DC Biasing – BJTs

Topic 4 (Chapter 4)

(Some materials are from Malvino's book)

Biasing

Biasing: Applying DC voltages to a transistor in order to turn it on so that it can amplify AC signals.

The Three Operating Regions

Active or Linear Region Operation

- Base–Emitter junction is forward biased
- Base–Collector junction is reverse biased

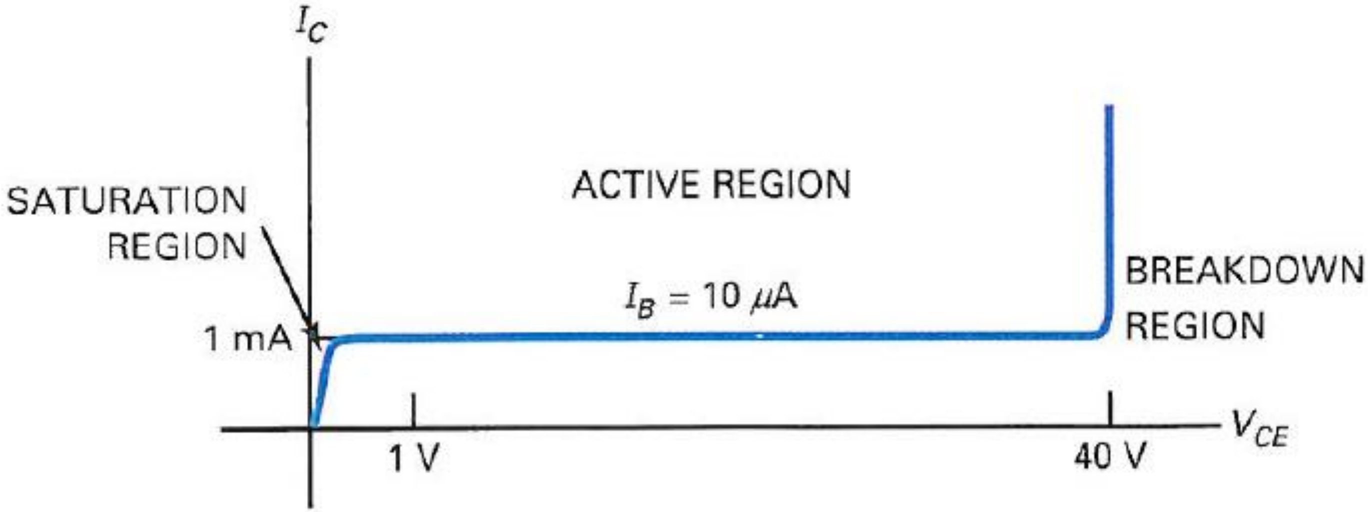
Cutoff Region Operation

- Base–Emitter junction is reverse biased

Saturation Region Operation

- Base–Emitter junction is forward biased
- Base–Collector junction is forward biased or near forward bias

Regions of operation



1. ***Active*** ***- - - used for <u>linear</u> amplification***
2. **Cutoff - - - used in <u>switching</u> applications**
3. **Saturation - - - used in <u>switching</u> applications**

- **Breakdown - - - can <u>destroy</u> the transistor and should be avoided**

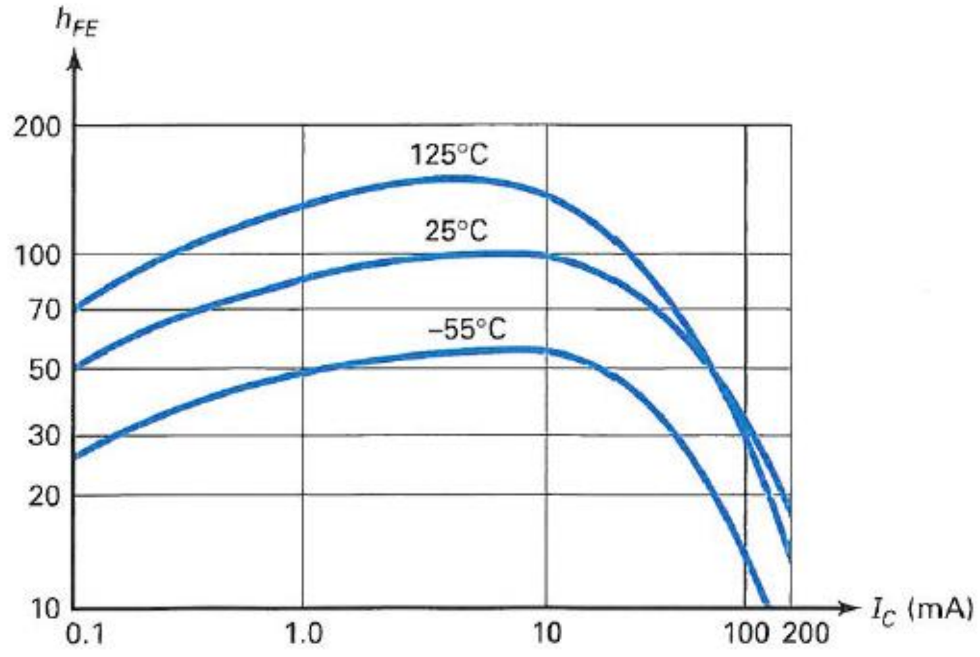
Current gain is not fixed

- Depends on:

✓ Transistor

✓ Collector current

✓ Temperature



DC Biasing Circuits

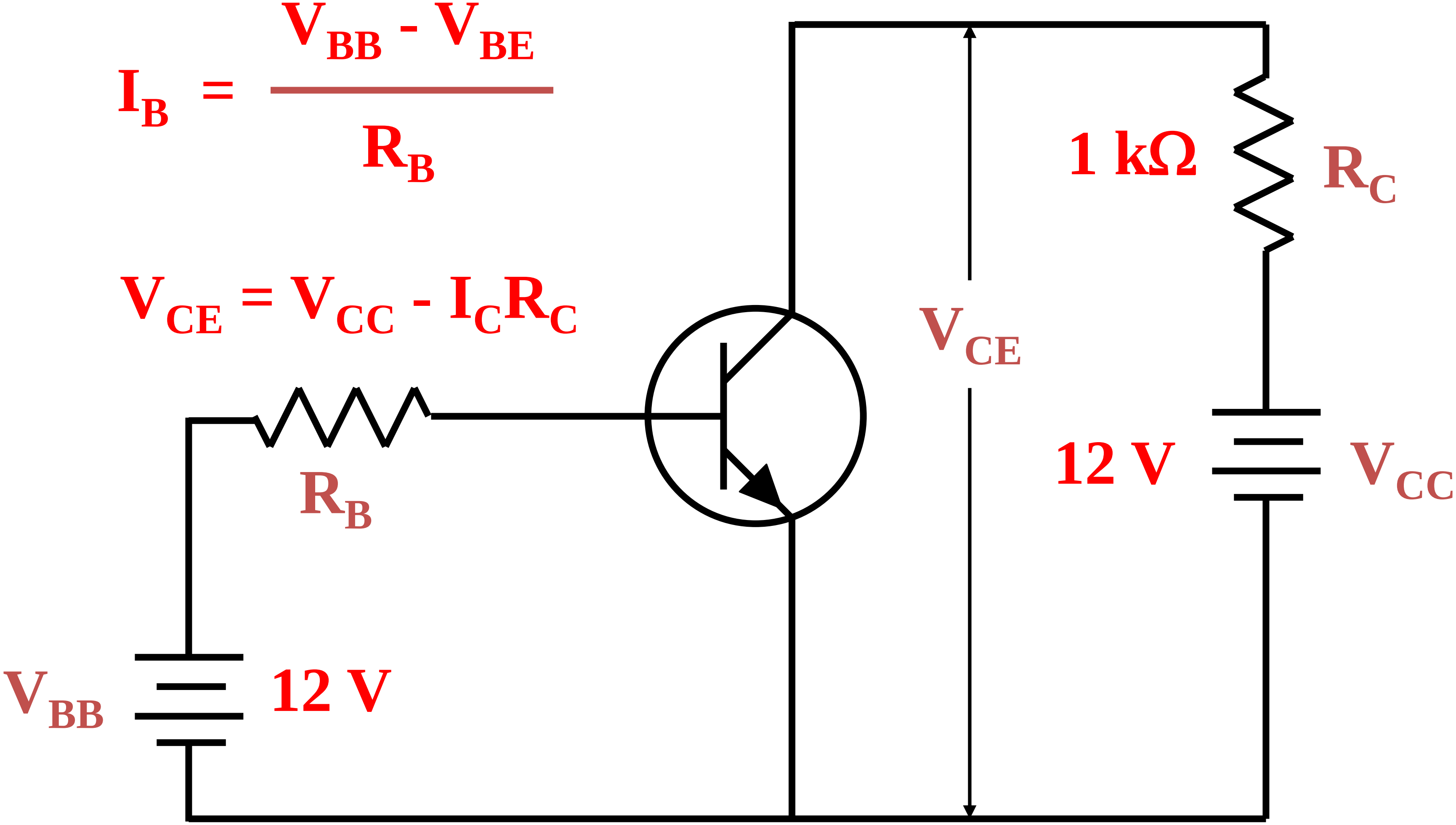
- Fixed-bias or Base-Bias
- Emitter Bias
- Voltage divider bias circuit
- DC bias with voltage feedback

Base-Bias or Fixed-Bias

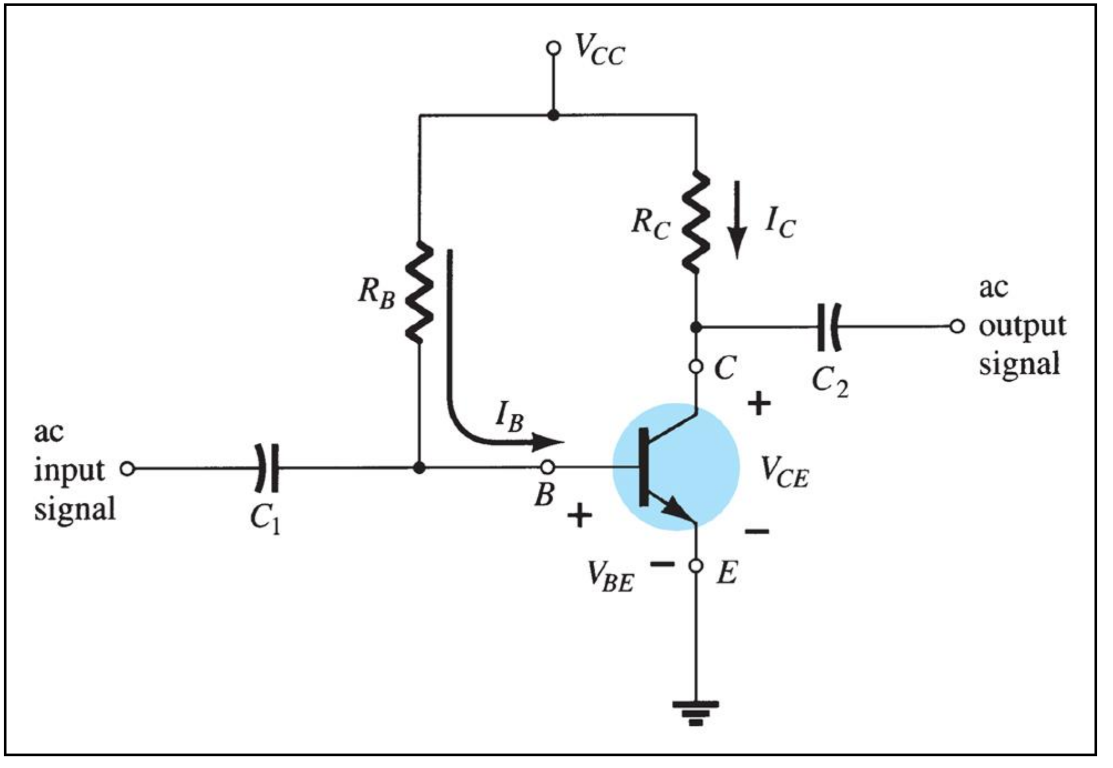
- Setting up a fixed value of **base current**
- Usually V_{BB} and V_{CC} are the same supply

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

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



Typical Base-Bias or Fixed-Bias Amplifier Circuit



- A single supply is used
- Coupling capacitors are used to shield the circuit from input and output DC voltages

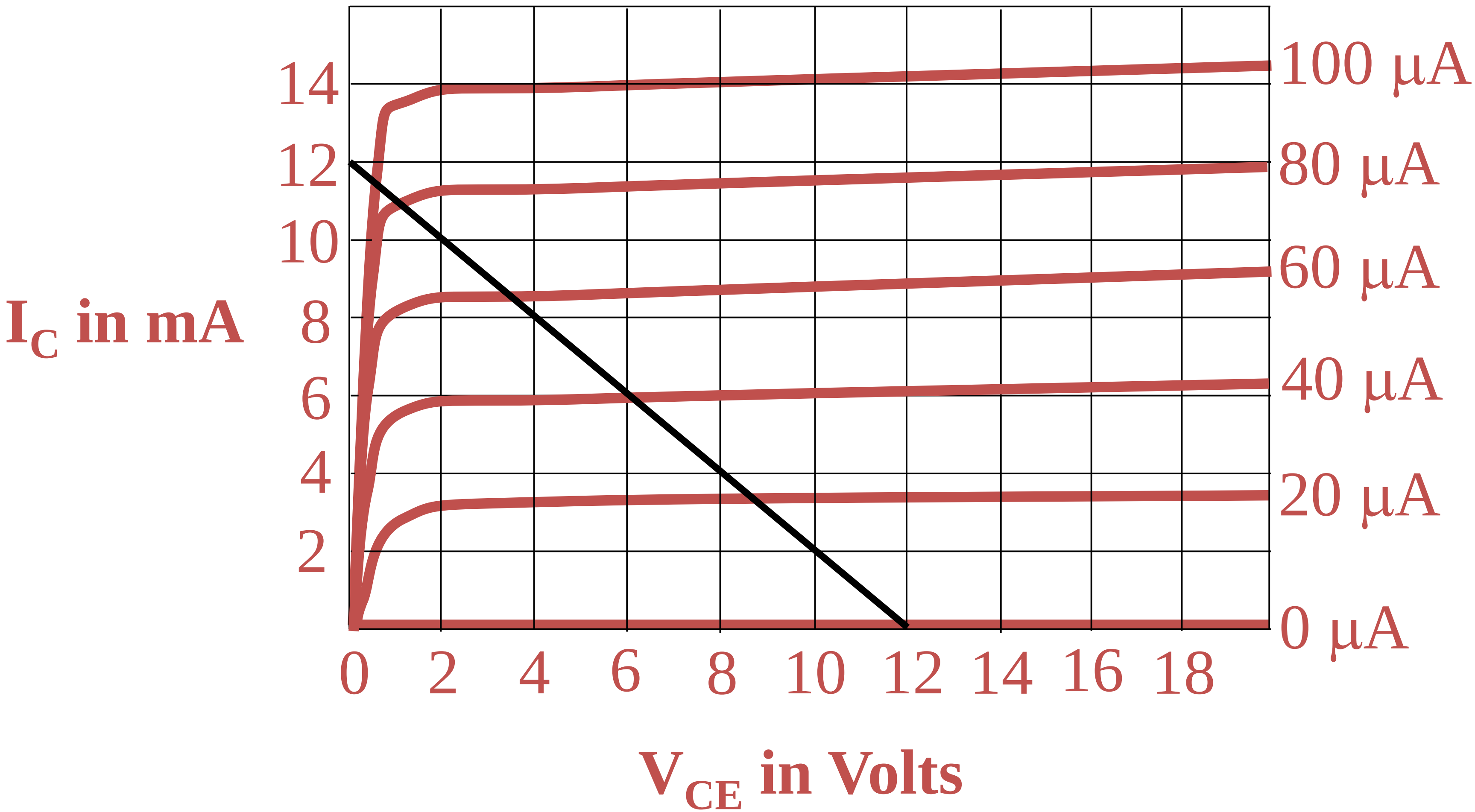
Load line

- A visual summary of all the possible transistor operating points
- Connects saturation current (I_{Csat}) to cutoff voltage ($V_{CEcutoff}$)

Load line

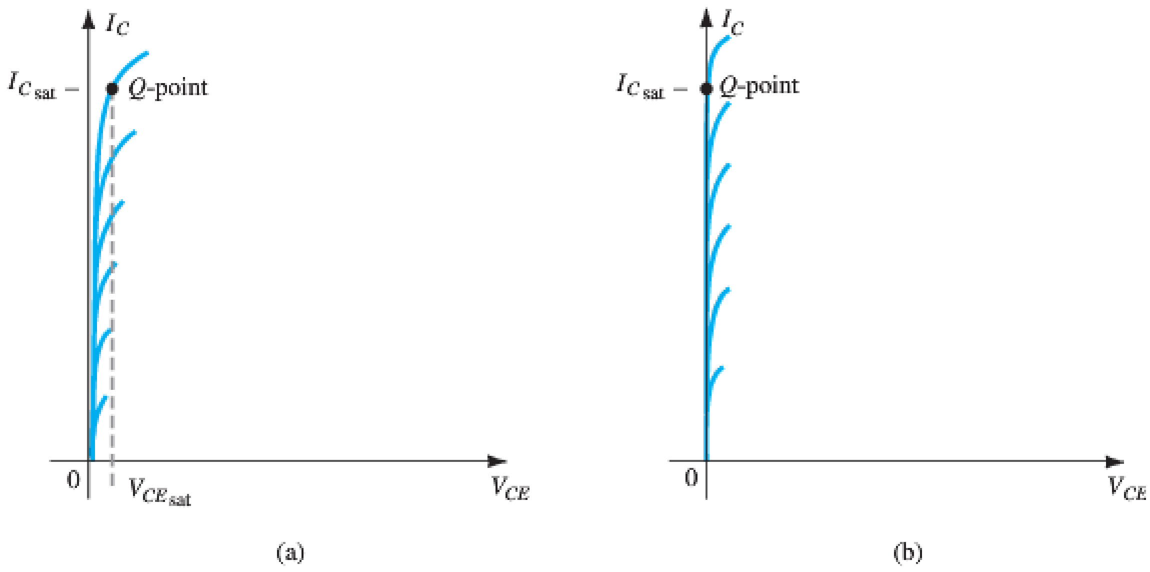
$$I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

A graph of this equation produces a load line.



Saturation

When the transistor is operating in **saturation**, current through the transistor is at its *maximum* possible value.

