Electrical, Electronic and Digital Principles (EEDP)

Lecture 4

BJT Amplifiers

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6

BJT Amplifiers

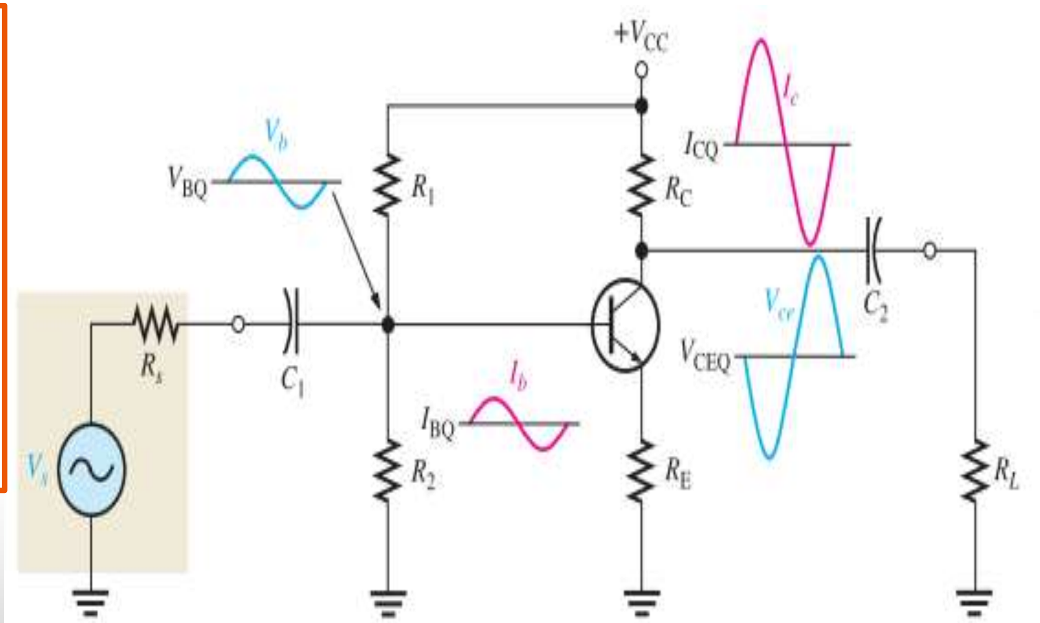
6–1 AMPLIFIER OPERATION

- ❖ The purpose of biasing is to establish a Q-point about which variations in current and voltage can occur in response to an ac input signal.
- ❖ In applications where small signal voltages must be amplified such as from an antenna or a microphone—variations about the Q-point are relatively small.
- ❖ Amplifiers designed to handle these small ac signals are often referred to as **small-signal amplifiers**.

The Linear Amplifier

A linear amplifier provides amplification of a signal without any distortion so that the output signal is an exact amplified replica of the input signal.

- ✓ The coupling capacitors block dc and thus prevent the internal source resistance, Rs, and the load resistance, RL, from changing the dc bias voltages at the base and collector.
- ✓ The capacitors ideally appear as shorts to the signal voltage.



Amplification in the ac Domain

- ✓ For an amplifying device, the output sinusoidal signal is greater than the input sinusoidal signal, or, stated another way, the output ac power is greater than the input ac power.

$\eta = P_o/P_i$ cannot be greater than 1.

In fact, a *conversion efficiency* is defined by $\eta = P_{o(ac)}/P_{i(dc)}$, where $P_{o(ac)}$ is the ac power to the load and $P_{i(dc)}$ is the dc power supplied.

- ✓ In other words, there is an "exchange" of dc power to the ac domain that permits establishing a higher output ac power.

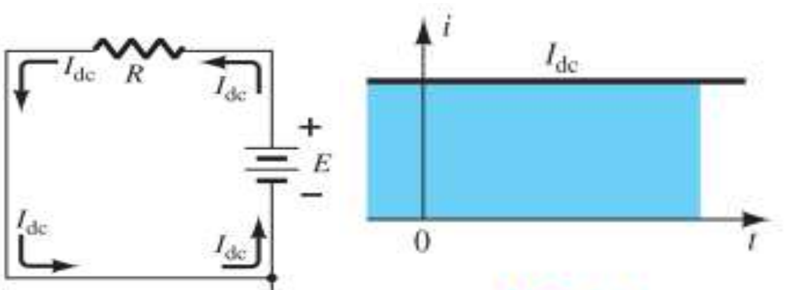


FIG. 5.1
Steady current established by a dc supply.

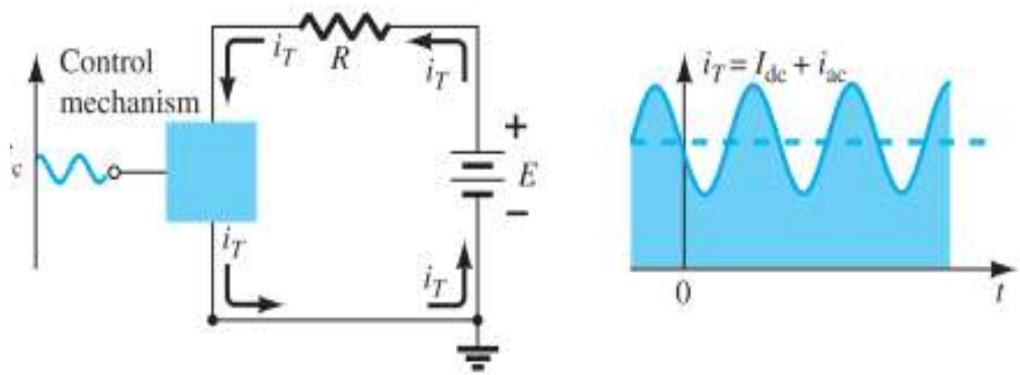


FIG. 5.2
Effect of a control element on the steady-state flow of the electrical system of Fig. 5.1.

Amplification in the ac Domain

$$i_{ac(p-p)} \gg i_{c(p-p)}$$

- ✓ The peak value of the oscillation in the output circuit is controlled by the established dc level.
- ✓ Any attempt to exceed the limit set by the dc level will result in a "clipping" (flattening)

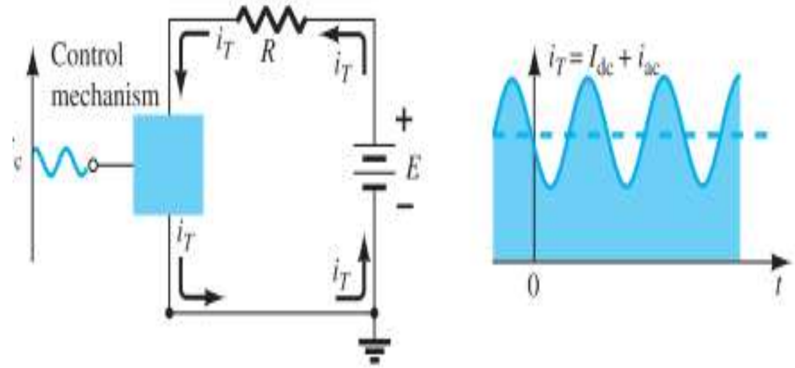


FIG. 5.2

Effect of a control element on the steady-state flow of the electrical system of Fig. 5.1.

