C H A P T E R

10

BIPOLAR JUNCTION TRANSISTORS: OPERATION, CIRCUIT MODELS, AND APPLICATIONS

Chapter 10 continues the discussion of electronic devices that began in Chapter 9 with the semiconductor diode. This chapter describes the operating characteristics of one of the two major families of electronic devices: bipolar transistors. Chapter 10 is devoted to a brief, qualitative discussion of the physics and operation of the bipolar junction transistor (BJT), which naturally follows the discussion of the *pn* junction in Chapter 9. The i-v characteristics of bipolar transistors and their operating states are presented. Large-signal circuit models for the BJT are then introduced, to illustrate how one can analyze transistor circuits by using basic circuit analysis methods. A few practical examples are discussed to illustrate the use of the circuit models.

This chapter introduces the operation of the bipolar junction transistor. Bipolar transistors represent one of two major families of electronic devices that can serve as amplifiers and switches. Chapter 10 reviews the operation of the bipolar junction transistor and presents simple models that permit the analysis and design of simple amplifier and switch circuits.

Learning Objectives

1. Understand the basic principles of amplification and switching. *Section 10.1*.
2. Understand the physical operation of bipolar transistors; determine the operating point of a bipolar transistor circuit. *Section 10.2*.
3. Understand the large-signal model of the bipolar transistor, and apply it to simple amplifier circuits. *Section 10.3*.
4. Select the operating point of a bipolar transistor circuit; understand the principle of small signal amplifiers. *Section 10.4*.
5. Understand the operation of a bipolar transistor as a switch, and analyze basic analog and digital gate circuits. *Section 10.5*.

10.1 TRANSISTORS AS AMPLIFIERS AND SWITCHES

A transistor is a three-terminal semiconductor device that can perform two functions that are fundamental to the design of electronic circuits: **amplification** and **switching.** Put simply, amplification consists of magnifying a signal by transferring energy to it from an external source, whereas a transistor switch is a device for controlling a relatively large current between or voltage across two terminals by means of a small control current or voltage applied at a third terminal. In this chapter, we provide an introduction to the two major families of transistors: *bipolar junction transistors,* or *BJTs;* and *field-effect transistors,* or *FETs*.

The operation of the transistor as a linear amplifier can be explained qualitatively by the sketch of Figure 10.1, in which the four possible modes of operation of a transistor are illustrated by means of circuit models employing controlled sources (you may wish to review the material on controlled sources in Section 2.1). In Figure 10.1, controlled voltage and current sources are shown to generate an output proportional to an input current or voltage; the proportionality constant μ is called the internal *gain* of the transistor. As will be shown, the BJT acts essentially as a current-controlled device, while the FET behaves as a voltage-controlled device.

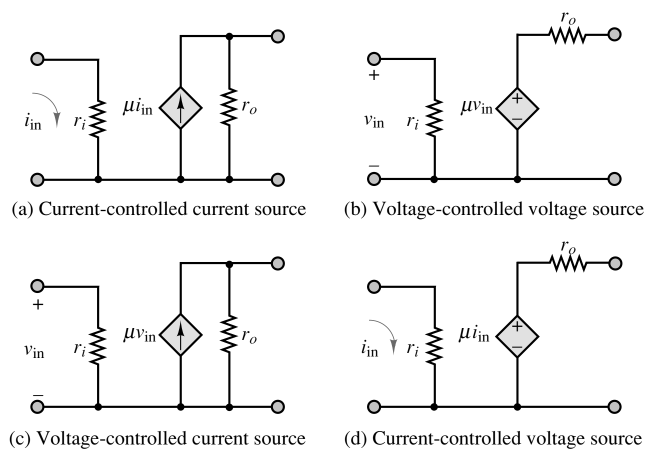


Figure 10.1 Controlled-source models of linear amplifier transistor operation

Transistors can also act in a nonlinear mode, as voltage- or current-controlled switches. When a transistor operates as a switch, a small voltage or current is used to control the flow of current between two of the transistor terminals in an on/off fashion. Figure 10.2 depicts the idealized operation of the transistor as a switch, suggesting that the switch is closed (on) whenever a control voltage or current is greater than zero and is open (off) otherwise. It will later become apparent that the conditions for the switch to be on or off need not necessarily be those depicted in Figure 10.2.

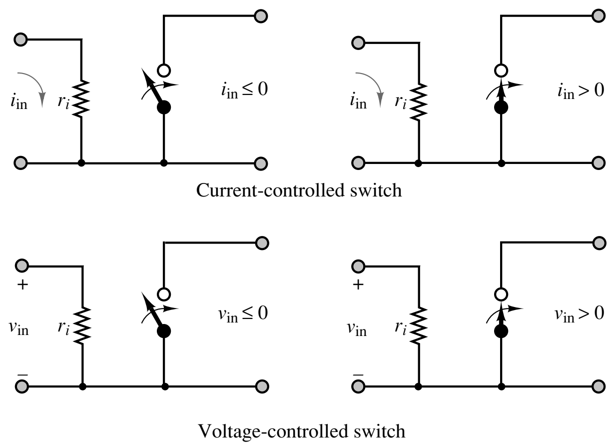


Figure 10.2 Models of ideal transistor switches

EXAMPLE 10.1 Model of Linear Amplifier

LO1

Problem

Determine the voltage gain of the amplifier circuit model shown in Figure 10.3.

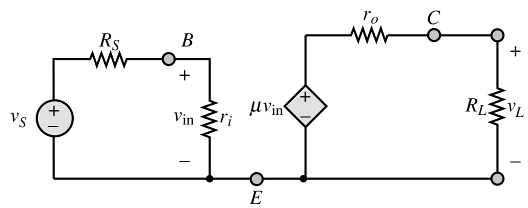


Figure 10.3

Solution

Known Quantities: Amplifier internal input and output resistances r_i and r_o; amplifier internal gain μ; source and load resistances R_S and R_L.

Find: $A_V = \dfrac{v_L}{v_S}$

Analysis: First determine the input voltage, v_{in}, using the voltage divider rule:

$$v_{\text{in}} = \frac{r_i}{r_i + R_S} v_S$$

Then, the output of the controlled voltage source is:

$$\mu v_{\text{in}} = \mu \frac{r_i}{r_i + R_S} v_S$$

and the output voltage can be found by the voltage divider rule:

$$v_L = \mu \frac{r_i}{r_i + R_S} v_S \times \frac{R_L}{r_o + R_L}$$

Finally, the amplifier voltage gain can be computed:

$$A_V = \frac{v_L}{v_S} = \mu \frac{r_i}{r_i + R_S} \times \frac{R_L}{r_o + R_L}$$

Comments: Note that the voltage gain computed above is always less than the transistor internal voltage gain, μ. One can easily show that if the conditions $r_i \gg R_S$ and $r_o \ll R_L$ hold, then the gain of the amplifier becomes approximately equal to the gain of the transistor. One can therefore conclude that the actual gain of an amplifier always depends on the relative values of source and input resistance, and of output and load resistance.

CHECK YOUR UNDERSTANDING

Repeat the analysis of Example 10.1 for the current-controlled voltage source model of Figure 10.1(d). What is the amplifier voltage gain? Under what conditions would the gain A be equal to μ / R_S?

Repeat the analysis of Example 10.1 for the current-controlled current source model of Figure 10.1(a). What is the amplifier voltage gain?

Repeat the analysis of Example 10.1 for the voltage-controlled current source model of Figure 10.1(c). What is the amplifier voltage gain?

Answers: $A = \mu \frac{1}{r_i + R_S} \frac{R_L}{r_o + R_L}$; $r_i \to 0$, $r_o \to 0$; $A = \frac{1}{r_i + R_S} \frac{r_o R_L}{r_o + R_L} \mu$; $A = \mu \frac{r_i}{r_i + R_S} \frac{r_o R_L}{r_o + R_L}$

10.2 OPERATION OF THE BIPOLAR JUNCTION TRANSISTOR

The pn junction studied in Chapter 9 forms the basis of a large number of semiconductor devices. The semiconductor diode, a two-terminal device, is the most direct application of the pn junction. In this section, we introduce the **bipolar junction transistor (BJT)**. As we did in analyzing the diode, we will introduce the physics of transistor devices as intuitively as possible, resorting to an analysis of their i-v characteristics to discover important properties and applications.

A BJT is formed by joining three sections of semiconductor material, each with a different doping concentration. The three sections can be either a thin n region sandwiched between p^+ and p layers, or a p region between n and n^+ layers, where the superscript plus indicates more heavily doped material. The resulting BJTs are called *pnp* and *npn* transistors, respectively; we discuss only the latter in this chapter. Figure 10.4 illustrates the approximate construction, symbols, and nomenclature for the two types of BJTs.

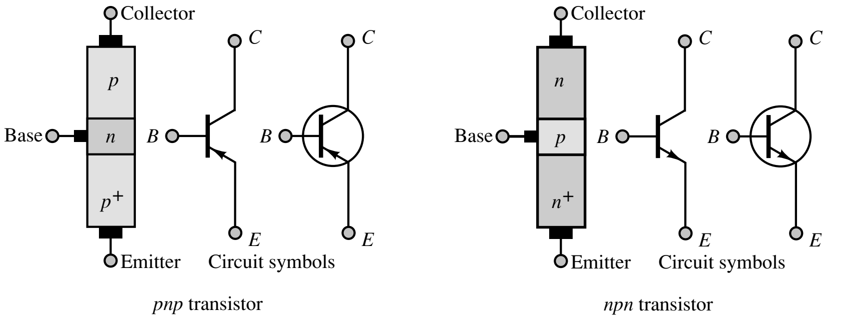
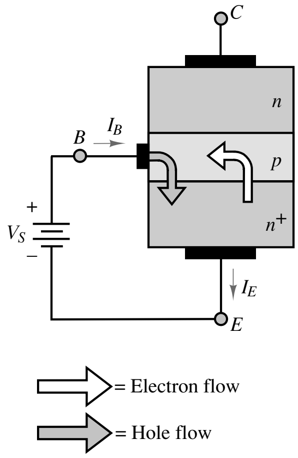


Figure 10.4 Bipolar junction transistors



The *BE* junction acts very much as an ordinary diode when the collector is open. In this case, $I_B = I_E$.

Figure 10.5 Current flow in an *npn* BJT

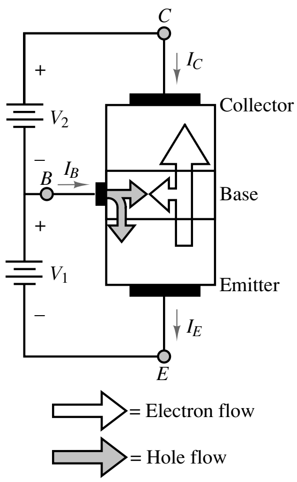
The operation of the *npn* BJT may be explained by considering the transistor as consisting of two back-to-back *pn* junctions. The **base-emitter (BE) junction** acts very much as a diode when it is forward-biased; thus, one can picture the corresponding flow of hole and electron currents from base to emitter when the collector is open and the *BE* junction is forward-biased, as depicted in Figure 10.5. Note that the electron current has been shown larger than the hole current, because of the heavier doping of the n side of the junction. Some of the electron-hole pairs in the base will recombine; the remaining charge carriers will give rise to a net flow of current from base to emitter. It is also important to observe that the base is much narrower than the emitter section of the transistor.

Imagine, now, reverse-biasing the **base-collector (BC) junction**. In this case, an interesting phenomenon takes place: the electrons "emitted" by the emitter with the *BE* junction forward-biased reach the very narrow base region, and after a few are lost to recombination in the base, most of these electrons are "collected" by the collector. Figure 10.6 illustrates how the reverse bias across the *BC* junction is in such a direction as to sweep the electrons from the emitter into the collector. This phenomenon can take place because the base region is kept particularly narrow. Since the base is narrow, there is a high probability that the electrons will have gathered enough momentum from the electric field to cross the reverse-biased collector-base junction and make it into the collector. The result is that there is a net flow of current from collector to emitter (opposite in direction to the flow of electrons), in addition to the hole current from base to emitter. The electron current flowing into the collector through the base is substantially larger than that which flows into the base from the external circuit. One can see from Figure 10.6 that if KCL is to be satisfied, we must have

$$I_E = I_B + I_C \tag{10.1}$$

The most important property of the bipolar transistor is that the small base current controls the amount of the much larger collector current

$$I_C = \beta I_B \tag{10.2}$$

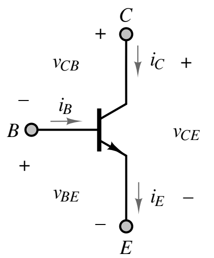


When the *BC* junction is reverse-biased, the electrons from the emitter region are swept across the base into the collector.

Figure 10.6 Flow of emitter electrons into the collector in an *npn* BJT where β is a current amplification factor dependent on the physical properties of the transistor. Typical values of β range from 20 to 200. The operation of a *pnp* transistor is completely analogous to that of the *npn* device, with the roles of the charge carriers (and therefore the signs of the currents) reversed. The symbol for a *pnp* transistor is shown in Figure 10.4.

The exact operation of bipolar transistors can be explained by resorting to a detailed physical analysis of the *npn* or *pnp* structure of these devices. The reader interested in such a discussion of transistors is referred to any one of a number of excellent books on semiconductor electronics. The aim of this book, however, is to provide an introduction to the basic principles of transistor operation by means of simple linear circuit models based on the device i-v characteristic. Although it is certainly useful for the non–electrical engineer to understand the basic principles of operation of electronic devices, it is unlikely that most readers will engage in the design of high-performance electronic circuits or will need a detailed understanding of the operation of each device. This chapter will therefore serve as a compendium of the basic ideas, enabling an engineer to read and understand electronic circuit diagrams and to specify the requirements of electronic instrumentation systems. The focus of this section will be on the analysis of the i-v characteristic of the *npn* BJT, based on the circuit notation defined in Figure 10.7. The device i-v characteristics will be presented qualitatively, without deriving the underlying equations, and will be utilized in constructing circuit models for the device.

The operation of the BJT is defined in terms of two currents and two voltages: i_B, i_C, v_{CE}, and v_{BE}.



KCL: $i_E = i_B + i_C$
KVL: $v_{CE} = v_{CB} + v_{BE}$

Figure 10.7 Definition of BJT voltages and currents

The number of independent variables required to uniquely define the operation of the transistor may be determined by applying KVL and KCL to the circuit of Figure 10.7. Two voltages and two currents are sufficient to specify the operation of the device. Note that since the BJT is a three-terminal device, it will not be sufficient to deal with a single i-v characteristic; two such characteristics are required to explain the operation of this device. One of these characteristics relates the base current, i_B to the base-emitter voltage v_{BE}; the other relates the collector current i_C to the collector-emitter voltage v_{CE}. The latter characteristic actually consists of a *family* of curves. To determine these i-v characteristics, consider the i-v curves of Figures 10.8 and 10.9, using the circuit notation of Figure 10.7. In Figure 10.8, the collector is open and the *BE* junction is shown to be very similar to a diode. The ideal current source I_{BB} injects a base current, which causes the junction to be forward-biased. By varying I_{BB}, one can obtain the open-collector *BE* junction i-v curve shown in the figure.

