Department of Biomedical Engineering
Bio-Medical circuits and electronics / Third stage
Lecturer: Dr. Hussam Jawad Kadhim AL_Janabi
Email: hussam.jawad@uomus.edu.iq

Lecture One

AMPLIFIER OPERATION

1.1 AMPLIFIER OPERATION

The biasing of a transistor is purely a dc 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.

After completing this lecture, you should be able to

- Describe amplifier operation
- Distinguish ac quantities from dc quantities
- Graphically illustrate amplifier operation
- Analyze ac load line operation

AC Quantities

The dc quantities were identified by nonitalic uppercase (capital) subscripts such as I_{C}, I_{E}, V_{C}, and V_{CE}. Lowercase italic subscripts are used to indicate ac quantities of rms, peak, and peak-to-peak currents and voltages: for example, I_c, I_e, I_b, V_c, and Vce (rms values are assumed unless otherwise stated). Instantaneous quantities are represented by both lowercase letters and subscripts such as i_c, i_e, i_b, and v_{ce}. Figure 1.1 illustrates these quantities for a specific voltage waveform.

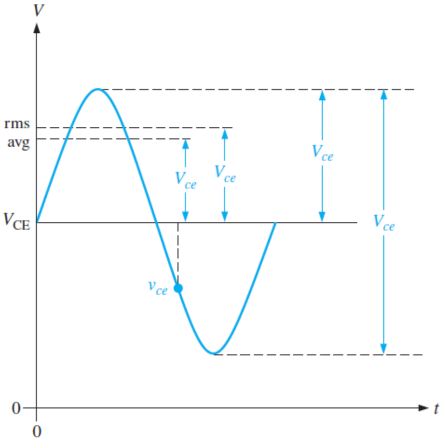


Figure 1.1

1.2 TRANSISTOR AC MODELS

A transistor model circuit uses various internal transistor parameters to represent its operation. Transistor models are described in this section based on resistance or *r* parameters.

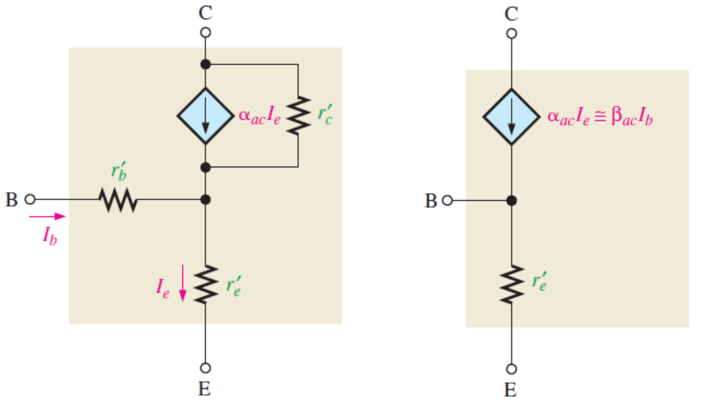
r Parameters

The five *r* parameters commonly used for BJTs are given in Table 1.1. The italic lowercase letter *r* with a prime denotes resistances internal to the transistor.

r PARAMETER DESCRIPTION	PARAMETER DESCRIPTION
α_{ac}	ac alpha (Ic/Ie)
β_{ac}	ac beta (Ic/Ib)
r'_e	ac emitter resistance
r'_b	ac base resistance
r'_c	ac collector resistance

r-Parameter Transistor Model

An ***r*-parameter** model for a BJT is shown in Figure 1.2 (a). For most general analysis work, it can be simplified as follows: The effect of the ac base resistance (r'_b) is usually small enough to neglect, so it can be replaced by a short. The ac collector resistance (r'_c) is usually several hundred kilohms and can be replaced by an open. The resulting simplified *r*-parameter equivalent circuit is shown in Figure 1.2(b). The interpretation of this model circuit in terms of a transistor's ac operation is as follows: A resistance (r'_e) appears between the emitter and base terminals. This is the resistance "seen" looking into the emitter of a forward-biased transistor. The collector effectively acts as a dependent current source of or, equivalently, represented by the diamond-shaped symbol. These factors are shown with a transistor symbol in Figure 1.3.