The superposition theorem is applicable for the analysis and design of the dc and ac components of a BJT network, permitting the separation of the analysis of the dc and ac responses of the system.

- ➢ Once the dc analysis is complete, the ac response can be determined using a completely ac analysis.
- ➢ However, one of the components appearing in the ac analysis of BJT networks will be determined by the dc conditions(link between the two types of analysis).

6–2 TRANSISTOR AC MODELS

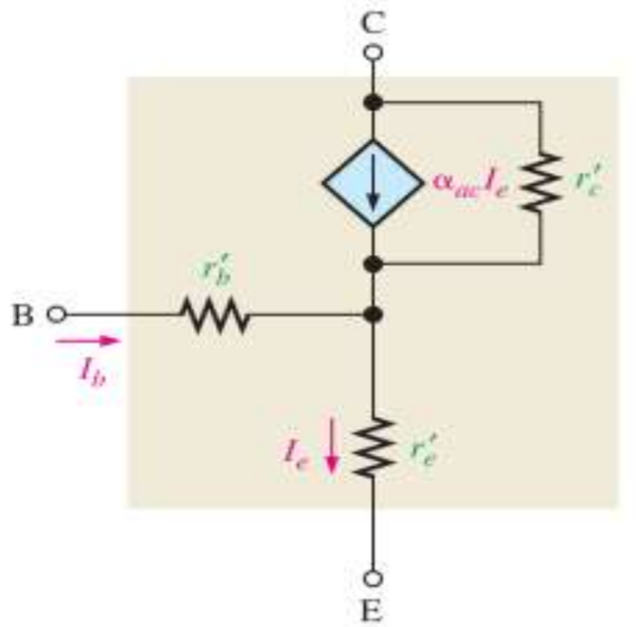
✓ To visualize the operation of a transistor in an amplifier circuit, it is often useful to represent the device by a model circuit.

A model is a combination of circuit elements, properly chosen, that best approximates the actual behavior of a semiconductor device under specific operating conditions.

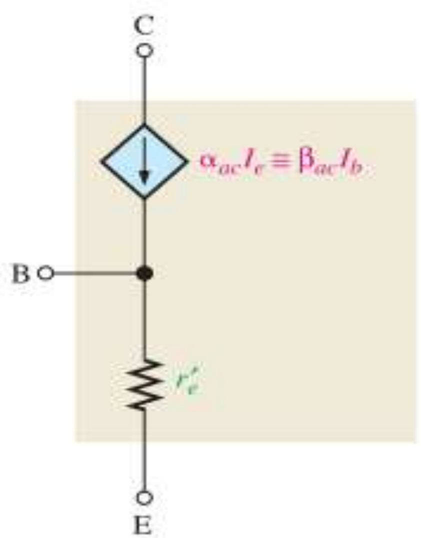
There are three models commonly used in the small-signal ac analysis of transistor

r_e model, the hybrid π model, and the hybrid equivalent model.

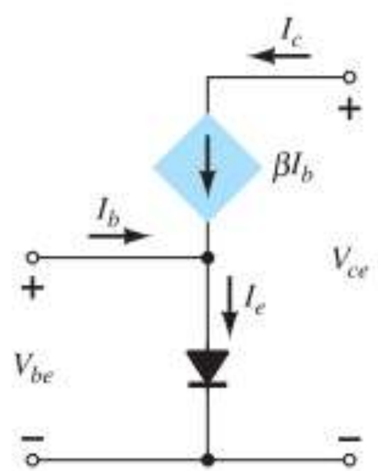
r-Parameter Transistor Model



(a) Generalized r-parameter model for a BJT



(b) Simplified r-parameter model for a BJT



r parameters.

r PARAMETER	DESCRIPTION
α_{ac}	ac alpha (I_c/I_e)
β_{ac}	ac beta (I_c/I_b)
r'_e	ac emitter resistance
r'_b	ac base resistance
r'_c	ac collector resistance

- ✓ The effect of the ac base resistance small enough to neglect
- ✓ (R_c or r_o) The ac collector resistance is usually hundreds of kilohms and can be replaced by an open.

Determining r'_e by a Formula

$$r'_e \cong \frac{25\text{ mV}}{I_E}$$

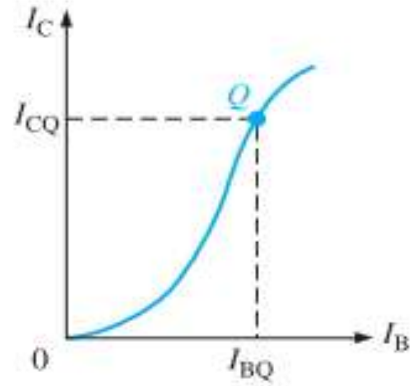
BE Forward diode resistance

Comparison of the AC Beta (β_{ac}) to the DC Beta (β_{DC})

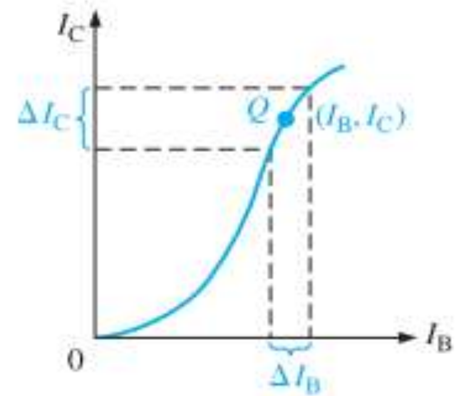
For a typical transistor, a graph of I_C versus I_B is nonlinear, as shown in Figure 6–7(a).

$$\beta_{DC} = I_C/I_B \text{ and } \beta_{ac} = \Delta I_C/\Delta I_B,$$

The values of these two quantities can differ slightly.

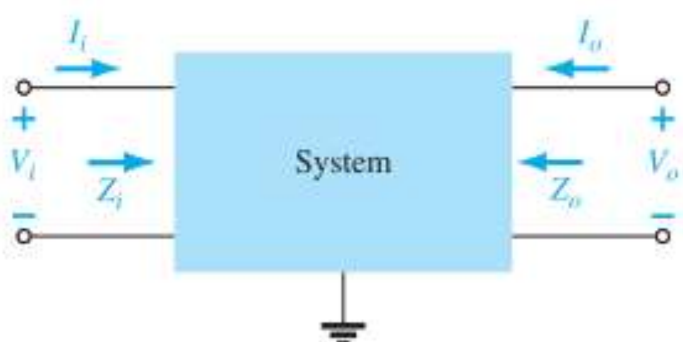


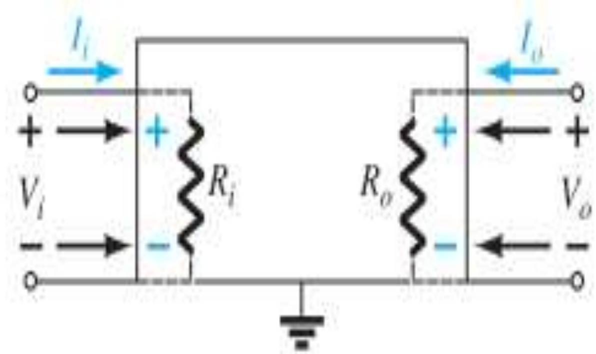
(a) $\beta_{DC} = I_C/I_B$ at Q-point



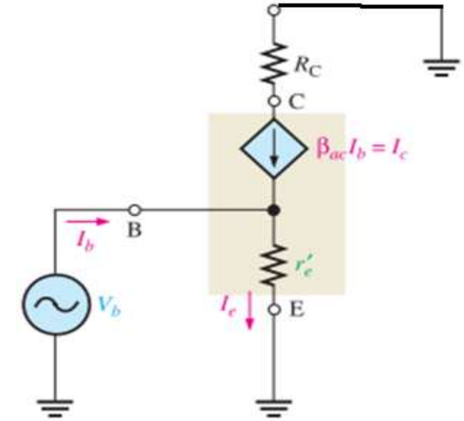
(b) $\beta_{ac} = \Delta I_C/\Delta I_B$

