EE 330
Lecture 35

- Current Source Biasing
- Current Sources and Mirrors
## Basic Amplifier Gain Table

<table>
<thead>
<tr>
<th>Circuit Type</th>
<th>MOS</th>
<th>BJT</th>
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<th>BJT</th>
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<th>BJT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$A_V$</strong></td>
<td>$-g_mR_C$</td>
<td>$\frac{g_m}{g_m+g_E}$</td>
<td>$g_mR_C$</td>
<td>$-\frac{R_C}{R_E}$</td>
<td>$\frac{2I_{DQ}R_C}{V_{EB}}$</td>
<td>$\frac{I_{CQ}R_E}{V_{EB}}$</td>
<td>$\frac{2I_{DQ}R_C}{V_{EB}}$</td>
<td>$\frac{I_{CQ}R_E}{V_{EB}}$</td>
</tr>
<tr>
<td><strong>$R_{in}$</strong></td>
<td>$r_{\pi}$</td>
<td>$r_{\pi}+\beta R_E$</td>
<td>$g_m^{-1}$</td>
<td>$r_{\pi}+\beta R_E$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td><strong>$R_{out}$</strong></td>
<td>$R_C$</td>
<td>$g_m^{-1}$</td>
<td>$R_C$</td>
<td>$R_C$</td>
<td>$\frac{2I_{DQ}}{V_{EB}}$</td>
<td>$\frac{I_{CQ}}{V_t}$</td>
<td>$\frac{2I_{DQ}}{V_{EB}}$</td>
<td>$\frac{I_{CQ}}{V_t}$</td>
</tr>
</tbody>
</table>

Can use these equations only when circuit is EXACTLY like that shown above!!
Basic Amplifier Characteristics Summary

**CE/CS**
- Large noninverting gain
- Low input impedance
- Moderate (or high) output impedance
- Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode

**CC/CD**
- Gain very close to +1 (little less)
- High input impedance for BJT (high for MOS)
- Low output impedance
- Widely used as a buffer

**CB/CG**
- Large noninverting gain
- Low input impedance
- Moderate (or high) output impedance
- Used more as current amplifier or, in conjunction with CD/CS to form two-stage cascode

**CEwRE/CSwRS**
- Reasonably accurate but somewhat small gain (resistor ratio)
- High input impedance
- Moderate output impedance
- Used when more accurate gain is required
High-gain BJT amplifier

\[ A_V = \frac{-g_m}{g_0 + G_C} \approx -g_m R_C \]

To make the gain large, it appears that all one needs to do is make \( R_C \) large!

\[ A_V \approx -g_m R_C = \frac{-I_{CQ} R_C}{V_t} \]

But \( V_t \) is fixed at approx 25mV and for good signal swing, \( I_{CQ} R_C < \frac{(V_{DD} - V_{EE})}{2} \)

\[ |A_V| < \frac{V_{DD} - V_{EE}}{2V_t} \]

If \( V_{DD} - V_{EE} = 5V \),

\[ |A_V| < \frac{5V}{2 \cdot 25mV} = 100 \]

Gain is practically limited with this supply voltage to around 100
High-gain MOS amplifier

\[ AV = \frac{-g_m}{g_0 + G_D} \approx -g_m R_D \]

To make the gain large, it appears that all one needs to do is make \( R_D \) large!

\[ AV = -g_m R_D = \frac{-2I_{DQ} R_D}{V_{EB}} \]

But \( V_{EB} \) is practically limited to around 100mV and for good signal swing, \( I_{DQ} R_D < (V_{DD} - V_{SS})/2 \)

\[ |AV| < \frac{V_{DD} - V_{SS}}{V_{EB}} \]

If \( V_{DD} - V_{SS} = 5V \) and \( V_{EB} = 100mV \),

\[ |AV| < \frac{5V}{100mV} = 50 \]

Gain is practically limited with this supply voltage to around 100

Are these fundamental limits on the gain of the BJT and MOS Amplifiers?
High-gain amplifier

This gain is very large!

