7. Fundamental Transistor Amplifier Configurations

Lecture notes: Sec. 5

Sedra & Smith (6th Ed): Sec. 5.4, 5.6 & 6.3-6.4
Sedra & Smith (5th Ed): Sec. 4.4, 4.6 & 5.3-5.4

Issues in developing a transistor amplifier:

1. **Find the iv characteristics of the elements for the signal** (which can be different than their characteristics equation for bias).
   - This will lead to different circuit configurations for bias versus signal
2. **Compute circuit response to the signal**
   - Focus on fundamental transistor amplifier configurations
3. **How to establish a Bias point** (bias is the state of the system when there is no signal).
   - Stable and robust bias point should be resilient to variations in $\mu_n C_{ox}(W/L), V_t$ (or β for BJT) due to temperature and/or manufacturing variability.
   - Bias point details impact small signal response (e.g., gain of the amplifier).

What are amplifier parameters?

Voltage Gain of the Circuit: $A = \dfrac{v_o}{v_{sig}}$

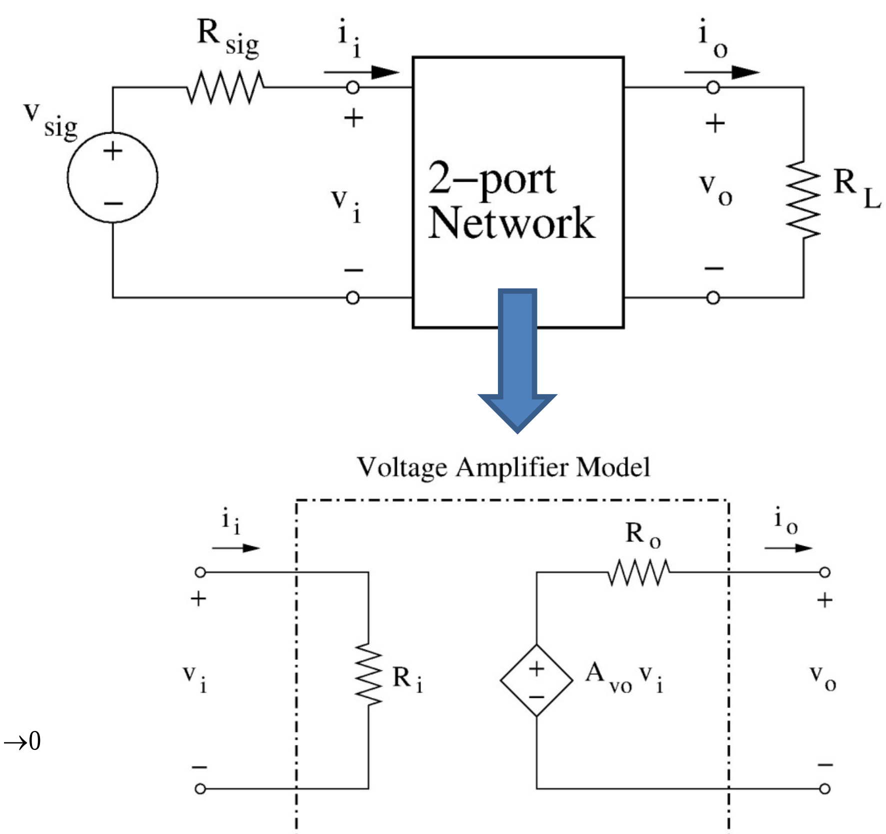
Voltage Gain of the Amplifier: $A_v = \dfrac{v_o}{v_i}$

Open-loop Gain: $A_{vo} = \left.\dfrac{v_o}{v_i}\right|_{R_L \to \infty}$

Input Resistance: $R_i = \dfrac{v_i}{i_i}$

Output Resistance of Amplifier: $R_o = -\left.\dfrac{v_o}{i_o}\right|_{v_{sig} \to 0}$

Output resistance is the Thevenin resistance between the output terminals!

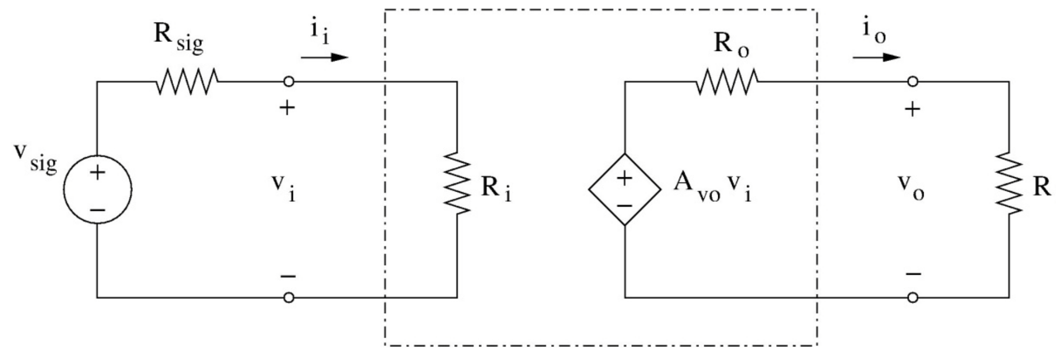


➢ In general R_i depends on R_L and R_o depends on R_{sig}

Observations on the amplifier parameters

Overall Gain :

$$A = \frac{v_o}{v_{sig}} = \frac{v_i}{v_{sig}} \times \frac{v_o}{v_i} = \frac{R_i}{R_i + R_{sig}} A_v$$



$$\frac{v_i}{v_{sig}} = \frac{R_i}{R_i + R_{sig}}$$

- Value of R_i is important.
  - For $R_i >> R_i$, $v_i \approx v_{sig}$
  - For $R_i = R_{sig}$, $v_i = 0.5\ v_{sig}$
  - For $R_i << R_{sig}$, $v_i \approx 0$
- Prefer "large" R_i

$$A_v = \frac{v_o}{v_i} = \frac{R_L}{R_L + R_o} A_{vo}$$

- A_{vo} is the maximum possible gain of the amplifier.
- Value of R_o is important.
  - For $R_o << R_L$, $A_v \approx A_{vo}$
  - For $R_o = R_L$, $A_v = 0.5\ A_{vo}$
  - For $R_o >> R_L$, $A_v \approx 0$
- Prefer "small" R_o

Some observation on single-transistor amplifiers

1. As we will discuss, there are many ways to bias a transistor. Thus, there are many practical single-transistor amplifier circuits.
   - Fortunately, signal circuits always reduce to one of **four fundamental configuration** .

2. We compute the voltage gain and input resistance of these four fundamental configurations in the presence of an arbitrary load R_L. Then:

   Overall Gain:

   $$A = \frac{v_o}{v_{sig}} = \frac{v_i}{v_{sig}} \times \frac{v_o}{v_i} = \frac{R_i}{R_i + R_{sig}} A_v$$

   Open-loop Gain:

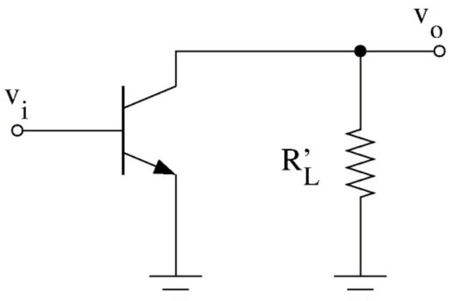
   $$A_{vo} = A_v \,|_{R_L \to \infty}$$

3. R_o is calculated in a real circuit (with R_{sig} & v_{sig}) once load is clearly identified.

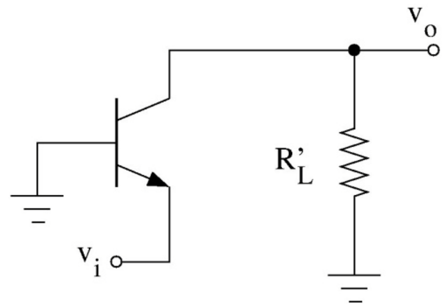
Fundamental Transistor Amplifier Configurations

We are considering only signal circuit here!