Input and output resistance of the BJT





Input Resistance at the Base $R_{in(base)}$



- use the simplified r-parameter model of the transistor.
- $Z_i = R_{in(base)}$

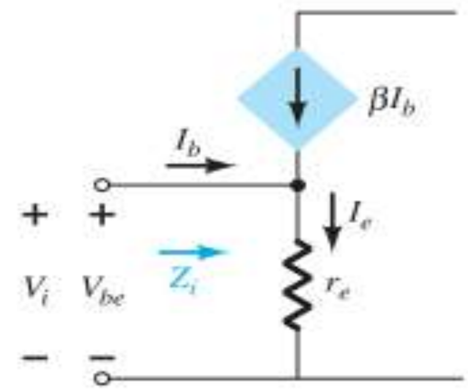
$$R_{in(base)} = \frac{V_{in}}{I_{in}} = \frac{V_b}{I_b}$$

$$Z_i = \frac{V_i}{I_b} = \frac{V_{be}}{I_b}$$

$$V_{be} = I_e r_e = (I_c + I_b) r_e = (\beta I_b + I_b) r_e$$
$$= (\beta + 1) I_b r_e$$

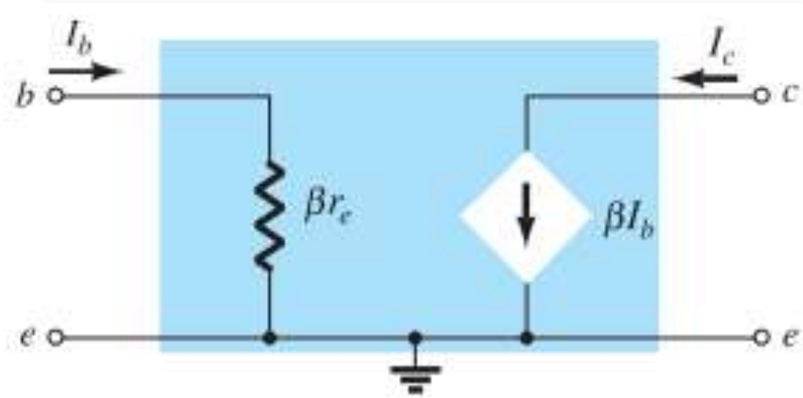
$$Z_i = \frac{V_{be}}{I_b} = \frac{(\beta + 1) I_b r_e}{I_b}$$

$$Z_i = (\beta + 1) r_e \cong \beta r_e$$



- ✓ now the input and output circuits are isolated and only linked by the controlled source
- ✓ This form is much easier to work with when analyzing networks.

Improved BJT equivalent circuit.



Output Characteristic

The output characteristic is not practically the same as assumed in the model with constant B curves

- ✓ Rather, they have a slope as shown In Fig. 5.15 that defines the output impedance of the device.
- ✓ The steeper the slope, the less the output impedance and the less ideal the transistor.
- ✓ In general, it is desirable to have large output impedances to avoid loading down the next stage of a design.

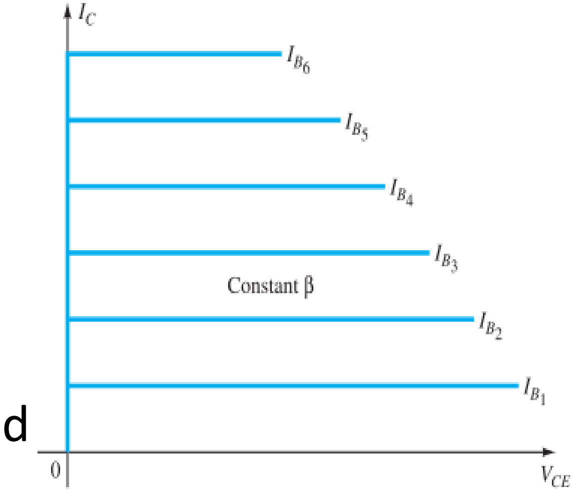


FIG. 5.11
Constant β characteristics.

$$r_o = \frac{\Delta V}{\Delta I} = \frac{V_A + V_{CE_Q}}{I_{C_Q}}$$

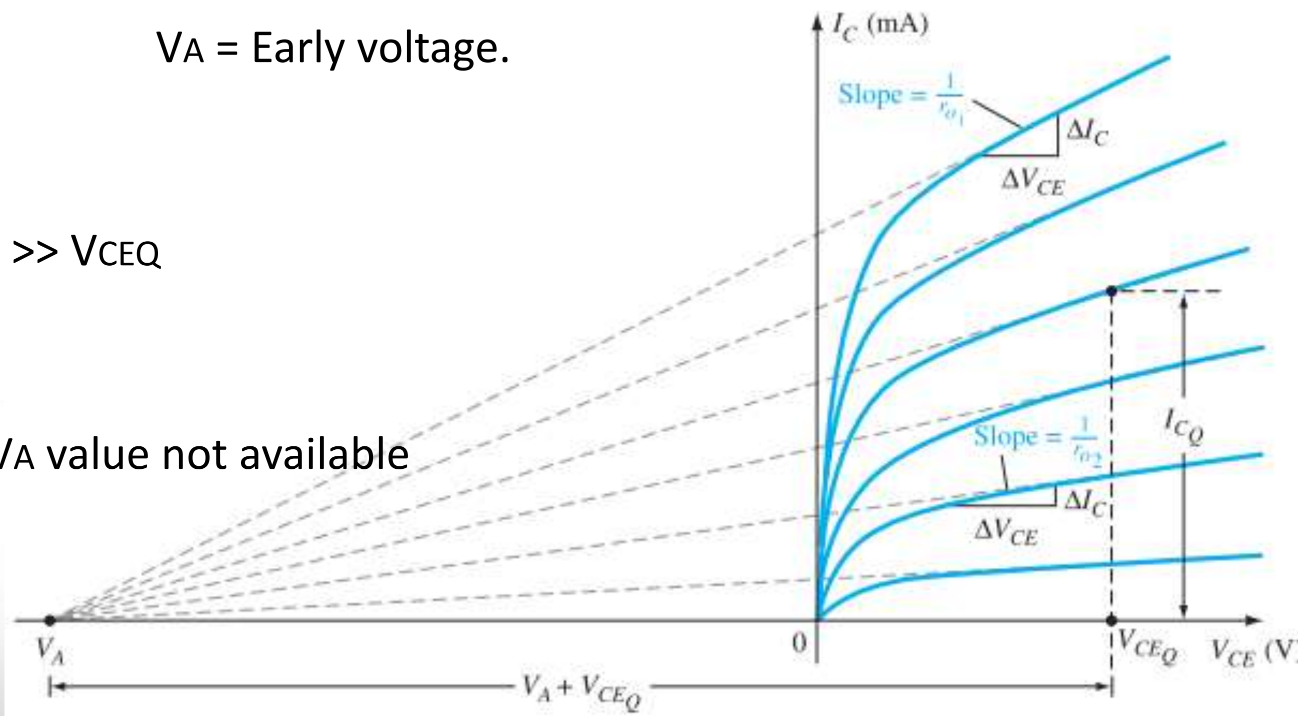
VA = Early voltage.

