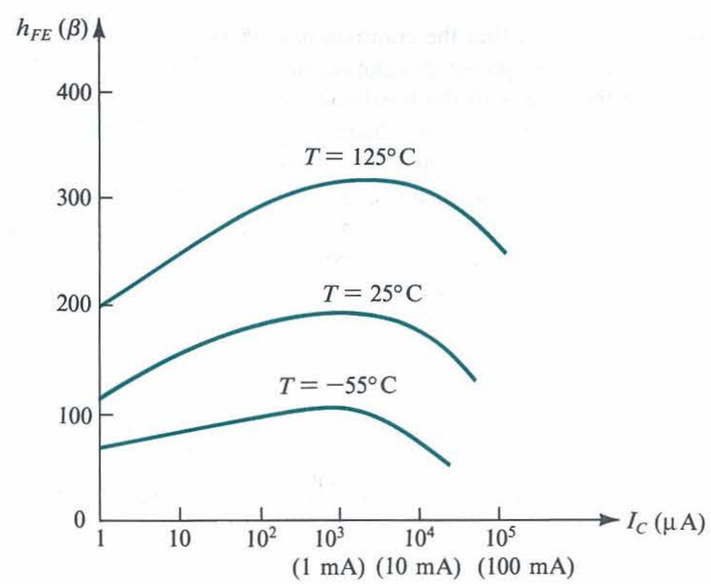

Figure 4.34 Typical dependence of β on I_C and on temperature in an integrated-circuit *npn* silicon transistor intended for operation around 1 mA.

Summary

- Depending on the bias conditions on its two junctions, the BJT can operate in one of three possible modes: cutoff (both junctions reverse biased), active (the EBJ forward biased and the CBJ reverse biased), and saturation (both junctions forward biased). Refer to Table 4.1.
- For amplifier applications, the BJT is operated in the active mode. Switching applications make use of the cutoff and saturation modes.
- A BJT operating in the active mode provides a collector current $i_C = I_S e^{|v_{BE}|/V_T}$. The base current $i_B = i_C/\beta$, and the emitter current $i_E = i_C + i_B$. Also, $i_C = \alpha i_E$, and thus $\beta = \alpha/(1-\alpha)$ and $\alpha = \beta/(\beta+1)$. See Table 4.2.
- To ensure operation in the active mode, the collector voltage of an *npn* transistor must be kept higher than approximately 0.4 V below the base voltage. For a *pnp* transistor, the collector voltage must be lower than approximately 0.4 V above the base voltage. Otherwise, the CBJ becomes forward biased, and the transistor enters the saturation region.
- At a constant collector current, the magnitude of the base–emitter voltage decreases by about 2 mV for every 1°C rise in temperature.
- The BJT will be at the edge of saturation when $|v_{CE}|$ is reduced to about 0.3 V. In saturation, $|v_{CE}| \simeq 0.2$ V, and the ratio of i_C to i_B is lower than β (i.e., $\beta_{\text{forced}} < \beta$).
- In the active mode, i_C shows a slight dependence on v_{CE}. This phenomenon, known as the Early effect, is modeled by ascribing a finite (i.e., noninfinite) output resistance to the BJT: $r_o = |V_A|/I'_C$, where V_A is the Early voltage and I'_C is the dc collector current without the Early effect taken into account. In discrete circuits, r_o plays a minor role and can usually be neglected. This is *not* the case, however, in integrated-circuit design (Chapter 7).
- The dc analysis of transistor circuits is greatly simplified by assuming that $|V_{BE}| \simeq 0.7$ V. Refer to Table 4.3.
- If the BJT is conducting, one assumes it is operating in the active mode and, using the active-mode model, proceeds to determine all currents and voltages. The validity of the initial assumption is then checked by determining whether the CBJ is reverse biased. If it is, the analysis is complete; otherwise, we assume the BJT is operating in saturation and redo the analysis, using the saturation-mode model and checking at the end that $I_C < \beta I_B$.

Computer Simulations Problems

SIM Problems identified by the Multisim/PSpice icon are intended to demonstrate the value of using SPICE simulation to verify hand analysis and design, and to investigate important issues such as allowable signal swing and amplifier nonlinear distortion. Instructions to assist in setting up PSPice and Multisim simulations for all the indicated problems can be found in the corresponding files on the website. Note that if a particular parameter value is not specified in the problem statement, you are to make a reasonable assumption.

Section 4.1: Device Structure and Physical Operation

4.1 The terminal voltages of various *npn* transistors are measured during operation in their respective circuits with the following results:

Case	E	B	C	Mode
1	0	0.7	0.7	
2	0	0.8	0.1	
3	−0.7	0	1.0	
4	−0.7	0	−0.6	
5	1.3	2.0	5.0	
6	0	0	5.0	

In this table, where the entries are in volts, 0 indicates the reference terminal to which the black (negative) probe of the voltmeter is connected. For each case, identify the mode of operation of the transistor.

4.2 Two transistors, fabricated with the same technology but having different junction areas, when operated at a base-emitter voltage of 0.75 V, have collector currents of 0.5 mA and 2 mA. Find I_S for each device. What are the relative junction areas?

4.3 Find the collector currents that you would expect for operation at $v_{BE} = 700$ mV for transistors for which $I_S = 10^{-13}$ A and $I_S = 10^{-18}$ A. For the transistor with the larger EBJ, what is the v_{BE} required to provide a collector current equal to that provided by the smaller transistor at $v_{BE} = 700$ mV? Assume active-mode operation in all cases.

4.4 Two transistors have EBJ areas as follows: $A_{E1} = 200\ \mu\text{m} \times 200\ \mu\text{m}$ and $A_{E2} = 0.4\ \mu\text{m} \times 0.4\ \mu\text{m}$. If the two transistors are operated in the active mode and conduct equal collector currents, what do you expect the difference in their v_{BE} values to be?