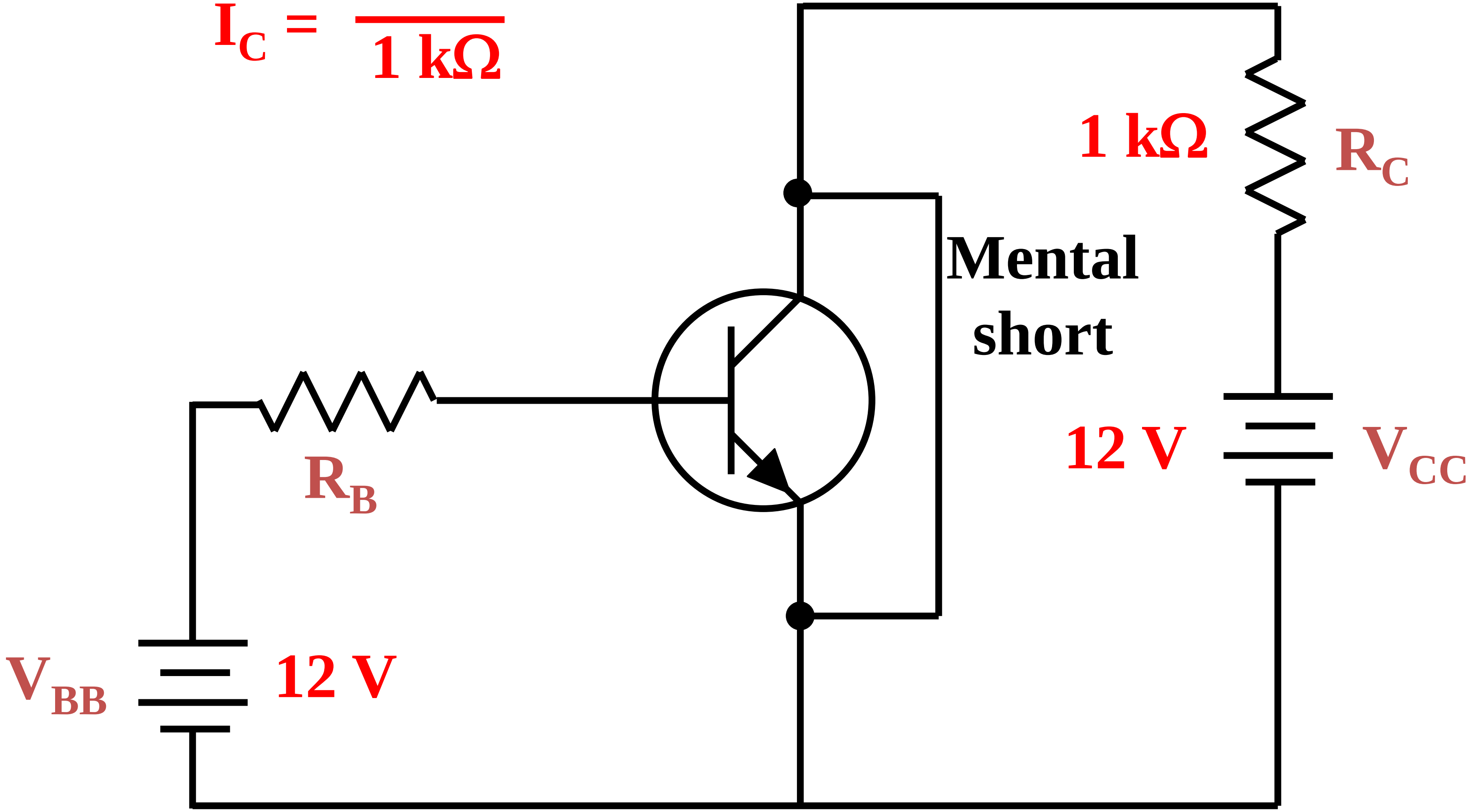


$$I_{Csat} = \frac{V_{CC}}{R_C}$$

$$V_{CE} \cong 0\ V$$

Understanding Saturation

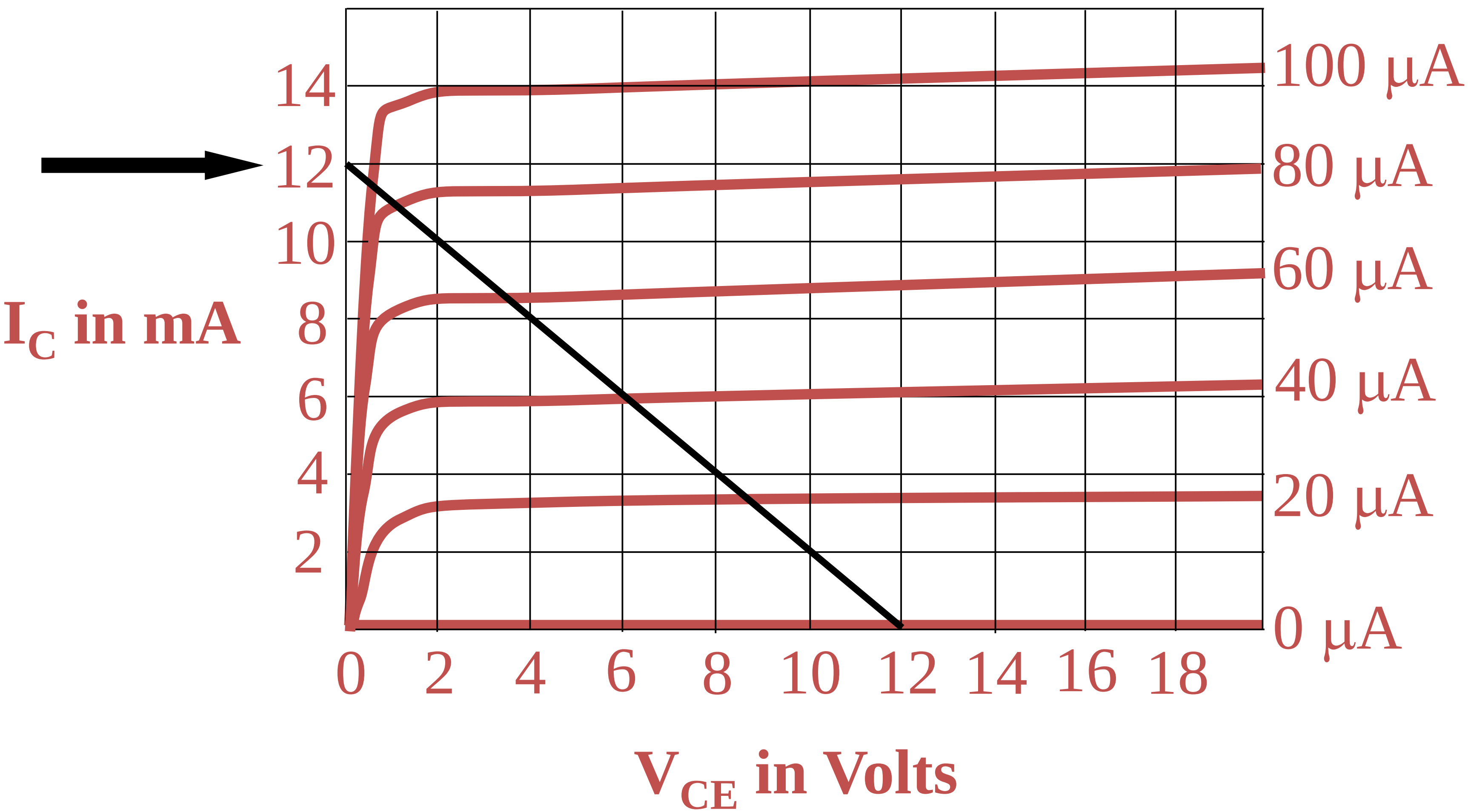
$$I_C = \frac{12\text{ V}}{1\text{ k}\Omega}$$



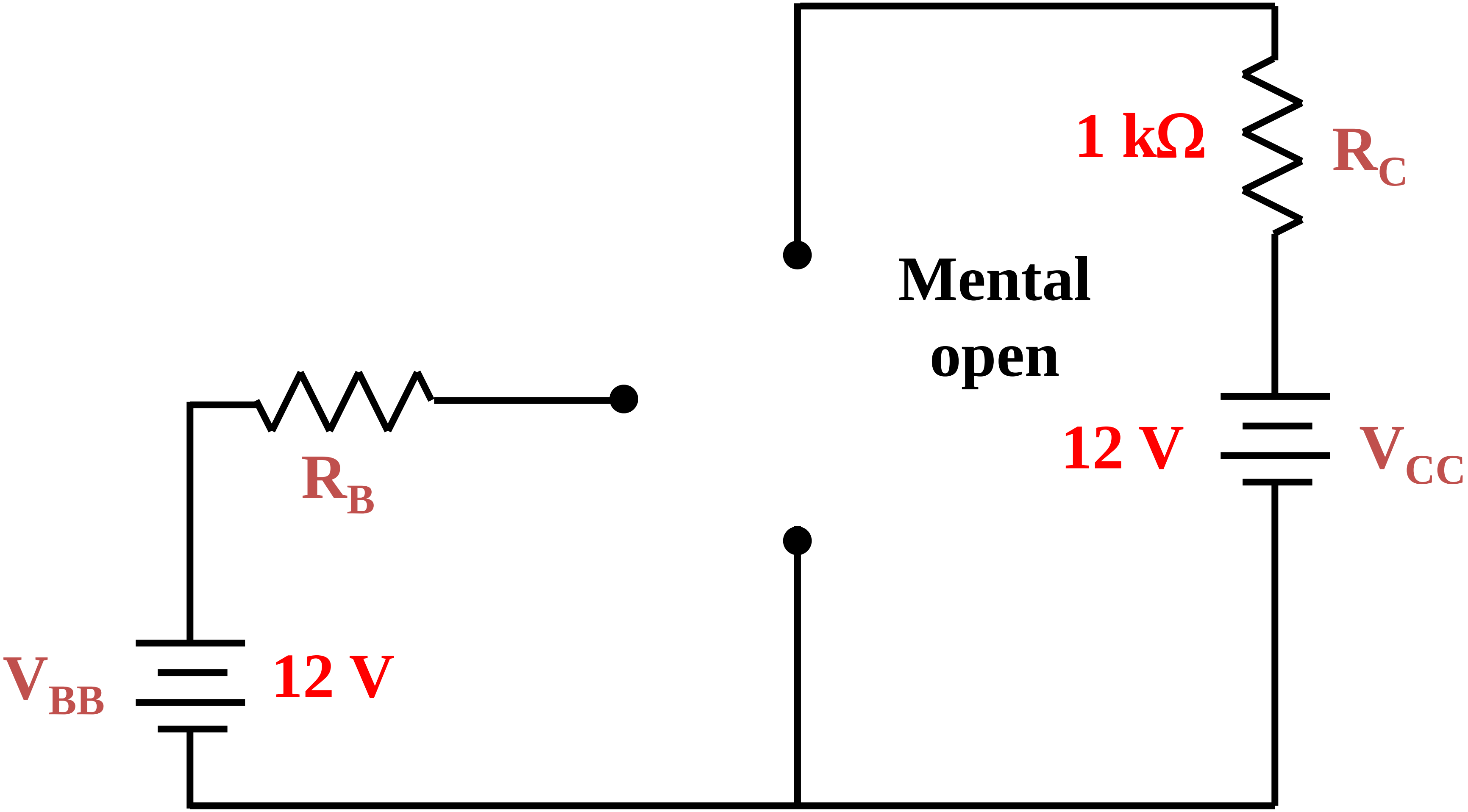
Understanding Saturation

$$I_C = \frac{12\text{ V}}{1\text{ k}\Omega} = 12\text{ mA}$$

This is the Saturation (maximum) current.

