Electronic Devices and Circuits

Characterizing an amplifier

- To study the performance of an amplifier as a basic building block
- Concept of Source and load
- Amplifier gets input from a source and provides output to the load

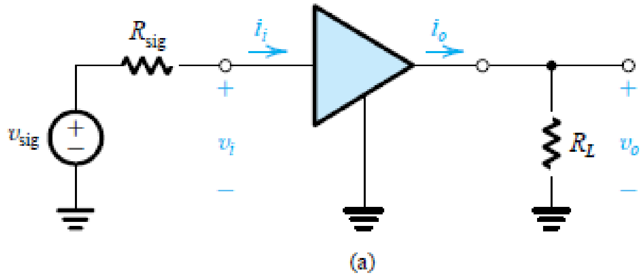
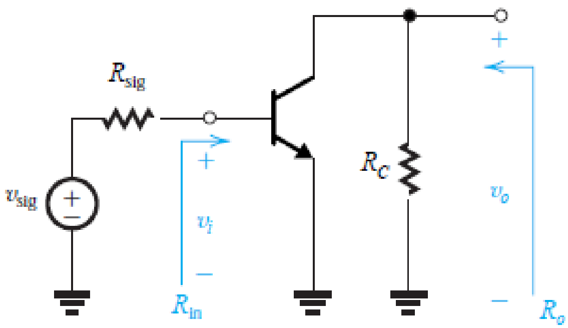


Figure 6.49 (a) An amplifier fed with a signal source (v_{sig}, R_{sig}) and providing its output across a load resistance R_L. (b) The circuit in (a) with the amplifier represented by its equivalent circuit model. (c) Determining the output resistance R_o of the amplifier.

Common Emitter Amplifier

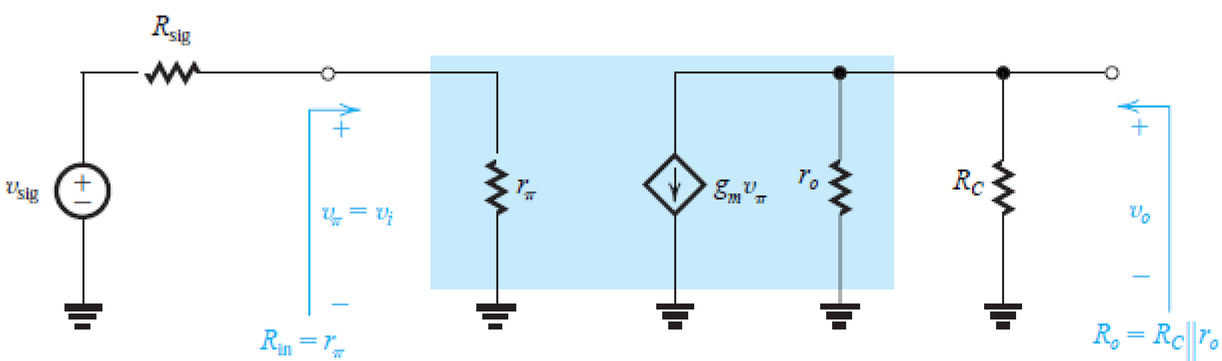


(a)

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

$$R_o = R_C \parallel r_o$$

$$R_o \simeq R_C$$



$$v_o = -(g_m v_\pi)(R_C \parallel r_o)$$

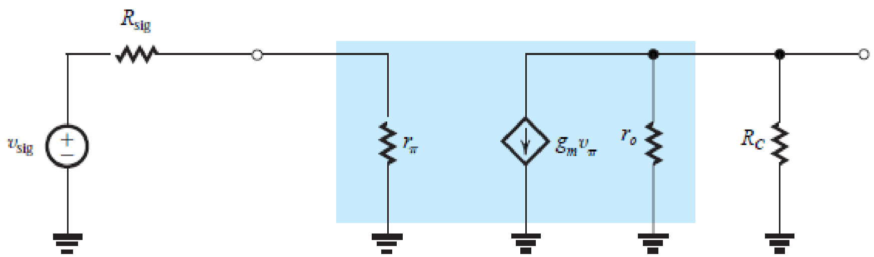
Since $v_\pi = v_i$, the open-circuit voltage gain $A_{vo} \equiv v_o/v_i$ can be obtained as

$$A_{vo} = -g_m(R_C \parallel r_o)$$

neglecting r_o is allowed only in discrete-circuit design.
r_o plays a central role in IC amplifiers.

$$A_{vo} \simeq (-g_m R_C)$$

Common Emitter Amplifier



$$A_{vo} = -g_m(R_C \| r_o)$$

$$A_v = A_{vo}\frac{R_L}{R_L + R_0}$$

$$A_v = g_m(R_C \| r_o)\frac{R_L}{R_L + R_0}$$

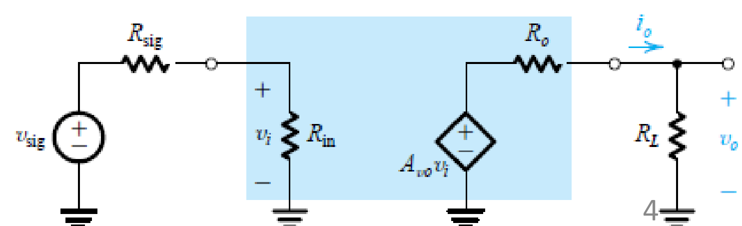
$$A_v = g_m(R_C \| r_o)\frac{R_L}{R_L + (R_C \| r_o)}$$

$$A_v = -g_m(R_C \| R_L \| r_o)$$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_v$$

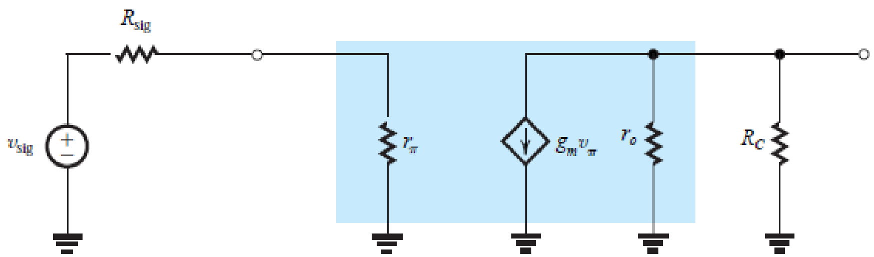
$$G_v \equiv \frac{v_o}{v_{sig}} = -\frac{r_\pi}{r_\pi + R_{sig}} g_m(R_C \| R_L \| r_o)$$

$$v_i = v_{sig} \frac{r_\pi}{r_\pi + R_{sig}}$$



(b)

A CE amplifier utilizes a BJT with $\beta = 100$ and $V_A = 100$ V, is biased at $I_C = 1$ mA and has a collector resistance $R_C = 5\ \text{k}\Omega$. Find R_{in}, R_o, and A_{vo}. If the amplifier is fed with a signal source having a resistance of 5 kΩ, and a load resistance $R_L = 5\ \text{k}\Omega$ is connected to the output terminal, find the resulting A_v and G_v. If $\hat{v}_\pi$ is to be limited to 5 mV, what are the corresponding $\hat{v}_{sig}$ and $\hat{v}_o$ with the load connected?



