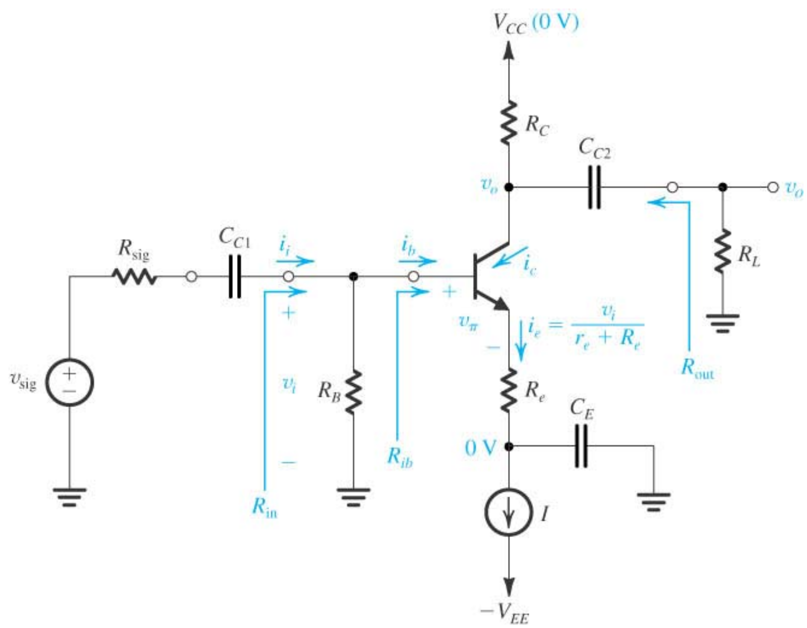
Lecture 2: Common Emitter Amplifier with Emitter Degeneration.

We'll continue our discussion of the basic types of BJT small-signal amplifiers by studying a variant of the CE amplifier that has an additional resistor added to the emitter lead:

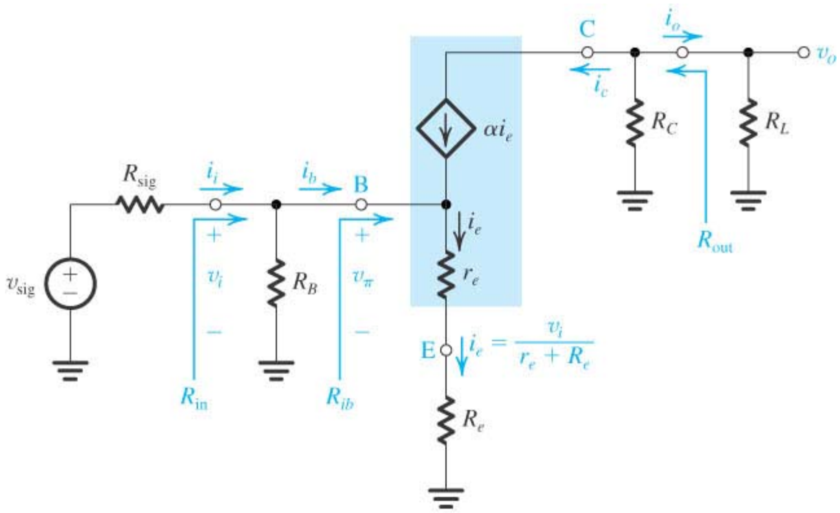


(Fig. 1)
(Sedra and Smith, 5^{th} ed.)

This is called "emitter degeneration" and has the effect of greatly enhancing the usefulness of the CE amplifier.

We'll calculate similar amplifier quantities for this circuit as those in the previous lecture for the CE amplifier.

In contrast to the previous lecture, we'll use a T small-signal model (R_e in series with r_e) for the BJT and we'll also drop r_o: it turns out to have little effect here but complicates the analysis.



(Fig. 2)
(Sedra and Smith, 5th ed.)