If a voltage source were now to be connected to the collector circuit, the voltage v_{CE} and, therefore, the collector current i_C could be varied, in addition to the base

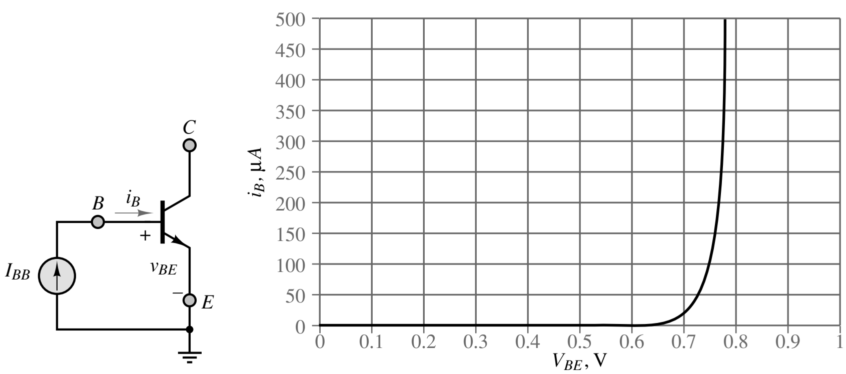
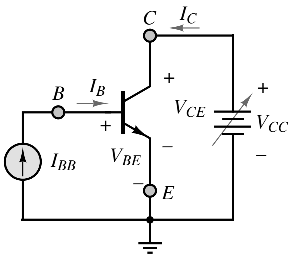
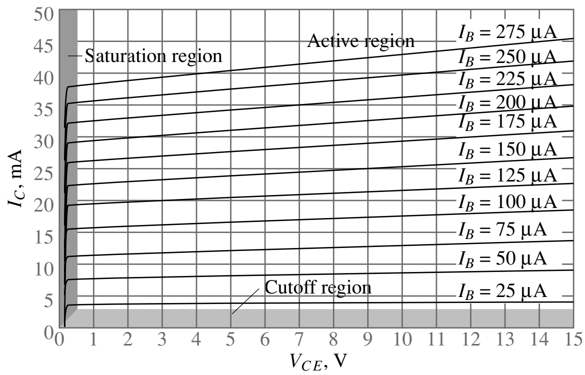


Figure 10.8 The *BE* junction open-collector curve



(a)

Figure 10.9(a) Ideal test circuit to determine the i-v characteristic of a BJT



(b)

Figure 10.9(b) The collector-emitter output characteristics of a BJT

current i_B. The resulting circuit is depicted in Figure 10.9(a). By varying both the base current and the collector-emitter voltage, one could then generate a plot of the device **collector characteristic.** This is also shown in Figure 10.9(b). Note that this figure depicts not just a single i_C-v_{CE} curve, but an entire family, since for each value of the base current i_B, an i_C-v_{CE} curve can be generated. Four regions are identified in the collector characteristic:

1. The **cutoff region,** where both junctions are reverse-biased, the base current is very small, and essentially no collector current flows.
2. The **active linear region,** in which the transistor can act as a linear amplifier, where the *BE* junction is forward-biased and the *CB* junction is reverse-biased.
3. The **saturation region,** in which both junctions are forward-biased.
4. The **breakdown region,** which determines the physical limit of operation of the device.

LO2

From the curves of Figure 10.9(b), we note that as v_{CE} is increased, the collector current increases rapidly, until it reaches a nearly constant value; this condition holds until the collector junction breakdown voltage BV_{CEO} is reached (for the purposes of this book, we shall not concern ourselves with the phenomenon of breakdown, except in noting that there are maximum allowable voltages and currents in a transistor). If we were to repeat the same measurement for a set of different values of i_B, the corresponding value of i_C would change accordingly, hence, the family of collector characteristic curves.

Determining the Operating Region of a BJT

Before we discuss common circuit models for the BJT, it will be useful to consider the problem of determining the operating region of the transistor. A few simple voltage measurements permit a quick determination of the state of a transistor placed in a

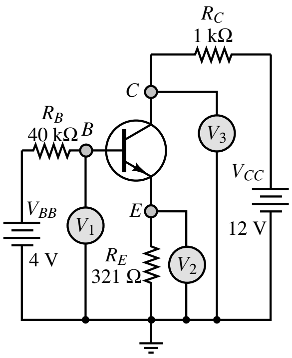


Figure 10.10 Determination of the operation region of a BJT

circuit. Consider, for example, the BJT described by the curves of Figure 10.9 when it is placed in the circuit of Figure 10.10. In this figure, voltmeters are used to measure the value of the collector, emitter, and base voltages. Can these simple measurements identify the operating region of the transistor? Assume that the measurements reveal the following conditions:

$$V_B = V_1 = 2 \text{ V} \qquad V_E = V_2 = 1.3 \text{ V} \qquad V_C = V_3 = 8 \text{ V}$$

What can be said about the operating region of the transistor?

The first observation is that knowing V_B and V_E permits determination of V_{BE}: $V_B - V_E = 0.7$ V. Thus, we know that the BE junction is forward-biased. Another quick calculation permits determination of the relationship between base and collector current: the base current is equal to

$$I_B = \frac{V_{BB} - V_B}{R_B} = \frac{4 - 2}{40{,}000} = 50 \ \mu\text{A}$$

while the collector current is

$$I_C = \frac{V_{CC} - V_C}{R_C} = \frac{12 - 8}{1{,}000} = 4 \text{ mA}$$

Thus, the current amplification (or gain) factor for the transistor is

$$\frac{I_C}{I_B} = \beta = 80$$

Such a value for the current gain suggests that the transistor is in the linear active region, because substantial current amplification is taking place (typical values of current gain range from 20 to 200). Finally, the collector-to-emitter voltage V_{CE} is found to be $V_{CE} = V_C - V_E = 8 - 1.3 = 6.7$ V.

At this point, you should be able to locate the operating point of the transistor on the curves of Figures 10.8 and 10.9. The currents I_B and I_C and the voltage V_{CE} uniquely determine the state of the transistor in the I_C-V_{CE} and I_B-V_{BE} characteristic curves. What would happen if the transistor were not in the linear active region? Examples 10.2 and 10.3 answer this question and provide further insight into the operation of the bipolar transistor.

LO2

EXAMPLE 10.2 Determining the Operating Region of a BJT

Problem

Determine the operating region of the BJT in the circuit of Figure 10.10 when the base voltage source V_{BB} is short-circuited.

Solution

Known Quantities: Base and collector supply voltages; base, emitter, and collector resistance values.

Find: Operating region of the transistor.

Schematics, Diagrams, Circuits, and Given Data: $V_{BB} = 0$; $V_{CC} = 12$ V; $R_B = 40$ kΩ; $R_C = 1$ kΩ; $R_E = 500$ Ω.

Analysis: Since $V_{BB} = 0$, the base will be at 0 V, and therefore the base-emitter junction is reverse-biased and the base current is zero. Thus the emitter current will also be nearly zero. From equation 10.1 we conclude that the collector current must also be zero. Checking these observations against Figure 10.9(b) leads to the conclusion that the transistor is in the cutoff state. In these cases the three voltmeters of Figure 10.10 will read zero for V_B and V_E and $+12$ V for V_C, since there is no voltage drop across R_C.

Comments: In general, if the base supply voltage is not sufficient to forward-bias the base-emitter junction, the transistor will be in the cutoff region.

CHECK YOUR UNDERSTANDING

Describe the operation of a *pnp* transistor in the active region, by analogy with that of the *npn* transistor.

EXAMPLE 10.3 Determining the Operating Region of a BJT

LO2

Problem

Determine the operating region of the BJT in the circuit of Figure 10.11.

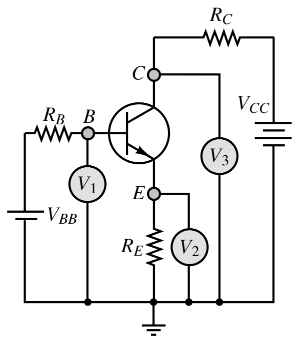


Figure 10.11

Solution

Known Quantities: Base, collector, and emitter voltages with respect to ground.

Find: Operating region of the transistor.

Schematics, Diagrams, Circuits, and Given Data: $V_1 = V_B = 2.7$ V; $V_2 = V_E = 2$ V; $V_3 = V_C = 2.3$ V.

Analysis: To determine the region of the transistor, we shall compute V_{BE} and V_{BC} to determine whether the *BE* and *BC* junctions are forward- or reverse-biased. Operation in the *saturation region* corresponds to forward bias at both junctions (and very small voltage drops); operation in the *active region* is characterized by a forward-biased *BE* junction and a reverse-biased *BC* junction.

From the available measurements, we compute:

$$V_{BE} = V_B - V_E = 0.7 \text{ V}$$

$$V_{BC} = V_B - V_C = 0.4 \text{ V}$$

Since both junctions are forward-biased, the transistor is operating in the saturation region. The value of $V_{CE} = V_C - V_E = 0.3$ V is also very small. This is usually a good indication that the BJT is operating in saturation.

Comments: Try to locate the operating point of this transistor in Figure 10.9(b), assuming that

$$I_C = \frac{V_{CC} - V_3}{R_C} = \frac{12 - 2.3}{1{,}000} = 9.7 \text{ mA}$$

CHECK YOUR UNDERSTANDING

For the circuit of Figure 10.11, the voltmeter readings are $V_1 = 3$ V, $V_2 = 2.4$ V, and $V_3 = 2.7$ V. Determine the operating region of the transistor.

Answer: Saturation

10.3 BJT LARGE-SIGNAL MODEL

The i-v characteristics and the simple circuits of the previous sections indicate that the BJT acts very much as a current-controlled current source: A small amount of current injected into the base can cause a much larger current to flow into the collector. This conceptual model, although somewhat idealized, is useful in describing a **large-signal model** for the BJT, that is, a model that describes the behavior of the BJT in the presence of relatively large base and collector currents, close to the limit of operation of the device. This model is certainly not a complete description of the properties of the BJT, nor does it accurately depict all the effects that characterize the operation of such devices (e.g., temperature effects, saturation, and cutoff); however, it is adequate for the intended objectives of this book, in that it provides a good qualitative feel for the important features of transistor amplifiers.

Large-Signal Model of the *npn* BJT

The large-signal model for the BJT recognizes three basic operating modes of the transistor. When the BE junction is reverse-biased, no base current (and therefore no forward collector current) flows, and the transistor acts virtually as an open circuit; the transistor is said to be in the *cutoff region*. In practice, there is always a leakage current flowing through the collector, even when $V_{BE} = 0$ and $I_B = 0$. This leakage current is denoted by I_{CEO}. When the BE junction becomes forward-biased, the transistor is said to be in the *active region,* and the base current is amplified by a factor of β at the collector:

$$I_C = \beta I_B \tag{10.3}$$

Since the collector current is controlled by the base current, the controlled-source symbol is used to represent the collector current. Finally, when the base current becomes sufficiently large, the collector-emitter voltage V_{CE} reaches its saturation limit, and the collector current is no longer proportional to the base current; this is called the *saturation region*. The three conditions are described in Figure 10.12 in terms of simple circuit models. The corresponding collector curves are shown in Figure 10.13.

The large-signal model of the BJT presented in this section treats the BE junction as an offset diode and assumes that the BJT in the linear active region acts as an ideal

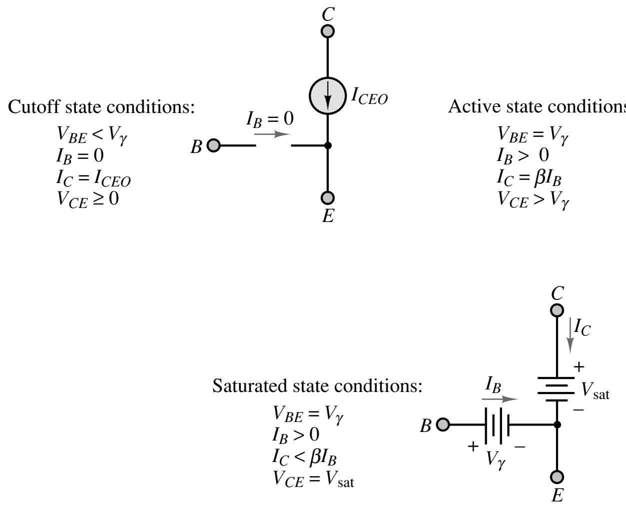


Figure 10.12 An *npn* BJT large-signal model

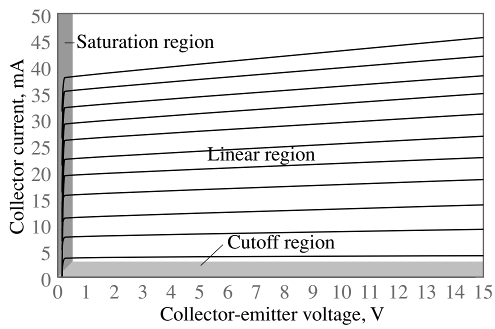


Figure 10.13 BJT collector characteristic

controlled current source. In reality, the *BE* junction is better modeled by considering the forward resistance of the *pn* junction; further, the BJT does not act quite as an ideal current-controlled current source. Nonetheless, the large-signal BJT model is a very useful tool for many applications. Example 10.4 illustrates the application of this large-signal model in a practical circuit and illustrates how to determine which of the three states is applicable, using relatively simple analysis.

FOCUS ON METHODOLOGY

USING DEVICE DATA SHEETS

One of the most important design tools available to engineers is the **device data sheet.** In this box we illustrate the use of a device data sheet for the 2N3904 bipolar transistor. This is an *npn general-purpose amplifier* transistor. Excerpts from the data sheet are shown below, with some words of explanation.

FIND IT ON THE WEB

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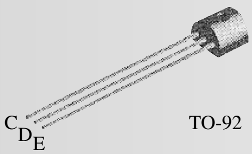
2N3904



TO-92

NPN general-purpose amplifier
This device is designed as a general purpose amplifier and switch.
The useful dynamic range extends to 100 mA as a switch and to 100 MHz as an amplifier.

ELECTRICAL CHARACTERISTICS

The section on electrical characteristics summarizes some of the important voltage and current specifications of the transistor. For example, you will find breakdown voltages (not to be exceeded), and cutoff currents. In this section you also find important modeling information, related to the *large-signal model* described in this chapter. The large-signal current gain of the transistor h_{FE} or β, is given as a function of collector current. Note that this parameter varies significantly (from 30 to 100) as the DC collector current varies. Also important are the *CE* and *BE* junction saturation voltages (the batteries in the large-signal model of Figure 10.12).

Electrical Characteristics $T_A = 25°C$ unless otherwise noted

Symbol	Parameter	Test Conditions	Min.	Max.	Units
Off Characteristics					
$V_{(BR)CEO}$	Collector-emitter breakdown voltage	$I_C = 1.0$ mA, $I_B = 0$	40		V
$V_{(BR)CBO}$	Collector-base breakdown voltage	$I_C = 10\ \mu$A, $I_E = 0$	60		V
$V_{(BR)EBO}$	Emitter-base breakdown voltage	$I_E = 10\ \mu$A, $I_C = 0$	6.0		V
I_{BL}	Base cutoff current	$V_{CE} = 30$ V, $V_{EB} = 0$		50	nA
I_{CEX}	Collector cutoff current	$V_{CE} = 30$ V, $V_{EB} = 0$		50	nA
On Characteristics					
h_{FE}	DC gain	$I_C = 0.1$ mA, $V_{CE} = 1.0$ V $I_C = 1.0$ mA, $V_{CE} = 1.0$ V $I_C = 10$ mA, $V_{CE} = 1.0$ V $I_C = 50$ mA, $V_{CE} = 1.0$ V $I_C = 100$ mA, $V_{CE} = 1.0$ V	40 70 100 60 30	 300	
$V_{CE(\mathrm{sat})}$	Collector-emitter saturation voltage	$I_C = 10$ mA, $I_B = 1.0$ mA $I_C = 50$ mA, $I_B = 5.0$ mA		0.2 0.3	V V
$V_{BE(\mathrm{sat})}$	Base-emitter saturation voltage	$I_C = 10$ mA, $I_B = 1.0$ mA $I_C = 50$ mA, $I_B = 5.0$ mA	0.065	0.85 0.95	V V

THERMAL CHARACTERISTICS

This table summarizes the thermal limitations of the device. For example, one can find the **power rating,** listed at 625 mW at 25°C. Note that in the entry for the total device power dissipation, **derating** information is also given. Derating implies that the device power dissipation will change as a function of temperature, in

(*Continued*)

(*Concluded*)

this case at the rate of 5 mW/°C. For example, if we expect to operate the diode at a temperature of 100°C, we calculate a derated power of

$$P = 625\text{ mW} - 75°\text{C} \times 5\text{ mW}/°\text{C} = 250\text{ mW}$$

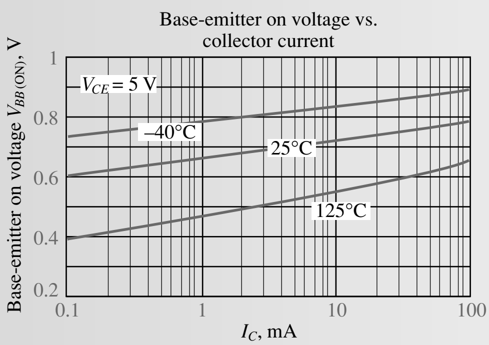
Thus, the diode operated at a higher temperature can dissipate only 250 mW.