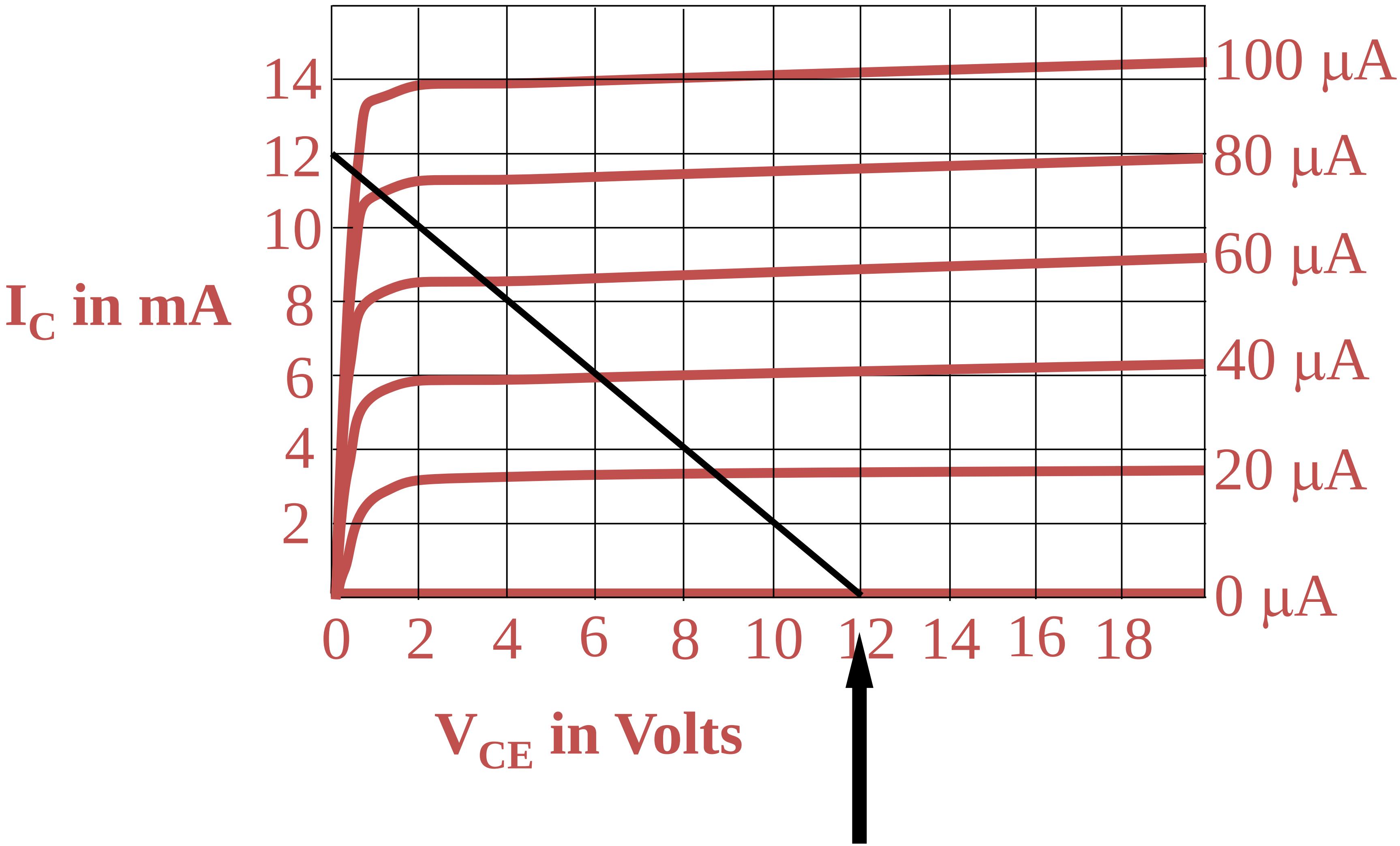


Understanding Cutoff



Understanding Cutoff

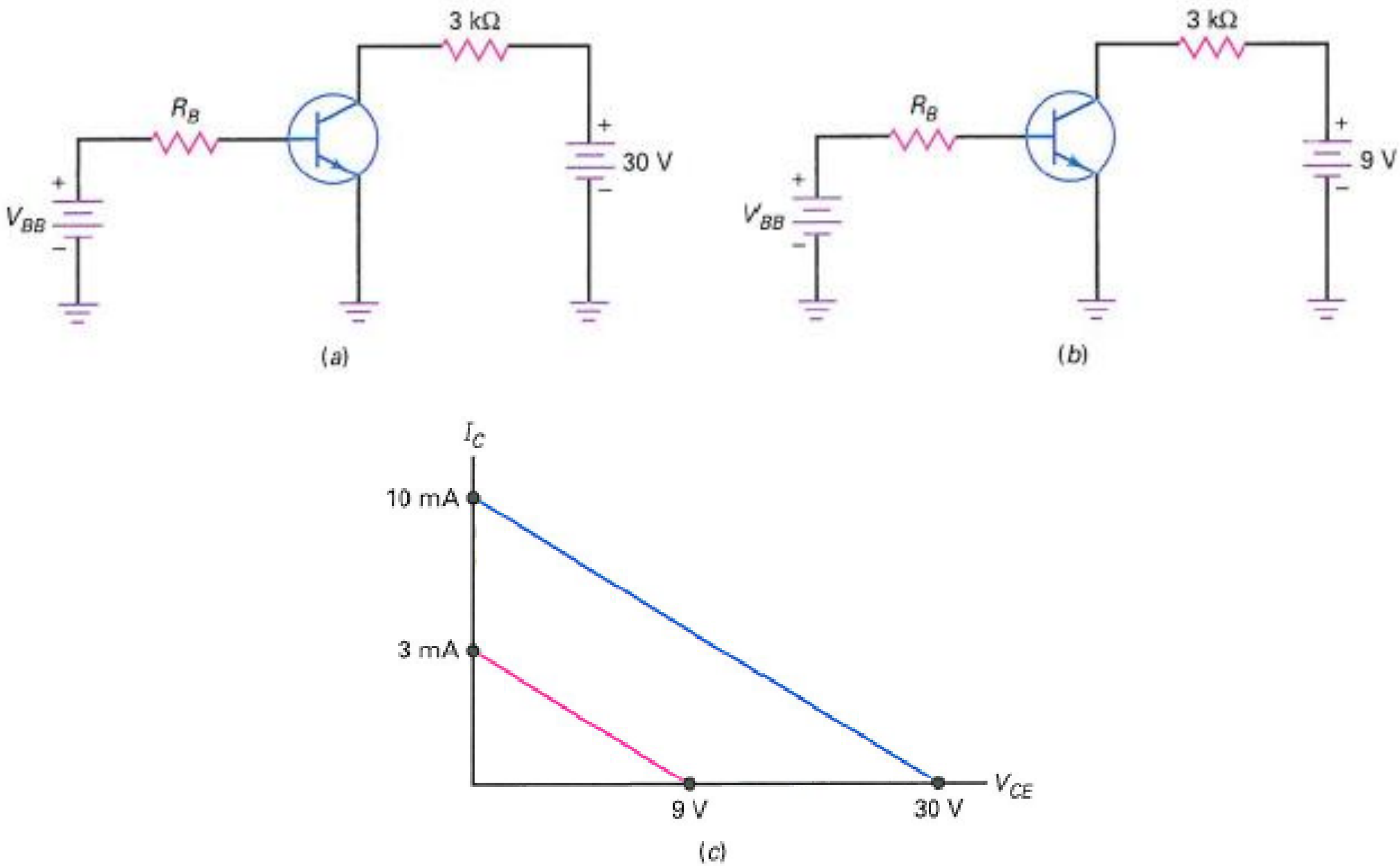
$$V_{CE(cutoff)} = V_{CC}$$



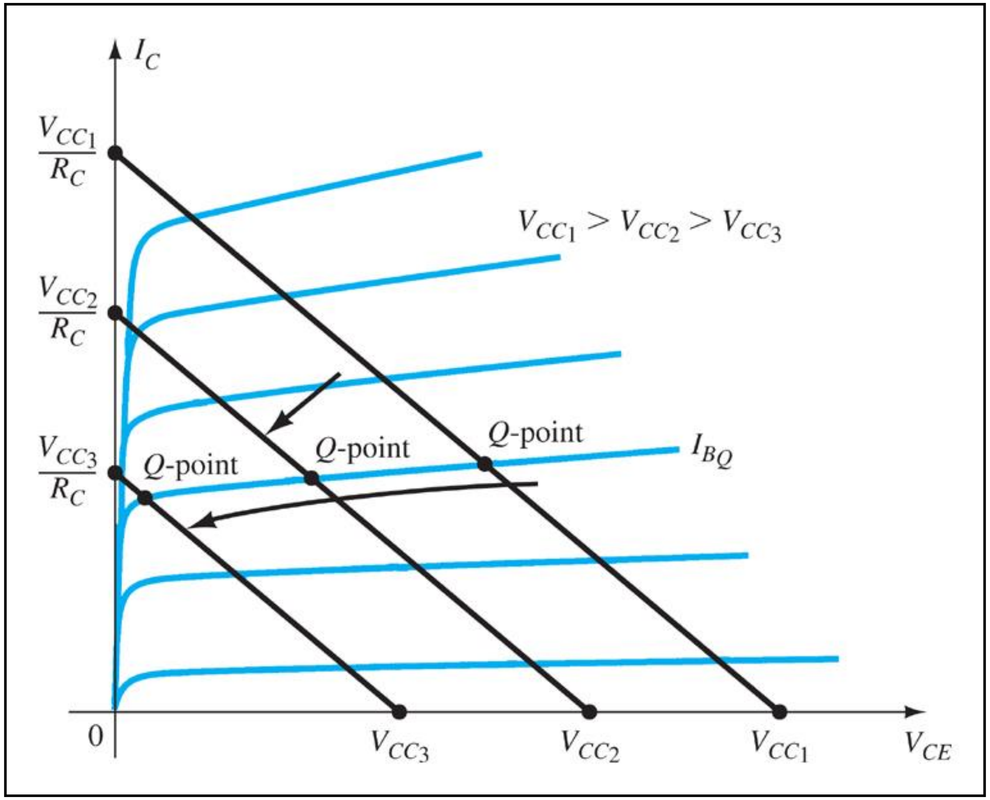
Example 7-1

What are the saturation current and the cutoff voltage in Fig. 7-4a?

Calculate the saturation and cutoff values for Fig. 7-4b.



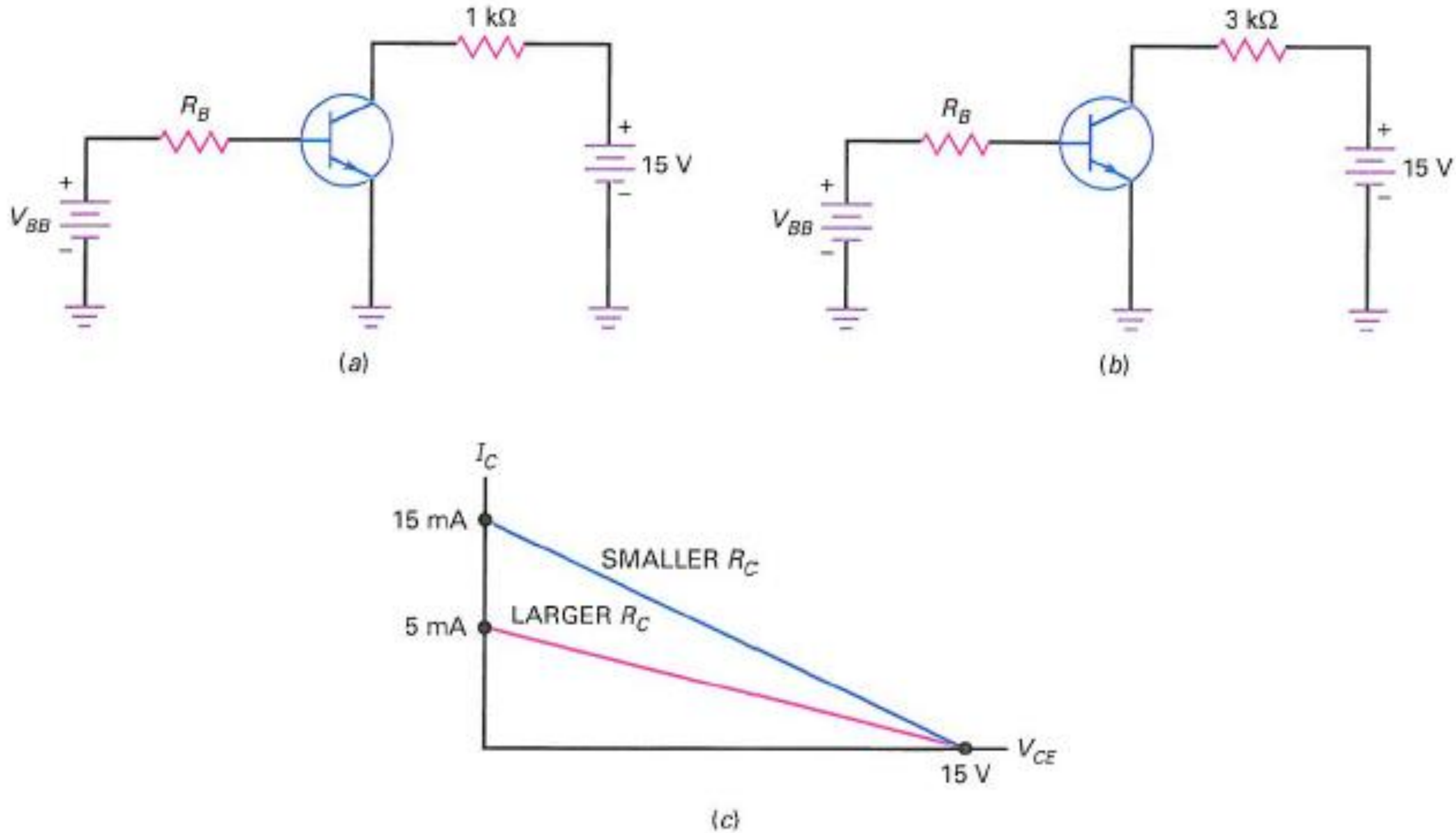
The Effect of V_{CC} on the Q-Point



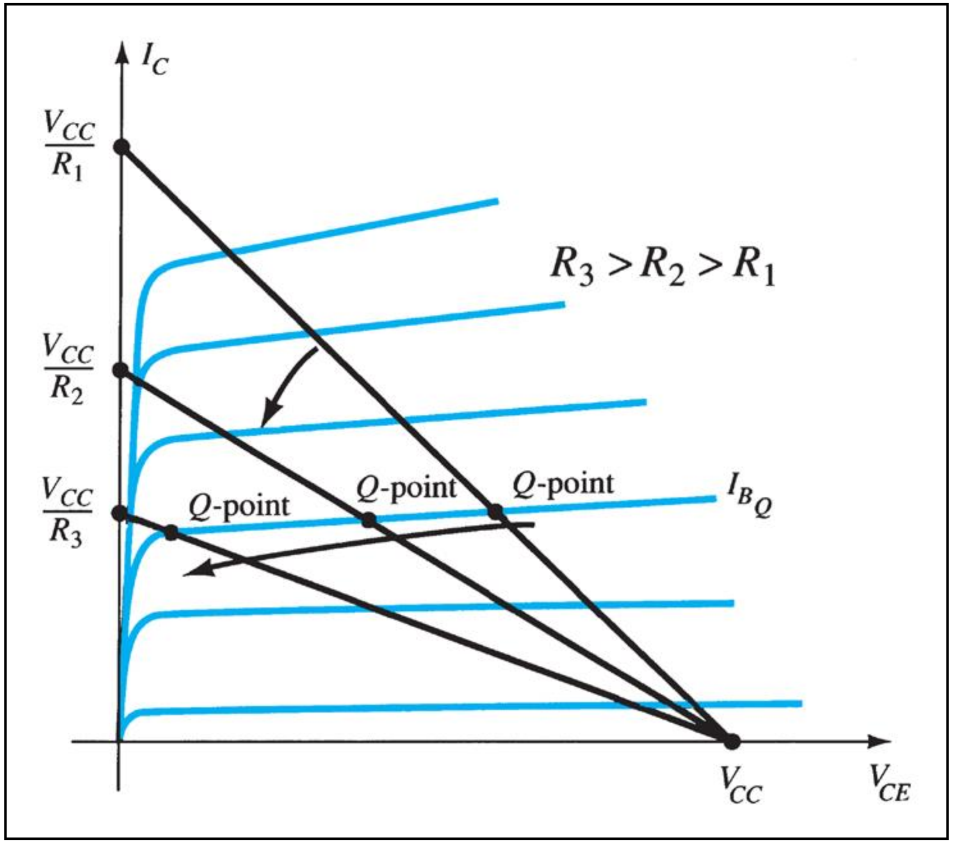
Example 7-3

What are the saturation current and the cutoff voltage in Fig. 7-5*a*?

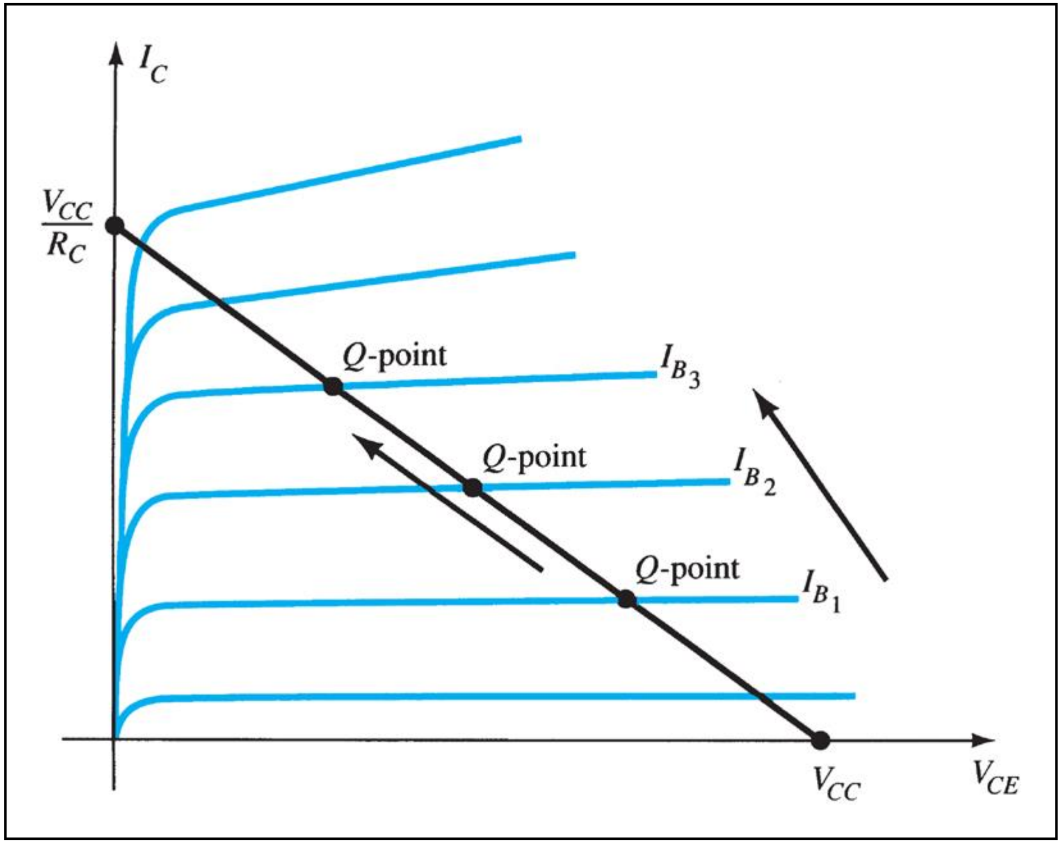
Calculate the saturation and cutoff values for Fig. 7-5*b*.



The Effect of R_C on the Q-Point



The Effect of I_B on the Q-Point



Operating point

- Determined by:

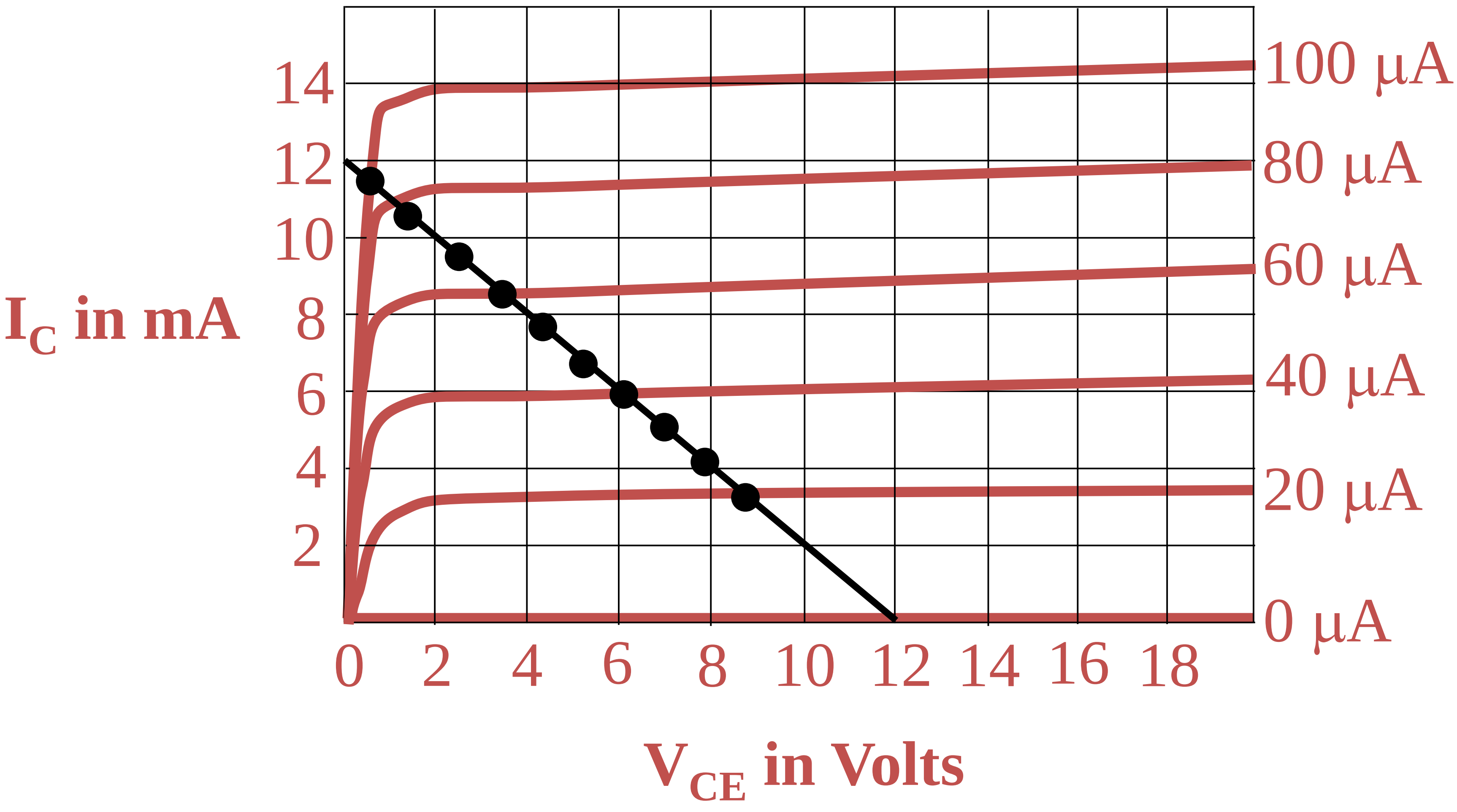
✓ Finding **saturation** current and **cutoff** voltage points

✓ Connecting points to produce a **load** line

✓ The <u>operating</u> (Q) point is established by the value of **base** current

Operating point

A circuit can operate at <u>any</u> point on the load line.

