Bipolar Junction Transistors

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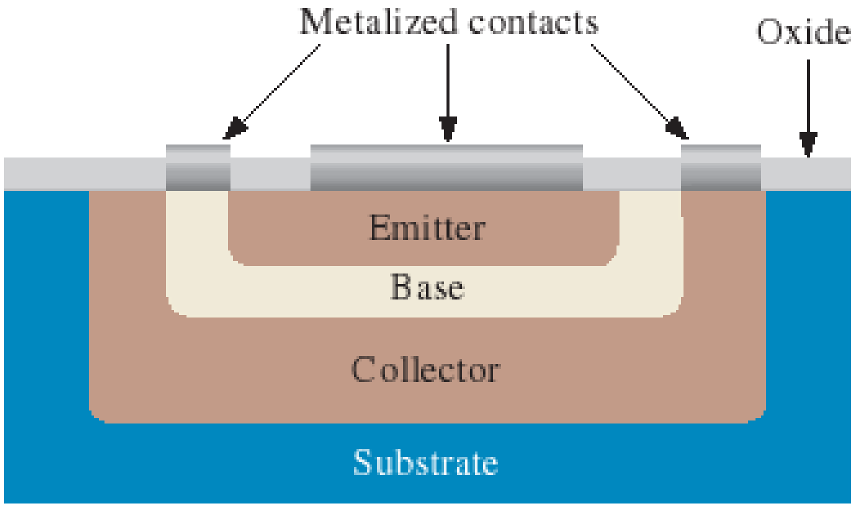
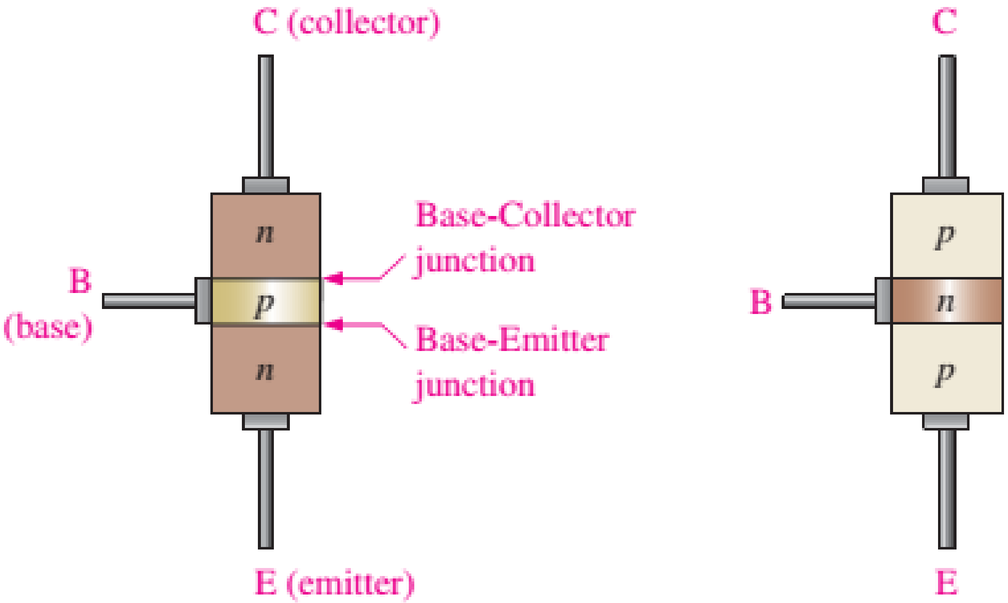
Bi-polar Junction Transistors (BJT)

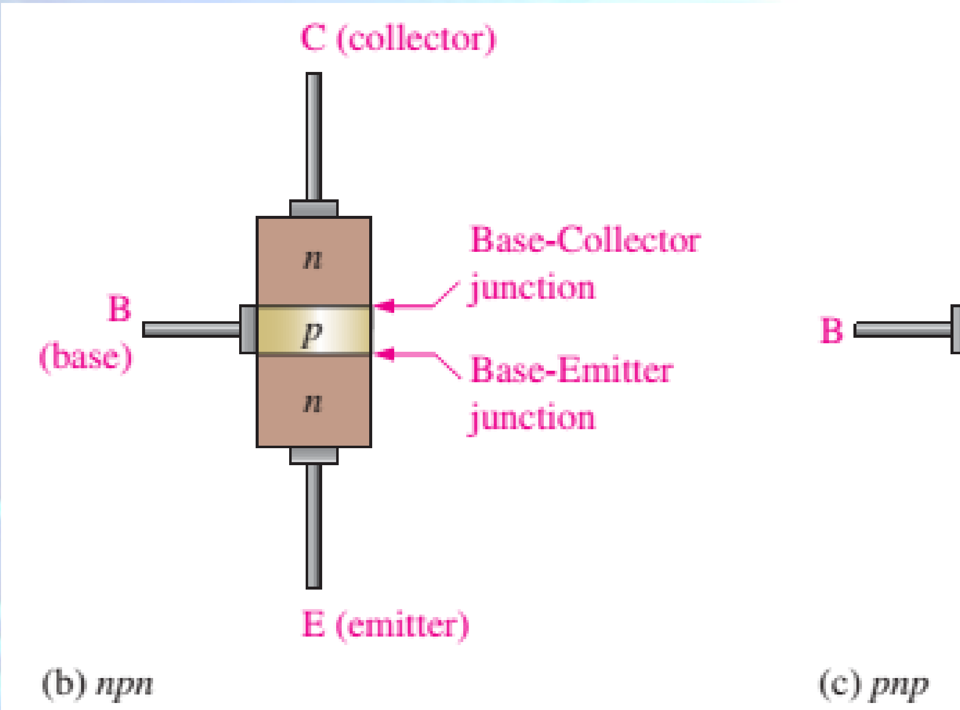
- The BJT is constructed with three doped semiconductor regions separated by two *pn* junctions
- The three regions are called emitter, base, and collector
- The term **bipolar** refers to the use of both holes and electrons as current carriers in the transistor structure



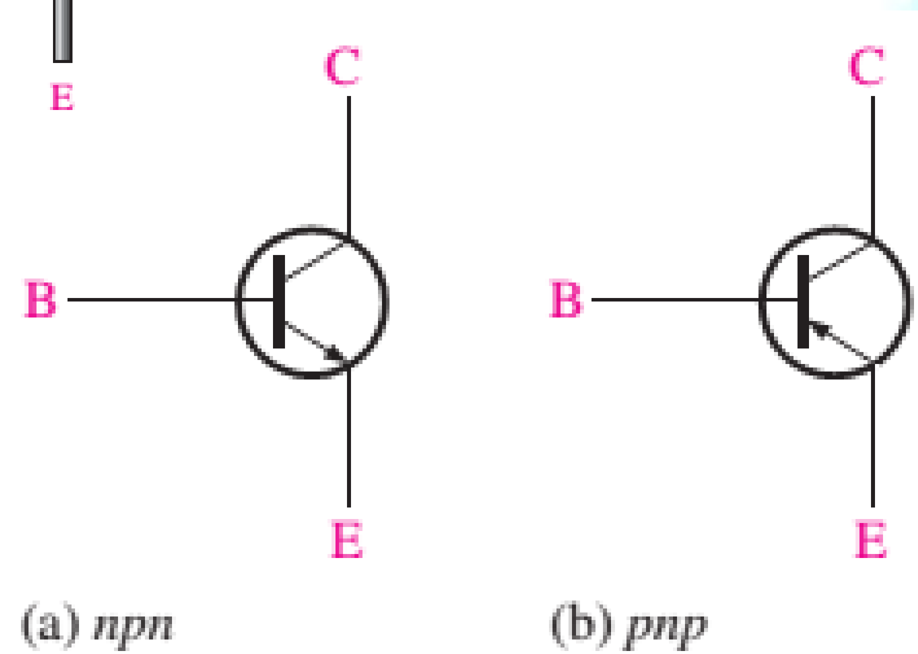


(b) *npn* (c) *pnp*

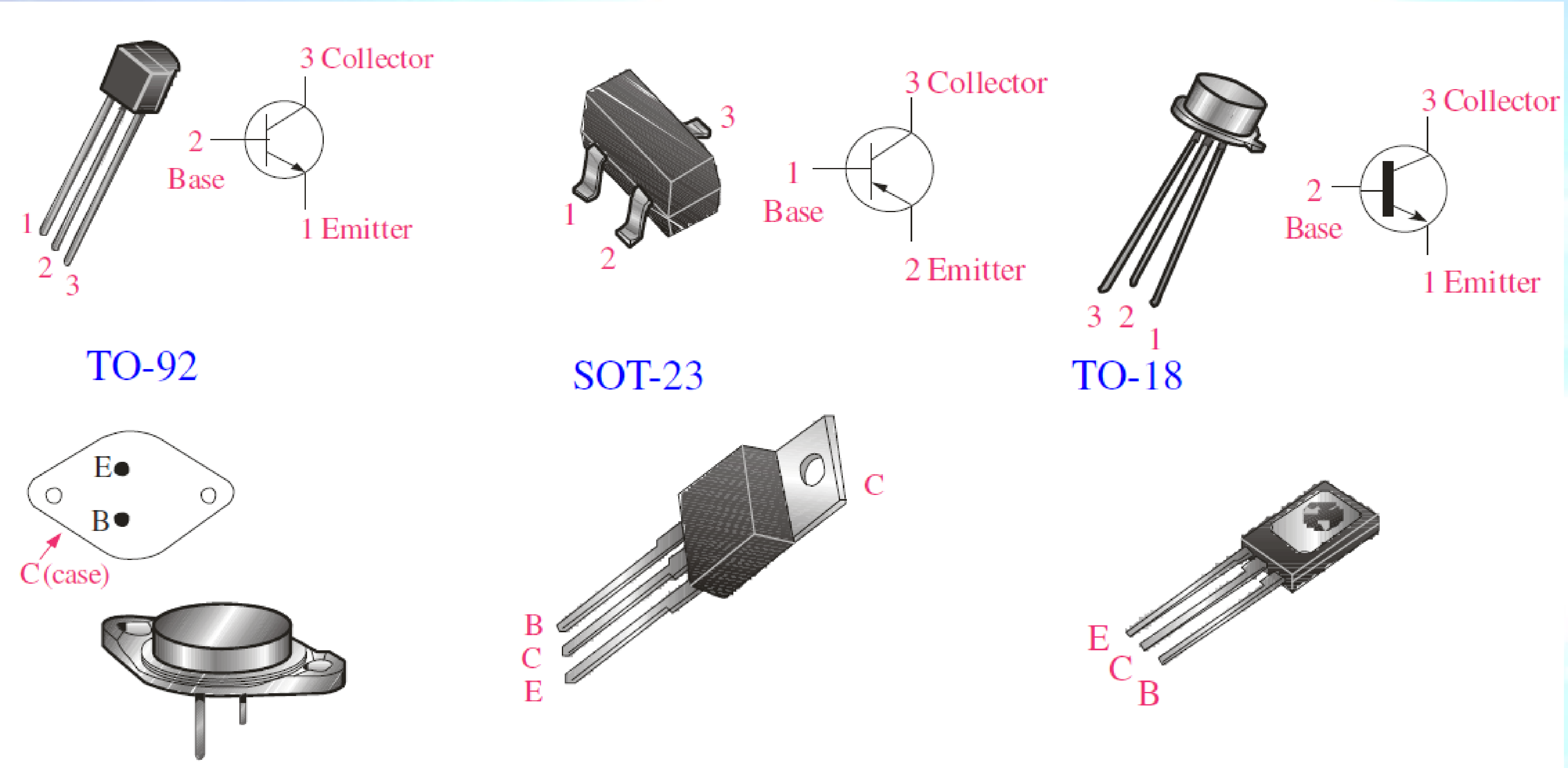
Bi-polar Junction Transistors (BJT)



Standard BJT symbols



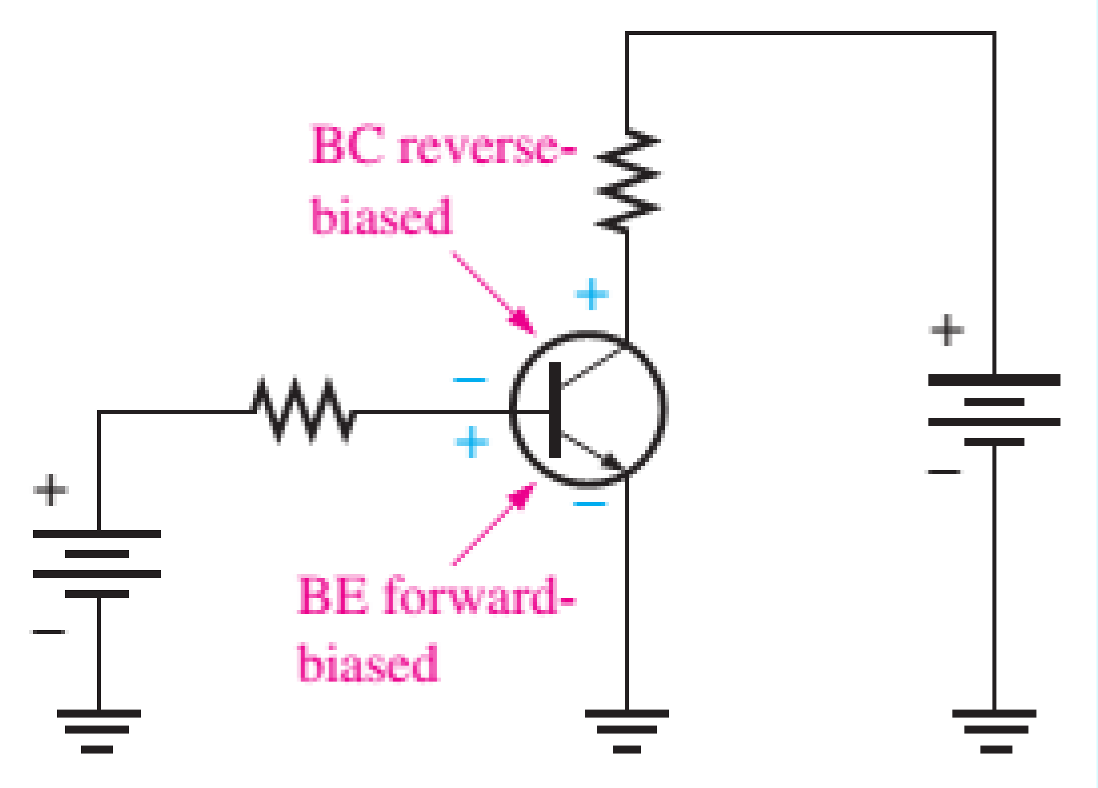
Common BJT pakages



Basic BJT operation

- In normal operation (e.g. amplifier) base-emitter (BE) junction is forward-biased and the base-collector (BC) junction is reverse-biased

n-p-n

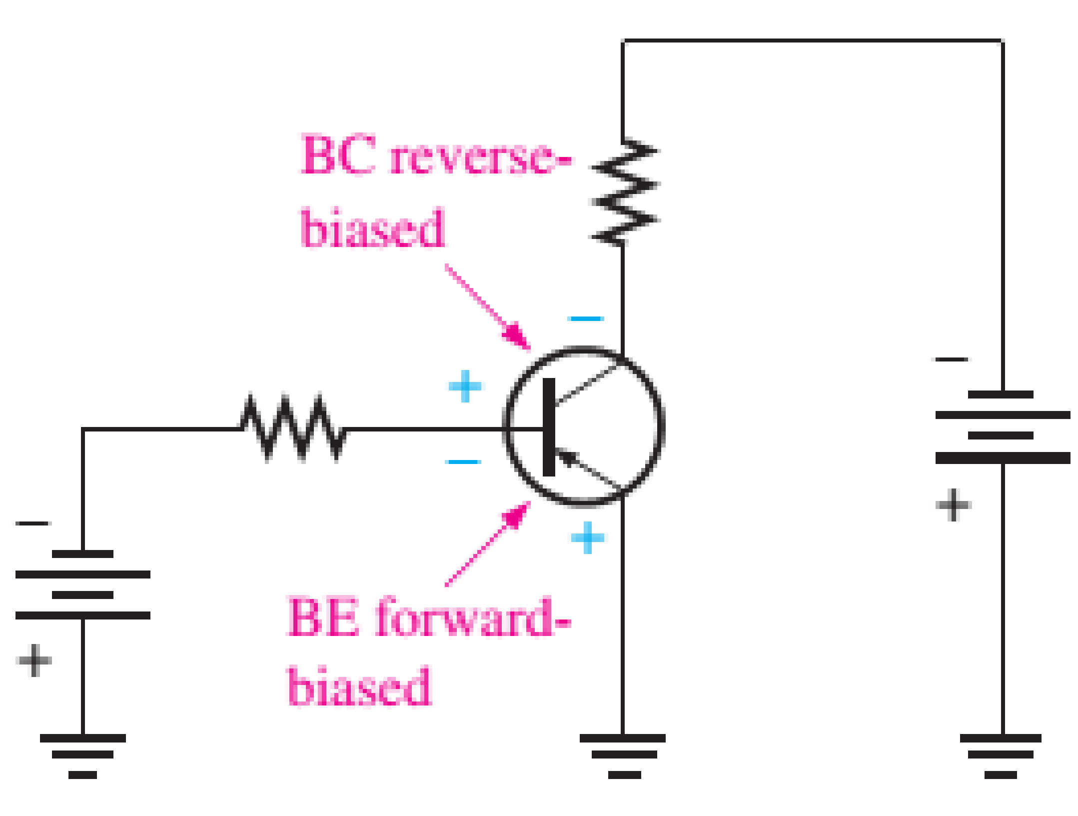


(a) *npn*

Basic BJT operation

- In normal operation (e.g. amplifier) base-emitter (BE) junction is forward-biased and the base-collector (BC) junction is reverse-biased

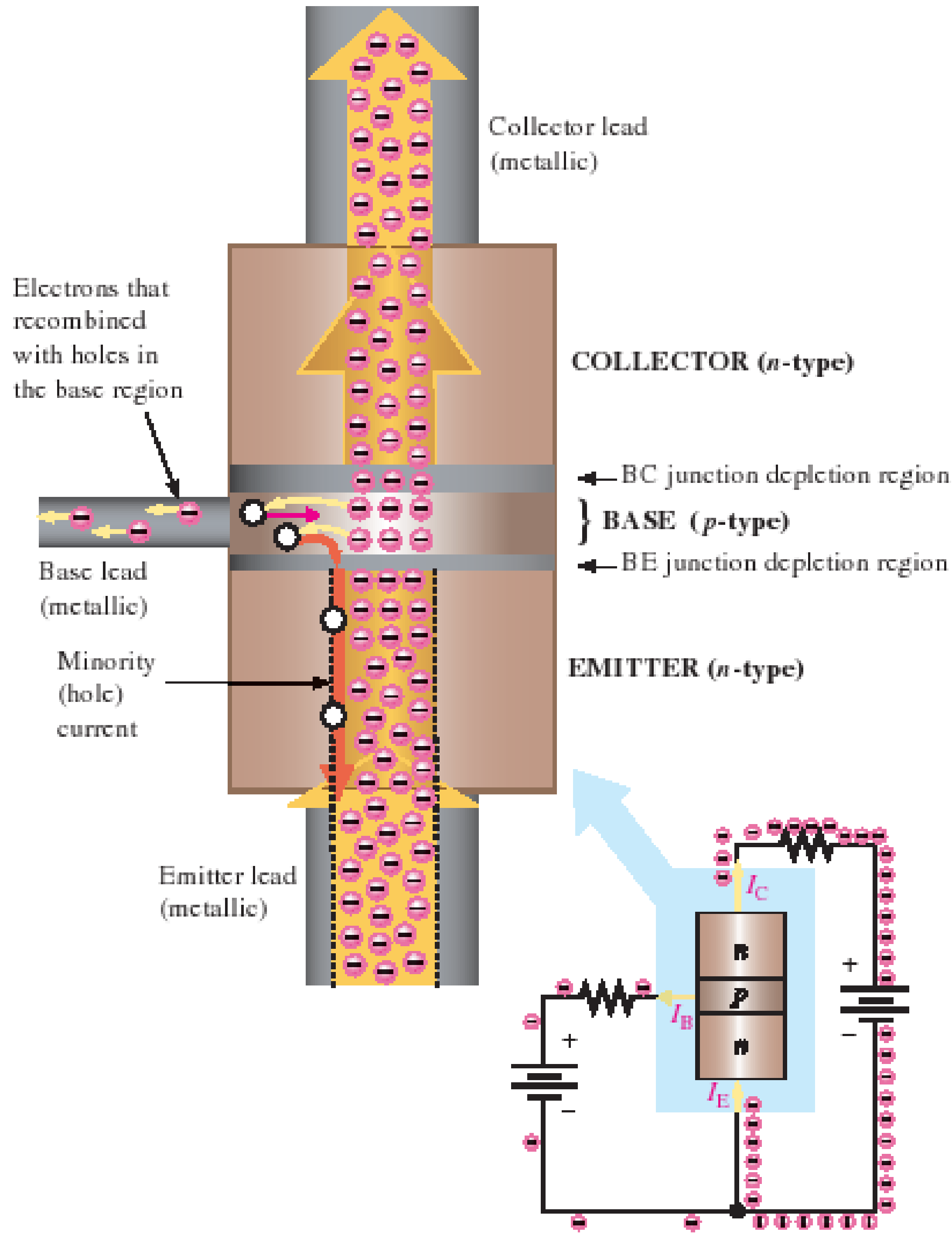
p-n-p



(b) *pnp*

Basic BJT operation

- To understand how a transistor operates, let's examine what happens inside the *npn* structure
  - The heavily doped *n*-type emitter region has a very high density of conduction-band (free) electrons
  - These free electrons easily diffuse through the forward-based BE junction into the lightly doped and very thin p-type base region
  - A small percentage of the total number of free electrons injected into the base region recombine with holes and move as valence electrons through the base region and into the emitter region as hole current, indicated by the red arrows
  - As the free electrons move toward the reverse-biased BC junction, they are swept across into the collector region by the attraction of the positive collector supply voltage



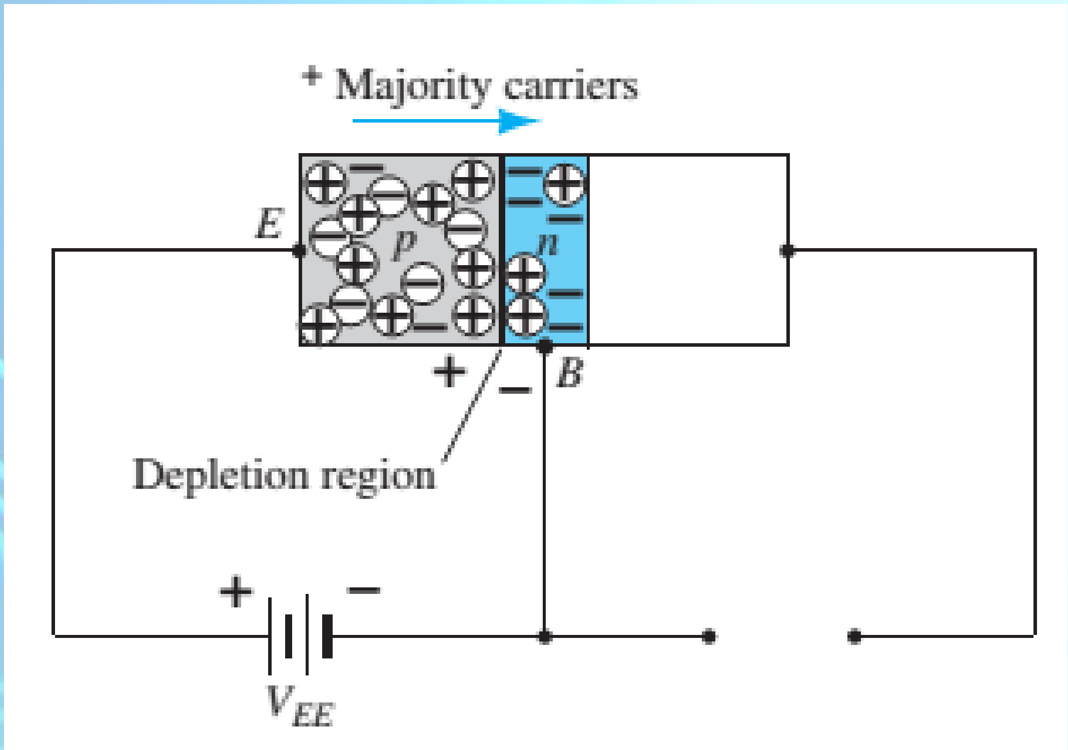
Collector lead
(metallic)
Electrons that
recombined
with holes in
the base region
COLLECTOR (n-type)
BC junction depletion region
BASE (p-type)
BE junction depletion region
Base lead
(metallic)
Minority
(hole)
current
EMITTER (n-type)
Emitter lead
(metallic)
I_C
n
p
n
I_B
I_E
+
–
+
–

Basic BJT operation

- The heavily doped *n*-type emitter region has a very high density of conduction-band (free) electrons
- The free electrons move through the collector region, into the external circuit, and then return into the emitter region along with the base current, as indicated
- The emitter current is slightly greater than the collector current because of the small base current that splits off from the total current injected into the base region from the emitter

Basic BJT operation

- *p-n-p* transistor is redrawn without the base-to-collector bias

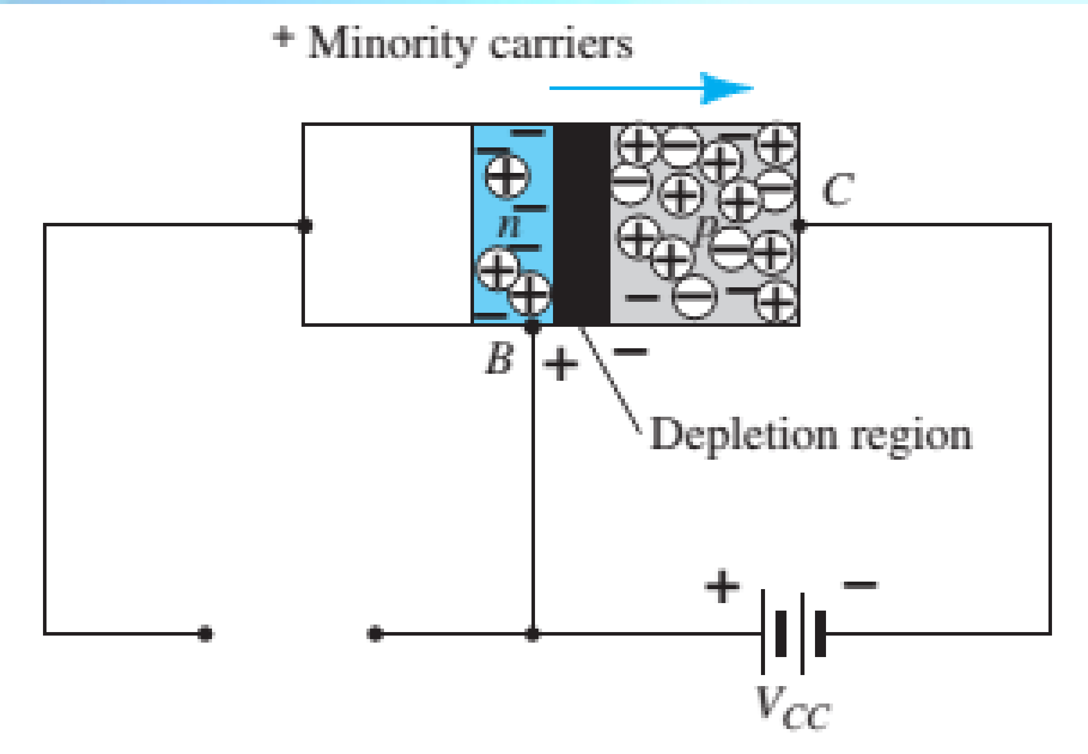


- BE junction forward biased
- Similar to forward biased diode

- Depletion region reduces
- A heavy current flows due to majority carriers

Basic BJT operation

- *p-n-p* transistor is redrawn without the base-to-emitter bias

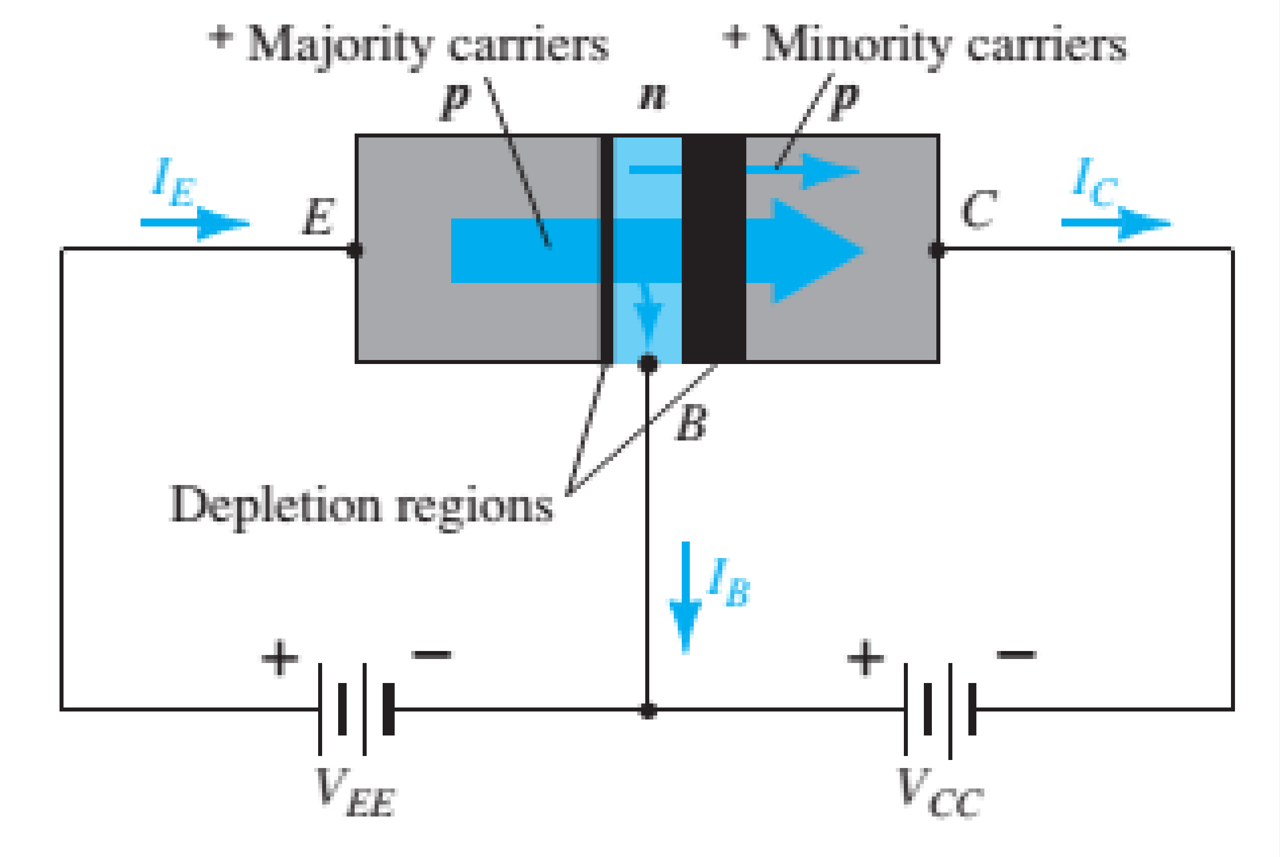


- BC junction reverse biased
- Similar to reverse biased diode

- Depletion region enlarges
- A small current flows due to minority carriers

Basic BJT operation

- *p-n-p* transistor drawn with normal biasing (combining previous)



$$\boxed{I_E = I_C + I_B}$$

BJT Currents

- Emitter current (I_E) is the sum of the collector current (I_C) and the base current (I_B),

$$I_E = I_C + I_B$$

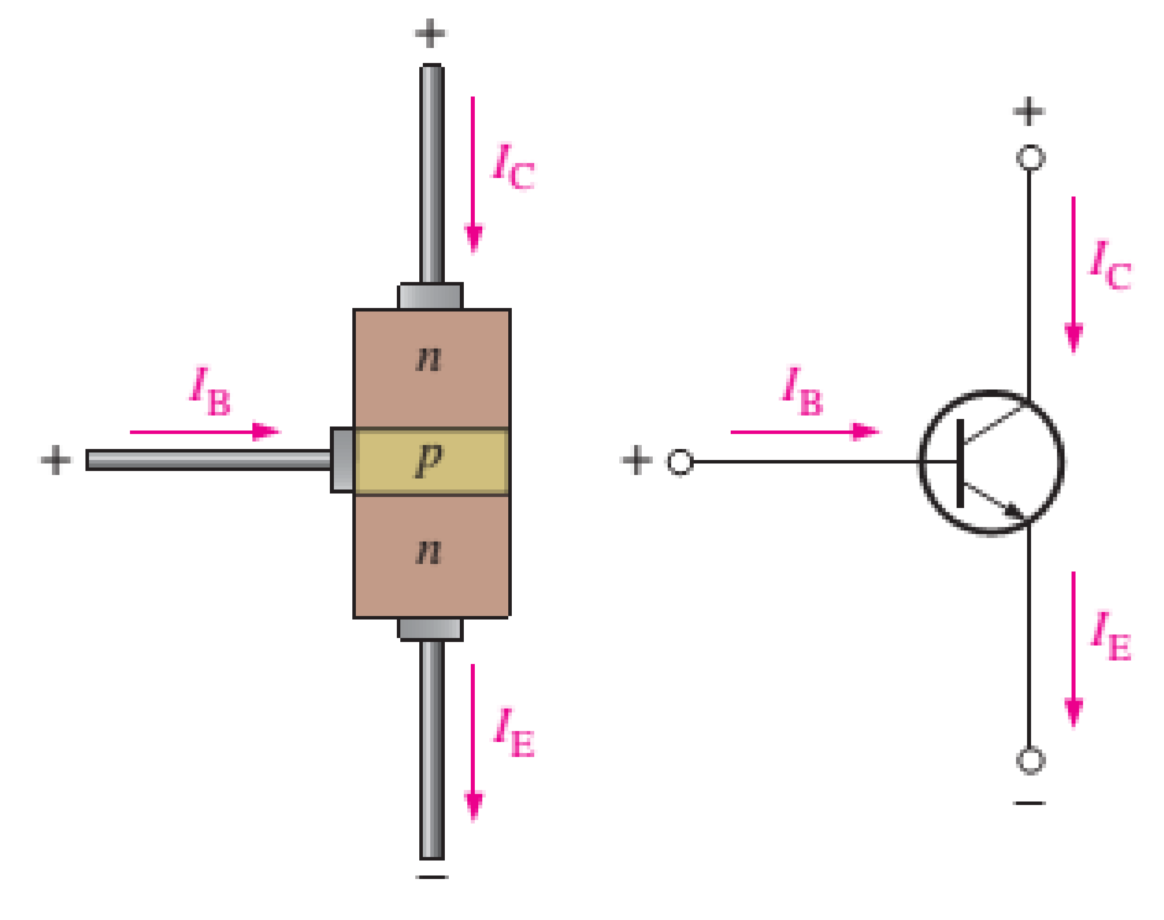
- Notice that the direction of the emitter current of the transistor, symbols the direction of conventional current