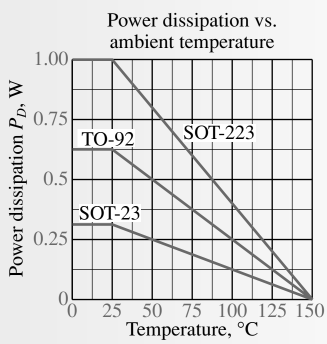
Thermal Characteristics $T_A = 25°\text{C}$ unless otherwise noted

Symbol	Characteristic	Max. 2N3904	Max. PZT3904	Units
P_D	Total device dissipation Derate above 25°C	625 5.0	1,000 8.0	mW mW/°C
$R_{\theta JC}$	Thermal resistance, junction to case	83.3		°C/W
$R_{\theta JA}$	Thermal resistance, junction to ambient	200	125	°C/W

TYPICAL CHARACTERISTIC CURVES

Device data sheets always include characteristic curves that may be useful to a designer. In this example, we include the base-emitter "on" voltage as a function of collector current, for three device temperatures. We also show the power dissipation versus ambient temperature derating curve for three different device *packages*. The transistor's ability to dissipate power is determined by its heat transfer properties; the package shown above is the TO-92 package; the SOT-223 and SOT-23 packages have different heat transfer characteristics, leading to different power dissipation capabilities.





EXAMPLE 10.4 LED Driver

LO3

Problem

Design a transistor amplifier to supply a LED. The LED is required to turn on and off following the on/off signal from a digital output port of a microcomputer. The circuit is shown in Figure10.14.

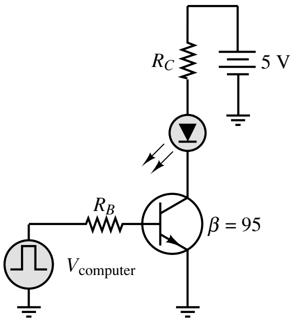


Figure 10.14 LED driver circuit

Solution

Known Quantities: Microprocessor output resistance and output signal voltage and current levels; LED offset voltage, required current, and power rating; BJT current gain and base-emitter junction offset voltage.

Find: Collector resistance R_C such that the transistor is in the saturation region when the computer outputs 5 V; power dissipated by LED.

Schematics, Diagrams, Circuits, and Given Data:
Microprocessor: output resistance $= R_B = 1\ \text{k}\Omega$; $V_{\text{ON}} = 5$ V; $V_{\text{OFF}} = 0$ V; $I = 5$ mA.
Transistor: $V_{CC} = 5$ V; $V_\gamma = 0.7$ V; $\beta = 95$; $V_{CE\text{sat}} = 0.2$ V.
LED: $V_{\gamma\text{LED}} = 1.4$ V; $I_{\text{LED}} > 15$ mA; $P_{\max} = 100$ mW.

Assumptions: Use the large-signal model of Figure 10.12.

Analysis: When the computer output voltage is zero, the BJT is clearly in the cutoff region, since no base current can flow. When the computer output voltage is $V_{\text{ON}} = 5$ V, we wish to drive the transistor into the saturation region. Recall that operation in saturation corresponds to small values of collector-emitter voltages, with typical values of V_{CE} around 0.2 V. Figure 10.15(a) depicts the equivalent base-emitter circuit when the computer output voltage is $V_{\text{ON}} = 5$ V. Figure 10.15(b) depicts the collector circuit, and Figure 10.15(c), the same collector circuit with the large-signal model for the transistor (the battery $V_{CE\text{sat}}$) in place of the BJT. From this saturation model we write

$$V_{CC} = R_C I_C + V_{\gamma\text{LED}} + V_{CE\text{sat}}$$

or

$$R_C = \frac{V_{CC} - V_{\gamma\text{LED}} - V_{CE\text{sat}}}{I_C} = \frac{3.4}{I_C}$$

We know that the LED requires at least 15 mA to be on. Let us suppose that 30 mA is a reasonable LED current to ensure good brightness. Then the value of collector resistance that would complete our design is, approximately, $R_C = 113\ \Omega$.

With the above design, the BJT LED driver will clearly operate as intended to turn the LED on and off. But how do we know that the BJT is in fact in the saturation region? Recall that the major difference between operation in the active and saturation regions is that in the active region the transistor displays a nearly constant current gain β while in the saturation

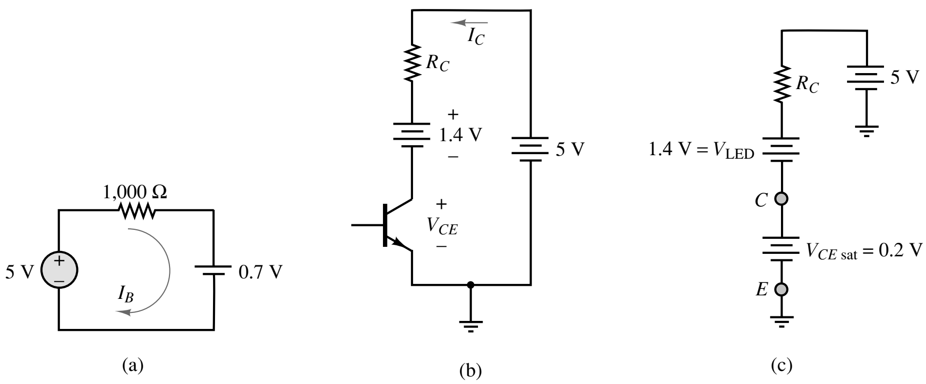


Figure 10.15 (a) *BE* circuit for LED driver; (b) equivalent collector circuit of LED driver, assuming that the BJT is in the linear active region; (c) LED driver equivalent collector circuit, assuming that the BJT is in the saturation region

region the current gain is much smaller. Since we know that the nominal β for the transistor is 95, we can calculate the base current, using the equivalent base circuit of Figure 10.15(a), and determine the ratio of base to collector current:

$$I_B = \frac{V_{ON} - V_\gamma}{R_B} = \frac{4.3}{1{,}000} = 4.3 \text{ mA}$$

The actual large-signal current gain is therefore equal to $30/4.3 = 6.7 \ll \beta$. Thus, it can be reasonably assumed that the BJT is operating in saturation.

We finally compute the LED power dissipation:

$$P_{LED} = V_{\gamma LED} I_C = 1.4 \times 0.3 = 42 \text{ mW} < 100 \text{ mW}$$

Since the power rating of the LED has not been exceeded, the design is complete.

Comments: Using the large-signal model of the BJT is quite easy, since the model simply substitutes voltage sources in place of the BE and CE junctions. To be sure that the correct model (e.g., saturation versus active region) has been employed, it is necessary to verify either the current gain or the value of the CE junction voltage. Current gains near the nominal β indicate active region operation, while small CE junction voltages denote operation in saturation.

CHECK YOUR UNDERSTANDING

Repeat the analysis of Example 10.4 for $R_S = 400\ \Omega$. In which region is the transistor operating? What is the collector current?

What is the power dissipated by the LED in Example 10.4 if $R_S = 30\ \Omega$?

Answers: Saturation; 8.5 mA; 159 mW

EXAMPLE 10.5 Simple BJT Battery Charger (BJT Current Source)

LO3

Problem

Design a constant-current battery charging circuit; that is, find the values of V_{CC}, R_1, R_2 (a potentiometer) that will cause the transistor Q_1 to act as a constant current source with selectable current range between 10 and 100 mA.

Solution

Known Quantities: Transistor large signal parameters, NiCd battery nominal voltage.

Find: V_{CC}, R_1, R_2.

Schematics, Diagrams, Circuits, and Given Data: Figure 10.16. $V_\gamma = 0.6$ V; $\beta = 100$.

Assumptions: Assume that the transistor is in the active region. Use the large-signal model with $\beta = 100$.

Analysis: According to the large-signal model, transistor Q_1 amplifies the base current by a

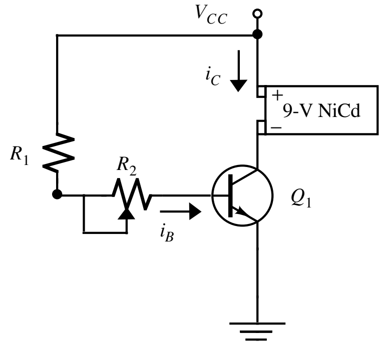


Figure 10.16 Simple battery charging circuit

factor of β. The transistor base current, i_B, is given by the expression:

$$i_B = \frac{V_{CC} - V_\gamma}{R_1 + R_2}$$

Since $i_C = \beta i_B$, the collector current, which is the battery charging current, we can solve the problem by satisfying the inequality

$$10 \text{ mA} \le i_C = \beta \left(\frac{V_{CC} - V_\gamma}{R_1 + R_2} \right) \le 100 \text{ mA}$$

The potentiometer R_2 can be set to any value ranging from zero to R_2, and the maximum current of 100 mA will be obtained when $R_2 = 0$. Thus, we can select a value of R_1 by setting

$$100 \text{ mA} = \beta \left(\frac{V_{CC} - V_\gamma}{R_1} \right) \quad \text{or } R_1 = \left(V_{CC} - V_\gamma \right) \frac{\beta}{10^{-1}} \ \Omega$$

We can select V_{CC} = 12 V (a value reasonably larger than the battery nominal voltage) and calculate

$$R_1 = (12 - 0.6) \frac{100}{10^{-1}} = 11,400 \ \Omega$$

Since 12 kΩ is a standard resistor value, we should select R_1= 12 kΩ, which will result in a slightly lower maximum current. The value of the potentiometer R_2 can be found as follows:

$$R_2 = \frac{\beta}{0.01} \left(V_{CC} - V_\gamma \right) - R_1 = 102,600 \ \Omega$$

Since 100-kΩ potentiometers are standard components, we can choose this value for our design, resulting in a slightly higher minimum current than the specified 10 mA.

Comments: A practical note on NiCd batteries: the standard 9-V NiCd batteries are actually made of eight 1.2-V cells. Thus the actual nominal battery voltage is 9.6 V. Further, as the battery becomes fully charged, each cell rises to approximately 1.3 V, leading to a full charge voltage of 10.4 V.

CHECK YOUR UNDERSTANDING

What will the collector-emitter voltage be when the battery is fully charged (10.4 V)? Is this consistent with the assumption that the transistor is in the active region?

Answer: $V_{CEQ} \approx 1.6$ V $> V_\gamma = 0.6$ V

EXAMPLE 10.6 Simple BJT Motor Drive Circuit

LO3

Problem

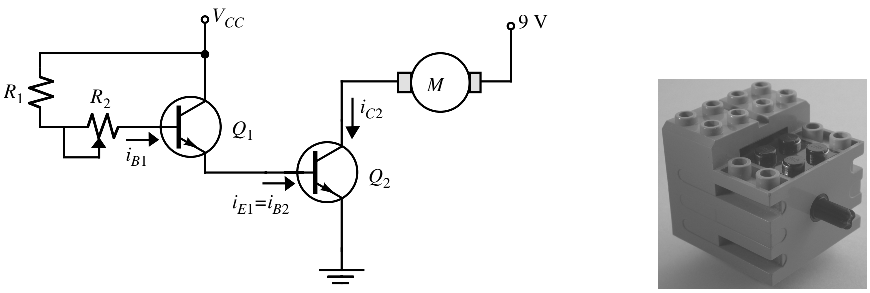
The aim of this example is to design a BJT driver for the Lego® 9V Technic motor, model 43362. Figure 10.17(a) shows the driver circuit and a picture of the motor. The motor has a maximum (stall) current of 340 mA. Minimum current to start motor rotation is 20 mA. The aim of the circuit is to control the current to the motor (and therefore the motor torque, which is proportional to the current) through potentiometer R_2.

Solution

Known Quantities: Transistor large-signal parameters, component values.

Find: Values of R_1 and R_2.

Schematics, Diagrams, Circuits, and Given Data: Figure 10.17. $V_\gamma = 0.6$ V; $\beta = 40$.



(a) BJT driver circuit

(b) Lego® 9V Technic motor, model 43362
Courtesy: Philippe "Philo" Hurbain

Figure 10.17 Motor Drive Circuit

Assumptions: Assume that the transistors are in the active region. Use the large-signal model with $\beta = 40$ for each transistor.

Analysis: The two-transistor configuration shown in Figure 10.17(a) is similar to a *Darlington pair*. This configuration is used very often and can be purchased as a single package. The emitter current from Q_1, $i_{E1} = (\beta + 1)\, i_{B1}$ becomes the base current for Q_2, and therefore,

$$i_{C2} = \beta i_{E1} = \beta(\beta + 1) i_{B1}.$$

The Q_1 base current is given by the expression

$$i_B = \frac{V_{CC} - V_\gamma}{R_1 + R_2}$$

Therefore the motor current can take the range.

$$i_{C2\,\min} \le \beta\,(\beta + 1)\left(\frac{V_{CC} - V_\gamma}{R_1 + R_2}\right) \le i_{C2\,\max}$$

The potentiometer R_2 can be set to any value ranging from zero to R_2 and the maximum (stall) current of 340 mA will be obtained when $R_2 = 0$. Thus, we can select a value of R_1 by choosing $V_{CC} = 12$ V and setting

$$i_{C2\max} = 0.34 \text{ A} = \beta(\beta+1)\left(\frac{V_{CC} - V_\gamma}{R_1}\right) \text{ or } R_1 = \frac{\beta(\beta+1)}{0.34}\left(V_{CC} - V_\gamma\right) = 54,988\ \Omega$$

Since 56 kΩ is a standard resistor value, we should select R_1= 56 kΩ, which will result in a slightly lower maximum current. The value of the potentiometer R_2 can be found from the minimum current requirement of 20 mA:

$$R_2 = \frac{\beta(\beta+1)}{0.02}\left(V_{CC} - V_\gamma\right) - R_1 = 879,810\ \Omega$$

Since 1-MΩ potentiometers are standard components, we can choose this value for our design, resulting in a slightly lower minimum current than the specified 20 mA.

Comments: While this design is quite simple, it only permits manual control of the motor current (and torque). If we wished to, say, have the motor under computer control, we would need a circuit that could respond to an external voltage. This design is illustrated in the homework problems.

CHECK YOUR UNDERSTANDING

Compute the actual current range provided by the circuit designed in Example 10.6.