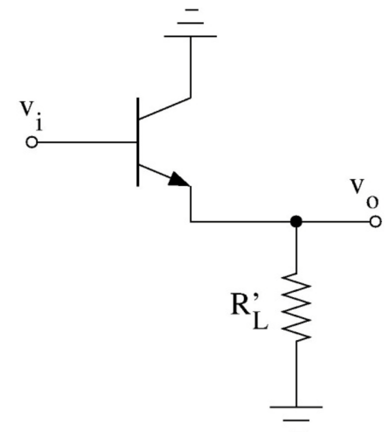
Possible BJT amplifier configurations



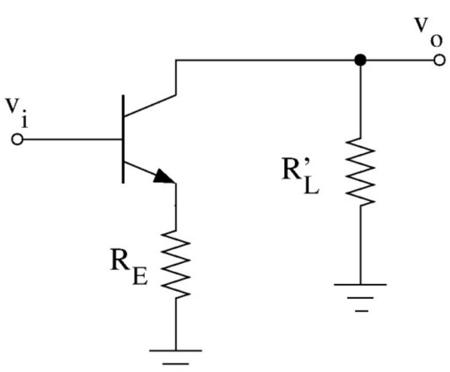
Common-Emitter



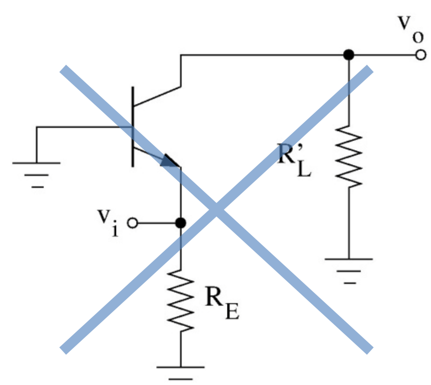
Common-Base



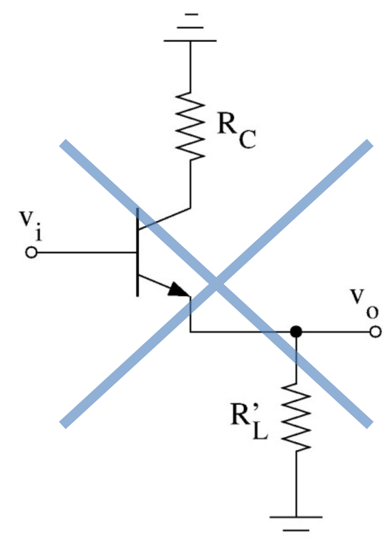
Common-Collector



Common-Emitter with R_E

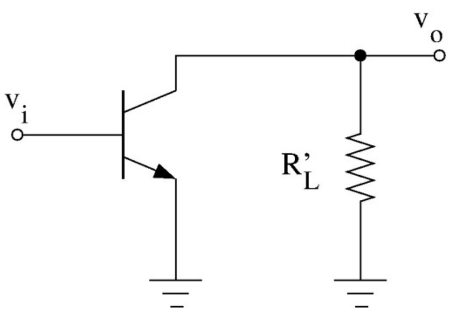


Same as Common Base
(v_i does not change)

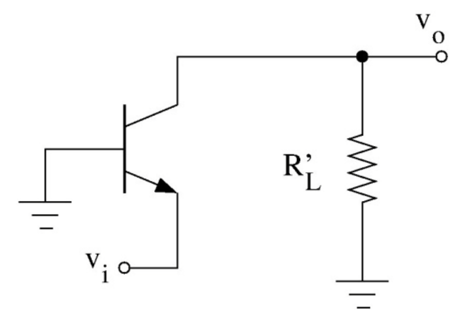


Not Useful

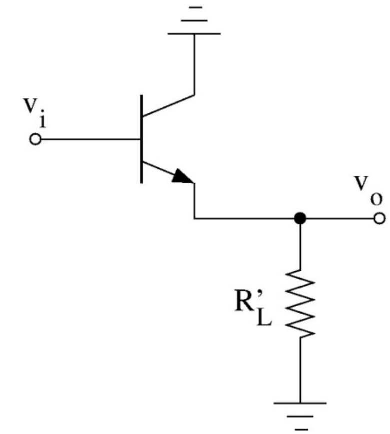
PNP configurations are the same as those of NPN (because of similar small-signal model)



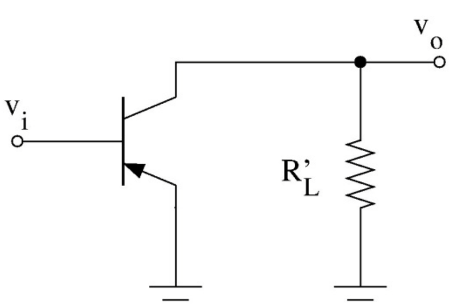
Common-Emitter



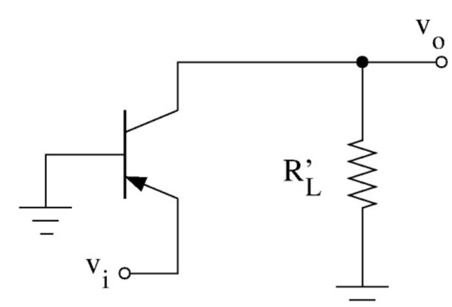
Common-Base



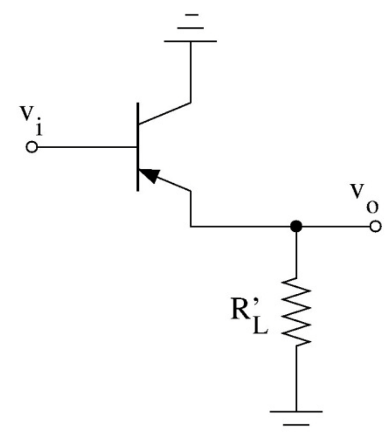
Common-Collector



Common-Emitter

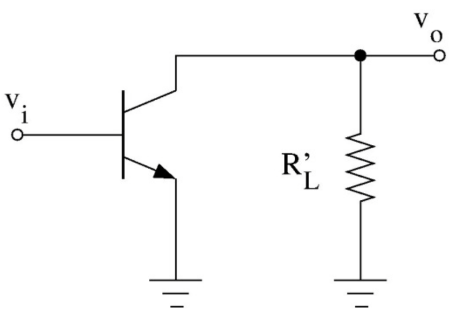


Common-Base

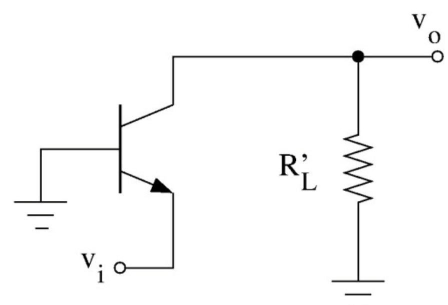


Common-Collector

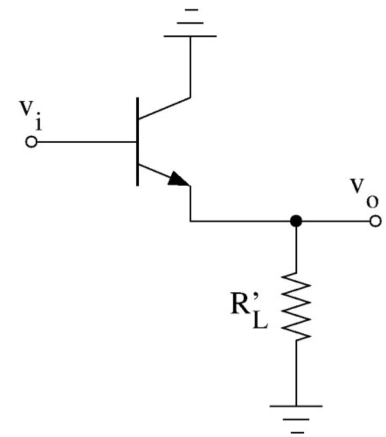
MOS fundamental configurations are analogous to BJTs