- I_B is very small compared to I_E or I_C
  - The magnitude of the base current is typically on the order of microamperes, as compared to milliamperes for the emitter and collector currents

BJT Currents

- n-p-n transistor

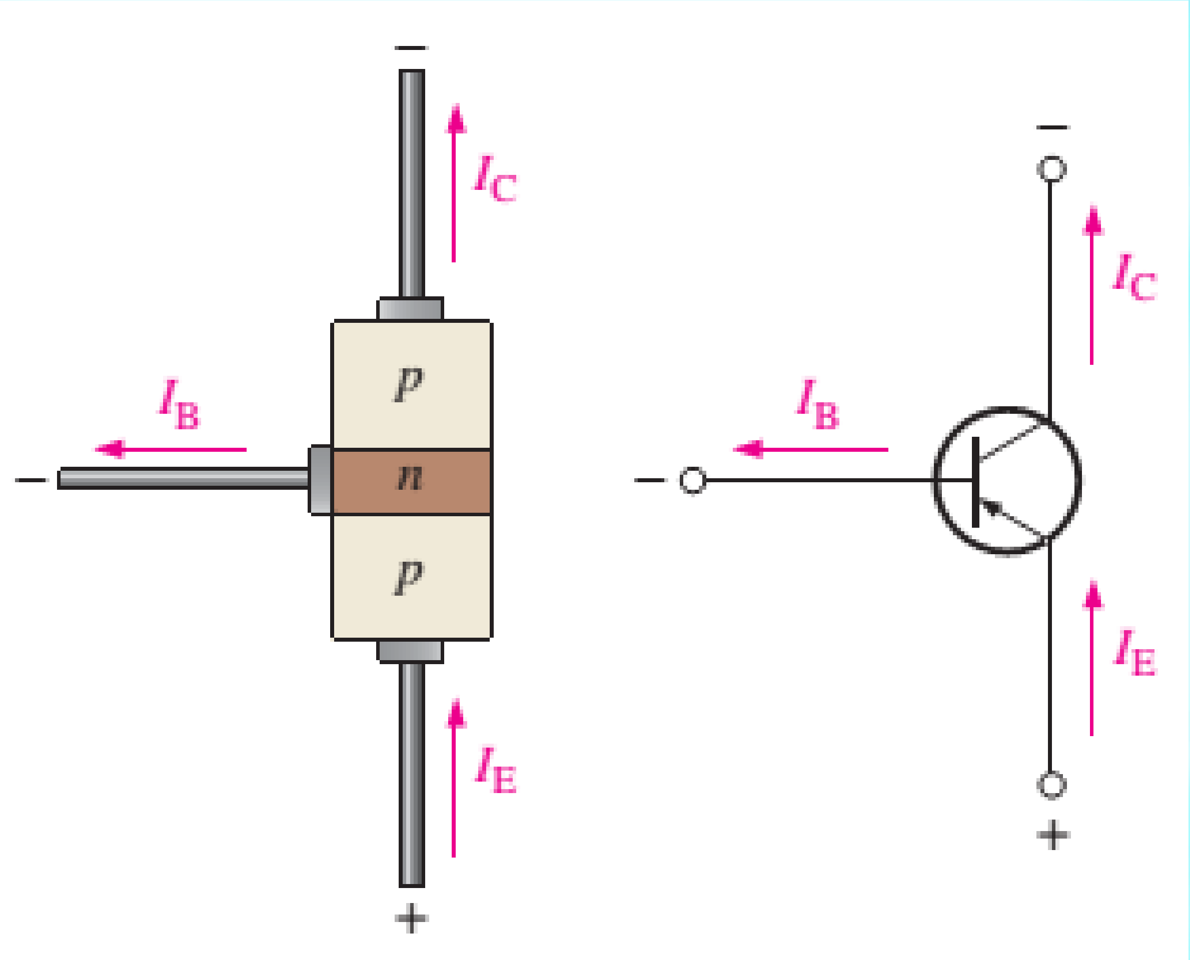
$$I_E = I_C + I_B$$



BJT Currents

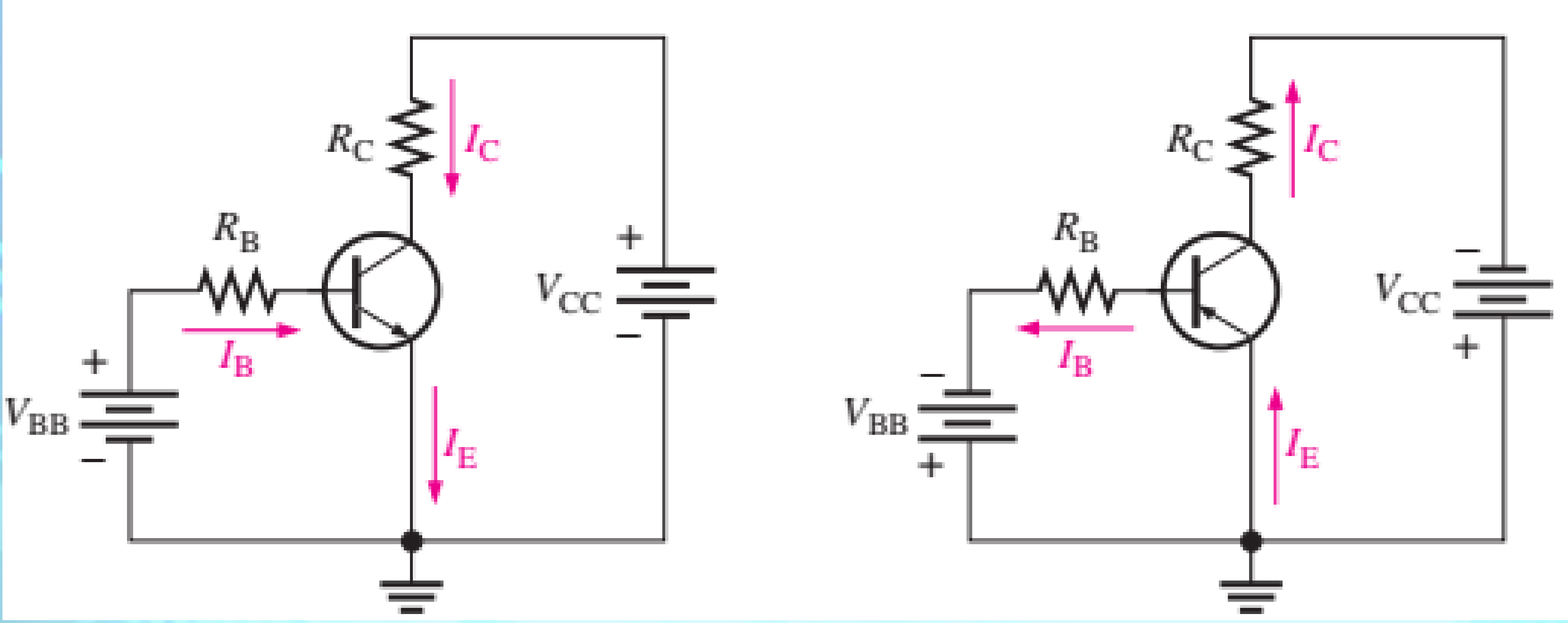
- p-n-p transistor

$$I_E = I_C + I_B$$



Transistor DC Bias Circuits

- When a transistor is connected to dc bias voltages, for both *npn* and *pnp* types, V_{BB} forward-biases the base-emitter junction, and V_{CC} reverse-biases the base-collector junction.



npn

pnp

BJT Parameters

- Two important parameters, β_{DC} (dc current gain) and α_{DC} are used to analyze a BJT circuits

- β_{DC} : DC current gain
  - Ratio of the dc collector current (I_C) to the dc base current (I_B)

$$\beta_{DC} = \frac{I_C}{I_B}$$

  - Typical values of β_{DC} range from less than 20 to 200 or higher

BJT Parameters

- α_{DC}
  - Ratio of the dc collector current (I_C) to the dc emitter current (I_E)

$$\alpha_{DC} = \frac{I_C}{I_E}$$

  - Typically, values of α_{DC} range from 0.95 to 0.99 or greater, but α_{DC} is always less than 1. The reason is that I_C is always slightly less than I_E by the amount of I_B
  - For example, if I_E = 100 mA and I_B = 1 mA, then I_C = 99 mA and α_{DC} = 0.99.

BJT Parameters

Determine the dc current gain β_{DC} and the emitter current I_E for a transistor where $I_B = 50\ \mu A$ and $I_C = 3.65\ mA$.

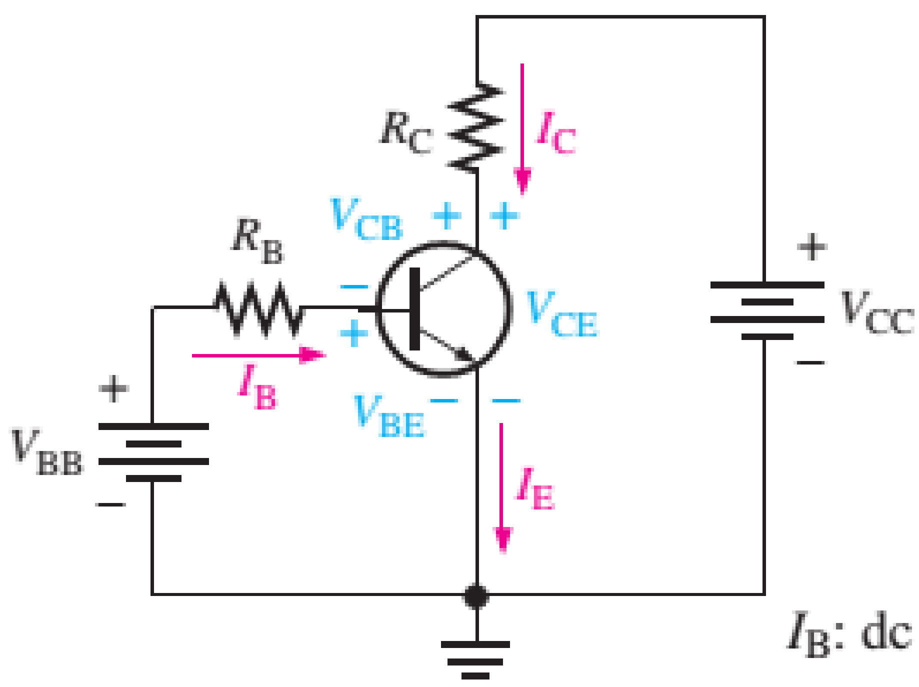
BJT Parameters

Determine the dc current gain β_{DC} and the emitter current I_E for a transistor where $I_B = 50\ \mu A$ and $I_C = 3.65$ mA.

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.65\text{ mA}}{50\ \mu\text{A}} = \mathbf{73}$$

$$I_E = I_C + I_B = 3.65\text{ mA} + 50\ \mu\text{A} = \mathbf{3.70\ mA}$$

BJT Circuit Analysis



Finding transistor currents and voltages

Notations used:

I_B: dc base current

I_E: dc emitter current

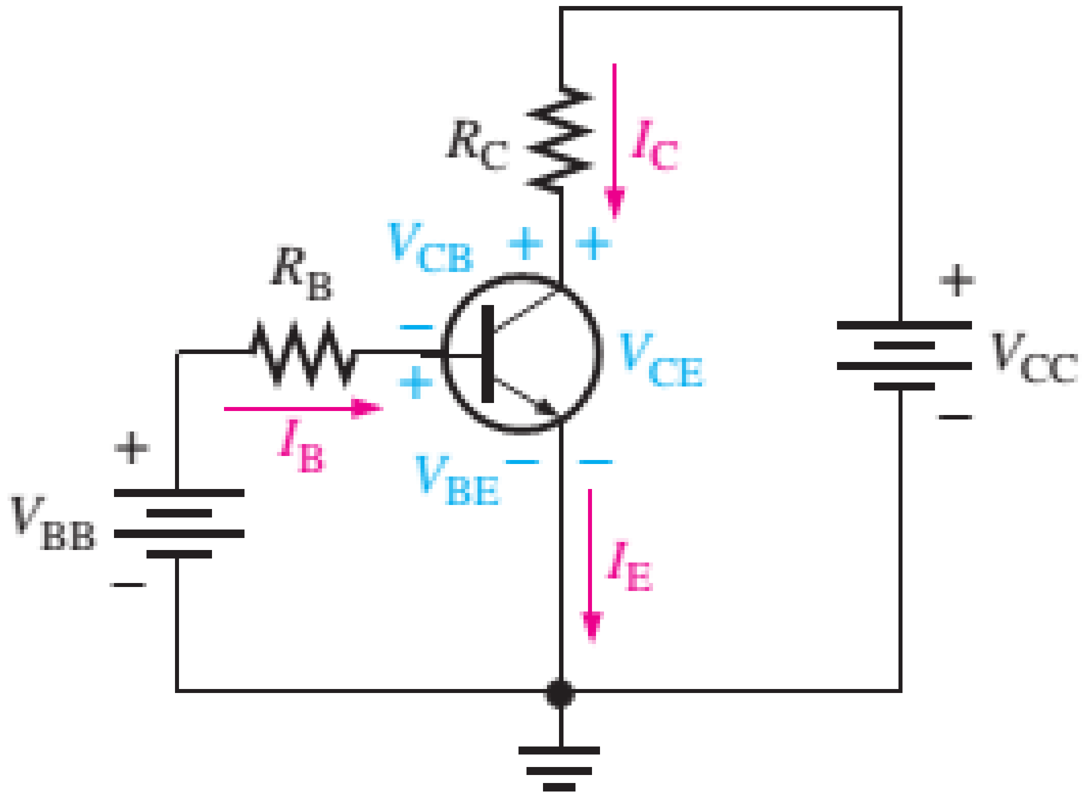
I_C: dc collector current

V_{BE}: dc voltage at base with respect to emitter

V_{CB}: dc voltage at collector with respect to base

V_{CE}: dc voltage at collector with respect to emitter

BJT Circuit Analysis



$$V_{BE} \cong 0.7\text{ V}$$

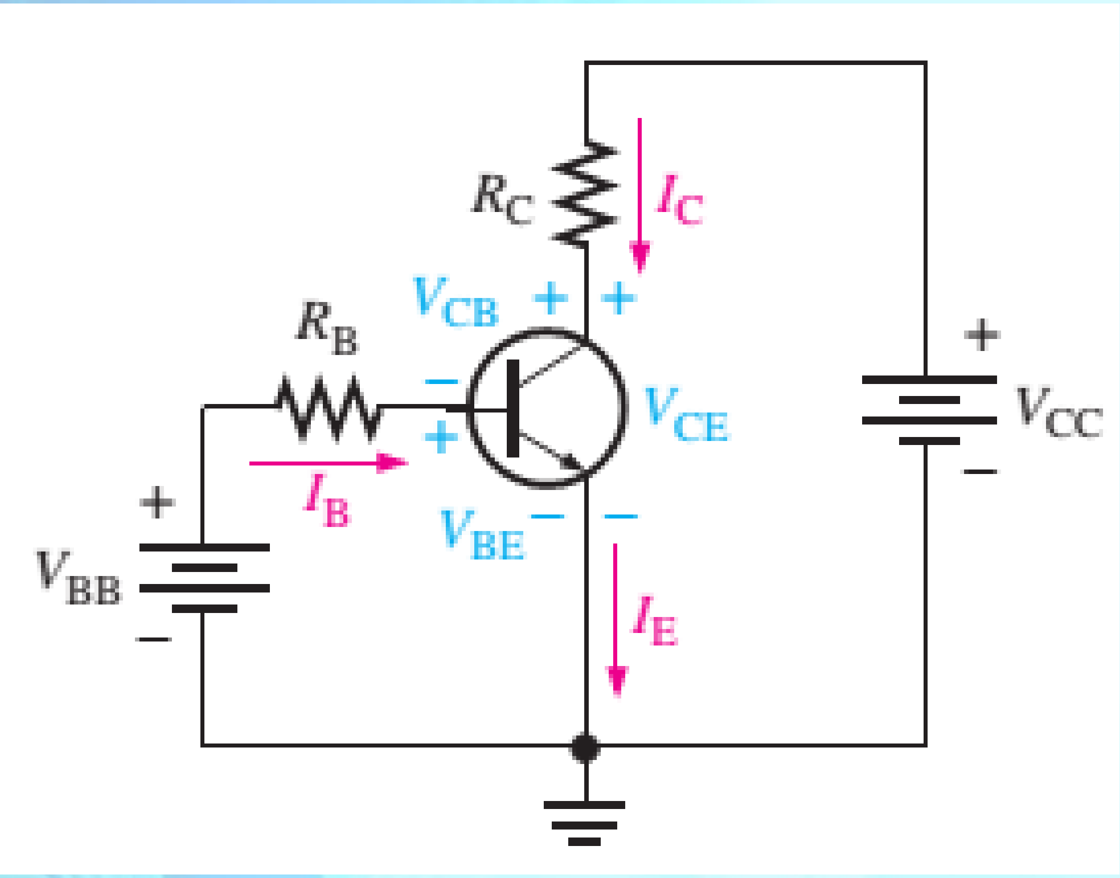
$$V_{R_B} = V_{BB} - V_{BE}$$

$$V_{R_B} = I_B R_B$$

$$I_B R_B = V_{BB} - V_{BE}$$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

BJT Circuit Analysis



$$V_{CE} = V_{CC} - V_{R_C}$$

$$V_{R_C} = I_C R_C$$

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

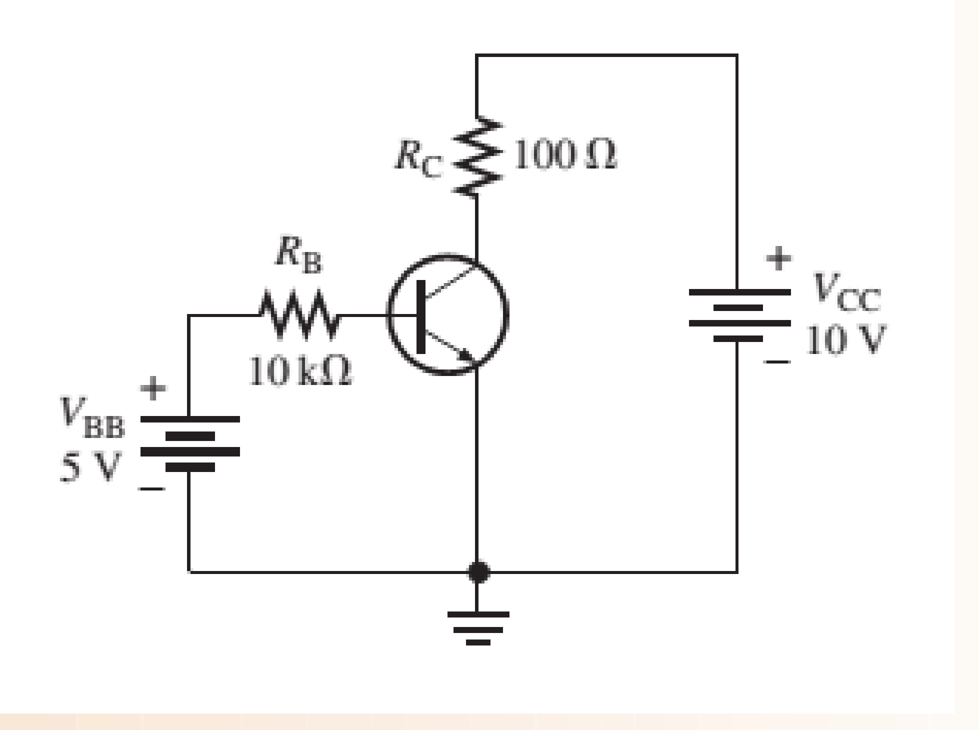
$$I_C = \beta_{DC} I_B.$$

$$V_{CB} = V_{CE} - V_{BE}$$

BJT Circuit Analysis

Determine I_B, I_C, I_E, V_{BE}, V_{CE}, and V_{CB} in the circuit of Figure 4–9. The transistor has a $\beta_{DC} = 150$.

FIGURE 4–9



BJT Circuit Analysis

$V_{BE} \cong$ **0.7 V.** Calculate the base, collector, and emitter currents as follows:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = \mathbf{430\ \mu A}$$

$$I_C = \beta_{DC} I_B = (150)(430\ \mu\text{A}) = \mathbf{64.5\ mA}$$

$$I_E = I_C + I_B = 64.5\text{ mA} + 430\ \mu\text{A} = \mathbf{64.9\ mA}$$

Solve for V_{CE} and V_{CB}.

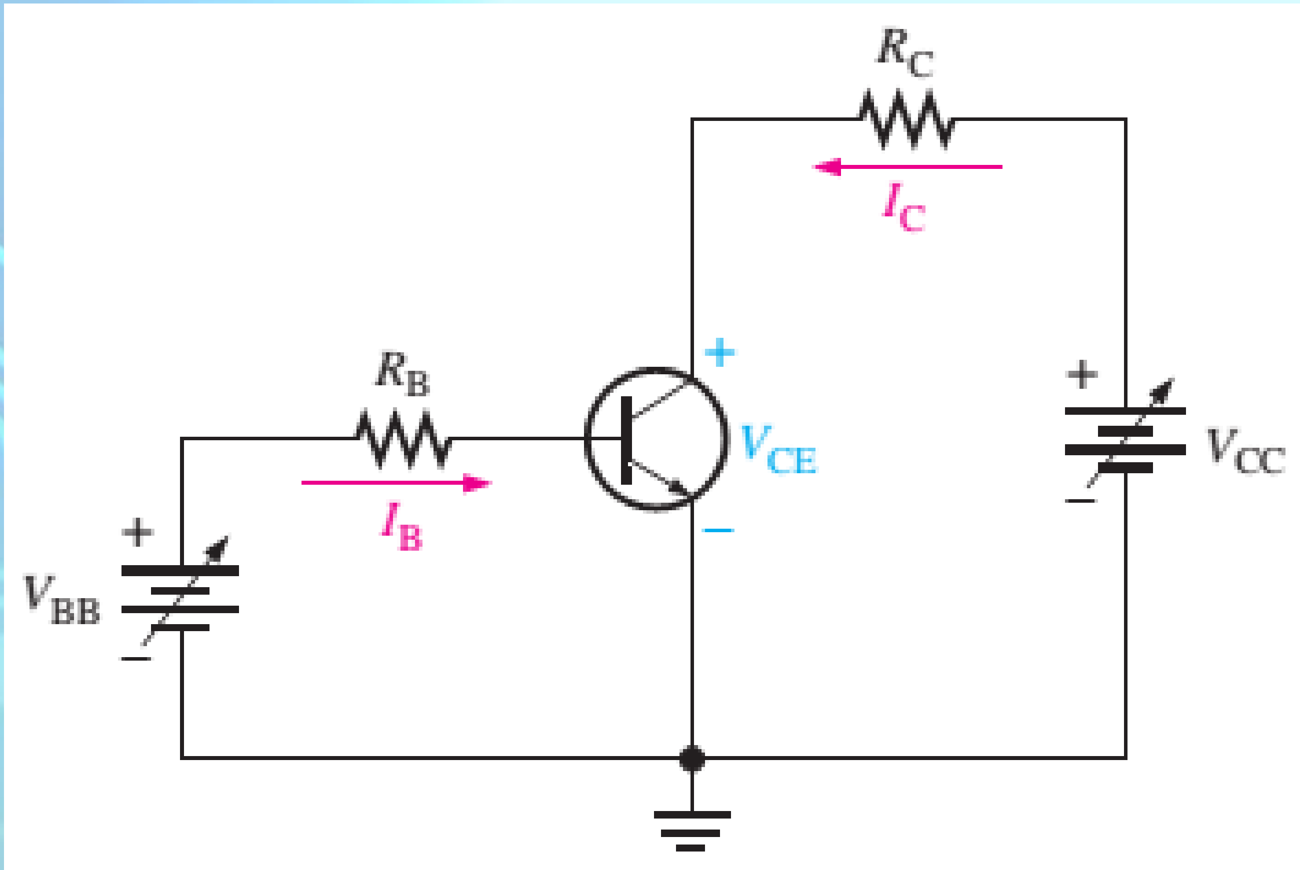
$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (64.5\text{ mA})(100\ \Omega) = 10\text{ V} - 6.45\text{ V} = \mathbf{3.55\ V}$$

$$V_{CB} = V_{CE} - V_{BE} = 3.55\text{ V} - 0.7\text{ V} = \mathbf{2.85\ V}$$

Since the collector is at a higher voltage than the base, the collector-base junction is reverse-biased.