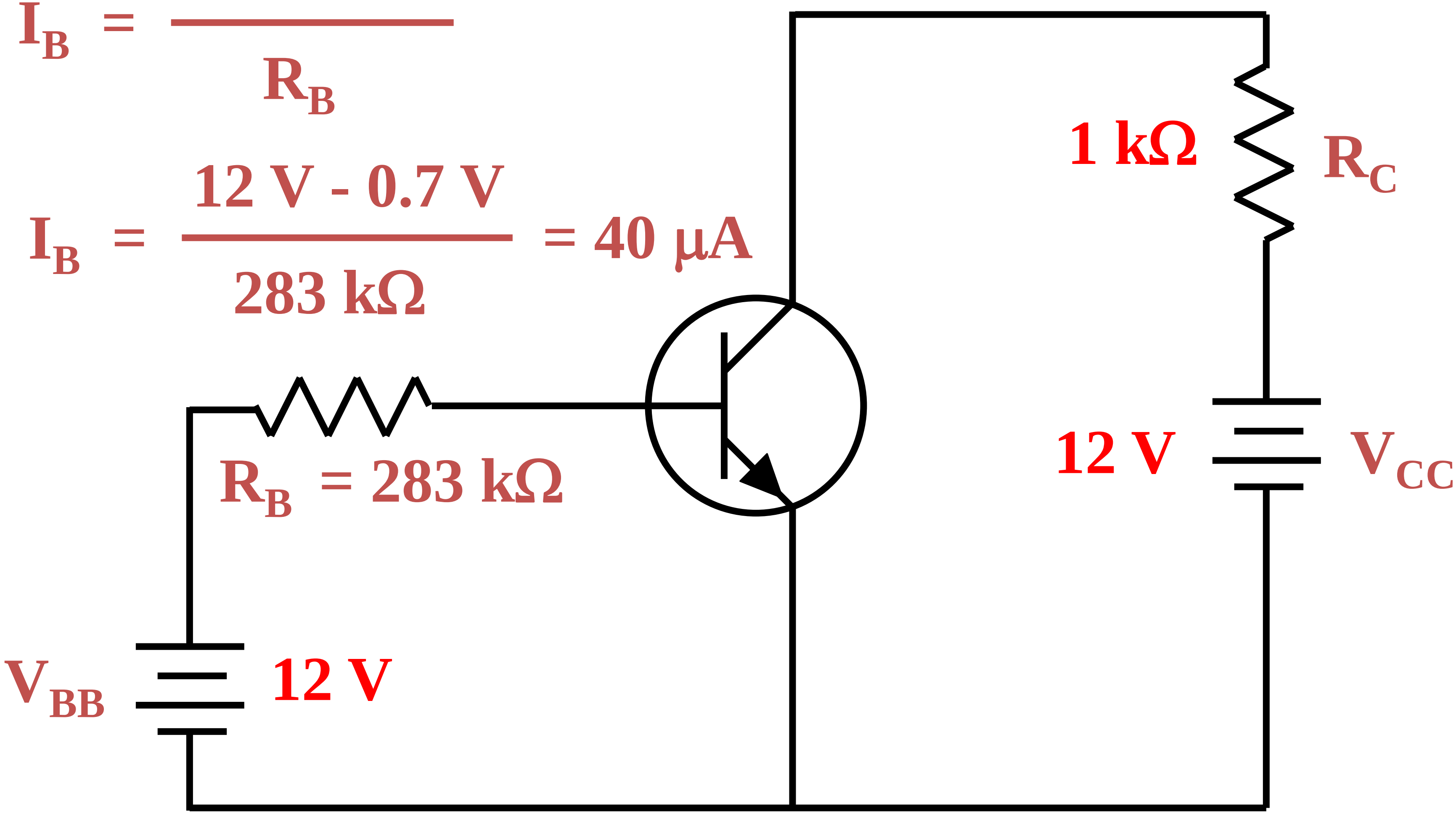


Operating point

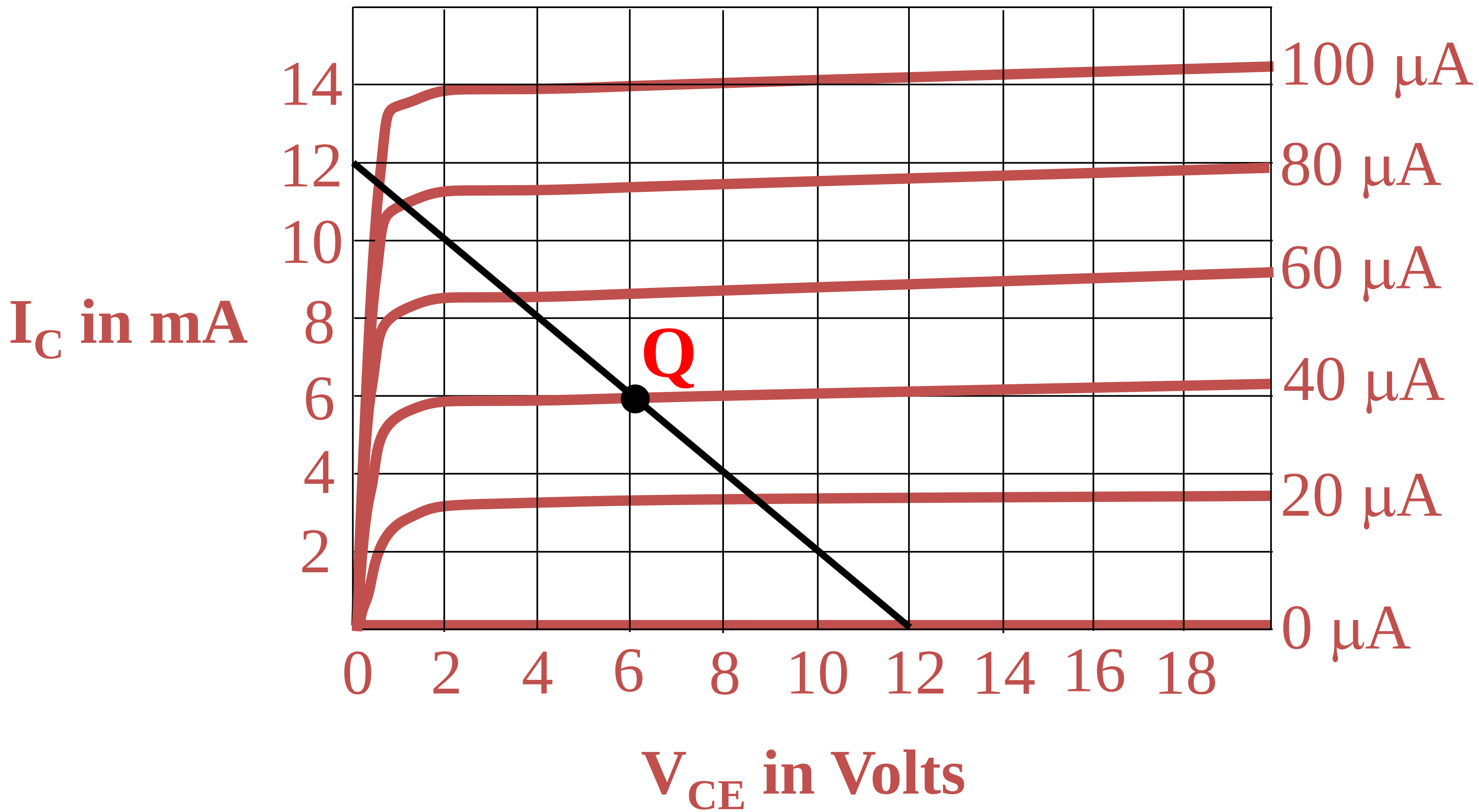
The **operating point** is determined by the base current.

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

$$I_B = \frac{12\ \text{V} - 0.7\ \text{V}}{283\ \text{k}\Omega} = 40\ \mu\text{A}$$

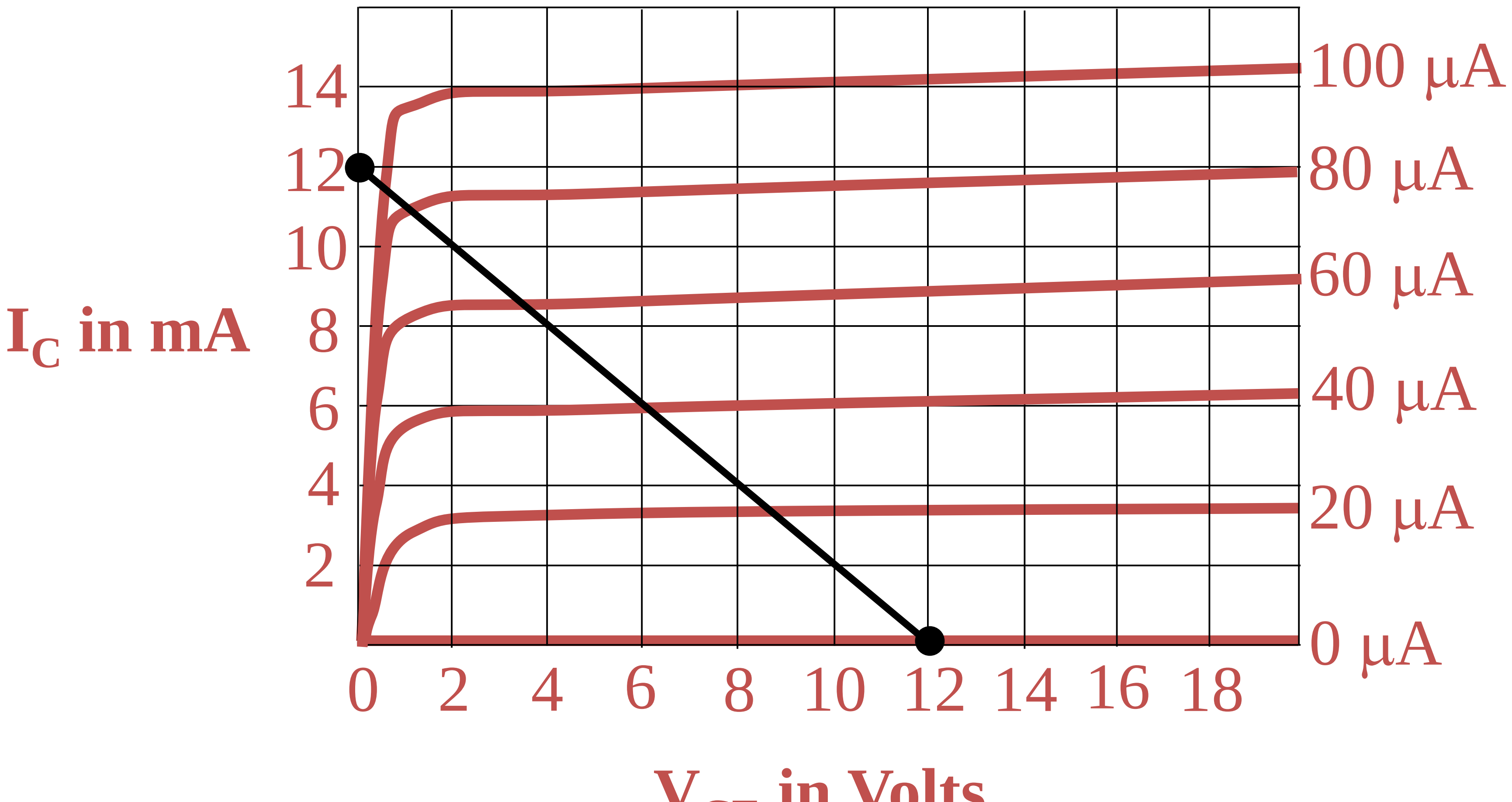


The operating point is called the Q or quiescent point.



This Q point is in the linear region.

Saturation and cutoff are <u>non-linear</u> operating points.



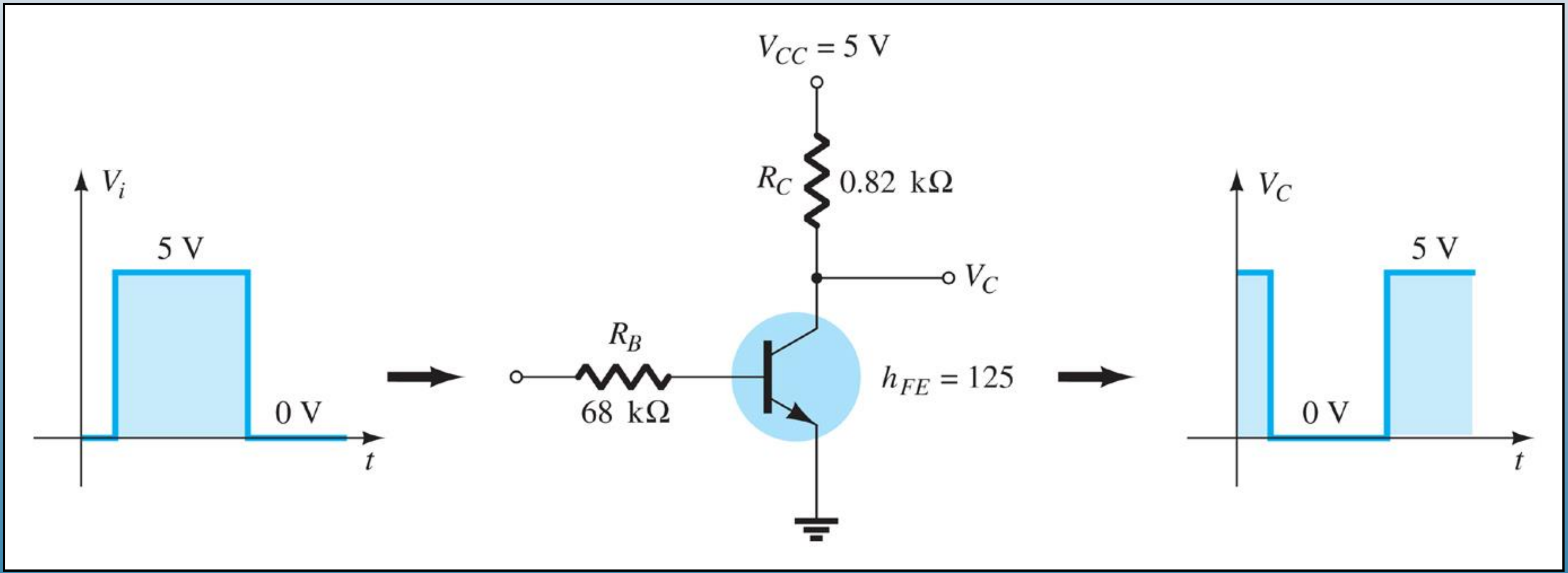
These Q points are used in switching applications.

Transistor circuits

- **Amplifying and switching**
- **Amplifying – Q point is in the active region**
- **Switching – Q point switches between saturation and cutoff**

Transistor Switching Networks

Transistors with only the DC source applied can be used as electronic switches.

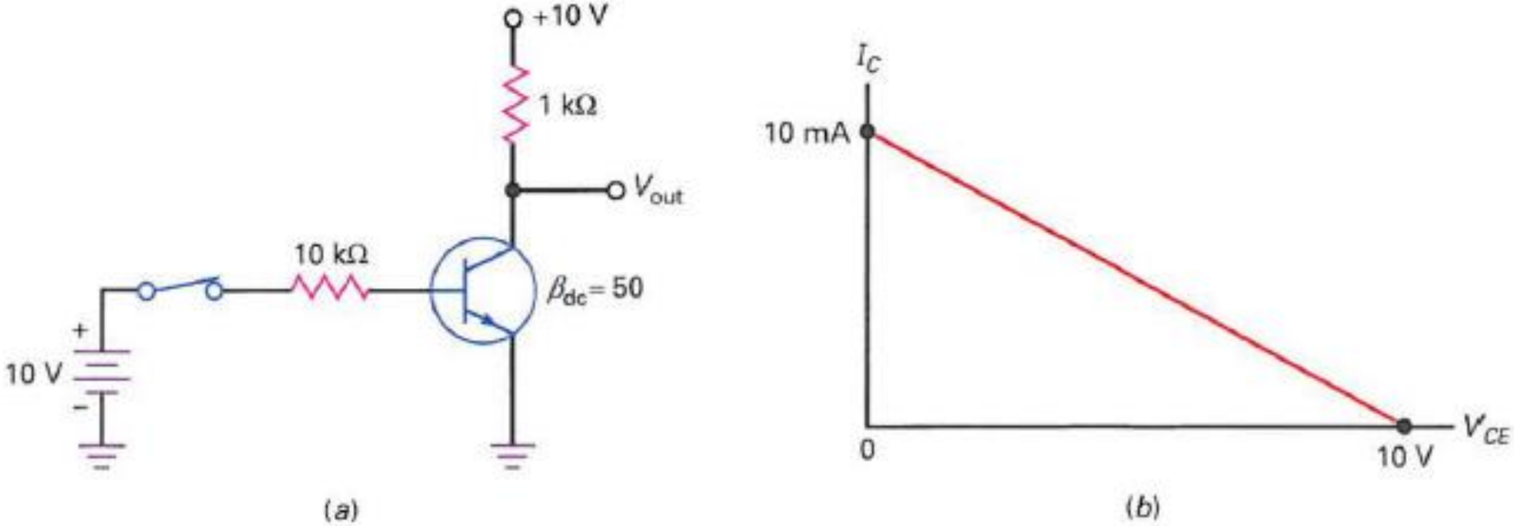


Transistor Switch Using Base Bias

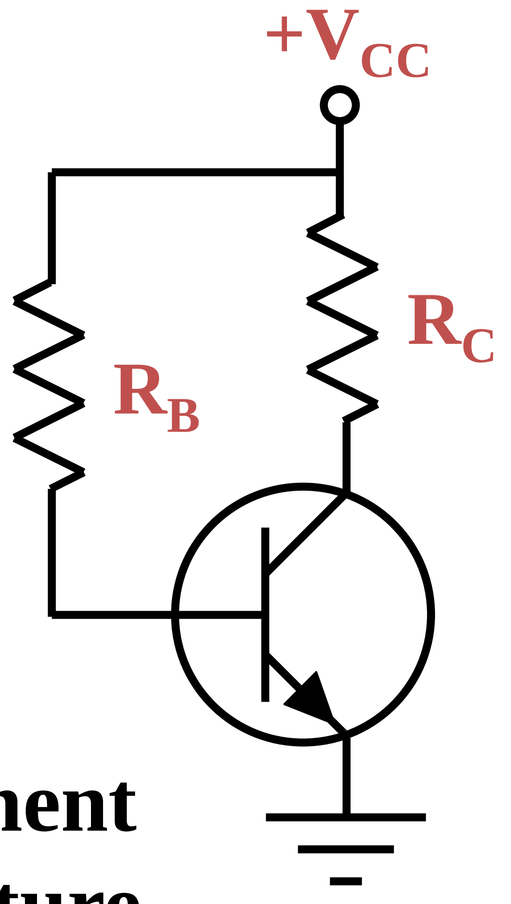
- Base bias is used
- The **Q point** switches between **saturation** and **cutoff**
- Switching circuits, also called **two-state circuits**, are used in digital applications

Hard Saturation Used In Transistor Switches

Figure 7-8 (a) Hard saturation; (b) load line.