(a) Generalized *r*-parameter model for a BJT (b) Simplified *r*-parameter model for a BJT

Figure 1.2

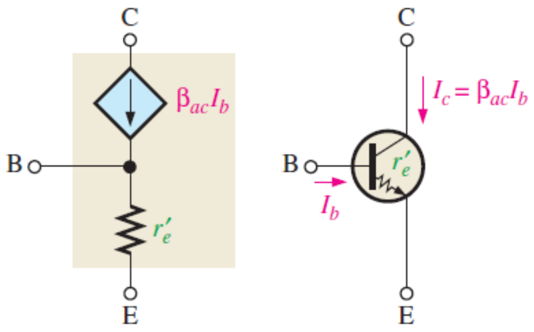


Figure 1.3

$$r'_e \cong \frac{25\text{ mV}}{I_E}$$, at temperature of 20°C.

EXAMPLE 1.1: Determine the r'_e of a transistor that is operating with a dc emitter current of 2 mA.

Solution

$$r'_e = \frac{25mV}{I_E} = \frac{25mV}{2mA} = 12.5\Omega$$

1.3 THE COMMON-EMITTER AMPLIFIER

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.

Figure 1.4 shows a **common-emitter** amplifier with voltage-divider bias and coupling capacitors *C*1 and *C*3 on the input and output, and a bypass capacitor, *C*2, 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° out of phase with the input. Because the ac signal is applied to the base terminal as the input and taken from the collector terminal as the output, the emitter is common to both the input and output signals. There is no signal at the emitter because the bypass capacitor effectively shorts the emitter to ground at the signal frequency. All amplifiers have a combination of both ac and dc operation, which must be considered, but keep in mind that the common-emitter designation refers to the ac operation.

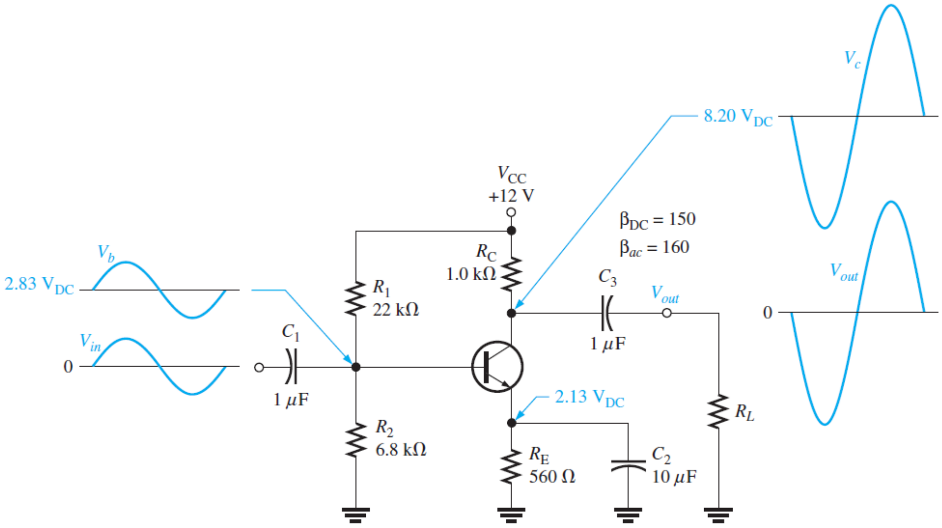


Figure 1.4: A common-emitter amplifier.

DC Analysis

To analyze the amplifier in Figure 1.4, the dc bias values must first be determined.