Too good to be true!

Need better model of MOS device!
This gain is very large (but realistic)!

But how can we make a current source?
Example: Determine the voltage gain of the following circuit

\[ V_{out} = \frac{V_{in}}{A_{E1}} \]

Since symmetric when \( V_{in} = 0 \)

\[ I_{C1} = I_{C2} = \frac{I_{EE}}{2} \]

\[ g_{m1} = g_{m2} = \frac{I_{EE}}{2V_t} \]
Example: Determine the voltage gain of the following circuit

\[ V_E (g_{\pi 1} + g_{\pi 1}) = g_{\pi 1} V_{IN} + g_{m1} (V_{IN} - V_E) + g_{m2} (-V_E) \]

\[ V_{OUT} = -R_{C1} g_{m1} (V_{IN} - V_E) \]

\[ V_E = (g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2}) = V_{IN} (g_{m1} + g_{\pi 1}) \]

\[ V_E = \frac{(g_{m1} + g_{\pi 1})}{(g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2})} V_{IN} \]

\[ V_{OUT} = -R_{C1} g_{m1} V_{IN} \left[ 1 - \frac{(g_{m1} + g_{\pi 1})}{(g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2})} \right] \]

\[ V_{OUT} = -R_{C1} g_{m1} V_{IN} \left[ \frac{g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2} - (g_{m1} + g_{\pi 1})}{(g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2})} \right] \]
Example: Determine the voltage gain of the following circuit

\[
\mathbf{V}_{\text{OUT}} = -R_{C1} g_m \mathbf{V}_{\text{IN}} \left[ \frac{g_{m1} + g_{m2} + g_{\pi 1} + g_{\pi 2} - (g_{m1} + g_{\pi 1})}{g_{\pi 1} + g_{\pi 2} + g_{m1} + g_{m2}} \right]
\]

\[
\mathbf{V}_{\text{OUT}} \approx -R_{C1} g_m \mathbf{V}_{\text{IN}} \left[ \frac{g_{m2}}{g_{m1} + g_{m2}} \right]
\]

\[
\mathbf{V}_{\text{OUT}} \approx \left[ -\frac{R_{C1} g_m}{2} \right] \mathbf{V}_{\text{IN}}
\]

\[
\mathbf{V}_{\text{OUT2}} \approx \left[ \frac{R_{C1} g_m}{2} \right] \mathbf{V}_{\text{IN}}
\]
Differential amplifier

\[ V_{OUT1} \approx -\left[ \frac{R_{C1}g_{m1}}{2} \right] \left( V_{IN1} - V_{IN2} \right) \]

\[ V_{OUT2} \approx \left[ \frac{R_{C1}g_{m1}}{2} \right] \left( V_{IN1} - V_{IN2} \right) \]

Very useful circuit
This is a basic Op Amp
How can we build the ideal current source?

What is the small-signal model of an actual current source?
Current Sources/Mirrors

If the base currents are neglected

\[ I_0 \approx \frac{(V_{CC} - 0.6V)}{R} \]
Current Sources/Mirrors

If the base currents are neglected

\[ I_0 = J_S A_{E_0} e^{\frac{V_{BE_0}}{V_t}} \]

\[ I_1 = J_S A_{E_1} e^{\frac{V_{BE_1}}{V_t}} \]

since \( V_{BE_1} = V_{BE_2} \)

\[ I_1 \approx \left( \frac{A_{E_1}}{A_{E_0}} \right) I_0 \]

Behaves as a current source!

