Chapter 12
Bipolar Junction Transistors

1. Bipolar Junction Transistor (BJT) operation in amplifier circuits.
2. Analysis of amplifiers:
   - Load-line technique
   - Large signal model
   - Small signal model
3. Amplifier performance

BJT Structure and Symbol

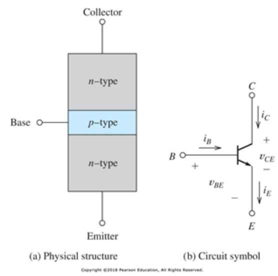


Figure 12.1 The *npn* BJT.

Equations of Operation

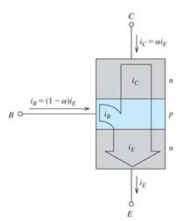


Figure 12.3 Only a small fraction of the emitter current flows into the base (provided that the collector–base junction is reverse biased and the base–emitter junction is forward biased).

$$i_E = I_{ES}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$$

Shockley equation

$$i_E = i_C + i_B \qquad i_C = \beta i_B$$

$$\alpha = \frac{i_C}{i_E} \qquad \beta = \frac{i_C}{i_B} = \frac{\alpha}{1-\alpha}$$

Case Study: Exercise 12.1

$$\beta = 50,\ I_{ES} = 10^{-14} A,\ v_{CE} = 5V$$

$$i_E = 10mA,\ V_T = 0.026V$$

$$Find \quad v_{BE},\ v_{BC},\ i_C,\ i_B,\ and\ \alpha$$

$$i_E = I_{ES}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$$

Common emitter circuit

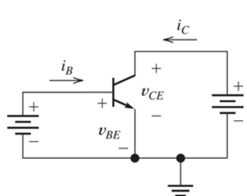


Figure 12.4 Common-emitter circuit configuration for the *npn* BJT.

$$v_{BC} = v_{BE} - v_{CE}$$

Common-emitter characteristics

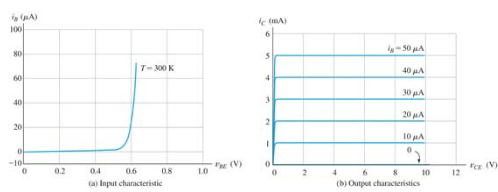


Figure 12.5 Common-emitter characteristics of a typical *npn* BJT.

Input Characteristic: $i_B \leftrightarrow v_{BE}$

Output Characteristics: $i_C \leftrightarrow v_{CE}$

Example 12.1: Find β

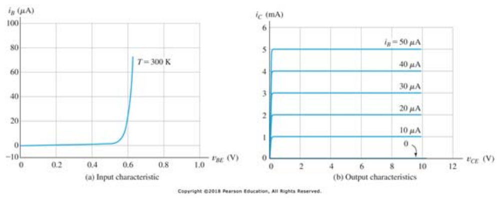


Figure 12.5 Common-emitter characteristics of a typical *npn* BJT.

$\beta = 100$

How does an amplifier work?

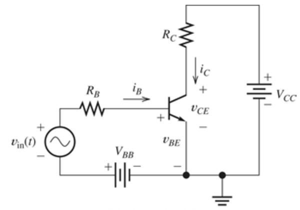


Figure 12.7 A simple common-emitter amplifier that can be analyzed by load-line techniques.

- DC circuit to provide basis
- AC signal to be amplified

Analysis of common emitter amplifier

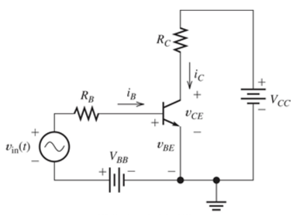


Figure 12.7 A simple common-emitter amplifier that can be analyzed by load-line techniques.

$V_{BB} + v_{\text{in}}(t) = R_B i_B(t) + v_{BE}(t)$ $\quad V_{CC} = R_C i_C + v_{CE}$

Load-line analysis

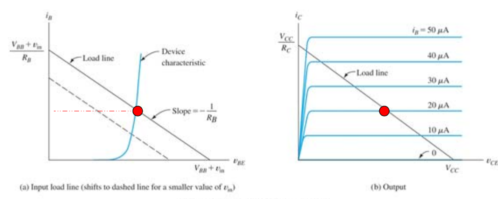


Figure 12.8 Load-line analysis of the amplifier of Figure 12.7.