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

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

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

$$I_C \cong I_E = 3.58\ mA$$

$$V_E = I_E R_E = (3.58\ mA)(560\ \Omega) = 2\ V$$

$$V_B = V_E + 0.7\ V = 2.7\ V$$

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

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

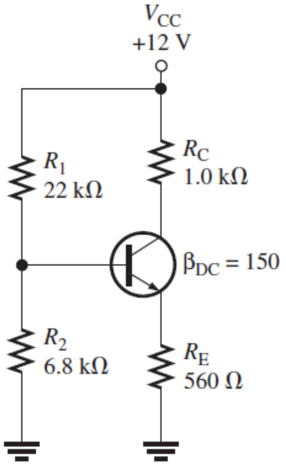


Figure 1.5

AC Analysis

To analyze the ac signal operation of an amplifier, an ac equivalent circuit is developed as follows:

1. The capacitors $C1$, $C2$, and $C3$ 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 0Ω
2. The dc source is replaced by ground

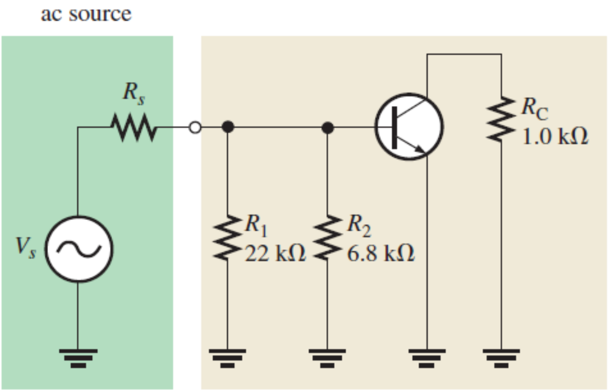


Figure 1.6

The amplifier in Figure 1.6 is called a common-emitter amplifier because the bypass capacitor *C*2 keeps the emitter at ac ground. Ground is the common point in the circuit.

Signal (AC) Voltage at the Base:

Three factors must be taken into account in determining the actual signal voltage at the base. These are the *source resistance* (*Rs*), the *bias resistance (R1//R2),* and the *ac input resistance* at the base of the transistor (*Rin*(*base*)). This is illustrated in Figure 1.7 (a) and is simplified by combining *R*1, *R*2, and *Rin*(*base*) in parallel to get the total **input resistance**, *Rin*(*tot*), which is the resistance “seen” by an ac source connected to the input, as shown in Figure 6.7(b).

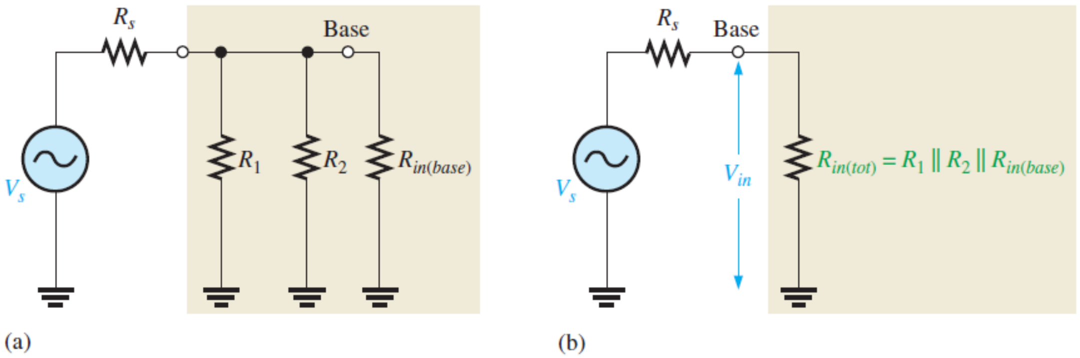


Figure 1.7: AC equivalent of the base circuit.

The total input resistance is expressed by the following formula:

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

As you can see in the figure, the source voltage, *Vs*, is divided down by *Rs* (source resistance) and *Rin*(*tot*) so that the ***signal voltage at the base*** of the transistor is found by the voltage- divider formula as follows:

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

Input Resistance at the Base: To develop an expression for the ac input resistance looking in at the base, use the simplified r-parameter model of the transistor. Figure 1.8 shows the transistor model connected to the external collector resistor, R_C. The input resistance looking in at the base is