Answer: $i_{C2\max} = 334$ mA; $i_{C2\min} = 17.7$ mA

Large-Signal Amplifier for Diode Thermometer

Problem:

In Chapter 9 we explored the use of a diode as the sensing element in an electronic thermometer (see the Focus on Measurements box "Diode Thermometer"). In the present example, we illustrate the design of a transistor amplifier for such a diode thermometer. The circuit is shown in Figure 10.18.

Solution:

Known Quantities— Diode and transistor amplifier bias circuits; diode voltage versus temperature response.

Find— Collector resistance and transistor output voltage versus temperature.

Schematics, Diagrams, Circuits, and Given Data— $V_{CC} = 12$ V; large-signal $\beta = 188.5$; $V_{BE} = 0.75$ V; $R_S = 500\ \Omega$; $R_B = 10$ kΩ.

Assumptions— Use a 1N914 diode and a 2N3904 transistor.

(*Continued*)

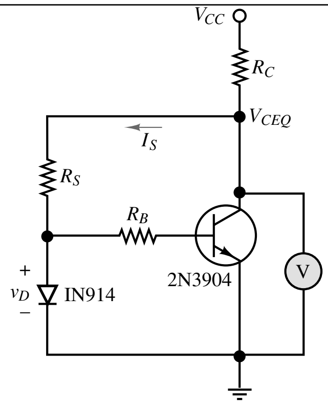
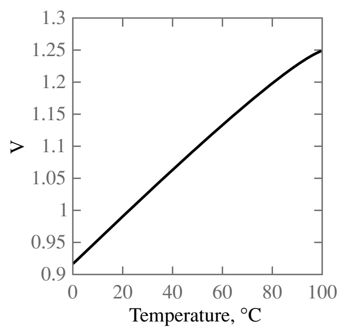


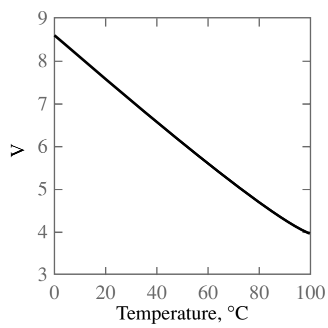
Figure 10.18 Large-signal amplifier for diode thermometer

Analysis— With reference to the circuit of Figure 10.18 and to the diode temperature response characteristic of Figure 10.19(a), we observe that the midrange diode thermometer output voltage is approximately 1.1 V. Thus, we should design the transistor amplifier so that when $v_D = 1.1$ V, the transistor output is in the center of the collector characteristic for minimum distortion. Since the collector supply is 12 V, we choose to have the Q point at $V_{CEQ} = 6$ V.



(a)

Figure 10.19(a) Diode voltage temperature dependence



(b)

Figure 10.19(b) Amplifier output

Knowing that the diode output voltage at the quiescent point is 1.1 V, we compute the quiescent base current

$$v_D - I_{BQ}R_B - V_{BEQ} = 0$$

$$I_{BQ} = \frac{v_D - V_{BEQ}}{R_B} = \frac{1.1 - 0.75}{10{,}000} = 35\ \mu\text{A}$$

(Continued)

(*Concluded*)

Knowing β, we can compute the collector current:

$$I_{CQ} = \beta I_{BQ} = 188.5 \times 35\ \mu\text{A} = 6.6\text{ mA}$$

Now we can write the collector equation and solve for the desired collector resistance:

$$V_{CC} - I_{CQ}R_C - V_{CEQ} = 0$$

$$R_C = \frac{V_{CC} - V_{CEQ}}{I_{CQ} + I_S} = \frac{12\text{ V} - 6\text{ V}}{6.6\text{ mA} + \left(\frac{V_{CEQ} - v_D}{R_S}\right)} = \frac{6\text{ V}}{16.4\text{ mA}} = 366\ \Omega$$

Once the circuit is designed according to these specifications, the output voltage can be determined by computing the base current as a function of the diode voltage (which is a function of temperature); from the base current, we can compute the collector current and use the collector equation to determine the output voltage $v_{\text{out}} = v_{CE}$. The result is plotted in Figure 10.19(b).

Comments—Note that the transistor amplifies the slope of the temperature by a factor of approximately 6. Observe also that the common-emitter amplifier used in this example causes a sign inversion in the output (the output voltage now decreases for increasing temperatures, while the diode voltage increases). Finally, we note that the design shown in this example assumes that the impedance of the voltmeter is infinite. This is a good assumption in the circuit shown, because a practical voltmeter will have a very large input resistance relative to the transistor output resistance. Should the thermometer be connected to another circuit, one would have to pay close attention to the input resistance of the second circuit to ensure that loading did not occur.

10.4 Selecting an Operating Point for a BJT

The family of curves shown for the collector i-v characteristic in Figure 10.9(b) reflects the dependence of the collector current on the base current. For each value of the base current i_B, there exists a corresponding i_C-v_{CE} curve. Thus, by appropriately selecting the base current and collector current (or collector-emitter voltage), we can determine the operating point, or ***Q* point,** of the transistor. The Q point of a device is defined in terms of the **quiescent** (or **idle**) **currents** and **voltages** that are present at the terminals of the device when DC supplies are connected to it. The circuit of Figure 10.20 illustrates an ideal **DC bias circuit,** used to set the Q point of the BJT in the approximate center of the collector characteristic. The circuit shown in Figure 10.20 is not a practical DC bias circuit for a BJT amplifier, but it is very useful for the purpose of introducing the relevant concepts. A practical bias circuit is discussed later in this section.

By appropriate choice of I_{BB}, R_C and V_{CC}, the desired Q point may be selected.

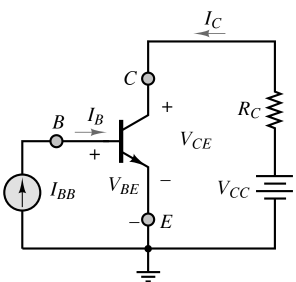


Figure 10.20 A simplified bias circuit for a BJT amplifier

Applying KVL around the base-emitter and collector circuits, we obtain the following equations:

$$I_B = I_{BB} \tag{10.4}$$

and

$$V_{CE} = V_{CC} - I_C R_C \tag{10.5}$$

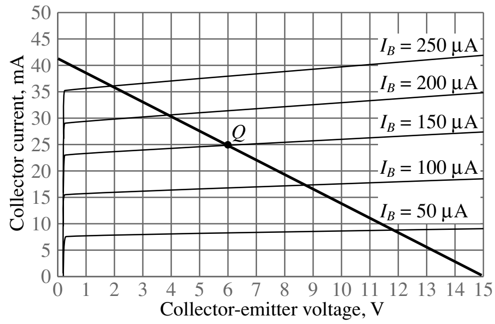


Figure 10.21 Load-line analysis of a simplified BJT amplifier

which can be rewritten as

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} \qquad \textbf{(10.6)}$$

Note the similarity of equation 10.6 to the load-line curves of Chapters 3 and 9. Equation 10.6 represents a line that intersects the I_C axis at $I_C = V_{CC}/R_C$ and the V_{CE} axis at $V_{CE} = V_{CC}$. The slope of the load line is $-1/R_C$. Since the base current I_B is equal to the source current I_{BB}, the operating point may be determined by noting that the load line intersects the entire collector family of curves. The intersection point at the curve that corresponds to the base current $I_B = I_{BB}$ constitutes the operating, or Q, point. The load line corresponding to the circuit of Figure 10.20 is shown in Figure 10.21, superimposed on the collector curves for the 2N3904 transistor. In Figure 10.21, $V_{CC} = 15$ V, $V_{CC}/R_C = 40$ mA, and $I_{BB} = 150\ \mu$A; thus, the Q point is determined by the intersection of the load line with the I_C-V_{CE} curve corresponding to a base current of 150 μA.

Once an operating point is established and direct currents I_{CQ} and I_{BQ} are flowing into the collector and base, respectively, the BJT can serve as a linear amplifier, as was explained in Section 10.2. Example 10.7 serves as an illustration of the DC biasing procedures just described.

EXAMPLE 10.7 Calculation of DC Operating Point for BJT Amplifier

LO4

Problem

Determine the DC operating point of the BJT amplifier in the circuit of Figure 10.22.

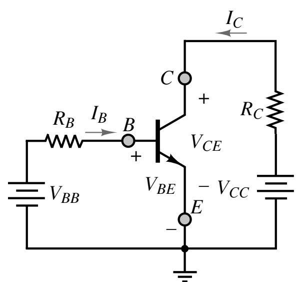


Figure 10.22

Solution

Known Quantities: Base, collector, and emitter resistances; base and collector supply voltages; collector characteristic curves; *BE* junction offset voltage.

Find: Direct (quiescent) base and collector currents I_{BQ} and I_{CQ} and collector-emitter voltage V_{CEQ}.

Schematics, Diagrams, Circuits, and Given Data: $R_B = 62.7$ kΩ; $R_C = 375\ \Omega$;

$V_{BB} = 10$ V; $V_{CC} = 15$ V; $V_\gamma = 0.6$ V. The collector characteristic curves are shown in Figure 10.21.

Assumptions: The transistor is in the active state.

Analysis: Write the load-line equation for the collector circuit:

$$V_{CE} = V_{CC} - R_C I_C = 15 - 375 I_C$$

The load line is shown in Figure 10.21; to determine the Q point, we need to determine which of the collector curves intersects the load line; that is, we need to know the base current. Applying KVL around the base circuit, and assuming that the BE junction is forward-biased (this results from the assumption that the transistor is in the active region), we get

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{V_{BB} - V_\gamma}{R_B} = \frac{10 - 0.6}{62{,}700} = 150\ \mu\text{A}$$

The intersection of the load line with the 150-μA base curve is the DC operating or quiescent point of the transistor amplifier, defined below by the three values:

$$V_{CEQ} = 7\text{ V} \qquad I_{CQ} = 22\text{ mA} \qquad I_{BQ} = 150\ \mu\text{A}$$

Comments: The base circuit consists of a battery in series with a resistance; we shall soon see that it is not necessary to employ two different voltage supplies for base and collector circuits, but that a single collector supply is sufficient to bias the transistor. Note that even in the absence of an external input to be amplified (AC source), the transistor dissipates power; most of the power is dissipated by the collector circuit: $P_{CQ} = V_{CEQ} \times I_{CQ} = 154$ mW.

CHECK YOUR UNDERSTANDING

How would the Q point change if the base current increased to 200 μA?

Answer: $V_{CEQ} \approx 4$ V, $I_{CQ} \approx 31$ mA

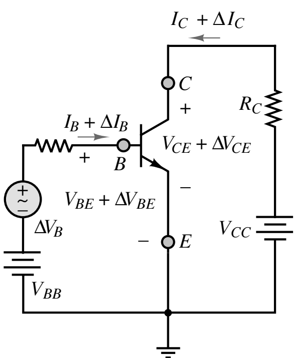


Figure 10.23 Circuit illustrating the amplification effect in a BJT

How can a transistor amplify a signal, then, given the V_{BE}-I_B and V_{CE}-I_C curves discussed in this section? The small-signal amplifier properties of the transistor are best illustrated by analyzing the effect of a small sinusoidal current superimposed on the DC flowing into the base. The circuit of Figure 10.23 illustrates the idea, by including a small-signal AC source, of strength ΔV_B, in series with the base circuit. The effect of this AC source is to cause sinusoidal oscillations ΔI_B about the Q point, that is, around I_{BQ}. A study of the collector characteristic indicates that for a sinusoidal oscillation in I_B, a corresponding, but larger oscillation will take place in the collector current. Figure 10.16 illustrates the concept. Note that the base current oscillates between 110 and 190 μA, causing the collector current to correspondingly fluctuate between 15.3 and 28.6 mA. The notation that will be used to differentiate between DC and AC (or fluctuating) components of transistor voltages and currents is as follows: DC (or quiescent) currents and voltages will be denoted by uppercase symbols, for example, I_B, I_C, V_{BE}, V_{CE}. AC components will be preceded by a Δ: $\Delta I_B(t)$, $\Delta I_C(t)$, $\Delta V_{BE}(t)$, $\Delta V_{CE}(t)$. The complete expression for one of these

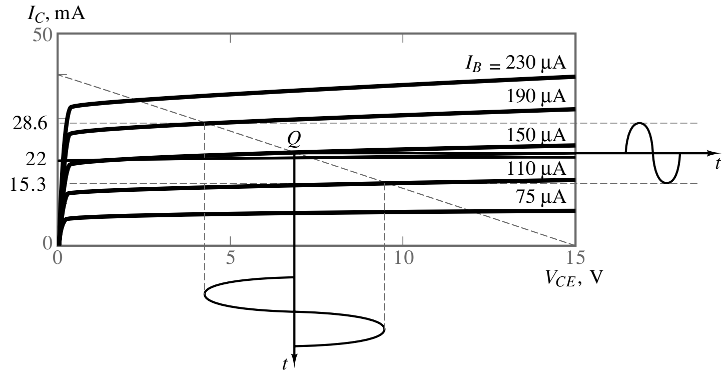


Figure 10.24 Amplification of sinusoidal oscillations in a BJT

quantities will therefore include both a DC term and a time-varying, or AC, term. For example, the collector current may be expressed by $i_C(t) = I_C + \Delta I_C(t)$.

The i-v characteristic of Figure 10.24 illustrates how an increase in collector current follows the same sinusoidal pattern of the base current but is greatly amplified. Thus, the BJT acts as a *current amplifier,* in the sense that any oscillations in the base current appear amplified in the collector current. Since the voltage across the collector resistance R_C is proportional to the collector current, one can see how the collector voltage is also affected by the amplification process. Example 10.8 illustrates numerically the effective amplification of the small AC signal that takes place in the circuit of Figure 10.23.

EXAMPLE 10.8 A BJT Small-Signal Amplifier

LO4

Problem

With reference to the BJT amplifier of Figure 10.25 and to the collector characteristic curves of Figure 10.21, determine (1) the DC operating point of the BJT, (2) the nominal current gain β at the operating point, and (3) the AC voltage gain $A_V = \Delta V_o/\Delta V_B$.

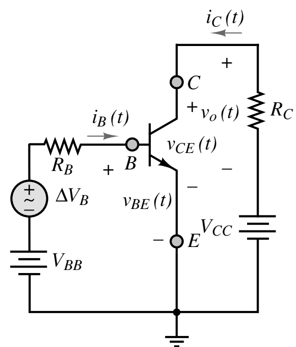


Figure 10.25

Solution

Known Quantities: Base, collector, and emitter resistances; base and collector supply voltages; collector characteristic curves; *BE* junction offset voltage.

Find: (1) DC (quiescent) base and collector currents I_{BQ} and I_{CQ} and collector-emitter voltage V_{CEQ}, (2) $\beta = \Delta I_C/\Delta I_B$, and (3) $A_V = \Delta V_o/\Delta V_B$.

Schematics, Diagrams, Circuits, and Given Data: $R_B = 10$ kΩ; $R_C = 375$ Ω; $V_{BB} = 2.1$ V; $V_{CC} = 15$ V; $V_\gamma = 0.6$ V. The collector characteristic curves are shown in Figure 10.21.

Assumptions: Assume that the *BE* junction resistance is negligible compared to the base resistance. Assume that each voltage and current can be represented by the superposition of a DC (quiescent) value and an AC component, for example, $v_0(t) = V_{0Q} + \Delta V_0(t)$.

