ECE 255: L19

Basic Amplifier Configurations
(Sedra and Smith, 7th Ed., Sec. 7.3)

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Lundstrom: 2019
Announcements

1) LTspice Project 2 due Wed. Feb. 27th by 5:00PM electronically. You should find your assigned your beta value in your grade book.

2) HW6 due Monday 2/25 by 5:00 PM

3) Exam 2 is Tuesday, March 5, 6:30-7:30 PM PHYS 112
Outline

1) T-model
2) Basic amplifier considerations
3) CE
4) CS
Simple hybrid pi model

\[ v_{be} = v_{\pi} = i_b r_\pi \]

\[ g_m = \frac{I_C}{V_T} \]

\[ g_m r_\pi = \beta \]

\[ r_o = \frac{V_A}{I_C} \]

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\[ v_{be} = i_b r_\pi = (i_b + \beta i_b) r_e = i_b (\beta + 1) r_e \]

\[ r_e = \frac{\alpha}{g_m} \approx \frac{1}{g_m} \ll r_\pi \]
The “T model” vs. hybrid -pi

\[ i_b = \frac{\nu_{be}}{r_\pi} \]

\[ i_c = g_m \nu_{be} \]

\[ i_e = i_b + i_c \]

\[ (\beta + 1)i_b = \nu_{be}(\beta + 1)/r_\pi \]

\[ i_c = g_m i_e r_e = \alpha i_e \]

\[ \nu_{be} = i_e r_e \]

\[ r_e = \frac{\alpha}{g_m} = \frac{r_\pi}{\beta + 1} \]
The “T model” vs. hybrid -pi

\[ I_C = 1.0 \text{ mA} \]

\[ \beta = 100 \]

\[ g_m = \frac{I_C}{V_T} = 39 \text{ mS} \]

\[ g_m r_\pi = \beta \]

\[ r_\pi = \frac{\beta}{g_m} = 2.6 \text{ k}\Omega \]

\[ \alpha = \frac{\beta}{\beta + 1} = 0.99 \]

\[ r_e = \frac{\alpha}{g_m} = \frac{0.99}{39 \times 10^{-3}} = 25 \text{ } \Omega \]

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Outline

1) T-model

2) Basic amplifier considerations

3) CE

4) CS
Transistors have 3 terminals, so one must be **common** between the input and output.
Common emitter

\[ V_{b} + i_{b} - V_{e} - C_{e} \]

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Common base

\[ v_i - \sum_{n=0}^{\infty} C_i \]
Also common base

\[ i_c = \beta i_e \]

\[ v_i \]

\[ v_0 \]
Common collector

\[ \varepsilon_i - \varepsilon_0 - C \]

\begin{align*}
\text{B} & \quad i_b \\
+ & \quad v_i \\
- & \quad - \\
\text{C} & \quad i_c \\
\text{E} & \quad i_e \\
+ & \quad v_0 \\
- & \quad - \\
\end{align*}
Amplifier model

Open circuit voltage gain

\[ A_{vo} = \frac{v_o}{v_i} \bigg|_{R_L=\infty} \]
 Amplifier with source and load

\[ G_v = \frac{v_o}{v_s} = \frac{R_{in}}{R_{in} + R_s} \times A_{vo} \times \frac{R_L}{R_L + R_o} \]

\[ v_i = v_s \frac{R_{in}}{R_{in} + R_s} \]

\[ v_o = A_{vo} v_i \frac{R_L}{R_L + R_o} \]
Amplifier with source and load

\[ G_i = \frac{i_o}{i_i} = \frac{v_o}{v_i} \frac{R_L}{R_{in}} = A_{vo} \frac{R_{in}}{R_L} \]

\[ G_p = \frac{p_o}{p_i} = \frac{v_o i_o}{v_s i_i} = G_v G_i \]
Outline

1) T-model

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Common emitter

\[ \begin{align*}
\eta_i & \quad - \quad \eta_0 \\
C E & \quad i_b = i_i \\
R_{series} & \quad R_C \\
B & \quad E \\
\eta_s & \quad \eta_i
\end{align*} \]
Draw the common emitter s.s. equiv. ckt.
Common emitter s.s. equiv. ckt.

