Basics: Amplifiers at Low Frequencies

Left is the equivalent circuit of a bipolar transistor; \( g_m = I_E / V_T = 1/r_e, V_T = kT/q \), \( r_e = r_{be} = \beta / g_m \), \( R_{ce} = (V_A + V_{CE}) / I_C \). On the right is the FET model. \( g_m = v_{sat} c_{ox} W_g \) (short-gate / velocity saturation model) or \( g_m = (\mu c_{ox} W_g / L_g)(V_{gs} - V_{th}) \) (long-gate / mobility limited model) \( R_{ds} = [(1/\lambda) + V_{DS}] / I_D \)

For the bipolar
\[
R_{in,base} = (\beta + 1)(r_e + R_{EE})
\]
\[
R_{in,emitter} = r_e + \frac{R_B}{\beta + 1} \left( \frac{r_{be} + R_{ce}}{r_{ce}} \right) \approx \left( r_e + \frac{R_B}{\beta + 1} \right)
\]
\[
R_{in,collector} = R_{ce} \left[ 1 + g_m R_{RE} \right] \frac{r_{be}}{r_{be} + R_{EE} + R_B} \approx R_{ce} \left( 1 + g_m R_{RE} \right)
\]

For the fet: THE EQUATIONS ARE THE SAME IF \( \beta \) is INFINITE!
\[
R_{in,gate} = \text{open}
\]
\[
R_{in,source} = \left( \frac{1}{g_m} \right) \left( \frac{R_{dd} + R_{ds}}{R_{ds}} \right) \approx \left( \frac{1}{g_m} \right)
\]
\[
R_{in,drain} = r_{ds} (1 + g_m R_{sx})
\]

Be warned that in the equations above \( R_{cc}, R_{EE} \) and \( R_B \) are the equivalent resistances seen by the transistor. So in, the amplifier circuits below, THINK: "what is the effective resistance seen by the transistor?", before plugging into the equations.
Amplifier Stages

Common Emitter and Common Source

- Common emitter:
  \[ R_{in} = R_B \parallel R_{in,base} = R_B \left( \beta + 1 \right) \left( R_{EE} + r_e \right) \]
  \[ V_{in} = \frac{R_{in}}{R_{in} + R_{gen}} \]
  \[ A_v = \frac{V_{out}}{V_{in}} = \frac{-R_{Leq}}{r_e + R_{re}} = -\left( R_e \parallel R_{out,collector} \right) r_e + R_{re} \]
  \[ R_{out} = R_c \parallel R_{out,collector} \]

- Common source:
  \[ R_{in} = R_{gs} \]
  \[ V_{in} = \frac{R_{in}}{R_{in} + R_{gen}} \]
  \[ A_v = \frac{V_{out}}{V_{in}} = \frac{-R_{Leq}}{R_{ss} + 1/g_m} = -\left( R_e \parallel R_{out,drain} \right) R_{ss} + 1/g_m \]
  \[ R_{out} = R_d \parallel R_{out,drain} \]

Common Collector (emitter follower) and common drain (source follower)

- for the emitter follower:
  \[ R_{in} = R_B \parallel R_{in,base} = R_B \left( \beta + 1 \right) \left( R_{EL} + r_e \right) \]
  \[ V_{in} = \frac{R_{in}}{R_{in} + R_{gen}} \]
  \[ A_v = \frac{V_{out}}{V_{in}} = \frac{R_{Leq}}{R_{Leq} + r_e} = \frac{R_{re} \parallel R_L}{R_{Leq} + r_e} \]
  \[ R_{out} = R_{re} \parallel R_{in,emitter} = R_{re} \left( r_e + \frac{R_B}{1 + \beta} \right) \]
For the source follower:

\[ R_{in} = R_g \]

\[ \frac{V_{in}}{V_{gen}} = \frac{R_{in}}{R_{in} + R_{gen}} \]

\[ A_v = \frac{V_{out}}{V_{in}} = \frac{R_{leq}}{R_{leq} + 1/g_m} = \frac{R_{cs} || R_{L} || R_{ds}}{R_{ss} || R_{e} || R_{ds} + 1/g_m} \]

\[ R_{out} = R_{ss} || R_{in,source} = R_{ss} || (1/g_m) \]

Common Base and common gate

For the common base:

\[ R_{in} = R_{EE} || R_{in,emitter} \]

\[ R_{in,emitter} = \left( r_e + \frac{R_B}{\beta + 1} \right) \left( \frac{r_{ce} + R_c || R_L}{r_{ce}} \right) \approx \left( r_e + \frac{R_B}{\beta + 1} \right) \]

\[ \frac{V_{in}}{V_{gen}} = \frac{R_{in}}{R_{in} + R_{gen}} \]

\[ A_v = \frac{V_{out}}{V_{in}} = \frac{R_{leq}}{R_{in,emitter}} = \frac{R_c || R_L}{R_{in,emitter}} \]

\[ R_{out} = R_c || R_{out,collector} \]

For the common gate

\[ R_{in} = R_{SS} || R_{in,source} \]

\[ R_{in,source} = \left( \frac{1}{g_m} \right) \left( \frac{r_{ds} + R_d || R_L}{r_{ds}} \right) \approx \left( \frac{1}{g_m} \right) \]

\[ \frac{V_{in}}{V_{gen}} = \frac{R_{in}}{R_{in} + R_{gen}} \]

\[ A_v = \frac{V_{out}}{V_{in}} = \frac{R_{leq}}{R_{in,source}} = \frac{R_d || R_L}{R_{in,source}} \]

\[ R_{out} = R_d || R_{out,drain} \]