BJT Characteristics Curve

- Analyze collector current, I_C, varies with the collector-to emitter voltage, V_{CE}, for specified values of base current, I_B



V_{BB} is fixed for a particular I_B

BJT Characteristics Curve

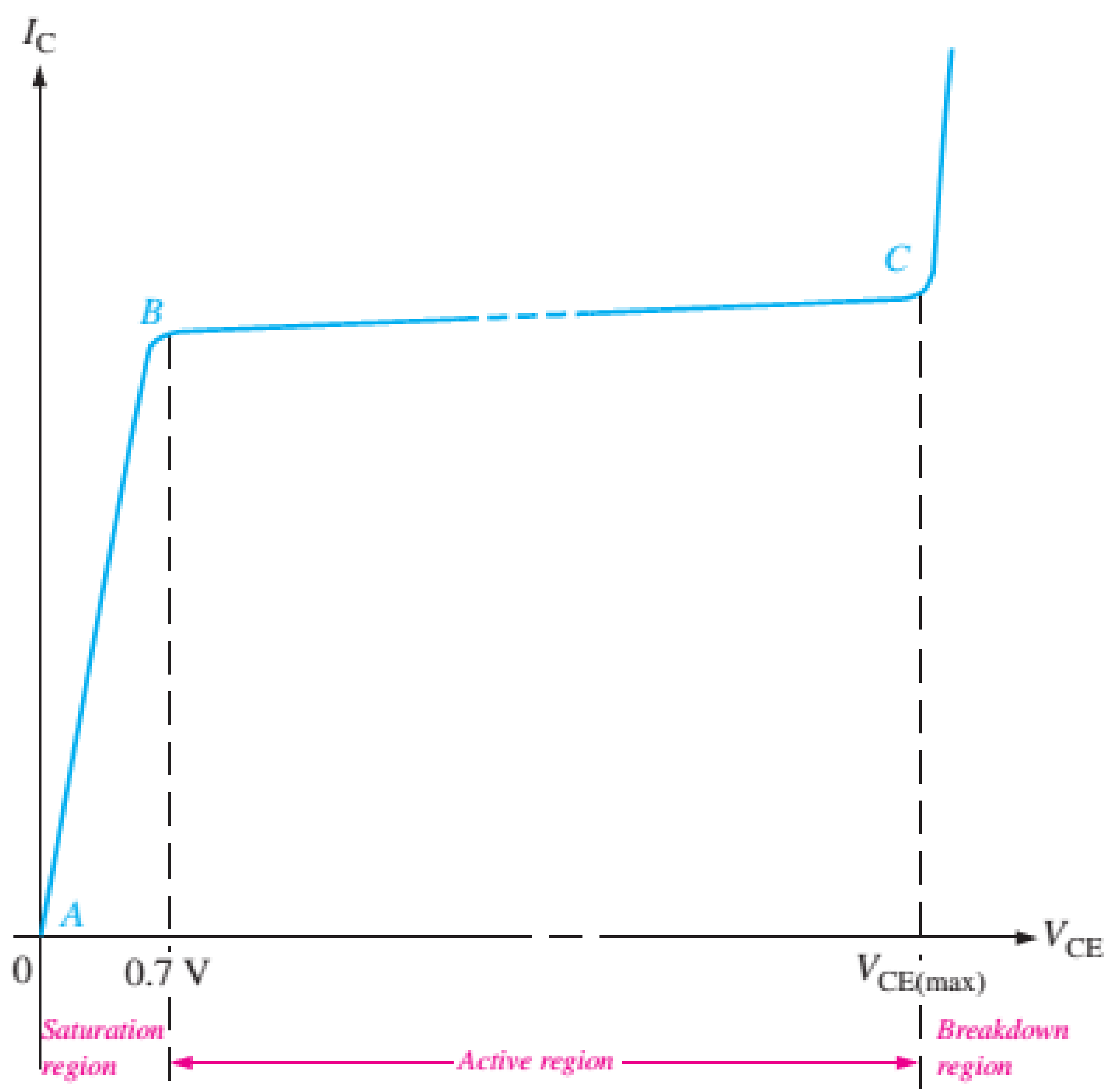
- Case A: **Saturation region**
  - Assume that V_{BB} is set to produce a certain value of I_B and V_{CC} is zero
    - Both the BE junction and the BC junction are forward-biased (V_B=0.7V and V_E=V_C= 0V)
  - V_{CC} is increased, V_{CE} increases as the collector current increases

- Case B: **Linear region**
  - When V_{CE} exceeds 0.7V, the base-collector junction becomes reverse-biased (base-emitter junction is forward-biased)
  - I_C levels off and remains essentially constant for a given value of I_B as V_{CE} continues to increase
  - The below relationship is valid

$$I_C = \beta_{DC} I_B.$$

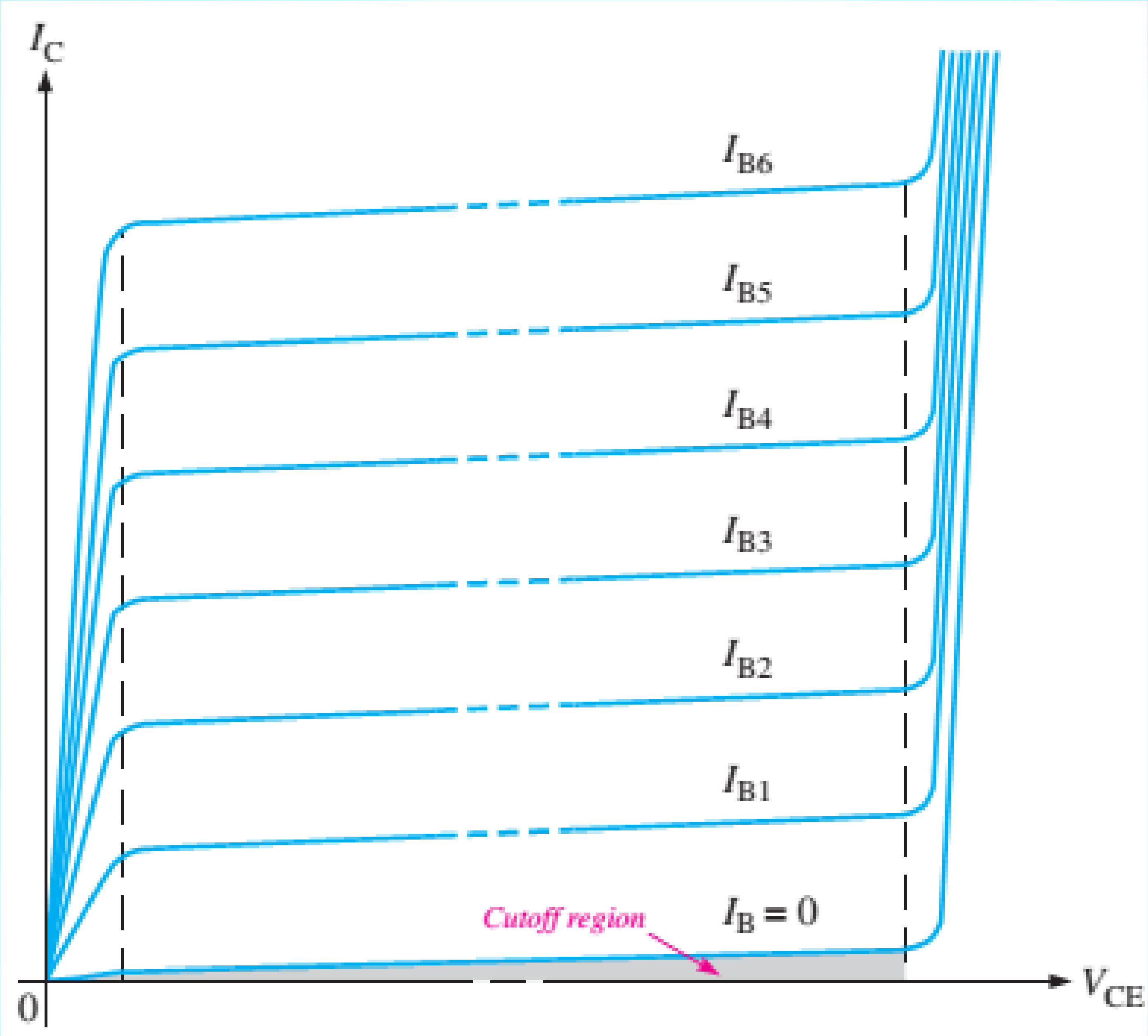
BJT Characteristics Curve

- Case C: **Breakdown region**
  - When V_{CE} reaches a sufficiently high voltage, the reverse-biased BC junction goes into breakdown and the collector current increases rapidly (base-emitter junction forward biased)
  - A transistor should never be operated in this breakdown region



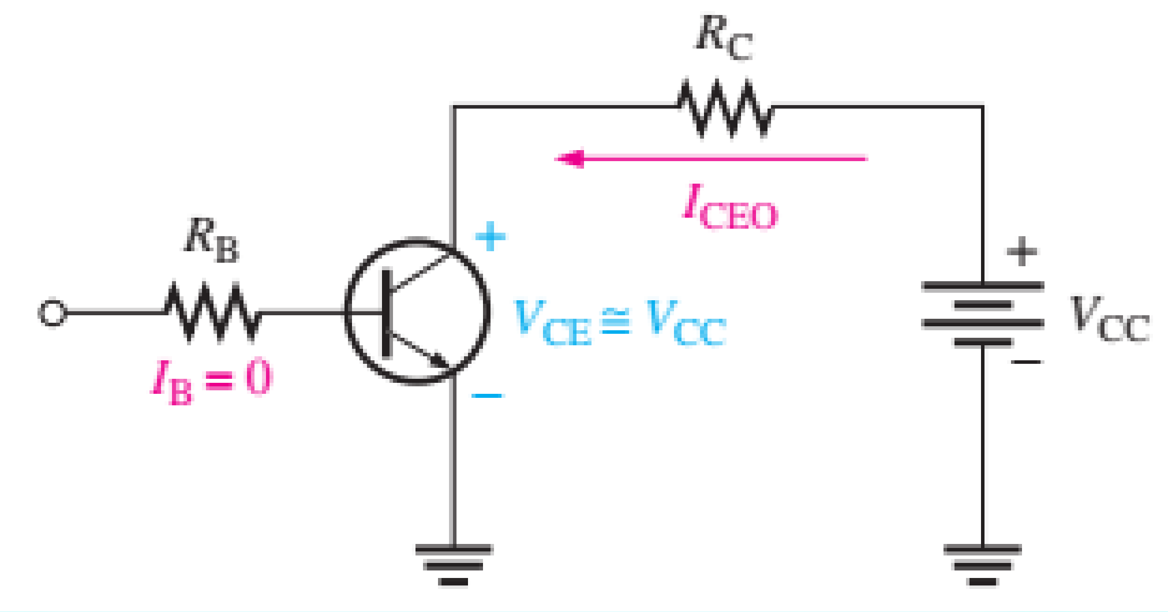
I_C
V_{CE}
A
B
C
0
0.7 V
$V_{CE(max)}$
Saturation region
Active region
Breakdown region

- A family of characteristic curves produced for several values of I_B



BJT Characteristics Curve

- **Cut-off region**
  - When $I_B = 0$, the transistor is in the cutoff region although there is a very small collector leakage current I_{CEO} (due mainly to thermally produced carriers)
  - Non-conducting state of a transistor
  - Both junctions reversed biased
  - Because I_C in cutoff is extremely small, it will usually be neglected in circuit analysis and $V_{CE} = V_{CC}$



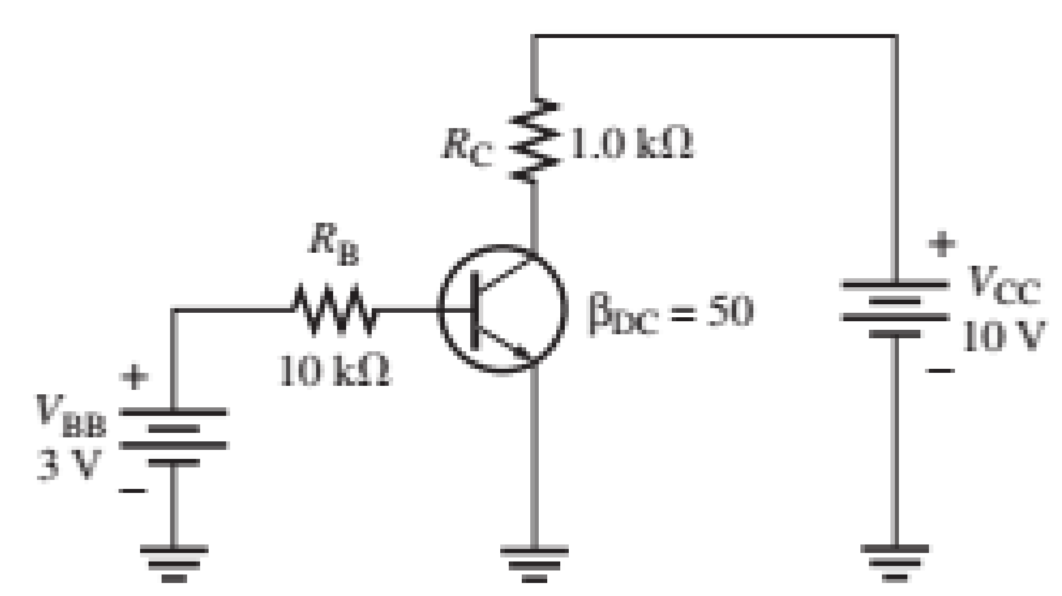
BJT Characteristics Curve

- **Saturation**
  - When the base-emitter junction becomes forward-biased and the base current is increased, the collector current also increases ($I_C = \beta_{DC} I_B$) and V_{CE} decreases as a result of more drop across the collector resistor ($V_{CE} = V_{CC} - I_C R_C$)
  - When V_{CE} reaches its saturation value, $V_{CE(sat)}$, the base-collector junction becomes forward-biased and I_C can increase no further even with a continued increase in I_B
  - At the point of saturation, the relation $I_C = \beta_{DC} I_B$ is no longer valid
  - $V_{CE(sat)}$ for a transistor occurs somewhere below the knee of the collector curves

BJT Characteristics Curve

Determine whether or not the transistor in Figure 4–16 is in saturation. Assume $V_{CE(sat)} = 0.2\text{ V}$.

FIGURE 4–16



BJT Characteristics Curve

First, determine $I_{C(sat)}$.

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{10\,V - 0.2\,V}{1.0\,k\Omega} = \frac{9.8\,V}{1.0\,k\Omega} = 9.8\,mA$$

Now, see if I_B is large enough to produce $I_{C(sat)}$.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3\,V - 0.7\,V}{10\,k\Omega} = \frac{2.3\,V}{10\,k\Omega} = 0.23\,mA$$

$$I_C = \beta_{DC} I_B = (50)(0.23\,mA) = 11.5\,mA$$

This shows that with the specified β_{DC}, this base current is capable of producing an I_C greater than $I_{C(sat)}$. Therefore, the **transistor is saturated,** and the collector current value of 11.5 mA is never reached. If you further increase I_B, the collector current remains at its saturation value of 9.8 mA.

Maximum Transistor Ratings

- A BJT, like any other electronic device, has limitations on its operation
- Typically, maximum ratings are given for collector-to-base voltage, collector-to-emitter voltage, emitter-to-base voltage, collector current, and power dissipation
- The product of V_{CE} and I_C must not exceed the maximum power dissipation. Both V_{CE} and I_C cannot be maximum at the same time
- If V_{CE} is maximum, I_C can be calculated as

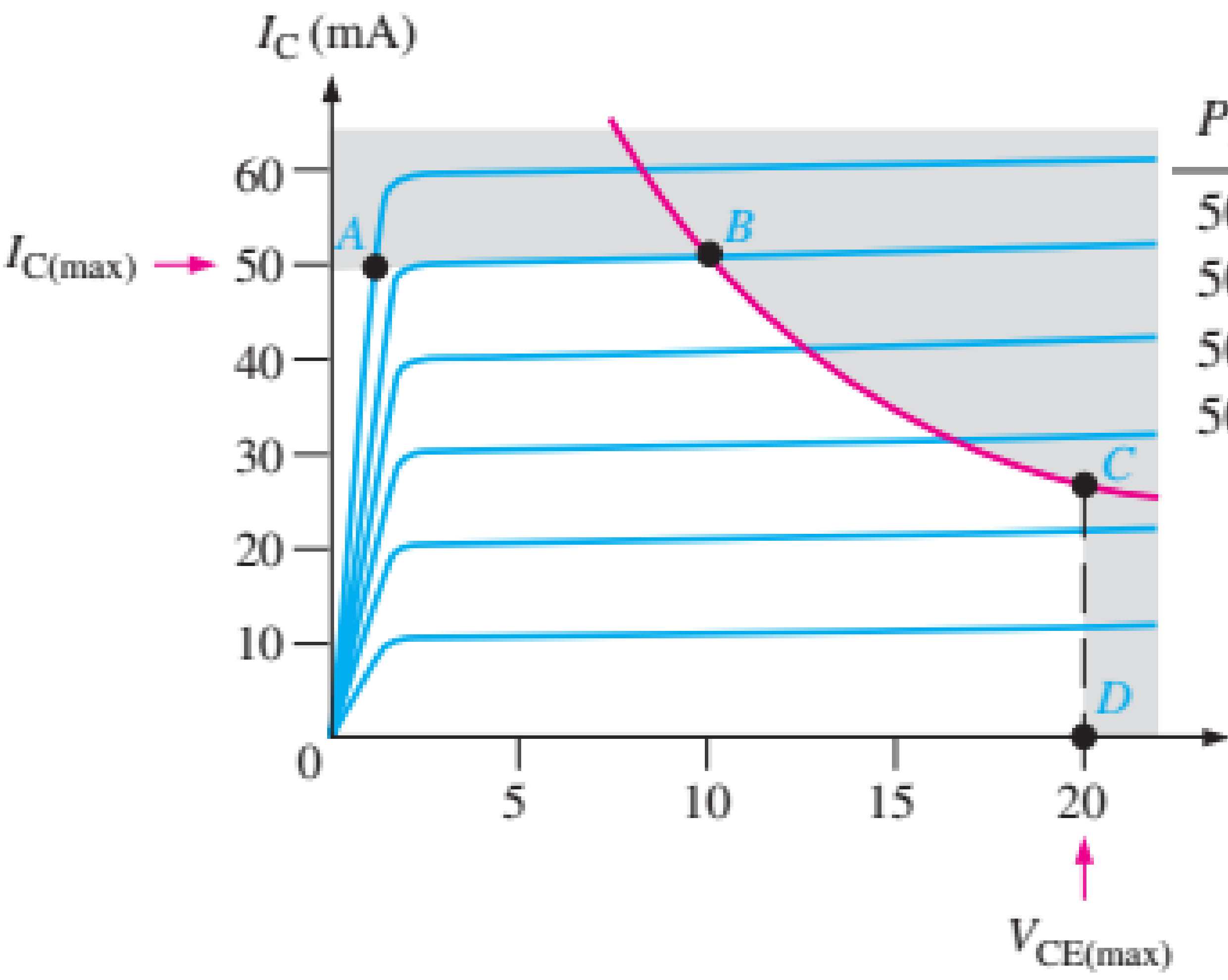
$$I_C = \frac{P_{D(max)}}{V_{CE}}$$

- If I_C is maximum, V_{CE} can be calculated by

$$V_{CE} = \frac{P_{D(max)}}{I_C}$$

Maximum Transistor Ratings

- A maximum power dissipation curve can be plotted on the collector characteristic curves



$P_{D(max)}$	V_{CE}	I_C
500 mW	5 V	100 mA
500 mW	10 V	50 mA
500 mW	15 V	33 mA
500 mW	20 V	25 mA

Maximum Transistor Ratings

- Assume $P_{D(max)}$ is 500 mW, $V_{CE(max)}$ is 20 V, and $I_{C(max)}$ is 50 mA
- The curve shows that this particular transistor cannot be operated in the shaded portion of the graph
- $I_{C(max)}$ is the limiting rating between points *A* and *B*, $P_{D(max)}$ is the limiting rating between points *B* and *C*, and $V_{CE(max)}$ is the limiting rating between points *C* and *D*

Maximum Transistor Ratings

A certain transistor is to be operated with $V_{CE} = 6$ V. If its maximum power rating is 250 mW, what is the most collector current that it can handle?

Maximum Transistor Ratings

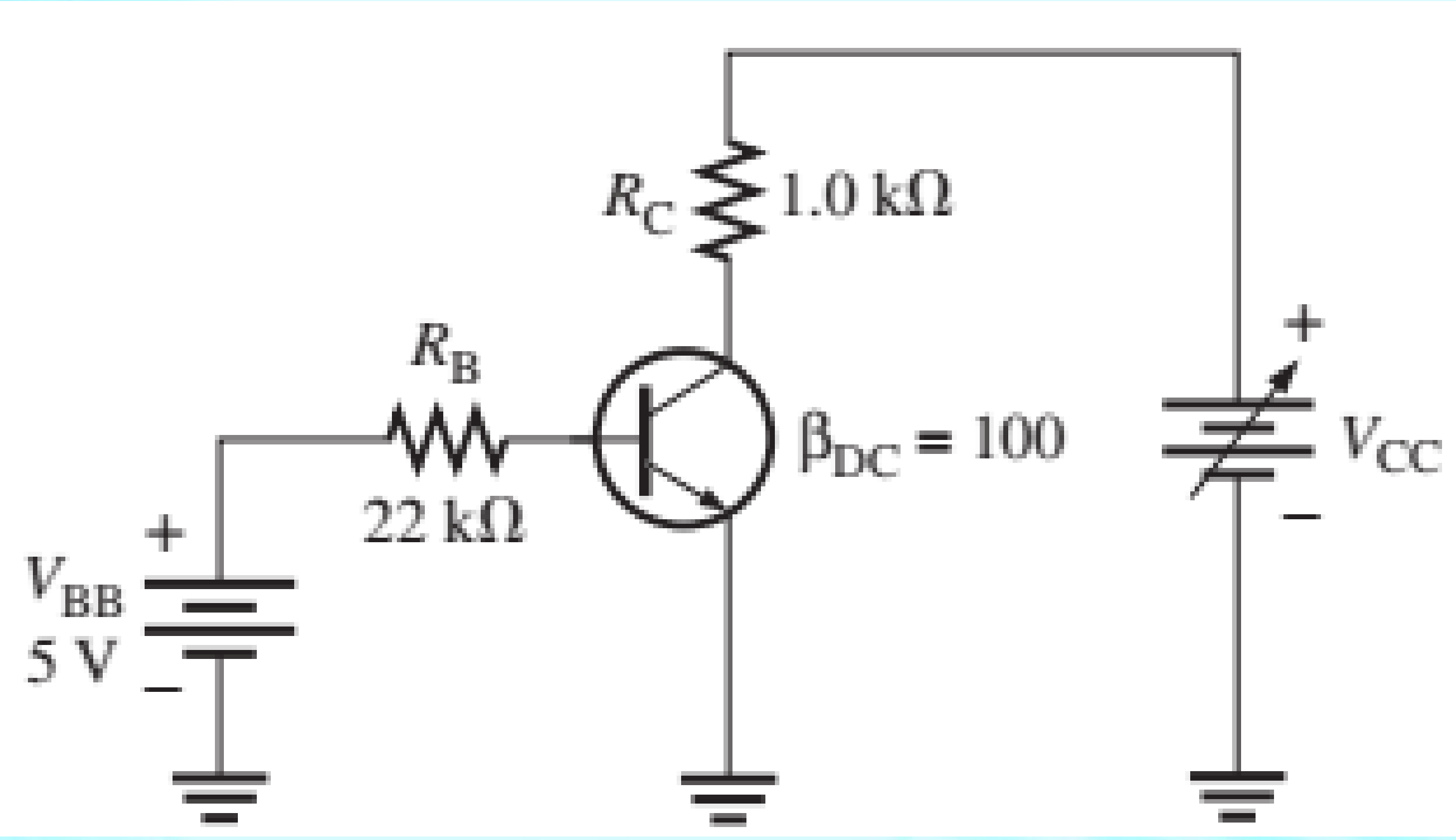
A certain transistor is to be operated with $V_{CE} = 6$ V. If its maximum power rating is 250 mW, what is the most collector current that it can handle?

$$I_C = \frac{P_{D(max)}}{V_{CE}} = \frac{250 \text{ mW}}{6 \text{ V}} = \mathbf{41.7 \text{ mA}}$$

This is the maximum current for this particular value of V_{CE}. The transistor can handle more collector current if V_{CE} is reduced, as long as $P_{D(max)}$ and $I_{C(max)}$ are not exceeded.

Maximum Transistor Ratings

The transistor in Figure has the following maximum ratings: $P_{D(max)} = 800$ mW, $V_{CE(max)} = 15$ V, and $I_{C(max)} = 100$ mA. Determine the maximum value to which V_{CC} can be adjusted without exceeding a rating.



First, find I_B so that you can determine I_C.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{22\text{ k}\Omega} = 195\ \mu\text{A}$$

$$I_C = \beta_{DC} I_B = (100)(195\ \mu\text{A}) = 19.5\text{ mA}$$

I_C is much less than $I_{C(max)}$ and ideally will not change with V_{CC}. It is determined only by I_B and β_{DC}.

The voltage drop across R_C is

$$V_{R_C} = I_C R_C = (19.5\text{ mA})(1.0\text{ k}\Omega) = 19.5\text{ V}$$

Now you can determine the value of V_{CC} when $V_{CE} = V_{CE(max)} = 15$ V.

$$V_{R_C} = V_{CC} - V_{CE}$$

So,

$$V_{CC(max)} = V_{CE(max)} + V_{R_C} = 15\text{ V} + 19.5\text{ V} = \mathbf{34.5\ V}$$

V_{CC} can be increased to 34.5 V, under the existing conditions, before $V_{CE(max)}$ is exceeded. However, at this point it is not known whether or not $P_{D(max)}$ has been exceeded.

$$P_D = V_{CE(max)} I_C = (15\text{ V})(19.5\text{ mA}) = 293\text{ mW}$$

Since $P_{D(max)}$ is 800 mW, it is *not* exceeded when $V_{CC} = 34.5$ V. So, $V_{CE(max)} = 15$ V is the limiting rating in this case.

BJT as an Amplifier

- Notation
  - AC current and voltage values are always rms unless stated otherwise
  - DC quantities always carry an uppercase roman (nonitalic) subscript
    For example, I_{B}, I_{C}, and I_{E} are the dc transistor currents. V_{BE}, V_{CB}, and V_{CE} are the dc voltages from one transistor terminal to another. Single subscripted voltages such as V_{B}, V_{C}, and V_{E} are dc voltages from the transistor terminals to ground
  - AC and all time-varying quantities always carry a lowercase italic subscript. For example, I_b, I_c, and I_e are the ac transistor currents. V_{be}, V_{cb}, and V_{ce} are the ac voltages from one transistor terminal to another. Single subscripted voltages such as V_b, V_c, and V_e are ac voltages from the transistor terminals to ground

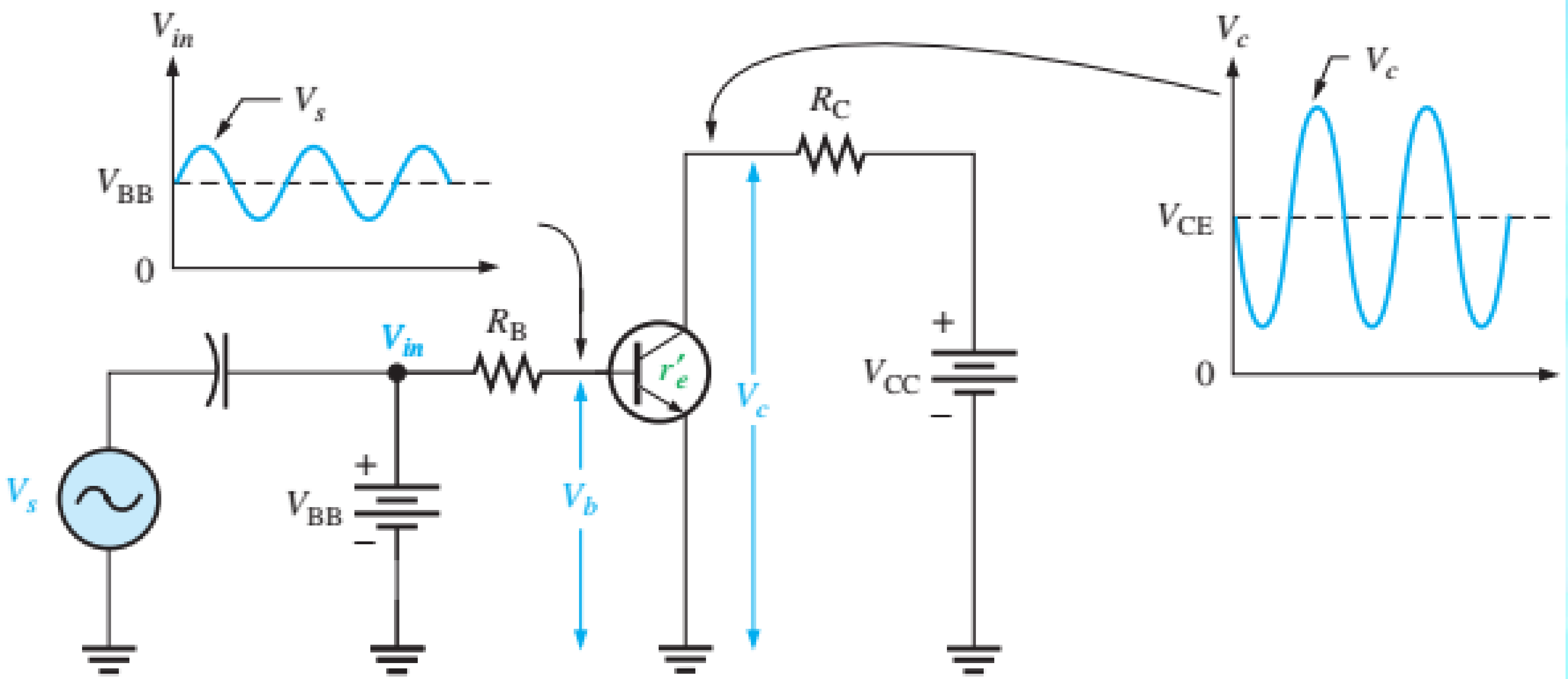
BJT as an Amplifier

- Notation
  - Transistors have internal ac resistances that are designated by lowercase *r'* with an appropriate subscript. For example, the internal ac emitter resistance is designated as r'_e.

  - Circuit resistances external to the transistor itself use the standard italic capital *R* with a subscript that identifies the resistance as dc or ac (when applicable), just as for current and voltage. For example R_E is an external dc emitter resistance and R_e is an external ac emitter resistance.

BJT as an Amplifier

- Voltage amplification



BJT as an Amplifier

- An ac voltage, V_s, is superimposed on the dc bias voltage V_{BB} by capacitive coupling as shown
- The dc bias voltage V_{CC} is connected to the collector through the collector resistor, R_C
- The ac input voltage produces an ac base current, which results in a much larger ac collector current. The ac collector current produces an ac voltage across R_C, thus producing an amplified, but inverted, reproduction of the ac input voltage in the active region of operation
- The forward-biased base-emitter junction presents a very low resistance to the ac signal. This internal ac emitter resistance is designated r'_e in Figure and appears in series with R_B.