$$g_m = \frac{I_C}{V_T} = \frac{1\text{ mA}}{0.025\text{ V}} = 40\text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40\text{ mA/V}} = 2.5\ \text{k}\Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{100\text{ V}}{1\text{ mA}} = 100\ \text{k}\Omega$$

$$R_{in} = r_\pi = 2.5\ \text{k}\Omega$$

$$R_o = R_C \| r_o$$
$$= 5 \| 100 = 4.76\ \text{k}\Omega$$

$$A_{vo} = -g_m(R_C \| r_o)$$
$$= -40\text{ mA/V} \quad (5\ \text{k}\Omega \| 100\ \text{k}\Omega)$$
$$= -190.5\text{ V/V}$$

$$A_v = A_{vo}\frac{R_L}{R_L + R_o}$$
$$= -190.5 \times \frac{5}{5 + 4.76} = -97.6\text{ V/V}$$

or

$$A_v = -g_m(R_C \| R_L \| r_o)$$
$$= -40(5 \| 5 \| 100) = -97.6\text{ V/V}$$

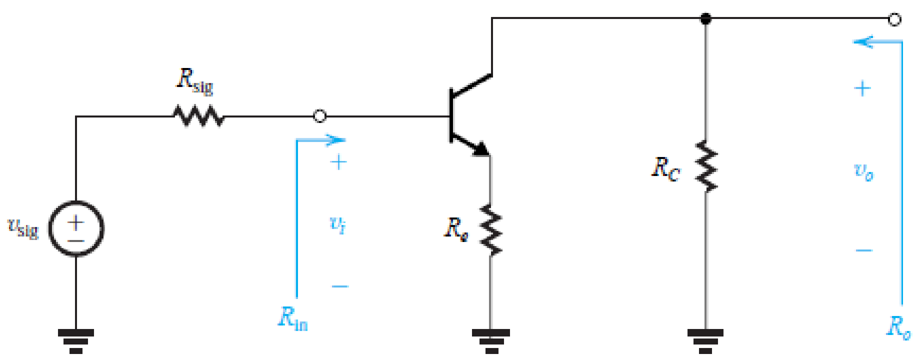
$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_v$$
$$= \frac{2.5}{2.5 + 5} \times -97.6 = -32.5\text{ V/V}$$

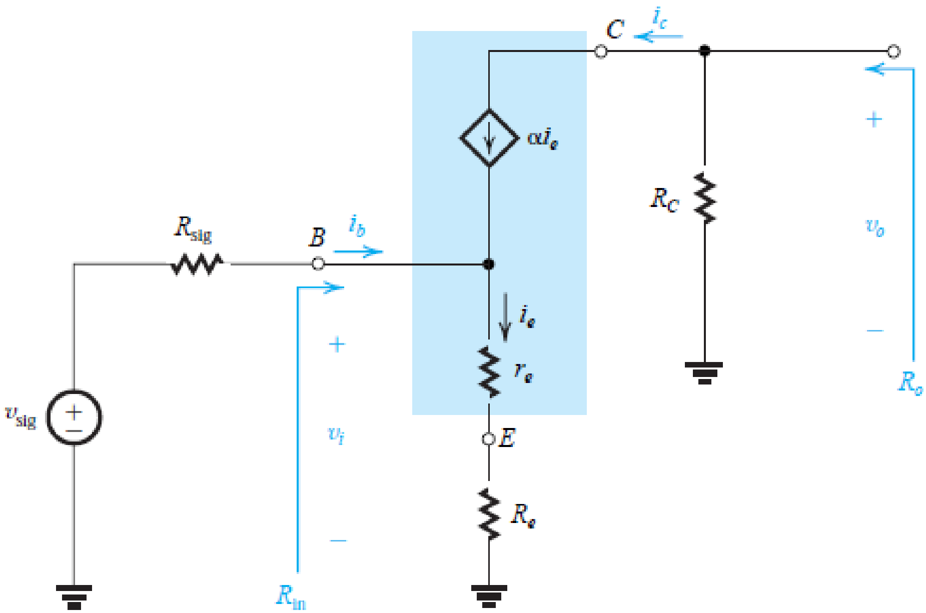
$$v_i = v_{sig}\frac{r_\pi}{r_\pi + R_{sig}}$$

$$\hat{v}_{sig} = \left(\frac{R_{in} + R_{sig}}{R_{in}}\right)\hat{v}_\pi = \frac{2.5 + 5}{2.5} \times 5 = 15\text{ mV}$$

$$\hat{v}_o = G_v \hat{v}_{sig} = 32.5 \times 0.015 = 0.49\text{ V}$$

Common Emitter Amplifier with emitter resistance





$$R_{in} \equiv \frac{v_i}{i_i}$$

$$R_{in} \equiv \frac{v_i}{i_b}$$

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

$$i_e = \frac{v_i}{r_e + R_e}$$

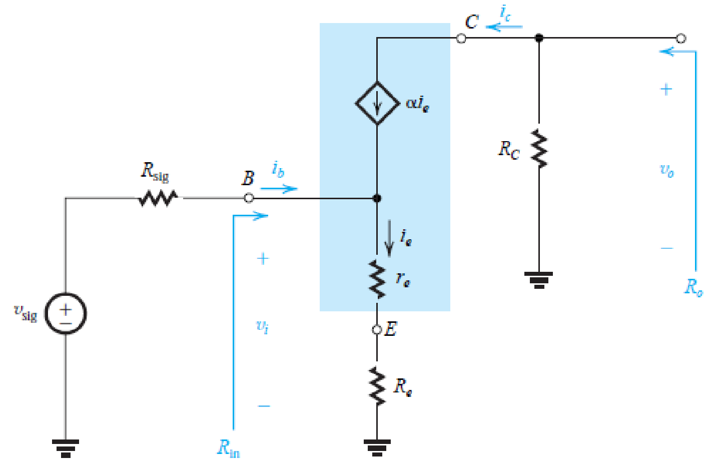
$$i_b = \frac{\dfrac{v_i}{r_e + R_e}}{\beta + 1}$$

$$i_b = \frac{v_i}{(\beta + 1)(r_e + R_e)}$$

$$R_{in} = \frac{v_i}{\dfrac{v_i}{(\beta + 1)(r_e + R_e)}}$$

$$R_{in} = (\beta + 1)(r_e + R_e)$$

Common Emitter Amplifier with emitter resistance



$$\frac{R_{in}(\text{with } R_e \text{ included})}{R_{in}(\text{without } R_e)} = \frac{(\beta+1)(r_e+R_e)}{(\beta+1)r_e}$$

$$= 1 + \frac{R_e}{r_e}$$

$$\simeq 1 + g_m R_e$$

) by inspection:

$$R_o = R_C$$

$$v_o = -i_c R_C$$

$$= -\alpha i_e R_C$$

$$i_e = \frac{v_i}{r_e + R_e}$$

$$v_o = \alpha \frac{v_i}{r_e + R_e} R_C$$

$$A_{vo} = -\alpha \frac{R_C}{r_e + R_e}$$

$$A_{vo} = -\frac{\alpha}{r_e} \frac{R_C}{1 + R_e/r_e}$$

$$A_{vo} = -\frac{g_m R_C}{1 + R_e/r_e}$$

$$\simeq -\frac{g_m R_C}{1 + g_m R_e}$$

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

$$= -\alpha \frac{R_C}{r_e + R_e} \frac{R_L}{R_L + R_C}$$

$$= -\alpha \frac{R_C \| R_L}{r_e + R_e}$$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} \times -\alpha \frac{R_C \| R_L}{r_e + R_e}$$

$$G_v = \frac{(\beta+1)(r_e+R_e)}{R_{sig} + (\beta+1)(r_e+R_e)} \times \frac{\beta}{(\beta+1)} \frac{R_C \| R_L}{(r_e+R_e)}$$

$$G_v = -\beta \frac{R_C \| R_L}{R_{sig} + (\beta+1)(r_e+R_e)}$$

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

$$\simeq \frac{1}{1 + g_m R_e}$$

Thus, for the same v_π, the signal at the input terminal of the amplifier, v_i, can be greater than for the CE amplifier by the factor $(1 + g_m R_e)$.