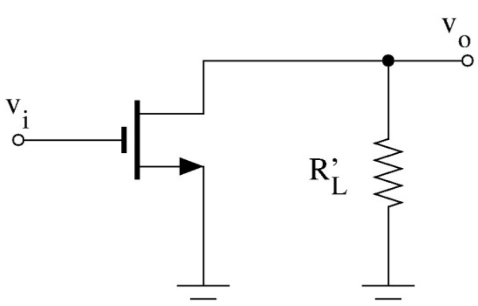
Common-Emitter



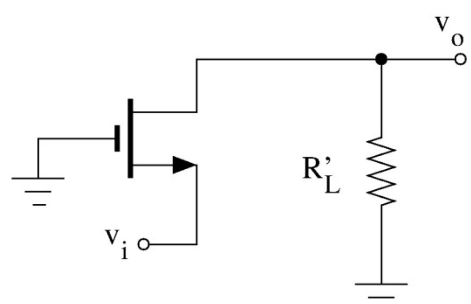
Common-Base



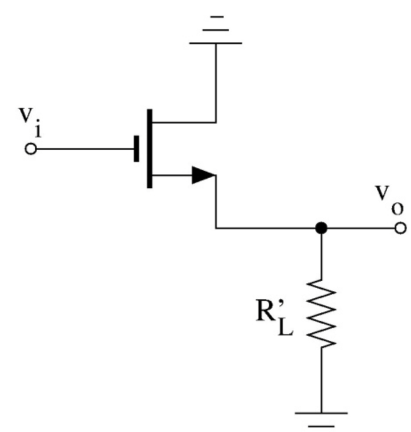
Common-Collector



Common-Source



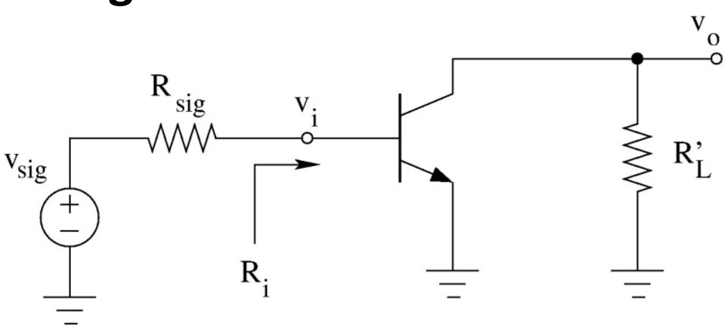
Common-Gate



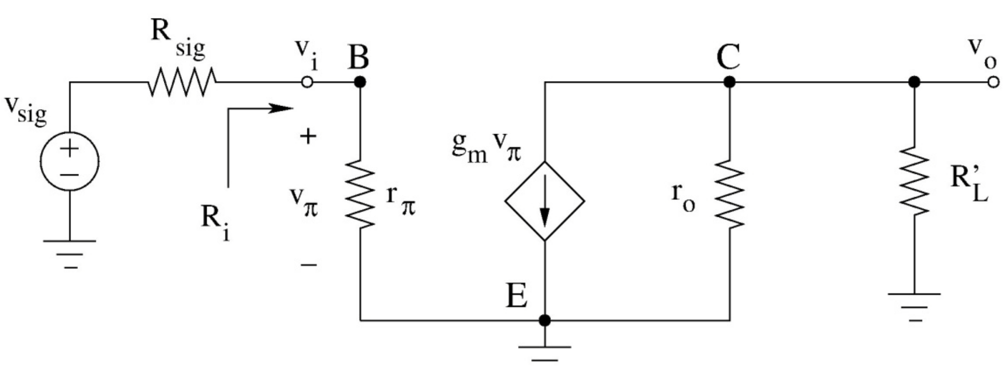
Common-Drain

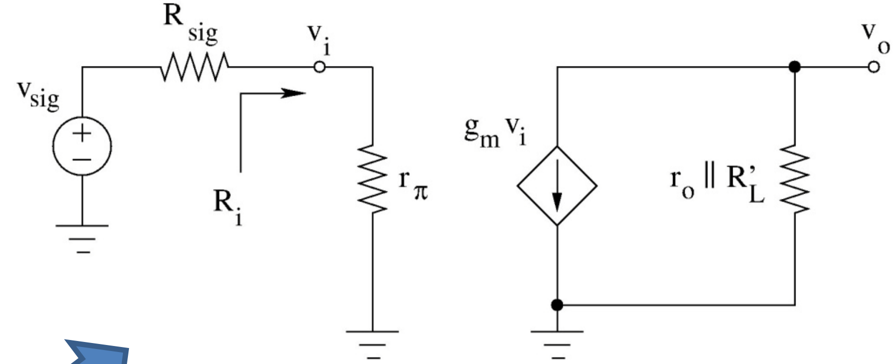
Common Emitter Configuration

Signal Circuit:



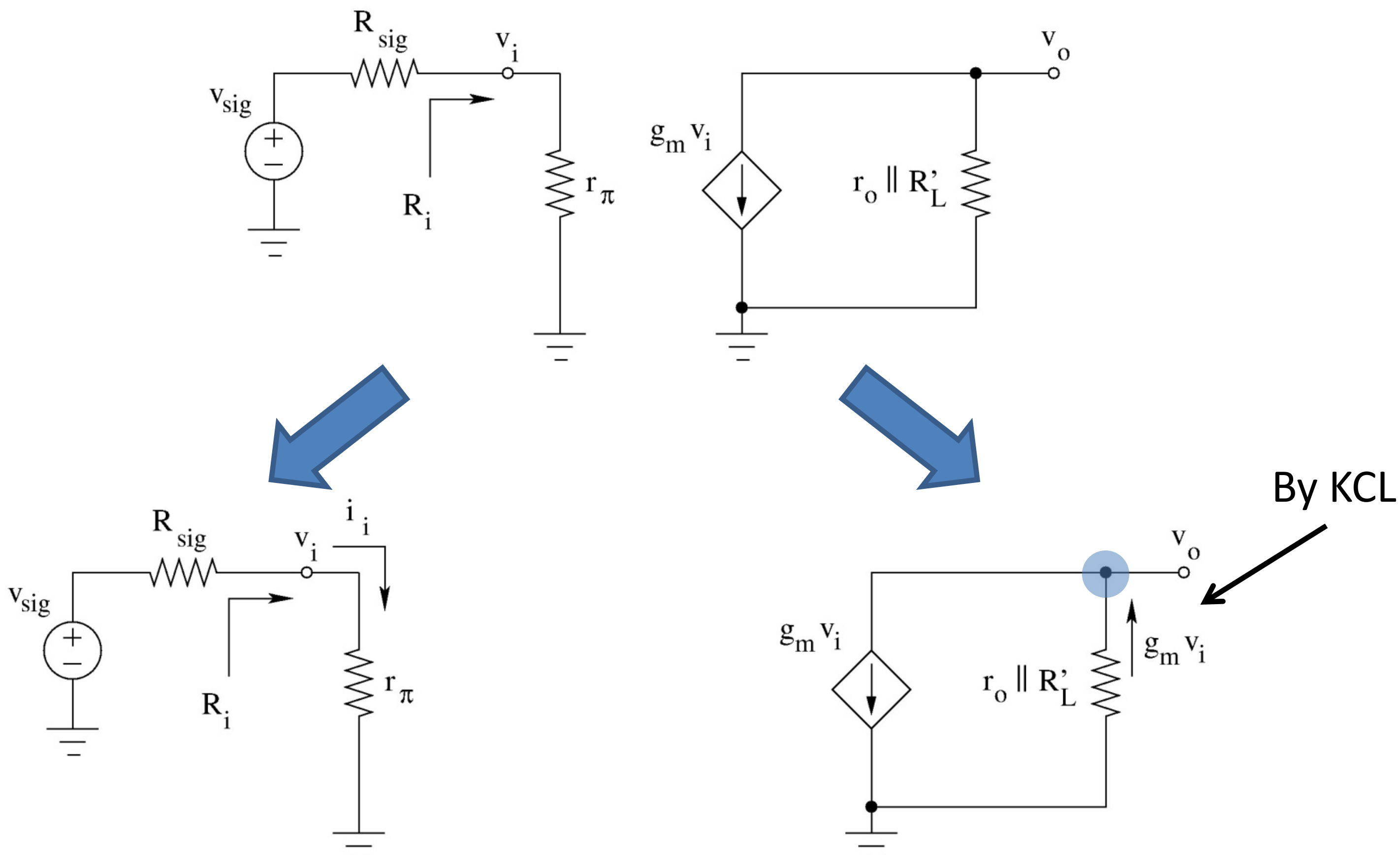
Signal Circuit with BJT SSM:





- r_o and R'_L are in parallel
- $v_\pi = v_i$

Common Emitter Configuration (A_v & R_i)