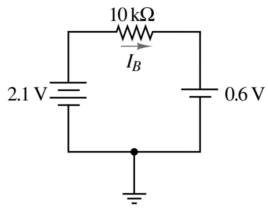


Figure 10.26

Analysis:

1. *DC operating point*. On the assumption the *BE* junction resistance is much smaller than R_B, we can state that the junction voltage is constant, $v_{BE}(t) = V_{BEQ} = V_\gamma$, and plays a role only in the DC circuit. The DC equivalent circuit for the base is shown in Figure 10.26 and described by the equation

$$V_{BB} = R_B I_{BQ} + V_{BEQ}$$

from which we compute the quiescent base current:

$$I_{BQ} = \frac{V_{BB} - V_{BEQ}}{R_B} = \frac{V_{BB} - V_\gamma}{R_B} = \frac{2.1 - 0.6}{10{,}000} = 150\ \mu\text{A}$$

To determine the DC operating point, we write the load-line equation for the collector circuit:

$$V_{CE} = V_{CC} - R_C I_C = 15 - 375 I_C$$

The load line is shown in Figure 10.27. The intersection of the load line with the 150-μA base curve is the DC operating or quiescent point of the transistor amplifier, defined below by the three values $V_{CEQ} = 7.2$ V, $I_{CQ} = 22$ mA, and $I_{BQ} = 150\ \mu$A.

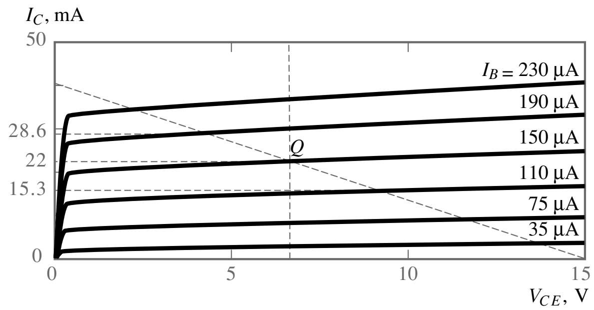


Figure 10.27 Operating point on the characteristic curve

2. *AC gain*. To determine the current gain, we resort, again, to the collector curves. Figure 10.27 indicates that if we consider the values corresponding to base currents of 190 and 110 μA, the collector will see currents of 28.6 and 15.3 mA, respectively. We can think of these collector current excursions ΔI_C from the Q point as corresponding to the effects of an oscillation ΔI_B in the base current, and we can calculate the current gain of the BJT amplifier according to

$$\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{28.6 \times 10^{-3} - 15.3 \times 10^{-3}}{190 \times 10^{-6} - 110 \times 10^{-6}} = 166.25$$

Thus, the nominal current gain of the transistor is approximately $\beta = 166$.

3. *AC voltage gain*. To determine the AC voltage gain $A_V = \Delta V_o / \Delta V_B$, we need to express ΔV_o as a function of ΔV_B. Observe that $v_o(t) = R_C i_C(t) = R_C I_{CQ} + R_C\, \Delta I_C(t)$. Thus we can write:

$$\Delta V_o(t) = -R_C\, \Delta I_C(t) = -R_C \beta\, \Delta I_B(t)$$

Using the principle of superposition in considering the base circuit, we observe that $\Delta I_B(t)$ can be computed from the KVL base equation

$$\Delta V_B(t) = R_B\, \Delta I_B(t) + \Delta V_{BE}(t)$$

but we had stated in part 1 that since the BE junction resistance is negligible relative to R_B, $\Delta V_{BE}(t)$ is also negligible. Thus,

$$\Delta I_B = \frac{\Delta V_B}{R_B}$$

Substituting this result into the expression for $\Delta V_o(t)$, we can write

$$\Delta V_o(t) = -R_C \beta \, \Delta I_B(t) = -\frac{R_C \, \beta \Delta V_B(t)}{R_B}$$

or

$$\frac{\Delta V_o(t)}{\Delta V_B} = A_V = -\frac{R_C}{R_B}\beta = -6.23$$

Comments: The circuit examined in this example is not quite a practical transistor amplifier yet, but it demonstrates most of the essential features of BJT amplifiers. We summarize them as follows.

- Transistor amplifier analysis is greatly simplified by considering the DC bias circuit and the AC equivalent circuits separately. This is an application of the principle of superposition.
- Once the bias point (or DC operating or quiescent point) has been determined, the current gain of the transistor can be determined from the collector characteristic curves. This gain is somewhat dependent on the location of the operating point.
- The AC voltage gain of the amplifier is strongly dependent on the base and collector resistance values. Note that the AC voltage gain is negative! This corresponds to a 180° phase inversion if the signal to be amplified is a sinusoid.

Many issues remain to be considered before we can think of designing and analyzing a practical transistor amplifier. It is extremely important that you master this example before studying the remainder of the section.

CHECK YOUR UNDERSTANDING

Calculate the Q point of the transistor if R_C is increased to 680 Ω.

Answer: $V_{CEQ} \approx 5$ V, $I_{BQ} \approx 110\ \mu$A, $I_{CQ} \approx 15$ mA

In discussing the DC biasing procedure for the BJT, we pointed out that the simple circuit of Figure 10.20 would not be a practical one to use in an application circuit. In fact, the more realistic circuit of Example 10.7 is also not a practical biasing circuit. The reasons for this statement are that two different supplies are required (V_{CC} and V_{BB})—a requirement that is not very practical—and that the resulting DC bias (operating) point is not very stable. This latter point may be made clearer by pointing out that the location of the operating point could vary significantly if, say, the current gain of the transistor β were to vary from device to device. A circuit that provides great improvement on both counts is shown in Figure 10.28. Observe, first, that the voltage supply V_{CC} appears across the pair of resistors R_1 and R_2, and that therefore

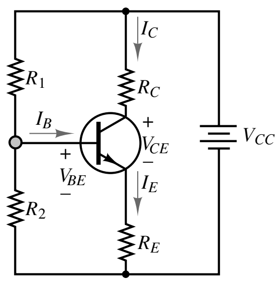


Figure 10.28 Practical BJT self-bias DC circuit

the base terminal for the transistor will see the Thévenin equivalent circuit composed of the equivalent voltage source

$$V_{BB} = \frac{R_2}{R_1 + R_2} V_{CC} \tag{10.7}$$

and of the equivalent resistance

$$R_B = R_1 \parallel R_2 \tag{10.8}$$

Figure 10.29(b) shows a redrawn DC bias circuit that makes this observation more evident. The circuit to the left of the dashed line in Figure 10.29(a) is represented in Figure 10.29(b) by the equivalent circuit composed of V_{BB} and R_B.

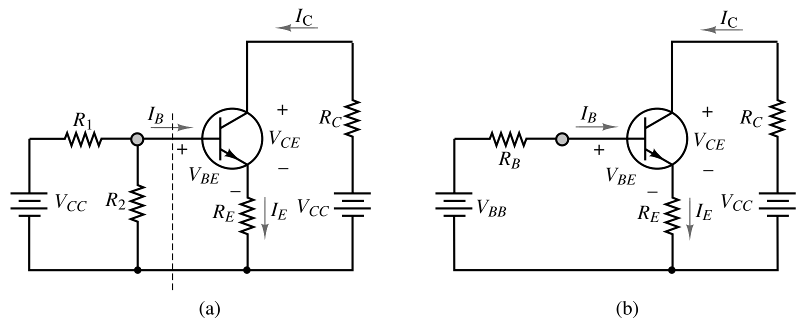


Figure 10.29 DC self-bias circuit represented in equivalent-circuit form

Recalling that the BE junction acts much as a diode, we note that the following equations describe the DC operating point of the self-bias circuit. Around the base-emitter circuit,

$$V_{BB} = I_B R_B + V_{BE} + I_E R_E = [R_B + (\beta + 1)R_E]I_B + V_{BE} \tag{10.9}$$

where V_{BE} is the BE junction voltage (diode forward voltage) and $I_E = (\beta + 1)I_B$. Around the collector circuit, on the other hand, the following equation applies:

$$V_{CC} = I_C R_C + V_{CE} + I_E R_E = I_C \left(R_C + \frac{\beta + 1}{\beta} R_E \right) + V_{CE} \tag{10.10}$$

since

$$I_E = I_B + I_C = \left(\frac{1}{\beta} + 1 \right) I_C$$

These two equations may be solved to obtain (1) an expression for the base current

$$I_B = \frac{V_{BB} - V_{BE}}{R_B + (\beta + 1)R_E} \tag{10.11}$$

from which the collector current can be determined as $I_C = \beta I_B$, and (2) an expression for the collector-emitter voltage

$$V_{CE} = V_{CC} - I_C \left(R_C + \frac{\beta + 1}{\beta} R_E \right) \tag{10.12}$$

This last equation is the load-line equation for the bias circuit. Note that the effective load resistance seen by the DC collector circuit is no longer just R_C, but is now given by

$$R_C + \frac{\beta + 1}{\beta} R_E \approx R_C + R_E$$

Example 10.9 provides a numerical illustration of the analysis of a DC self-bias circuit for a BJT.

EXAMPLE 10.9 Practical BJT Bias Circuit

LO4

Problem

Determine the DC bias point of the transistor in the circuit of Figure 10.28.

Solution

Known Quantities: Base, collector, and emitter resistances; collector supply voltage; nominal transistor current gain; BE junction offset voltage.

Find: DC (quiescent) base and collector currents I_{BQ} and I_{CQ} and collector-emitter voltage V_{CEQ}.

Schematics, Diagrams, Circuits, and Given Data: $R_1 = 100\ \text{k}\Omega$; $R_2 = 50\ \text{k}\Omega$; $R_C = 5\ \text{k}\Omega$; $R_E = 3\ \text{k}\Omega$; $V_{CC} = 15$ V; $V_\gamma = 0.7$ V, $\beta = 100$.

Analysis: We first determine the equivalent base voltage from equation 10.7

$$V_{BB} = \frac{R_2}{R_1 + R_2} V_{CC} = \frac{50}{100 + 50} 15 = 5\ \text{V}$$

and the equivalent base resistance from equation 10.8

$$R_B = R_1 \| R_2 = 33.3\ \text{k}\Omega$$

Now we can compute the base current from equation 10.11

$$I_B = \frac{V_{BB} - V_{BE}}{R_B + (\beta + 1)R_E} = \frac{V_{BB} - V_\gamma}{R_B + (\beta + 1)R_E} = \frac{5 - 0.7}{33{,}000 + 101 \times 3{,}000} = 12.8\ \mu\text{A}$$

and knowing the current gain of the transistor β, we can determine the collector current:

$$I_C = \beta I_B = 1.28\ \text{mA}$$

Finally, the collector-emitter junction voltage can be computed with reference to equation 10.12:

$$V_{CE} = V_{CC} - I_C \left(R_C + \frac{\beta + 1}{\beta} R_E \right)$$

$$= 15 - 1.28 \times 10^{-3} \left(5 \times 10^3 + \frac{101}{100} \times 3 \times 10^3 \right) = 4.78\ \text{V}$$

Thus, the Q point of the transistor is given by:

$$V_{CEQ} = 4.78\ \text{V} \qquad I_{CQ} = 1.28\ \text{mA} \qquad I_{BQ} = 12.8\ \mu\text{A}$$

CHECK YOUR UNDERSTANDING

In the circuit of Figure 10.29, find the value of V_{BB} that yields a collector current $I_C = 6.3$ mA. What is the corresponding collector-emitter voltage? Assume that $V_{BE} = 0.6$ V, $R_B = 50$ kΩ, $R_E = 200$ Ω, $R_C = 1$ kΩ, $B = 100$, and $V_{CC} = 14$ V. What percentage change in collector current would result if β were changed to 150 in Example 10.9? Why does the collector current increase less than 50 percent?

Answers: $V_{BB} = 5$ V, $V_{CE} = 6.44$ V; 3.74%. Because R_E provides negative feedback action that will keep I_C and I_E nearly constant

The material presented in this section has illustrated the basic principles that underlie the operation of a BJT and the determination of its Q point.

10.5 BJT SWITCHES AND GATES

In describing the properties of transistors, it was suggested that, in addition to serving as amplifiers, three-terminal devices can be used as electronic switches in which one terminal controls the flow of current between the other two. It had also been hinted in Chapter 9 that diodes can act as on/off devices as well. In this section, we discuss the operation of diodes and transistors as electronic switches, illustrating the use of these electronic devices as the switching circuits that are at the heart of **analog** and **digital gates.** Transistor switching circuits form the basis of digital logic circuits, which are discussed in greater detail in Chapter 13. The objective of this section is to discuss the internal operation of these circuits and to provide the reader interested in the internal workings of digital circuits with an adequate understanding of the basic principles.

An **electronic gate** is a device that, on the basis of one or more input signals, produces one of two or more prescribed outputs; as will be seen shortly, one can construct both digital and analog gates. A word of explanation is required, first, regarding the meaning of the words *analog* and *digital*. An analog voltage or current—or, more generally, an analog signal—is one that varies in a continuous fashion over time, in *analogy* (hence the expression *analog*) with a physical quantity. An example of an analog signal is a sensor voltage corresponding to ambient temperature on any given day, which may fluctuate between, say, 30 and 50°F. A digital signal, on the other hand, is a signal that can take only a finite number of values; in particular, a commonly encountered class of digital signals consists of **binary signals,** which can take only one of two values (for example, 1 and 0). A typical example of a binary signal would be the control signal for the furnace in a home heating system controlled by a conventional thermostat, where one can think of this signal as being "on" (or 1) if the temperature of the house has dropped below the thermostat setting (desired value), or "off" (or 0) if the house temperature is greater than or equal to the set temperature (say, 68°F). Figure 10.30 illustrates the appearance of the analog and digital signals in this furnace example.

The discussion of digital signals will be continued and expanded in Chapters 13, 14, and 15. Digital circuits are an especially important topic, because a large part of today's industrial and consumer electronics is realized in digital form.

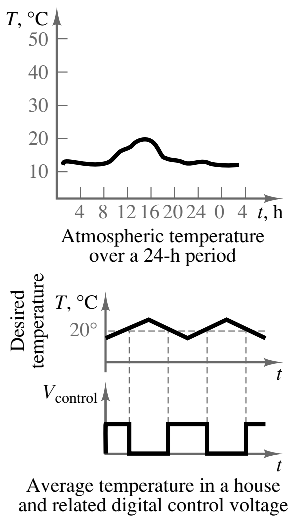


Figure 10.30 Illustration of analog and digital signals

Diode Gates

You will recall that a diode conducts current when it is forward-biased and otherwise acts very much as an open circuit. Thus, the diode can serve as a switch if properly employed. The circuit of Figure 10.31 is called an **OR gate;** it operates as follows. Let voltage levels greater than, say, 2 V correspond to a "logic 1" and voltages less than 2 V represent a "logic 0." Suppose, then, that input voltages v_A and v_B can be equal to either 0 V or 5 V. If $v_A = 5$ V, diode D_A will conduct; if $v_A = 0$ V, D_A will act as an open circuit. The same argument holds for D_B. It should be apparent, then, that the voltage across the resistor R will be 0 V, or logic 0, if both v_A and v_Bx are 0. If either v_A or v_B is equal to 5 V, though, the corresponding diode will conduct, and—assuming an offset model for the diode with $V_\gamma = 0.6$ V—we find that $v_{\text{out}} = 4.4$ V, or logic 1. Similar analysis yields an equivalent result if both v_A and v_B are equal to 5 V.

This type of gate is called an OR gate because v_{out} is equal to logic 1 (or "high") if either v_A *or* v_B is on, while it is logic 0 (or "low") if neither v_A *nor* v_B is on. Other functions can also be implemented; however, the discussion of diode gates will be limited to this simple introduction, because diode gate circuits, such as the one of Figure 10.31, are rarely, if ever, employed in practice. Most modern digital circuits employ transistors to implement switching and gate functions.

