o1} \text{ and } R_D = r_{o3}. \]

**(Figure 13: Problem 3.d)**

**(Figure 14: Common-source amplifier with source degeneration)**

(Av) of this type of amplifier is:

\[ A_v = -G_m R_{out} \text{ where:} \]

\[ G_m = \frac{g_m r_o}{R_S + (1 + g_m R_S)r_o} \text{ and } R_{OUT} = R_D \parallel [(1 + g_m r_o)R_S + r_o]. \]

Therefore the voltage gain is:

\[ A_v = -\frac{g_m r_o}{R_S + (1 + g_m R_S)r_o} \cdot R_D \parallel [(1 + g_m r_o)R_S + r_o] \]

\[ \text{and} \]

\[ R_{OUT} = R_D \parallel [(1 + g_m r_o)R_S + r_o]. \]