4.5 In this problem, we contrast two BJT integrated-circuit fabrication technologies: For the "old" technology, a typical *npn* transistor has $I_S = 2 \times 10^{-15}$ A, and for the "new" technology, a typical *npn* transistor has $I_S = 2 \times 10^{-18}$ A. These typical devices have vastly different junction areas and base width. For our purpose here we wish to determine the v_{BE} required to establish a collector current of 1 mA in each of the two typical devices. Assume active-mode operation.

4.6 In a particular BJT, the base current is 10 μA, and the collector current is 800 μA. Find β and α for this device.

4.7 Find the values of β that correspond to α values of 0.5, 0.8, 0.9, 0.95, 0.98, 0.99, 0.995, and 0.999.

4.8 Find the values of α that correspond to β values of 1, 2, 10, 20, 50, 100, 200, 500, and 1000.

***4.9** Show that for a transistor with α close to unity, if α changes by a small per-unit amount $(\Delta\alpha/\alpha)$, the corresponding per-unit change in β is given approximately by

$$\frac{\Delta\beta}{\beta} \simeq \beta\left(\frac{\Delta\alpha}{\alpha}\right)$$

Now, for a transistor whose nominal β is 100, find the percentage change in its α value corresponding to a drop in its β of 10%.

4.10 An *npn* transistor of a type whose β is specified to range from 50 to 300 is connected in a circuit with emitter grounded, collector at +10 V, and a current of 10 μA injected into the base. Calculate the range of collector and emitter currents that can result. What is the maximum power dissipated in the transistor? (*Note:* Perhaps you can see why this is a bad way to establish the operating current in the collector of a BJT.)

4.11 Measurements made on a number of transistors operating in the active mode with $i_E = 1$ mA indicate base currents

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem of 10 μA, 20 μA, and 50 μA. For each device, find i_C, β, and α.

4.12 A BJT is specified to have $I_S = 5 \times 10^{-15}$ A and β that falls in the range of 50 to 200. If the transistor is operated in the active mode with v_{BE} set to 0.700 V, find the expected range of i_C, i_B, and i_E.

4.13 Measurements of V_{BE} and two terminal currents taken on a number of *npn* transistors operating in the active mode are tabulated below. For each, calculate the missing current value as well as α, β, and I_S as indicated by the table.

Transistor	a	b	c	d	e
V_{BE} (mV)	700	690	580	780	820
I_C (mA)	1.000	1.000		10.10	
I_B (μA)	10		5	120	1050
I_E (mA)		1.020	0.235		75.00
α					
β					
I_S					

4.14 When operated in the active mode, a particular *npn* BJT conducts a collector current of 1 mA and has $v_{BE} = 0.70$ V and $i_B = 10$ μA. Use these data to create specific transistor models of the form shown in Fig. 4.5(a) to (d).

4.15 Using the *npn* transistor model of Fig. 4.5(b), consider the case of a transistor for which the base is connected to ground, the collector is connected to a 5-V dc source through a 2-kΩ resistor, and a 2-mA current source is connected to the emitter with the polarity so that current is drawn out of the emitter terminal. If $\beta = 100$ and $I_S = 5 \times 10^{-15}$ A, find the voltages at the emitter and the collector and calculate the base current.

D 4.16 Consider an *npn* transistor operated in the active mode and represented by the model of Fig. 4.5(d). Let the transistor be connected as indicated by the equivalent circuit shown in Fig. 4.6(b). It is required to calculate the values of R_B and R_C that will establish a collector current I_C of 0.5 mA and a collector-to-emitter voltage V_{CE} of 1 V. The BJT is specified to have $\beta = 50$ and $I_S = 5 \times 10^{-15}$ A.

4.17 An *npn* transistor has a CBJ with an area 100 times that of the EBJ. If $I_S = 10^{-15}$ A, find the voltage drop across EBJ and across CBJ when each is forward biased and conducting a current of 1 mA. Also find the forward current each junction would conduct when forward biased with 0.5 V.

***4.18** Use Eqs. (4.14), (4.15), and (4.16) to show that an *npn* transistor operated in saturation exhibits a collector-to-emitter voltage, V_{CEsat}, given by

$$V_{CEsat} = V_T \ln\left[\left(\frac{I_{SC}}{I_S}\right)\frac{1+\beta_{forced}}{1-\beta_{forced}/\beta}\right]$$

Use this relationship to evaluate V_{CEsat} for $\beta_{forced} = 50$, 10, 5, and 1 for a transistor with $\beta = 100$ and with a CBJ area 100 times that of the EBJ. Present your results in a table.

***4.19** We wish to investigate the operation of the *npn* transistor in saturation using the model of Fig. 4.9. Let $I_S = 10^{-15}$ A, $v_{BE} = 0.7$ V, $\beta = 100$, and $I_{SC}/I_S = 100$. For each of three values of v_{CE} (namely, 0.4 V, 0.3 V, and 0.2 V), find v_{BC}, i_{BC}, i_{BE}, i_B, i_C, and i_C/i_B. Present your results in tabular form. Also find v_{CE} that results in $i_C = 0$.

4.20 Consider the *pnp* large-signal model of Fig. 4.11(b) applied to a transistor having $I_S = 10^{-14}$ A and $\beta = 50$. If the emitter is connected to ground, the base is connected to a current source that pulls 10 μA out of the base terminal, and the collector is connected to a negative supply of –5 V via a 8.2-kΩ resistor, find the collector voltage, the emitter current, and the base voltage.