$$r_o \cong \frac{V_A}{I_{C_Q}}$$

VA >> VCEQ

$$r_o = \frac{\Delta V_{CE}}{\Delta I_C}$$

If VA value not available



Output Resistance

The output impedance will appear as a resistor in parallel with the output as shown in Fig. 5.16 .

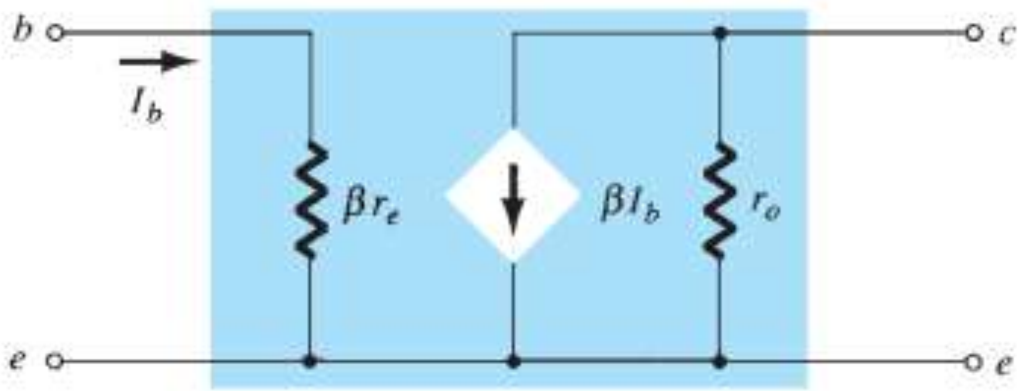
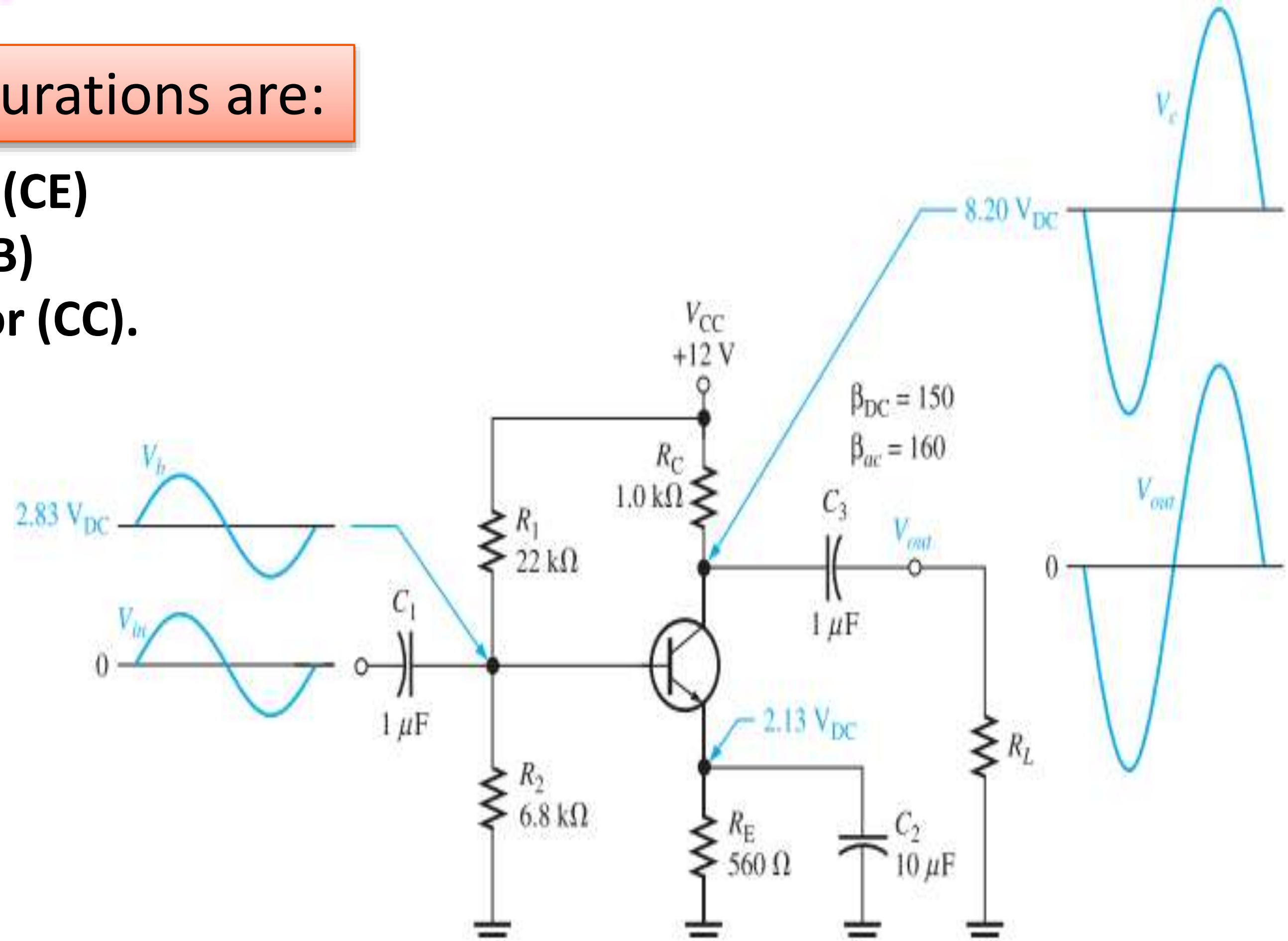


FIG. 5.16
r_e model for the common-emitter transistor configuration including effects of r_o.

6–3 THE COMMON-EMITTER AMPLIFIER

Three amplifier configurations are:

1. **The Common-Emitter (CE)**
2. **The Common-Base (CB)**
3. **The Common-Collector (CC).**



- ✓ The common-emitter (CE) configuration has the emitter as the common terminal, or ground, to an ac signal.
- ✓ CE amplifiers exhibit high voltage gain and high current gain.