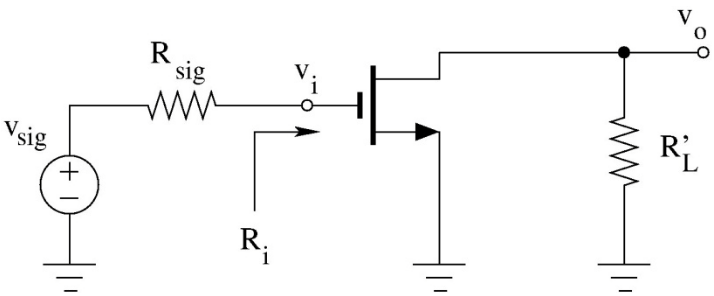
$$i_i = \frac{v_i}{r_\pi} \Rightarrow R_i = \frac{v_i}{i_i} = r_\pi$$

$$v_o = -g_m v_i (r_o \parallel R'_L)$$

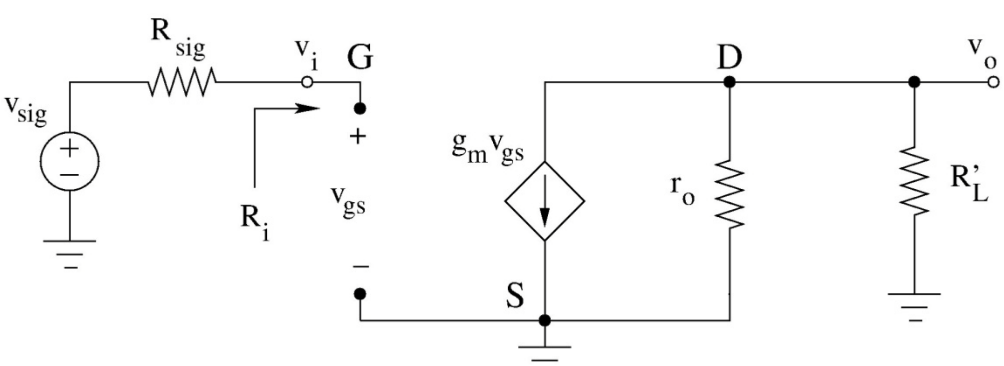
$$A_v = \frac{v_o}{v_i} = -g_m (r_o \parallel R'_L)$$

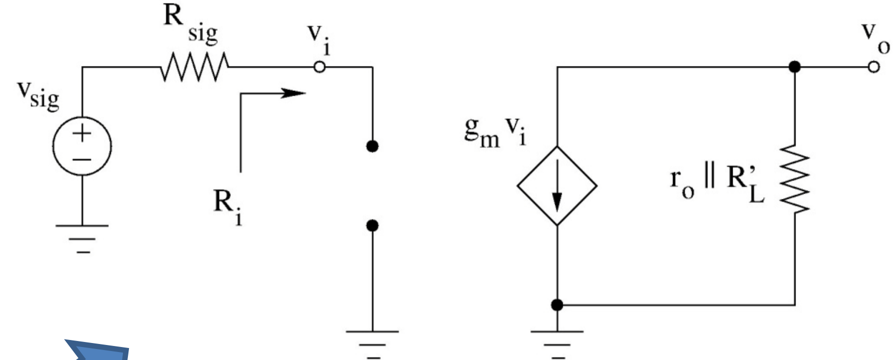
Common Source Configuration

Signal Circuit:



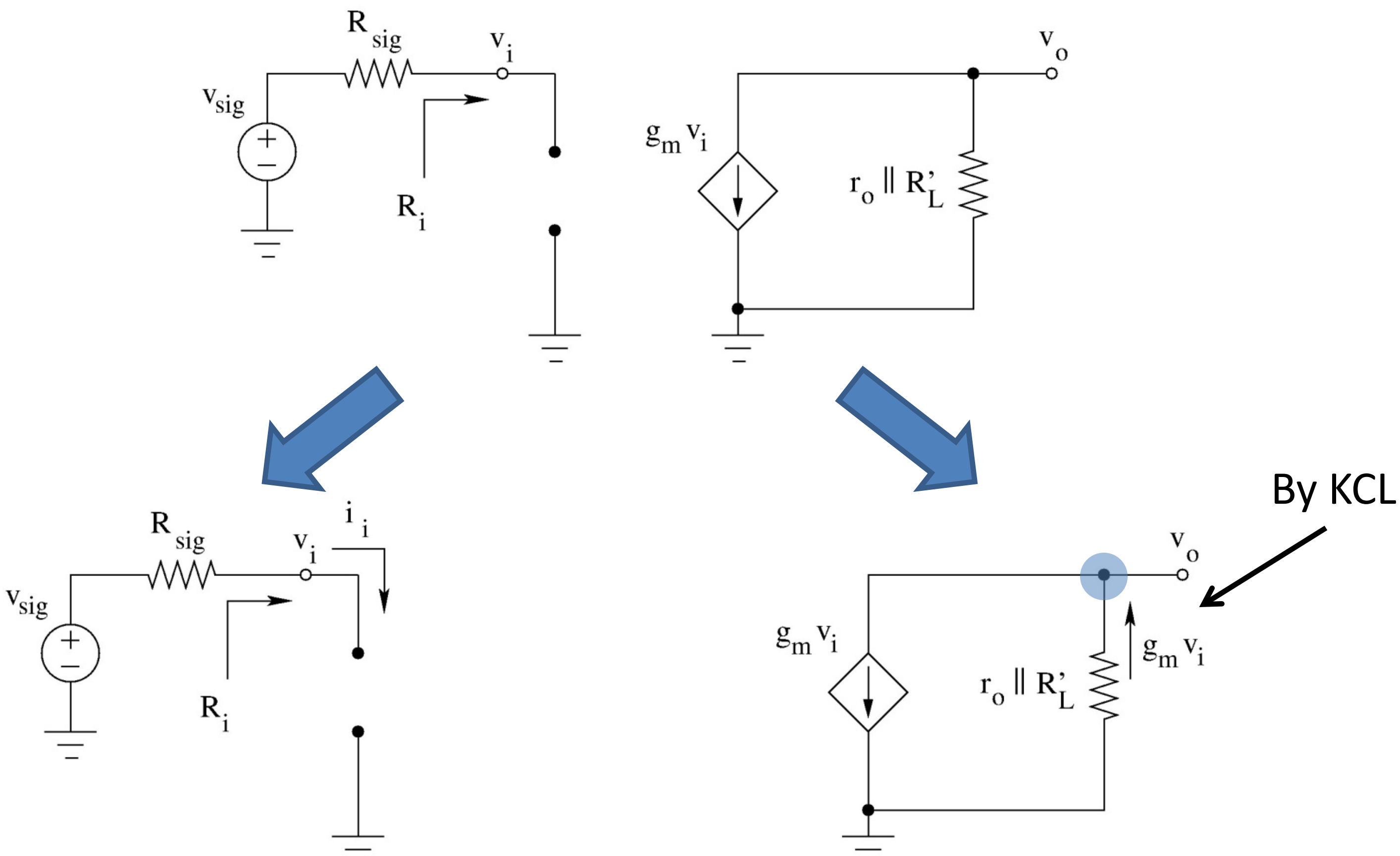
Signal Circuit with MOS SSM:





- r_o and R'_L are in parallel
- $v_{gs} = v_i$

Common Source Configuration (A_v & R_i)