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

The base voltage is

$$V_b = I_e r'_e$$

and since $I_e \cong I_c$,

$$I_b \cong \frac{I_e}{\beta_{ac}}$$

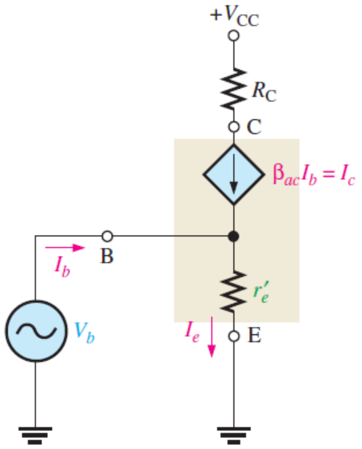


Figure 1.8

Substituting for V_b and I_b,

$$R_{in(base)} = \frac{V_b}{I_b} = \frac{I_e r'_e}{I_e/\beta_{ac}}$$

Cancelling *Ie*,

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

Output Resistance: The output resistance of the common-emitter amplifier is the resistance looking in at the collector and is approximately equal to the collector resistor.

$$\boldsymbol{R_{out} \cong R_C}$$

EXAMPLE 1.2: Determine the signal voltage at the base of the transistor in Figure 1.9. This circuit is the ac equivalent of the amplifier in Figure 1.4 with a 10 mV rms, 300Ω signal source. I_E was previously found to be 3.80 mA.

Solution

First, determine the ac emitter resistance

$$r'_e \approx \frac{25\ mV}{I_E} = \frac{25\ mV}{3.80\ mA} = 6.58\Omega$$

Then

$$Rin(base) = \beta_{ac} r'_e = 160(6.58\ \Omega) = 1.05\ \text{k}\Omega$$

Next, determine the total input resistance viewed from the source.

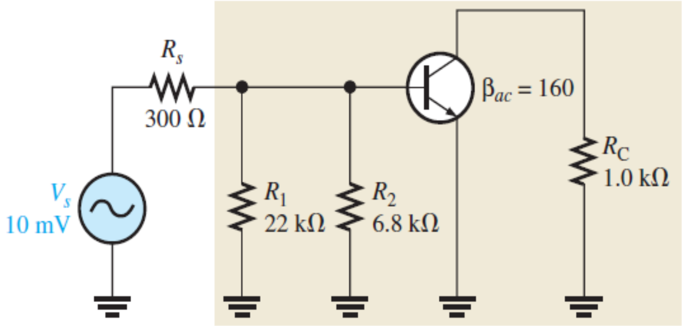


Figure 1.9

$$R_{in(tot)} = R_1 \,//\, R_2 \,//\, R_{in(base)} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\mathbf{22k\Omega}}+\frac{\mathbf{1}}{\mathbf{6.8k\Omega}}+\frac{\mathbf{1}}{\mathbf{1.05k\Omega}}} = 873\Omega$$

The source voltage is divided down by R_s and $R_{in(tot)}$, so the signal voltage at the base is the voltage across $R_{in(tot)}$.

$$V_b = \left(\frac{R_{in(tot)}}{R_s+R_{in(tot)}}\right) V_s = \left(\frac{873\Omega}{1173\Omega}\right) 10\text{mV} = 7.44\ \text{mV}$$

As you can see, there is significant attenuation (reduction) of the source voltage due to the source resistance and amplifier's input resistance combining to act as a voltage divider.

Voltage Gain

The ac voltage gain expression for the common-emitter amplifier is developed using the model circuit in Figure 1.10. The gain is the ratio of ac output voltage at the collector (Vc) to ac input voltage at the base (Vb).

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_c}{V_b}$$

Notice in the figure that $Vc = \alpha_{ac} I_e R_C = I_e R_C$ and $V_b = I_e r'_e$. *Therefore,*

$$A_v = \frac{I_e R_C}{I_e r'_e}$$

The Ie terms cancel, so

$$\boldsymbol{A_v = \frac{R_C}{r'_e}}$$

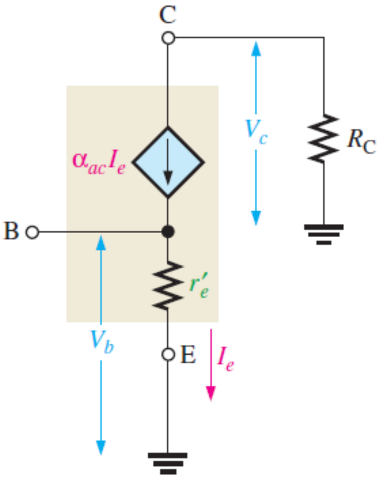


Figure 1. 10

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

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

This attenuation is produced by the source resistance and total input resistance of the amplifier acting as a voltage divider.