6–3 The Common-Emitter Amplifier

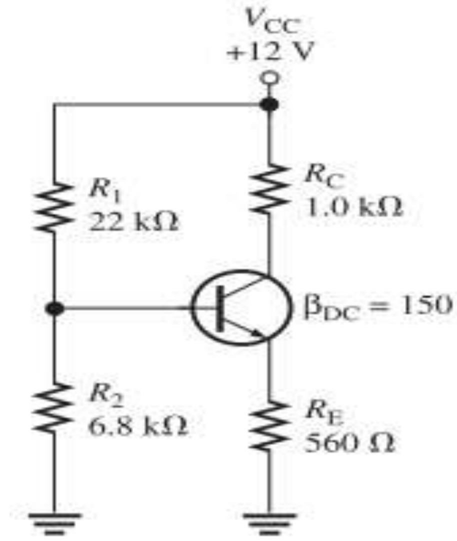
- The figure shows a CE amplifier with voltage-divider bias and coupling capacitors C1 and C3 on the input and output and a **bypass capacitor**, C2, from emitter to ground.
- The input signal, Vin, is capacitively coupled to the base terminal,
- The output signal, Vout, is capacitively coupled from the collector to the load.

✓ The amplified output is 180^{o} out of phase with the input

✓ There is no signal at the emitter because the bypass capacitor effectively shorts the emitter to ground at the signal frequency.

DC Analysis

- a dc equivalent circuit is developed by removing the coupling and bypass capacitors because they appear open as far as the dc bias is concerned.



$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{(6.8\,\text{k}\Omega)(22\,\text{k}\Omega)}{6.8\,\text{k}\Omega + 22\,\text{k}\Omega} = 5.19\,\text{k}\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{6.8\,\text{k}\Omega}{6.8\,\text{k}\Omega + 22\,\text{k}\Omega}\right)12\text{ V} = 2.83\text{ V}$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{2.83\text{ V} - 0.7\text{ V}}{560\,\Omega + 34.6\,\Omega} = 3.58\text{ mA}$$

$$I_C \cong I_E = 3.58\text{ mA}$$

$$V_E = I_E R_E = (3.58\text{ mA})(560\,\Omega) = 2\text{ V}$$

$$V_B = V_E + 0.7\text{ V} = 2.7\text{ V}$$

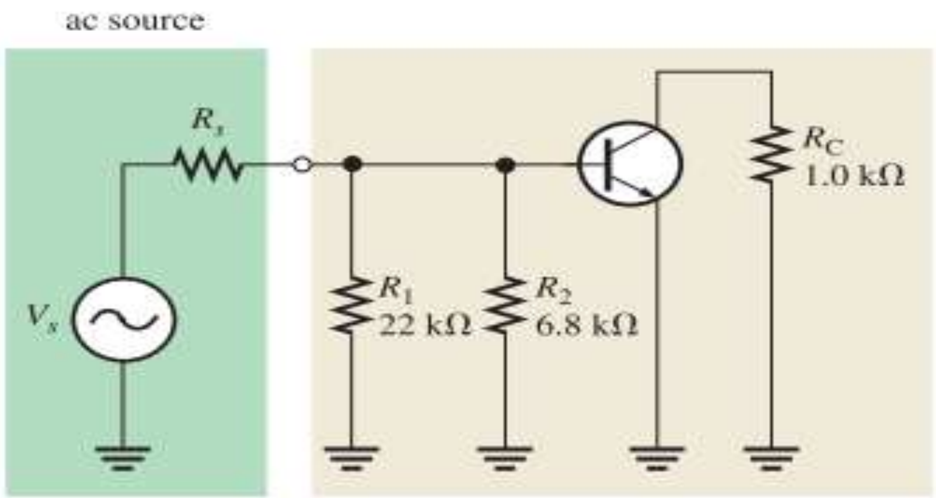
$$V_C = V_{CC} - I_C R_C = 12\text{ V} - (3.58\text{ mA})(1.0\,\text{k}\Omega) = 8.42\text{ V}$$

$$V_{CE} = V_C - V_E = 8.42\text{ V} - 2\text{ V} = 6.42\text{ V}$$

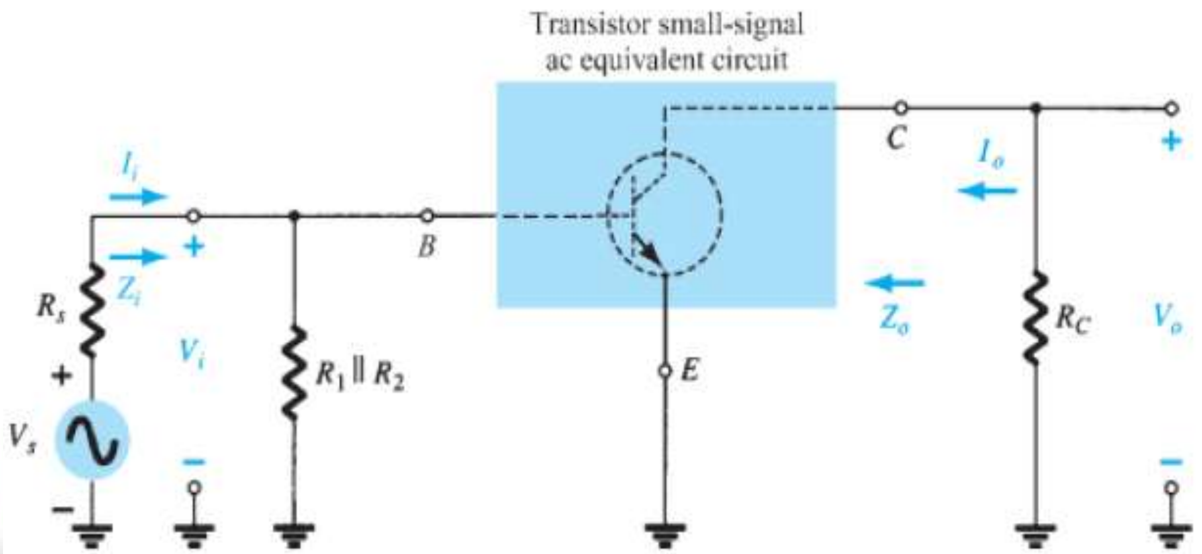
AC Analysis

an ac equivalent circuit is developed as

1. The capacitors C_1, C_2, and C_3 are replaced by effective shorts because their values are selected so that X_C is negligible at the signal frequency and can be considered to be 0 Ω.
2. The dc source is replaced by ground.



