Basic Single-Transistor Amplifier Configurations

**MOSFET**
- (a) Common Source (CS)
- (b) Common Gate (CG)
- (c) Common Drain (CD) or Source Follower

**BJT**
- (d) Common-Emitter (CE)
- (e) Common-Base (CB)
- (f) Common-Collector (CC) or Emitter Follower
Two-Port Model of Amplifiers

\[ G_v = \frac{R_{in}}{R_{in} + A_{v0}} R_s \]

In addition to gain, it's important to have proper input and output resistances.

Procedure to find \( R_s \):
- Ground input, remove \( R_{sig} \)
- Apply a test current source at output (conceptually, not experimentally), find voltage at output terminal.

\[ R_s = \frac{v_o}{i_t} \]

Common-Source (CS) Amplifier

Previously, using MOSFET equation (on p. 11-4), we derived analytically:

\[ A_v = -g_m V_{DS} R_D \]

(The process is cumbersome, tedious, and will go quickly out of hand with more complex circuits)

Using hybrid-pi model, it is almost trivial to solve:

\[ A_v = -g_m R_D \]

With load resistance, \( R_L \):
- Since \( R_v \) is in parallel with \( R_D \)

\[ G_v = -g_m \left( R_D || R_L \right) \]

\[ R_{in} = \infty \]

\[ R_0 = R_D \]
Common-Emitter (CE) Amplifier

Again, using hybrid-pi model, it can be easily solved:

\[ A_v = -g_m R_C \]

With load resistance, \( R_L \):

Since \( R_L \) is in parallel with \( R_D \):

\[ G_v = -g_m \left( \frac{R_C \parallel R_L}{R_{\text{eq}} + r_a} \right) \]

\[ R_{\text{in}} = r_a \]

\[ R_C = R_C \]

T-Equivalent Circuit Model for MOSFET (without \( r_o \))

No change in circuit since the additional dependent current source has the same current

Same current with the dependent current source replaced by equivalent resistance

No change in circuit since no current will flow through the new connected path
CS with Source Resistance (Source Degeneration)

You can analyze the circuit using hybrid-pi model. (Try it!)

However, whenever there is a resistor connected to source, it is much easier to use the "T-model"

\[ v_D = -iR_D \]
\[ v_I = i \left( \frac{1}{g_m + R_s} \right) \]
\[ A_v = - \frac{R_D}{1 + g_m R_S} = \frac{1}{g_m R_S} \]

Gain reduced by \((1 + g_m R_S)\) compared with standard CS amplifier

\[ R_s = \infty \]
\[ R_s = R_D \]

Note:

\[ A_v = - \frac{R_D}{1 + R_s} = \frac{\text{Total resistance in Drain}}{\text{Total resistance in Source}} \]

\(R_s\) provides negative feedback, which

1. stabilize drain current
2. increase linearity by keeping \(v_P\) small

\[ v_P = v_I \frac{g_m}{1 + R_s} = v_I \frac{1}{g_m + R să} \]

3. Increase usable bandwidth
T-Model for BJT

Hybrid-pi Model

T-Model without \( r_0 \)

T-Model with \( r_0 \)

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CE with Emitter Resistance (Emitter Degeneration)

\[ v_C = -i_C R_C \]

\[ v_i = i_i \left( \frac{1}{g_m} + R_i \right) \]

\[ A_v = -\frac{R_C}{1/g_m + R_i} \frac{i_I}{i_i} = -\alpha \frac{g_m R_C}{1 + g_m R_C} \]

where \( \alpha = \frac{i_i}{i_C} = \frac{\beta}{\beta + 1} \) (usually \( \alpha \approx 1 \))

Note: \( R_m \) is boosted significantly:

\[ R_m = \frac{i_i \left( \frac{1}{g_m} + R_i \right)}{i_i} = \left( \beta + 1 \right) \left( \frac{1}{g_m} + R_i \right) \]

\[ R_m = r_p + \left( \beta + 1 \right) R_i \]

\[ R_o = R_C \]

\[ G_v = -\alpha \frac{g_m R_C}{1 + g_m R_C} \frac{R_m}{R_{stg} + R_m} \]
**CE with Emitter Resistance**  
*(Emitter Degeneration)*