4.21 A *pnp* transistor modeled with the circuit in Fig. 4.11 (b) is connected with its base at ground, collector at –2.0 V, and a 1-mA current is injected into its emitter. If the transistor is said to have $\beta = 10$, what are its base and collector currents? In which direction do they flow? If $I_S = 10^{-15}$ A, what voltage results at the emitter? What does the collector current become if a transistor with $\beta = 1000$ is substituted? (*Note:* The fact that the collector current changes by less than 10% for a large change in β illustrates that this is a good way to establish a specific collector current.)

4.22 A *pnp* power transistor operates with an emitter-to-collector voltage of 5 V, an emitter current of 5 A, and $V_{EB} = 0.8$ V. For $\beta = 20$, what base current is required? What is I_S for this transistor? Compare the emitter–base junction area of this transistor with that of a small-signal transistor that conducts $i_C = 1$ mA with $v_{EB} = 0.70$ V. How much larger is it?

4.23 While Fig. 4.5 provides four possible large-signal equivalent circuits for the *npn* transistor, only two equivalent circuits for the *pnp* transistor are provided in Fig. 4.11. Supply the missing two.

4.24 By analogy to the *npn* case shown in Fig. 4.9, give the equivalent circuit of a *pnp* transistor in saturation.

Section 4.2: Current–Voltage Characteristics

4.25 For the circuits in Fig. P4.25, assume that the transistors have very large β. Some measurements have been made on these circuits, with the results indicated in the figure. Find the values of the other labeled voltages and currents.

4.26 Measurements on the circuits of Fig. P4.26 produce labeled voltages as indicated. Find the value of β for each transistor.

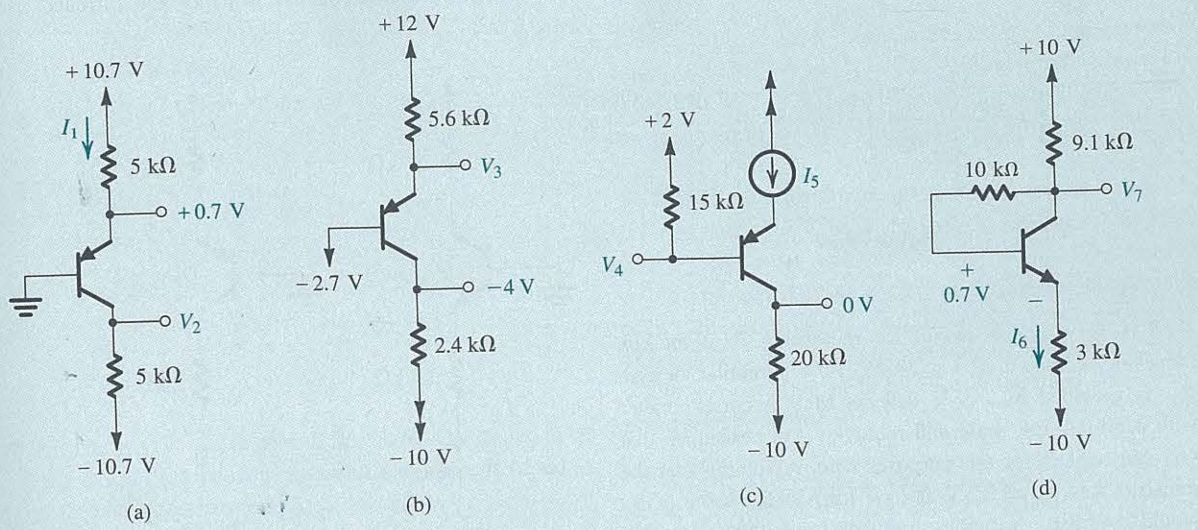

Figure P4.25

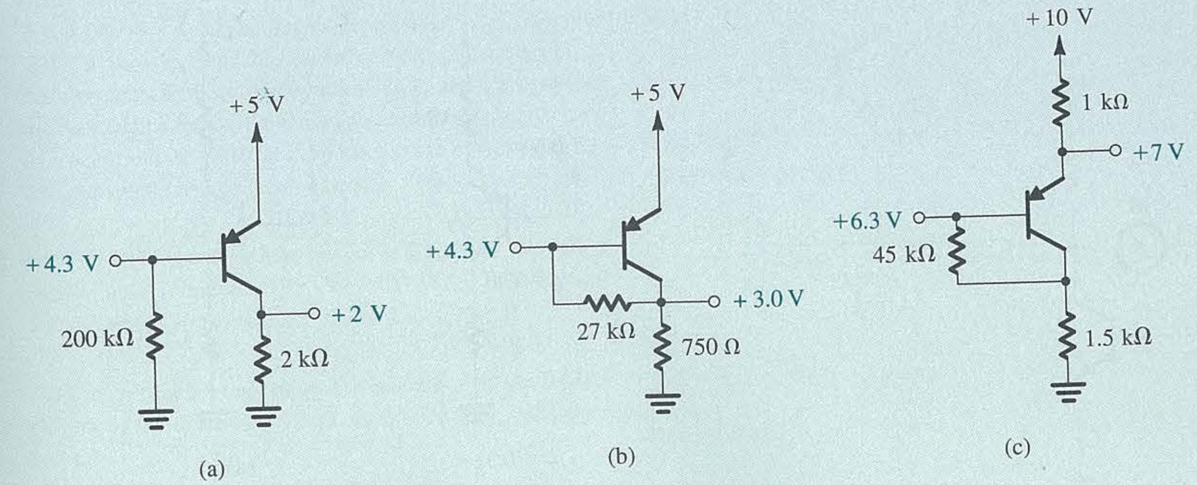

Figure P4.26

D 4.27 Design the circuit in Fig. P4.27 to establish a current of 0.5 mA in the emitter and a voltage of −0.5 V at the collector. The transistor $v_{EB} = 0.64$ V at $I_E = 0.1$ mA, and $\beta = 100$. To what value can R_C be increased while the collector current remains unchanged?