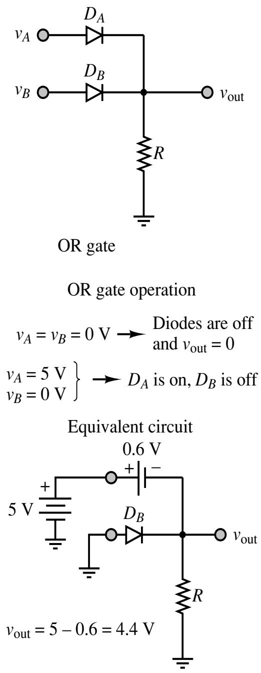


Figure 10.31 Diode OR gate

BJT Gates

In discussing large-signal models for the BJT, we observed that the i-v characteristic of this family of devices includes a *cutoff* region, where virtually no current flows through the transistor. On the other hand, when a sufficient amount of current is injected into the base of the transistor, a bipolar transistor will reach *saturation,* and a substantial amount of collector current will flow. This behavior is quite well suited to the design of electronic gates and switches and can be visualized by superimposing a load line on the collector characteristic, as shown in Figure 10.32.

The operation of the simple **BJT switch** is illustrated in Figure 10.32, by means of load-line analysis. Writing the load-line equation at the collector circuit, we have

$$v_{CE} = V_{CC} - i_C R_C \tag{10.13}$$

and

$$v_{\text{out}} = v_{CE} \tag{10.14}$$

Thus, when the input voltage v_{in} is low (say, 0 V), the transistor is in the cutoff region and little or no current flows, and

$$v_{\text{out}} = v_{CE} = V_{CC} \tag{10.15}$$

so that the output is "logic high."

When v_{in} is large enough to drive the transistor into the saturation region, a substantial amount of collector current will flow and the collector-emitter voltage will be reduced to the small saturation value $V_{CE\text{sat}}$, which is typically a fraction of a volt. This corresponds to the point labeled B on the load line. For the input voltage v_{in} to drive the BJT of Figure 10.32 into saturation, a base current of approximately 50 μA will be required. Suppose, then, that the voltage v_{in} could take the values 0 or 5 V. Then if $v_{\text{in}} = 0$ V, v_{out} will be nearly equal to V_{CC}, or, again, 5 V. If, on the other hand, $v_{\text{in}} = 5$ V and R_B is, say, equal to 89 kΩ [so that the base current required for saturation flows into the base: $i_B = (v_{\text{in}} - V_\gamma)/R_B = (5 - 0.6)/89{,}000 \approx 50\ \mu$A], we have the BJT in saturation, and $v_{\text{out}} = V_{CE\text{sat}} \approx 0.2$ V.

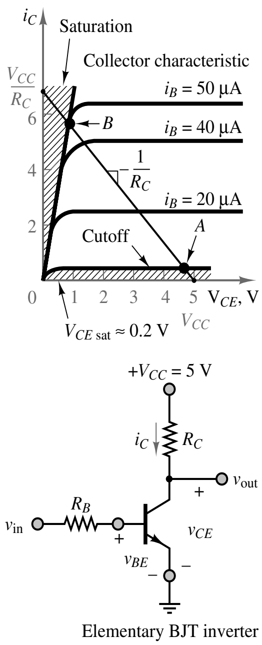


Figure 10.32 BJT switching characteristic

Thus, you see that whenever v_{in} corresponds to a logic high (or logic 1), v_{out} takes a value close to 0 V, or logic low (or 0); conversely, $v_{\text{in}} =$ "0" (logic "low") leads to $v_{\text{out}} =$ "1." The values of 5 and 0 V for the two logic levels 1 and 0 are quite common in practice and are the standard values used in a family of logic circuits denoted by the acronym **TTL,** which stands for **transistor-transistor logic.**[1] One of the more common TTL blocks is the **inverter** shown in Figure 10.32, so called because it "inverts" the input by providing a low output for a high input, and vice versa. This type of inverting, or "negative," logic behavior is quite typical of BJT gates (and of transistor gates in general).

In the following paragraphs, we introduce some elementary BJT logic gates, similar to the diode gates described previously; the theory and application of digital logic circuits are discussed in Chapter 13. Example 10.10 illustrates the operation of a **NAND gate,** that is, a logic gate that acts as an inverted AND gate (thus the prefix N in NAND, which stands for NOT).

LO5

EXAMPLE 10.10 TTL NAND Gate

Problem

Complete the table below to determine the logic gate operation of the TTL NAND gate of Figure 10.33.

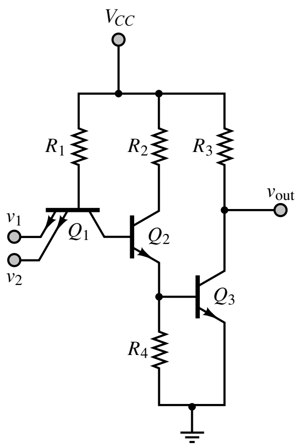


Figure 10.33 TTL NAND gate

v_1	v_2	State of Q_1	State of Q_2	v_{out}
0 V	0 V			
0 V	5 V			
5 V	0 V			
5 V	5 V			

Solution

Known Quantities: Resistor values; $V_{BE\text{on}}$ and $V_{CE\text{sat}}$ for each transistor.

Find: v_{out} for each of the four combinations of v_1 and v_2.

Schematics, Diagrams, Circuits, and Given Data: $R_1 = 5.7\ \text{k}\Omega$; $R_2 = 2.2\ \text{k}\Omega$; $R_3 = 2.2\ \text{k}\Omega$; $R_4 = 1.8\ \text{k}\Omega$; $V_{CC} = 5$ V; $V_{BE\text{on}} = V_\gamma = 0.7$ V; $V_{CE\text{sat}} = 0.2$ V.

Assumptions: Treat the BE and BC junctions of Q_1 as offset diodes. Assume that the transistors are in saturation when conducting.

Analysis: The inputs to the TTL gate, v_1 and v_2, are applied to the emitter of transistor Q_1. The transistor is designed so as to have two emitter circuits in parallel. Transistor Q_1 is modeled by the offset diode model, as shown in Figure 10.34. We now consider each of the four cases.

1. $v_1 = v_2 = 0$ V. With the emitters of Q_1 connected to ground and the base of Q_1 at 5 V, the BE junction will clearly be forward-biased and Q_1 is on. This result means that the base current of Q_2 (equal to the collector current of Q_1) is negative, and therefore Q_2 must be off. If Q_2 is off, its emitter current must be zero, and therefore no base current can flow

[1]TTL logic values are actually quite flexible, with v_{HIGH} as low as 2.4 V and v_{LOW} as high as 0.4 V.

into Q_3, which is in turn also off. With Q_3 off, no current flows through R_3, and therefore $v_{out} = 5 - v_{R3} = 5$ V.

2. $v_1 = 5$ V; $v_2 = 0$ V. Now, with reference to Figure 10.34, we see that diode D_1 is still forward-biased, but D_2 is now reverse-biased because of the 5-V potential at v_2. Since one of the two emitter branches is capable of conducting, base current will flow and Q_1 will be on. The remainder of the analysis is the same as in case 1, and Q_2 and Q_3 will both be off, leading to $v_{out} = 5$ V.
3. $v_1 = 0$ V; $v_2 = 5$ V. By symmetry with case 2, we conclude that, again, one emitter branch is conducting, and therefore Q_1 will be on, Q_2 and Q_3 will both be off, and $v_{out} = 5$ V.
4. $v_1 = 5$ V; $v_2 = 5$ V. When both v_1 and v_2 are at 5 V, diodes D_1 and D_2 are both strongly reverse-biased, and therefore no emitter current can flow. Thus, Q_1 must be off. Note, however, that while D_1 and D_2 are reverse-biased, D_3 is forward-biased, and therefore a current will flow into the base of Q_2; thus, Q_2 is on and since the emitter of Q_2 is connected to the base of Q_3, Q_3 will also see a positive base current and will be on. To determine the output voltage, we assume that Q_3 is operating in saturation. Then, applying KVL to the collector circuit, we have

$$V_{CC} = I_{C3}R_3 + V_{CE3}$$

or

$$I_{C3} = \frac{V_{CC} - V_{CE3}}{R_C} = \frac{V_{CC} - V_{CE\text{sat}}}{R_C} = \frac{5 - 0.2}{2{,}200} = 2.2 \text{ mA}$$

and

$$v_{out} = V_{CC} - I_C R_3 = 5 - 2.2 \times 10^{-3} \times 2.2 \times 10^{-3} = 5 - 4.84 = 0.16 \text{ V}$$

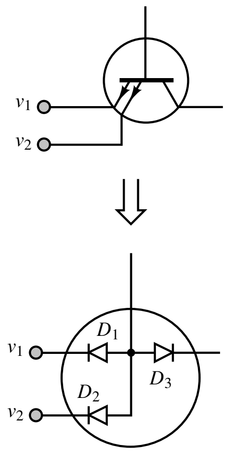


Figure 10.34

These results are summarized in the next table. The output values are consistent with TTL logic; the output voltage for case 4 is sufficiently close to zero to be considered zero for logic purposes.

v_1	v_2	State of Q_2	State of Q_3	v_{out}
0 V	0 V	Off	Off	5 V
0 V	5 V	Off	Off	5 V
5 V	0 V	Off	Off	5 V
5 V	5 V	On	On	0.16 V

Comments: While exact analysis of TTL logic gate circuits could be tedious and involved, the method demonstrated in this example—to determine whether transistors are on or off—leads to very simple analysis. Since in logic devices one is interested primarily in logic levels and not in exact values, this approximate analysis method is very appropriate.

CHECK YOUR UNDERSTANDING

Using the BJT switching characteristic of Figure 10.32, find the value of R_B required to drive the transistor to saturation, assuming that this state corresponds to a base current of 50 μA, if the minimum v_{in} for which we wish to turn the transistor on is 2.5 V.

Answer: $R_B \le 348$ kΩ

The analysis method employed in Example 10.10 can be used to analyze any TTL gate. With a little practice, the calculations of this example will become familiar. The homework problems will reinforce the concepts developed in this section.

Conclusion

This chapter introduces the bipolar junction transistor, and by way of simple circuit model demonstrates its operation as an amplifier and a switch. Upon completing this chapter, you should have mastered the following learning objectives:

1. *Understand the basic principles of amplification and switching*. Transistors are three-terminal electronic semiconductor devices that can serve as amplifiers and switches.
2. *Understand the physical operation of bipolar transistors; determine the operating point of a bipolar transistor circuit*. The bipolar junction transistor has four regions of operation. These can be readily identified by simple voltage measurements.
3. *Understand the large-signal model of the bipolar transistor, and apply it to simple amplifier circuits*. The large-signal model of the BJT is very easy to use, requiring only a basic understanding of DC circuit analysis, and can be readily applied to many practical situations.
4. *Select the operating point of a bipolar transistor circuit*. Biasing a bipolar transistor consists of selecting the appropriate values for the DC supply voltage(s) and for the resistors that comprise a transistor amplifier circuit. When biased in the forward active region, the bipolar transistor acts as a current-controlled current source, and can amplify small currents injected into the base by as much as a factor of 200.
5. *Understand the operation of a bipolar transistor as a switch and analyze basic analog and digital gate circuits*. The operation of a BJT as a switch is very straightforward, and consists of designing a transistor circuit that will go from cut-off to saturation when an input voltage changes from a high to a low value, or vice versa. Transistor switches are commonly used to design digital logic gates.

HOMEWORK PROBLEMS

Section 10.2: Operation of the Bipolar Junction Transistor

10.1 For each transistor shown in Figure P10.1, determine whether the *BE* and *BC* junctions are forward- or reverse-biased, and determine the operating region.

10.2 Determine the region of operation for the following transistors:

a. *npn*, $V_{BE} = 0.8$ V, $V_{CE} = 0.4$ V

b. *npn*, $V_{CB} = 1.4$ V, $V_{CE} = 2.1$ V

c. *pnp*, $V_{CB} = 0.9$ V, $V_{CE} = 0.4$ V

d. *npn*, $V_{BE} = -1.2$ V, $V_{CB} = 0.6$ V

10.3 Given the circuit of Figure P10.3, determine the operating point of the transistor. Assume the BJT is a silicon device with $\beta = 100$. In what region is the transistor?

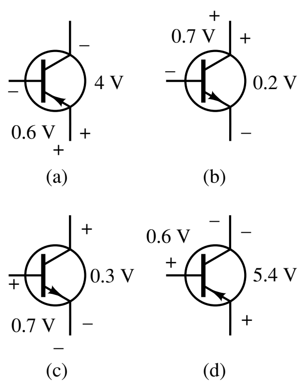


Figure P10.1

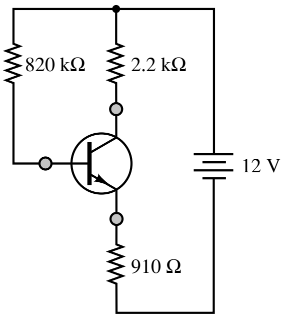


Figure P10.3

10.4 The magnitudes of a *pnp* transistor's emitter and base currents are 6 and 0.1 mA, respectively. The magnitudes of the voltages across the emitter-base and collector-base junctions are 0.65 and 7.3 V. Find

a. V_{CE}.

b. I_C.

c. The total power dissipated in the transistor, defined here as $P = V_{CE}I_C + V_{BE}I_B$.

10.5 Given the circuit of Figure P10.5, determine the emitter current and the collector-base voltage. Assume the BJT has $V_\gamma = 0.6$ V.

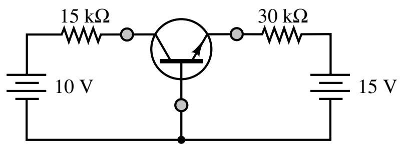


Figure P10.5

10.6 Given the circuit of Figure P10.6, determine the operating point of the transistor. Assume a 0.6-V offset voltage and $\beta = 150$. In what region is the transistor?

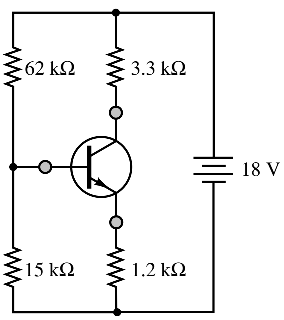


Figure P10.6

10.7 Given the circuit of Figure P10.7, determine the emitter current and the collector-base voltage. Assume the BJT has a 0.6-V offset voltage at the *BE* junction.

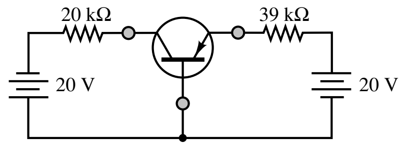


Figure P10.7

10.8 If the emitter resistor in Problem 10.7 (Figure P10.7) is changed to 22 kΩ, how does the operating point of the BJT change?

10.9 The collector characteristics for a certain transistor are shown in Figure P10.9.

a. Find the ratio I_C/I_B for $V_{CE} = 10$ V and $I_B = 100$, 200, and 600 μA.

b. The maximum allowable collector power dissipation is 0.5 W for $I_B = 500$ μA. Find V_{CE}.

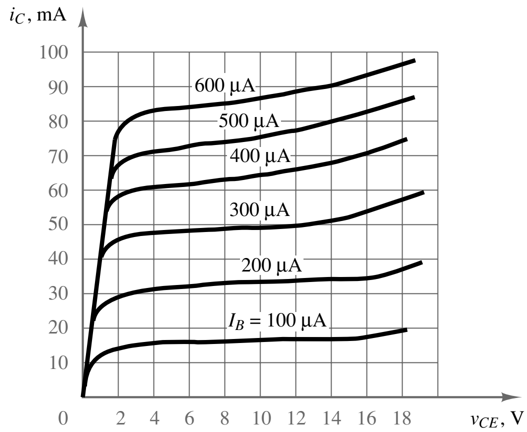


Figure P10.9

(*Hint:* A reasonable approximation for the power dissipated at the collector is the product of the collector voltage and current $P = I_C V_{CE}$, where P is the permissible power dissipation, I_C is the quiescent collector current, and V_{CE} is the operating point collector-emitter voltage.)