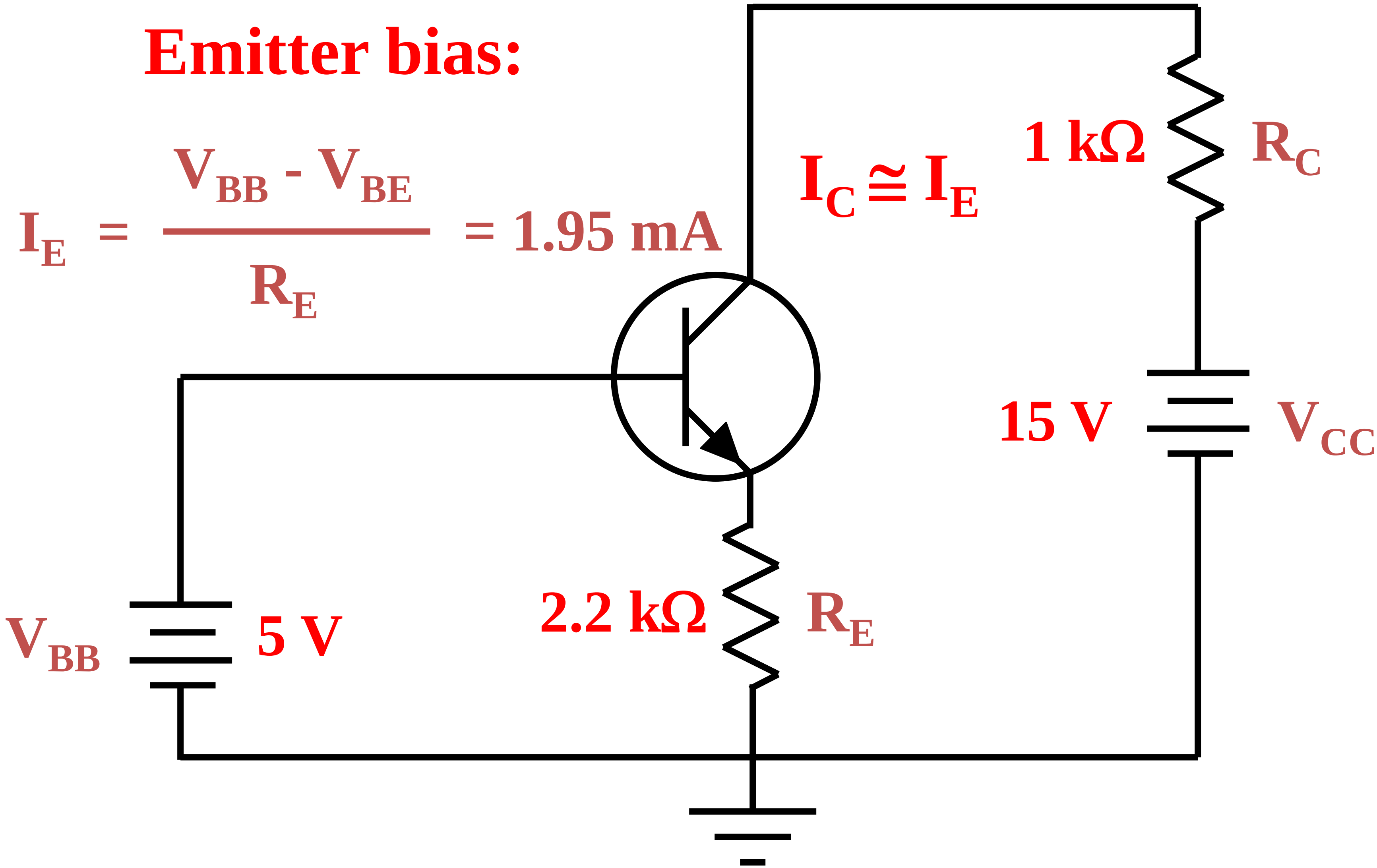
Problems with Base bias



- The least predictable
- Q point moves with replacement
- Q point moves with temperature
- Not practical

Emitter bias:

$$I_E = \frac{V_{BB} - V_{BE}}{R_E} = 1.95\ \text{mA}$$



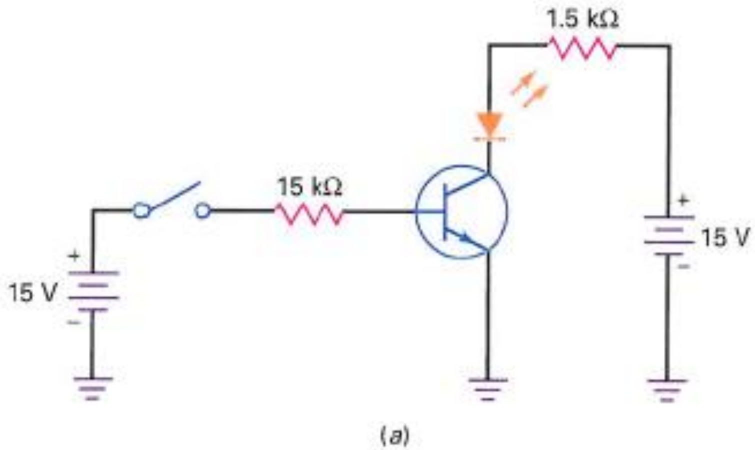
$$V_C = 15\ \text{V} - (1.95\ \text{mA})(1\ \text{k}\Omega) = 13.1\ \text{V}$$

$$V_{CE} = 13.1\ \text{V} - 4.3\ \text{V} = 8.8\ \text{V}$$

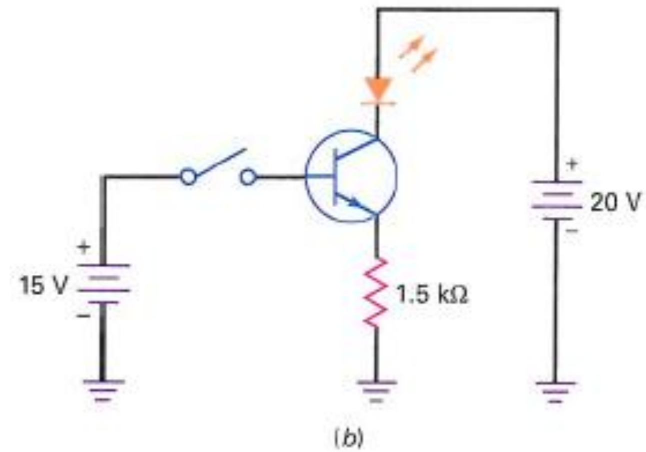
Comparing Base Bias and Emitter Bias

- **Base bias is subject to variations in transistor current gain.**
- **Base bias is subject to temperature effects.**
- **Emitter bias almost eliminates these effects.**
- **The transistor current gain is not required when solving circuits with emitter bias.**

Base-Biased and Emitter-Biased LED Drivers



Base-biased

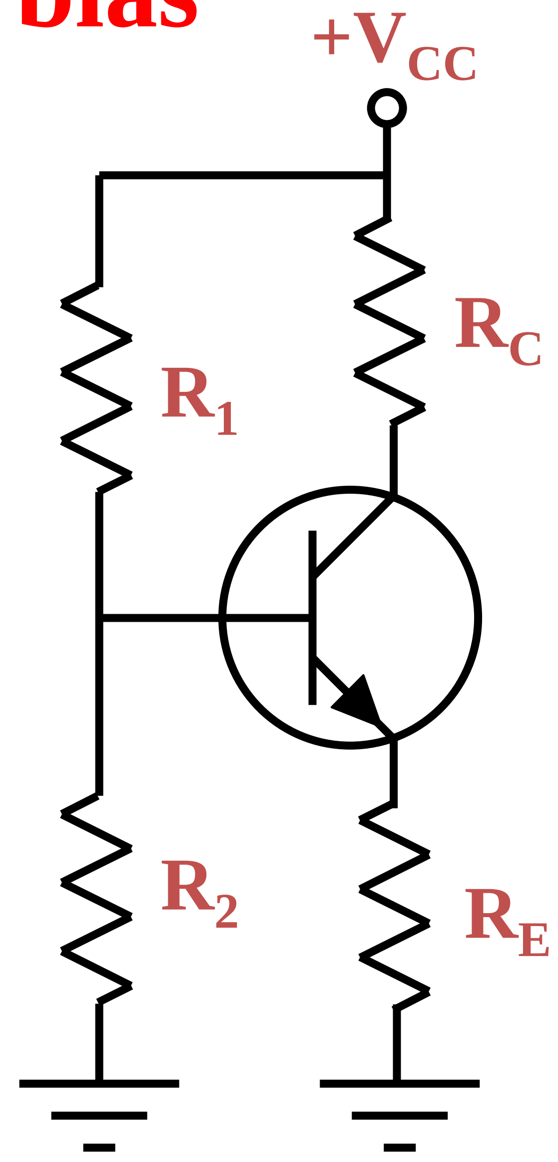


Emitter-biased

- **The base-biased LED driver is designed to operate between cutoff and hard saturation**
  - **LED voltage drop changes LED current and brightness**
- **The emitter-biased LED driver is designed to operate between cutoff and active region**
  - **LED voltage drop has no effect on LED current**

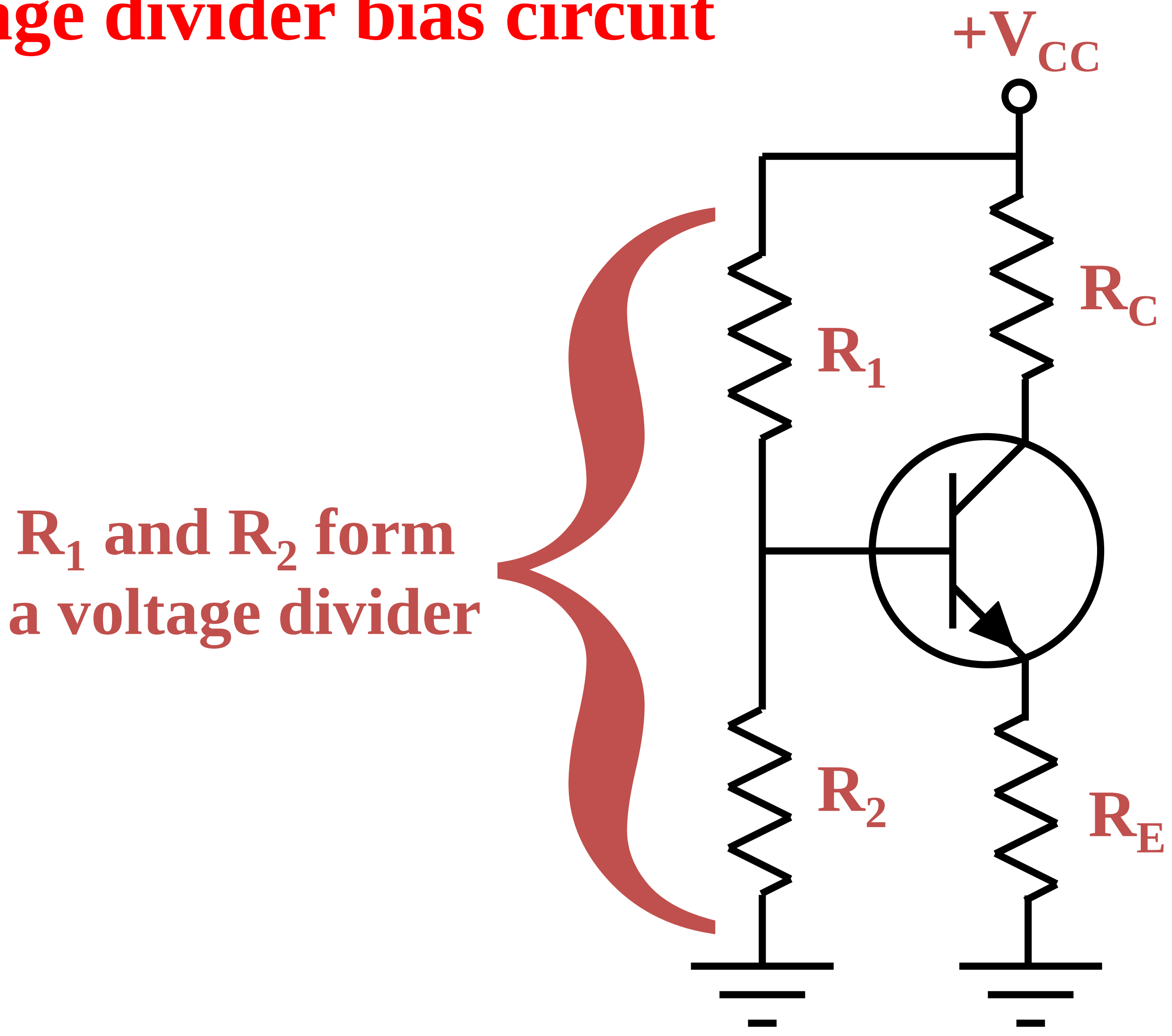
Voltage divider bias

- Base circuit contains a **voltage divider**
- Most widely used
- Known as **VDB**



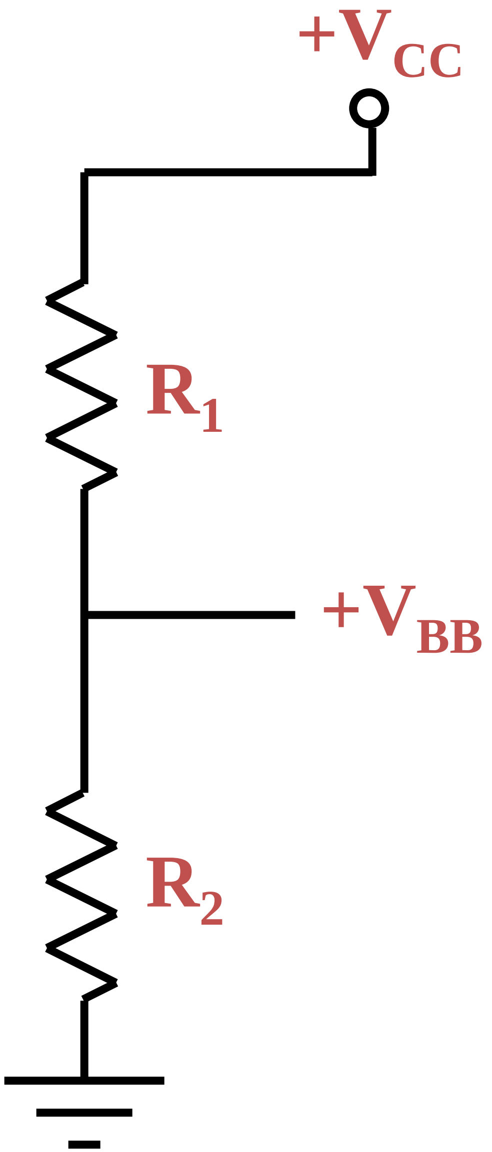
- **Very stable**
- **Eliminates the need for two supplies of emitter bias.**
  - **Requires just 1 supply**
- **The most popular**

Voltage divider bias circuit



Divider analysis:

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



ASSUMPTION: The <u>base</u> current is normally <u>much smaller</u> than the divider current.

Now the circuit can be viewed this way:

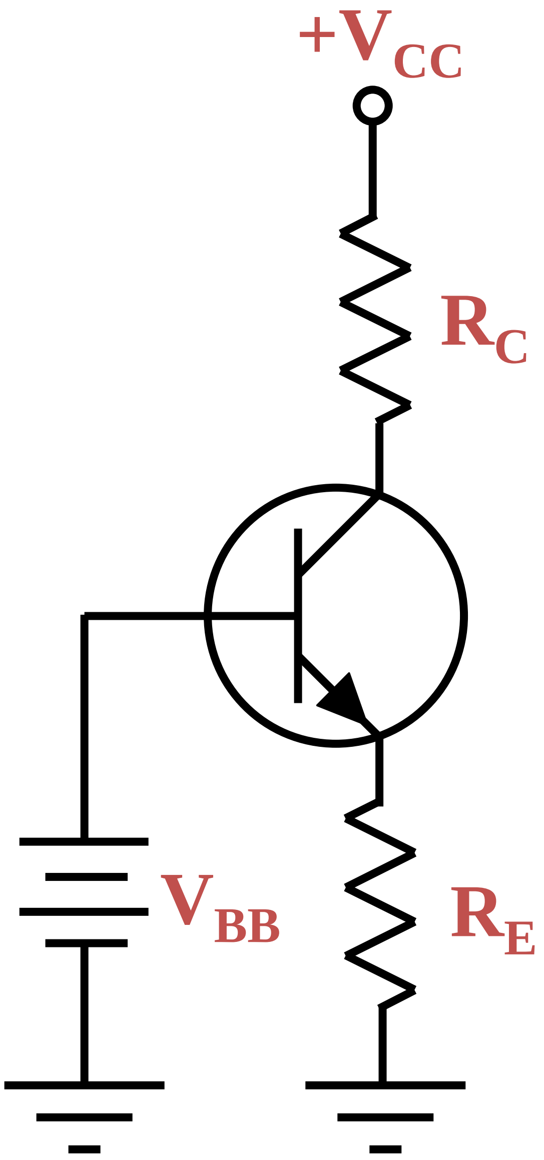
To complete the analysis:

$$I_E = \frac{V_{BB} - V_{BE}}{R_E}$$

$$I_C \cong I_E$$

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

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



Example 8-1

What is the collector-emitter voltage in Fig. 8-2?

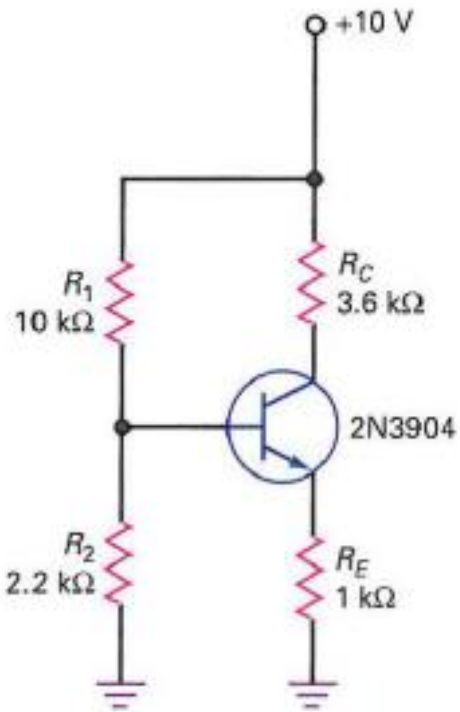


Figure 8-2 Example.

SOLUTION The voltage divider produces an unloaded output voltage of:

$$V_{BB} = \frac{2.2\text{ k}\Omega}{10\text{ k}\Omega + 2.2\text{ k}\Omega} 10\text{ V} = 1.8\text{ V}$$

Subtract 0.7 V from this to get:

$$V_E = 1.8\text{ V} - 0.7\text{ V} = 1.1\text{ V}$$

The emitter current is:

$$I_E = \frac{1.1\text{ V}}{1\text{ k}\Omega} = 1.1\text{ mA}$$

Since the collector current almost equals the emitter current, we can calculate the collector-to-ground voltage like this:

$$V_C = 10\text{ V} - (1.1\text{ mA})(3.6\text{ k}\Omega) = 6.04\text{ V}$$

The collector-emitter voltage is:

$$V_{CE} = 6.04 - 1.1\text{ V} = 4.94\text{ V}$$

Here is an important point: The calculations in this preliminary analysis do not depend on changes in the transistor, the collector current, or the temperature. This is why the Q point of this circuit is stable, almost rock-solid.