Comparison of CE amplifier with and without emitter resistance

To summarize, including a resistance R_e in the emitter of the CE amplifier results in the following characteristics:

1. The input resistance R_{in} is increased by the factor $(1 + g_m R_e)$.
2. The voltage gain from base to collector, A_v, is reduced by the factor $(1 + g_m R_e)$.
3. For the same nonlinear distortion, the input signal v_i can be increased by the factor $(1 + g_m R_e)$.

For the CE amplifier specified in Example 6.17, what value of R_e is needed to raise R_{in} to a value four times that of R_{sig}? With R_e included, find A_{vo}, R_o, A_v, and G_v. Also, if $\hat{v}_\pi$ is limited to 5 mV, what are the corresponding values of $\hat{v}_{sig}$ and $\hat{v}_o$?

A CE amplifier utilizes a BJT with $\beta = 100$ and $V_A = 100$ V, is biased at $I_C = 1$ mA and has a collector resistance $R_C = 5$ kΩ. Find R_{in}, R_o, and A_{vo}. If the amplifier is fed with a signal source having a resistance of 5 kΩ, and a load resistance $R_L = 5$ kΩ is connected to the output terminal, find the resulting A_v and G_v. If $\hat{v}_\pi$ is to be limited to 5 mV, what are the corresponding $\hat{v}_{sig}$ and $\hat{v}_o$ with the load connected?

$$R_{in} = 4\,R_{sig} = 4 \times 5 = 20 \text{ k}\Omega$$

$$20 = (\beta + 1)\,(r_e + R_e)$$

$$r_e + R_e \simeq 200\ \Omega$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40 \text{ mA/V}} = 2.5 \text{ k}\Omega$$

$$r_e = \frac{r_\pi}{\beta + 1}$$

$$r_e = \frac{2.5k}{101} = 24.75\Omega$$

$$R_e = 200 - 25 = 175\ \Omega$$

$$A_{vo} = -\alpha\,\frac{R_C}{r_e + R_e}$$

$$\simeq \left(-\frac{5000}{25 + 175}\right) = -25 \text{ V/V}$$

$$R_o = R_C = 5 \text{ k}\Omega \text{ (unchanged)}$$

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

$$= -25 \times \frac{5}{5 + 5} = -12.5 \text{ V/V}$$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}}\,A_v$$

$$= -\frac{20}{20 + 5} \times 12.5 = -10 \text{ V/V}$$

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

$$\hat{v}_i = \hat{v}_\pi\left(\frac{r_e + R_e}{r_e}\right)$$

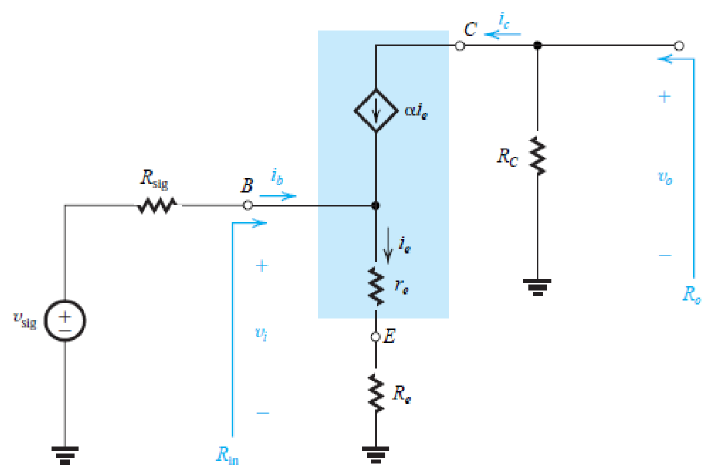
$$= 5\left(1 + \frac{175}{25}\right) = 40 \text{ mV}$$

$$\hat{v}_{sig} = \hat{v}_i\,\frac{R_{in} + R_{sig}}{R_{in}}$$

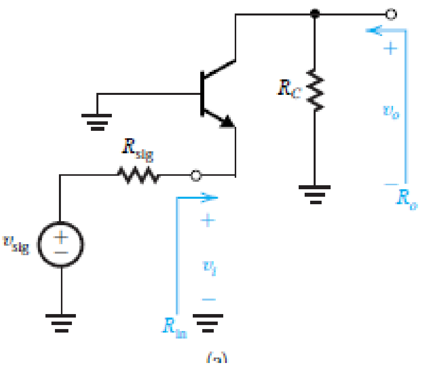
$$= 40\left(1 + \frac{5}{20}\right) = 50 \text{ mV}$$

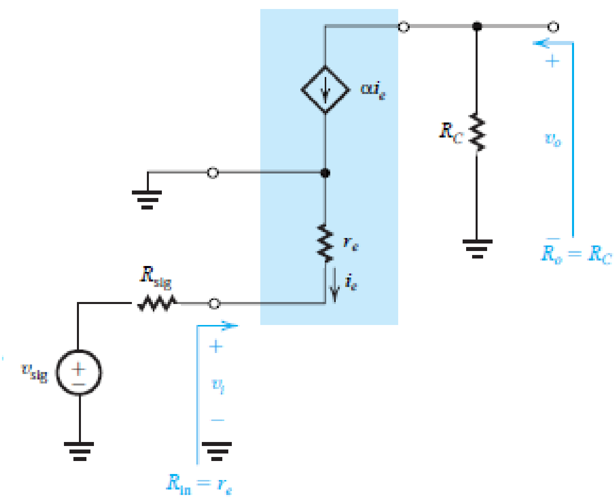
$$\hat{v}_o = \hat{v}_{sig} \times |G_v|$$