Actually termed a “sink” current since coming out of load
Current Sources/Mirrors

- Multiple Outputs Possible
- Can be built at sourcing or sinking currents
- Also useful as a current amplifier
- MOS counterparts work very well and are not plagued by base current
Current Sources/Mirrors

Multiple-Output Bipolar Current Sink

\[ I_k = \left[ \frac{A_{E_k}}{A_{E_0}} \right] I_0 \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source

\[ I_k = \left[\frac{A_{E_k}}{A_{E_0}}\right] I_0 \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source and Sink

\[ I_{nk} = ? \quad I_{pk} = ? \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source and Sink

\[ I_{nk} = \left[ \frac{A_{Enk}}{A_{E0}} \right] I_0 \]

\[ I_{pk} = \left[ \frac{A_{En1}}{A_{E0}} \right] \left[ \frac{A_{Epk}}{A_{Ep0}} \right] I_0 \]
Current Sources/Mirrors

- Termed a “current mirror”
- Output current linearly dependent on $I_{in}$
- Serves as a current amplifier
- Widely used circuit

$$I_{out} = \left[ \frac{A_{E1}}{A_{E0}} \right] I_{in}$$
Current Sources/Mirrors

n讨厌n current mirror amplifier

\[ i_{\text{out}} = ? \]
Current Sources/Mirrors

nnpn current mirror amplifier

\[ i_{\text{out}} = \left[ \frac{A_{E1}}{A_{E0}} \right] i_{\text{in}} \]

Amplifiers both positive and negative currents
Current Sources/Mirrors

n-channel Current Mirror

\[ I_{\text{out}} = ? \]
Current Sources/Mirrors

If process parameters are matched, it follows that

\[
I_{\text{out}} = \left[ \frac{W_1}{W_0} \frac{L_0}{L_1} \right] I_{\text{in}}
\]

Current mirror gain can be accurately controlled

Layout is important to get accurate gain (for both MOS and BJT)
Layout of Current Mirrors

Example with $M = 2$

Standard layout

Gate area after fabrication depicted
Layout of Current Mirrors

Example with $M = 2$

Standard layout

Better Layout

$M = \begin{bmatrix} \frac{W_2}{W_1} & \frac{L_1}{L_2} \end{bmatrix}$

$M = \begin{bmatrix} \frac{2W_1 + 2\Delta W}{W_1 + 2\Delta W} & \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \end{bmatrix} \neq 2$

$M = \begin{bmatrix} \frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} & \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \end{bmatrix} = 2$
Layout of Current Mirrors

Example with $M = 2$

Standard layout

Better Layout

Even Better Layout

This is termed a common-centroid layout
Current Sources/Mirrors

n-channel current mirror current amplifier

\[ i_{\text{out}} = \left[ \frac{W_2}{W_1} \frac{L_1}{L_2} \right] i_{\text{in}} \]

Amplifiers both positive and negative currents
Current Sources/Mirrors

\[ I_k = \left[ \frac{W_k}{W_0} \frac{L_0}{L_k} \right] I_0 \]

multiple output n-channel current sink array

multiple output p-channel current source array
High-gain amplifier

How can we build the current source?

What is the small-signal model of an actual current source?
Basic Current Sources and Sinks

Basic Bipolar Current Sinks

- \( V_{xx} \)
- \( I_x = J_S A E e^{\frac{V_{xx}}{V_t}} \)
- \( I_x \approx \frac{V_{CC} - 0.6V}{R} \)

Basic Bipolar Current Sources

- \( V_{CC} \)
- \( I_x \)

Very practical methods for biasing the BJTs can be used. Current Mirrors often used for generating sourcing and sinking currents.
Basic Current Sources and Sinks

Small-signal Model of BJT Current Sinks and Sources

Small-signal model of all other BJT Sinks and Sources are the same
Basic Current Sources and Sinks

Small-signal Model of BJT Current Sinks and Sources

Small-signal model of all other MOS Sinks and Sources are the same
High-gain amplifier

\[ A_V = \frac{-g_m}{g_0} \]

\[ A_V = \frac{-g_{m1}}{g_{01} + g_{02}} \approx \frac{-g_{m1}}{2g_{01}} \]
High-gain amplifier

\[ AV = \frac{-g_m}{g_0} \]

- Nonideal current source decreased the gain by a factor of 2
- But the voltage gain is still quite large

Can the gain be made even larger?
End of Lecture 35