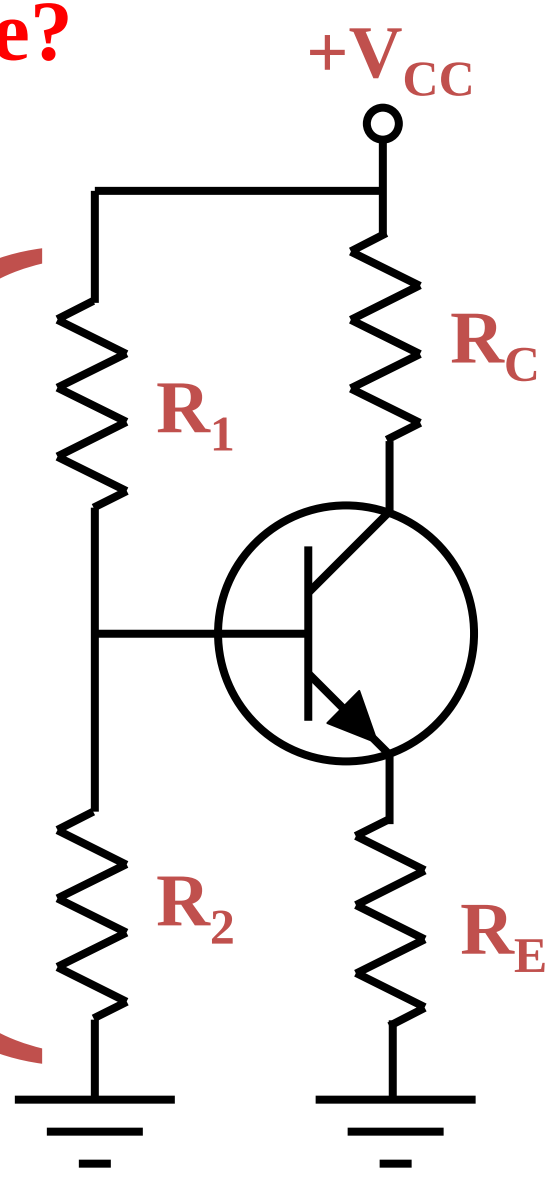
VDB analysis

- The **base** current must be much smaller than current through the divider
- With the base voltage constant, the circuit produces a **stable Q point** under varying operational conditions

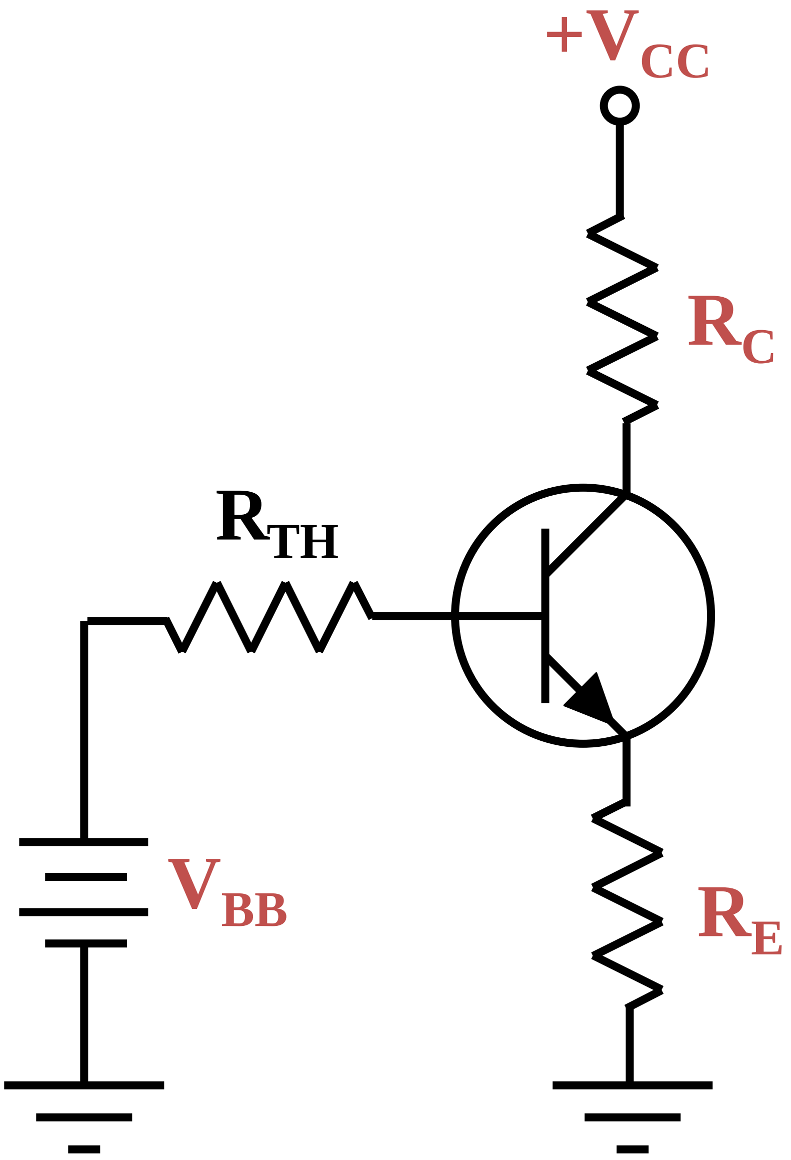
Is the divider a <u>stiff</u> source?

Find the Thevenin resistance.

$$R_{TH} = R_1 \| R_2$$

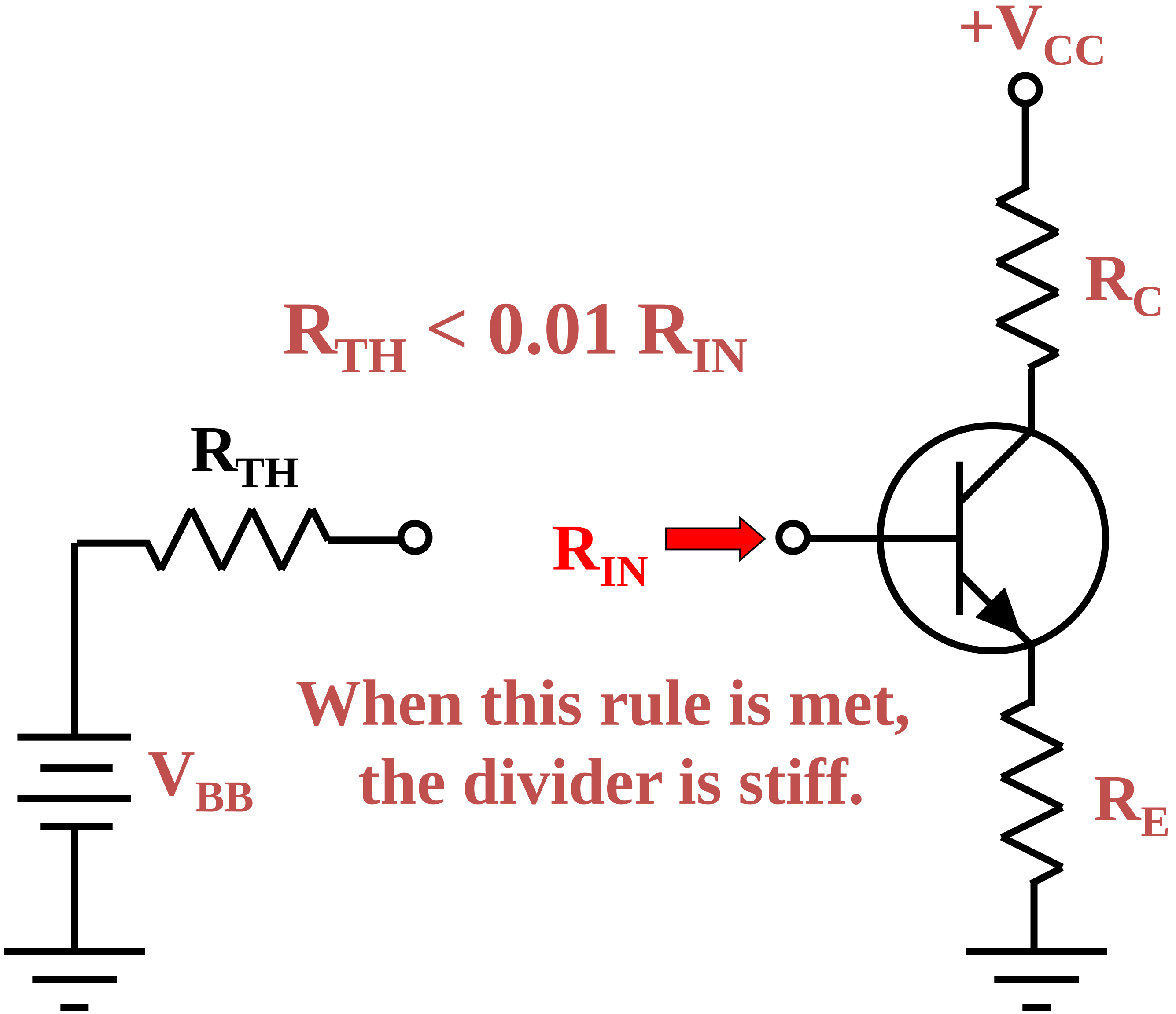


A Thevenin model of the bias circuit:



The 100:1 rule applied to the bias circuit:

$R_{TH} < 0.01\ R_{IN}$



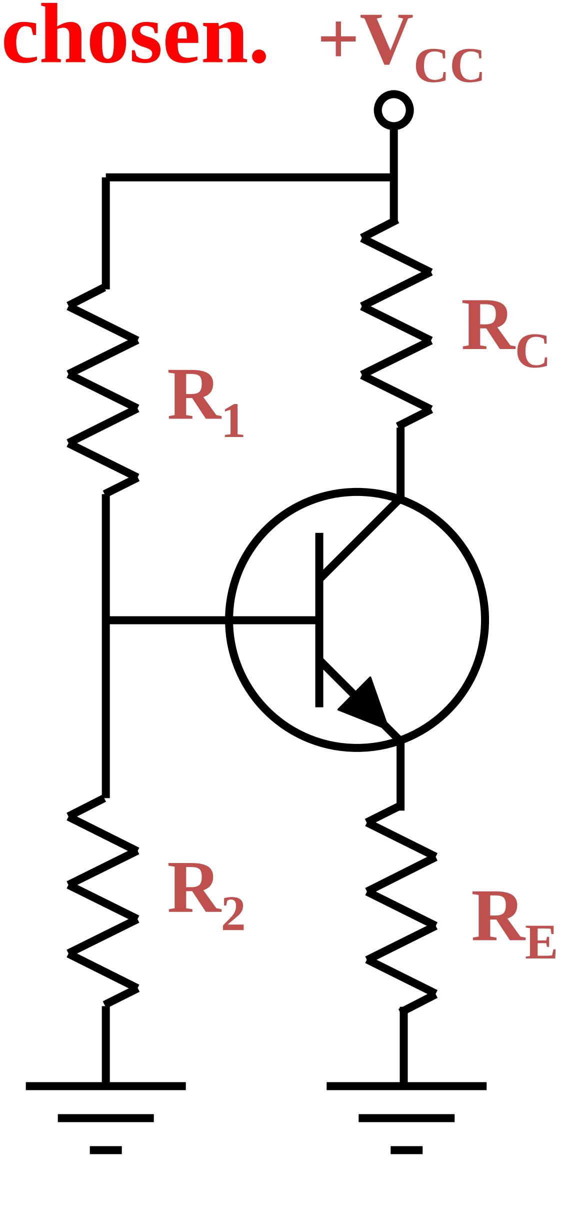
When this rule is met, the divider is stiff.

Sometimes a <u>firm divider</u> is chosen.

$$R_1 \| R_2 < 0.1\ \beta_{dc} R_E$$

A closer approximation:

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_1 \| R_2}{\beta_{dc}}}$$



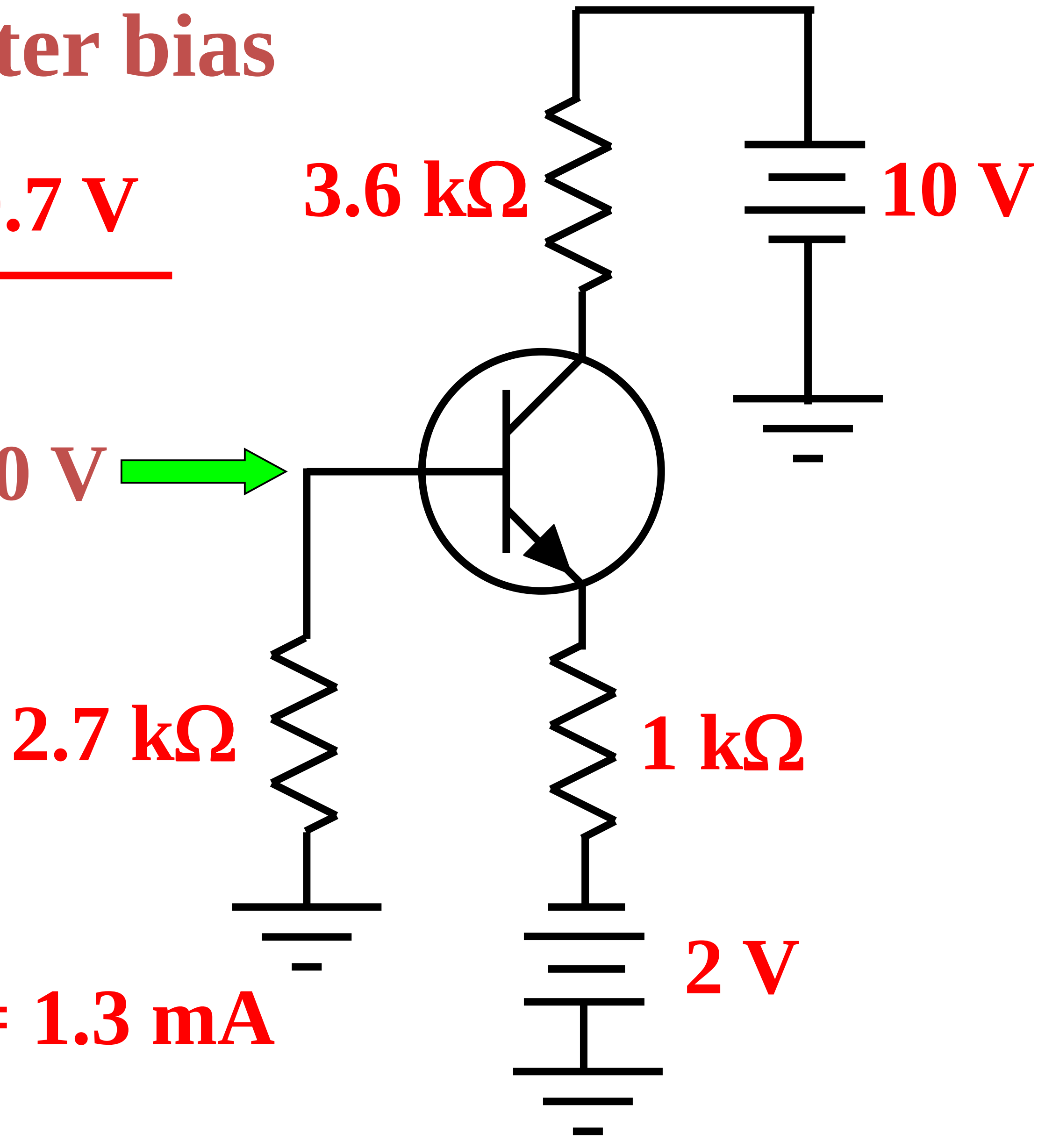
VDB load line and Q point

- **VDB is derived from emitter bias**
- **The Q point is immune to changes in current gain**
- **The Q point is moved by varying the emitter resistor**

Two-supply emitter bias

$$I_E = \frac{V_{EE} - 0.7\ \text{V}}{R_E}$$

Assume 0 V

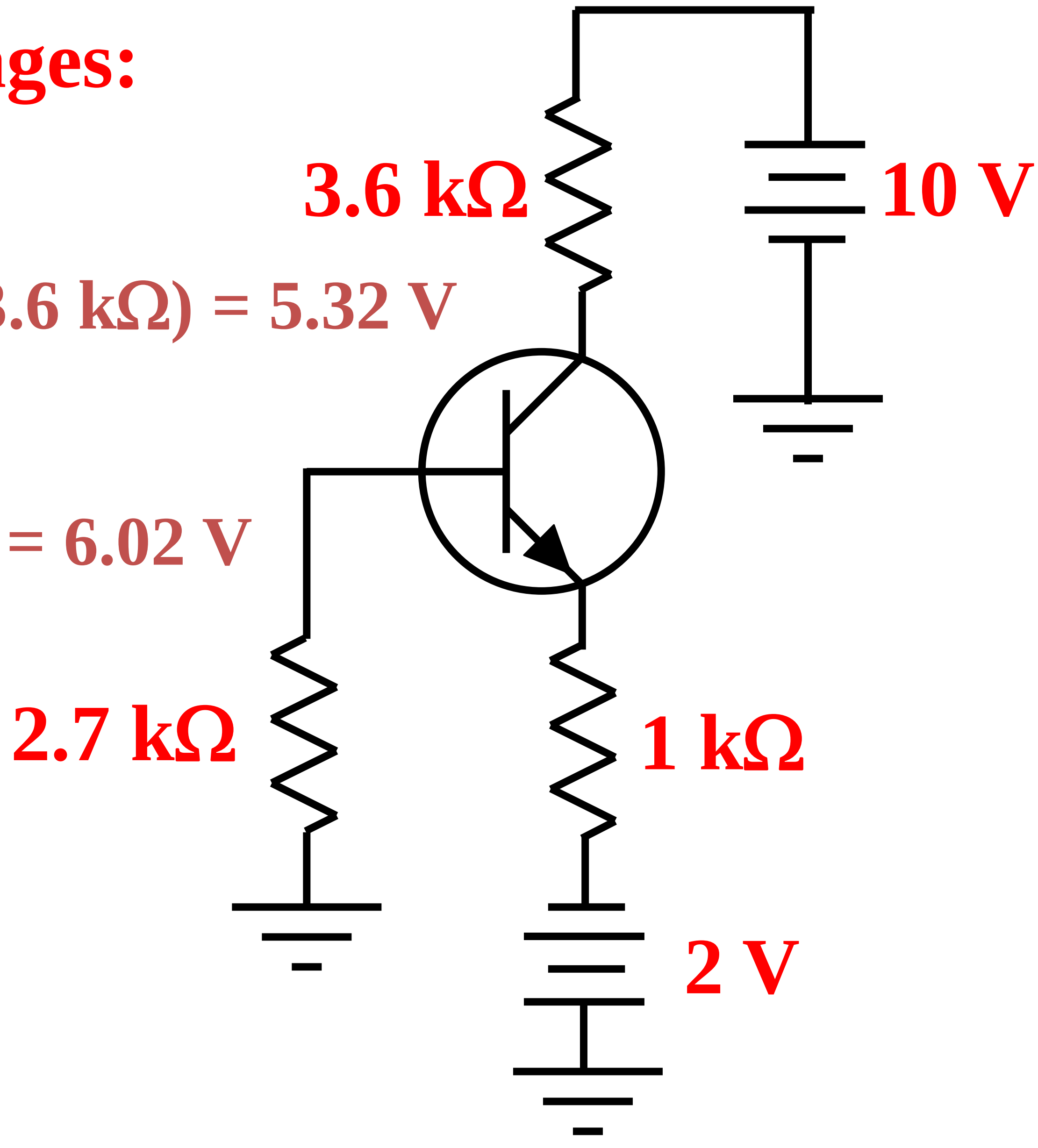


$$I_E = \frac{2\ \text{V} - 0.7\ \text{V}}{1\ \text{k}\Omega} = 1.3\ \text{mA}$$

Find the voltages:

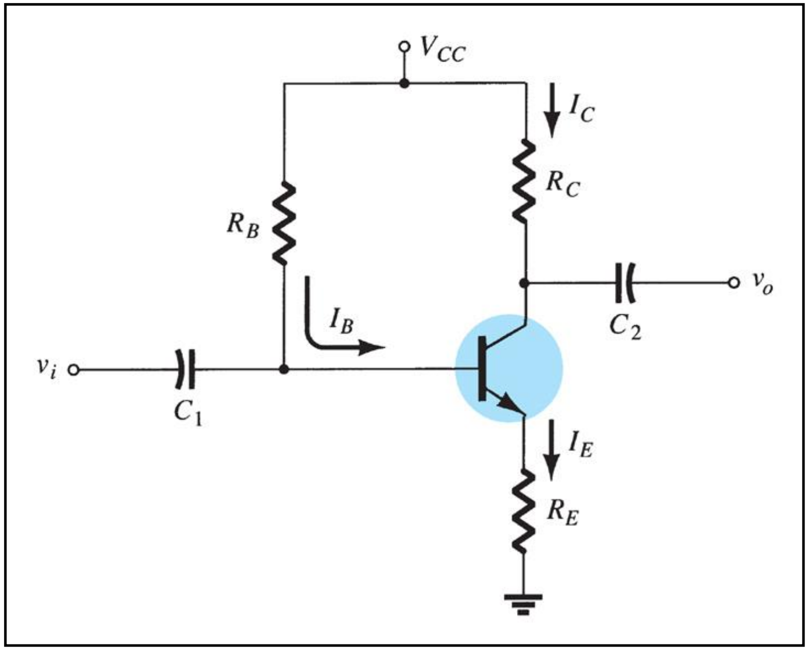
V_C = 10 V - (1.3 mA)(3.6 kΩ) = 5.32 V

V_{CE} = 5.32 V - (-0.7 V) = 6.02 V



Other Biasing Techniques

Emitter-feedback bias or Emitter-Stabilized Bias Circuit



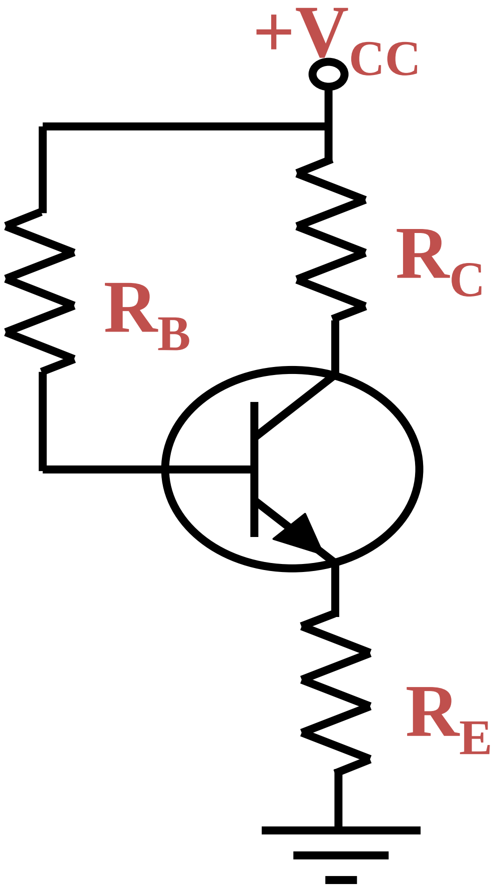
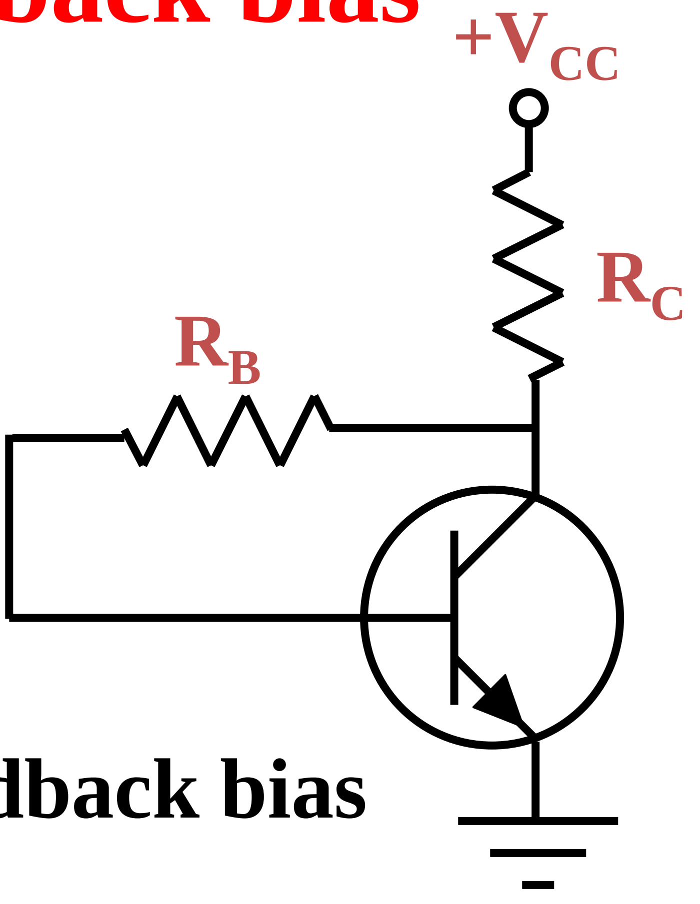


Figure: DC Equivalent Circuit

- Adding an emitter resistor to base-bias stabilizes the circuit.
- **Uses Feedback Compensation**
- **Q point still moves**
- **Not popular**

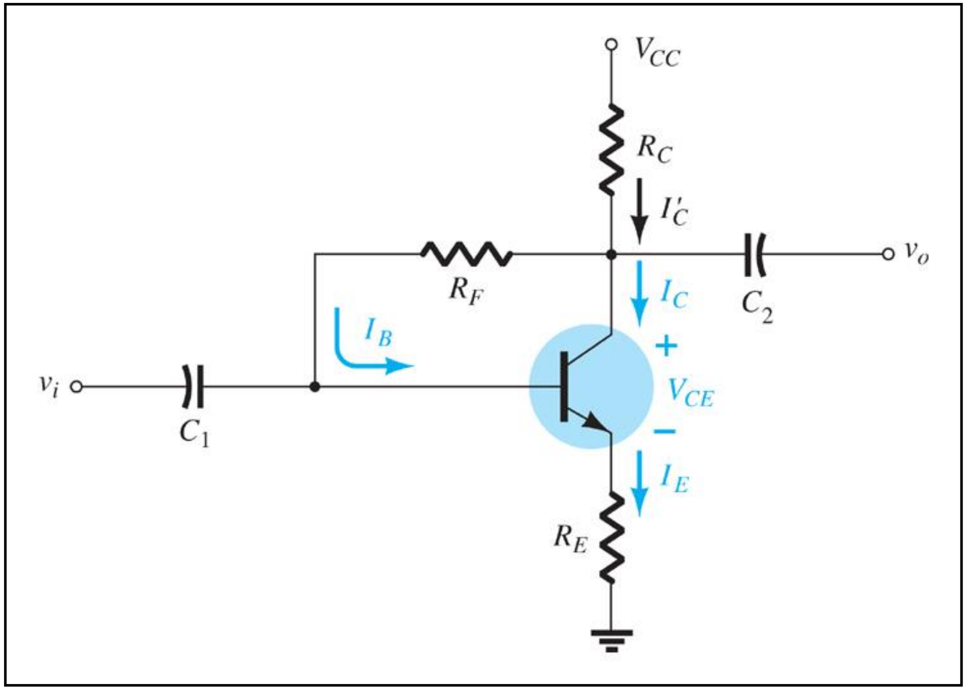
Collector-feedback bias

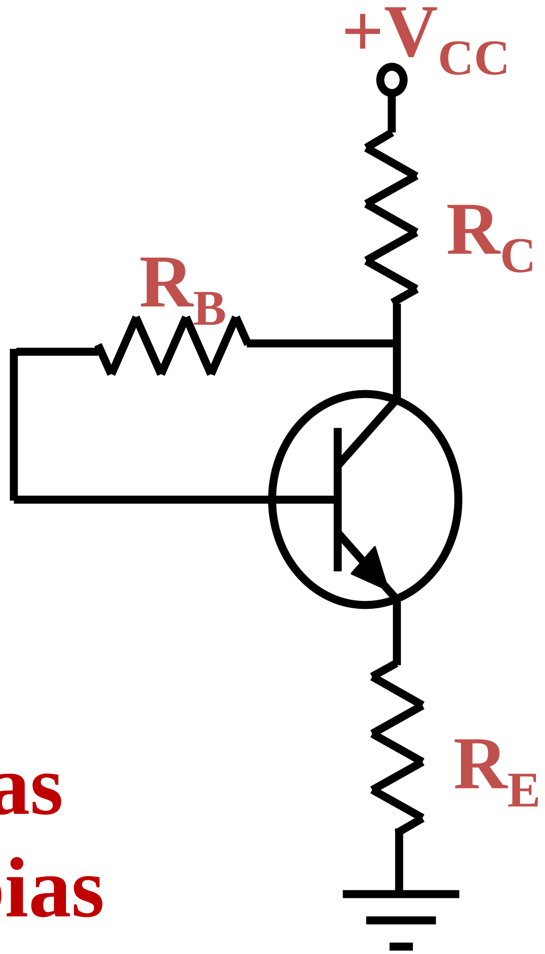


- Better than emitter-feedback bias
- Q point still moves
- Some applications because of circuit simplicity

Collector- and emitter-feedback bias:

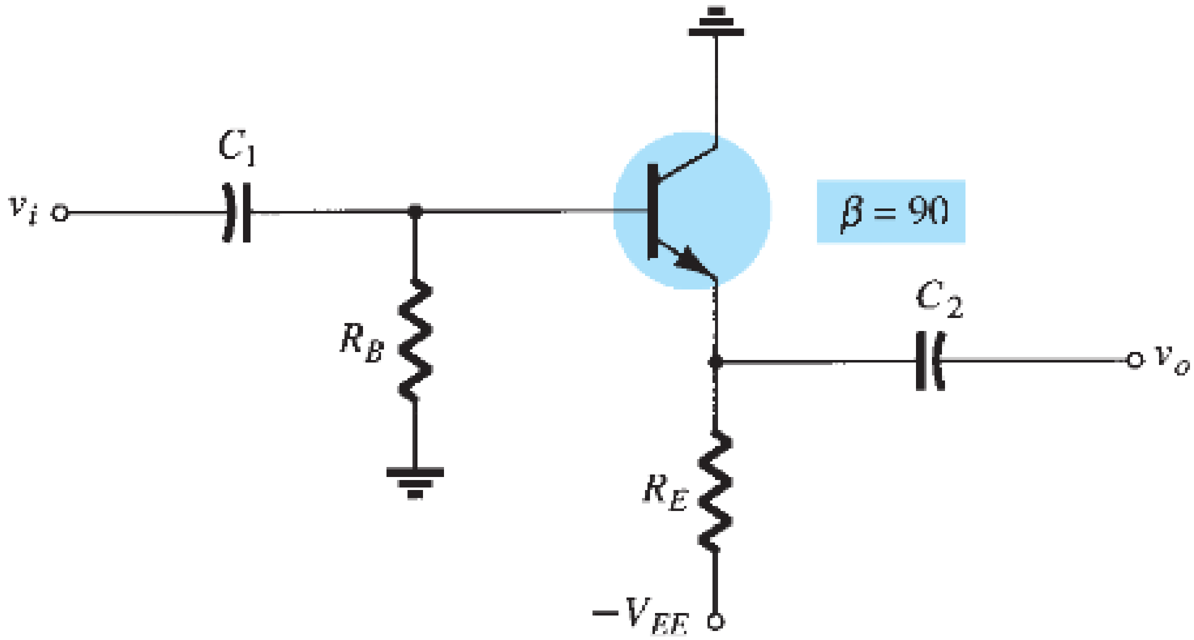
Our text calls it DC Bias With Voltage Feedback





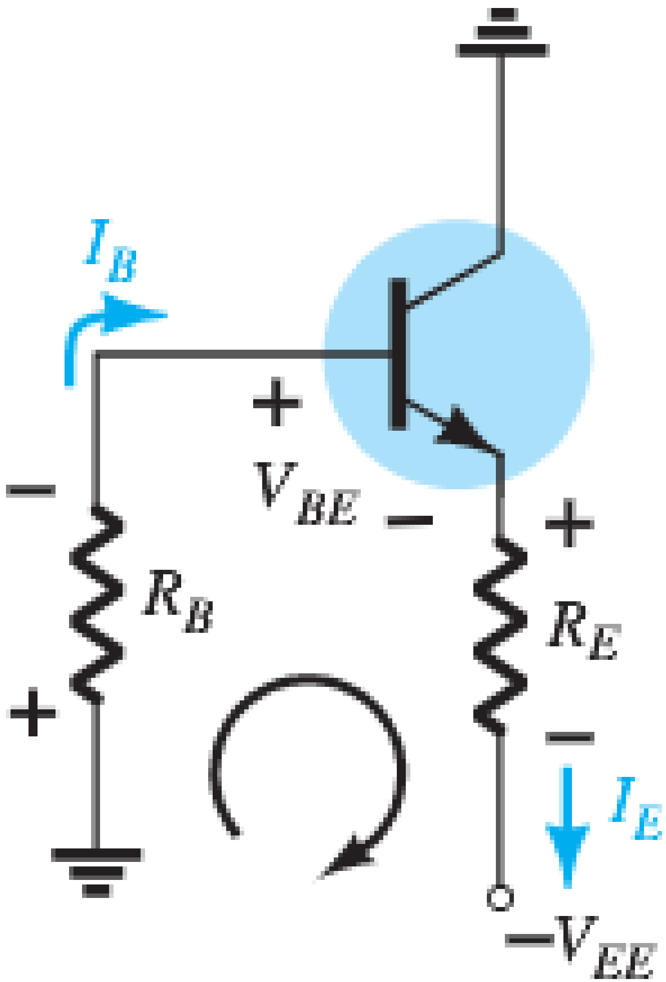
- **Better than emitter-feedback bias**
- **Not as good as voltage-divider bias**
- **Limited application**

EMITTER-FOLLOWER CONFIGURATION



- The output is taken off the emitter terminal
  - In fact, any of the bias configurations can be used so long as there is a resistor in the emitter leg.

EMITTER-FOLLOWER DC ANALYSIS



$$-I_BR_B - V_{BE} - I_ER_E + V_{EE} = 0$$

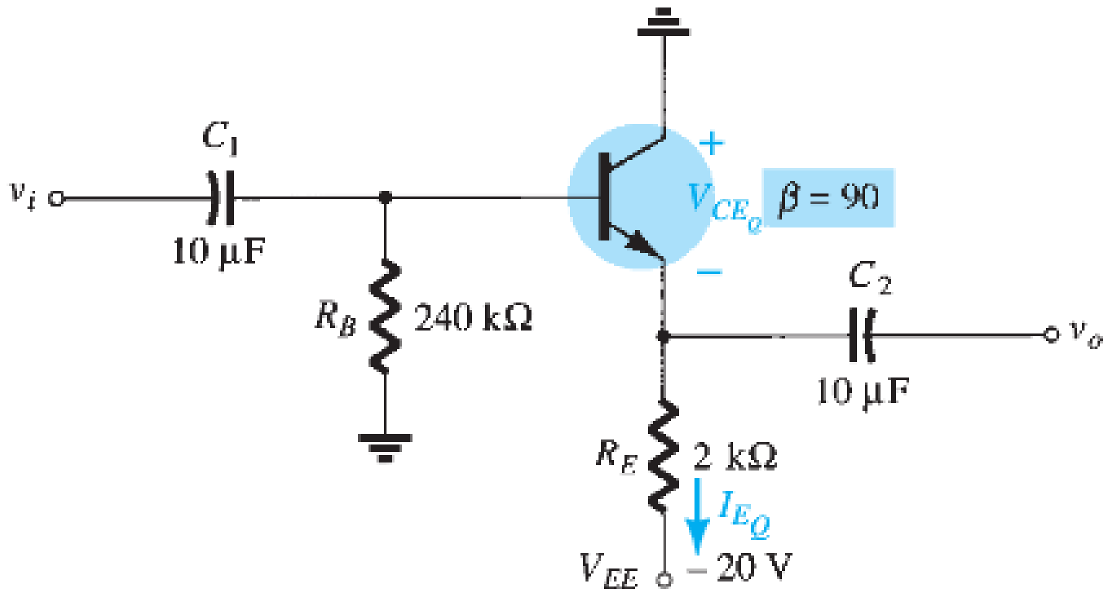
$$I_E = (\beta + 1)I_B$$

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

$$-V_{CE} - I_ER_E + V_{EE} = 0$$

$$\boxed{V_{CE} = V_{EE} - I_ER_E}$$

EXAMPLE 4.16 Determine V_{CE_Q} and I_{E_Q} for the network of Fig. 4.48.