$$= 50 \times 10 = 500 \text{ mV} = 0.5 \text{ V}$$



Common Base Amplifier





$$R_{in} = r_e$$

$$R_o = R_C$$

$$v_o = -\alpha i_e R_C$$

$$i_e = -\frac{v_i}{r_e}$$

$$v_o = -\alpha\left(-\frac{v_i}{r_e}\right)R_C$$

$$A_{vo} \equiv \frac{v_o}{v_i}$$

$$= \frac{\alpha}{r_e}R_C$$

$$= g_m R_C$$

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

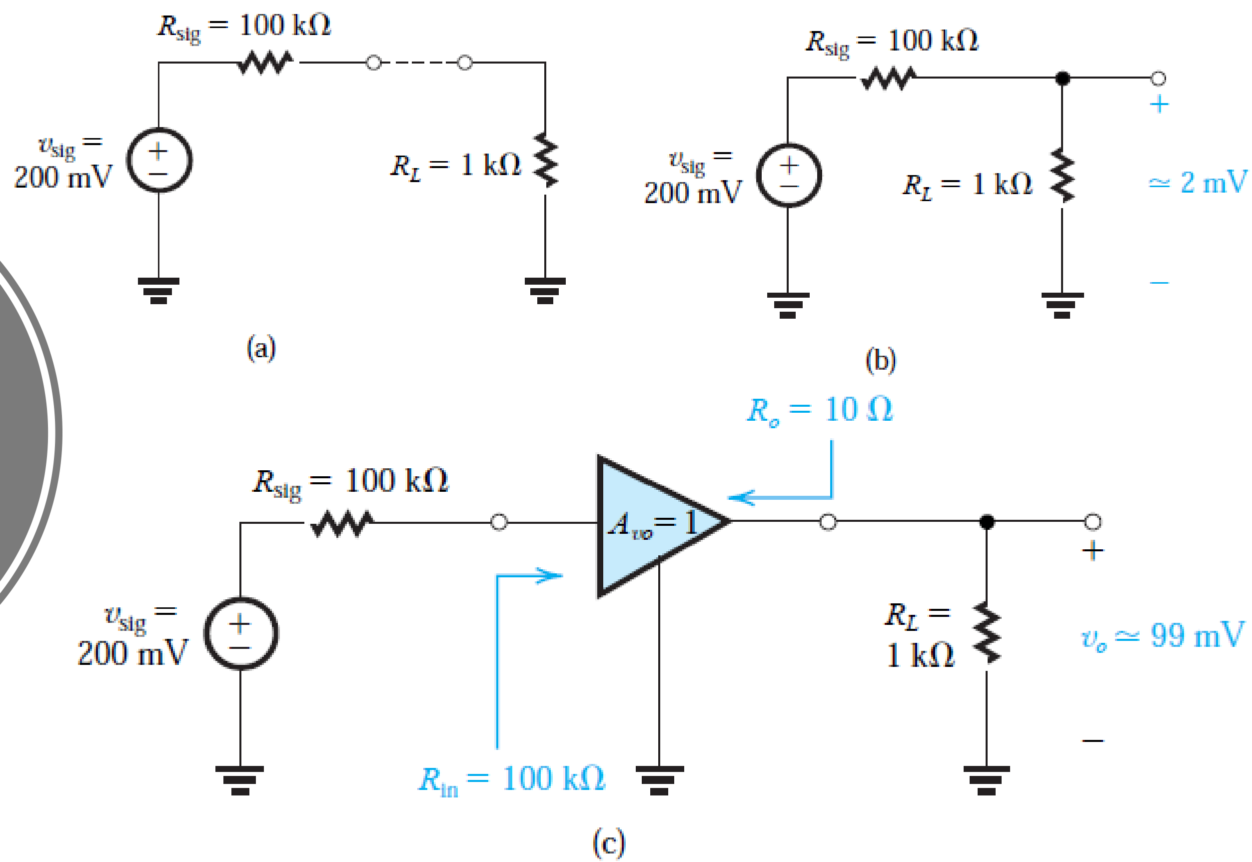
$$= \frac{r_e}{R_{sig} + r_e}$$

$$A_v = g_m(R_C \| R_L)$$

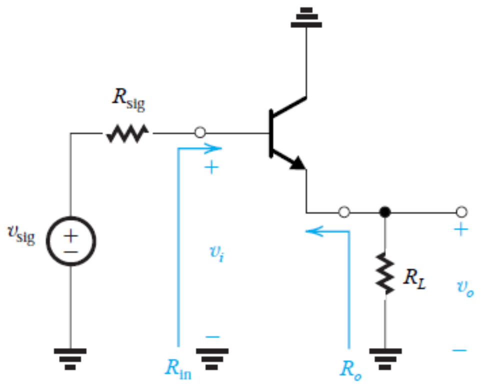
$$G_v = \frac{r_e}{R_{sig} + r_e}\; g_m(R_C \| R_L)$$

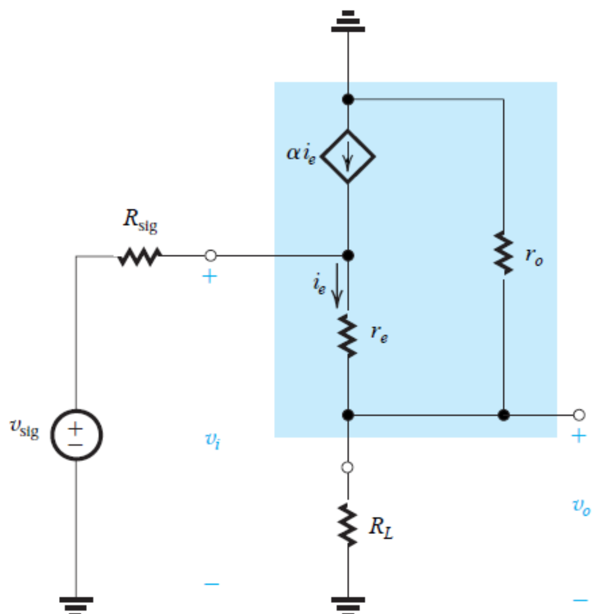
$$= \alpha\;\frac{R_C \| R_L}{R_{sig} + r_e}$$