BJT as an Amplifier

- The ac base voltage is $V_b = I_e r_e'$

- The ac collector voltage, V_c, equals the ac voltage drop across R_C : $V_c = I_c R_C$

- Since $I_c \approx I_e$ the ac collector voltage is : $V_c \approx I_e R_C$

- V_b can be considered the transistor ac input voltage where $V_b = V_s - I_b R_B$

- V_c can be considered the transistor ac output voltage

BJT as an Amplifier

- Since *voltage gain* is defined as the ratio of the output voltage to the input voltage,

$$A_V = \frac{V_c}{V_b}$$

$$A_V = \frac{V_c}{V_b} \approx \frac{I_e R_C}{I_e r_e'}$$

$$A_V \approx \frac{R_C}{r_e'}$$

- Equation shows that the transistor provides amplification in the form of voltage gain, which is dependent on the values of R_C and r_e'

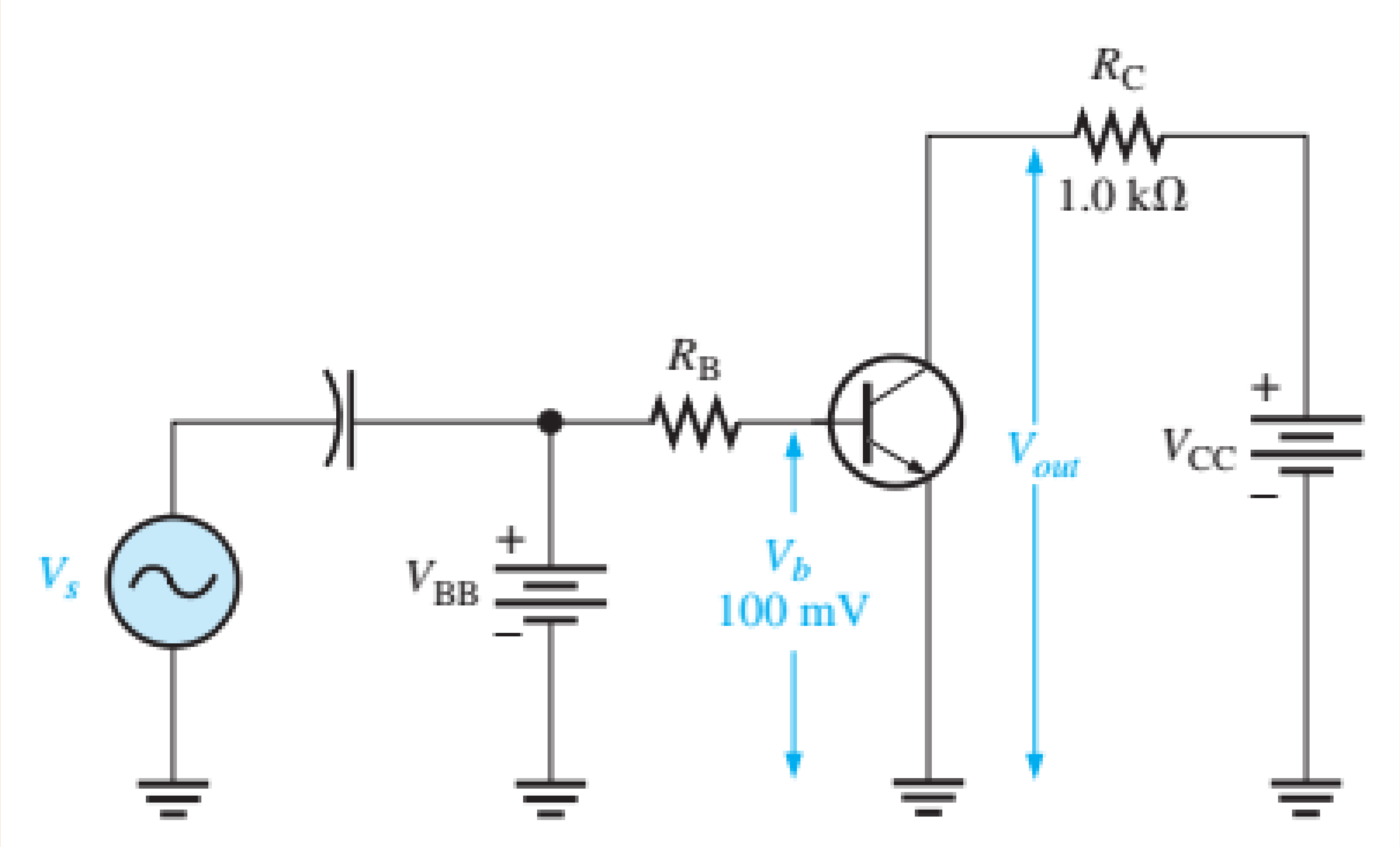
BJT as an Amplifier

- Since R_C is always considerably larger in value than r_e', the output voltage for this configuration is greater than the input voltage

-

BJT as an Amplifier

Determine the voltage gain and the ac output voltage in Figure if $r'_e = 50\ \Omega$.



BJT as an Amplifier

The voltage gain is

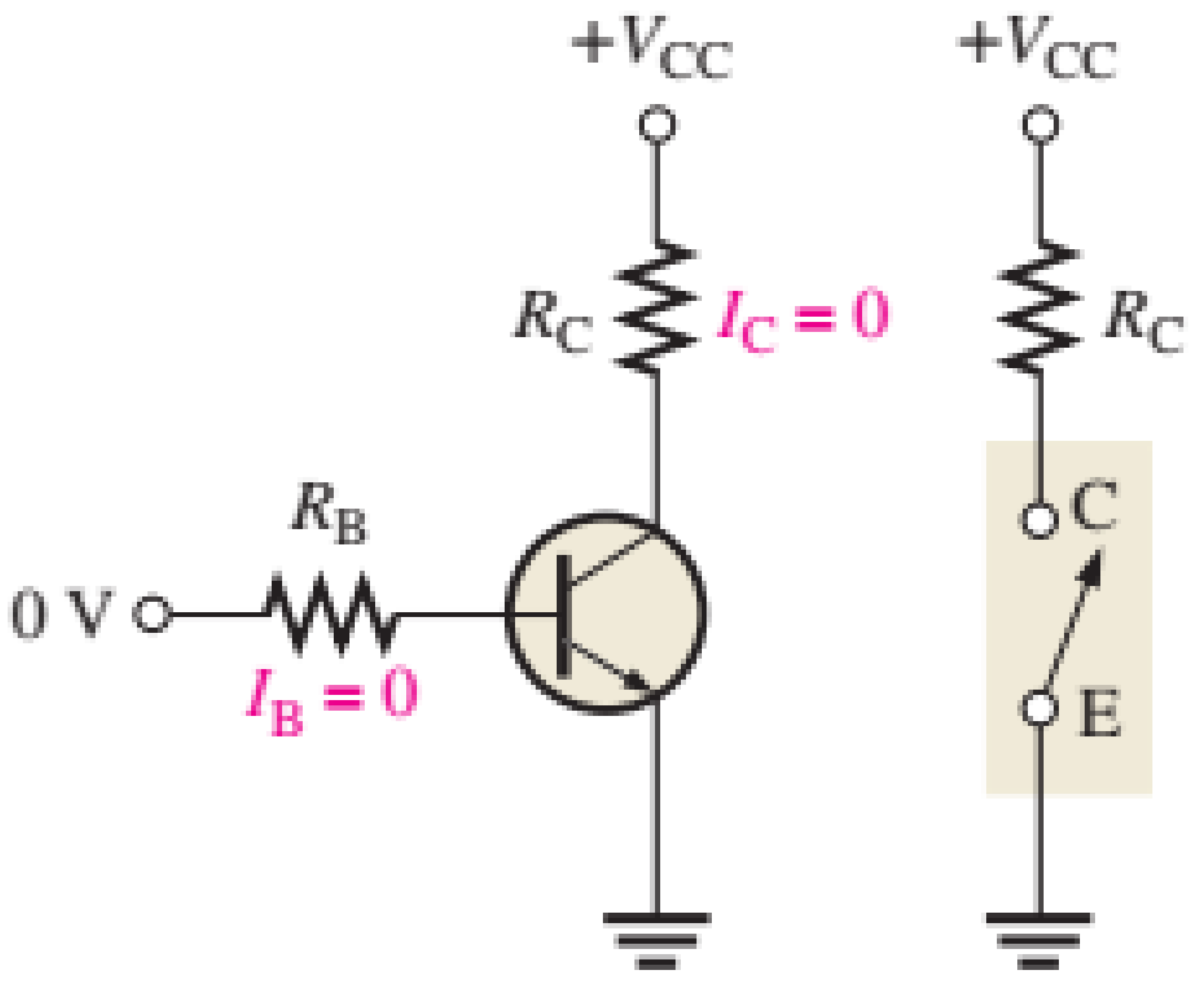
$$A_v \cong \frac{R_C}{r'_e} = \frac{1.0\,\text{k}\Omega}{50\,\Omega} = \mathbf{20}$$

Therefore, the ac output voltage is

$$V_{out} = A_v V_b = (20)(100\,\text{mV}) = \mathbf{2\ V\ rms}$$

BJT as an Switch

- Open switch



(a) Cutoff — open switch

BJT as an Switch

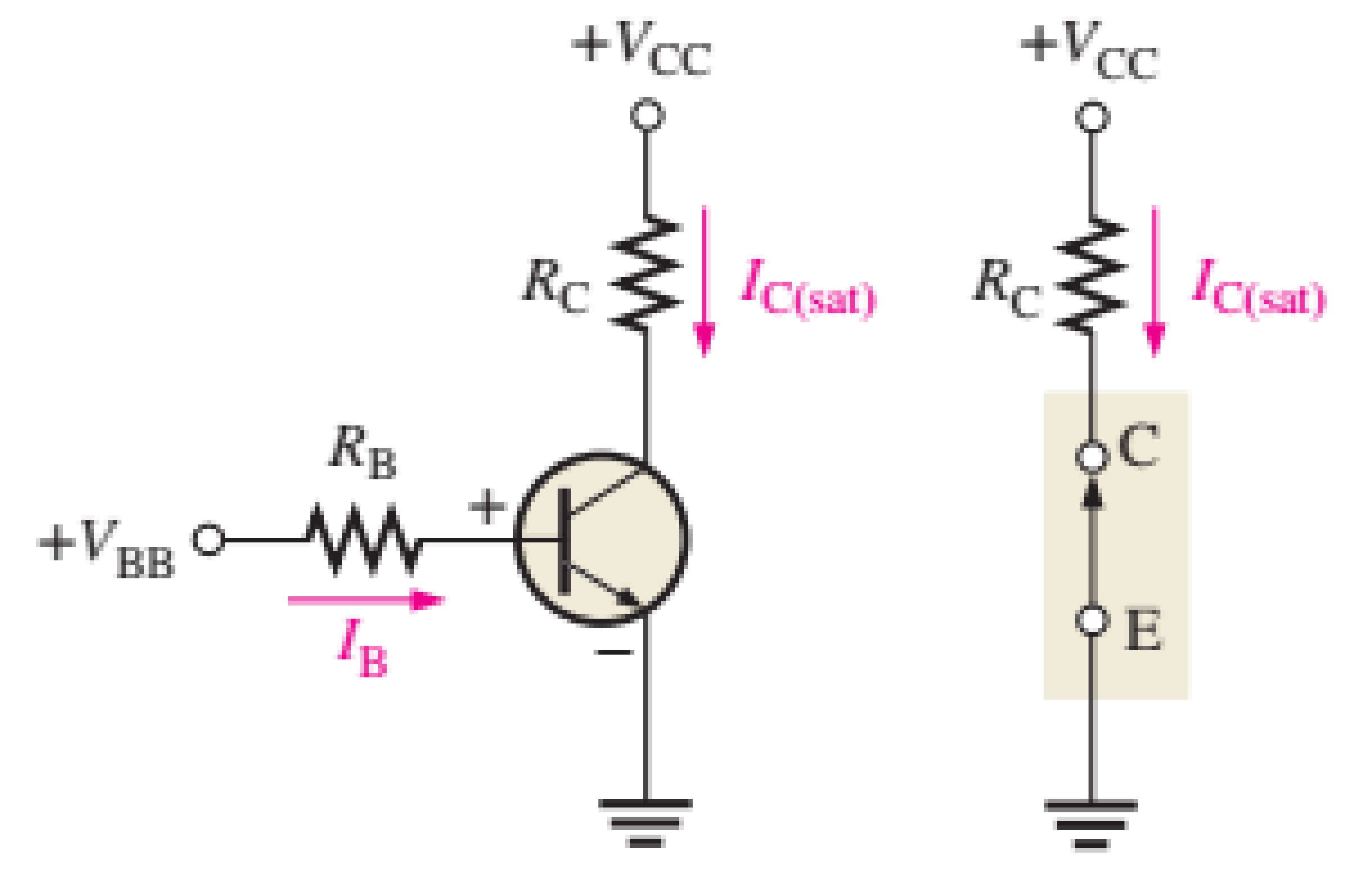
- The transistor is in the cutoff region because the base-emitter junction is not forward-biased. In this condition, there is, ideally, an *open* between collector and emitter, as indicated by the switch equivalent

- ***Conditions in Cutoff***
  - A transistor is in the cutoff region when the base-emitter junction is not forward-biased.
  - Neglecting leakage current, all of the currents are zero, and V_{CE} is equal to V_{CC}.

$$V_{CE(cutoff)} = V_{CC}$$

BJT as an Switch

- Closed switch



(b) Saturation — closed switch

BJT as an Switch

- The transistor is in the saturation region because the base-emitter junction and the base-collector junction are forward-biased and the base current is made large enough to cause the collector current to reach its saturation value
- In this condition, there is, ideally, a *short* between collector and emitter, as indicated by the switch equivalent
- Actually, a small voltage drop across the transistor of up to a few tenths of a volt normally occurs, which is the saturation voltage, $V_{CE(sat)}$

BJT as an Switch

- ***Conditions in Saturation***
  - When the base-emitter junction is forward-biased and there is enough base current to produce a maximum collector current, the transistor is saturated
  - The formula for collector saturation current is

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C}$$

  - Since $V_{CE(sat)}$ is very small compared to V_{CC}, it can usually be neglected

BJT as an Switch

- ***Conditions in Saturation***
  - The minimum value of base current needed to produce saturation is

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta_{DC}}$$

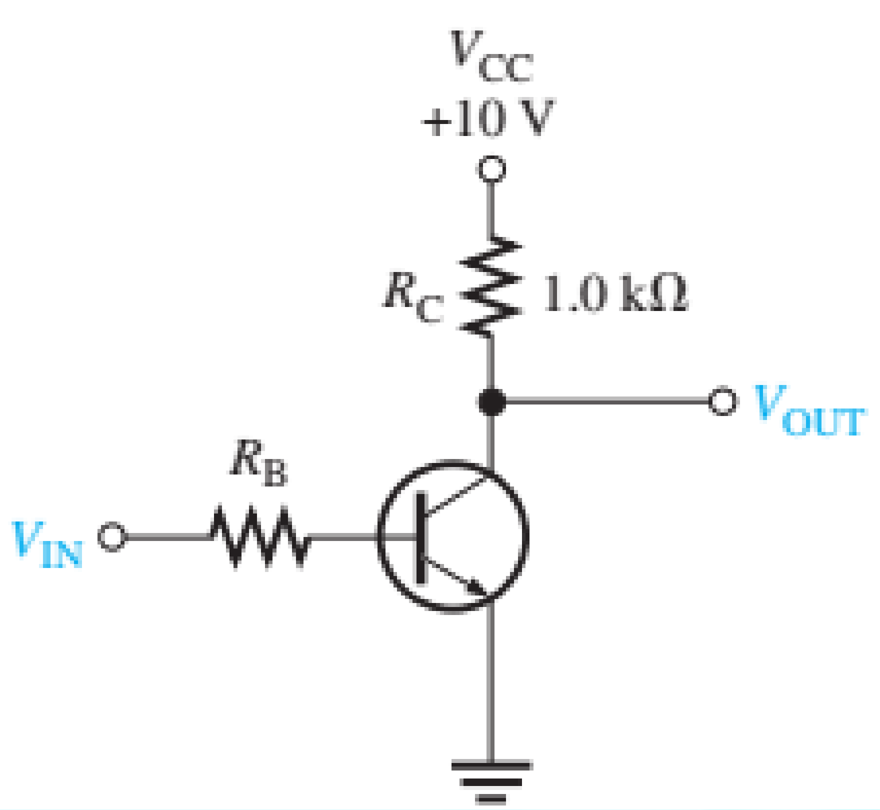
  - Normally, I_B should be significantly greater than $I_{B(min)}$ to ensure that the transistor is saturated

BJT as an Switch

(a) For the transistor circuit in Figure what is V_{CE} when $V_{IN} = 0$ V?

(b) What minimum value of I_B is required to saturate this transistor if β_{DC} is 200? Neglect $V_{CE(sat)}$.

(c) Calculate the maximum value of R_B when $V_{IN} = 5$ V.



(a) When $V_{IN} = 0$ V, the transistor is in cutoff (acts like an open switch) and

$$V_{CE} = V_{CC} = \mathbf{10\ V}$$

(b) Since $V_{CE(sat)}$ is neglected (assumed to be 0 V),

$$I_{C(sat)} = \frac{V_{CC}}{R_C} = \frac{10\ \text{V}}{1.0\ \text{k}\Omega} = 10\ \text{mA}$$

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta_{DC}} = \frac{10\ \text{mA}}{200} = \mathbf{50\ \mu A}$$

This is the value of I_B necessary to drive the transistor to the point of saturation. Any further increase in I_B will ensure the transistor remains in saturation but there cannot be any further increase in I_C.

(c) When the transistor is on, $V_{BE} \cong 0.7$ V. The voltage across R_B is

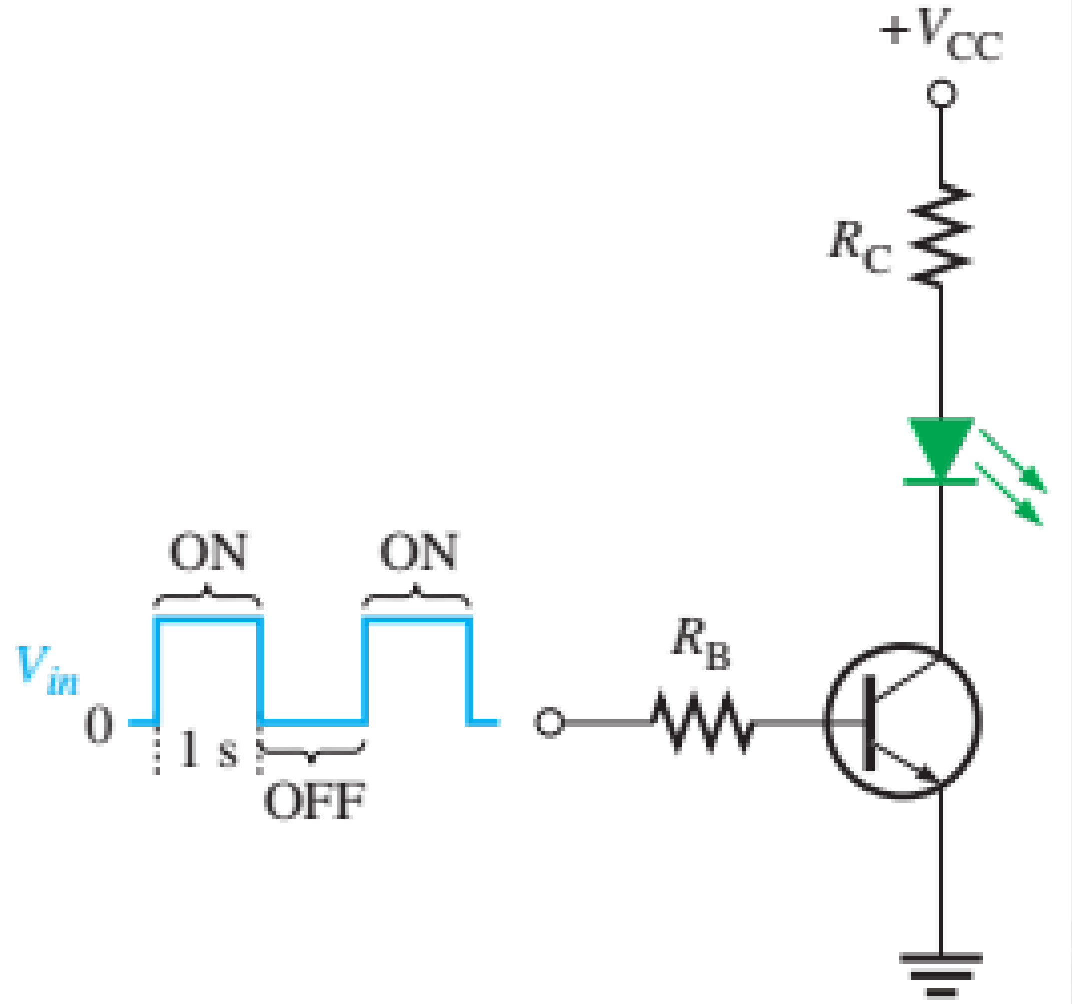
$$V_{R_B} = V_{IN} - V_{BE} \cong 5\ \text{V} - 0.7\ \text{V} = 4.3\ \text{V}$$

Calculate the maximum value of R_B needed to allow a minimum I_B of 50 μA using Ohm's law as follows:

$$R_{B(max)} = \frac{V_{R_B}}{I_{B(min)}} = \frac{4.3\ \text{V}}{50\ \mu\text{A}} = \mathbf{86\ k\Omega}$$

BJT as an Switch

- **A Simple Application of a Transistor Switch**
  - The transistor in figure is used as a switch to turn the LED on and off

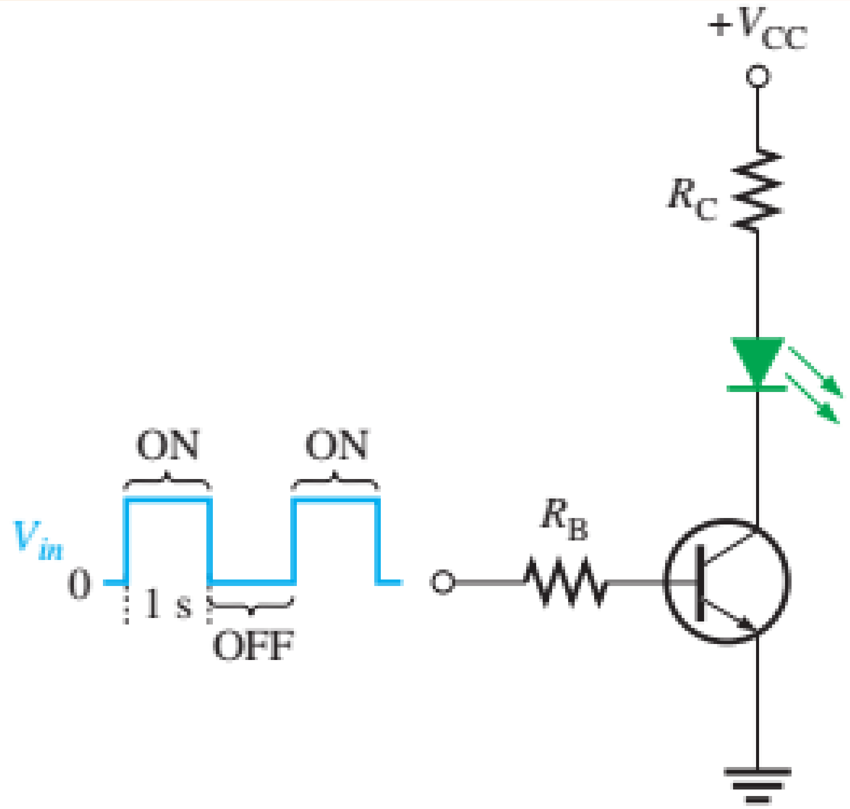


BJT as an Switch

- For example, a square wave input voltage with a period of 2s is applied to the input as indicated
- When the square wave is at 0 V, the transistor is in cutoff; and since there is no collector current, the LED does not emit light.
- When the square wave goes to its high level, the transistor saturates. This forward-biases the LED, and the resulting collector current through the LED causes it to emit light.
- Thus, the LED is on for 1 second and off for 1 second

BJT as an Switch

The LED in Figure requires 30 mA to emit a sufficient level of light. Therefore, the collector current should be approximately 30 mA. For the following circuit values, determine the amplitude of the square wave input voltage necessary to make sure that the transistor saturates. Use double the minimum value of base current as a safety margin to ensure saturation. $V_{CC} = 9$ V, $V_{CE(sat)} = 0.3$ V, $R_C = 220\ \Omega$, $R_B = 3.3\ k\Omega$, $\beta_{DC} = 50$, and $V_{LED} = 1.6$ V.



BJT as an Switch

$$I_{C(sat)} = \frac{V_{CC} - V_{LED} - V_{CE(sat)}}{R_C} = \frac{9\text{ V} - 1.6\text{ V} - 0.3\text{ V}}{220\ \Omega} = 32.3\text{ mA}$$

$$I_{B(min)} = \frac{I_{C(sat)}}{\beta_{DC}} = \frac{32.3\text{ mA}}{50} = 646\ \mu\text{A}$$

To ensure saturation, use twice the value of $I_{B(min)}$, which is 1.29 mA. Use Ohm's law to solve for V_{in}.

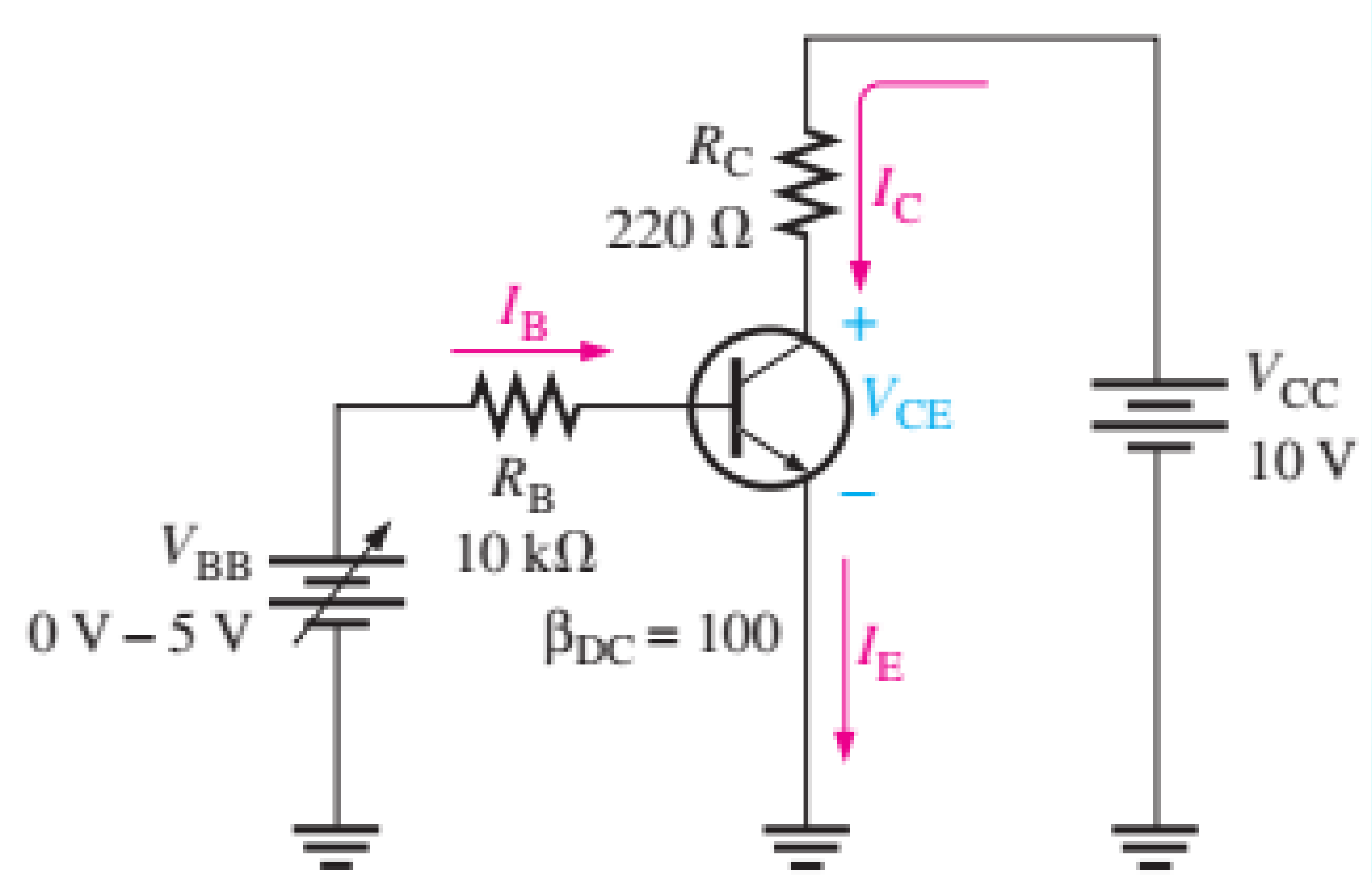
$$I_B = \frac{V_{R_B}}{R_B} = \frac{V_{in} - V_{BE}}{R_B} = \frac{V_{in} - 0.7\text{ V}}{3.3\text{ k}\Omega}$$

$$V_{in} - 0.7\text{ V} = 2I_{B(min)}R_B = (1.29\text{ mA})(3.3\text{ k}\Omega)$$

$$V_{in} = (1.29\text{ mA})(3.3\text{ k}\Omega) + 0.7\text{ V} = \mathbf{4.96\ V}$$

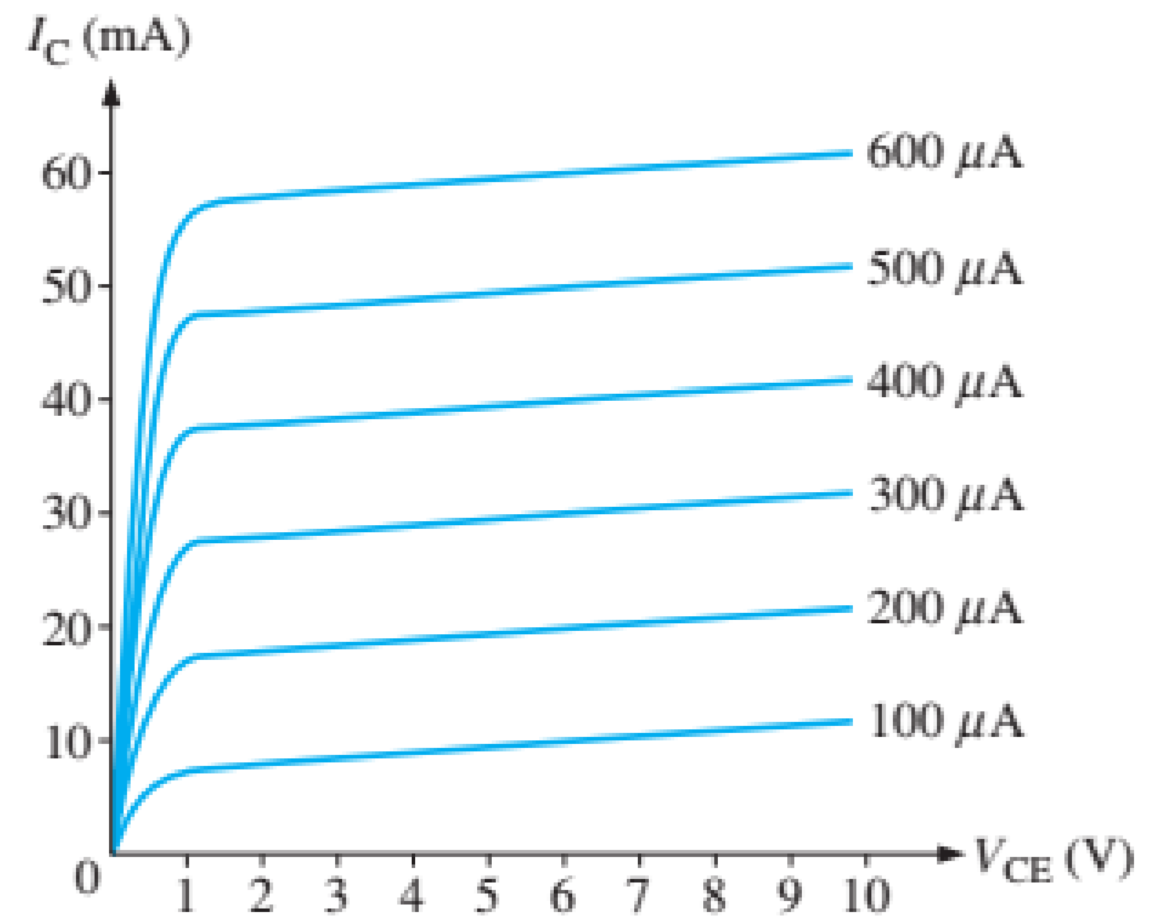
DC Operating Point

- The transistor in Figure is biased with V_{CC} and V_{BB} to obtain certain values of I_B, I_C, I_E, and V_{CE}