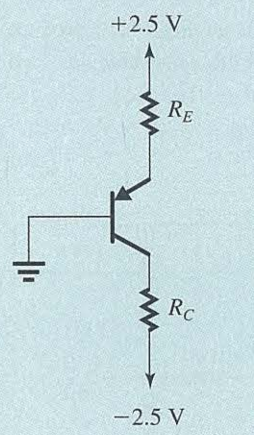

Figure P4.27

4.28 A very simple circuit for measuring β of an *npn* transistor is shown in Fig. P4.28. In a particular design, V_{CC} is provided by a 9-V battery; M is a current meter with a 50-μA full scale and relatively low resistance that you can neglect for our purposes here. Assuming that the transistor has $V_{BE} = 0.7$ V at $I_E = 1$ mA, what value of R_C would establish a resistor current of 1 mA? Now, to what value β does a meter reading of full scale correspond? What of is β if the meter reading is 1/5 of full scale? 1/10 of full scale?

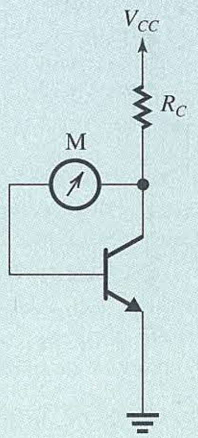

Figure P4.28

D 4.29 Examination of the table of standard values for resistors with 5% tolerance in Appendix J reveals that the closest values to those found in the design of Example 4.2 are 5.1 kΩ and 4.8 kΩ. For these values, use approximate calculations (e.g., $V_{BE} \simeq 0.7$ V and $\alpha \simeq 1$) to determine the values of collector current and collector voltage that are likely to result.

4.30 For each of the circuits shown in Fig. P4.30, find the emitter, base, and collector voltages and currents. Use $\beta = 50$, but assume $|V_{BE}| = 0.8$ V independent of current level.

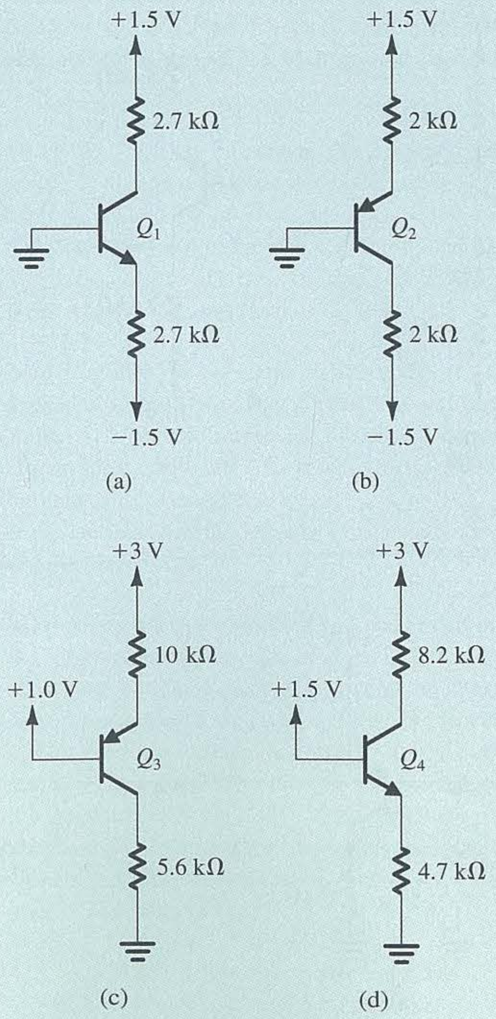

Figure P4.30

D 4.31 Design the circuit in Fig. P4.31 to establish $I_C = 0.2$ mA and $V_C = 0.5$ V. The transistor exhibits v_{BE} of 0.8 V at $i_C = 1$ mA, and $\beta = 100$.

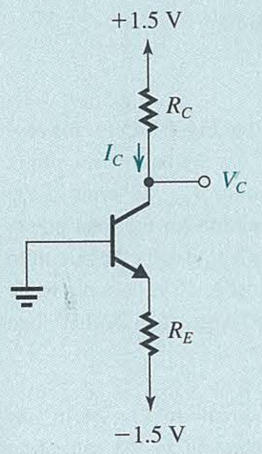

Figure P4.31

4.32 The current I_{CBO} of a small transistor is measured to be 10 nA at 25°C. If the temperature of the device is raised to 125°C, what do you expect I_{CBO} to become?

4.33 Augment the model of the *npn* BJT shown in Fig. 4.19(a) by a current source representing I_{CBO}. Assume that r_o is very large and thus can be neglected. In terms of this addition, what do the terminal currents i_B, i_C, and i_E become? If the base lead is open-circuited while the emitter is connected to ground, and the collector is connected to a positive supply, find the emitter and collector currents.

4.34 A BJT whose emitter current is fixed at 1 mA has a base–emitter voltage of 0.70 V at 25°C. What base–emitter voltage would you expect at 0°C? At 100°C?

4.35 A particular *pnp* transistor operating at an emitter current of 0.5 mA at 20°C has an emitter–base voltage of 692 mV.

(a) What does v_{EB} become if the junction temperature rises to 50°C?

(b) If the transistor is operated at a fixed emitter–base voltage of 700 mV, what emitter current flows at 20°C? At 50°C?