Effect of $R_e$ (called "Emitter Degeneration"):  
1. Increase input resistance by $(1 + g_m R_e)$  
2. Reduce voltage gain by $(1 + g_m R_e)$  
3. Reduce $v_m$ by $(1 + g_m R_e)$  
   → lower nonlinear distortion  
4. Voltage gain less dependent on $\beta$  
5. Improved high frequency response

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**Common-Gate (CG) Amplifier**

$R_{srf}$ connected to source  
→ Use the "T-model"  
$v_i = -iR_D$  
$v_i = -(1/g_m)$  
$A_v = \frac{R_D}{1/g_m} = g_m R_D$

$R_m = 1/g_m$  
$v_i = v_{srf} \frac{R_m}{R_s + R_m} = v_{srf} \frac{1/g_m}{R_s + 1/g_m}$  
$G_v = g_m R_D \frac{1/g_m}{R_s + 1/g_m} = \frac{R_D}{R_s + 1/g_m}$  
$R_s = R_D$  
Low input resistance
### Common-Base (CB) Amplifier

- \( R_{sfg} \) connected to Emitter
- Use the "T-model"
  - \( v_o = -iR_C \)
  - \( v_i = -i(1/g_m) \)
  - \( A_v = \frac{R_C}{1/g_m} = g_m R_C \)

\[ R_{in} = \frac{1}{g_m} \]
\[ v_i = v_{sfg} \]
\[ G_v = g_m R_C \frac{1}{g_m R_{sfg} + 1/g_m} = \frac{R_C}{R_{sfg} + 1/g_m} \]
\[ R_o = R_C \]

### Unity-Gain Buffer Voltage Amplifier

- Driving low impedance load directly:
  - \( R_{sfg} = 1 \text{ MΩ} \)
  - \( v_{sig} = 1V \)
  - \( R_f = 1 \text{ kΩ} \)
  - \( v_o \approx 1 \text{ mV} \)

- Driving low impedance load with unity-gain buffer:
  - \( R_{sfg} = 1 \text{ MΩ} \)
  - \( v_{sig} = 1V \)
  - \( R_f = 1 \text{ kΩ} \)
  - \( v_o = 0.9 \text{ V} \)
  - \( R_o \) very large
Common-Drain (CD) Amplifier (Source Follower)

- Source Follower
- Source Follower with T-Model

\[ R_L \text{ connected to source} \]
\[ v_0 = v_0 \frac{R_L}{R_L + 1/g_m} \]
\[ A_v = \frac{R_L}{R_L + 1/g_m} \rightarrow 1 \text{ when } R_L \gg 1/g_m \]

\[ R_m = \infty \]
\[ G_v = \frac{R_L}{R_L + 1/g_m} \]
\[ R_s = 1/g_m \text{ Low output resistance} \]

Common-Collector (CC) Amplifier (Emitter Follower)

- Emitter Follower
- Emitter Follower with T-Model

\[ R_L \text{ connected to Emitter} \]
\[ v_0 = v_0 \frac{R_L}{R_L + 1/g_m} \]
\[ A_v = \frac{R_L}{R_L + 1/g_m} \rightarrow 1 \text{ when } R_L \gg 1/g_m \]

\[ R_m = (\beta + 1)(R_L + 1/g_m) \]
\[ G_v = \frac{R_L}{R_L + 1/g_m} \]
\[ R_s = 1/g_m \text{ Low output resistance} \]
Input and Output Resistance of Emitter Follower

Intuition:
• Resistance on emitter side is multiplied by \((1+\beta)\) when “seen” from base (input side) – High input resistance
• Resistance on base side is divided by \((1+\beta)\) when “seen” from emitter side – Low output resistance

Comparison of Different Amplifier Configurations

• MOS has higher input \(\left(\infty\right)\) impedance
• BJT has higher gain \((g_m)\)
• IC uses MOS, discrete circuits favors BJT
• CS / CE provides the bulk of the gain
• CD / CC used as voltage buffer in output stage
### Summary of MOSFET Amplifiers