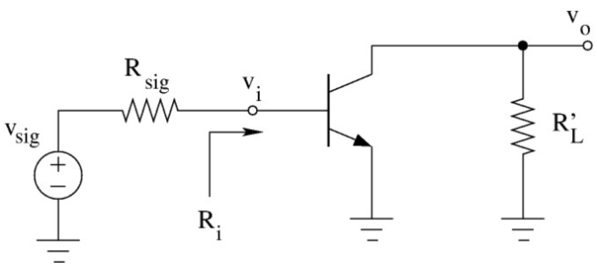


$$i_i = 0 \Rightarrow R_i = \frac{v_i}{i_i} = \infty$$

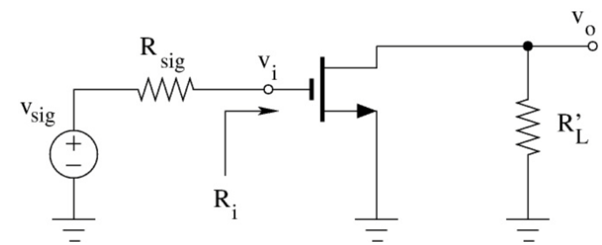
$$v_o = -g_m v_i (r_o \parallel R_L')$$

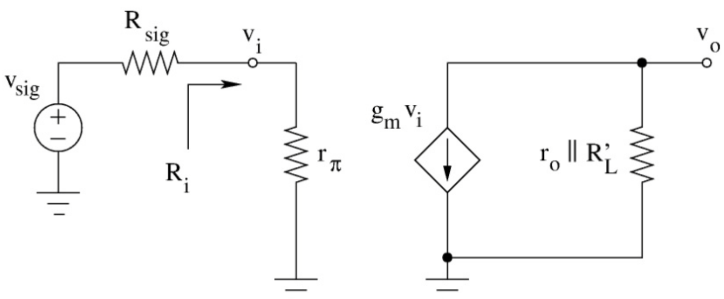
$$A_v = \frac{v_o}{v_i} = -g_m (r_o \parallel R_L')$$

Common Source & Common Emitter Configurations are "similar"

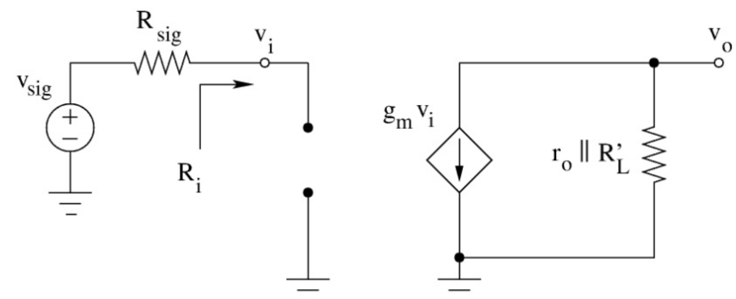


Signal Circuit





Signal Circuit with transistor SSM



$$A_v = \frac{v_o}{v_i} = -g_m (r_o \parallel R'_L)$$

$$R_i = r_\pi$$

Similar formula if we let $r_\pi \to \infty$

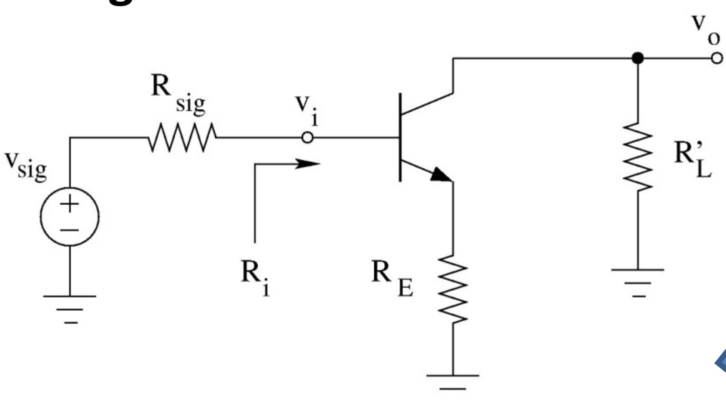
$$A_v = \frac{v_o}{v_i} = -g_m (r_o \parallel R'_L)$$

$$R_i = \infty$$

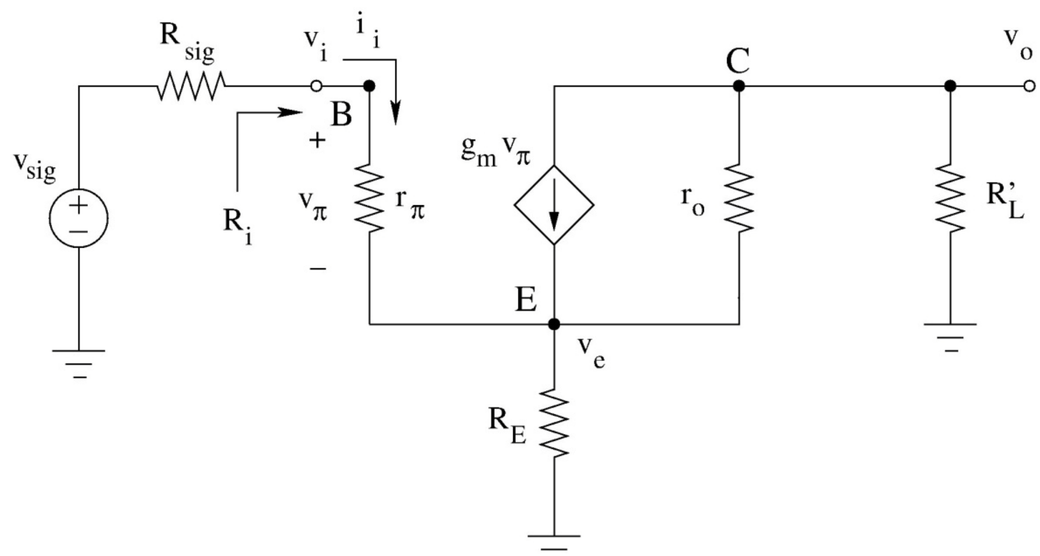
Note that A_v & R_i are independent of v_{sig} & R_{sig}

Common Emitter Configuration with R_E

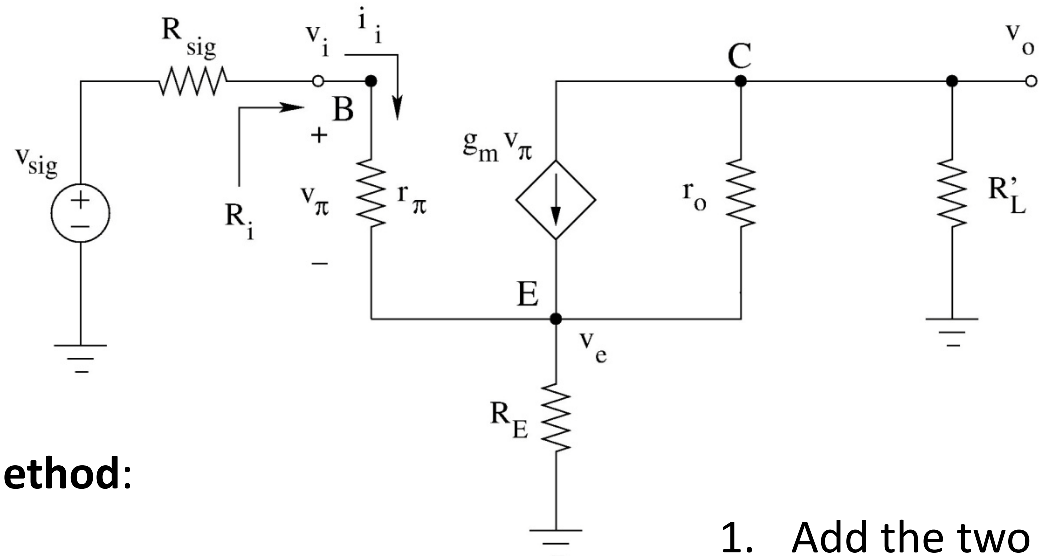
Signal Circuit:



Signal Circuit with BJT SSM:



Common Emitter Configuration with R_E (A_v & R_i)



Node voltage method:

$$v_\pi = v_i - v_e$$

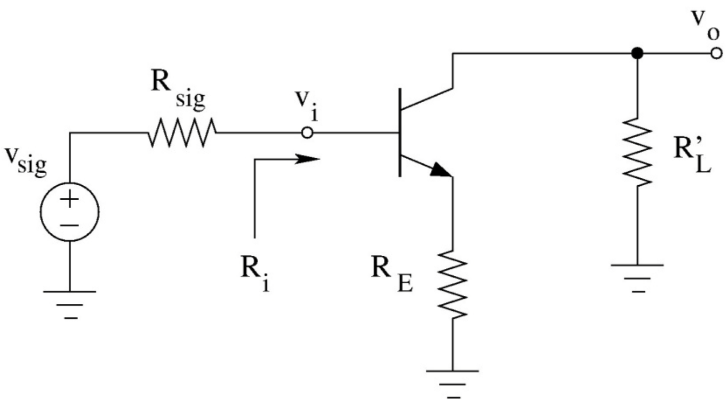
Node v_e $\quad \dfrac{v_e}{R_E} + \dfrac{v_e - v_i}{r_\pi} + \dfrac{v_e - v_o}{r_o} - g_m(v_i - v_e) = 0$