(b) With an input signal voltage



an ac equivalent circuit using the model

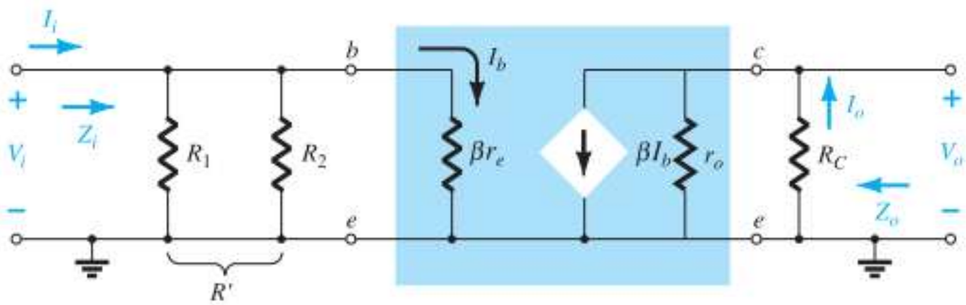
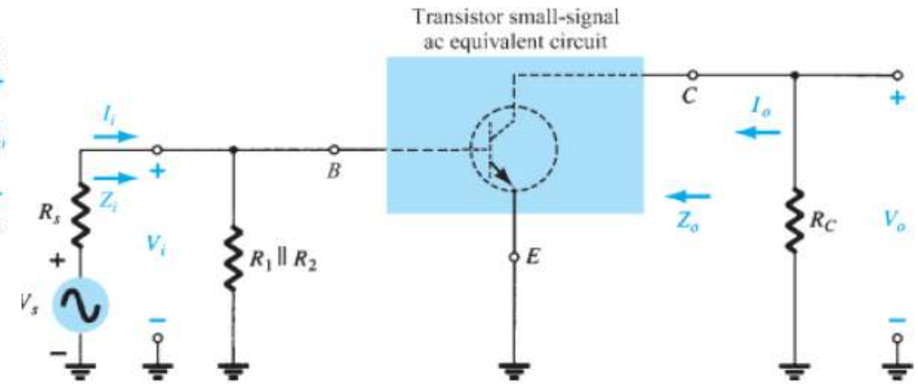


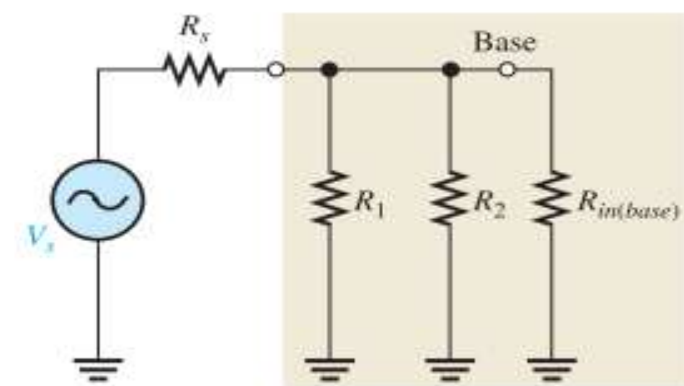
FIG. 5.27
Substituting the r_e equivalent circuit into the ac equivalent network of Fig. 5.26.

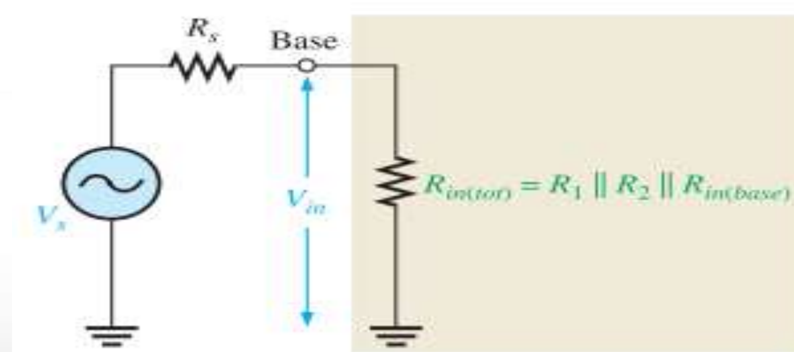


Total Input Resistance

is the resistance "seen" by an ac source connected to the input

$$R_{in(tot)} = R_1 \| R_2 \| R_{in(base)}$$

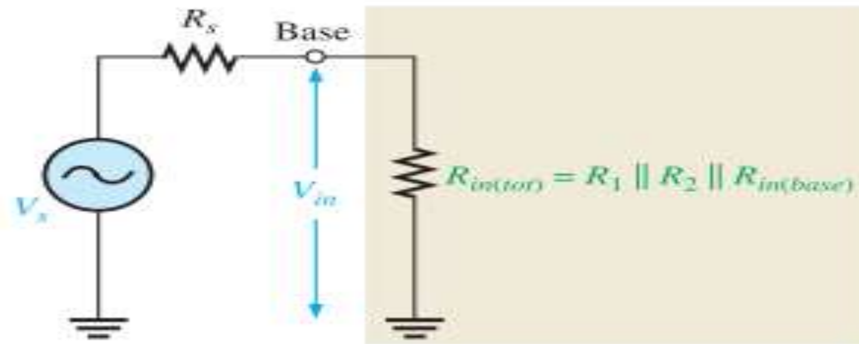




Signal (AC) Voltage at the Base

Two factors for determining the actual signal voltage at the base:

1. The source resistance (Rs),
2. The ac input resistance at the base of the transistor $R_{in(base)}$



✓ The signal voltage at the base of the transistor is found by the voltage-divider:

$$V_b = \left(\frac{R_{in(tot)}}{R_s + R_{in(tot)}}\right)V_s$$

A high value of input resistance is desirable so that the amplifier will not excessively load the signal source.

If $R_s \ll R_{in(tot)}$, then $V_b \cong V_s$ where V_b is the input voltage, V_{in}, to the amplifier.

Total Output Resistance

- The output resistance of any system is defined as the resistance Ro (Zo) determined when Vi = 0.

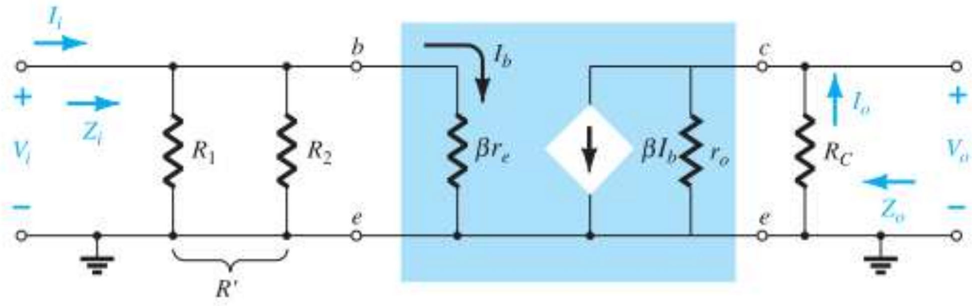
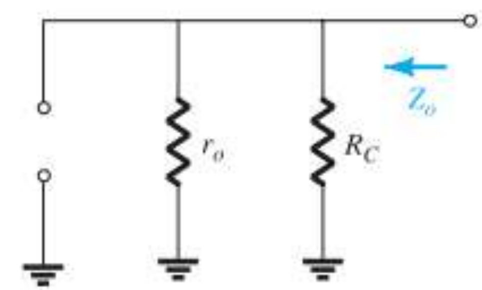


FIG. 5.27
Substituting the r_e equivalent circuit into the ac equivalent network of Fig. 5.26.

when Vi =0, Ii = Ib = 0, resulting in an open-circuit equivalence for the current source.