The overall voltage gain of the amplifier $A'v$,, is the voltage gain from base to collector, V_c/V_b, times the reciprocal of the attenuation, V_b/V_s.

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

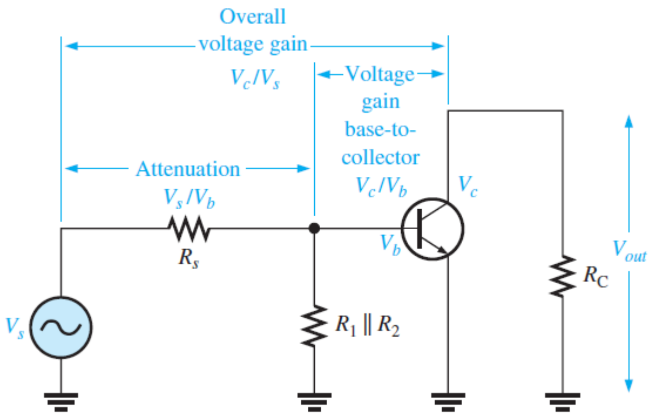


Figure 1. 11

Effect of the Emitter Bypass Capacitor on Voltage Gain

The emitter **bypass capacitor**, which is $C2$ in Figure 1.4, provides an effective short to the ac signal around the emitter resistor. With the bypass capacitor, the gain of a given amplifier is maximum and equal to R_C / r'_e.

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 0Ω) compared to R_E. *The bypass capacitor should be at least 10 times smaller than R_E at the minimum frequency for which the amplifier must operate.*

EXAMPLE 1.3: Select a minimum value for the emitter bypass capacitor, C_2, in Figure 1.12 if the amplifier must operate over a frequency range from 200 Hz to 10kHz.

Solution

The X_C of the bypass capacitor, C_2, should be at least ten times less than R_E.

$$X_C = \frac{R_E}{10} = \frac{560\Omega}{10} = 56\Omega$$

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

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

This is the minimum value for the bypass capacitor for this circuit. You can always use a larger value, although cost and physical size may impose limitations.

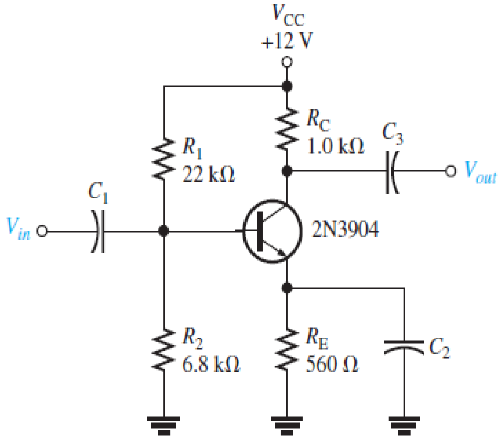


Figure 1. 12

Voltage Gain Without the Bypass Capacitor

Without the bypass capacitor, the emitter is no longer at ac ground.

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

The effect of R_E is to decrease the ac voltage gain.

EXAMPLE 1.4: Calculate the base-to-collector voltage gain of the amplifier in Figure 1.12, both without and with an emitter bypass capacitor, if there is no load resistor. Assume $r'_e = 6.58\ \Omega$

Solution

Without C_2, the gain is $Av = \frac{R_C}{r'e + R_E} = \frac{1\ k\Omega}{6.58+560} = \frac{1\ k\Omega}{567\ \Omega} = 1.76$

With C_2, the gain is $Av = \frac{R_C}{r'e+} = \frac{1\ k\Omega}{6.58} = 152$

As you can see, the bypass capacitor makes quite a difference.

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 β. Although bypassing RE does produce the maximum voltage gain, there is a stability problem because the ac voltage gain is dependent on r'_e. Also, r'_e depends on I_E and on temperature. This causes the gain to be unstable over changes in temperature because when r'_e increases, the gain decreases and vice versa.

