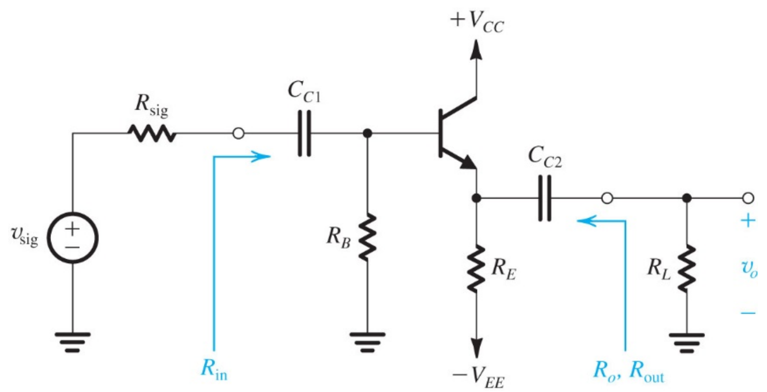
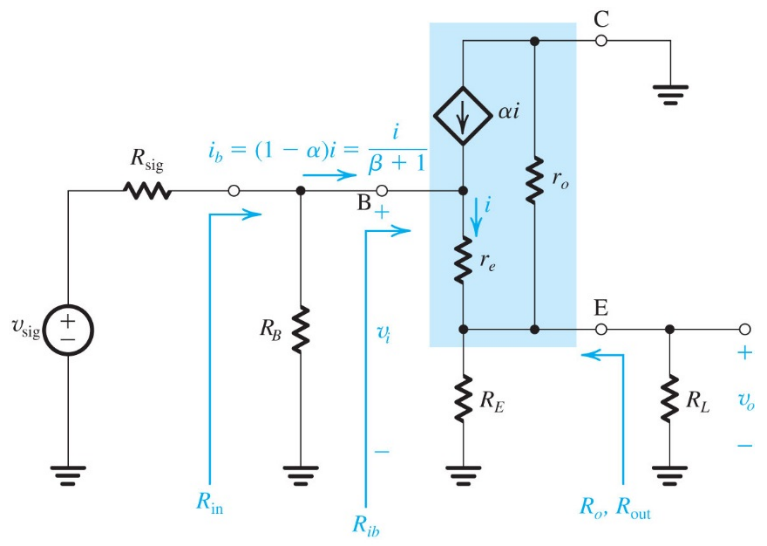
Lecture 21: Common Collector (Emitter Follower) Amplifier.

The third, and final, small-signal BJT amplifier we will consider is the common collector amplifier shown below:



(Fig. 7.59a)

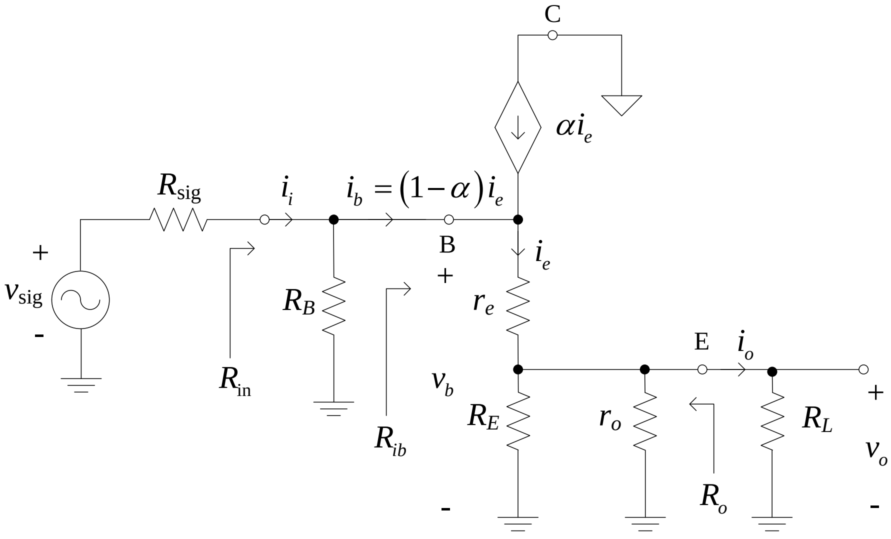
The small-signal equivalent circuit is shown in Fig. 7.59b:



(Fig. 7.59b)

We've included r_o in this model since it can have an appreciable effect on the operation of this amplifier. Additionally, its effects can be accounted for analytically quite simply.

Notice that r_o is connected from the emitter to an AC ground. We can considerably simplify the AC small-signal analysis of this circuit by moving the collector-side lead of r_o to the DC ground, as shown below:



(Fig. 1)

Similar to the previous BJT amplifiers, we'll determine the characteristics of this one by solving for R_{in}, G_v, G_i, A_{is}, and R_o.