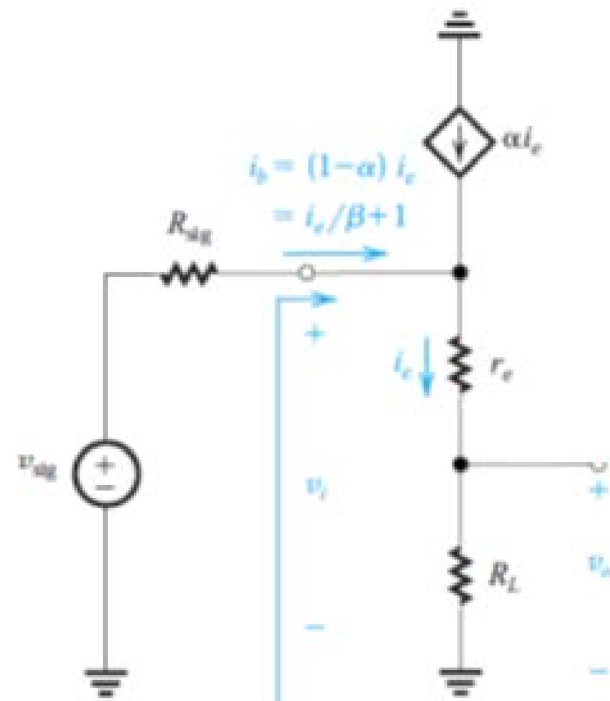
The need for Voltage buffer

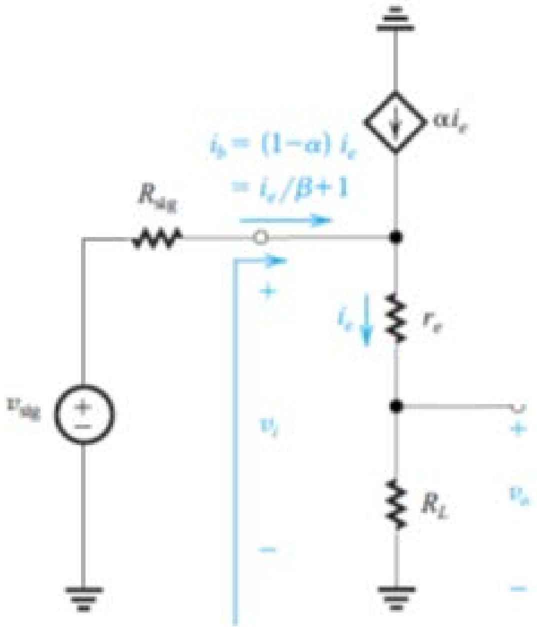


Common Collector Amplifier or Emitter Follower









$$R_{in} = \frac{v_i}{i_b}$$

Substituting for $i_b = i_e/(\beta+1)$ where i_e is given by

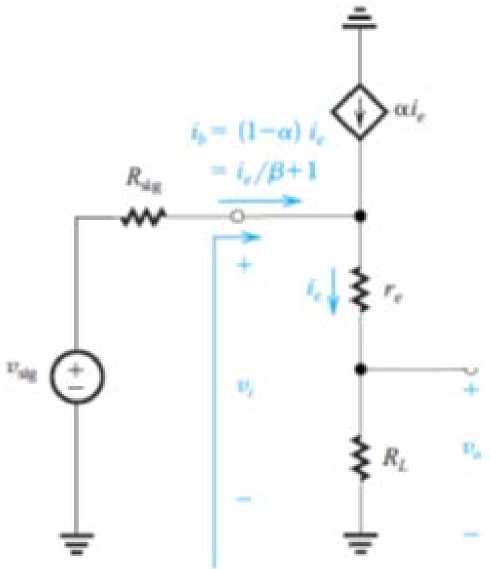
$$i_e = \frac{v_i}{r_e + R_L}$$

$$R_{in} = \frac{v_i}{\frac{i_e}{\beta+1}}$$

$$R_{in} = \frac{v_i(\beta+1)}{i_e}$$

$$R_{in} = \frac{v_i(\beta+1)}{\frac{v_i}{r_e+R_L}}$$

$$R_{in} = (\beta+1)(r_e+R_L)$$



Setting $R_L = \infty$ yields A_{vo},

$$A_{vo} = 1$$

$$A_v \equiv \frac{v_o}{v_i} = \frac{R_L}{R_L + r_e}$$

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

$$= \frac{(\beta+1)(r_e + R_L)}{(\beta+1)(r_e + R_L) + R_{\text{sig}}}$$

$$G_v \equiv \frac{v_o}{v_{sig}} = \frac{v_i}{v_{sig}} \times A_v = \frac{(\beta+1)R_L}{(\beta+1)R_L + (\beta+1)r_e + R_{\text{sig}}}$$

To determine R_o, refer to Fig. and look back into the emitter (i.e., behind or excluding R_L) while setting $v_i = 0$ (i.e., grounding the base). You will see r_e of the BJT, thus

$$R_o = r_e$$

TABLE Characteristics of BJT Amplifiers[a, b, c]

	R_{in}	A_{vo}	R_o	A_v	G_v
Common emitter	$(\beta+1)r_e$	$-g_m R_C$	R_C	$-g_m(R_C \parallel R_L)$ $-\alpha\dfrac{R_C \parallel R_L}{r_e}$	$-\beta\dfrac{R_C \parallel R_L}{R_{sig}+(\beta+1)r_e}$
Common emitter with R_e	$(\beta+1)(r_e+R_e)$	$-\dfrac{g_m R_C}{1+g_m R_e}$	R_C	$\dfrac{-g_m(R_C \parallel R_L)}{1+g_m R_e}$ $-\alpha\dfrac{R_C \parallel R_L}{r_e+R_e}$	$-\beta\dfrac{R_C \parallel R_L}{R_{sig}+(\beta+1)(r_e+R_e)}$
Common base	r_e	$g_m R_C$	R_C	$g_m(R_C \parallel R_L)$ $\alpha\dfrac{R_C \parallel R_L}{r_e}$	$\alpha\dfrac{R_C \parallel R_L}{R_{sig}+r_e}$
Emitter follower	$(\beta+1)(r_e+R_L)$	1	r_e	$\dfrac{R_L}{R_L+r_e}$	$\dfrac{R_L}{R_L+r_e+R_{sig}/(\beta+1)}$

Comparison of amplifiers

1. The CE configuration is the one best suited for realizing the bulk of the gain required in an amplifier. Depending on the magnitude of the gain required, either a single stage or a cascade of two or three stages can be used.
2. Including a resistor R_e in the emitter lead of the CE stage provides a number of performance improvements at the expense of gain reduction.
3. The low input resistance of the CB amplifier makes it useful only in specific applications. As we shall see in Chapter 9, it has a much better high-frequency response than the CE amplifier. This superiority will make it useful as a high-frequency amplifier, especially when combined with the CE circuit. We shall see one such combination in Chapter 7.
4. The emitter follower finds application as a voltage buffer for connecting a high-resistance source to a low-resistance load and as the output stage in a multistage amplifier, where its purpose is to equip the amplifier with a low output-resistance.

Consider a CB amplifier utilizing a BJT biased at $I_C = 1$ mA and with $R_C = 5$ kΩ. Determine R_{in}, A_{vo}, and R_o. If the amplifier is loaded in $R_L = 5$ kΩ, what value of A_v results? What G_v is obtained if $R_{sig} = 5$ kΩ?

$$g_m = \frac{I_C}{V_T} = \frac{1\text{ mA}}{0.025\text{ V}} = 40\text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40\text{ mA/V}} = 2.5\text{ k}\Omega$$

$$r_e = \frac{r_\pi}{\beta + 1}$$

$$r_e = \frac{2.5k}{101} = 24.75\Omega$$

$$R_{in} = r_e$$

$$A_{vo} \equiv \frac{v_o}{v_i}$$

$$= g_m R_C$$

$$A_{vo} = 40m(5k)$$

$$A_{vo} = 200\, V/V$$

$$R_o = R_C$$

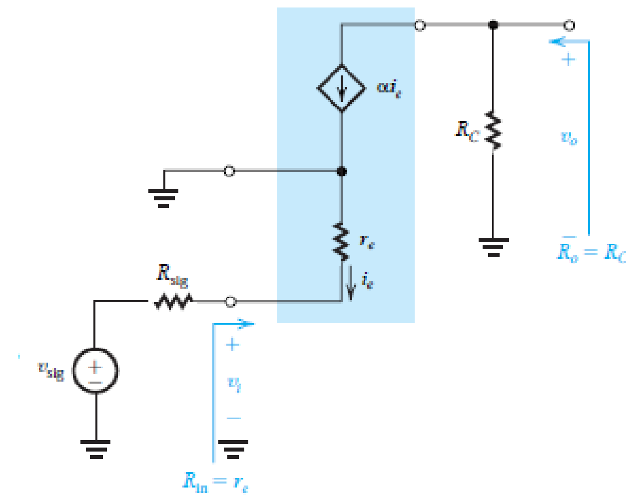
$$A_v = A_{vo}\frac{R_L}{R_L + R_o}$$

$$A_v = 200\left(\frac{5k}{5k + 5k}\right)$$

$$A_v = 100\, V/V$$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_v$$

$$G_v = 100\left(\frac{25}{25 + 5k}\right)$$



25 Ω; 200 V/V; 5 kΩ; 100 V/V; 0.5 V/V

It is required to design an emitter follower to implement the buffer amplifier of Fig. 6.54(c). Specify the required bias current I_E and the minimum value the transistor β must have. Determine the maximum allowed value of v_{sig} if v_π is to be limited to 5 mV in order to obtain reasonably linear operation. With $v_{sig} = 200$ mV, determine the signal voltage at the output if R_L is changed to 2 kΩ, and to 0.5 kΩ.