Swamping r'_e to Stabilize the Voltage Gain

Swamping is a method used to minimize the effect of r'_e without reducing the voltage gain to its minimum value. Swamping is, in effect, a compromise between having a bypass capacitor across R_E and having no bypass capacitor at all. The total external emitter resistance, R_E, is formed with two separate emitter resistors, R_{E1} and R_{E2}. One of the resistors, R_{E2}, is bypassed and the other is not.

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

EXAMPLE 1.5: Determine the voltage gain of the swamped amplifier in Figure 1.13. Assume that the bypass capacitor has a negligible reactance for the frequency at which the amplifier is operated. Assume $r'_e = 20\ \Omega$**.**

Solution

R_{E2} is bypassed by C_2. R_{E1} is more than ten times so the approximate voltage gain is

$$Av = \frac{R_C}{R_{E1}} = \frac{3.3\ k\Omega}{330\ k\Omega} = 10$$

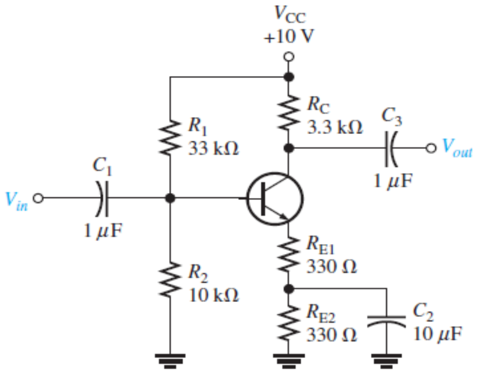


Figure 1. 13

EXAMPLE 1.6: For the amplifier in Figure 1.14,

(a) Determine the dc collector voltage.

(b) Determine the ac collector voltage.

(c) Draw the total output voltage waveform.

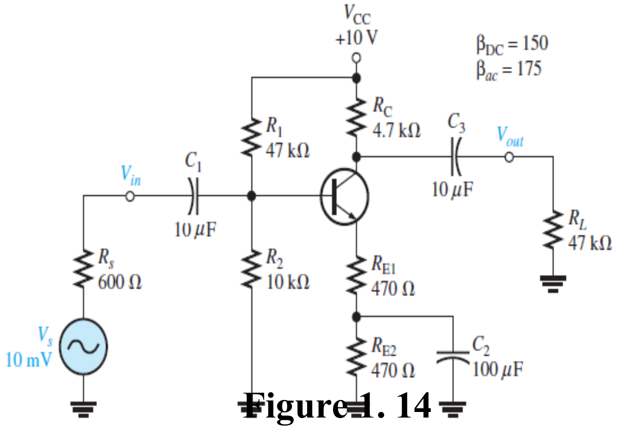


Figure 1. 14

Solution

(a) Determine the dc bias values using the dc equivalent circuit in Figure 1.15.

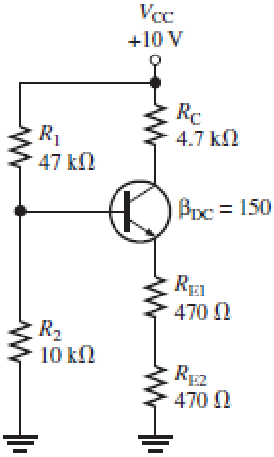


Figure 1. 15

Apply Thevenin's theorem and Kirchhoff's voltage law to the base-emitter circuit in Figure 1.15.

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{(47\ k\Omega)\ (10\ k\Omega)}{47\ k\Omega + 10\ k\Omega} = 8.25\ k\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC} = \left(\frac{10\ k\Omega}{47\ k\Omega + 10\ k\Omega}\right)\ 10V = 1.75V$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{1.75 - 0.7}{940 + 8250\ /150} = 1.06\ \text{mA}$$

$I_C \approx I_E = 1.06$ mA

$V_E = I_E(R_{E1} + R_{E2}) = (1.06\ \text{mA})(940\ \Omega) = 1$ V

$V_B = V_E + 0.7\ \text{V} = 1\ \text{V} - 0.7\ \text{V} = 0.3$ V

$V_C = V_{CC} - I_C R_C = 10\ \text{V} - (1.06\ \text{mA})(4.7\ \text{k}\Omega) = \mathbf{5.02\ V}$

(b) The ac analysis is based on the ac equivalent circuit in Figure 1.14.