4.36 Consider a transistor for which the base–emitter voltage drop is 0.7 V at 10 mA. What current flows for $v_{BE} = 0.5$ V? Evaluate the ratio of the slopes of the i_C–v_{BE} curve at $v_{BE} = 700$ mV and at $v_{BE} = 500$ mV. The large ratio confirms the point that the BJT has an "apparent threshold" at $v_{BE} \simeq 0.5$ V.

4.37 Use Eq. (4.18) to plot i_C versus v_{CE} for an *npn* transistor having $I_S = 10^{-15}$ A and $V_A = 100$ V. Provide curves for $v_{BE} = 0.65, 0.70, 0.72, 0.73,$ and 0.74 volts. Show the characteristics for v_{CE} up to 15 V.

***4.38** In the circuit shown in Fig. P4.38, current source I is 1.1 mA, and at 25°C $v_{BE} = 680$ mV at $i_E = 1$ mA. At 25°C with $\beta = 100$, what currents flow in R_1 and R_2? What voltage would you expect at node E? Noting that the temperature coefficient of v_{BE} for I_E constant is −2 mV/°C, what is the TC of v_E? For an ambient temperature of 75°C, what voltage would you expect at node E? Clearly state any simplifying assumptions you make.

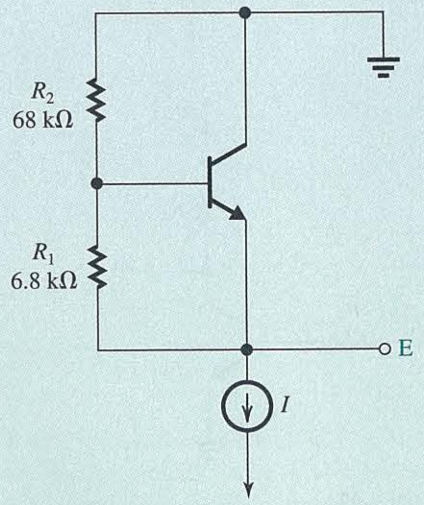

Figure P4.38

4.39 For a BJT having an Early voltage of 50 V, what is its output resistance at 1 mA? At 100 μA?

4.40 For a particular *npn* transistor operating at a v_{BE} of 680 mV and $I_C = 1$ mA, the i_C–v_{CE} characteristic has a slope of 0.8×10^{-5} $\mho$. To what value of output resistance does this correspond? What is the value of the Early voltage for this transistor? For operation at 10 mA, what would the output resistance become?

4.41 Measurements of the i_C–v_{CE} characteristic of a small-signal transistor operating at $v_{BE} = 710$ mV show that $i_C = 1.1$ mA at $v_{CE} = 5$ V and that $i_C = 1.3$ mA at $v_{CE} = 15$ V. What is the corresponding value of i_C near saturation? At what value of v_{CE} is $i_C = 1.2$ mA? What is the value of the Early voltage for this transistor? What is the output resistance that corresponds to operation at $v_{BE} = 710$ mV?

4.42 Give the *pnp* equivalent circuit models that correspond to those shown in Fig. 4.19 for the *npn* case.

4.43 A BJT operating at $i_B = 10$ μA and $i_C = 1.0$ mA undergoes a reduction in base current of 1.0 μA. It is found that when v_{CE} is held constant, the corresponding reduction in collector current is 0.08 mA. What are the values of β and the incremental β or β_{ac} that apply? If the base current is increased from 10 μA to 12 μA and v_{CE} is increased from 8 V to 10 V, what collector current results? Assume $V_A = 100$ V.

4.44 For the circuit in Fig. P4.44 let $V_{CC} = 10$ V, $R_C = 1$ kΩ, and $R_B = 10$ kΩ. The BJT has $\beta = 50$. Find the value of V_{BB} that results in the transistor operating

(a) in the active mode with $V_C = 2$ V;
(b) at the edge of saturation;
(c) deep in saturation with $\beta_{forced} = 10$.

Assume $V_{BE} \simeq 0.7$ V.

SIM D ***4.45** Consider the circuit of Fig. P4.45 for the case $V_{BB} = V_{CC}$. If the BJT is saturated, use the equivalent circuit of Fig. 4.21 to derive an expression for β_{forced} in terms of V_{CC} and (R_B/R_C). Also derive an expression for the total power dissipated in the circuit. For $V_{CC} = 5$ V, design the circuit to obtain operation at a forced β as close to 10 as possible while limiting the power dissipation to no larger than 20 mW. Use 1% resistors (see Appendix J).

4.46 The *pnp* transistor in the circuit in Fig. P4.46 has $\beta = 50$. Show that the BJT is operating in the saturation mode and find β_{forced} and V_C. To what value should R_B be increased in order for the transistor to operate at the edge of saturation?

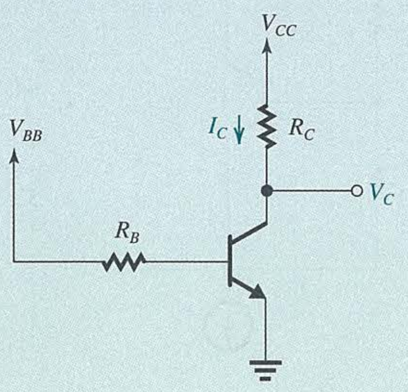

Figure P4.44

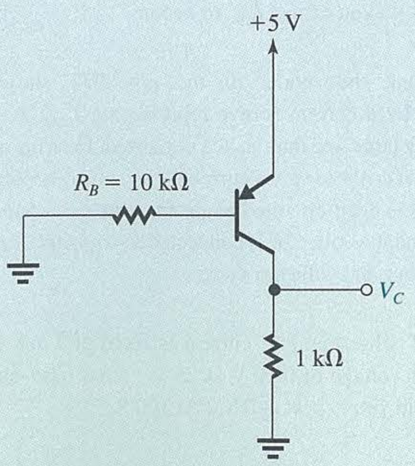

Figure P4.46

Section 4.3: BJT Circuits at DC

4.47 The transistor in the circuit of Fig. P4.47 has a very high β. Find V_E and V_C for V_B (a) +2.0 V, (b) +1.7 V, and (c) 0 V.