Node v_o $\quad \dfrac{v_o}{R_L'} + \dfrac{v_o - v_e}{r_o} + g_m(v_i - v_e) = 0$

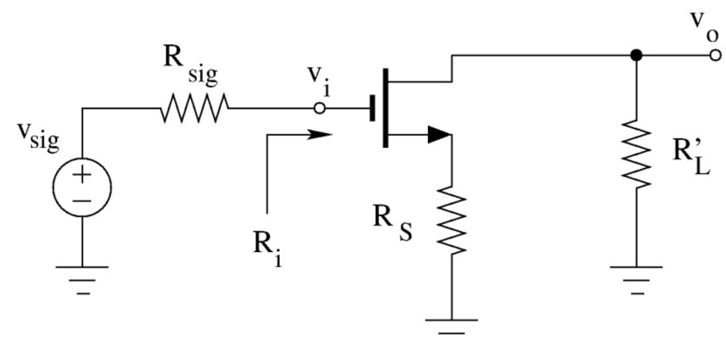
1. Add the two node equations to get v_e in terms of v_o and v_i
2. Substitute for v_e in Node v_o equation to find v_o and gain
3. Compute i_i in terms of node voltages. Then $R_i = v_i / i_i$
4. Lengthy calculations (See Notes).

$$A_v = \frac{v_o}{v_i} \approx -\frac{g_m R_L'}{1 + g_m R_E + (R_L'/r_o)(1 + R_E/r_\pi)} \qquad R_i \approx r_\pi + \frac{g_m r_\pi R_E}{1 + (R_L'/r_o)(1 + R_E/r_\pi)}$$

Common Source Configuration with R_S (A_v & R_i)



Signal Circuit



$$A_v = \frac{v_o}{v_i} \approx -\frac{g_m R'_L}{1 + g_m R_E + (R'_L / r_o)(1 + R_E / r_\pi)}$$

$$R_i \approx r_\pi + \frac{g_m r_\pi R_E}{1 + (R'_L / r_o)(1 + R_E / r_\pi)}$$

Let $r_\pi \to \infty$

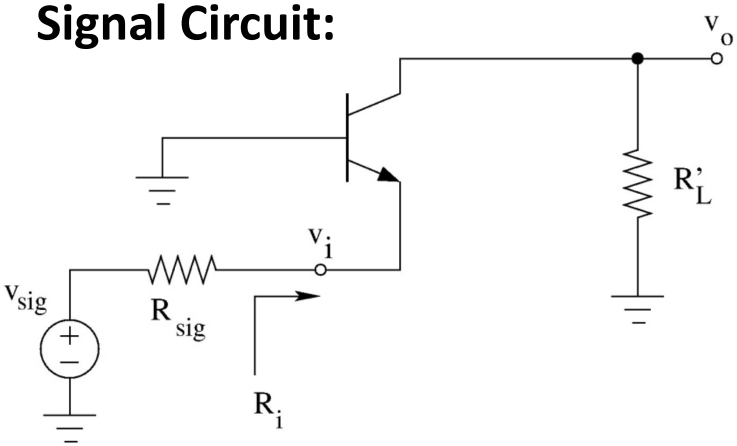
$R_E \to R_S$

$$A_v = \frac{v_o}{v_i} \approx -\frac{g_m R'_L}{1 + g_m R_S + (R'_L / r_o)}$$

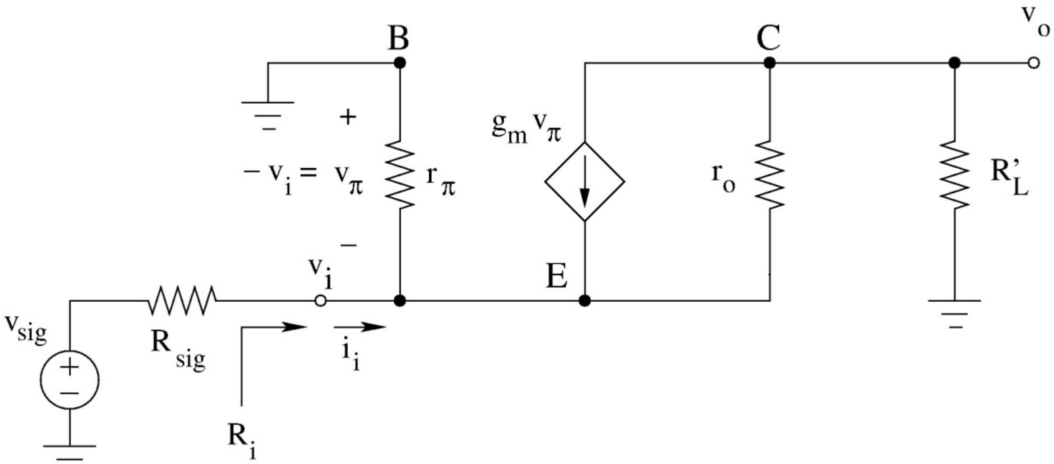
$$R_i = \infty$$

Common Base Configuration (Gain)

Signal Circuit:



Signal Circuit with BJT SSM:



Node voltage method:

$$v_\pi = -v_i$$

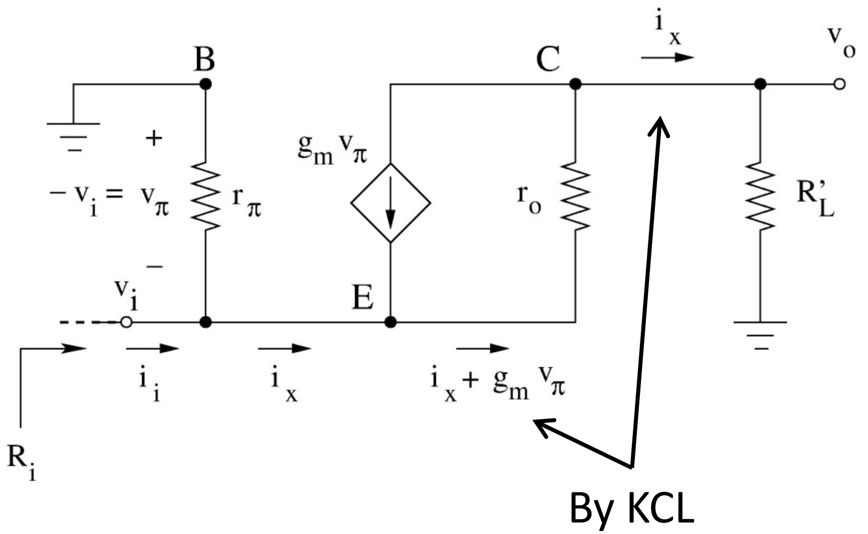
Node v_o $\quad \dfrac{v_o}{R_L'} + \dfrac{v_o - v_i}{r_o} + g_m(-v_i) = 0$

$$\frac{v_o}{r_o \parallel R_L'} = \frac{1 + g_m r_o}{r_o} v_i$$

$$A_v = \frac{v_o}{v_i} = \frac{1 + g_m r_o}{r_o}(r_o \parallel R_L')$$

$$A_v \approx g_m (r_o \parallel R_L')$$

Common Base Configuration (R_i)