$R_o = 10\ \Omega,$

$r_e = 10\ \Omega.$

$10\ \Omega = \dfrac{V_T}{I_E}$

$I_E = 2.5$ mA

$R_{in} = (\beta + 1)(r_e + R_L)$

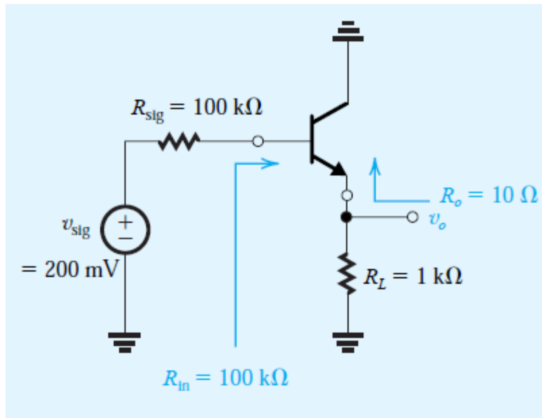
$100 = (\beta + 1)(0.01 + 1)$

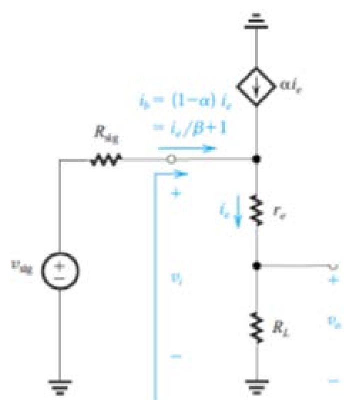
Thus, the BJT should have a β wit

$$G_v \equiv \frac{v_o}{v_{sig}} = \frac{R_L}{R_L + r_e + \dfrac{R_{sig}}{(\beta+1)}}$$

Assuming $\beta = 100$

$G_v = 0.5$





Thus when $v_{sig} = 200$ mV, the signal at the output will be 100 mV

$$v_\pi = \frac{v_o}{R_L} \times r_e$$

$$= \frac{100}{1000} \times 10 = 1 \text{ mV}$$

If $\hat{v}_\pi = 5$ mV then v_{sig} can be increased by a factor of 5, resulting in $\hat{v}_{sig} = 1$ V.

$$\frac{R_{sig}}{\beta+1} + r_e = \frac{100}{101} + 0.01 = 1 \text{ k}\Omega$$

For $R_L = 2$ kΩ, $\quad v_o = 200 \text{ mV} \times \dfrac{2}{2+1} = 133.3$ mV

for $R_L = 0.5$ kΩ, $\quad v_o = 200 \text{ mV} \times \dfrac{0.5}{0.5+1} = 66.7$ mV

Resistance Reflection Rule

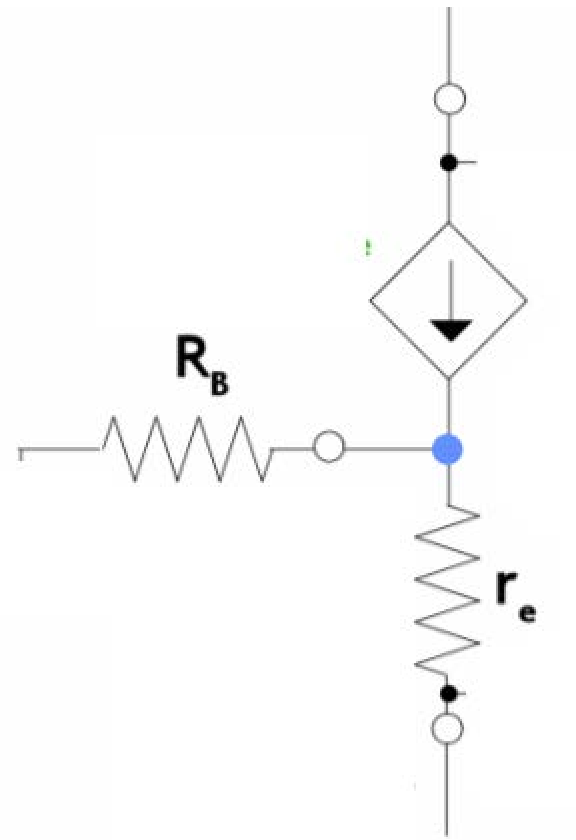
When looking into the base, the input resistance is the base resistance plus (β+1) times total resistance in the emitter

When looking into the emitter, the input resistance is the emitter resistance plus whatever is the base resistance divided by (β+1)

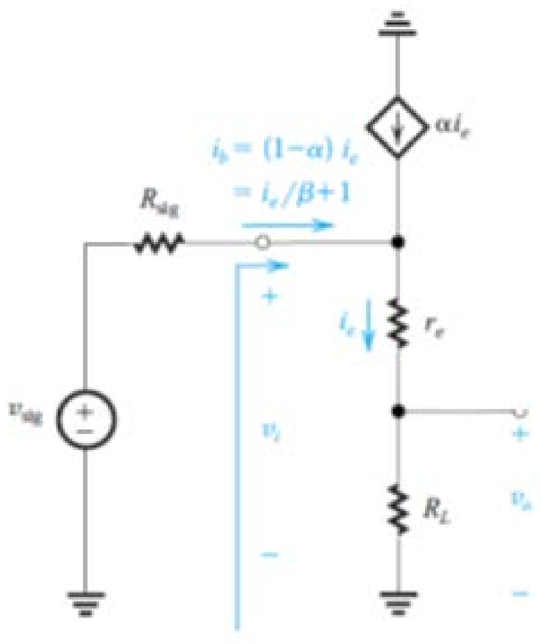
The β+1 rule takes advantage of the relationship between i_E and i_B.