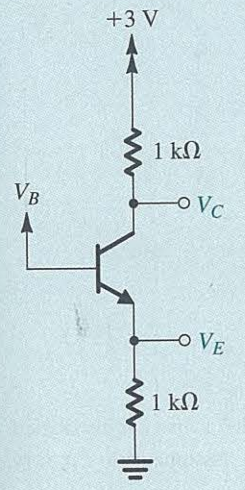

Figure P4.47

4.48 The transistor in the circuit of Fig. P4.48 has a very high β. Find the highest value of V_B for which the transistor still operates in the active mode. Also, find the value of V_B for which the transistor operates in saturation with a forced β of 2.

4.49 Consider the operation of the circuit shown in Fig. P4.49 for V_B at –1 V, 0 V, and +1 V. Assume that β is very high. What values of V_E and V_C result? At what value of V_B does the emitter current reduce to one-tenth of its value for $V_B = 0$ V? For what value of V_B is the transistor just at the edge of conduction? ($v_{BE} = 0.5$ V) What values of V_E and V_C correspond? For what value of V_B does the transistor reach the edge of saturation? What values of V_C and V_E correspond? Find the value of V_B for which the transistor operates in saturation with a forced β of 2.

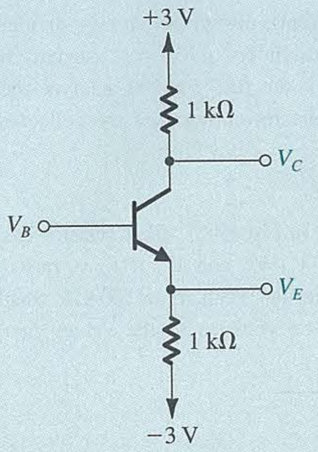

Figure P4.49

4.50 A single measurement indicates the emitter voltage of the transistor in the circuit of Fig. P4.50 to be 1.0 V. Under the assumption that $|V_{BE}| = 0.7$ V, what are V_B, I_B, I_E, I_C, V_C, β, and α? (*Note:* Isn't it surprising what a little measurement can lead to?)

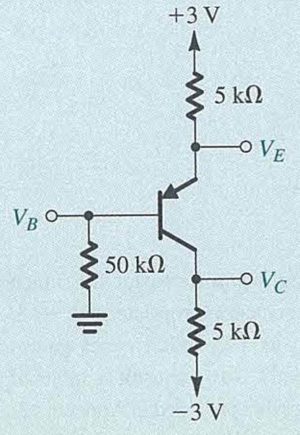

Figure P4.50

D 4.51 Consider the circuit in Fig. P4.51 with the base voltage V_B obtained using a voltage divider across the 3-V supply. Assuming the transistor β to be very large (i.e., ignoring the base current), design the voltage divider to obtain $V_B = 1.2$ V. Design for a 0.1-mA current in the voltage divider. Now, if the BJT $\beta = 100$, analyze the circuit to determine the collector current and the collector voltage.

4.52 In the circuit shown in Fig. P4.52, the transistor has $\beta = 40$. Find the values of V_B, V_E, and V_C. If R_B is raised to 100 kΩ, what voltages result? With $R_B = 100$ kΩ, what value of β would return the voltages to the values first calculated?

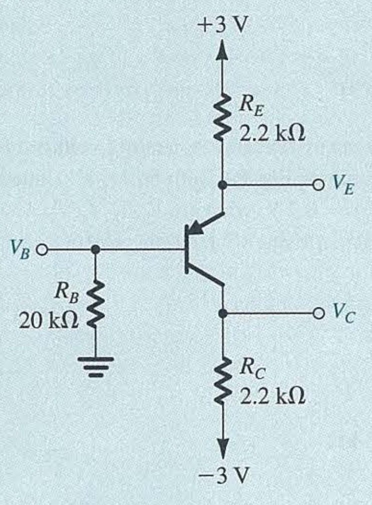

Figure P4.52

D 4.53 Design a circuit using a *pnp* transistor for which $\alpha \simeq 1$ using two resistors connected appropriately to ±3 V so that $I_E = 0.5$ mA and $V_{BC} = 1$ V. What exact values of R_E and R_C would be needed? Now, consult a table of standard 5% resistor values (e.g., that provided in Appendix J) to select suitable practical values. What values of resistors have you chosen? What are the values of I_E and V_{BC} that result?

SIM 4.54 For the circuit in Fig. P4.54, find V_B, V_E, and V_C for $R_B = 100$ kΩ, 10 kΩ, and 1 kΩ. Let $\beta = 100$.

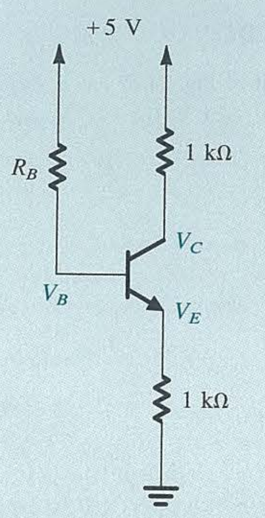

Figure P4.54

4.55 For the circuits in Fig. P4.55, find values for the labeled node voltages and branch currents. Assume β to be very high.