\[ i_b = i_i \]

\[ v_i = v_{\pi} \]

\[ v_s \]

\[ R_{\text{series}} \]

\[ r_{\pi} \]

\[ + \]

\[ g_m v_{\pi} \]

\[ R_c \]

\[ v_0 \]

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Common emitter analysis

\[ A_{v_o} = \frac{v_o}{v_i} \]

\[ R_{in} = \frac{v_i}{i_i} \]

\[ R_o = \frac{v_o}{i_o} \]
Common emitter analysis

\[ v_o = -g_m v_i R_C = -g_m v_i R_C \]

open circuit voltage gain

\[ A_{v_o} = \frac{v_o}{v_i} = -g_m R_C \]

Effect of \( r_0 \)?

\[ R_{in} = r_{\pi} \]

\[ R_o = R_C \]

\[ A_v = -g_m \left( R_C \parallel R_L \right) \]

with load attached

\[ G_v = \frac{v_o}{v_s} = \frac{v_i}{v_s} \frac{v_o}{v_i} = - \left( \frac{r_{\pi}}{r_{\pi} + R_s} \right) g_m \left( R_C \parallel R_L \right) \]
Common emitter

$$I_C = 1 \text{ mA} \quad \beta = 100 \quad kT/q = 0.026 \text{ V}$$

$$V_A = 100 \text{ V}$$

$$R_{series} = 50 \text{ k}\Omega$$

$$i_b = i_i$$

$$R_C = 10 \text{ k}\Omega$$
Common emitter results

\[
A_v = \frac{v_o}{v_i} = -g_m R_C
\]

\[
R_{in} = r_\pi
\]

\[
R_o = R_C
\]

\[
A_v = -g_m \left( R_C \parallel R_L \right)
\]

\[
G_v = \frac{v_o}{v_s} = -\left( \frac{r_\pi}{r_\pi + R_S} \right) g_m \left( R_C \parallel R_L \right)
\]

\[
24
\]

\[
\begin{align*}
I_C &= 1.0 \text{ mA} \\
g_m &= I_C / V_T = 39 \text{ mS} \\
g_m r_\pi &= \beta \\
r_\pi &= \beta / g_m = 2.6 \text{ k}\Omega \\
R_{in} &= 2.6 \text{ k}\Omega \\
R_o &= 10 \text{ k}\Omega \\
A_{v_o} &= -g_m R_C = -390 \\
G_v &= -\left( \frac{2.6}{2.6 + 50} \right) 39 (10 \parallel 5) = -6.4
\end{align*}
\]
Alternatively

\[ G_v = \frac{v_o}{v_s} = \frac{R_{in}}{R_{in} + R_s} \times A_{vo} \times \frac{R_L}{R_L + R_o} \]

\[ R_{in} = r_\pi \]

\[ A_{vo} = \frac{v_o}{v_i} = -g_m R_C \]

\[ R_o = R_C \]
Common emitter with “emitter degeneration”

\[ i_c - \frac{\nu_0}{R_C} = \frac{i_b - i_i}{R_{series}} + R_E = 1 \text{k}\Omega \]

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Draw the small signal equiv. ckt.
Small signal equiv. ckt.

\[ i_b = i_i \]

\[ i_c \]

Effect of \( r_0 \)?
\[ \nu_o = -g_m \nu \pi R_C \]

\[ \nu_i = \nu \pi + \nu R_E \]

\[ \nu_i = \nu \pi + (i_b + \beta i_b) R_E \]

\[ \nu_i = \nu \pi + (\beta + 1) \frac{\nu \pi}{r \pi} R_E \]

\[ \nu_i = \frac{\nu \pi}{r \pi} \left( r \pi + (\beta + 1) R_E \right) \]

\[ \nu \pi = \nu_i \frac{r \pi}{r \pi + (\beta + 1) R_E} \]

Do you see how to get this “by inspection”? 
“resistance reflection rule”

\[ R_{in} = r_\pi + (\beta + 1) R_E \]
V pi in terms of input voltage

\[ v_\pi = \frac{r_\pi}{r_\pi + (\beta + 1)R_E} v_i \]
Common emitter with emitter resistor

\[ \nu_o = -g_m \nu_\pi R_C \]

\[ \nu_\pi = \nu_i \frac{r_\pi}{r_\pi + (\beta + 1)R_E} \]

\[ A_{\nu_o} = -\frac{r_\pi}{r_\pi + (\beta + 1)R_E} (g_m R_C) \]

\[ R_{in} = r_\pi + (\beta + 1)R_E \]

\[ R_o = R_C \]

\[ A_{\nu_o} = \frac{2.6}{2.6 + (101)1}(-390) = -9.8 \]