At the base side, total resistance is
$R_B + (\beta + 1)r_e$

At the emitter side, total resistance is
$$r_e + \frac{R_B}{\beta + 1}$$

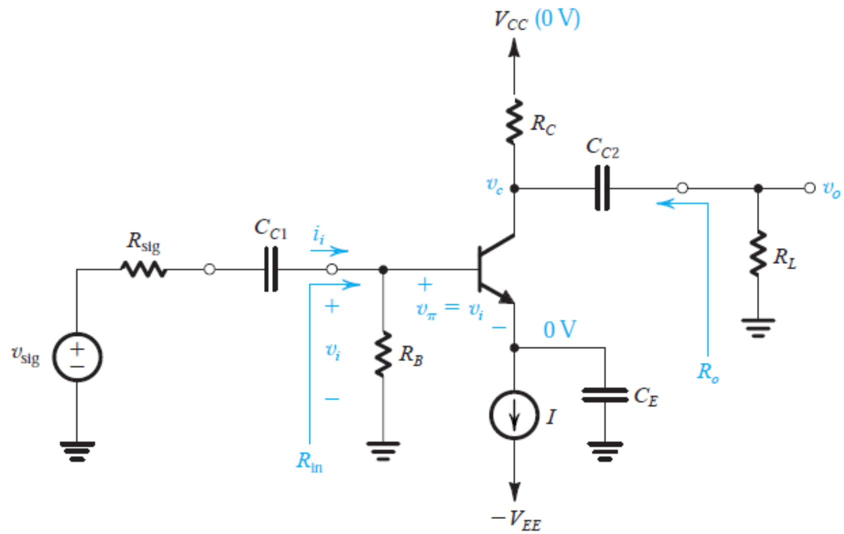


Resistance Reflection Rule

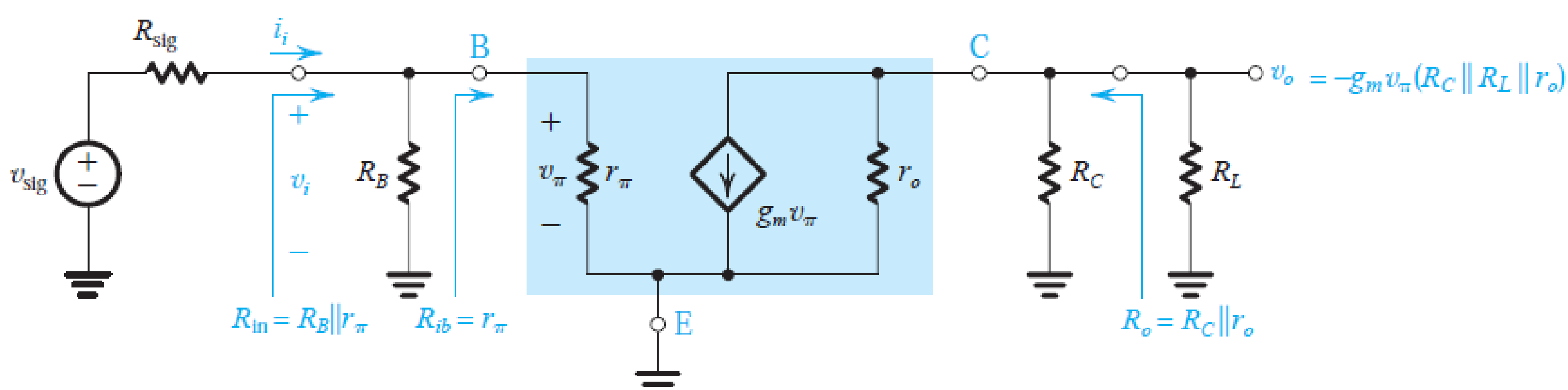


$$R_{\text{in}} = (\beta+1)(r_e+R_L)$$

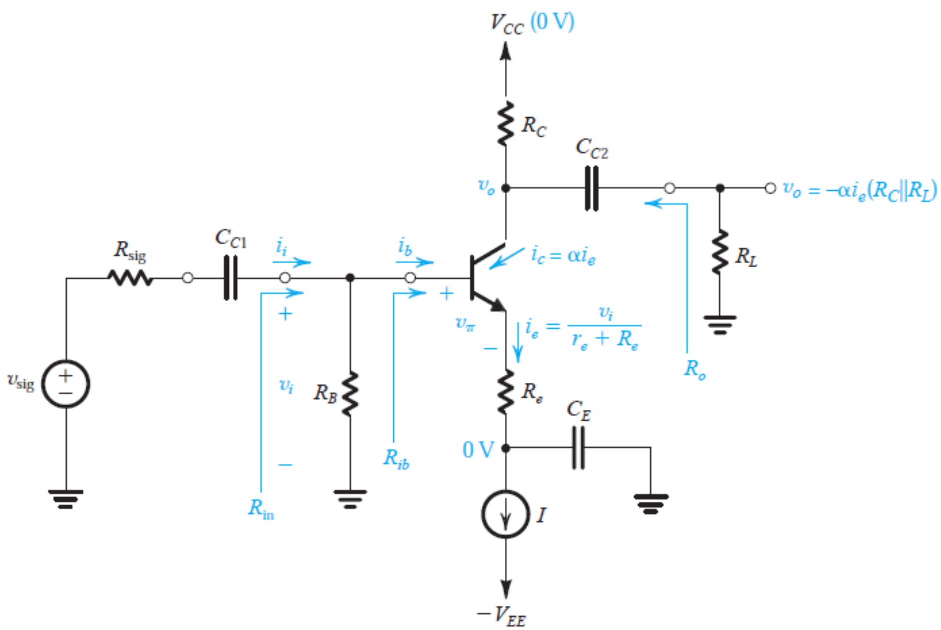
The discrete BJT amplifiers

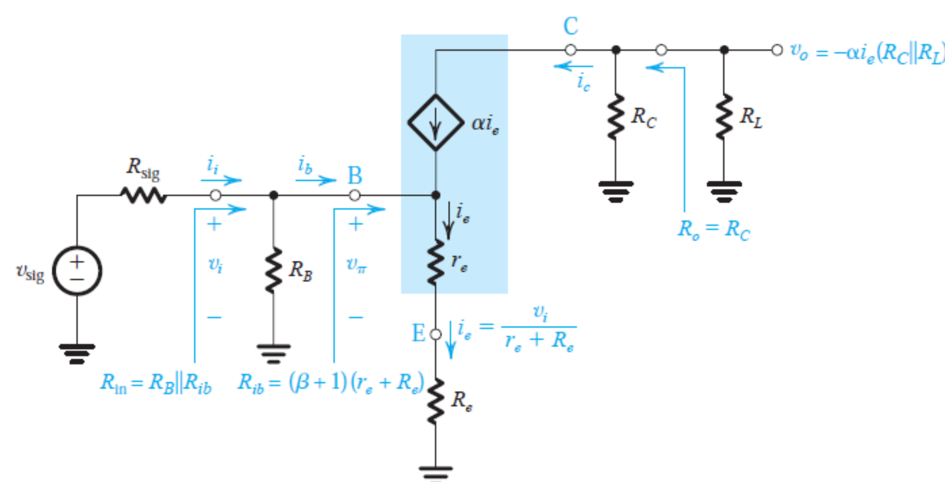


$$R_{in} = R_B \| r_\pi$$

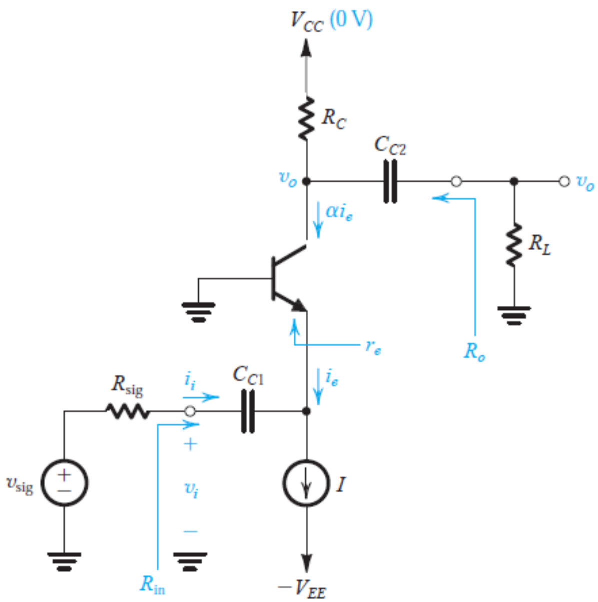


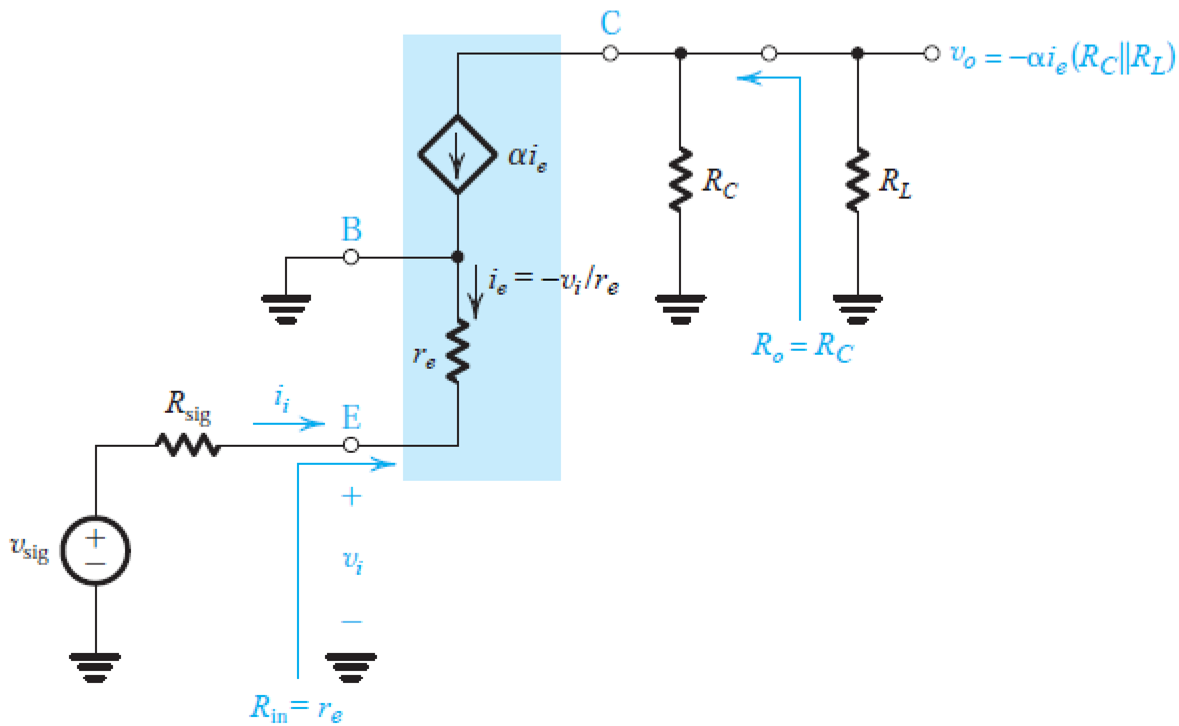
Common Emitter Amplifier with emitter resistance



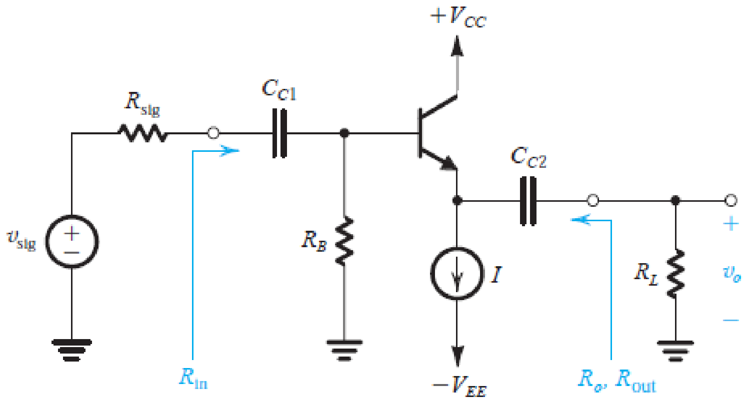


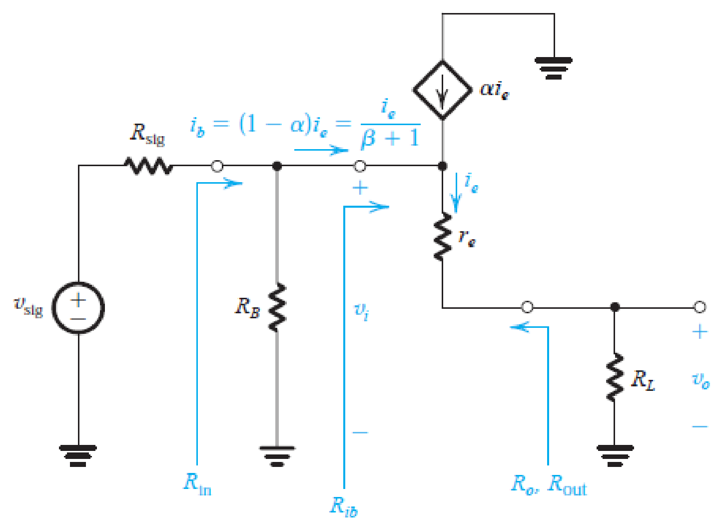