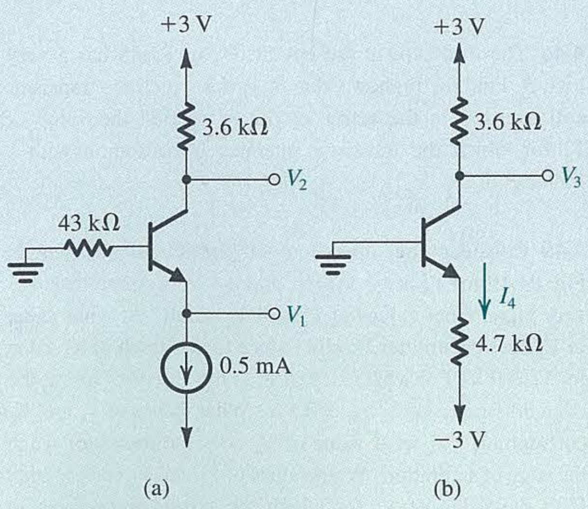

Figure P4.55

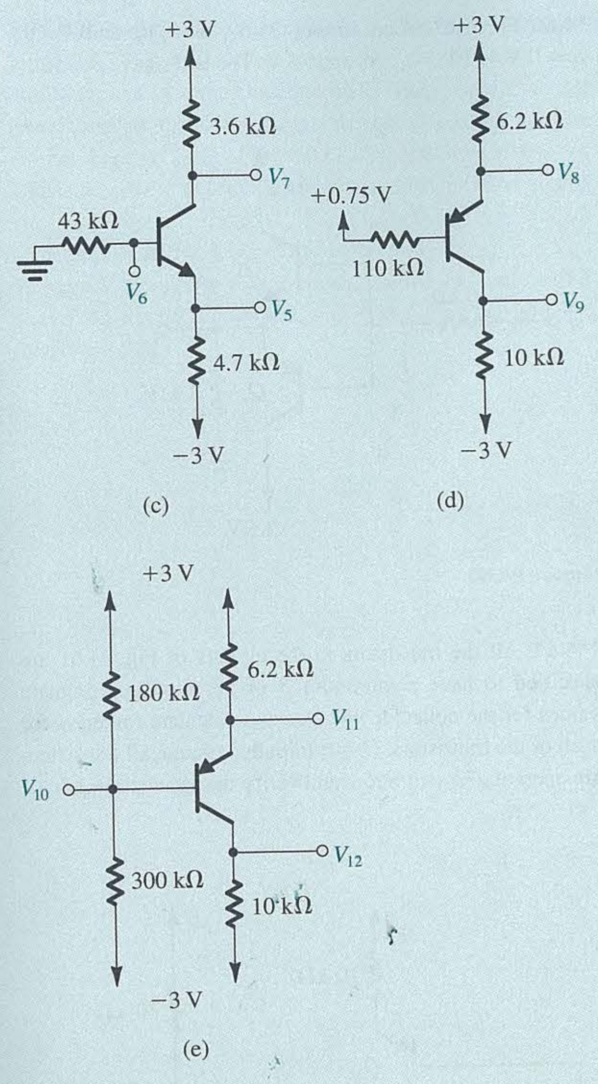

Figure P4.55 *continued*

***4.56** Repeat the analysis of the circuits in Problem 4.55 using $\beta = 100$. Find all the labeled node voltages and branch currents.

D 4.57 The *pnp* transistor in the circuit of Fig. P4.57 has $\beta = 50$. Find the value for R_C to obtain $V_C = +2$ V. What happens if the transistor is replaced with another having $\beta = 100$? Give the value of V_C in the latter case.

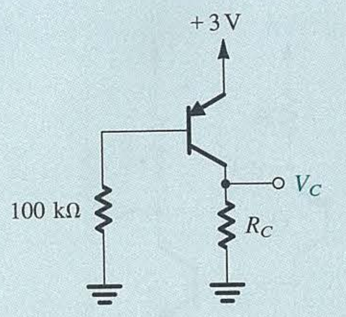

Figure P4.57

D **4.58 It is required to design the circuit in Fig. P4.58 so that a current of 1 mA is established in the emitter and a voltage of −1 V appears at the collector. The transistor type used has a nominal β of 100. However, the β value can be as low as 50 and as high as 150. Your design should ensure that the specified emitter current is obtained when $\beta = 100$ and that at the extreme values of β the emitter current does not change by more than 10% of its nominal value. Also, design for as large a value for R_B as possible. Give the values of R_B, R_E, and R_C to the nearest kilohm. What is the expected range of collector current and collector voltage corresponding to the full range of β values?

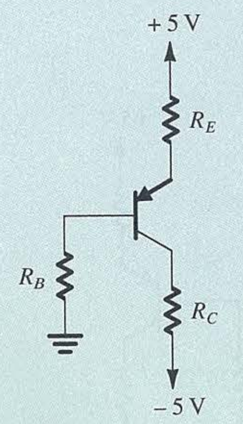

Figure P4.58

D *4.59 Using $\beta = \infty$, design the circuit shown in Fig. P4.59 so that the emitter currents of Q_1, Q_2, and Q_3

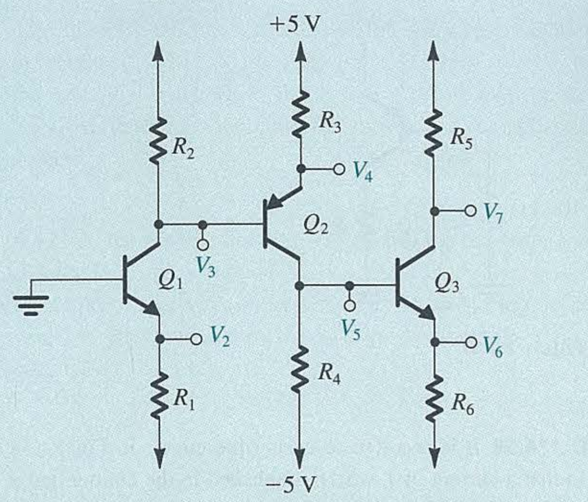

Figure P4.59

are 0.5 mA, 0.5 mA, and 1 mA, respectively, and $V_3 = 0$, $V_5 = -2$ V, and $V_7 = 1$ V. For each resistor, select the nearest standard value utilizing the table of standard values for 5% resistors in Appendix J. Now, for $\beta = 100$, find the values of V_3, V_4, V_5, V_6, and V_7.