$V_{BB} + v_{\text{in}}(t) = R_B i_B(t) + v_{BE}(t)$ $\quad V_{CC} = R_C i_C + v_{CE}$

Operating point: Q-point with $v_{in} = 0$

Example 12.2

$V_{CC} = 10V$

$V_{BB} = 1.6V$

$R_B = 40k\Omega$

$R_C = 2k\Omega$

$v_{in}(t) = 0.4\sin(2000\pi t)$

Find maximum, minimum and Q-point values of v_{CE}

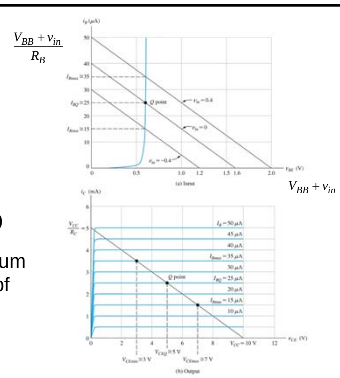


Figure 12.9 Load-line analysis for Example 12.2.

Example 12.2- continued

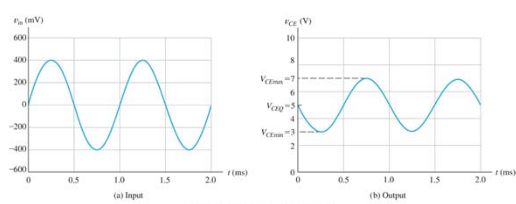


Figure 12.10 Voltage waveforms for the amplifier of Figure 12.7. See Example 12.2.

Inverting amplifier

Nonlinear distortion

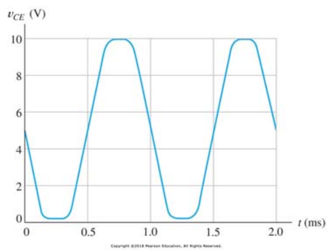


Figure 12.11 Output of the amplifier of Example 12.2 for $v_{in}(t) = 1.2 \sin(2000\pi t)$ showing gross nonlinear distortion.

Saturation and cut-off

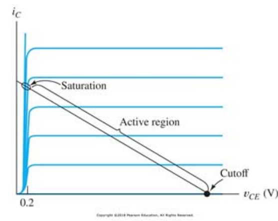


Figure 12.12 Amplification occurs in the active region. Clipping occurs when the instantaneous operating point enters saturation or cutoff. In saturation, $v_{CE} \cong 0.2$ V.

When i_C becomes zero, we say that the transistor is cutoff. When v_{CE} is around 0.2 V, we say that the transistor is in saturation.

Application: Electronic switches

One particular application of Transistors working as a switch is electrical ignition in auto-industry to replace "points" (a mechanically operated switch)

Advantages:

- No wear out
- Many more improvements in ignition control

PNP Bipolar junction transistors

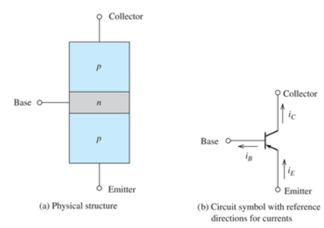


Figure 12.13 The *pnp* BJT.

Except for reversal of current directions and voltage polarities, the *pnp* BJT is almost identical to the *npn* BJT.

Common-emitter characteristics

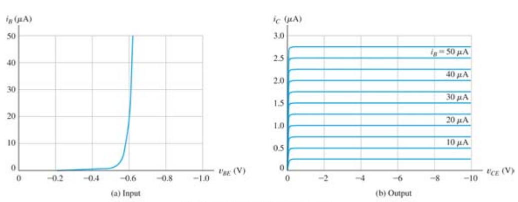
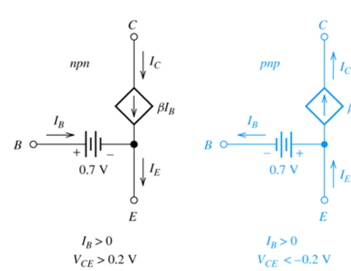


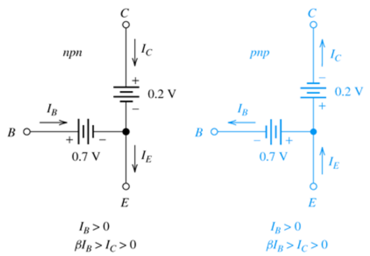
Figure 12.14 Common-emitter characteristics for a *pnp* BJT.

Large-signal dc circuit models
(Active-Region Model)



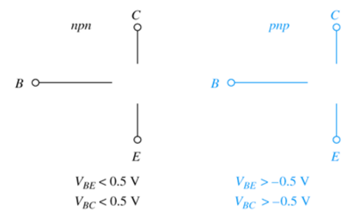
(a) Active region

Large-signal dc circuit models
(Saturation-Region Model)



(b) Saturation region

Large-signal dc circuit models
(Cutoff-Region Model)



(c) Cutoff region

Case Study: Example 12.6

$I_C = ?$

$V_{CE} = ?$

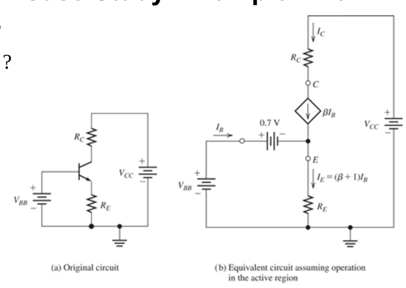


Figure 12.21 Circuit for Example 12.6.