\( (R_E = 0 : A_{\nu_o} = -390) \)

\[ R_{in} = 2.6 + (101)1 = 103.6 \, \text{k}\Omega \]

\( (R_E = 0 : R_{in} = 2.6 \, \text{k}\Omega) \)

\[ R_o = 10 \, \text{k}\Omega \]

\( (R_E = 0 : R_o = 10 \, \text{k}\Omega) \)
"Precision amplifier"

\[ A_{v_o} = \frac{r_\pi}{r_\pi + (\beta + 1)R_E} (-g_m R_C) \]

If:

\[(\beta + 1)R_E \gg r_\pi\]

\[ A_{v_o} \approx -\frac{g_m r_\pi}{(\beta + 1)R_E} R_C = \frac{\beta}{(\beta + 1)} \left( -\frac{R_C}{R_E} \right) \]

\[ A_{v_o} \approx -\frac{10}{1} = -10 \]
CE with “emitter degeneration” summary

\[
A_{v_o} = \frac{r_\pi}{r_\pi + (\beta + 1)R_E}(-g_m R_C) \approx - \frac{R_C}{R_E}
\]

\[
R_{in} = r_\pi + (\beta + 1)R_E
\]

\[
R_o = R_C
\]

Physical reason:
Negative feedback

Effect of \( R_L \)?

Compared to the \( R_E = 0 \) case:
Lower voltage gain
Higher input resistance
Same output resistance
Negative feedback

\[ \frac{\nu_i - \nu_0}{C} = \frac{i_i}{R_C} + \frac{i_c}{R_s} \]

\[ i_b = i_i \]

\[ R_{\text{series}} \]

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Common source

\[ i_g = i_i \quad \text{and} \quad v_i = v_s \]

\[ \text{Common source} \]

Lundstrom: 2019
## CE vs. CS

<table>
<thead>
<tr>
<th>Common Emitter</th>
<th>Common Source</th>
</tr>
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<tbody>
<tr>
<td>$A_{v_o} = \frac{v_o}{v_i} = -g_m R_C$</td>
<td>$A_{v_o} = \frac{v_o}{v_i} = -g_m R_D$</td>
</tr>
<tr>
<td>$R_{in} = r_\pi$</td>
<td>$R_{in} = \infty$</td>
</tr>
<tr>
<td>$R_o = R_C$</td>
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Common source with source degeneration

\[ i_c = \gamma_i \]

\[ \gamma_i = \frac{R_D}{R_D + R_E} \]

\[ v_0 = \frac{R_E}{R_D + R_E} v_s \]

\[ \gamma_i = \frac{R_D}{R_D + R_E} \]

\[ v_0 = \frac{R_E}{R_D + R_E} v_s \]

\[ \gamma_i = \frac{R_D}{R_D + R_E} \]

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<td>[ A_{v_o} = \frac{r_\pi}{r_\pi + (\beta + 1)R_E}(-g_mR_C) ]</td>
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CE vs. CS with emitter/source degeneration

**Common Emitter**

\[ A_{v_o} = \frac{r_\pi}{r_\pi + (\beta + 1) R_E} \left( -g_m R_C \right) \]

\[ R_{in} = r_\pi + (\beta + 1) R_E \]

\[ R_o = R_C \]

**Common Source**

\[ A_{v_o} = \frac{1}{1 + \frac{(\beta + 1) R_S}{r_\pi}} \left( -g_m R_D \right) \]

\[ g_m r_\pi = \beta \]

\[ A_{v_o} = \frac{1}{1 + g_m R_S} \left( -g_m R_D \right) \]

\[ R_{in} = \infty \]

\[ R_o = R_D \]
Amplifiers are characterized in terms of their open-circuit voltage gain, input resistance, and output resistance.

The CE amplifier has high (negative) gain, moderate input impedance and moderate output resistance.

Emitter degeneration ($R_E > 0$) lowers the gain but increases the input impedance.

The CS amplifier has moderate (negative) gain, high input impedance and moderate output resistance.
Basic Amplifier Configurations

1) T-model

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