**Table 7.4  Characteristics of MOSFET Amplifiers**

<table>
<thead>
<tr>
<th>Amplifier type</th>
<th>$R_{in}$</th>
<th>$A_{vo}$</th>
<th>$R_{o}$</th>
<th>$A_{v}$</th>
<th>$G_{v}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common source (Fig. 7.35)</td>
<td>$\infty$</td>
<td>$-g_m R_D$</td>
<td>$R_D$</td>
<td>$-g_m (R_D \parallel R_L)$</td>
<td>$-g_m (R_D \parallel R_L)$</td>
</tr>
<tr>
<td>Common source with $R_i$ (Fig. 7.37)</td>
<td>$\infty$</td>
<td>$\frac{g_m R_D}{1 + g_m R_i}$</td>
<td>$R_D$</td>
<td>$\frac{-g_m (R_D \parallel R_L)}{1 + g_m R_i}$</td>
<td>$\frac{-g_m (R_D \parallel R_L)}{1 + g_m R_i}$</td>
</tr>
<tr>
<td>Common gate (Fig. 7.39)</td>
<td>$\frac{1}{g_m}$</td>
<td>$g_m R_D$</td>
<td>$R_D$</td>
<td>$g_m (R_D \parallel R_L)$</td>
<td>$\frac{R_L}{R_m + 1/g_m}$</td>
</tr>
<tr>
<td>Source follower (Fig. 7.42)</td>
<td>$\infty$</td>
<td>$1$</td>
<td></td>
<td></td>
<td>$\frac{R_L}{R_m + 1/g_m}$</td>
</tr>
</tbody>
</table>

* For the interpretation of $R_{in}$, $A_{vo}$, and $R_o$, refer to Fig. 7.34(b).

### Summary of BJT Amplifiers

**Table 7.5  Characteristics of BJT Amplifiers**

<table>
<thead>
<tr>
<th>Amplifier type</th>
<th>$R_{in}$</th>
<th>$A_{vo}$</th>
<th>$R_{o}$</th>
<th>$A_{v}$</th>
<th>$G_{v}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common emitter (Fig. 7.36)</td>
<td>$(\beta + 1) r_e$</td>
<td>$-g_m R_C$</td>
<td>$R_C$</td>
<td>$-g_m (R_C \parallel R_L)$</td>
<td>$\frac{-g_m (R_C \parallel R_L)}{R_m + (\beta + 1) r_e}$</td>
</tr>
<tr>
<td>Common emitter with $R_i$ (Fig. 7.38)</td>
<td>$(\beta + 1) (r_e + R_i)$</td>
<td>$\frac{-g_m R_C}{1 + g_m R_i}$</td>
<td>$R_C$</td>
<td>$\frac{-g_m (R_C \parallel R_L)}{1 + g_m R_i}$</td>
<td>$\frac{-g_m (R_C \parallel R_L)}{R_m + (\beta + 1) (r_e + R_i)}$</td>
</tr>
<tr>
<td>Common base (Fig. 7.40)</td>
<td>$r_e$</td>
<td>$g_m R_C$</td>
<td>$R_C$</td>
<td>$g_m (R_C \parallel R_L)$</td>
<td>$\alpha \frac{R_L}{R_m + r_e}$</td>
</tr>
</tbody>
</table>
| Emitter follower (Fig. 7.43) | $(\beta + 1) (r_e + R_L)$ | $1$ | $r_e$ | $\frac{R_L}{R_e + r_e}$ | $\frac{R_L + r_e + \frac{R_m (\beta + 1)}{\beta + 1}}{R_m}

* For the interpretation of $R_{in}$, $A_{vo}$, and $R_o$, refer to Fig. 7.34.
* Setting $\beta = \infty (\alpha = 1)$ and replacing $r_e$ with $1/g_m$, $R_C$ with $R_D$, and $R_L$ with $R_L$ results in the corresponding formulas for MOSFET amplifiers (Table 7.4).