10.10 Given the circuit of Figure P10.10, assume both transistors are silicon-based with $\beta = 100$. Determine:

a. I_{C1}, V_{C1}, V_{CE1}

b. I_{C2}, V_{C2}, V_{CE2}

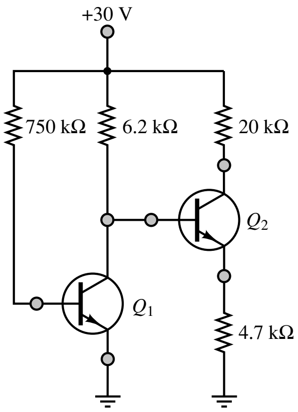


Figure P10.10

10.11 Use the collector characteristics of the 2N3904 *npn* transistor to determine the operating point (I_{CQ}, V_{CEQ}) of the transistor in Figure P10.11. What is the value of β at this point?

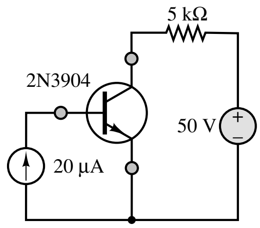


Figure P10.11

10.12 For the circuit given in Figure P10.12, verify that the transistor operates in the saturation region by computing the ratio of collector current to base current.
(*Hint:* With reference to Figure 10.20, $V_\gamma = 0.6$ V, $V_{\text{sat}} = 0.2$ V.)

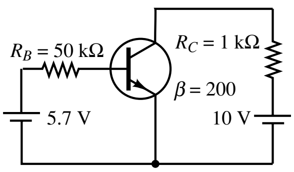


Figure P10.12

10.13 For the circuit in Figure 10.28 in the text, V_{CC} =20 V, $R_C = 5$ kΩ, and $R_E = 1$ kΩ. Determine the region of operation of the transistor if:

a. $I_C = 1$ mA, $I_B = 20\ \mu$A, $V_{BE} = 0.7$ V

b. $I_C = 3.2$ mA, $I_B = 0.3$ mA, $V_{BE} = 0.8$ V

c. $I_C = 3$ mA, $I_B = 1.5$ mA, $V_{BE} = 0.85$ V

10.14 For the circuit shown in Figure P10.14, determine the base voltage V_{BB} required to saturate the transistor. Assume that $V_{CE\text{sat}} = 0.1$ V, $V_{BE\text{sat}} = 0.6$ V, and $\beta = 50$.

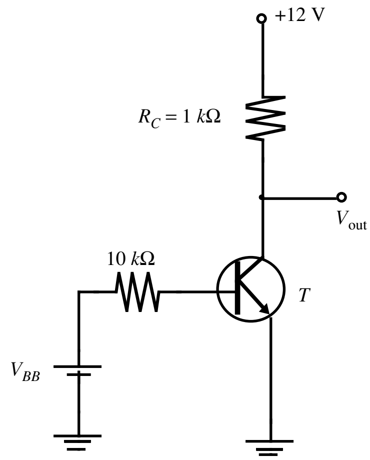


Figure P10.14

10.15 An *npn* transistor is operated in the active region with the collector current 60 times the base current and with junction voltages of $V_{BE} = 0.6$ V and $V_{CB} = 7.2$ V. If $|I_E| = 4$ mA, find (a) I_B and (b) V_{CE}.

10.16 Use the collector characteristics of the 2N3904 *npn* transistor shown in Figure P10.16(a) and (b) to determine the operating point (I_{CQ}, V_{CEQ}) of the transistor in Figure P10.16(c). What is the value of β at this point?

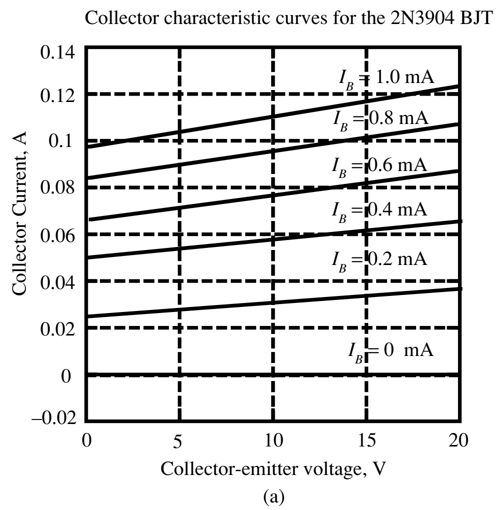


Figure P10.16 *Continued*

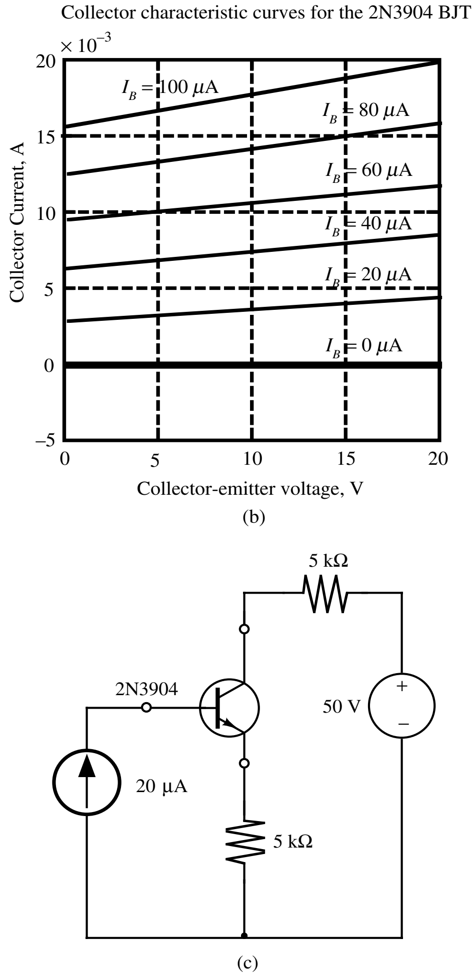


Figure P10.16

Section 10.3: **BJT Large-Signal Model**

10.17 With reference to the LED driver of Example 10.4, Figure 10.14 in the text, assume that we need to drive an LED that requires $I_{\text{LED}} = 10$ mA. All other values are unchanged. Find the range of collector resistance R_C values that will permit the transistor to supply the required current.

10.18 With reference to the diode thermometer of The Focus on Measurements box "Large-Signal Amplifier for Diode Thermometer," Figure 10.18, let $R_B = 33\ \text{k}\Omega$, $V_{CEQ} = 6$ V, v_D (voltage across diode) = 1.1 V, $V_{BEQ} = 0.75$ V. Find the value of R_C that is required to achieve the given Q point.

10.19 With reference to the LED driver of Example 10.4, Figure 10.14 in the text, assume that $R_C = 340\ \Omega$ that we need to drive an LED that requires $I_{\text{LED}} \geq 10$ mA, and that the maximum base current that can be supplied by the microprocessor is 5 mA. All other parameters and requirements are the same as in Example 10.4. Determine the range of values of the base resistance R_B that will satisfy this requirement.

10.20 Use the same data given in Problem 10.19, but assume that $R_B = 10\ \text{k}\Omega$. Find the minimum value of β that will ensure correct operation of the LED driver.

10.21 Repeat Problem 10.20 for the case of a microprocessor operating on a 3.3-V supply (that is, $V_{\text{on}} = 3.3$ V).

10.22 Consider the LED driver circuit of Figure 10.14 in the text. This circuit is now used to drive an automotive fuel injector (an electromechanical solenoid valve). The differences in the circuit are as follows: The collector resistor and the LED are replaced by the fuel injector, which can be modeled as a series *RL* circuit. The voltage supply for the fuel injector is 13 V (instead of 5 V). For the purposes of this problem, it is reasonable to assume $R = 12\ \Omega$ and $L \sim 0$. Assume that the maximum current that can be supplied by the microprocessor is 1 mA, that the current required to drive the fuel injector must be at least 1 A, and that the transistor saturation voltage is $V_{CE\text{sat}} = 1$ V. Find the minimum value of β required for the transistor.

10.23 With reference to Problem 10.22, assume $\beta = 2{,}000$. Find the allowable range of R_B.

10.24 With reference to Problem 10.22, a new generation of power-saving microcontrollers operates on 3.3-V supplies (that is, $V_{\text{on}} = 3.3$ V). Assume $\beta = 2{,}000$. Find the allowable range of R_B.

10.25 The circuit shown in Figure P10.25 is a 9-V battery charger. The purpose of the Zener diode is to provide a constant voltage across resistor R_2, such that the transistor will source a constant emitter (and therefore collector) current. Select the values of R_2, R_1, and V_{CC} such that the battery will be charged with a constant 40-mA current.

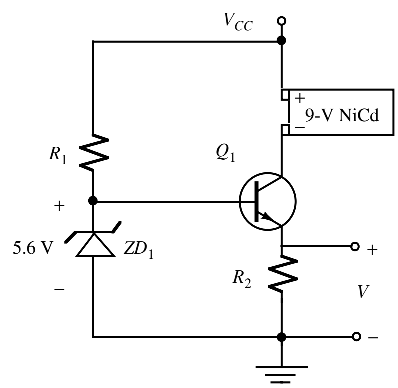


Figure P10.25

10.26 The circuit of Figure P10.26 is a variation of the battery charging circuit of Problem 10.25. Analyze the operation of the circuit and explain how this circuit will provide a decreasing charging current (taper current cycle) until the NiCd battery is fully charged (10.4 V—see note in Example 10.5). Choose appropriate values of V_{CC} and R_1 that would result in a practical design. Use standard resistor values.

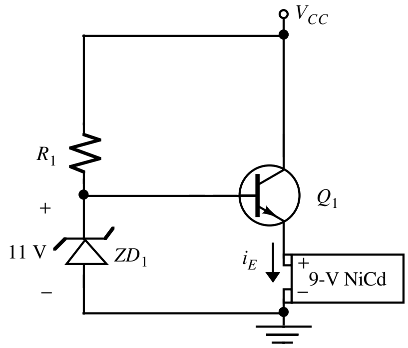


Figure P10.26

10.27 The circuit of Figure P10.27 is a variation of the motor driver circuit of Example 10.6. The external voltage v_{in} represents the analog output of a microcontroller, and ranges between zero and 5 V. Complete the design of the circuit by selecting the value of the base resistor, R_b, such that the motor will see the maximum design current when $v_{in} = 5$ V. Use the transistor β value and the design specifications for motor maximum and minimum current given in Example 10.6.

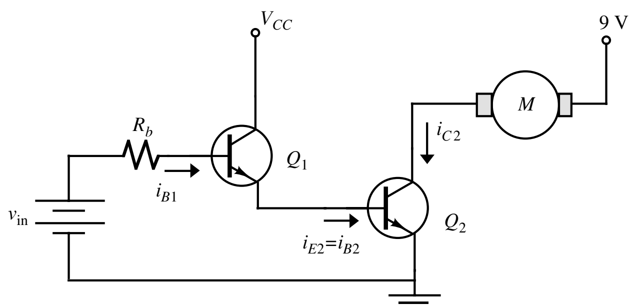


Figure P10.27

10.28 For the circuit in Figure 10.22 in the text, $R_C = 1\ \text{k}\Omega$, $V_{BB} = 5$ V, $\beta_{min} = 50$, and $V_{CC} = 10$ V. Find the range of R_B so that the transistor is in the saturation state.

10.29 For the circuit in Figure 10.22 in the text, $V_{CC} = 5$ V, $R_C = 1\ \text{k}\Omega$, $R_B = 10\ \text{k}\Omega$, and $\beta_{min} = 50$. Find the range of values of V_{BB} so that the transistor is in saturation.

10.30 For the circuit in Figure 10.20 in the text, $I_{BB} = 20\ \mu\text{A}$, $R_C = 2\ \text{k}\Omega$, $V_{CC} = 10$ V, and $\beta = 100$. Find I_C, I_E, V_{CE}, and V_{CB}.

10.31 The circuit shown in Figure P10.31 is a common-emitter amplifier stage. Determine the Thévenin equivalent of the part of the circuit containing R_1, R_2, and V_{CC} with respect to the terminals of R_2. Redraw the schematic, using the Thévenin equivalent.

$V_{CC} = 20$ V $\quad \beta = 130$
$R_1 = 1.8\ \text{M}\Omega \quad R_2 = 300\ \text{k}\Omega$
$R_C = 3\ \text{k}\Omega \quad R_E = 1\ \text{k}\Omega$
$R_L = 1\ \text{k}\Omega \quad R_S = 0.6\ \text{k}\Omega$
$v_S = 1\ \cos(6.28 \times 10^3 t)$ mV

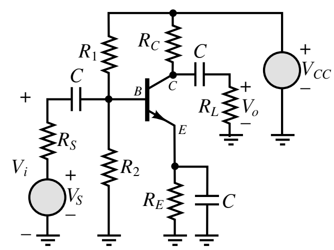


Figure P10.31

10.32 The circuit shown in Figure P10.32 is a common-collector (also called an emitter follower) amplifier stage implemented with an *npn* silicon transistor. Determine V_{CEQ} at the DC operating or Q point.

$V_{CC} = 12$ V $\quad \beta = 130$
$R_1 = 82\ \text{k}\Omega \quad R_2 = 22\ \text{k}\Omega$
$R_S = 0.7\ \text{k}\Omega \quad R_E = 0.5\ \text{k}\Omega$
$R_L = 16\ \Omega$

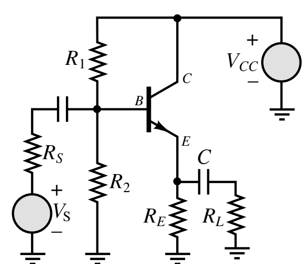


Figure P10.32

10.33 Shown in Figure P10.33 is a common-emitter amplifier stage implemented with an *npn* silicon transistor and two DC supply voltages (one positive and one negative) instead of one. The DC bias circuit connected to the base consists of a single resistor. Determine V_{CEQ} and the region of operation.

$V_{CC} = 12$ V $\quad V_{EE} = 4$ V
$\beta = 100 \quad R_B = 100$ kΩ
$R_C = 3$ kΩ $\quad R_E = 3$ kΩ
$R_L = 6$ kΩ $\quad R_S = 0.6$ kΩ
$v_S = 1\ \cos(6.28 \times 10^3 t)$ mV

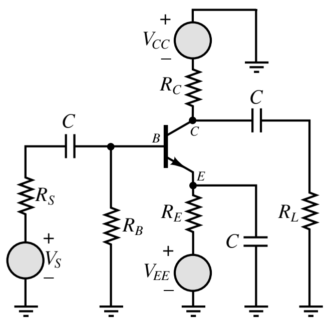


Figure P10.33

10.34 Shown in Figure P10.34 is a common-emitter amplifier stage implemented with an *npn* silicon transistor. The DC bias circuit connected to the base consists of a single resistor; however, it is connected directly between base and collector. Determine V_{CEQ} and the region of operation.