DC Operating Point

- The collector characteristic curves for this particular transistor are shown in Figure, we will use these curves to graphically illustrate the effects of dc bias

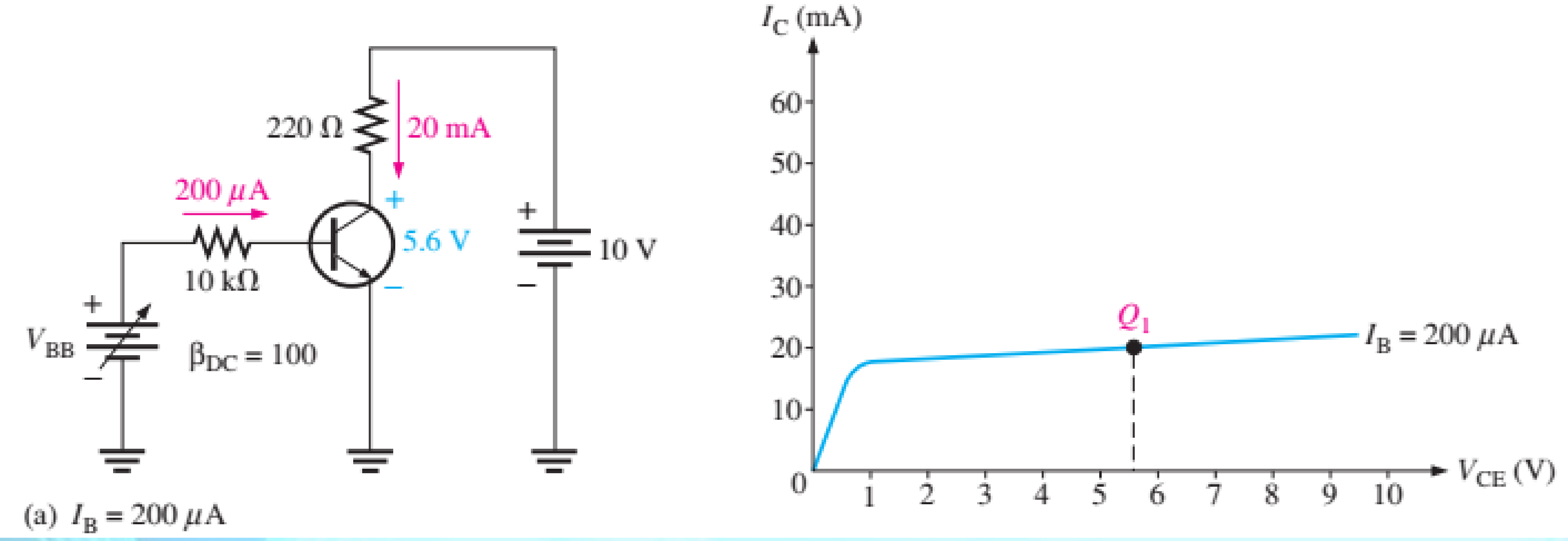


DC Operating Point

- We assign three values to I_B and observe what happens to I_C and V_{CE}
- First, V_{BB} is adjusted to produce an I_B of 200 µA as shown in Figure (next slide). Since $I_C = \beta_{DC} I_B$ the collector current is 20 mA, as indicated, and

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (20\text{ mA})(220\ \Omega) = 10\text{ V} - 4.4\text{ V} = 5.6\text{ V}$$

DC Operating Point

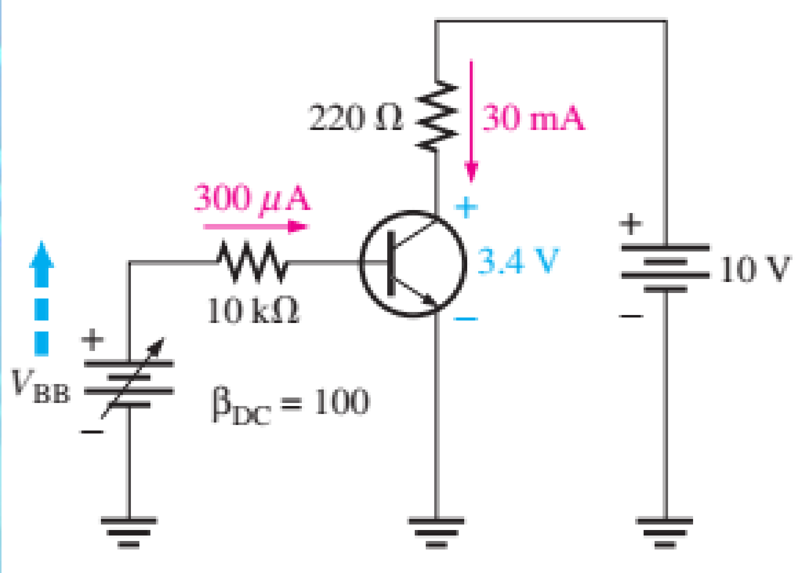


This Q-point is shown on the graph of Figure as *Q*1

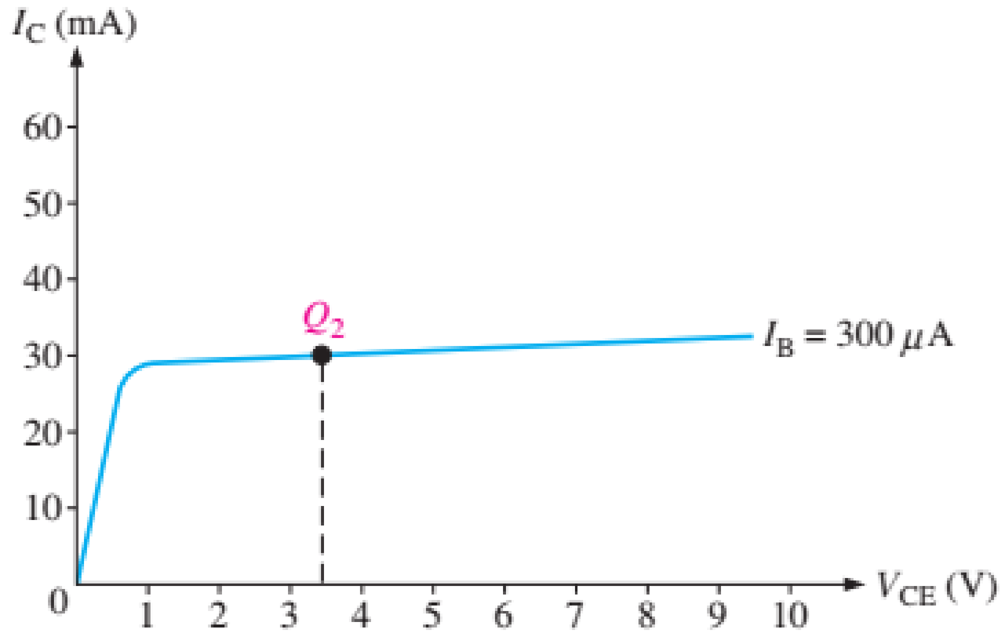
DC Operating Point

- Next, as shown in Figure, V_{BB} is increased to produce an I_B of 300 µA and an I_C of 30 mA

$$V_{CE} = 10\text{ V} - (30\text{ mA})(220\ \Omega) = 10\text{ V} - 6.6\text{ V} = 3.4\text{ V}$$



(b) Increase I_B to 300 μA by increasing V_{BB}

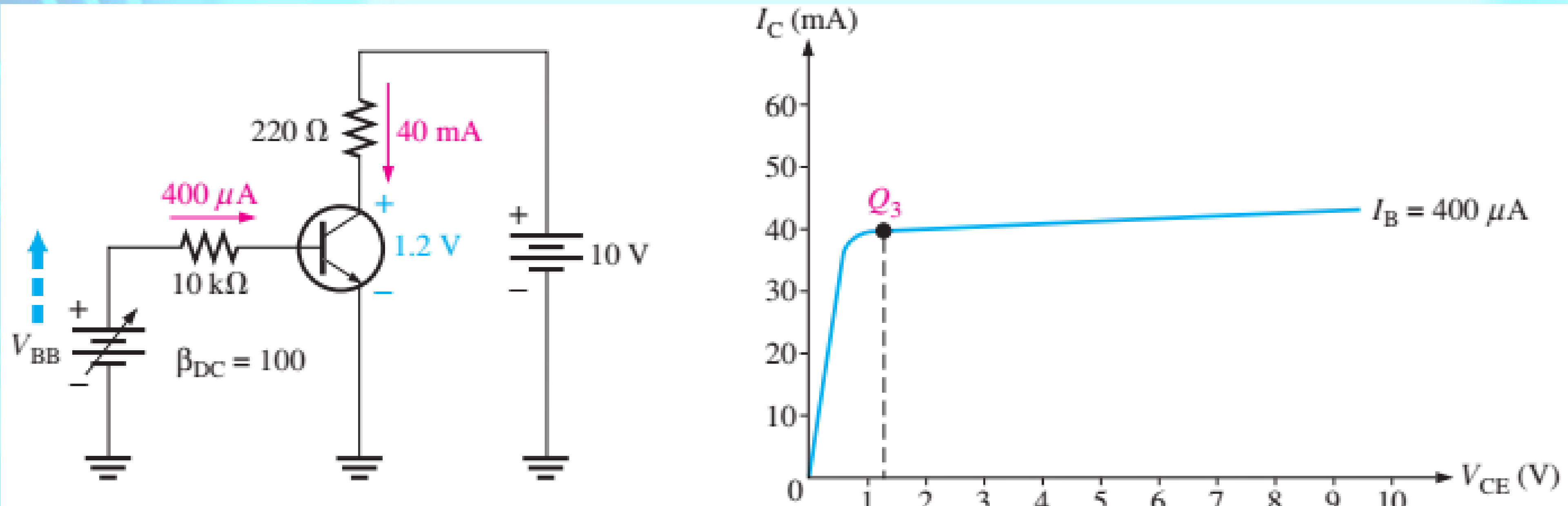


This Q-point is shown on the graph of Figure as *Q*2

DC Operating Point

- Finally, V_{BB} is increased to give an I_B of 400 µA and an I_C of 40 mA

$$V_{CE} = 10\text{ V} - (40\text{ mA})(220\ \Omega) = 10\text{ V} - 8.8\text{ V} = 1.2\text{ V}$$



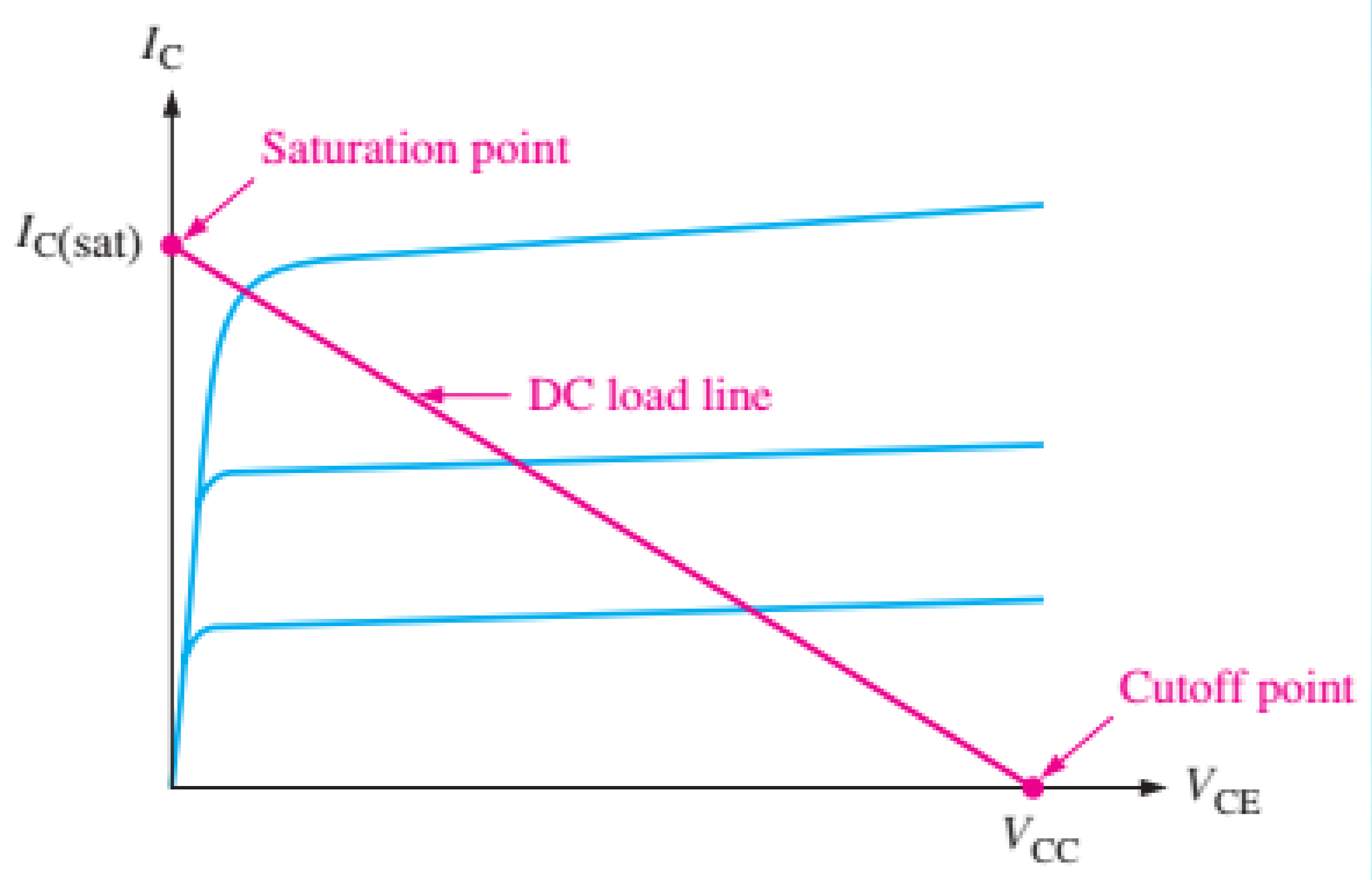
(c) Increase I_B to 400 µA by increasing V_{BB}

This Q-point is shown on the graph of Figure as *Q*3

DC Load Line

- The dc operation of a transistor circuit can be described graphically using a **dc load line**.
- This is a straight line drawn on the characteristic curves from the saturation value where $I_C = I_{C(sat)}$ on the y-axis to the cutoff value where $V_{CE} = V_{CC}$ on the x-axis, as shown in Figure (next slide).
- The load line is determined by the external circuit (V_{CC} and R_C), not the transistor itself

DC Load Line



DC Load Line

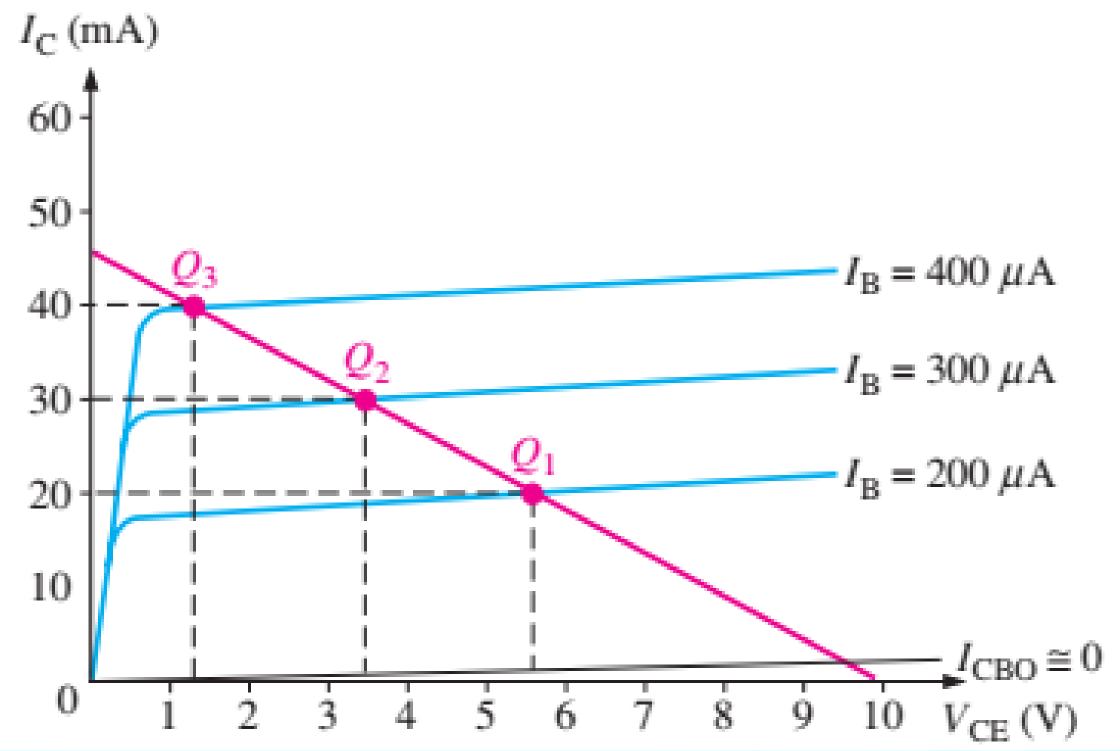
- The equation for I_C is:

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

- This is the equation of the load line with a slope of $-1/R_C$, an x intercept of $V_{CE}=V_{CC}$, and a y intercept of V_{CC}/R_C, which is $I_{C(sat)}$

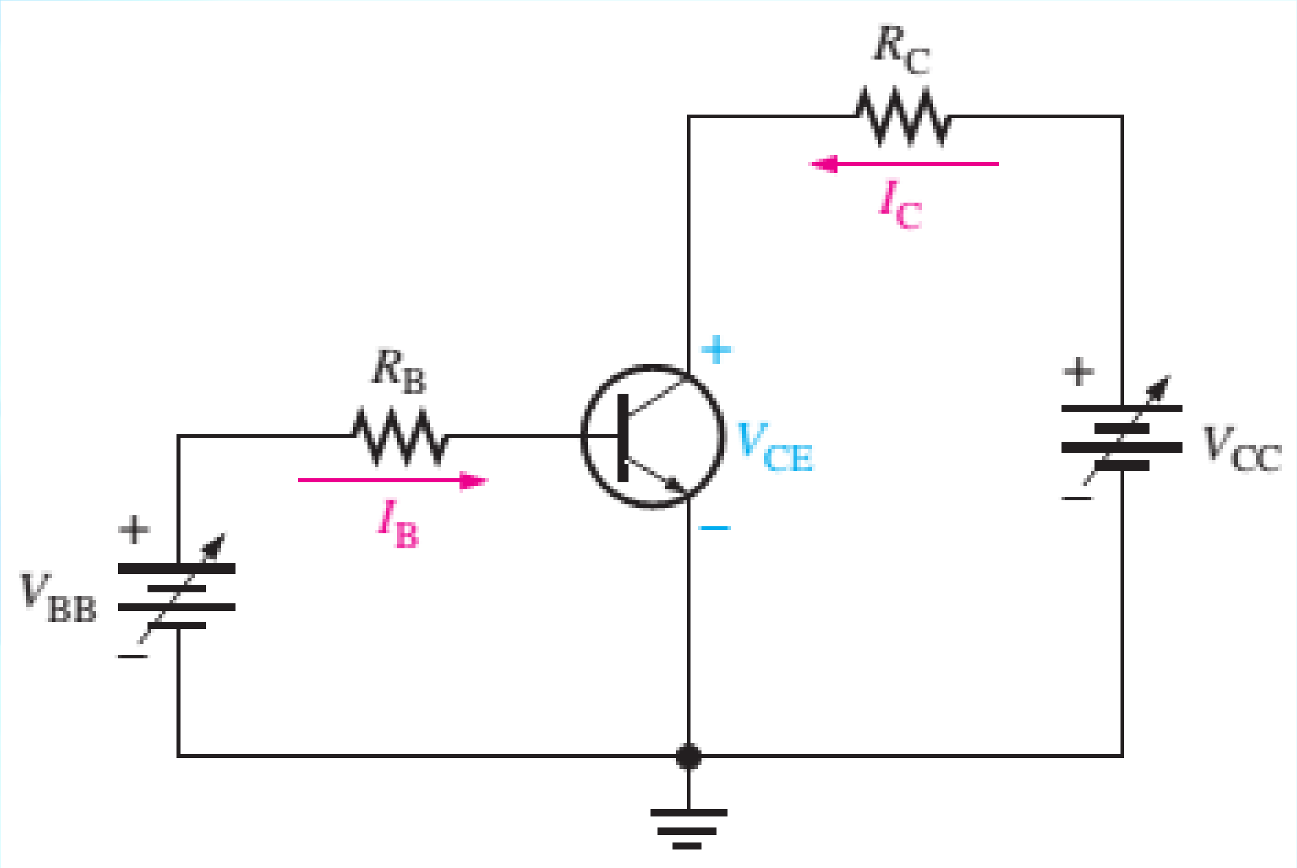
DC Load Line

- The point at which the load line intersects a characteristic curve represents the Q-point for that particular value of I_B
- Below Figure illustrates the Q-point on the load line for each value of I_B considered in the previous example.



DC Load Line

- Relationship between I_C and V_{CE}
  - Determined by the external components

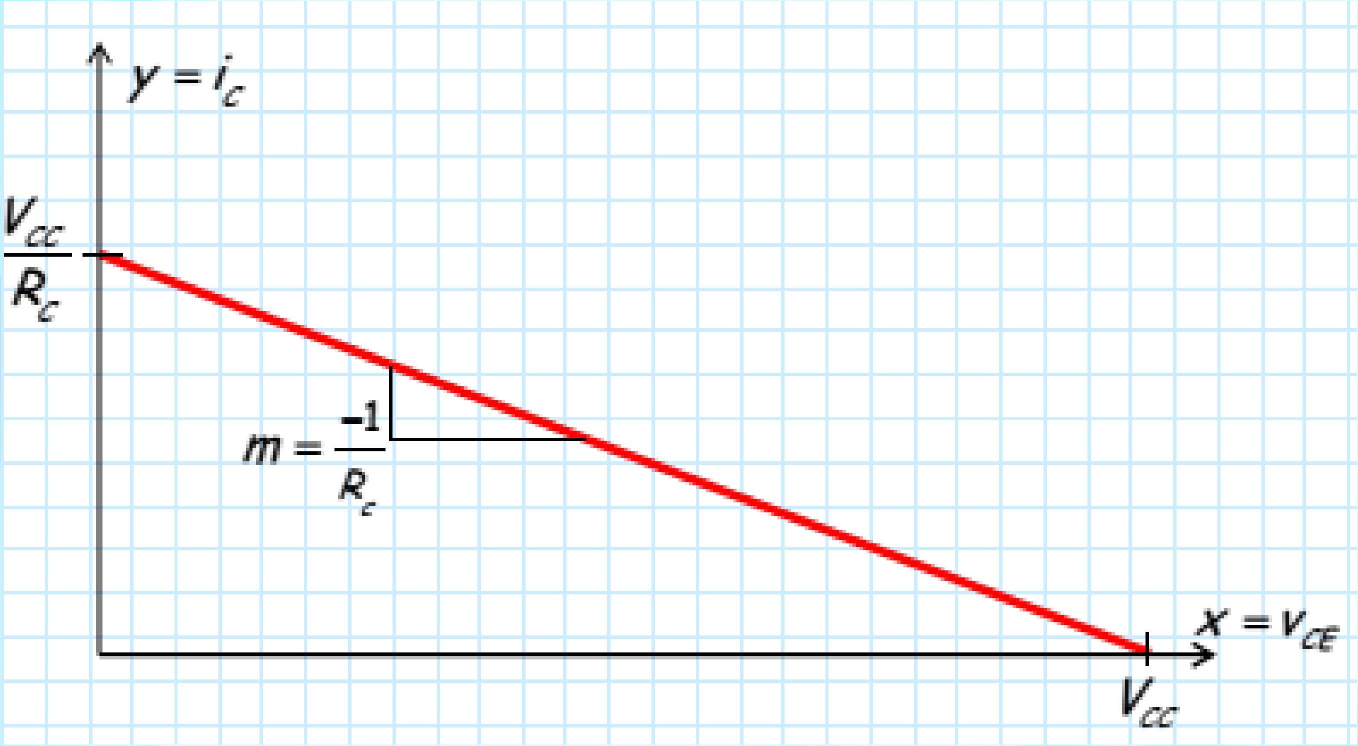


DC Load Line

- Relationship between I_C and V_{CE}

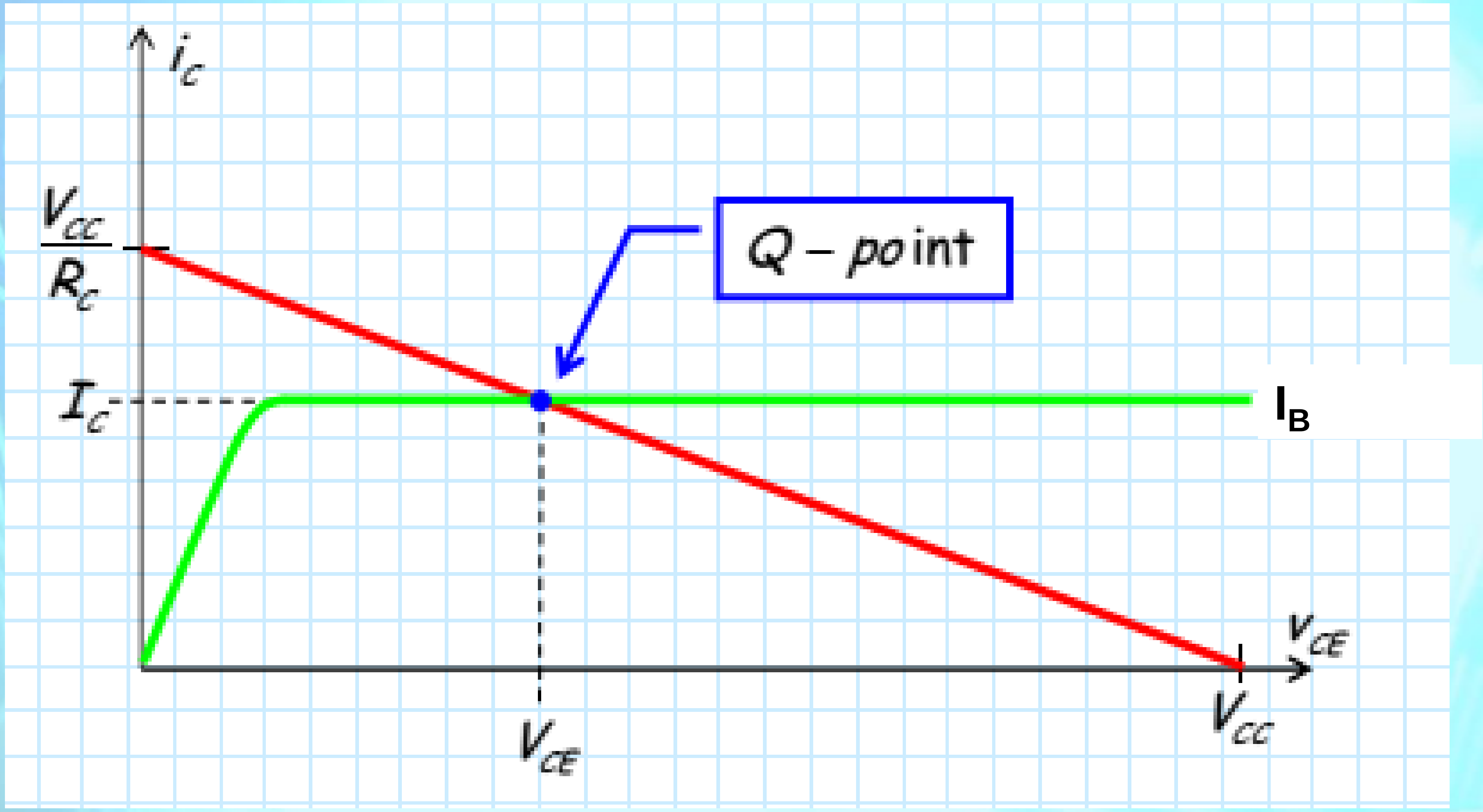
$$V_{CC} = I_C R_C + V_{CE}$$

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



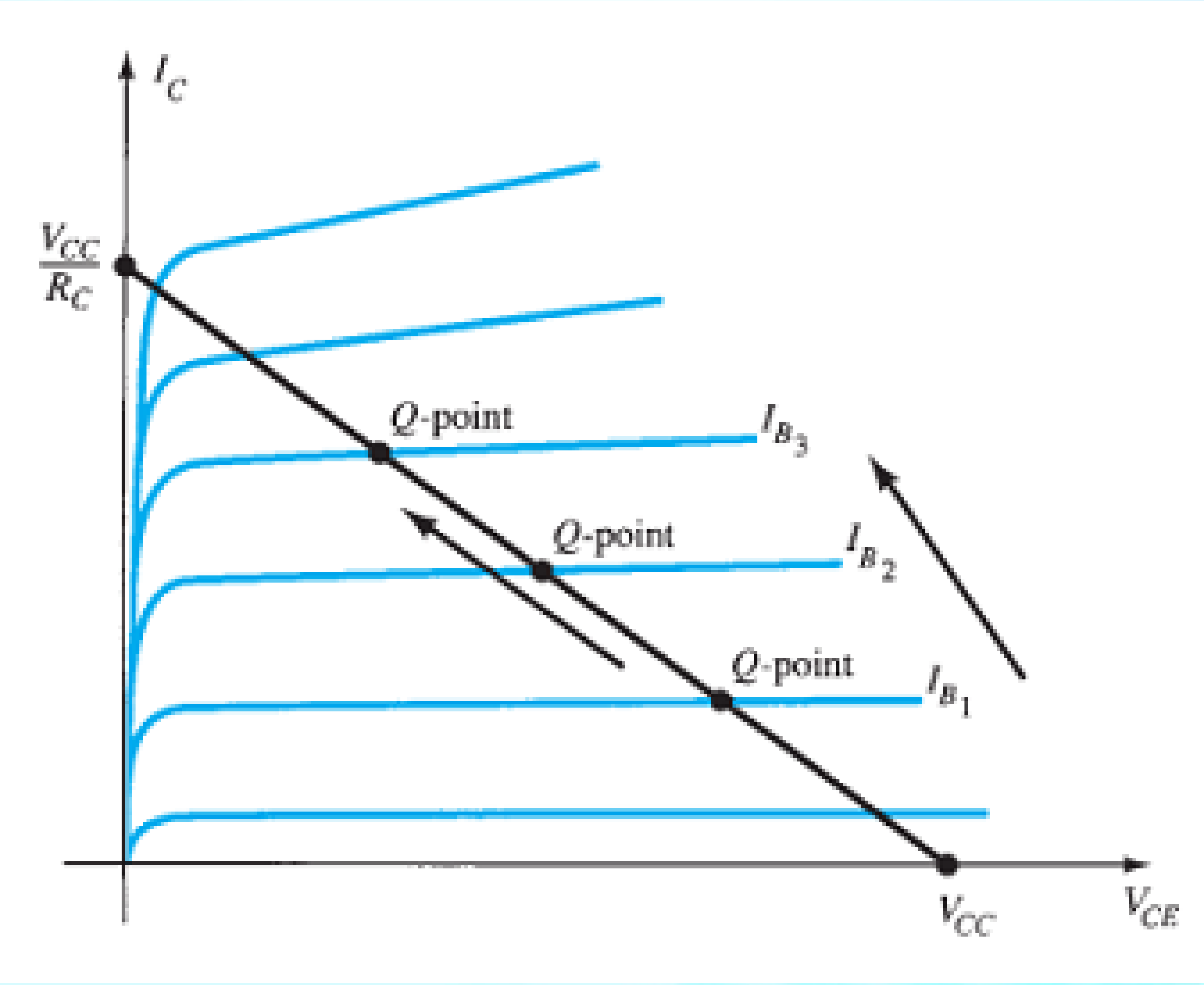
Operating Point

- The intersection of the two curves defines the operating point (Q-point, quiescent point)