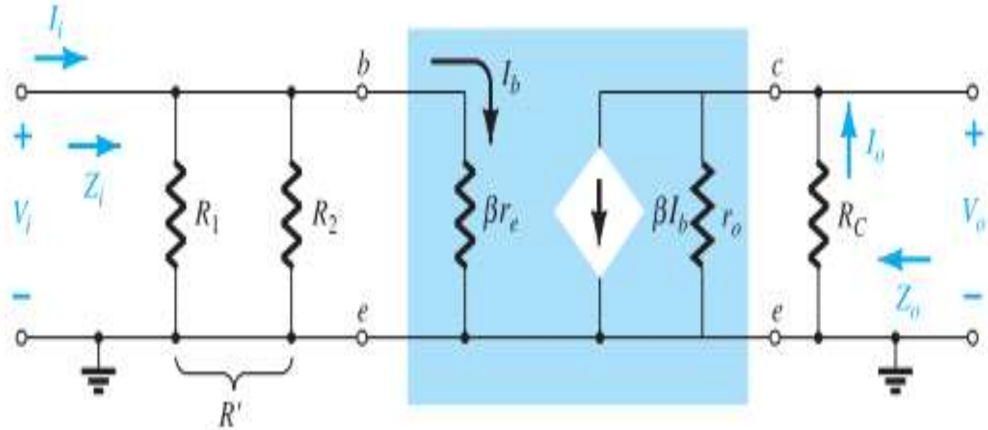
$$Z_o = R_C \| r_o$$

If $r_o \geq 10R_C$, the approximation $R_C \| r_o \cong R_C$ is frequently applied, and

$$Z_o \cong R_C \qquad _{r_o \geq 10R_C}$$

Voltage Gain

The gain is the ratio of ac output voltage at the collector (Vc) to ac input voltage at the base (Vb).



$$V_o = -(\beta I_b)(R_C \| r_o)$$

$$I_b = \frac{V_i}{\beta r_e}$$

$$\frac{V_c}{V_b}$$

the voltage gain from base to collector.

$$V_o = -\beta\left(\frac{V_i}{\beta r_e}\right)(R_C \| r_o)$$

$$A_v = \frac{V_o}{V_i} = \frac{-R_C \| r_o}{r_e}$$

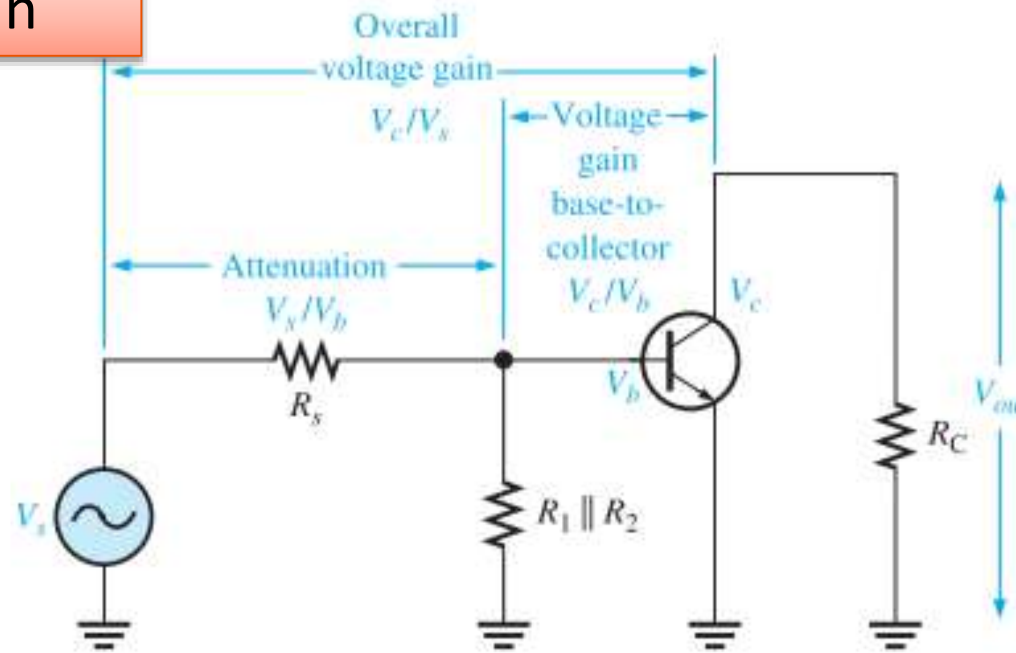
Phase Relationship The negative sign of Eq. (5.15) reveals a 180° phase shift between V_o and V_i.

For $r_o \geq 10R_C$,

$$A_v = \frac{V_o}{V_i} \cong -\frac{R_C}{r_e} \quad r_o \geq 10R_C$$

To get the overall gain of the amplifier from the source voltage to collector, the attenuation of the input circuit must be included

Attenuation and the Overall Gain



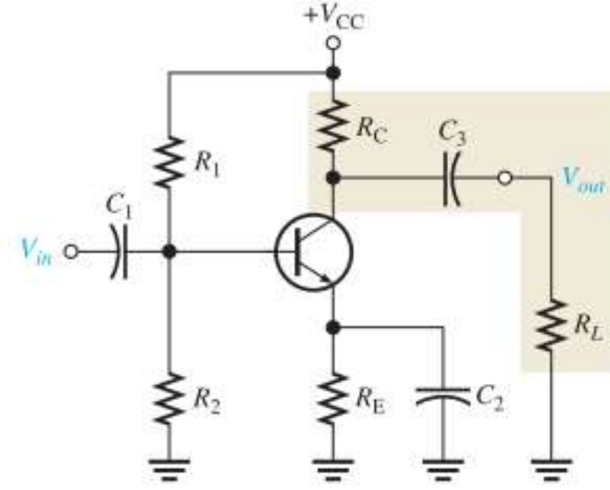
$$\text{Attenuation} = \frac{V_s}{V_b} = \frac{R_s + R_{in(tot)}}{R_{in(tot)}}$$

Overall Voltage Gain

$$A'_v = \left(\frac{V_c}{V_b}\right)\left(\frac{V_b}{V_s}\right) = \frac{V_c}{V_s}$$

Effect of a Load on the Voltage Gain

When a resistor, RL, is connected to the output through the coupling capacitor C3, as shown in Figure 6–17(a), it creates a load on the circuit.

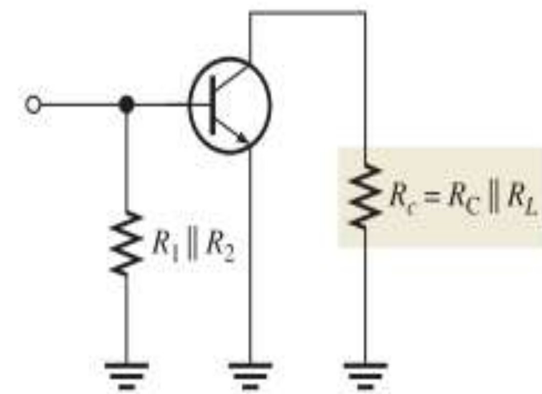


(a) Complete amplifier

$$R_c = \frac{R_C R_L}{R_C + R_L}$$

Replacing R_C with R_c in the voltage gain expression gives

$$A_v = \frac{R_c}{r'_e}$$



(b) AC equivalent ($X_{C1} = X_{C2} = X_{C3} = 0$)

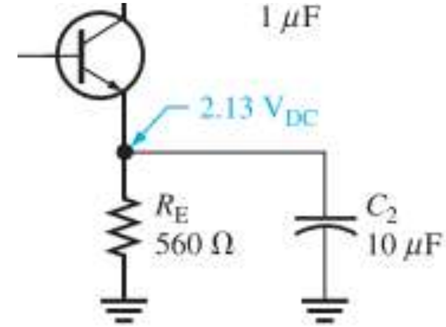
When $R_c < R_C$ because of R_L, the voltage gain is reduced.