The first thing to do in the ac analysis is calculate r'_e

$$r'_e \approx \frac{25\ mV}{I_E} = r'_e \approx \frac{25\ mV}{1.06\ mA} = 23.6\ \Omega$$

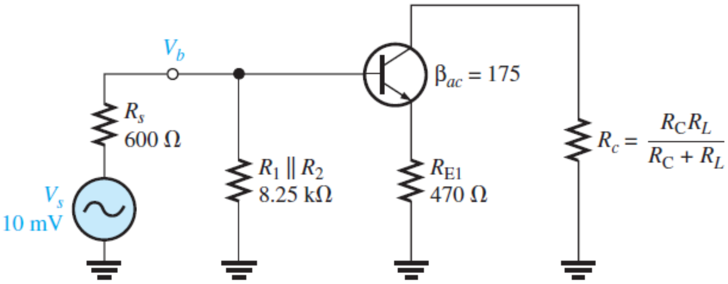


Figure 1. 16

Next, determine the attenuation in the base circuit. Looking from the 600 Ω source, the total *Rin* is

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

$$R_{in(base)} = \beta_{ac}(r'_e + R_{E1}) = 175(494\ \Omega) = 86.5\ \text{k}\Omega$$

Therefore,

$$R_{in(tot)} = 47\ \text{k}\Omega\ //\ 10\ \text{k}\Omega\ //\ 86.5\ \text{k}\Omega = 7.53\ \text{k}\Omega$$

The attenuation from source to base is

$$\text{Attenuation} = \frac{V_s}{V_b} = \frac{R_s + R_{in(tot)}}{R_{in(tot)}} = \frac{600\ \Omega + 7.53\ k\Omega}{7.53\ k\Omega} = 1.08$$

Before *Av* can be determined, you must know the ac collector resistance *Rc*.

$$Rc = \frac{R_C\,R_L}{R_C + R_L} = \frac{(4.7\ k\Omega)\ (47k\Omega)}{(4.7\ k\Omega) + (47k\Omega)} = 4.27\ \text{k}\Omega$$

The voltage gain from base to collector is

$$Av \approx \frac{R_c}{R_{E1}} = \frac{4.27\ \text{k}\Omega}{470\ \text{k}\Omega} = 9.09$$

The overall voltage gain is the reciprocal of the attenuation times the amplifier voltage gain.

$$A'v = \left(\frac{V_b}{V_s}\right)Av = (0.93)(9.09) = 8.45$$

The source produces 10 mV rms, so the rms voltage at the collector is

$$V_c = A'_v V_s = (8.45)(10\text{ mV}) = \mathbf{84.5\ mV}$$

(c) The coupling capacitor, C_3, keeps the dc level from getting to the output. So, V_{out} is equal to the ac component of the collector voltage $V_{out(p)} = (84.5\text{ mV})(1.414) = 119$ mV

as indicated in Figure 1.17. The source voltage, *Vs*, is shown to emphasize the phase inversion.

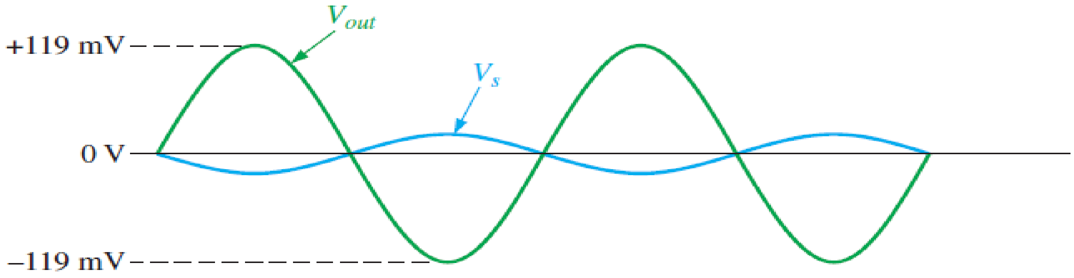


Figure 1. 17