- <u>Input resistance, R_{in}</u>. Looking into the base of the BJT,

$$R_{ib} = \frac{v_b}{i_b} \tag{1}$$

From the circuit above, we see that

$$v_b = i_e \left(r_e + R_E \parallel r_o \parallel R_L \right) \tag{2}$$

Substituting this and $i_b = i_e / (\beta + 1)$ into (1) yields

$$R_{ib} = (\beta + 1)\left(r_e + R_E \parallel r_o \parallel R_L \right) \qquad (7.157),(3)$$

This expression for R_{ib} follows the so-called resistance reflection rule: the input resistance is (β+1) times the total resistance in the emitter lead of the amplifier, as seen in the T small-signal model. (We saw a similar result in Lecture 19 for the CE amplifier with emitter degeneration.)

In the special case when $r_e \ll R_E \| R_L \ll r_o$ then

$$R_{ib} \approx (\beta+1)(R_E \| R_L) \tag{4}$$

which can potentially be a large value.

Referring to circuit above, the input resistance to the amplifier is

$$R_{\text{in}} = R_B \| R_{ib} \underbrace{=}_{(3)} R_B \| \left[(\beta+1)(r_e + R_E \| r_o \| R_L)\right] \quad (7.156),(5)$$

- <u>Small-signal voltage gain, G_v</u>. We'll first calculate the partial voltage gain

$$A_v \equiv \frac{v_o}{v_b} \tag{6}$$

Beginning at the output,

$$v_o = \frac{R_E \| r_o \| R_L}{R_E \| r_o \| R_L + r_e} v_b \quad (7.159),(7)$$

from which we can directly determine that

$$A_v = \frac{R_E \| r_o \| R_L}{R_E \| r_o \| R_L + r_e} \tag{8}$$

The overall (from the input to the output) small-signal voltage gain G_v is defined as

$$G_v \equiv \frac{v_o}{v_{\text{sig}}} \tag{9}$$

We can equivalently write this voltage gain as

$$G_v = \frac{v_b}{v_{\text{sig}}} \cdot \frac{v_o}{v_b} \underbrace{=}_{(6)} \frac{v_b}{v_{\text{sig}}} A_v \tag{10}$$

with A_v given in (8).

By simple voltage division at the input to the small-signal equivalent circuit

$$v_b = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} v_{\text{sig}} \tag{11}$$

Substituting this result into (10) yields an expression for the overall small-signal voltage gain

$$G_v \equiv \frac{v_o}{v_{\text{sig}}} = \frac{R_E \| r_o \| R_L}{R_E \| r_o \| R_L + r_e} \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \tag{7.160}$$

or

$$G_v = \frac{R_E \| r_o \| R_L}{R_E \| r_o \| R_L + r_e} \frac{R_B \| \left[(\beta+1)(r_e + R_E \| r_o \| R_L) \right]}{R_B \| \left[(\beta+1)(r_e + R_E \| r_o \| R_L) \right] + R_{\text{sig}}} \tag{12}$$

We can observe directly that each of the two factors in this expression is less than one, so this overall small-signal voltage gain is less than unity.

In the special instance that $r_o \gg R_E \| R_L$ then (12) simplifies to

$$G_v \approx \frac{R_E \| R_L}{R_E \| R_L + r_e} \frac{R_B \| \left[(\beta+1)(r_e + R_E \| R_L) \right]}{R_B \| \left[(\beta+1)(r_e + R_E \| R_L) \right] + R_{\text{sig}}} \tag{13}$$

and if $R_B \gg (\beta+1)(r_e + R_E \parallel R_L)$ then this further simplifies to

$$G_v \approx \frac{R_E \parallel R_L}{r_e + R_E \parallel R_L + \dfrac{R_{\text{sig}}}{\beta+1}} \tag{14}$$

We see from this expression that under the above two assumptions and a third $R_E \parallel R_L \gg r_e + R_{\text{sig}}/(\beta+1)$, the small-signal voltage gain is less than but approximately equal to one. This means that

$$G_v \equiv \frac{v_o}{v_{\text{sig}}} \lesssim 1 \quad \text{or} \quad v_o \lesssim v_{\text{sig}} \tag{15}$$

Because of this result, the common collector amplifier is also called an emitter follower amplifier.

- <u>Overall small-signal current gain, G_i</u>. By definition

$$G_i \equiv \frac{i_o}{i_i} \tag{16}$$

Using current division at the output of the small-signal equivalent circuit above

$$i_o = \frac{r_o \parallel R_E}{r_o \parallel R_E + R_L} i_e = \frac{r_o \parallel R_E}{r_o \parallel R_E + R_L}(\beta+1) i_b \tag{17}$$

while using current division at the input

$$i_b = \frac{R_B}{R_B + R_{ib}} i_i \tag{18}$$

Substituting this into (17) gives

$$i_o = \frac{r_o \parallel R_E}{r_o \parallel R_E + R_L}(\beta+1)\frac{R_B}{R_B + R_{ib}} i_i \quad (19)$$

from which we find that

$$G_i \equiv \frac{i_o}{i_i} = \frac{(\beta+1)(r_o \parallel R_E)R_B}{(r_o \parallel R_E + R_L)(R_B + R_{ib})} \quad (20)$$

or $$G_i = \frac{(\beta+1)(r_o \parallel R_E)R_B}{(r_o \parallel R_E + R_L)\left[R_B + (\beta+1)(r_e + R_E \parallel r_o \parallel R_L)\right]} \quad (21)$$