$V_{CC} = 12$ V
$\beta = 130 \quad R_B = 325$ kΩ
$R_C = 1.9$ kΩ $\quad R_E = 2.3$ kΩ
$R_L = 10$ kΩ $\quad R_S = 0.5$ kΩ
$v_S = 1\ \cos(6.28 \times 10^3 t)$ mV

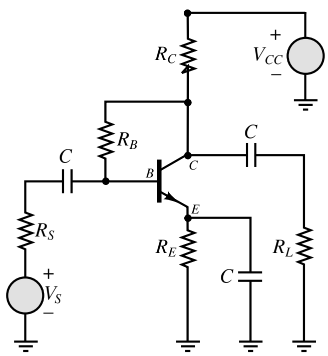


Figure P10.34

10.35 For the circuit shown in Figure P10.35 v_S is a small sine wave signal with average value of 3 V. If $\beta = 100$ and $R_B = 60$ kΩ.

a. Find the value of R_E so that I_E is 1 mA.

b. Find R_C so that V_C is 5 V.

c. For $R_L = 5$ kΩ, find the small-signal equivalent circuit of the amplifier.

d. Find the voltage gain.

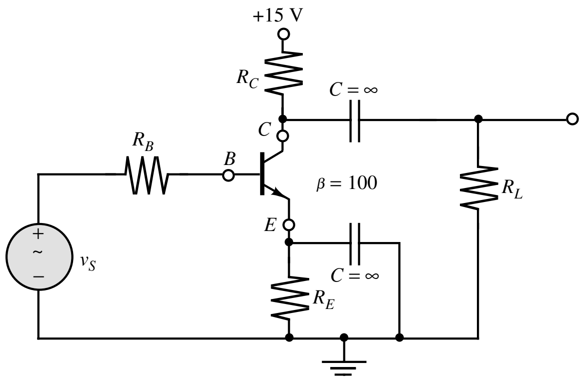


Figure P10.35

10.36 The circuit in Figure P10.36 is in the common-collector configuration. Assuming $R_C = 200\ \Omega$:

a. Find the operating point of the transistor.

b. If the voltage gain is defined as $v_{\text{out}}/v_{\text{in}}$, find the voltage gain. If the current gain is defined as $i_{\text{out}}/i_{\text{in}}$, find the current gain.

c. Find the input resistance, r_i.

d. Find the output resistance, r_o.

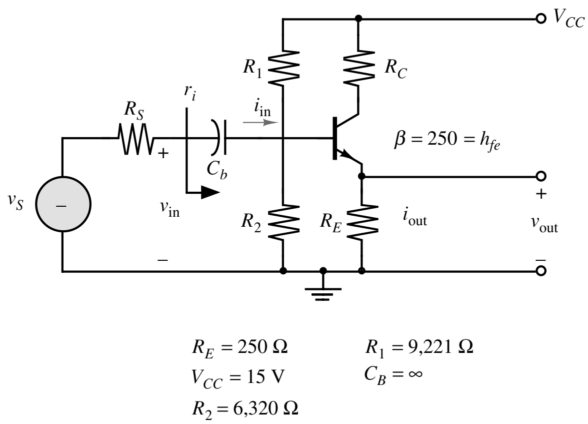


Figure P10.36

10.37 The circuit that supplies energy to an automobile's fuel injector is shown in Figure P10.37(a). The internal circuitry of the injector can be modeled as shown in Figure P10.37(b). The injector will inject gasoline into the intake manifold when $I_{inj} \geq 0.1$ A. The voltage V_{signal} is a pulse train whose shape is as shown in Figure P10.37(c). If the engine is cold and under start-up conditions, the signal duration, τ, is determined by the equation

$$\tau = \text{BIT} \times K_C + \text{VCIT}$$

where

BIT = Basic injection time = 1 ms
K_C = Compensation constant of temperature of coolant (T_C)
VCIT = Voltage-compensated injection time

The characteristics of VCIT and K_C are shown in Figure P10.37(d).
If the transistor, Q_1, saturates at $V_{CE} = 0.3$ V and $V_{BE} = 0.9$ V, find the duration of the fuel injector pulse if

a. $V_{batt} = 13$ V, $T_C = 100°$C
b. $V_{batt} = 8.6$ V, $T_C = 20°$C

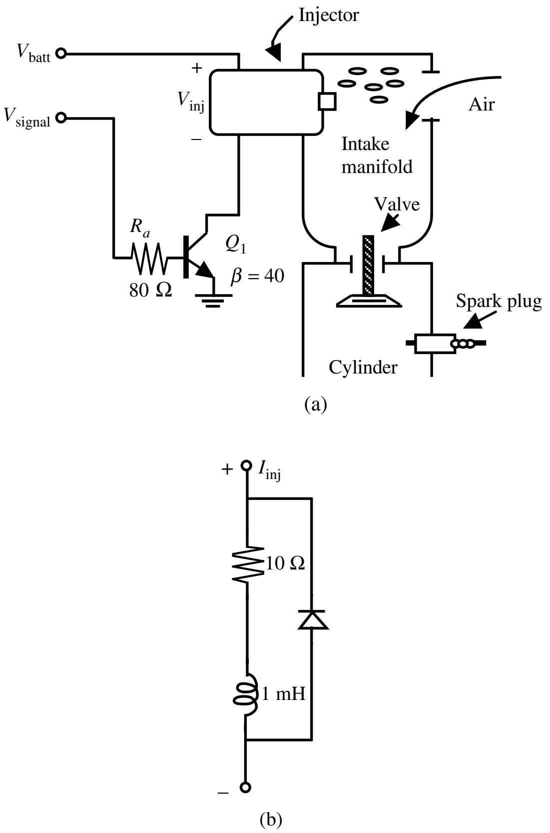


Figure P10.37 *Continued*

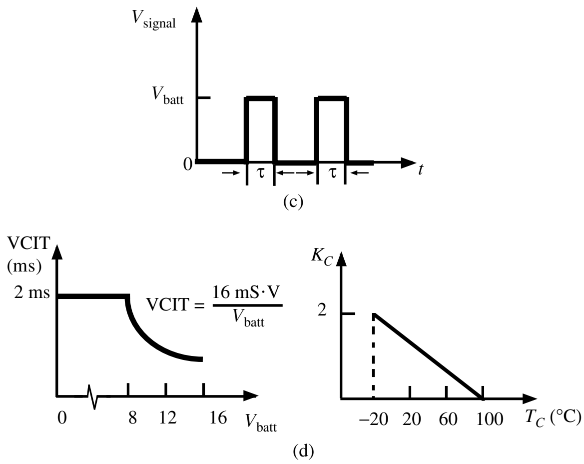


Figure P10.37

10.38 The circuit shown in Figure P10.38 is used to switch a relay that turns a light off and on under the control of a computer. The relay dissipates 0.5 W at 5 VDC. It switches on at 3 VDC and off at 1.0 VDC. What is the maximum frequency with which the light can be switched? The inductance of the relay is 5 mH, and the transistor saturates at 0.2 V, $V_\gamma = 0.8$ V.

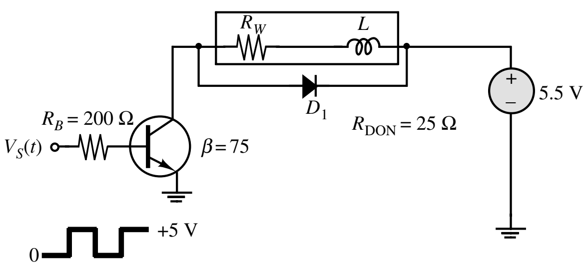


Figure P10.38

10.39 A Darlington pair of transistors is connected as shown in Figure P10.39. The transistor parameters for large-signal operation are Q_1: $\beta = 130$; Q_2: $\beta = 70$. Calculate the overall current gain.

10.40 The transistor shown in Figure P10.40 has $V_X = 0.6$ V. Determine values for R_1 and R_2 such that

a. The DC collector-emitter voltage, V_{CEQ}, is 5 V.
b. The DC collector current, I_{CQ}, will vary no more than 10% as β varies from 20 to 50.
c. Values of R_1 and R_2 which will permit maximum symmetrical swing in the collector current. Assume $\beta = 100$.

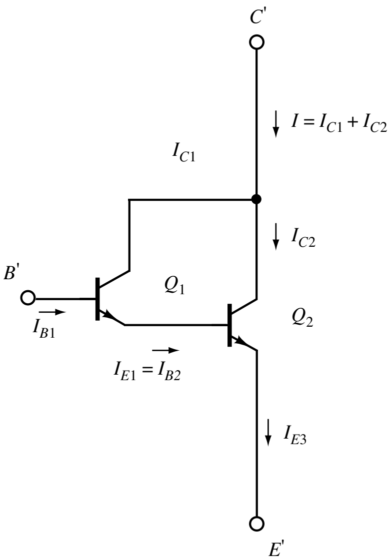


Figure P10.39

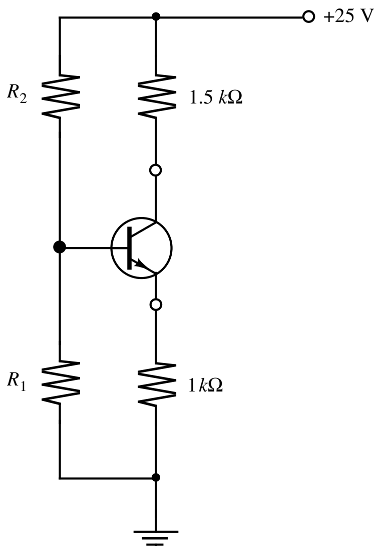


Figure P10.40

Section 10.4: BJT Switches and Gates

10.41 Show that the circuit of Figure P10.41 functions as an OR gate if the output is taken at v_{o1}.

10.42 Show that the circuit of Figure P10.41 functions as a NOR gate if the output is taken at v_{o2}.

10.43 Show that the circuit of Figure P10.43 functions as an AND gate if the output is taken at v_{o1}.

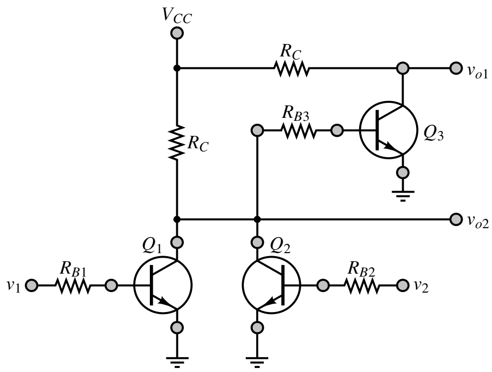


Figure P10.41

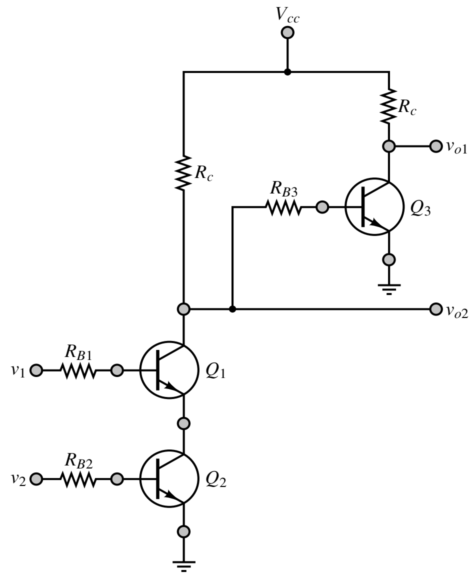


Figure P10.43

10.44 Show that the circuit of Figure P10.43 functions as a NAND gate if the output is taken at v_{o2}.

10.45 In Figure P10.45, the minimum value of v_{in} for a high input is 2.0 V. Assume that transistor Q_1 has a β of at least 10. Find the range for resistor R_B that can guarantee that the transistor Q_1 is on.

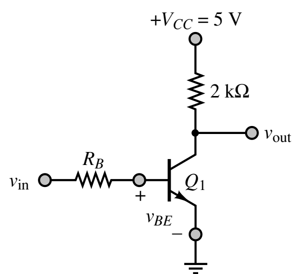


Figure P10.45

10.46 Figure P10.46 shows a circuit with two transistor inverters connected in series, where $R_{1C} = R_{2C} = 10$ kΩ and $R_{1B} = R_{2B} = 27$ kΩ.

a. Find v_B, v_{out}, and the state of transistor Q_1 when v_{in} is low.

b. Find v_B, v_{out}, and the state of transistor Q_1 when v_{in} is high.

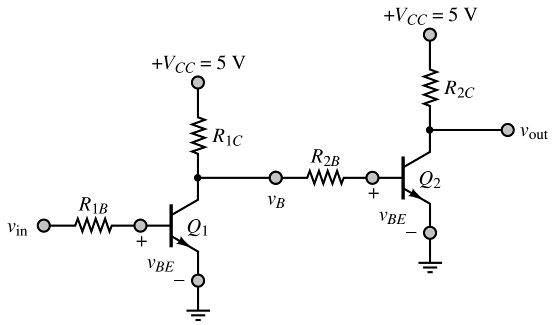


Figure P10.46

10.47 For the inverter of Figure P10.47, $R_B = 5$ kΩ and $R_{C1} = R_{C2} = 2$ kΩ. Find the minimum values of β_1 and β_2 to ensure that Q_1 and Q_2 saturate when v_{in} is high.

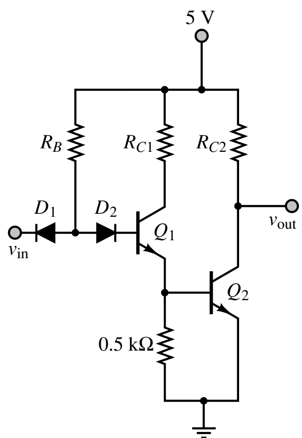


Figure P10.47

10.48 For the inverter of Figure P10.47, $R_B = 4$ kΩ, $R_{C1} = 2.5$ kΩ, and $\beta_1 = \beta_2 = 4$. Show that Q_1 saturates when v_{in} is high. Find a condition for R_{C2} to ensure that Q_2 also saturates.

10.49 The basic circuit of a TTL gate is shown in the circuit of Figure P10.49. Determine the logic function performed by this circuit.

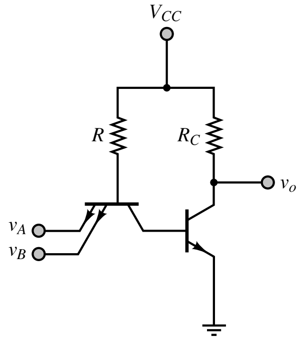


Figure P10.49

10.50 Figure P10.50 is a circuit diagram for a three-input TTL NAND gate. Assuming that all the input voltages are high, find v_{B1}, v_{B2}, v_{B3}, v_{C2}, and v_{out}. Also indicate the operating region of each transistor.

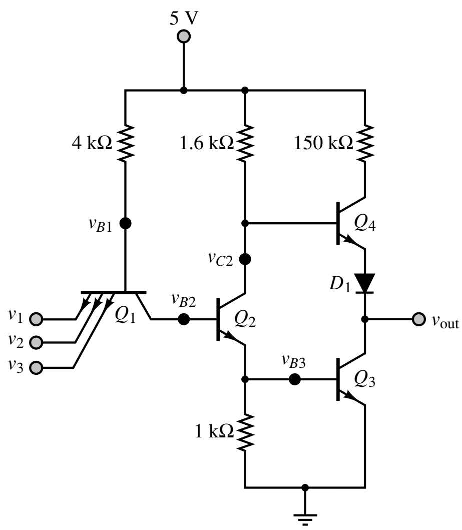


Figure P10.50

10.51 Show that when two or more emitter-follower outputs are connected to a common load, as shown in the circuit of Figure P10.51, the OR operation results; that is, $v_o = v_1$ OR v_2.

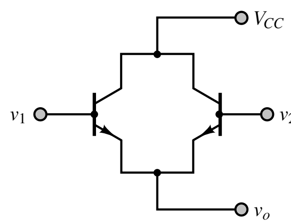


Figure P10.51