Define $R_x = \dfrac{v_i}{i_x}$

KCL: $$i_i = \frac{v_i}{r_\pi} + i_x = \frac{v_i}{r_\pi} + \frac{v_i}{R_x} = \frac{v_i}{r_\pi \parallel R_x}$$

$$R_i = \frac{v_i}{i_i} = r_\pi \parallel R_x$$

KVL: $$v_i = (i_x + g_m v_\pi) r_o + i_x R'_L$$

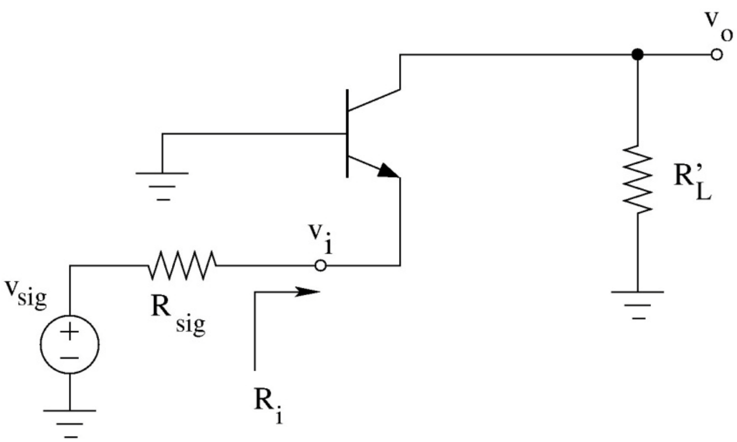
$$v_\pi = -v_i$$

$$v_i (1 + g_m r_o) = i_x (r_o + R'_L)$$

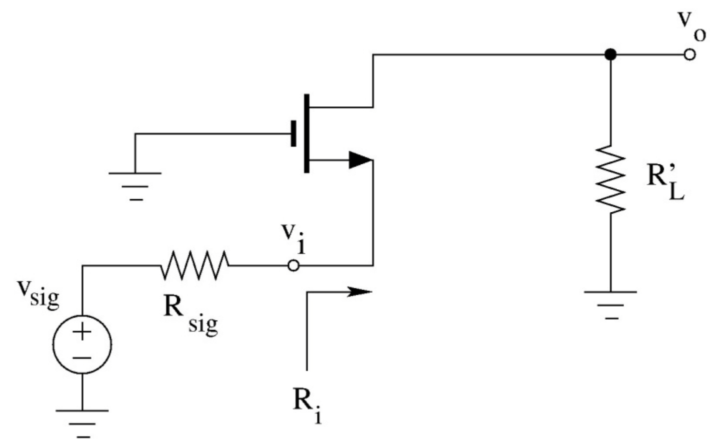
$$R_x = \frac{v_i}{i_x} = \frac{r_o + R'}{1 + g_m r_o}$$

$$\boxed{R_i = r_\pi \parallel R_x = r_\pi \parallel \frac{r_o + R'_L}{1 + g_m r_o}}$$

Common Gate Configuration (A_v & R_i)



Signal Circuit



$$A_v = \frac{v_o}{v_i} \approx g_m(r_o \parallel R'_L)$$

$$R_i = r_\pi \parallel \frac{r_o + R'_L}{1 + g_m r_o}$$

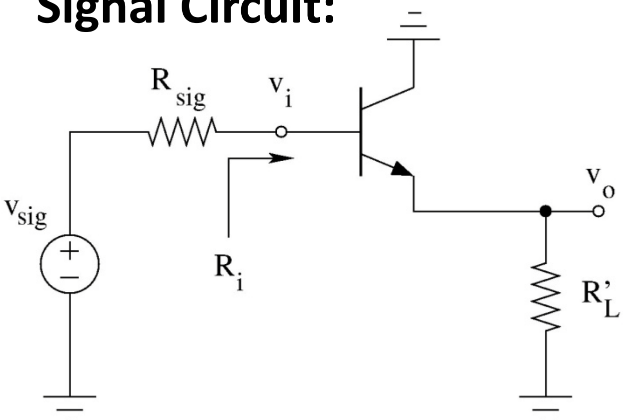
Let $r_\pi \rightarrow \infty$

$$A_v = \frac{v_o}{v_i} \approx g_m(r_o \parallel R'_L)$$

$$R_i = \frac{r_o + R'_L}{1 + g_m r_o}$$

Common Collector Configuration (Emitter Follower)

Signal Circuit:



Node voltage method:

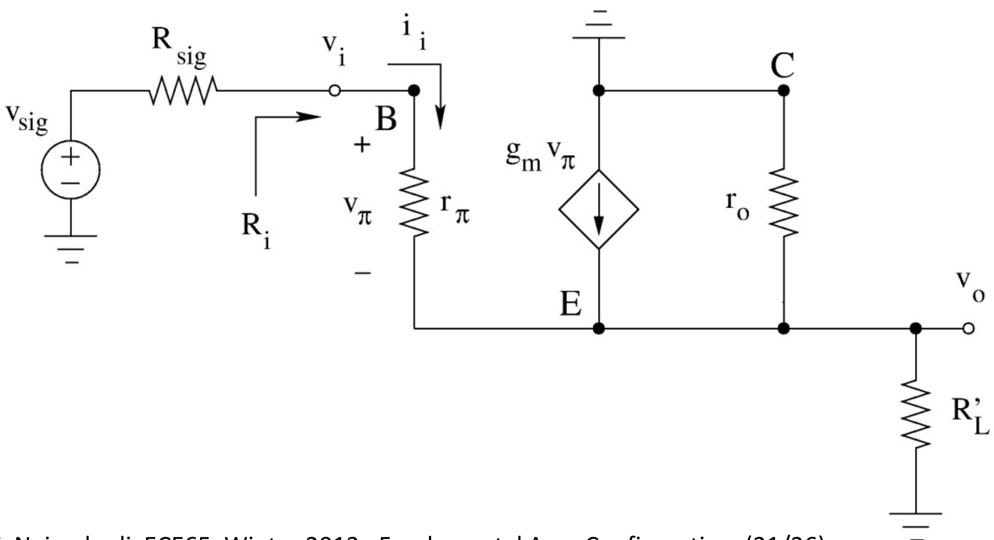
$$v_\pi = v_i - v_o$$

Node v_o $\dfrac{v_o}{R'_L} + \dfrac{v_o - v_i}{r_\pi} + \dfrac{v_o}{r_o} - g_m (v_i - v_o) = 0$

$$\frac{v_o}{r_o \parallel R'_L} + \left(1 + \frac{1}{g_m r_\pi}\right) v_o = g_m \left(1 + \frac{1}{g_m r_\pi}\right) v_i \approx g_m v_i$$

$$g_m r_\pi = \beta >> 1$$

Signal Circuit with BJT SSM:



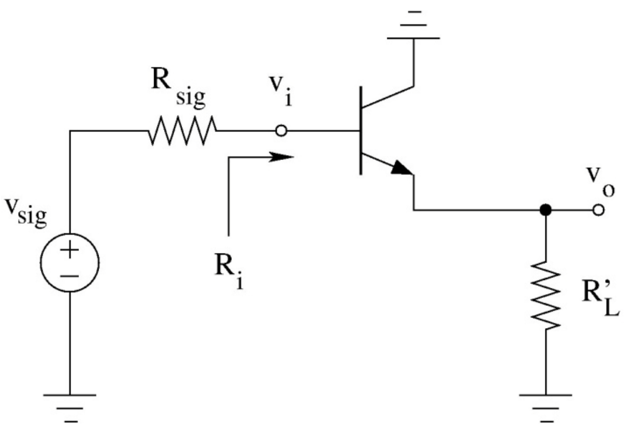
$$\boxed{A_v = \frac{v_o}{v_i} = \frac{g_m (r_o \parallel R'_L)}{1 + g_m (r_o \parallel R'_L)}}$$

$$i_i = \frac{v_i - v_o}{r_\pi} = \frac{v_i}{r_\pi} \times (1 - A_v)$$

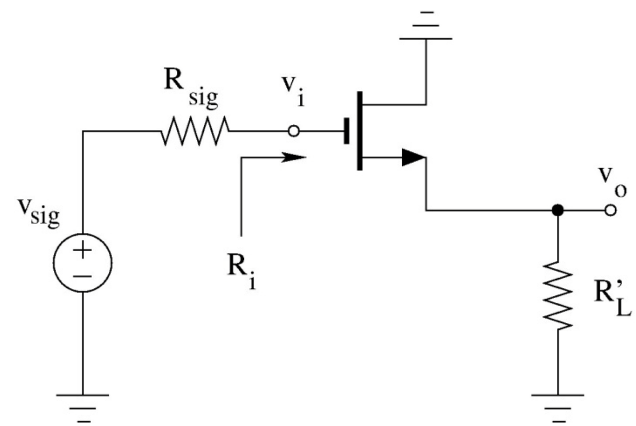
$$R_i = \frac{v_i}{i_i} = \frac{r_\pi}{1 - A_v}$$

$$\boxed{R_i = r_\pi + g_m r_\pi (r_o \parallel R'_L) = r_\pi + \beta (r_o \parallel R'_L)}$$