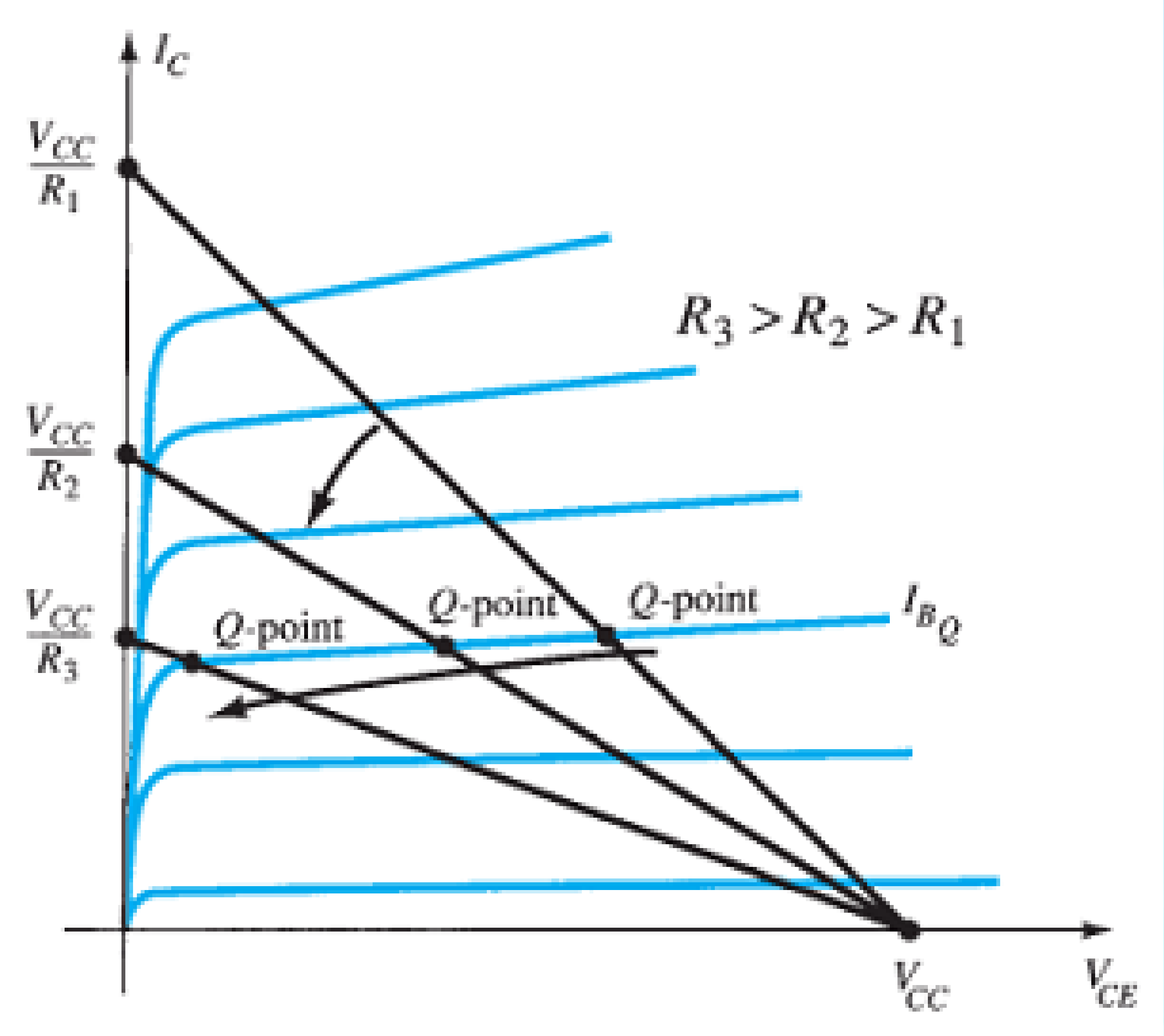
Operating Point

Movement of Q-point for different levels of I_B



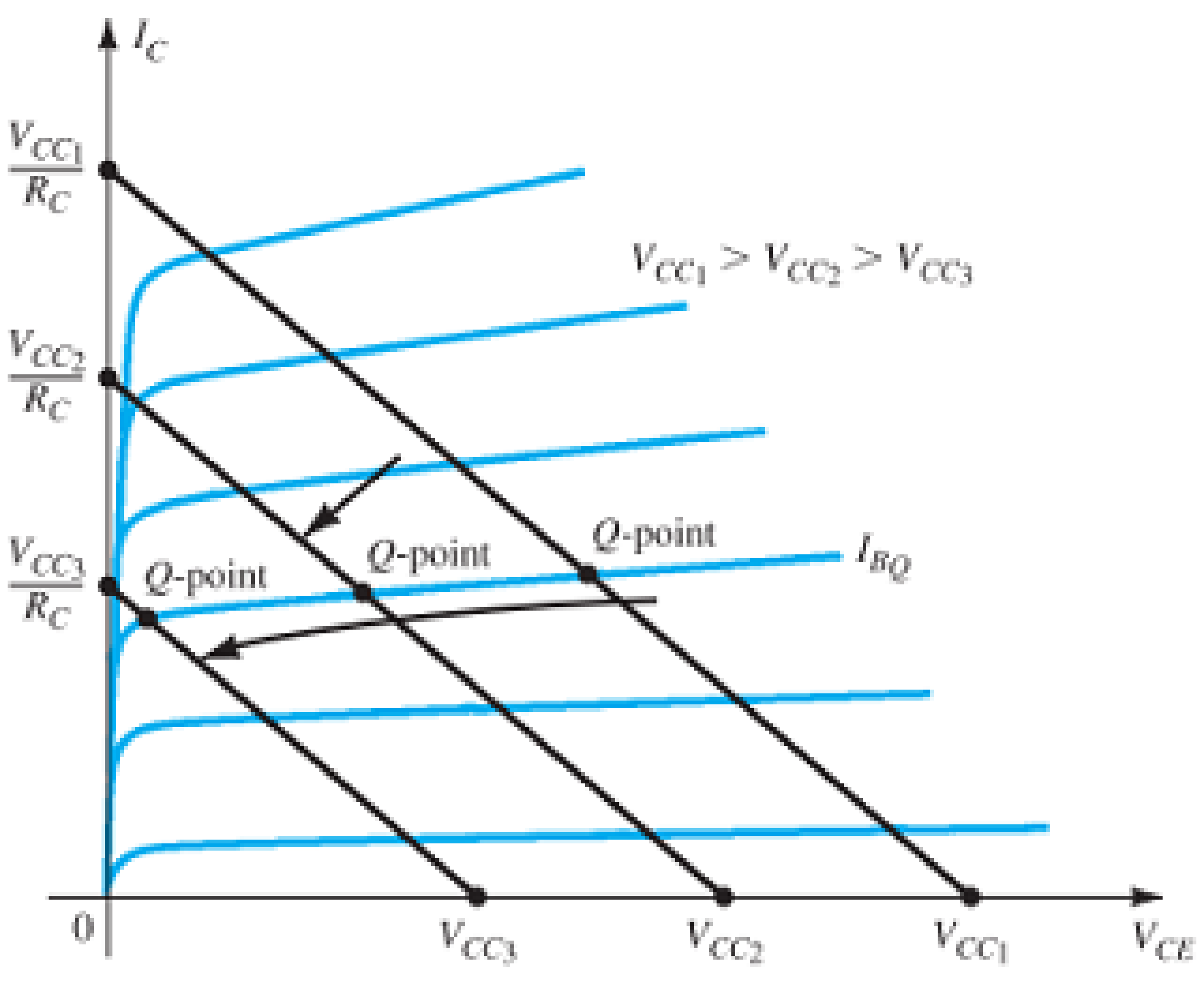
Operating Point

Effect of increasing R_C on load-line and Q-point



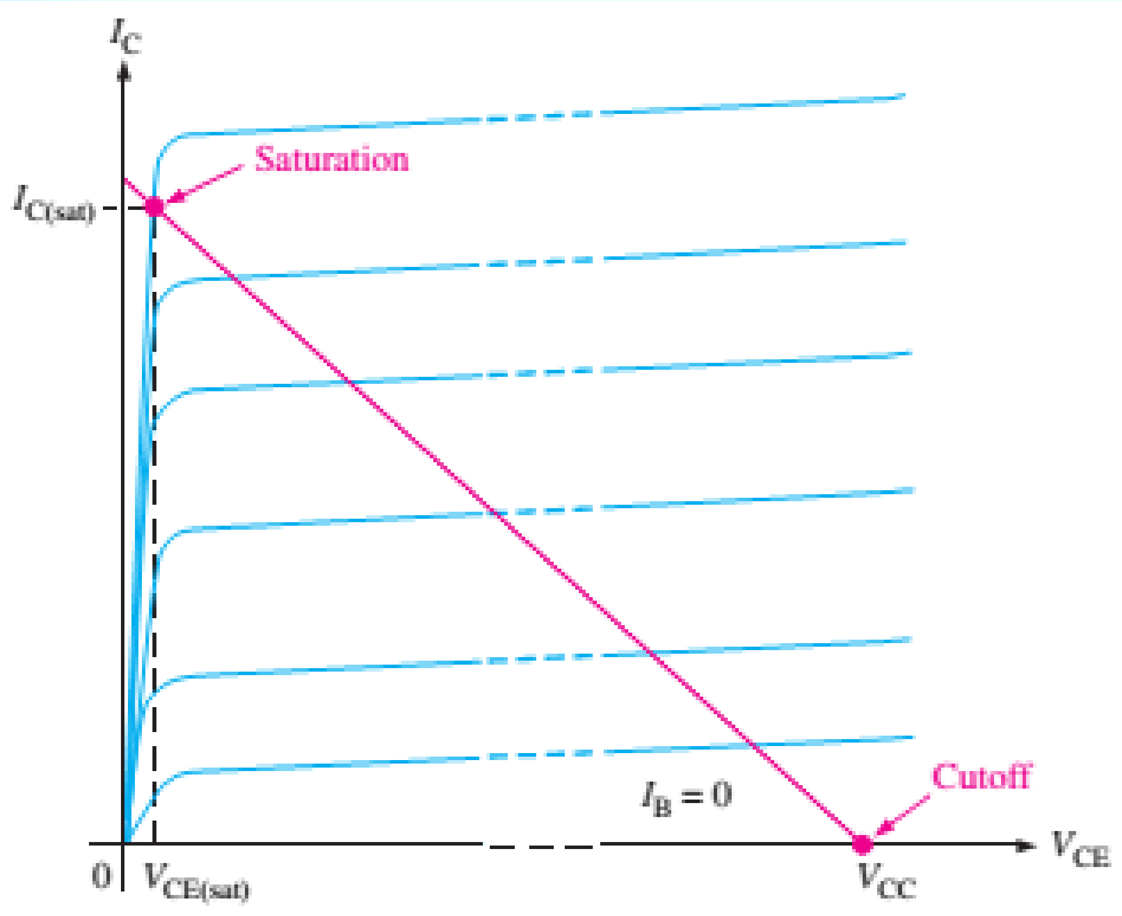
Operating Point

Effect of decreasing V_{CC} on load-line and Q-point



BJT Characteristics Curve

- Saturation
  - When I_B is increased I_C is increased ($I_C=\beta I_B$) and V_{CE} decreases
  - However due to the limitations of V_{CC} I_C will reach saturation $I_{C(sat)}$, and will not increase further even though I_B is increased



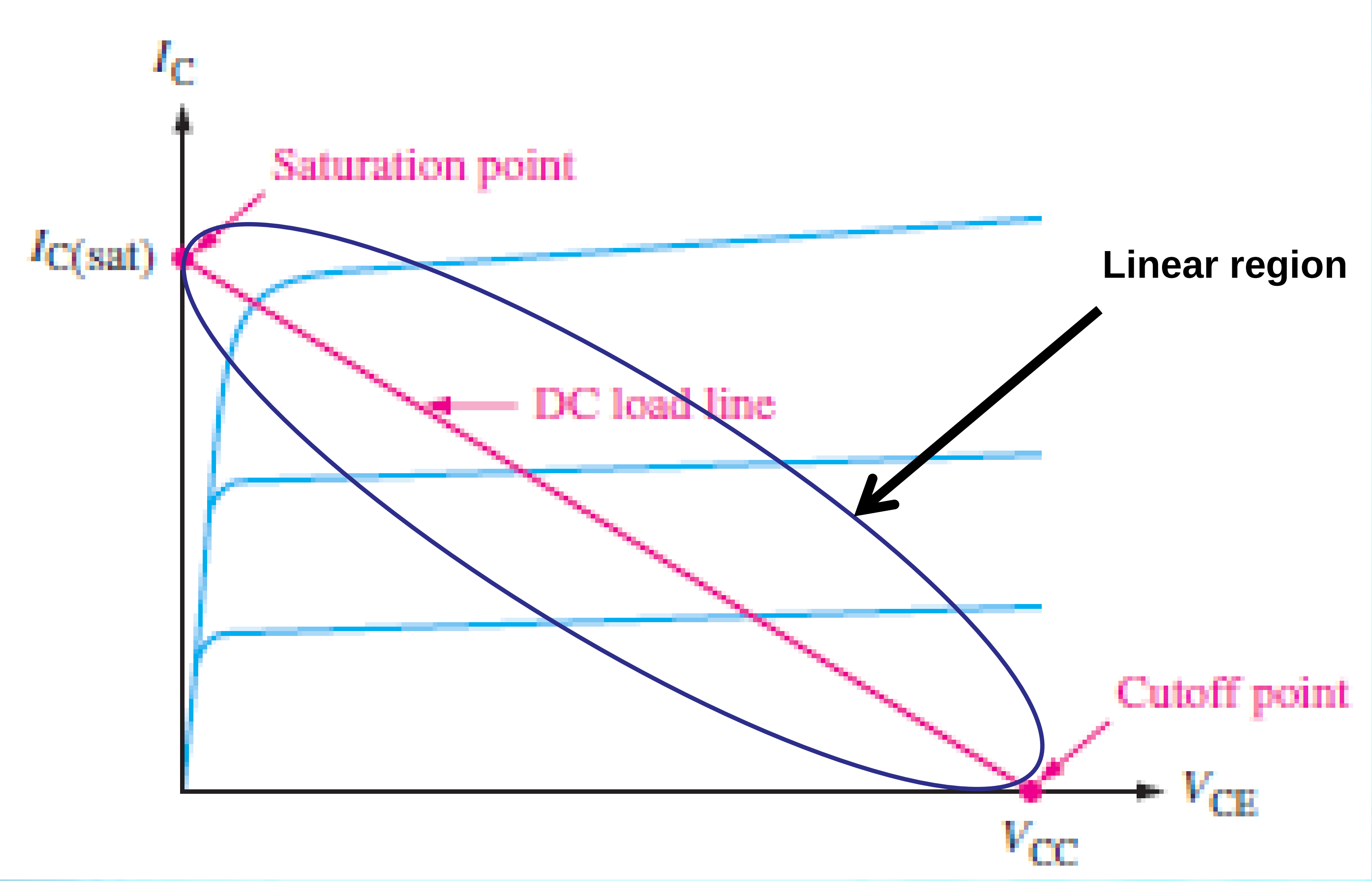
BJT Characteristics Curve

- A transistor must be properly biased with a dc voltage in order to operate as a linear amplifier

- **DC Bias**
  - Bias establishes the dc operating point (**Q-point)** for proper linear operation of an amplifier.
  - If an amplifier is not biased with correct dc voltages on the input and output, it can go into saturation or cutoff when an input signal is applied

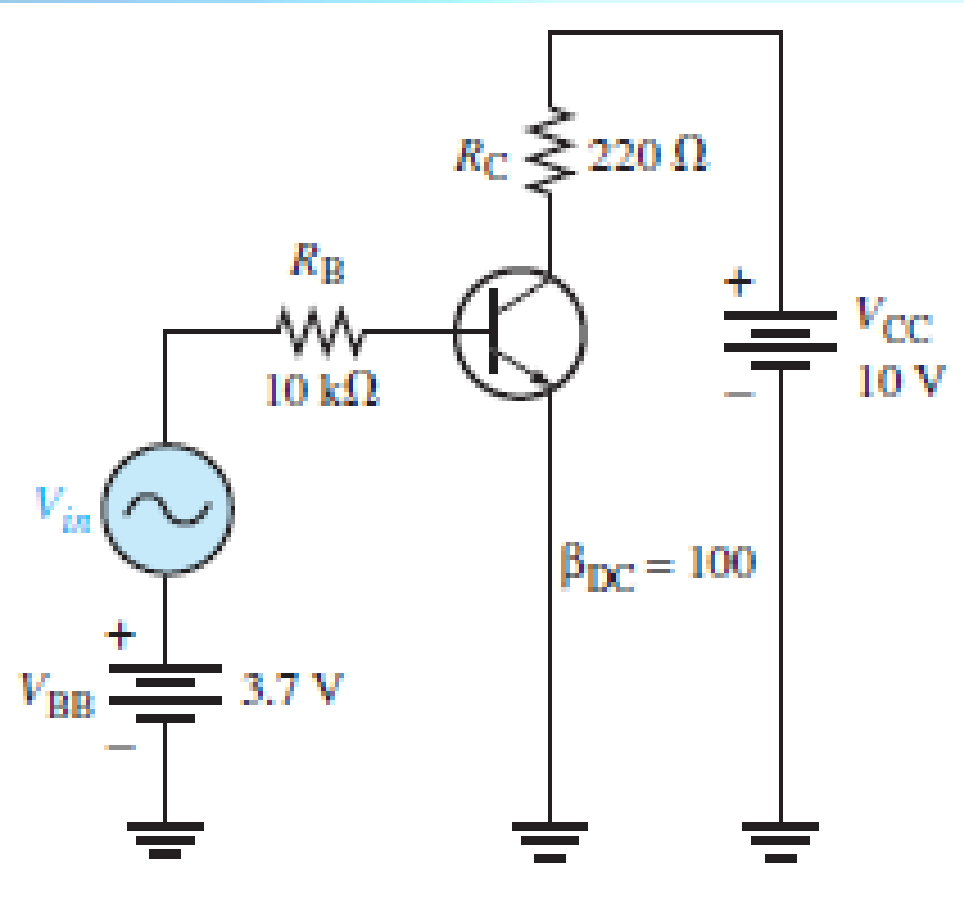
- **Linear region operation**
  - The region along the load line between saturation and cutoff
  - As long as the transistor is operated in this region, the output voltage is ideally a linear reproduction of the input.

Linear Region Operation



Linear Region Operation

- Lets find the DC operating values of the below circuit



$$I_{BQ} = \frac{V_{BB} - 0.7\text{ V}}{R_B} = \frac{3.7\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = 300\ \mu\text{A}$$

$$I_{CQ} = \beta_{DC} I_{BQ} = (100)(300\ \mu\text{A}) = 30\text{ mA}$$

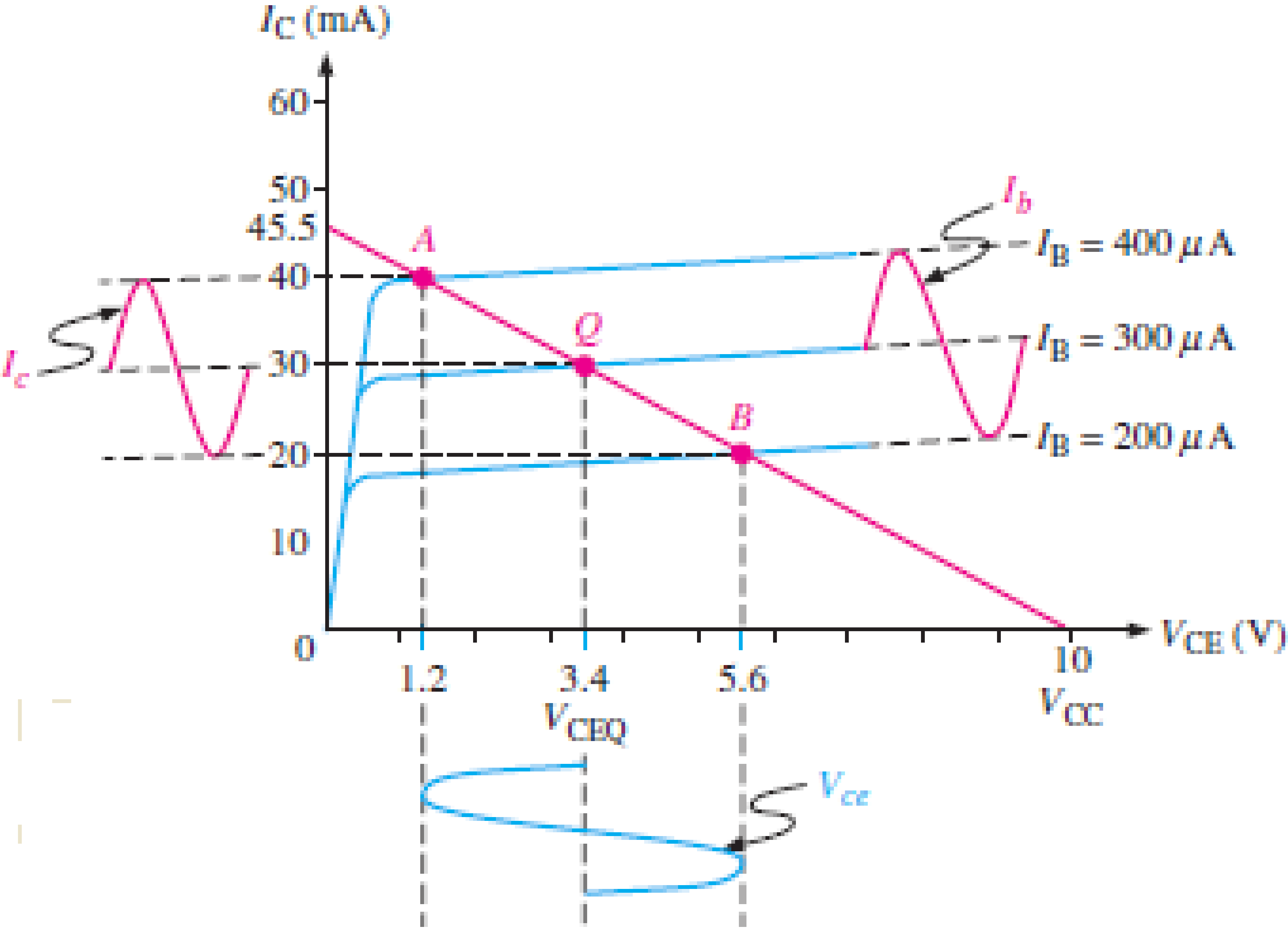
$$V_{CEQ} = V_{CC} - I_{CQ}R_C = 10\text{ V} - (30\text{ mA})(220\ \Omega) = 3.4\text{ V}$$

Linear Region Operation

- Assume a sinusoidal voltage, *Vin, is now superimposed* on V_{BB}, *causing the* I_B *to vary sinusoidally 100μA above and below its Q-point* value of *300μA*

- This, causes the I_C to vary 10mA above and below its Q-point value of 30mA

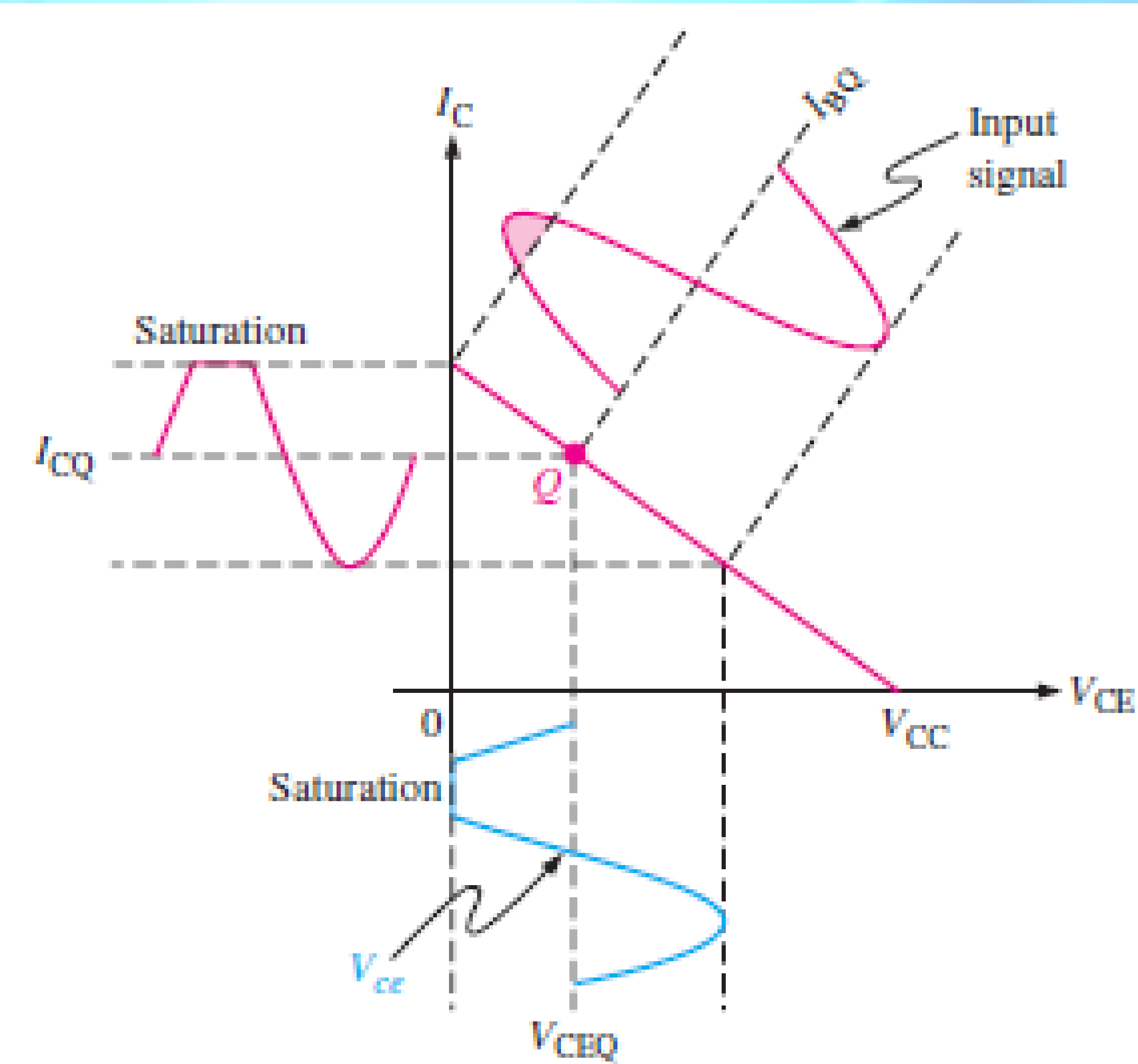
- As a result of the variation in I_C, the V_{CE} varies 2.2V above and below its Q-point value of 3.4V



I_C (mA)
60
50
45.5
40
30
20
10
0
I_b
$I_B = 400\ \mu A$
$I_B = 300\ \mu A$
$I_B = 200\ \mu A$
I_c
A
Q
B
1.2
3.4
V_{CEQ}
5.6
10
V_{CC}
V_{CE} (V)
V_{ce}

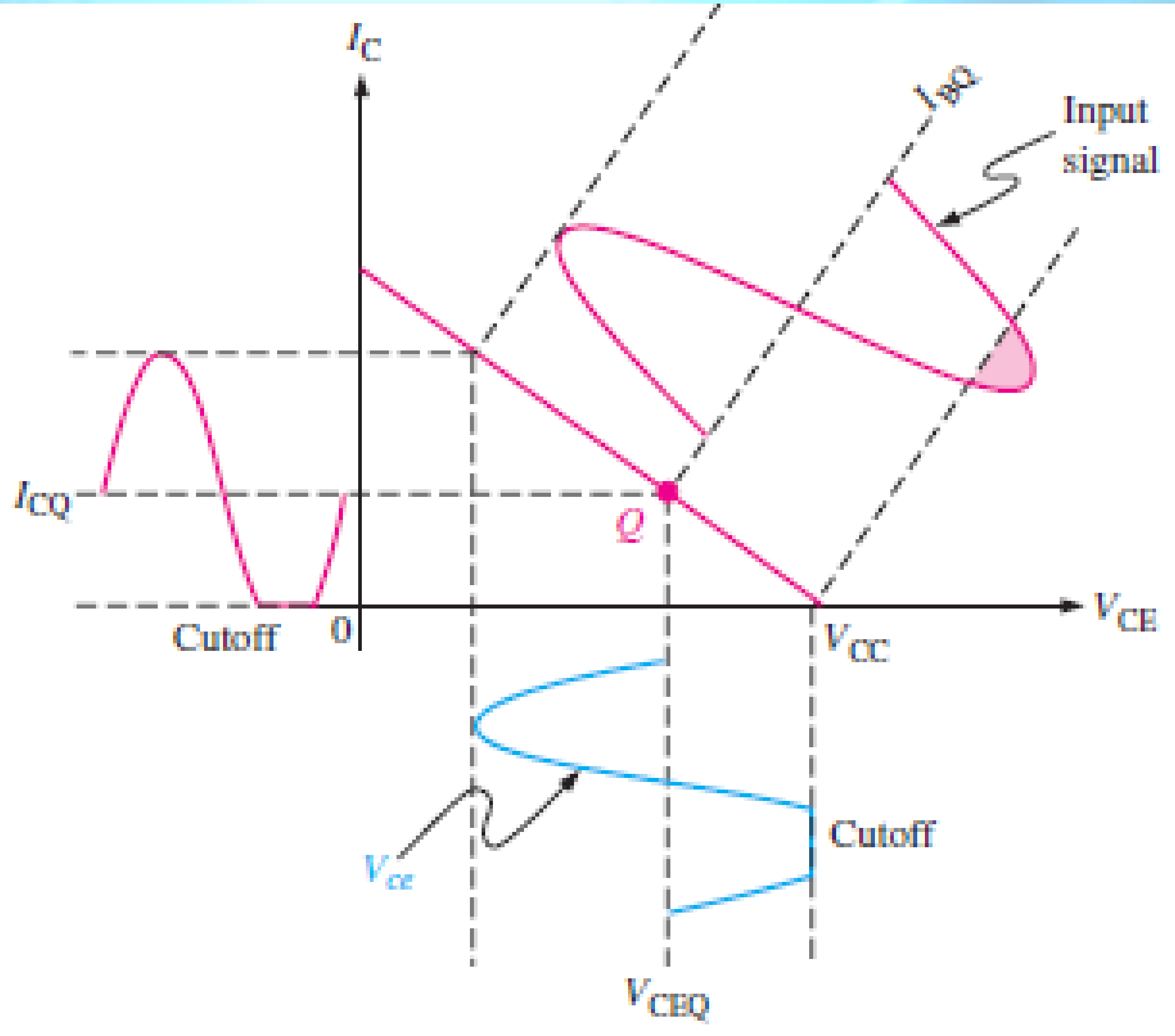
Waveform Distortion

Transistor is driven into saturation because the Q-point is too close to saturation for the given input signal.