***4.60** For the circuit in Fig. P4.60, find V_B and V_E for $v_I = 0$ V, +2 V, –2.5 V, and –5 V. The BJTs have $\beta = 50$.

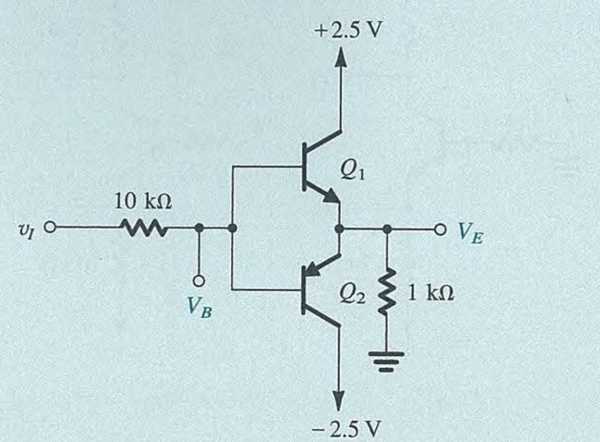

Figure P4.60

****4.61** All the transistors in the circuits of Fig. P4.61 are specified to have a minimum β of 50. Find approximate values for the collector voltages and calculate forced β for each of the transistors. (*Hint:* Initially, assume all transistors are operating in saturation, and verify the assumption.)

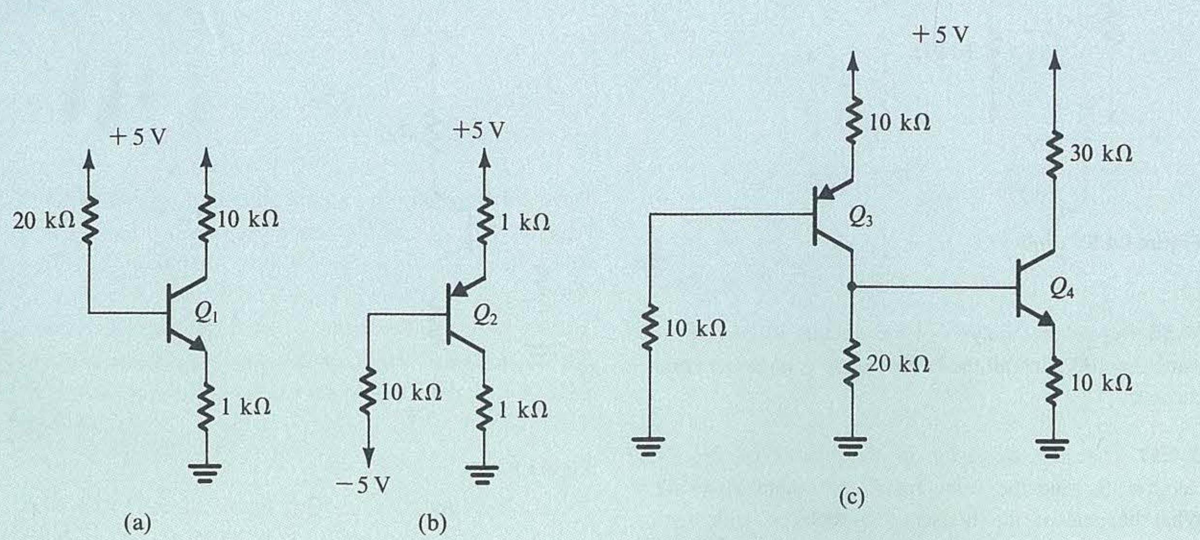

Figure P4.61

*****4.62** Consider the circuit shown in Fig. P4.62. It resembles that in Fig. 4.30 but includes other features. First, note diodes D_1 and D_2 are included to make design (and analysis) easier and to provide temperature compensation for the emitter–base voltages of Q_1 and Q_2. Second, note resistor R, whose purpose is to provide negative feedback (more on this later in the book!). Using $|V_{BE}|$ and $V_D = 0.7$ V independent of current, and $\beta = \infty$, find the voltages V_{B1}, V_{E1}, V_{C1}, V_{B2}, V_{E2}, and V_{C2}, initially with R open-circuited and then with R connected. Repeat for $\beta = 100$, with R open-circuited initially, then connected.

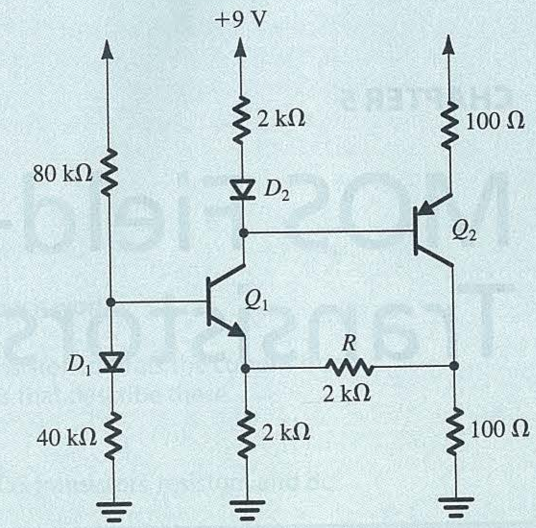

Figure P4.62