Example 12.6

$$V_{CC} = 15V, V_{BB} = 5V, R_E = 2k\Omega, R_C = 2k\Omega, \beta = 100$$

$$V_{BB} = 0.7 + I_E R_E \Rightarrow I_E = \frac{V_{BB} - 0.7}{R_E} = 2.15mA$$

$$I_C = \beta I_B$$

$$I_E = I_B + I_C = (\beta + 1) I_B$$

Analysis of Four-Resistor Bias Circuit

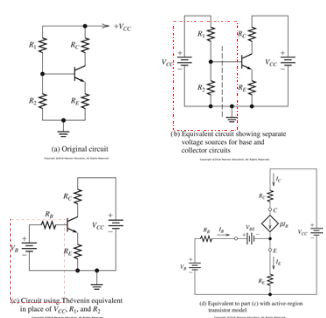
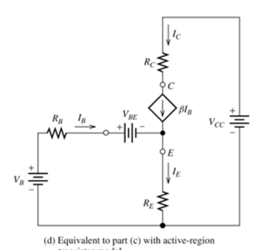


Figure 12.22 Four-resistor bias circuit.

Equivalent circuit



$$R_B = \frac{1}{1/R_1 + 1/R_2} = R_1 \| R_2$$

$$V_B = V_{CC} \frac{R_2}{R_1 + R_2}$$

$$I_B = \frac{V_B - V_{BE}}{R_B + (\beta + 1) R_E}$$

Case Study: Example 12.7

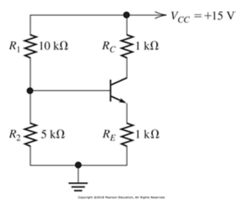


Figure 12.23 Circuit for Example 12.7.

$$R_B = \frac{1}{1/R_1 + 1/R_2} = 3.33k\Omega$$

$$V_B = V_{CC}\frac{R_2}{R_1 + R_2} = 5V$$

$$I_B = \frac{V_B - V_{BE}}{R_B + (\beta + 1)R_E} = 41.2\mu A$$

Small signal equivalent circuits

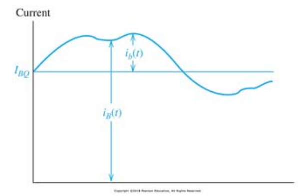


Figure 12.24 Illustration of the Q-point base current I_{BQ}, signal current $i_b(t)$, and total base current $i_B(t)$.

$$i_B(t) = i_{BQ} + i_b(t)$$

$$v_{BE}(t) = V_{BEQ} + v_{be}(t)$$

$i_b(t)$: the signal current flowing into the base
I_{BQ} : the dc current that flows when the signal is absent
$i_B(t)$: the total base current.

Small-Signal Equivalent Circuit for the BJT

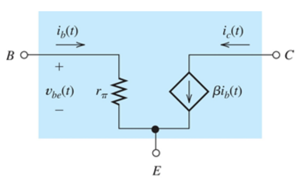
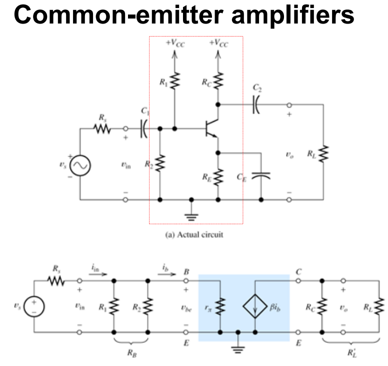


Figure 12.26 Small-signal equivalent circuit for the BJT.

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{V_T}{I_{BQ}}$$

$$i_C(t) = \beta i_b(t)$$

Common-emitter amplifiers



$$R_L' = R_L \| R_C = \frac{1}{1/R_L + 1/R_C}$$

Voltage gain

$$A_v = \frac{v_o}{v_{\text{in}}} = -\frac{R_L'\beta}{r_\pi}$$

Open loop voltage gain

$$A_{vo} = \frac{v_o}{v_{\text{in}}} = -\frac{R_C\beta}{r_\pi}$$

Input impedance

$$Z_{\text{in}} = \frac{v_{\text{in}}}{i_{\text{in}}} = \frac{1}{1/R_B + 1/r_\pi}$$

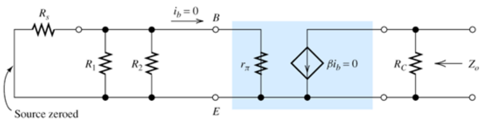
Current gain

$$A_i = \frac{i_o}{i_{\text{in}}} = A_v\frac{Z_{\text{in}}}{R_L}$$

Power gain

$$G = A_i A_v$$

Output impedance



(c) Equivalent circuit used to find Z_o

$$Z_o = R_C$$

The common-emitter amplifier is inverting and has large voltage gain magnitude, large current gain, and large power gain.