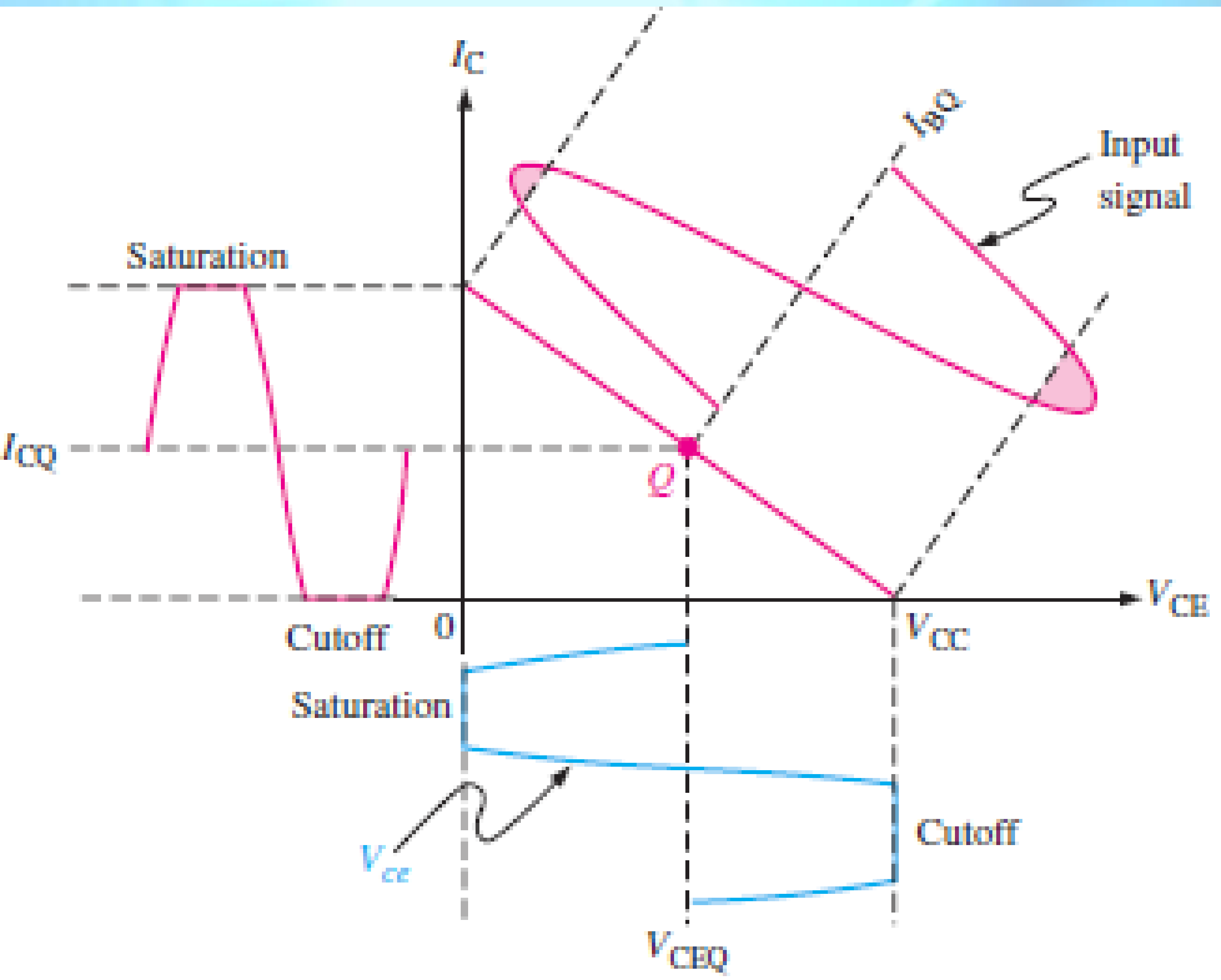
Waveform Distortion

Transistor is driven into cutoff because the Q-point is too close to cutoff for the given input signal.



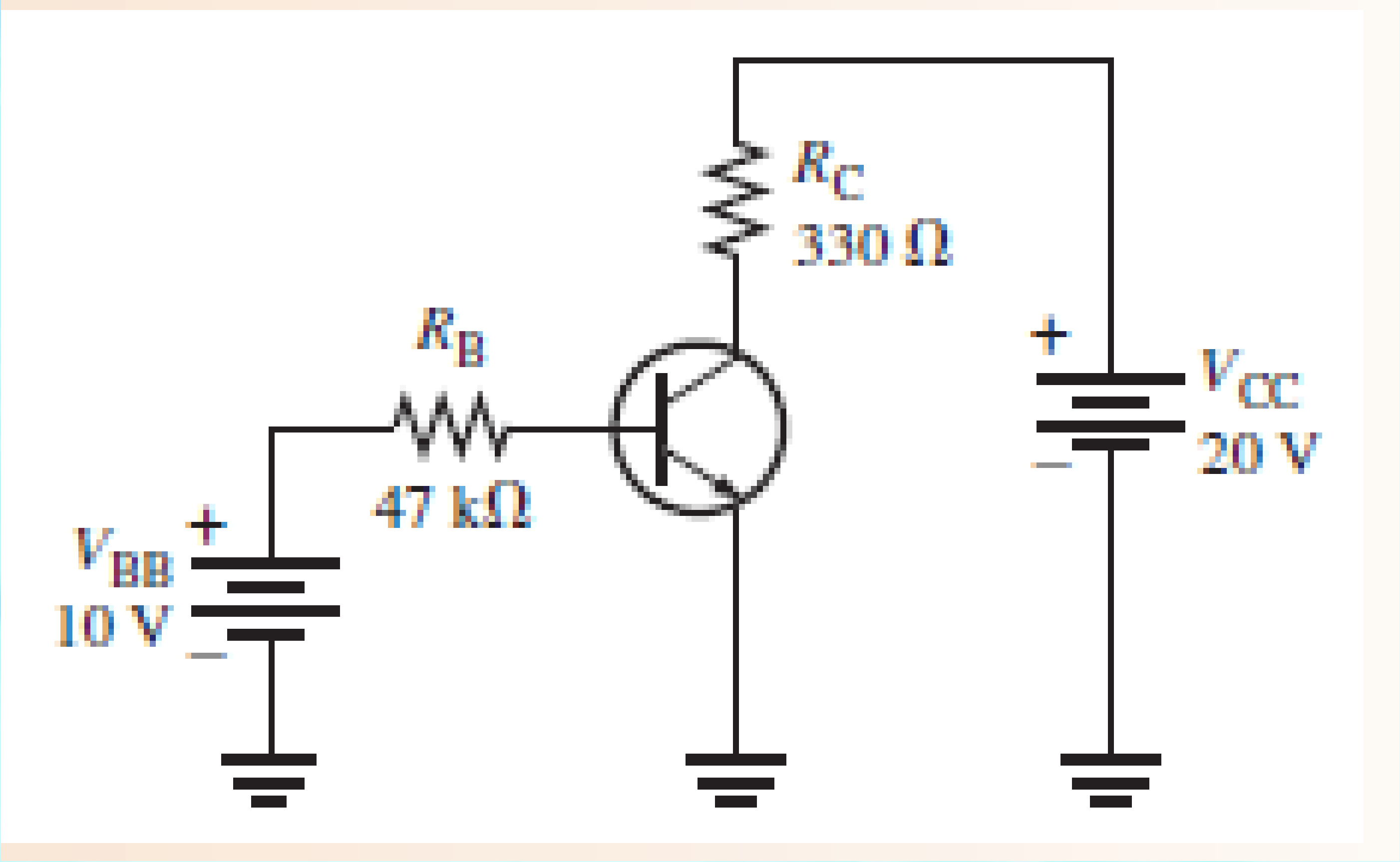
Waveform Distortion

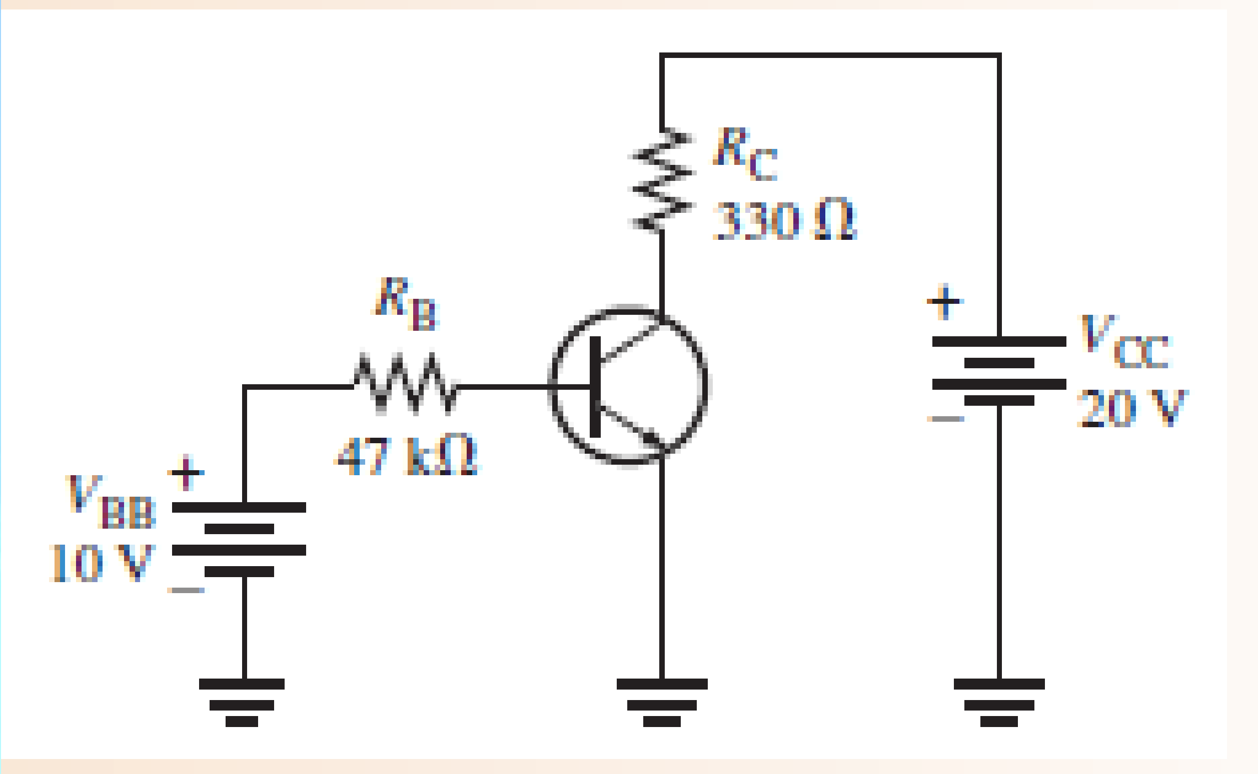
Transistor is driven into both saturation and cutoff because the input signal is too large



Problem

Determine the Q-point for the circuit in Figure and draw the dc load line. Find the maximum peak value of base current for linear operation. Assume $\beta_{DC} = 200$.





The Q-point is defined by the values of I_C and V_{CE}.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{10\text{ V} - 0.7\text{ V}}{47\text{ k}\Omega} = 198\ \mu\text{A}$$

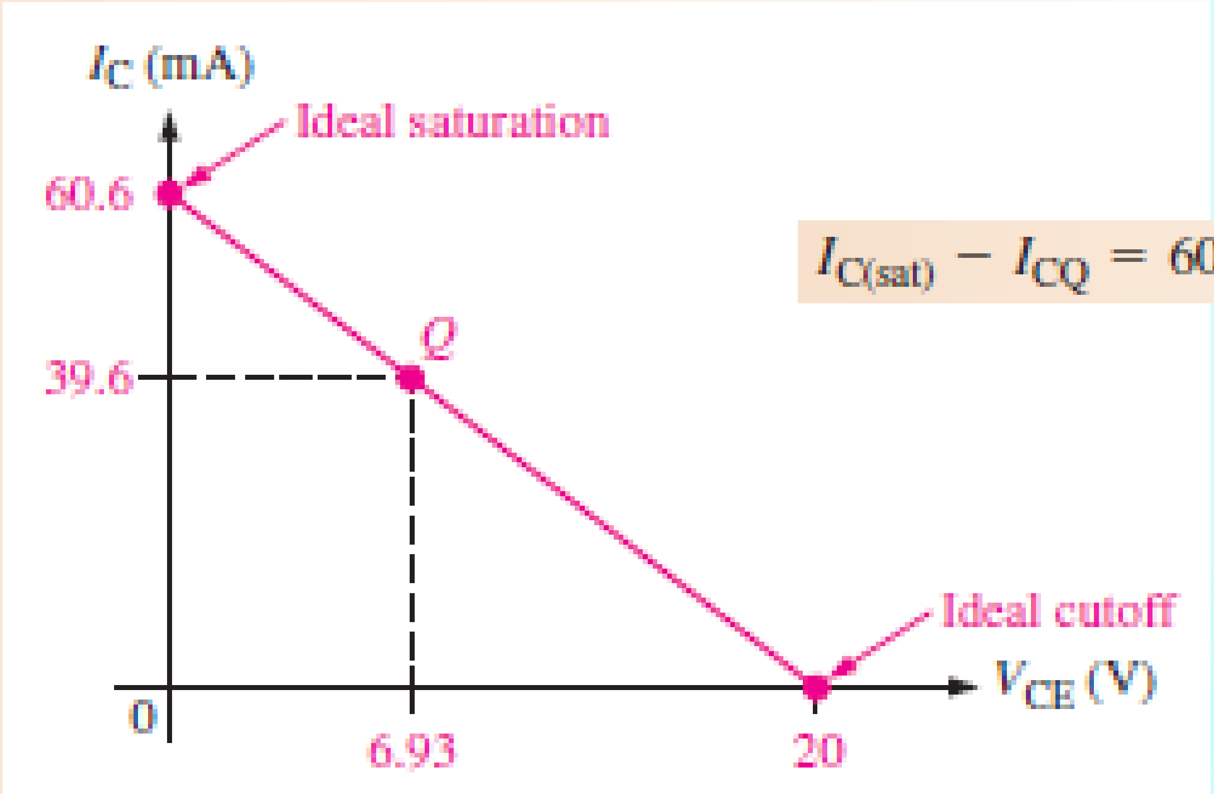
$$I_C = \beta_{DC} I_B = (200)(198\ \mu\text{A}) = \mathbf{39.6\ mA}$$

$$V_{CE} = V_{CC} - I_C R_C = 20\text{ V} - 13.07\text{ V} = \mathbf{6.93\ V}$$

The Q-point is at $I_C = 39.6$ mA and at $V_{CE} = 6.93$ V.

Since $I_{C(cutoff)} = 0$, you need to know $I_{C(sat)}$ to determine how much variation in collector current can occur and still maintain linear operation of the transistor.

$$I_{C(sat)} = \frac{V_{CC}}{R_C} = \frac{20\ \text{V}}{330\ \Omega} = 60.6\ \text{mA}$$



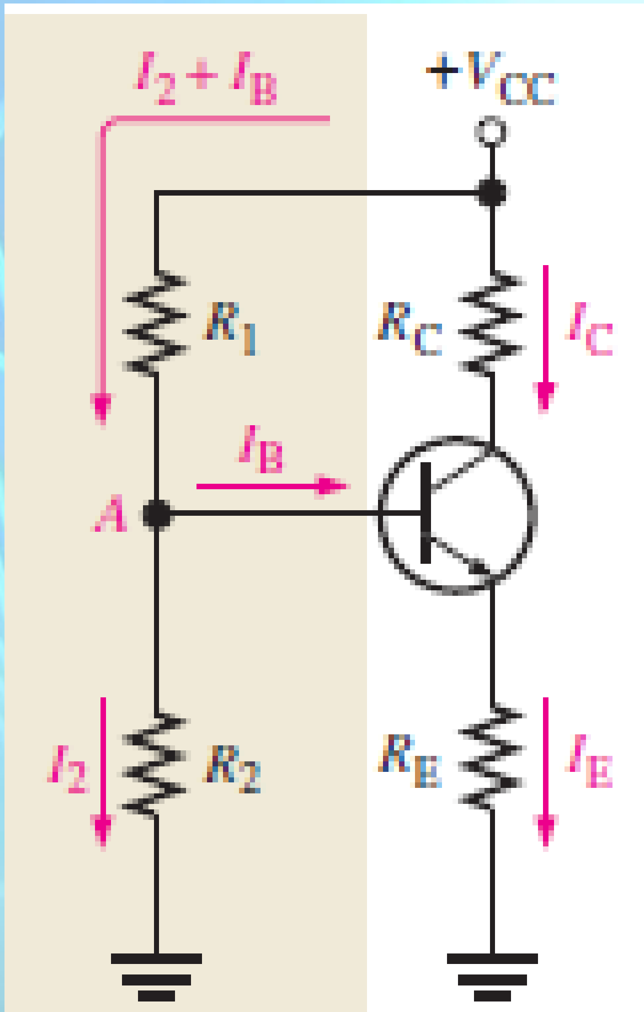
$$I_{C(sat)} - I_{CQ} = 60.6\ \text{mA} - 39.6\ \text{mA} = 21.0\ \text{mA}$$

But I_C can decrease by 39.6mA before cutoff (I_C=0) is reached. Thus the limiting variation is 21mA as the Q-point is closer to saturation than to cutoff.

$$I_{b(peak)} = \frac{I_{c(peak)}}{\beta_{DC}} = \frac{21\ \text{mA}}{200} = 105\ \mu\text{A}$$

Voltage-Divider Bias

- Method of biasing a transistor for linear operation using a single source resistive voltage divider



Shift Voltage Divider: Generally, voltage-divider bias circuits are designed such that : $I_B <<< I_2$

$$V_B \cong \left(\frac{R_2}{R_1 + R_2}\right)V_{CC}$$

$$V_E = V_B - V_{BE}$$

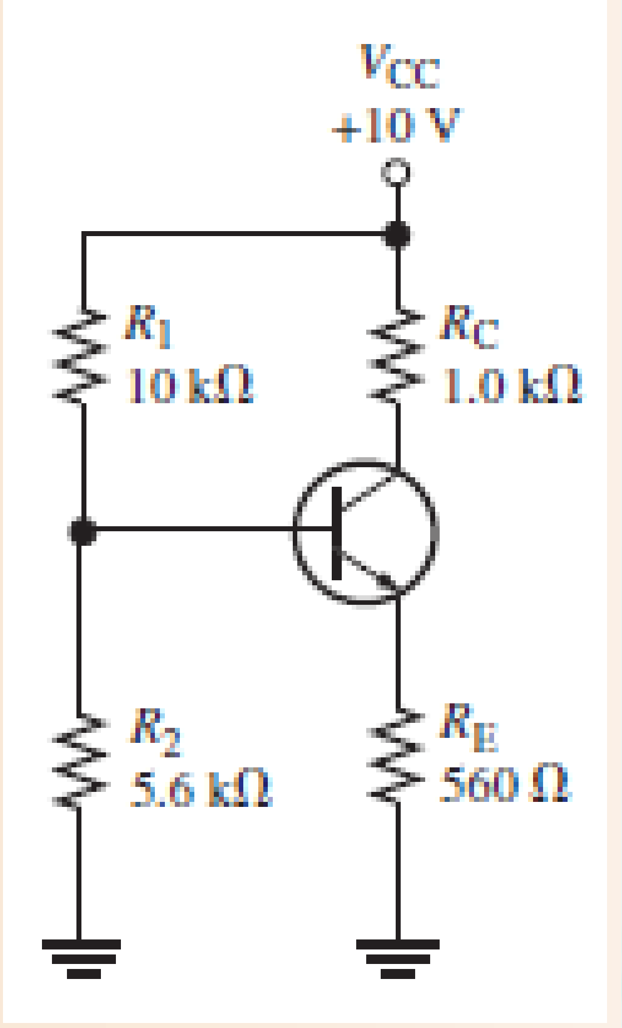
$$I_C \cong I_E = \frac{V_E}{R_E}$$

$$V_C = V_{CC} - I_C R_C$$

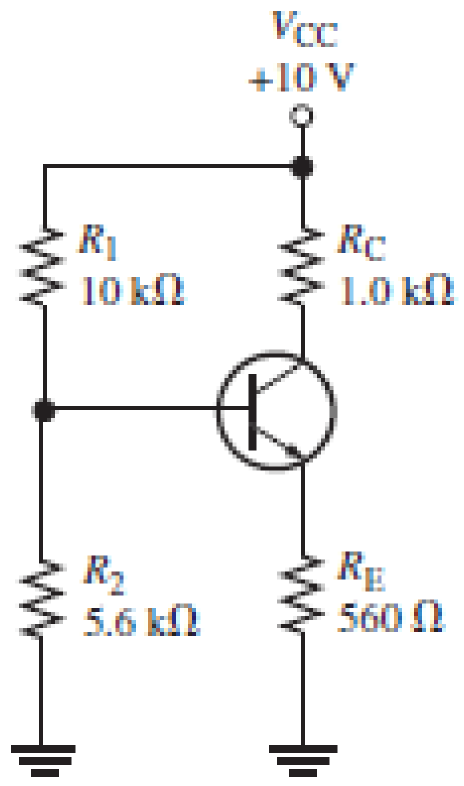
$$V_{CE} = V_C - V_E$$

Problem

Determine V_{CE} and I_C in the stiff voltage-divider biased transistor circuit if $\beta_{DC} = 100$.



Solution



The base voltage is

$$V_B \cong \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{5.6\text{ k}\Omega}{15.6\text{ k}\Omega}\right)10\text{ V} = 3.59\text{ V}$$

So,

$$V_E = V_B - V_{BE} = 3.59\text{ V} - 0.7\text{ V} = 2.89\text{ V}$$

and

$$I_E = \frac{V_E}{R_E} = \frac{2.89\text{ V}}{560\ \Omega} = 5.16\text{ mA}$$

Therefore,

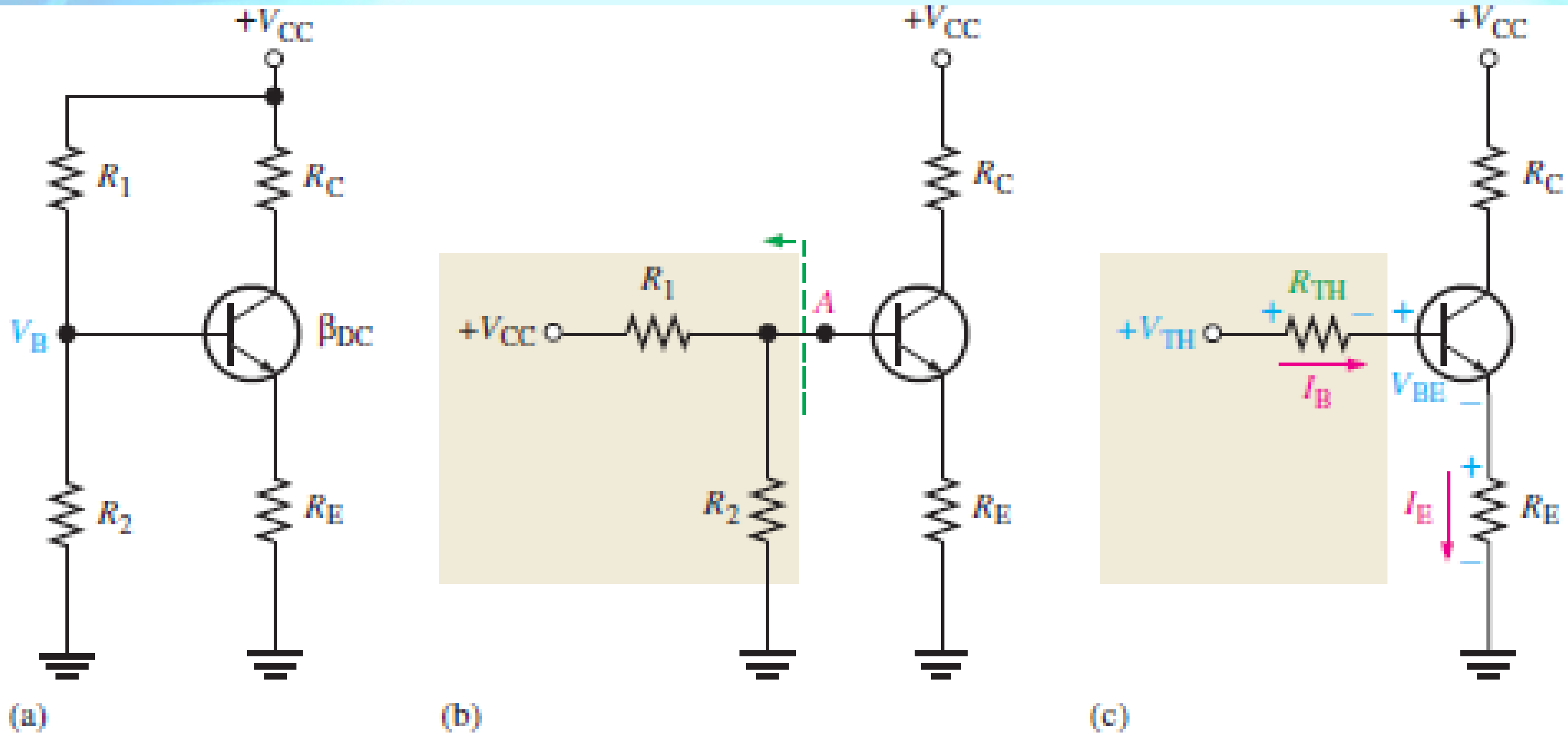
$$I_C \cong I_E = \mathbf{5.16\text{ mA}}$$

and

$$V_C = V_{CC} - I_C R_C = 10\text{ V} - (5.16\text{ mA})(1.0\text{ k}\Omega) = 4.84\text{ V}$$
$$V_{CE} = V_C - V_E = 4.84\text{ V} - 2.89\text{ V} = \mathbf{1.95\text{ V}}$$

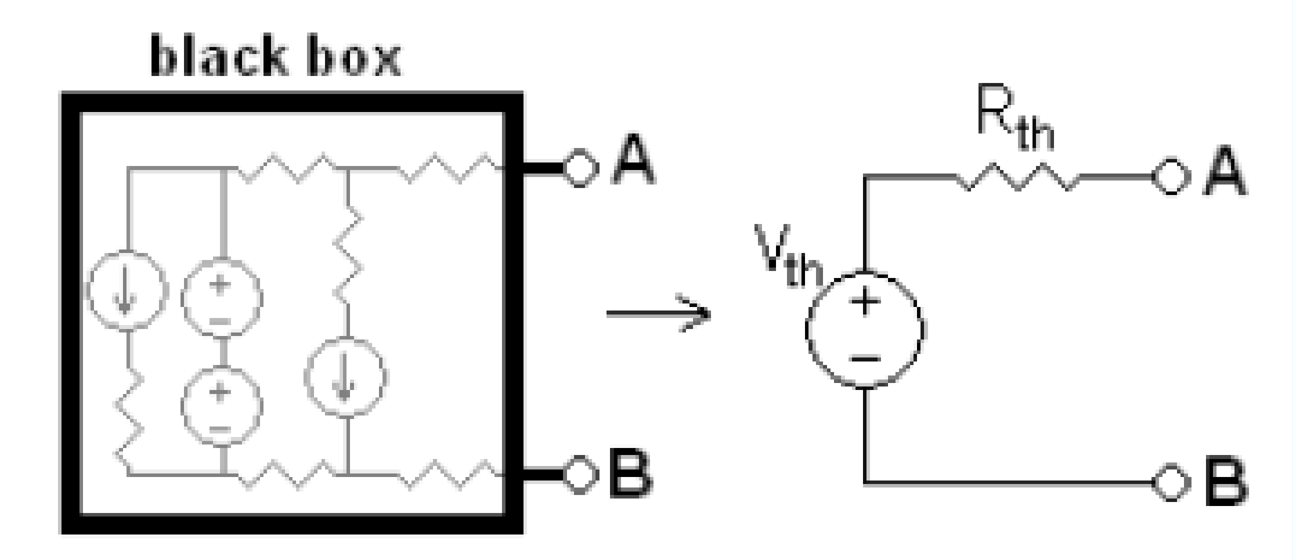
Voltage-Divider Bias

- In the previous analysis of the Voltage-Divider Bias circuit we did not consider the base current loading effect
- To analyze circuit with loading effect lets obtain a equivalent base emitter circuit using Thevenin's theorem