Common Drain Configuration (Source Follower)



Signal Circuit



$$A_v = \frac{v_o}{v_i} = \frac{g_m (r_o \parallel R'_L)}{1 + g_m (r_o \parallel R'_L)}$$

$$R_i = g_m r_\pi (r_o \parallel R'_L) = \beta (r_o \parallel R'_L)$$

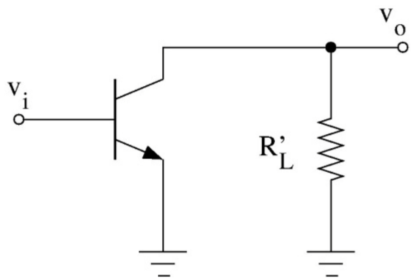
Let $r_\pi \to \infty$

$$A_v = \frac{v_o}{v_i} = \frac{g_m (r_o \parallel R'_L)}{1 + g_m (r_o \parallel R'_L)}$$

$$R_i = \infty$$

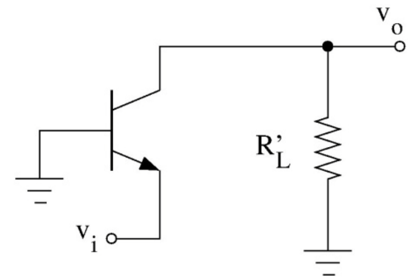
BJT Basic Amplifier Configurations
(PNP circuits are identical)

Common Emitter



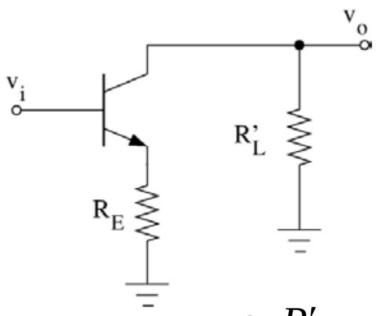
$$A_v = -g_m(r_o \parallel R_L'), \quad R_i = r_\pi$$

Common Base



$$A_v = g_m(r_o \parallel R_L'), \quad R_i = r_\pi \parallel \frac{r_o + R_L'}{1 + g_m r_o}$$

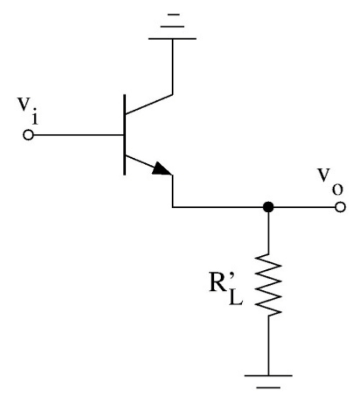
Common Emitter with R_E



$$A_v \approx -\frac{g_m R_L'}{1 + g_m R_E + (R_L'/r_o)(1 + R_E/r_\pi)}$$

$$R_i \approx r_\pi + \frac{g_m r_\pi R_E}{1 + (R_L'/r_o)(1 + R_E/r_\pi)}$$

Common Collector/ Emitter Follower

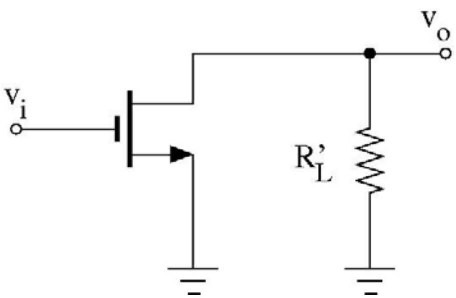


$$A_v = \frac{g_m(r_o \parallel R_L')}{1 + g_m(r_o \parallel R_L')}$$

$$R_i = r_\pi + \beta(r_o \parallel R_L')$$

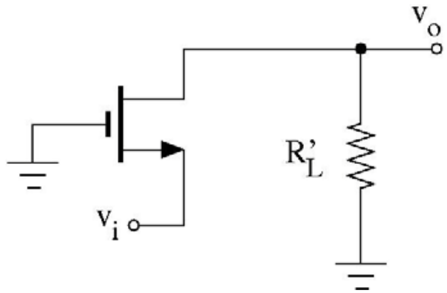
MOS Basic Amplifier Configurations
(PMOS circuits are identical)

Common Source



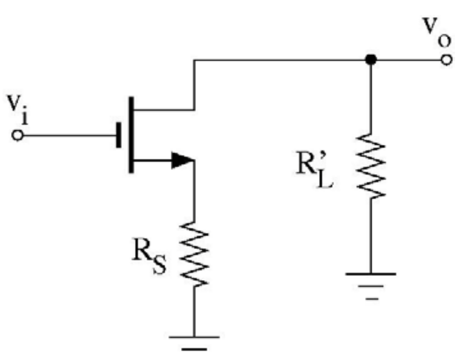
$$A_v = -g_m (r_o \parallel R'_L), \quad R_i = \infty$$

Common Gate



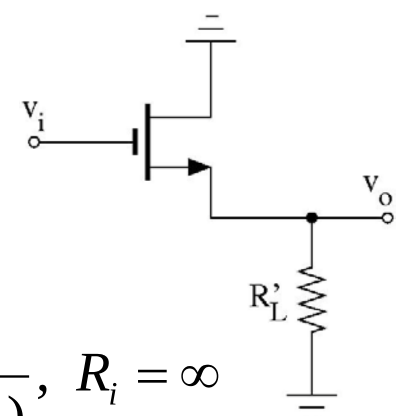
$$A_v = g_m (r_o \parallel R'_L), \quad R_i = \frac{r_o + R'_L}{1 + g_m r_o}$$

Common Source with RS



$$A_v = -\frac{g_m R'_L}{1 + g_m R_S + R'_L / r_o}, \quad R_i = \infty$$

Common Drain/Source Follower



$$A_v = \frac{g_m (r_o \parallel R'_L)}{1 + g_m (r_o \parallel R'_L)}, \quad R_i = \infty$$

Observations of Transistor Amplifiers (1)

- Common-Emitter has a high gain of $A_v = -g_m(r_o \parallel R'_L)$ and a "medium" $R_i = r_\pi$ (several k).
  - Minus sign in the gain reflects a 180° phase shift in the output.
- Common-Base also has a high gain of $A_v \approx g_m(r_o \parallel R'_L)$ but a "low" R_i (several hundred Ω) which significantly affects the overall circuit gain.

- Common-Source has a high gain of $A_v = -g_m(r_o \parallel R'_L)$ (but lower than the BJT analog, CE amplifier). It has an infinite R_i.
- Common-Gate also has a high gain of $A_v \approx g_m(r_o \parallel R'_L)$ but a "low" R_i (several hundred Ω).

CE and CS configurations are the main gain cells in ICs.
CB and CG configurations have superior high-frequency response (discussed in ECE102).

Observations of Transistor Amplifiers (2)

- Common-Emitter with R_E has a much lower gain compared to a CE amplifier (i.e., no R_E) but has a much larger R_i .
  - Amplifier gain is also much less sensitive to BJT parameters (i.e., β).
  - It is used primarily in discrete circuits because it does not need a by-pass capacitor (will be discussed later).
- Common-Source with R_S has a much lower gain compared to a CS amplifier (i.e., no R_S). It has an infinite R_i .

- Common-Collector (emitter follower) and Common-Drain (source follower) configurations have a gain ≤ 1 . They have a large R_i (infinite for CD) and a low R_o (as we will see later). They are usually configured to get a gain close to 1 and used either as a "buffer" or as a "current amplifier" to drive a load.

*Buffers are discussed later in the context of multi-stage amplifiers