Common Base Amplifier

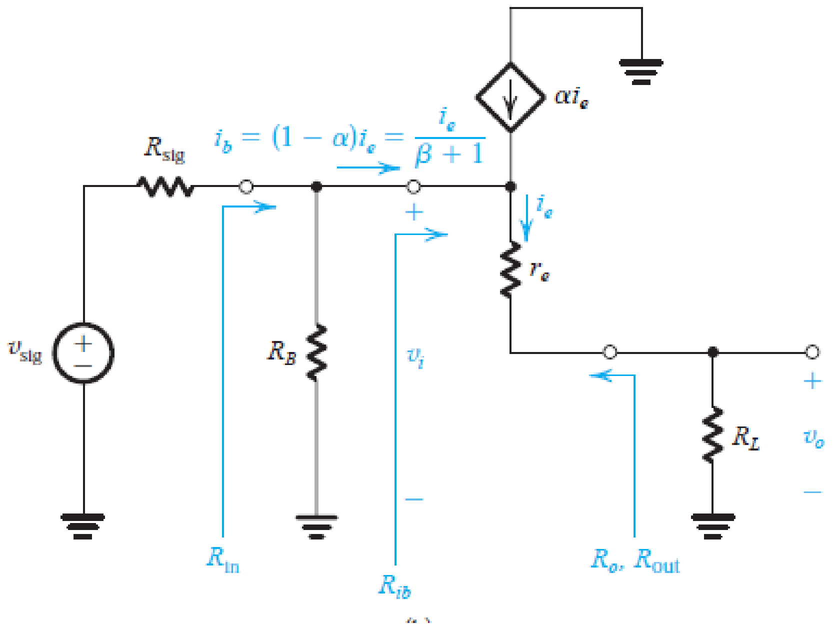




Common Collector Amplifier







select as large a value for R_B as permitted by dc bias considerations, since a low R_B could defeat the purpose of the emitter follower. To appreciate this point recall that the most important feature of the emitter follower is that it multiplies R_L by $(\beta+1)$, thus presenting a high input resistance to the signal source. Here, however, R_B appears in parallel with this increased resistance, resulting in

$$R_{in} = R_B \| (\beta+1)(r_e+R_L) \tag{6.114}$$

Thus ideally, R_B should be much larger than $(\beta+1)\ (r_e+R_L)$.