Example 12.8

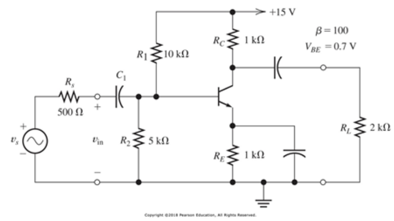


Figure 12.28 Common-emitter amplifier of Example 12.8.

$$Find \quad A_v, A_{vo}, Z_{in}, A_i, G, Z_o$$

From example 12.7, one finds

$$I_{CQ} = 4.12mA \qquad V_T = 0.026V, \beta = 100$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = 631\Omega$$

$$R_B = R_1 \| R_2 = 3.33k\Omega, \quad R_L' = R_L \| R_C = 667\Omega$$

$$A_v = -\frac{R_L'\beta}{r_\pi} = -106 \qquad A_{vo} = -\frac{R_C\beta}{r_\pi} = -158$$

$$Z_{in} = \frac{1}{1/R_B + 1/r_\pi} = 531\Omega \qquad A_i = A_v\frac{Z_{in}}{R_L} = -28.1$$

$$G = A_i A_v = 2980 \qquad Z_o = R_C = 1k\Omega$$

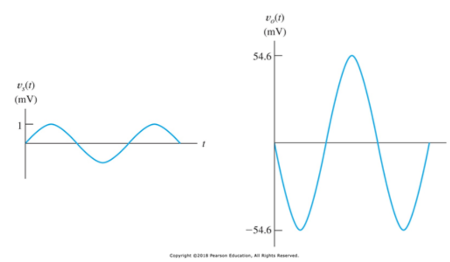
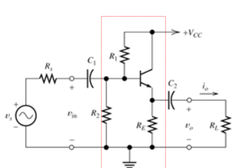
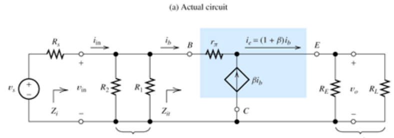


Figure 12.29 Source and output voltages for Example 12.8.

Emitter followers



(a) Actual circuit

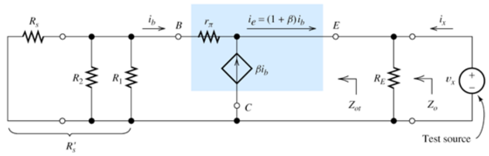


(b) Small-signal equivalent circuit

$$R_B = R_1 \| R_2 = \frac{1}{1/R_1 + 1/R_2} \qquad R_L' = R_L \| R_E = \frac{1}{1/R_L + 1/R_E}$$

$$v_o = R_L'(1+\beta)i_b \qquad v_{in} = r_\pi i_b + R_L'(1+\beta)i_b$$

Output Impedance



(c) Equivalent circuit used to find output impedance Z_o

$$R'_s = \frac{1}{1/R_s + 1/R_1 + 1/R_2}$$

$$i_b + \beta i_b + i_x = \frac{v_x}{R_E}$$

$$v_x + r_\pi i_b + R'_s i_b = 0$$

Case Study: Example 12.9

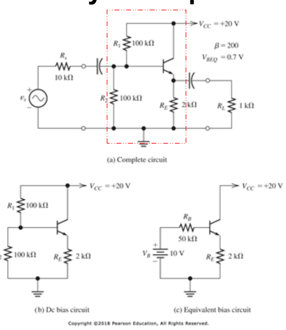


Figure 12.31 Emitter follower of Example 12.9.

$$V_B = R_B I_{BQ} + V_{BEQ} + R_E(1+\beta)I_{BQ} = 6.72V$$

$$I_{BQ} = 20.6\mu A \quad I_{CQ} = \beta I_{BQ} = 4.12mA \quad V_{CEQ} = V_{CC} - R_E I_{EQ} = 11.7V$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = 1260\Omega$$

$$R_B = R_1 \| R_2 = 50k\Omega, \quad R'_L = R_L \| R_E = 667\Omega$$

$$A_v = \frac{(1+\beta)R'_L}{r_\pi + (1+\beta)R'_L} = 0.991$$

Comments on Emitter follower

Even though the voltage gain of the emitter follower is less than unity, the current gain and power gain can be large.