However, if RL>> RC then:

$$R_c \cong R_C$$

and the load has very little effect on the gain.

Effect of the Emitter Bypass Capacitor on Voltage Gain



- ✓ The emitter bypass capacitor, which is C2 in Figure , provides an effective short to the ac signal around the emitter resistor, thus **keeping the emitter at ac ground**

- ➢ The value of the bypass capacitor must be large enough so that its reactance over the frequency range of the amplifier is very small (Ideally 0 ohms) compared to RE.
- ➢ A good rule-of-thumb is that the capacitive reactance, XC, of the bypass capacitor should be at least 10 times smaller than RE at the minimum frequency for which the amplifier must operate

EXAMPLE 6–4

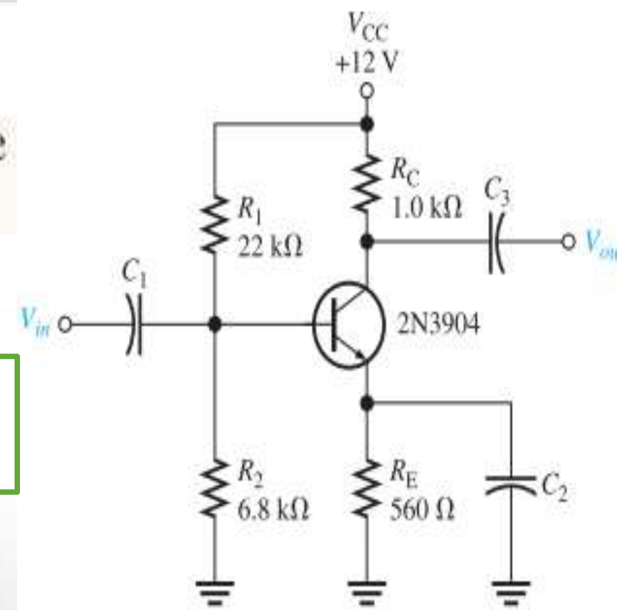
$$10X_C \leq R_E$$

Select a minimum value for the emitter bypass capacitor, C_2, in Figure 6–16 if the amplifier must operate over a frequency range from 200 Hz to 10 kHz.

$$X_{C2} = \frac{R_E}{10} = \frac{560\ \Omega}{10} = 56\ \Omega$$

Determine the capacitance value at the minimum frequency of 200 Hz as follows

$$C_2 = \frac{1}{2\pi f X_{C2}} = \frac{1}{2\pi(200\text{ Hz})(56\ \Omega)} = \mathbf{14.2\ \mu F}$$



Effect of the Emitter Bypass Capacitor on Voltage Gain

Voltage Gain Without the Bypass Capacitor

- ✓ **Without** the bypass capacitor, the emitter is no longer at ac ground.
- ✓ Instead, RE is seen by the ac signal between the emitter and ground and effectively adds to re’ in the voltage gain formula and reduces the gain:

$$A_v = \frac{R_C}{r'_e + R_E}$$

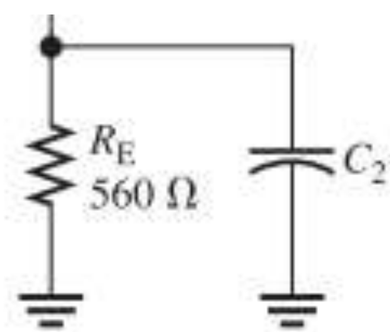
Proof (Page 288- Boylstad)

EXAMPLE 6–5 Calculate the base-to-collector voltage gain of the amplifier in Figure 6–16 both without and with an emitter bypass capacitor if there is no load resistor.

$$r'_e = 6.58\ \Omega$$

Without C2, the gain is

$$A_v = \frac{R_C}{r'_e + R_E} = \frac{1.0\,\text{k}\Omega}{567\ \Omega} = 1.76$$



With C2, the gain is

$$A_v = \frac{R_C}{r'_e} = \frac{1.0\,\text{k}\Omega}{6.58\ \Omega} = 152$$

Stability of the Voltage Gain

- ✓ Stability is a measure of how well an amplifier maintains its design values over changes in temperature or for a transistor with a different B.
- ✓ Although bypassing RE does produce the maximum voltage gain, there is a stability problem because the ac voltage gain is dependent on r_e

$$A_v = R_C / r'_e.$$

- ✓ Since r_e depends on I_E and on temperature, the gain is unstable over changes in temperature
- ✓ With no bypass capacitor, the gain is decreased because R_E is now in the ac circuit and the gain became:

$$A_v = \frac{R_C}{r'_e + R_E} \cong \frac{R_C}{R_E}$$

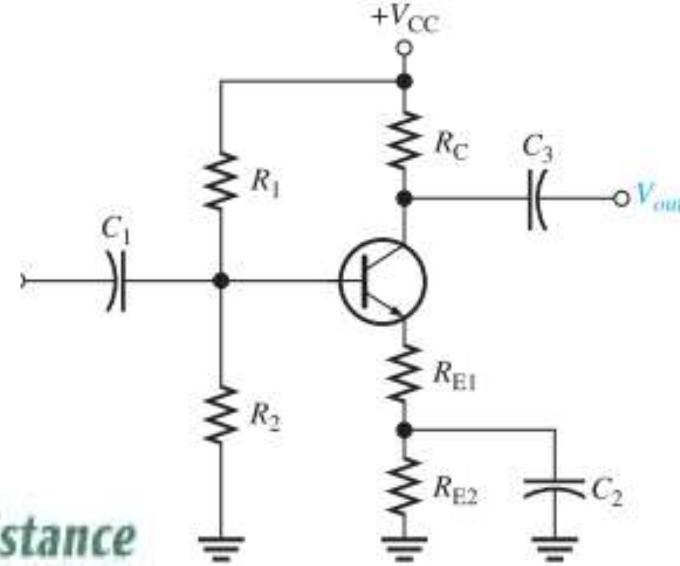
➢ **How to minimize the effect of r_e without reducing the voltage gain to its minimum value.**

Swamping

Swamping RE effect on the Gain

- Swamping is a compromise between having a bypass capacitor across RE and having no bypass capacitor at all.
- In a swamped amplifier, RE is partially bypassed so that a reasonable gain can be achieved, and the effect of re on the gain is greatly reduced or eliminated.

$$A_v = \frac{R_C}{r'_e + R_{E1}}$$



- If RE1 is at least ten times larger than re then the effect of re is minimized and the approximate voltage gain for the swamped amplifier is:

$$A_v \cong \frac{R_C}{R_{E1}}$$

The Effect of Swamping on the Amplifier's Input Resistance

$$R_{in(base)} = \beta_{ac}(r'_e + R_{E1})$$