- Input resistance, R_{in}. From this circuit, we see directly that the input resistance at the base R_{ib} is defined as

$$R_{ib} \equiv \frac{v_i}{i_b} \tag{1}$$

Notice that here $v_i \neq v_\pi$, unlike the CE amplifier w/o emitter degeneration. Referring to the small-signal circuit we see that

$$v_i = i_e\left(r_e + R_e\right) \tag{2}$$

and

$$i_b = \frac{i_e}{\beta + 1} \tag{3}$$

Substituting these into (1) gives

$$R_{ib} = \left(\beta + 1\right)\left(r_e + R_e\right) \qquad (7.107),(4)$$

We see from this expression that the base input resistance is $\beta+1$ times the total resistance in the emitter circuit. This is called the resistance reflection rule and applies to the T small-signal BJT model.

[In the previous lecture, we see in Fig. 7.56(b) that

$$R_{ib} = r_\pi$$

but $r_\pi = (\beta+1) r_e$, which obeys this resistance reflection rule since there is no R_e in that circuit.]

This base input resistance can be much larger than without the emitter resistance. That's often a good thing. The designer can change R_e to achieve a desired input resistance [> $(\beta+1)r_e$].

The total input resistance to this CE amplifier with emitter degeneration is then

$$R_{\text{in}} = R_B \parallel R_{ib} = R_B \parallel \left[(\beta+1)(r_e + R_e) \right] \tag{5}$$

- Small-signal voltage gain, G_v. We'll first calculate the partial voltage gain

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

At the output,

$$v_o = -\alpha i_e (R_C \parallel R_L) \tag{7}$$

Substituting for i_e from (2) gives

$$A_v = \frac{-\alpha\left(R_C \parallel R_L\right)}{r_e + R_e} \tag{8}$$

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

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

We can equivalently write this voltage gain as

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

with A_v given in (8).

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

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

Substituting this result and (8) into (10) yields the final expression for the overall small-signal voltage gain

$$G_v = \frac{v_o}{v_{\text{sig}}} = \frac{-\alpha\left(R_C \parallel R_L\right)}{r_e + R_e} \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \tag{12}$$

Using R_{in} in (5) and assuming $R_B \gg R_{ib}$ then (12) simplifies to

$$G_v \approx \frac{-\beta\left(R_C \parallel R_L\right)}{R_{\text{sig}} + \left(\beta + 1\right)\left(r_e + R_e\right)} \qquad \text{(7.113),(13)}$$

Notice that this gain is actually **smaller** than the CE amplifier without emitter degeneration [because of the $(\beta+1)R_e$ term in the denominator]. However, because of this term it can be shown that the gain is less sensitive to variations in β.

- Overall small-signal current gain, G_i. By definition

$$G_i \equiv \frac{i_o}{i_i} \tag{14}$$

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

$$i_o = \frac{-R_C}{R_C + R_L} i_c = \frac{-\alpha R_C}{R_C + R_L} i_e \tag{15}$$