- Short circuit current gain, A_{is}. In the case of a short circuit load ($R_L = 0$), G_i in (21) reduces to the short circuit current gain:

$$A_{is} = \frac{i_{os}}{i_i} = \frac{(\beta+1)R_B}{R_B + (\beta+1)r_e} \quad (22)$$

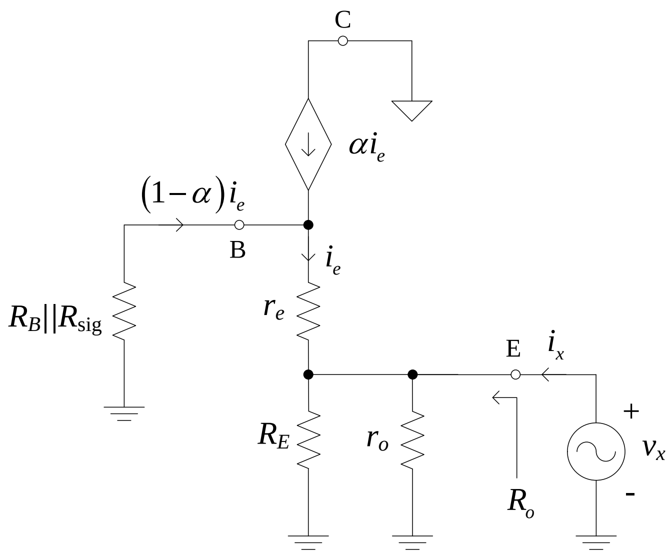
In the case that $R_B \gg (\beta+1)(r_e + R_E \parallel R_L) = (\beta+1)r_e$, as was used earlier, then

$$A_{is} \approx \beta + 1 \quad (23)$$

which can be very large.

So even though the amplifier has a voltage gain less than one (and approaching one in certain circumstances), it has a very large small-signal current gain. Overall, the amplifier can provide power gain to the AC signal.

- Output resistance, R_o. With $v_{\text{sig}} = 0$ in the small-signal equivalent circuit, we're left with



It is a bit difficult to determine R_o directly from this circuit because of the dependent current source. The trick here is to apply a signal source v_x and then determine i_x. The output resistance is computed from the ratio of these quantities as

$$R_o \equiv \frac{v_x}{i_x} \tag{24}$$

Applying KVL from the output through the input of this circuit gives

$$\begin{aligned} v_x &= -i_e r_e - (1-\alpha) i_e \left(R_{\text{sig}} \parallel R_B\right) \\ &= -i_e \left[(1-\alpha)\left(R_{\text{sig}} \parallel R_B\right) + r_e\right] \end{aligned} \tag{25}$$

Using KCL at the output

$$i_x = \frac{v_x}{r_o \parallel R_E} - i_e \tag{26}$$

Substituting (26) into (25)

$$v_x = \left(i_x - \frac{v_x}{r_o \parallel R_E} \right) \left[(1-\alpha)\left(R_{\text{sig}} \parallel R_B \right) + r_e \right]$$

$$v_x \left[1 + \frac{(1-\alpha)\left(R_{\text{sig}} \parallel R_B \right) + r_e}{r_o \parallel R_E} \right] = i_x \left[(1-\alpha)\left(R_{\text{sig}} \parallel R_B \right) + r_e \right] \quad (27)$$

Forming the ratio of v_x and i_x in (27) gives

$$R_o = \frac{v_x}{i_x} = \frac{(1-\alpha)\left(R_{\text{sig}} \parallel R_B \right) + r_e}{1 + \dfrac{(1-\alpha)\left(R_{\text{sig}} \parallel R_B \right) + r_e}{r_o \parallel R_E}}$$

or

$$R_o = \frac{\left(r_o \parallel R_E \right)\left[(1-\alpha)\left(R_{\text{sig}} \parallel R_B \right) + r_e \right]}{r_o \parallel R_E + (1-\alpha)\left(R_{\text{sig}} \parallel R_B \right) + r_e}$$

such that $R_o = \left(r_o \parallel R_E \right) \parallel \left[(1-\alpha)\left(R_{\text{sig}} \parallel R_B \right) + r_e \right]$

This is equivalent to

$$R_o = \left(r_o \parallel R_E \right) \parallel \left(\frac{R_{\text{sig}} \parallel R_B}{\beta + 1} + r_e \right) \qquad (7.161),(28)$$

In the case $r_o \parallel R_E$ is "large", then

$$R_o \approx \frac{R_{\text{sig}} \parallel R_B}{\beta + 1} + r_e \qquad (29)$$

which is generally relatively small.

Summary

Summary of the CC (emitter follower) small-signal amplifier:

1. High input resistance.
2. G_v less than one, and can be close to one.
3. A_{is} can be large.
4. Low output resistance.

These characteristics mean that the emitter follower amplifier is highly suited as a voltage buffer amplifier.