Voltage-Divider Bias

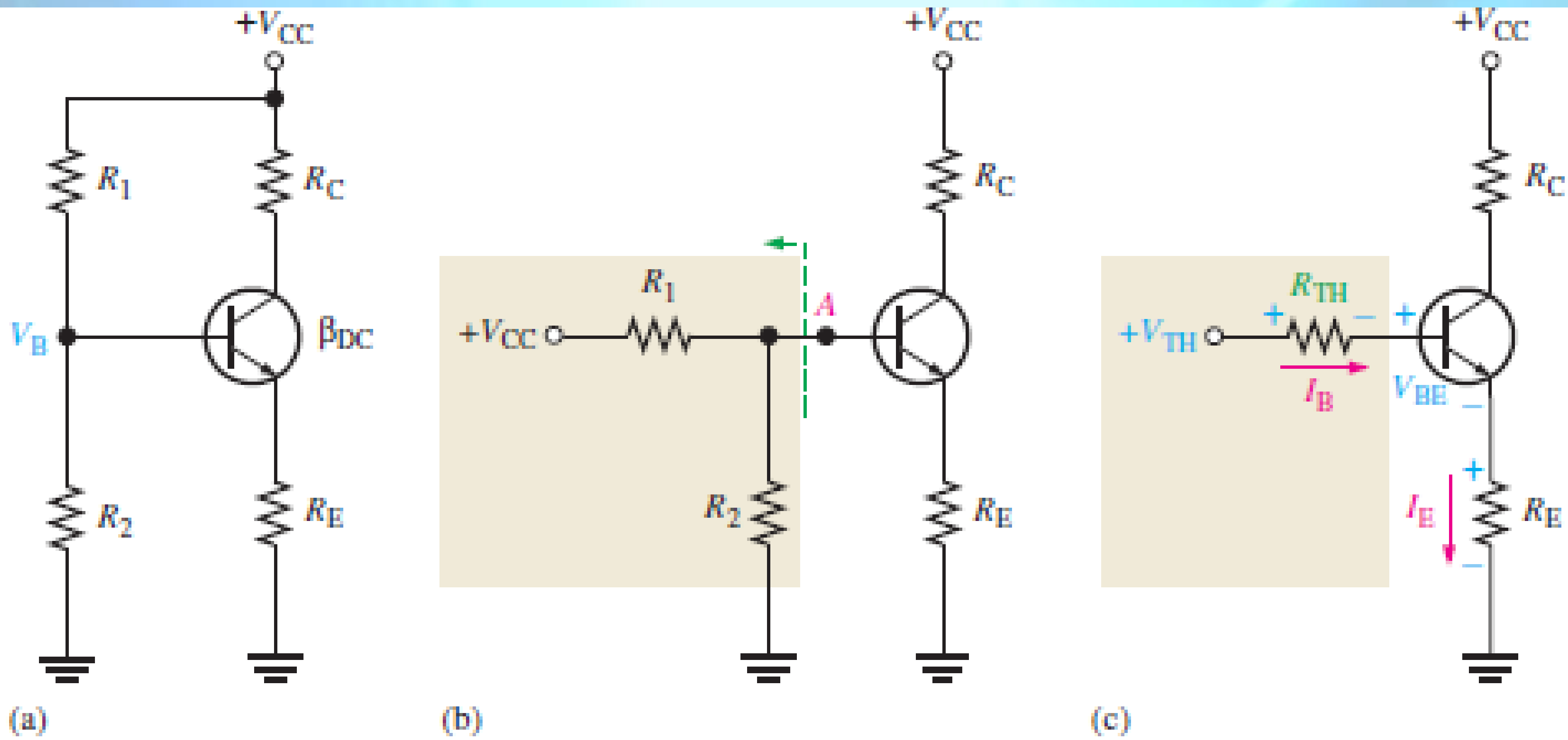
- **Thevenin's theorem**
  - Any linear electrical network with voltage and current sources and only resistances can be replaced at terminals A-B by an equivalent voltage source V_{th} in series connection with an equivalent resistance R_{th}



Voltage-Divider Bias

- **Calculating the Thevenin's equivalent**
  - Step 1: Calculate the output voltage, V_{AB}, when in open circuit condition (no load resistor—meaning infinite resistance). This is V_{Th}
  - Step 2: Calculate the output current, I_{AB}, when the output terminals are short circuited (load resistance is 0). R_{Th} equals V_{Th} divided by this I_{AB}.
  - Step 2 could also be thought of as:
    - Replace the independent voltage sources with short circuits, and independent current sources with open circuits. Then calculate the resistance between terminals A and B. This is R_{Th}

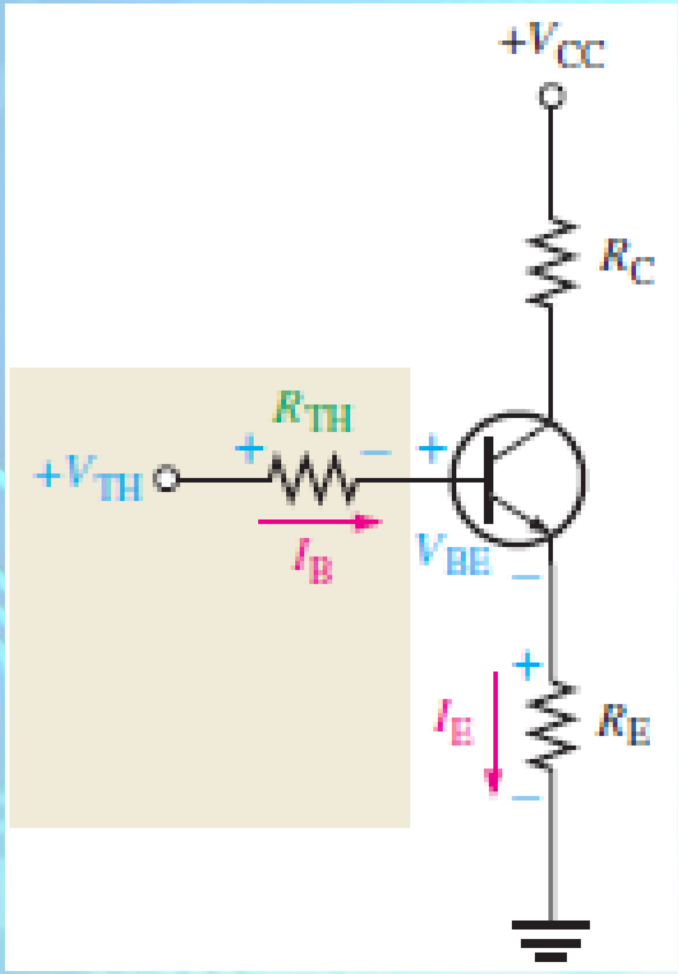
Voltage-Divider Bias



$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC}$$

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$$

Voltage-Divider Bias



$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC}$$

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$$

$$I_B = {}^{I_E}/_{(B_{DC}+1)}$$

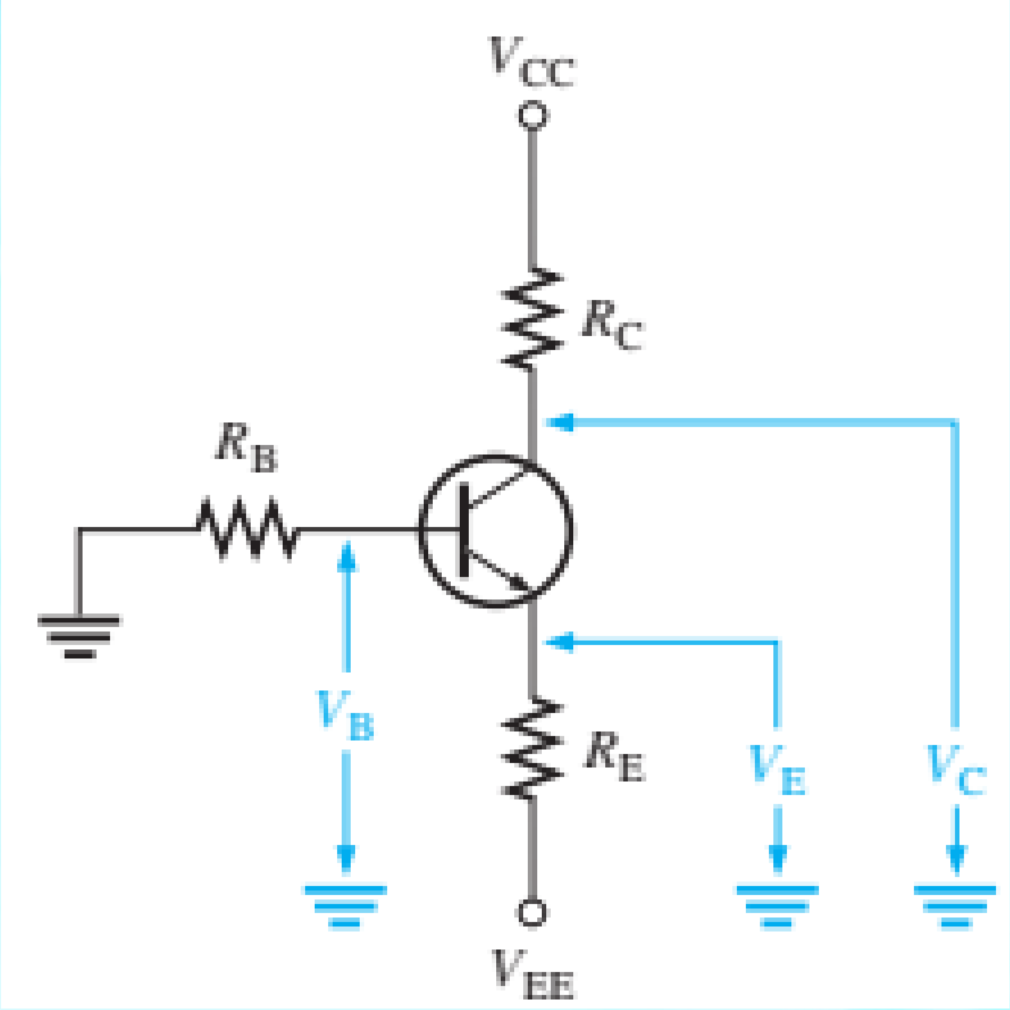
$$V_{TH} - V_{R_{TH}} - V_{BE} - V_{R_E} = 0$$

$$V_{TH} = I_B R_{TH} + V_{BE} + I_E R_E$$

Can find I_E and other current & voltage values

Other Bias Methods

- **Emitter Bias**
  - Emitter bias uses both a positive and a negative supply voltage



Other Bias Methods

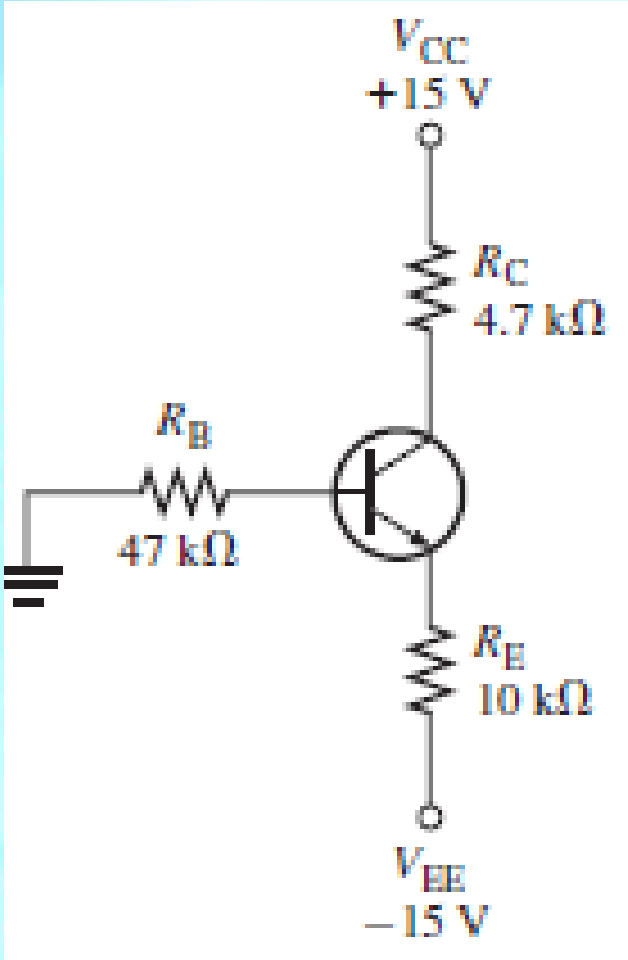
- The small base current causes the base voltage to be slightly below ground
- The emitter voltage is one diode drop less than this
- The combination of this small drop across R_B and V_{BE} forces the emitter to be at approximately -1V
- Using this approximation, you can obtain the emitter current as
- $I_E = \frac{V_E - V_{EE}}{R_E} = \frac{-1 - V_{EE}}{R_E}$
- V_{EE} is entered as a negative value in this equation

Other Bias Methods

- You can apply the approximation that $I_C \approx I_E$ to calculate the collector voltage
- $V_C = V_{CC} - I_C R_C$
- $V_C \approx V_{CC} - I_E R_C$

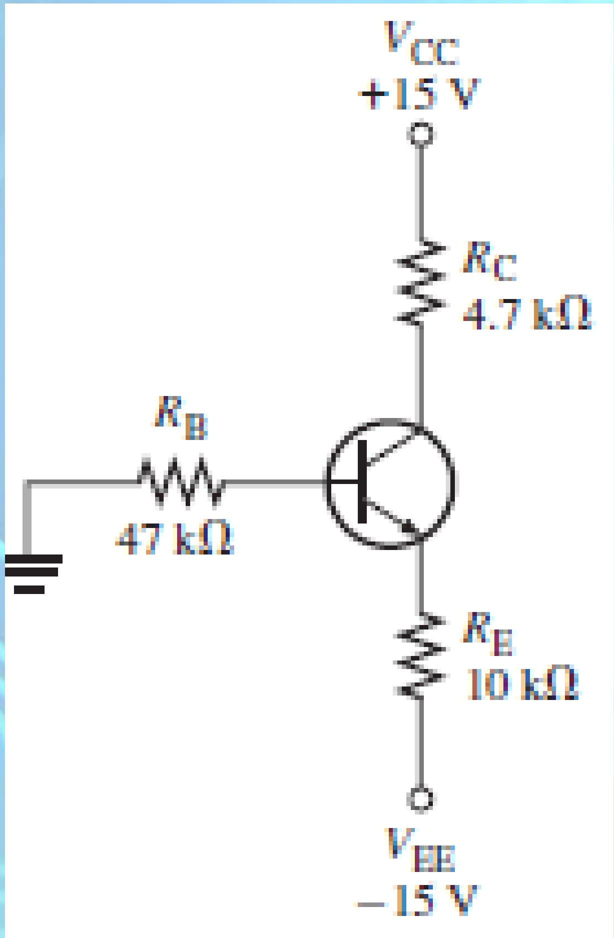
Other Bias Methods

Calculate I_E and V_{CE} for the circuit in Figure using the approximations $V_E \cong -1$ V and $I_C \cong I_E$.



Emiter bias

Other Bias Methods



Approximations

$V_E \cong -1\text{ V}$ and $I_C \cong I_E$.

$$V_E \cong -1\text{ V}$$

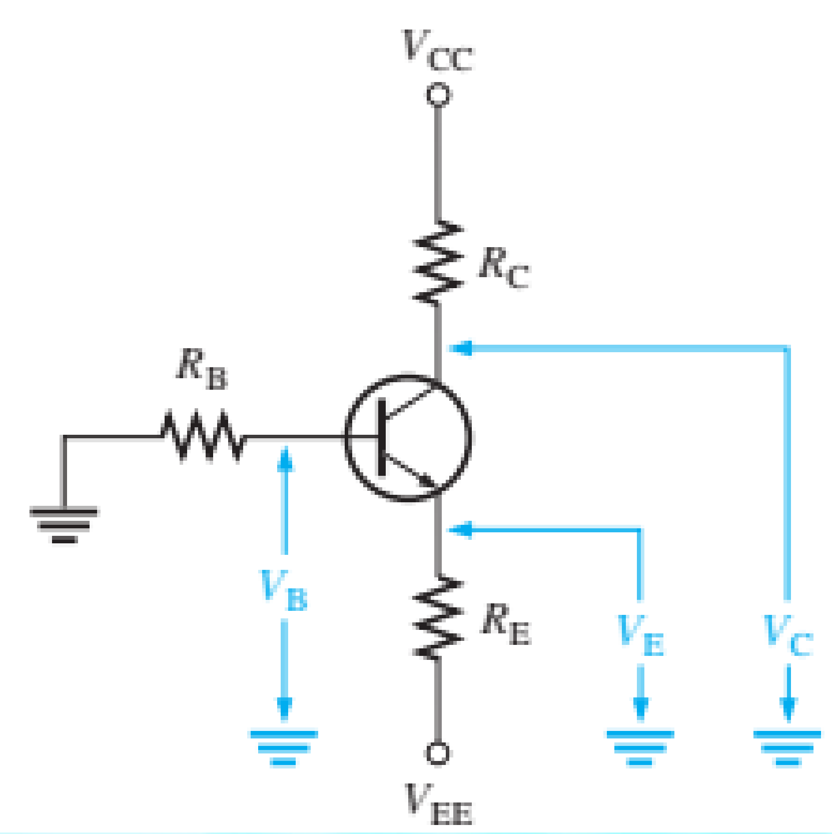
$$I_E = \frac{-V_{EE} - 1\text{ V}}{R_E} = \frac{-(-15\text{ V}) - 1\text{ V}}{10\text{ k}\Omega} = \frac{14\text{ V}}{10\text{ k}\Omega} = 1.4\text{ mA}$$

$$V_C = V_{CC} - I_C R_C = +15\text{ V} - (1.4\text{ mA})(4.7\text{ k}\Omega) = 8.4\text{ V}$$

$$V_{CE} = 8.4\text{ V} - (-1) = 9.4\text{ V}$$

Other Bias Methods

- The approximation that V_E = -1 and the neglect of β_{DC} may not be accurate enough for design work or detailed analysis
- In this case, Kirchhoff's voltage law can be applied as follows to develop a more detailed formula for I_E
- $0 - V_{R_B} - V_{BE} - V_{R_E} = V_{EE}$
- $V_{EE} + V_{R_B} + V_{BE} + V_{R_E} = 0$
- Substituting, using Ohm's law,
- $V_{EE} + I_B R_B + V_{BE} + I_E R_E = 0$



Other Bias Methods

- Substituting for $I_B \approx {}^{I_E}/_{\beta_{DC}}$

$$\left(\frac{I_E}{\beta_{DC}}\right)R_B + I_E R_E + V_{BE} = -V_{EE}$$

- Factoring out I_E and solving for I_E

$$I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}}$$

- The emitter voltage with respect to ground is

$$V_E = V_{EE} + I_E R_E$$

Other Bias Methods

- The base voltage with respect to ground is

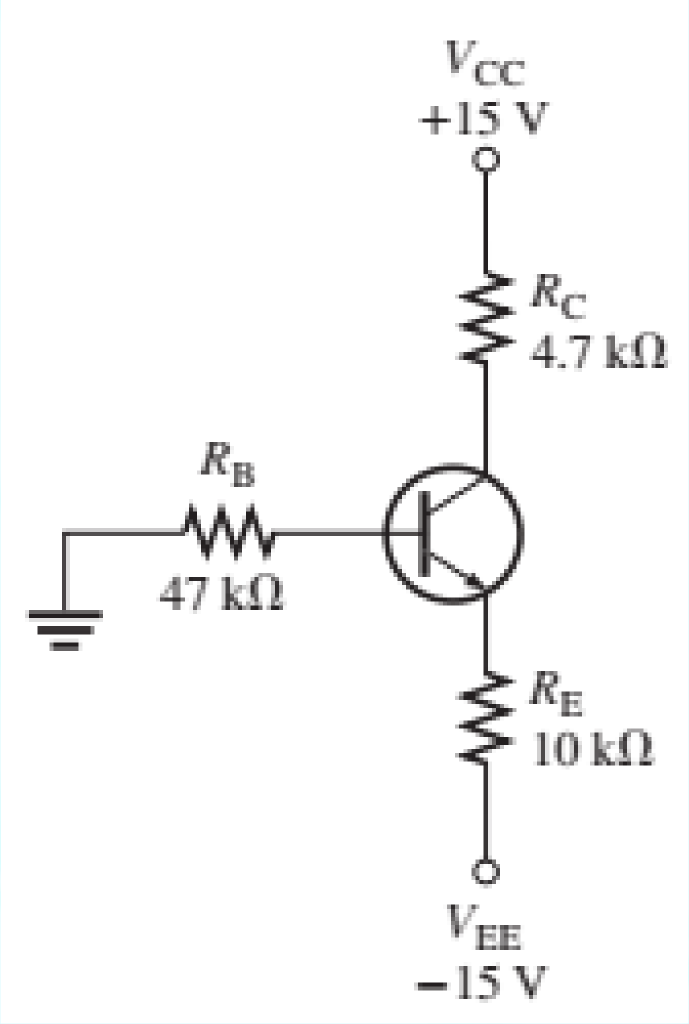
$$V_B = V_E + V_{BE}$$

- The collector voltage with respect to ground is

$$V_C = V_{CC} - I_C R_C$$

Other Bias Methods

Determine how much the Q-point (I_C, V_{CE}) for the circuit in Figure will change if β_{DC} increases from 100 to 200 when one transistor is replaced by another.



For $\beta_{DC} = 100$,

$$I_{C(1)} \cong I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{-(-15\text{ V}) - 0.7\text{ V}}{10\text{ k}\Omega + 47\text{ k}\Omega/100} = 1.37\text{ mA}$$

$$V_C = V_{CC} - I_{C(1)}R_C = 15\text{ V} - (1.37\text{ mA})(4.7\text{ k}\Omega) = 8.56\text{ V}$$

$$V_E = V_{EE} + I_ER_E = -15\text{ V} + (1.37\text{ mA})(10\text{ k}\Omega) = -1.3\text{ V}$$

Therefore,

$$V_{CE(1)} = V_C - V_E = 8.56\text{ V} - (-1.3\text{ V}) = 9.83\text{ V}$$

For $\beta_{DC} = 200$,

$$I_{C(2)} \cong I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{-(-15\text{ V}) - 0.7\text{ V}}{10\text{ k}\Omega + 47\text{ k}\Omega/200} = 1.38\text{ mA}$$

$$V_C = V_{CC} - I_{C(2)}R_C = 15\text{ V} - (1.38\text{ mA})(4.7\text{ k}\Omega) = 8.51\text{ V}$$

$$V_E = V_{EE} + I_ER_E = -15\text{ V} + (1.38\text{ mA})(10\text{ k}\Omega) = -1.2\text{ V}$$

Therefore,

$$V_{CE(2)} = V_C - V_E = 8.51\text{ V} - (-1.2\text{ V}) = 9.71\text{ V}$$

The percent change in I_C as β_{DC} changes from 100 to 200 is

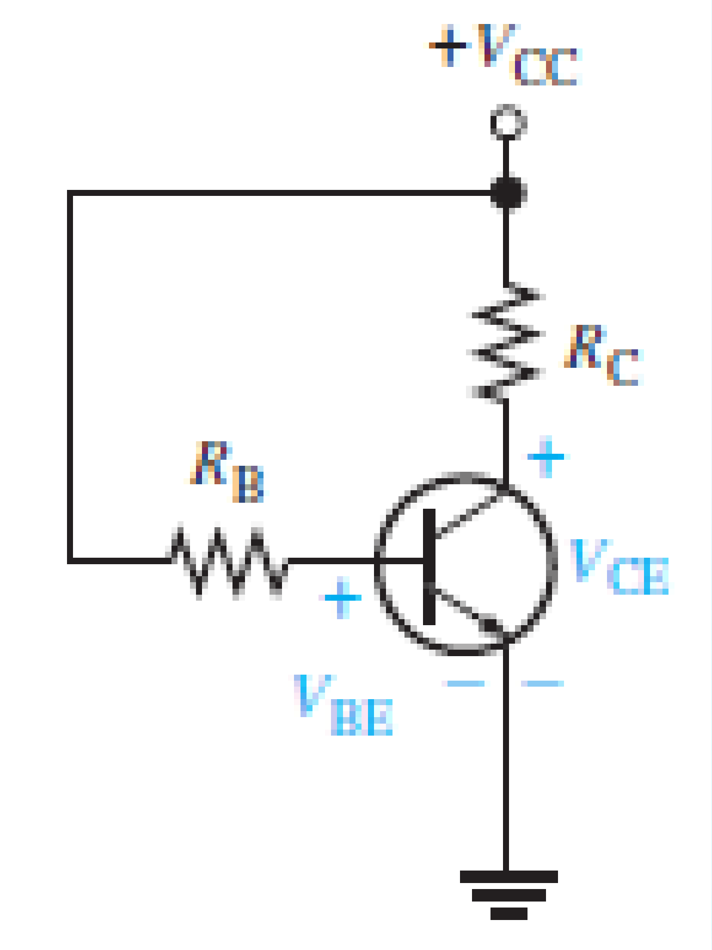
$$\%\Delta I_C = \left(\frac{I_{C(2)} - I_{C(1)}}{I_{C(1)}}\right)100\% = \left(\frac{1.38\text{ mA} - 1.37\text{ mA}}{1.37\text{ mA}}\right)100\% = 0.730\%$$

The percent change in V_{CE} is

$$\%\Delta V_{CE} = \left(\frac{V_{CE(2)} - V_{CE(1)}}{V_{CE(1)}}\right)100\% = \left(\frac{9.71\text{ V} - 9.83\text{ V}}{9.83\text{ V}}\right)100\% = \mathbf{-1.22\%}$$

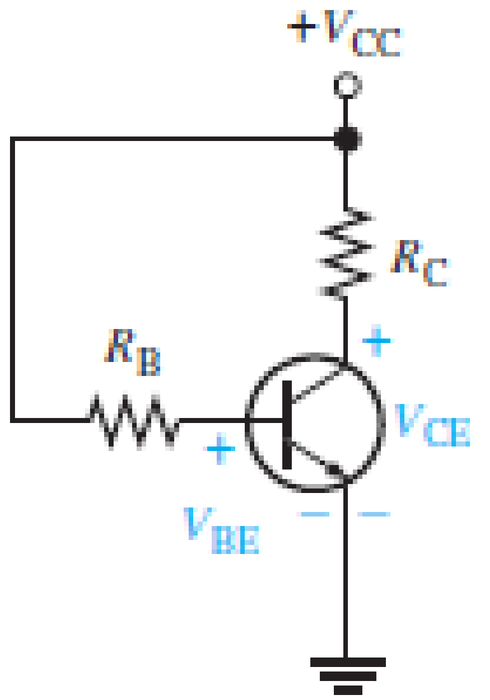
Other Bias Methods

- **Base bias**
  - Analyze the circuit and obtain expressions for I_B and I_C



Other Bias Methods

- Analyze the circuit and obtain expressions for I_B and I_C



$$V_{CC} - V_{R_B} - V_{BE} = 0$$

Substituting $I_B R_B$ for V_{R_B}, you get

$$V_{CC} - I_B R_B - V_{BE} = 0$$

Then solving for I_B,

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

Kirchhoff's voltage law applied around the collector circuit

$$V_{CC} - I_C R_C - V_{CE} = 0$$

Solving for V_{CE},

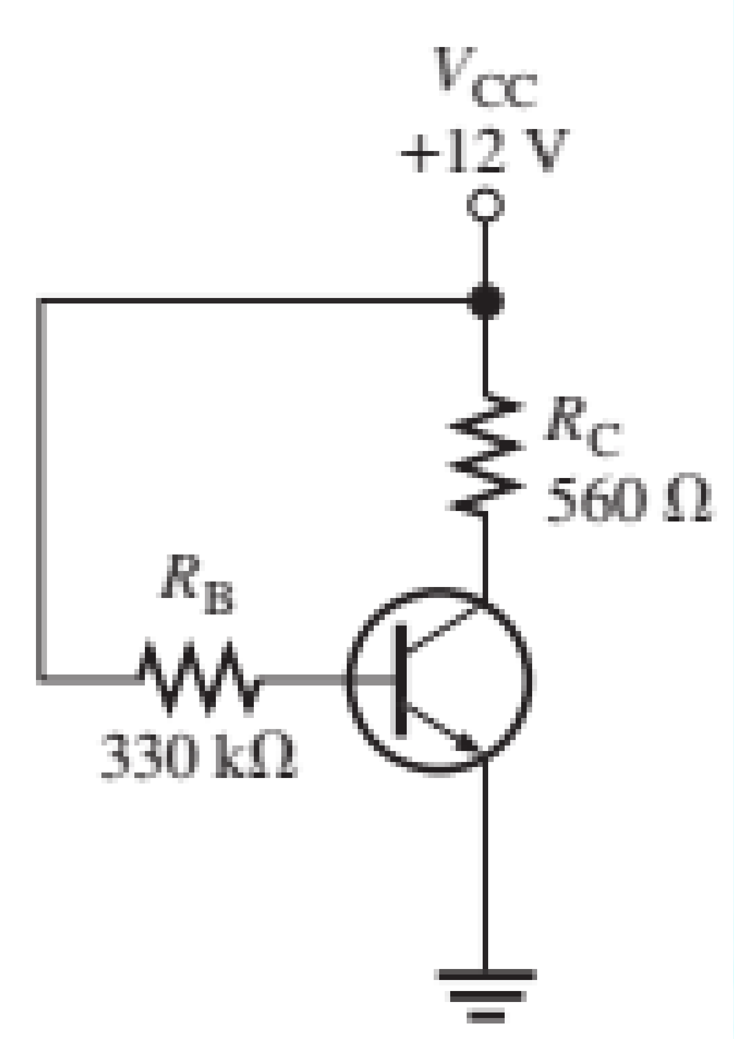
$$\boldsymbol{V_{CE} = V_{CC} - I_C R_C}$$

Substituting the expression for I_B into the formula $I_C = \beta_{DC} I_B$

$$\boldsymbol{I_C = \beta_{DC}\left(\frac{V_{CC} - V_{BE}}{R_B}\right)}$$

Other Bias Methods

Determine how much the Q-point (I_C, V_{CE}) for the circuit in Figure will change over a temperature range where β_{DC} increases from 100 to 200.



Other Bias Methods

For $\beta_{DC} = 100$,

$$I_{C(1)} = \beta_{DC}\left(\frac{V_{CC} - V_{BE}}{R_B}\right) = 100\left(\frac{12\text{ V} - 0.7\text{ V}}{330\text{ k}\Omega}\right) = 3.42\text{ mA}$$

$$V_{CE(1)} = V_{CC} - I_{C(1)}R_C = 12\text{ V} - (3.42\text{ mA})(560\ \Omega) = 10.1\text{ V}$$

For $\beta_{DC} = 200$,

$$I_{C(2)} = \beta_{DC}\left(\frac{V_{CC} - V_{BE}}{R_B}\right) = 200\left(\frac{12\text{ V} - 0.7\text{ V}}{330\text{ k}\Omega}\right) = 6.84\text{ mA}$$

$$V_{CE(2)} = V_{CC} - I_{C(2)}R_C = 12\text{ V} - (6.84\text{ mA})(560\ \Omega) = 8.17\text{ V}$$

The percent change in I_C as β_{DC} changes from 100 to 200 is

$$\%\Delta I_C = \left(\frac{I_{C(2)} - I_{C(1)}}{I_{C(1)}}\right)100\%$$

$$= \left(\frac{6.84\text{ mA} - 3.42\text{ mA}}{3.42\text{ mA}}\right)100\% = \mathbf{100\%}\text{ (an increase)}$$

The percent change in V_{CE} is

$$\%\Delta V_{CE} = \left(\frac{V_{CE(2)} - V_{CE(1)}}{V_{CE(1)}}\right)100\%$$

$$= \left(\frac{8.17\text{ V} - 10.1\text{ V}}{10.1\text{ V}}\right)100\% = \mathbf{-19.1\%}\text{ (a decrease)}$$

Other Bias Methods

- As you can see, the Q-point is very dependent on β_{DC} in this circuit and therefore makes the base bias arrangement very unreliable. Consequently, base bias is not normally used if linear operation is required. However, it can be used in switching applications.

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