while at the input

$$i_b = \frac{R_B}{R_B + R_{ib}} i_i \tag{16}$$

Substituting $i_e = (\beta + 1) i_b$ and (16) into (15) gives

$$i_o = \frac{-\alpha R_C}{R_C + R_L} (\beta + 1) \frac{R_B}{R_B + R_{ib}} i_i$$

or

$$G_i = \frac{-\beta R_B R_C}{(R_C + R_L)(R_B + R_{ib})} \tag{17}$$

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

$$A_{is} = \frac{-\beta R_B}{R_B + R_{ib}} \tag{18}$$

In the usual circumstance when $R_B \gg R_{ib}$, then

$$A_{is} \approx -\beta \tag{19}$$

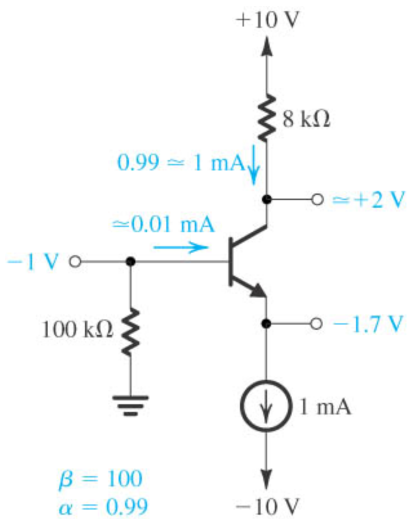
which is the same value as for a CE amplifier since there is no R_e in this expression.

- Output resistance, R_{out}. Referring to the small-signal equivalent circuit above and shorting out the input $v_{sig} = 0$

$$R_{out} = R_C \tag{20}$$

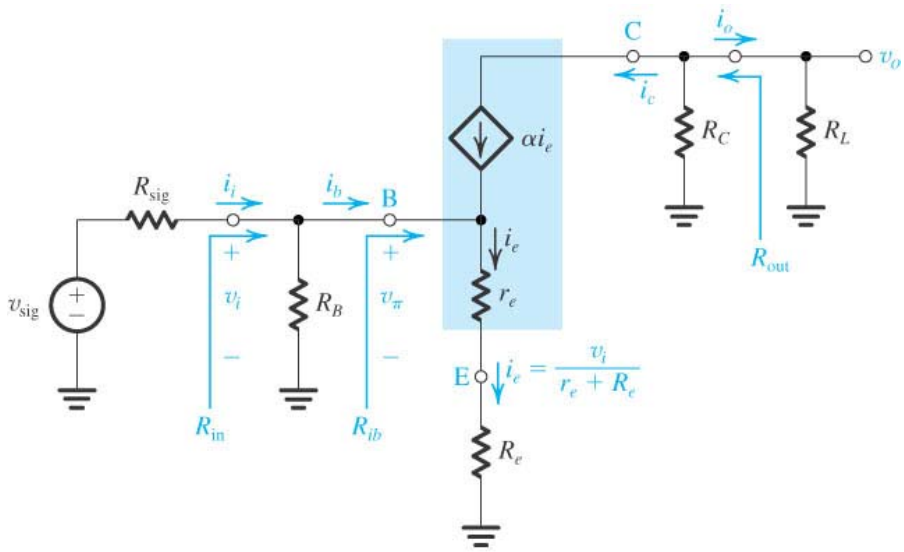
which is the same as the CE amplifier (when ignoring r_o).

Example N19.1 (Somewhat similar to text Example 7.8). Given a CE amplifier with emitter degeneration having $R_{sig} = R_L = 5$ kΩ. The circuit is biased as shown:



(Fig. 3)
(Sedra and Smith, 5th ed.)

The small-signal equivalent circuit for this CE amplifier with emitter degeneration is the same as that shown earlier in this lecture:



(Fig. 4)
(Sedra and Smith, 5th ed.)

With $I_E = 1$ mA, then $r_e = V_T / I_E = 25 \text{ mV}/1 \text{ mA} = 25\ \Omega$.

- Find the value of R_e that gives $R_{\text{in}} = 4R_{\text{sig}} = 20\ \text{k}\Omega$. From (5) $R_{\text{in}} = R_B \,||\, R_{ib}$, which implies that $R_{ib} = 25\ \text{k}\Omega$. Using (4)

$$R_{ib} = (\beta + 1)(r_e + R_e) \quad \Rightarrow \quad r_e + R_e = \frac{R_{ib}}{\beta + 1}$$

or

$$R_e = \frac{R_{ib}}{\beta + 1} - r_e = \frac{25{,}000}{101} - 25 = 222.5\ \Omega$$

We can choose this R_e without considering its effect on I_E or the bias because a current source bias is being used. Tricky! If another biasing method were used, this might not be the case.

- Determine the output resistance. From (20),

$$R_{\text{out}} = R_C = 8 \text{ k}\Omega$$

- Compute the overall small-signal voltage gain. Using (12)

$$G_v = \frac{v_o}{v_{\text{sig}}} = \frac{-\alpha\left(R_C \parallel R_L\right)}{r_e + R_e}\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}}$$

$$G_v = \frac{-0.99(3{,}080)}{25 + 222.5}\frac{20{,}000}{20{,}000 + 5{,}000} = -9.86 \text{ V/V}$$

- Determine the open circuit small-signal voltage gain, G_{vo}. This is the overall gain but with an open circuit load. Hence, from this description we can define

$$G_{vo} = G_v\big|_{R_L = \infty}$$

Using (12) once again but with $R_L = \infty$ gives for the CE amplifier with emitter degeneration

$$G_{vo} = \frac{-\alpha R_C R_{\text{in}}}{\left(r_e + R_e\right)\left(R_{\text{in}} + R_{\text{sig}}\right)} \tag{21}$$

For this particular amplifier

$$G_{vo} = \frac{-0.99 \cdot 8{,}000 \cdot 20{,}000}{(25 + 222.5)(20{,}000 + 5{,}000)} = -25.6 \text{ V/V}$$

Note that this is not the same open circuit gain A_{vo} used in the text. A_{vo} is the partial open circuit voltage gain

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

which using (8) is

$$A_{vo} = \frac{-\alpha R_C}{r_e + R_e} \qquad (22)$$

For this amplifier

$$A_{vo} = \frac{-0.99 \cdot 8{,}000}{25 + 222.5} = -32 \text{ V/V}$$

Can you physically explain why G_{vo} and A_{vo} are different values?

- Compute the overall current gain and the short circuit current gain. Using (17)

$$G_i = \frac{-\beta R_B R_C}{(R_C + R_L)(R_B + R_{ib})}$$

$$= \frac{-100 \cdot 100{,}000 \cdot 8{,}000}{(8{,}000 + 5{,}000)(100{,}000 + 25{,}000)} = -49.2 \text{ A/A}$$

For the short circuit current gain, we use (18)

$$A_{is} = \frac{-\beta R_B}{R_B + R_{ib}} = \frac{-100 \cdot 100{,}000}{100{,}000 + 25{,}000} = -80 \text{ A/A}$$

- If v_π is limited to 5 mV, what is the maximum value for v_{sig} with and without R_e included? Find the corresponding v_o. To address this question, we need an expression relating v_{sig} and v_π. From (11) we know that

$$v_i = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} v_{\text{sig}} \qquad (11)$$

while at the input to the small-signal equivalent circuit above

$$v_\pi = \frac{r_e}{r_e + R_e} v_i \tag{23}$$

Substituting (11) into (23) gives

$$v_{\text{sig}} = \frac{R_{\text{in}} + R_{\text{sig}}}{R_{\text{in}}} \frac{r_e + R_e}{r_e} v_\pi \tag{24}$$

With $v_\pi = 5$ mV, then

$$v_{\text{sig}} = \frac{20,000 + 5,000}{20,000} \frac{25 + R_e}{25} 5 \text{ mV}$$

or

$$v_{\text{sig}} = 0.25\left(25 + R_e\right) \text{ mV} \tag{25}$$

If $R_e = 0$, then from (25) $v_{\text{sig}} = 6.25$ mV is the maximum input signal voltage and because $G_v = -9.86$ V/V, the corresponding output voltage is $v_o = G_v v_{\text{sig}} = -61.6$ mV. If R_e = 222.5 Ω, then from (25) $v_{\text{sig}} = 61.9$ mV is the maximum input signal voltage and the corresponding output voltage is $v_o = -610.1$ mV.

This is a demonstration of yet another benefit of emitter degeneration: the amplifier can handle larger input signals (and hence potentially larger output voltages) **without incurring nonlinear distortion**.