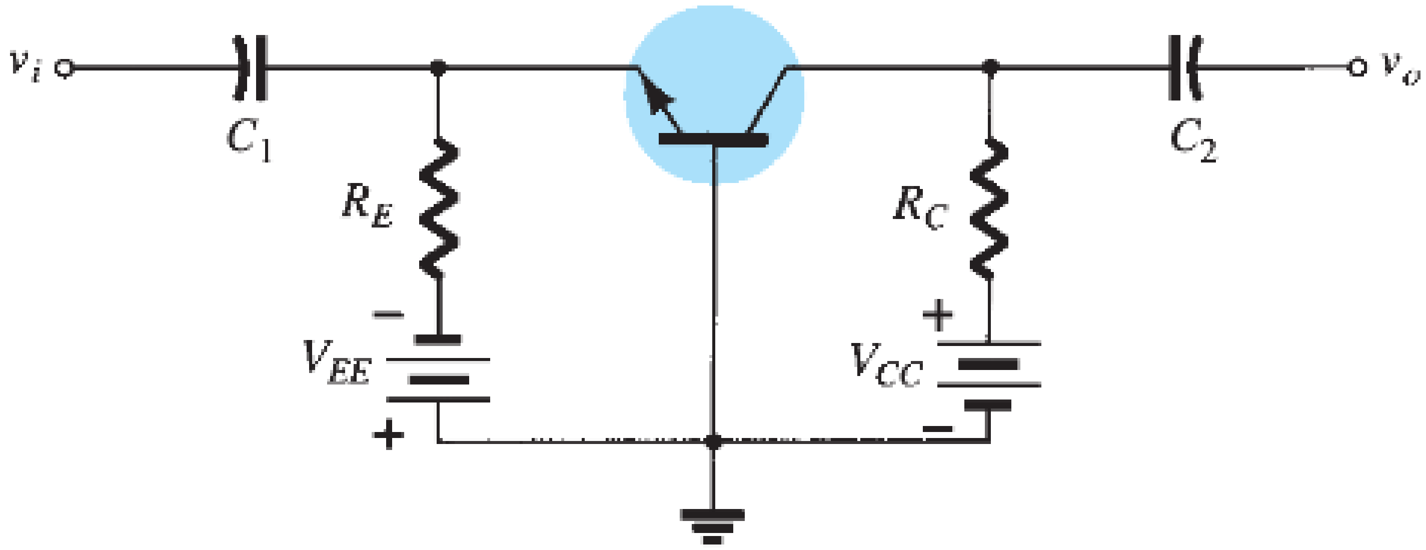
$$I_B = \frac{V_{EE} - V_{BE}}{R_B + (\beta + 1)R_E}$$

$$= \frac{20\text{ V} - 0.7\text{ V}}{240\text{ k}\Omega + (90 + 1)2\text{ k}\Omega} = \frac{19.3\text{ V}}{240\text{ k}\Omega + 182\text{ k}\Omega}$$

$$= \frac{19.3\text{ V}}{422\text{ k}\Omega} = 45.73\ \mu\text{A}$$

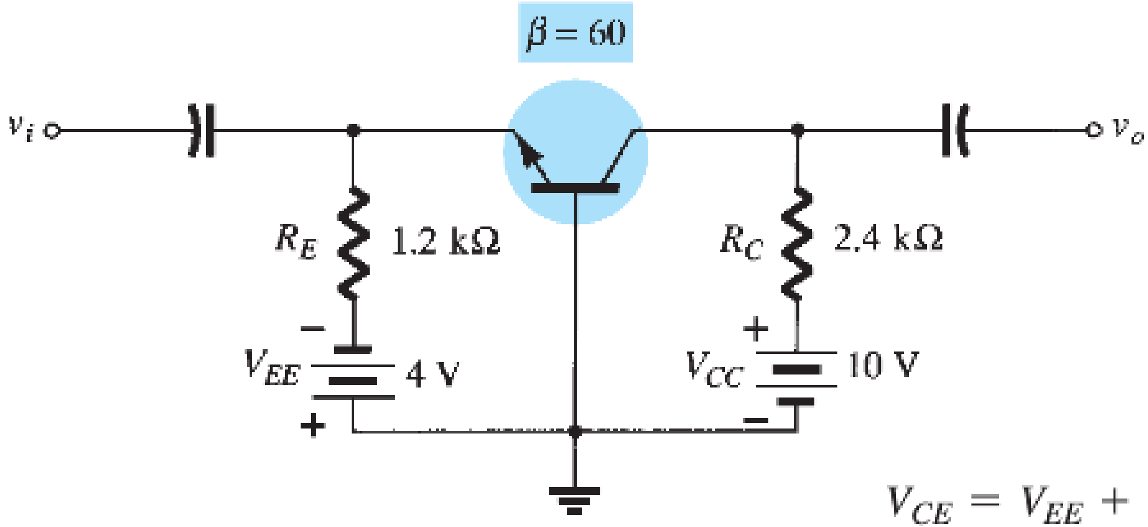
$$V_{CE_Q} = V_{EE} - I_E R_E$$
$$= V_{EE} - (\beta + 1)I_B R_E$$
$$= 20\text{ V} - (90 + 1)(45.73\ \mu\text{A})(2\text{ k}\Omega)$$
$$= 20\text{ V} - 8.32\text{ V}$$
$$= \mathbf{11.68\ V}$$
$$I_{E_Q} = (\beta + 1)I_B = (91)(45.73\ \mu\text{A})$$
$$= 4.16\text{ mA}$$

COMMON-BASE CONFIGURATION



- The input signal is applied at the emitter terminal
- The base is at ground potential.
- It is a fairly popular configuration because in the ac domain it has a very low input impedance, high output impedance, and good gain.

EXAMPLE 4.17 Determine the currents I_E and I_B and the voltages V_{CE} and V_{CB} for the common-base configuration of Fig. 4.52.



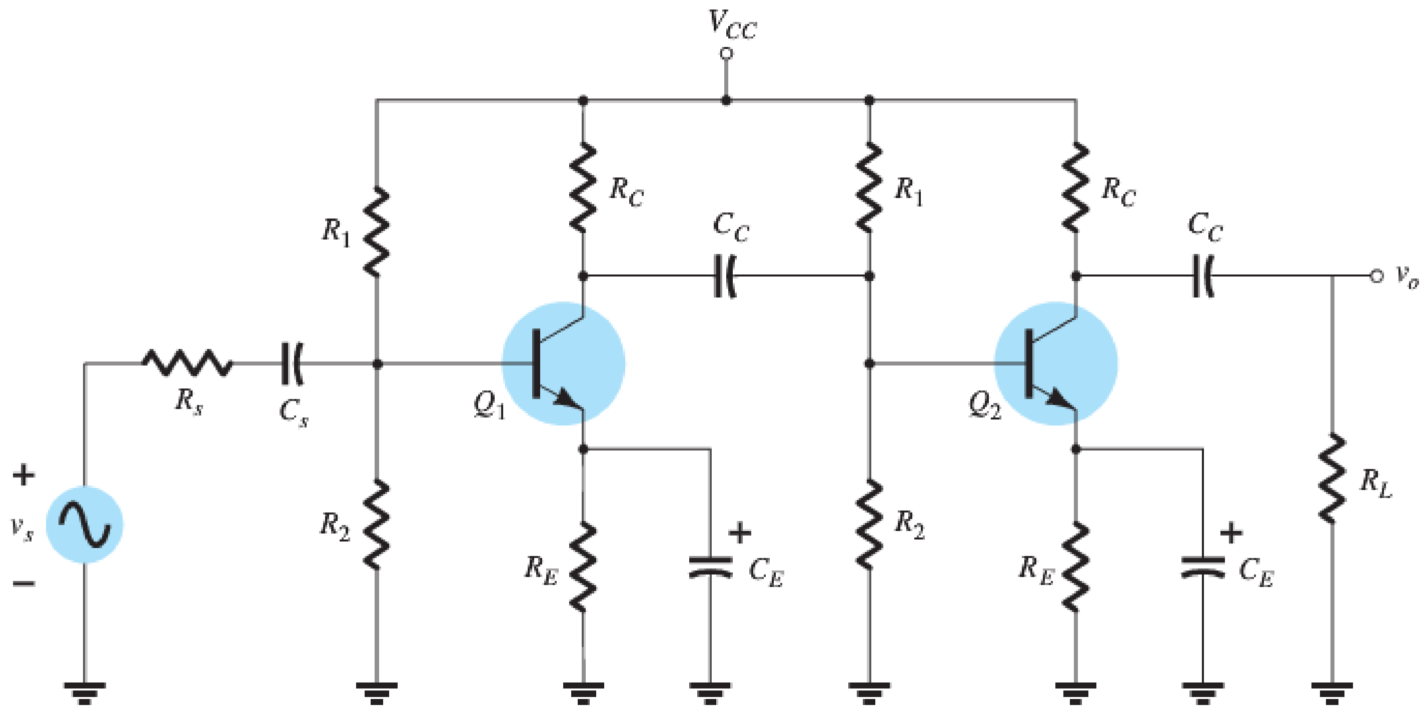
$$I_E = \frac{V_{EE} - V_{BE}}{R_E} = \frac{4\text{ V} - 0.7\text{ V}}{1.2\text{ k}\Omega} = \mathbf{2.75\text{ mA}}$$

$$I_B = \frac{I_E}{\beta + 1} = \frac{2.75\text{ mA}}{60 + 1} = \frac{2.75\text{ mA}}{61} = \mathbf{45.08\ \mu A}$$

$$\begin{aligned} V_{CE} &= V_{EE} + V_{CC} - I_E(R_C + R_E) \\ &= 4\text{ V} + 10\text{ V} - (2.75\text{ mA})(2.4\text{ k}\Omega + 1.2\text{ k}\Omega) \\ &= 14\text{ V} - (2.75\text{ mA})(3.6\text{ k}\Omega) \\ &= 14\text{ V} - 9.9\text{ V} \\ &= \mathbf{4.1\text{ V}} \end{aligned}$$

$$\begin{aligned} V_{CB} &= V_{CC} - I_C R_C = V_{CC} - \beta I_B R_C \\ &= 10\text{ V} - (60)(45.08\ \mu\text{A})(24\text{ k}\Omega) \\ &= 10\text{ V} - 6.49\text{ V} \\ &= \mathbf{3.51\text{ V}} \end{aligned}$$

Multiple BJT Networks:
R-C Coupled BJT Amplifiers



- The R–C coupling is probably the most common.
- The collector output of one stage is fed directly into the base of the next stage using a coupling capacitor C_C
- The capacitor is chosen to ensure that it will block dc between the stages and act like a short circuit to any ac signal.

Multiple BJT Networks:
R-C Coupled BJT Amplifiers

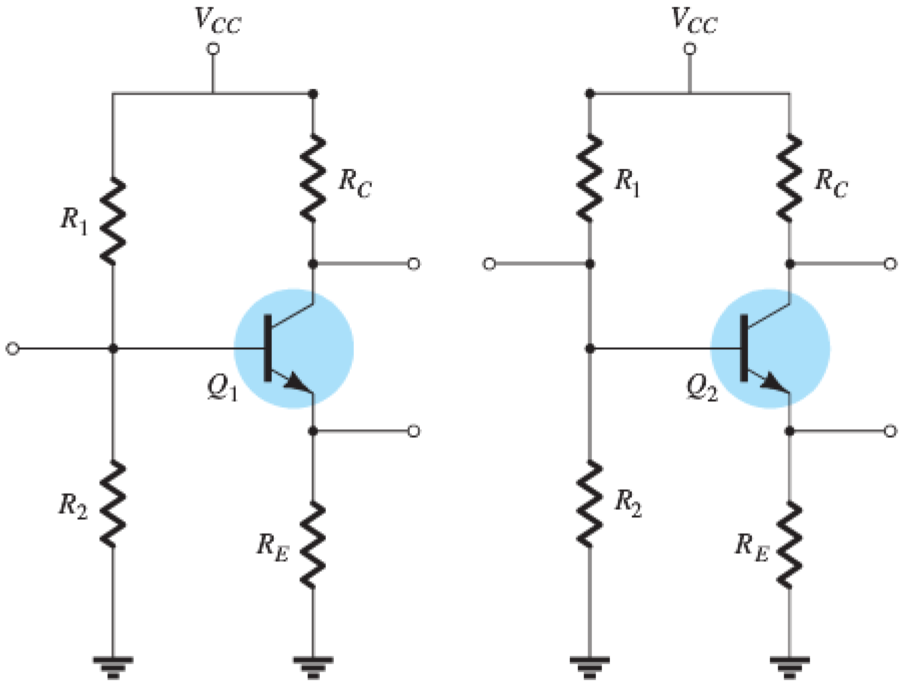


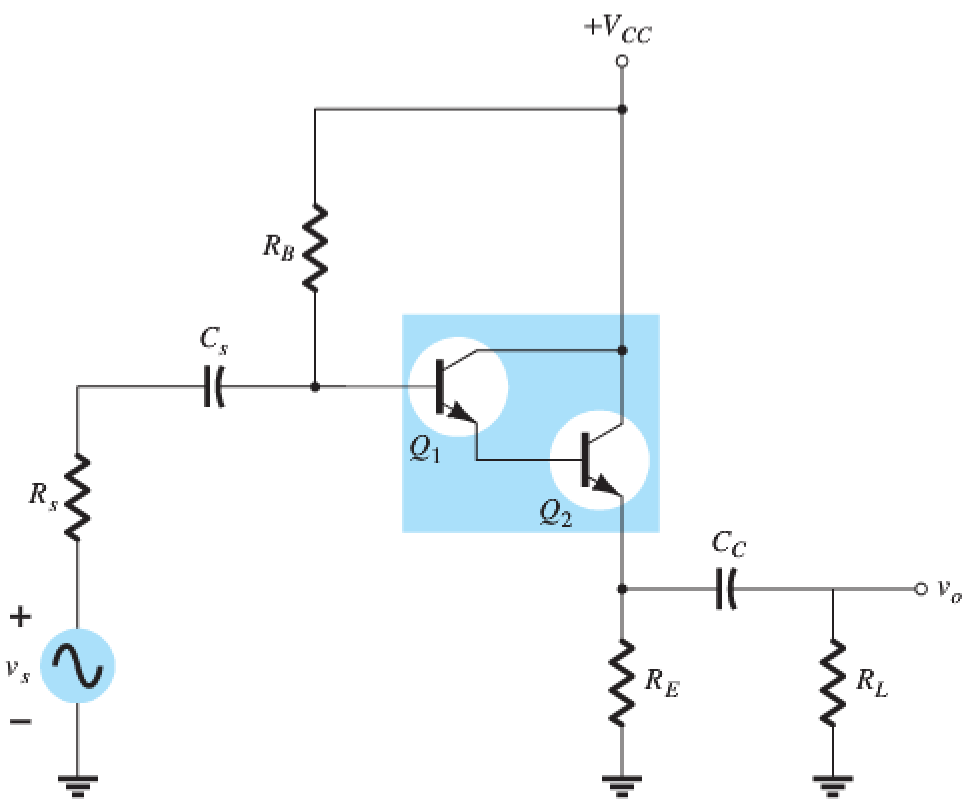
FIG. 4.65
DC equivalent of Fig. 4.64.

- Substituting an open-circuit equivalent for C_C and the other capacitors of the network results in the two bias circuits

Multiple BJT Networks:

The Darlington Configuration

- The output of one stage is directly fed into the input of the succeeding stage.



- **If the output is taken directly off the emitter terminal, the ac gain is very close to 1 but the input impedance is very high**
  - **Attractive for use in amplifiers operating off sources that have a relatively high internal resistance.**
- **If the output taken off the collector terminal, the configuration would provide a very high gain**

The Darlington Configuration

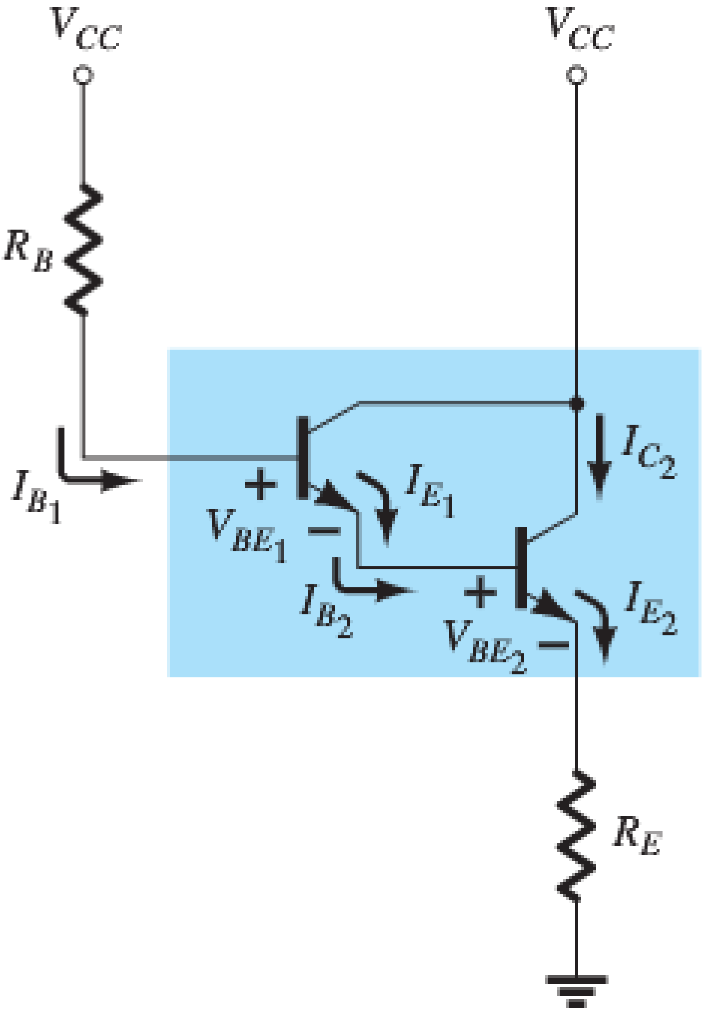


FIG. 4.67
DC equivalent of Fig. 4.66.

$$I_{B_2} = I_{E_1} = (\beta_1 + 1)I_{B_1}$$

$$I_{E_2} = (\beta_2 + 1)I_{B_2} = (\beta_2 + 1)(\beta_1 + 1)I_{B_1}$$

Assuming $\beta \gg 1$ for each transistor,

$$\boxed{\beta_D = \beta_1\beta_2}$$

$$I_{B_1} = \frac{V_{CC} - V_{BE_1} - V_{BE_2}}{R_B + (\beta_D + 1)R_E}$$

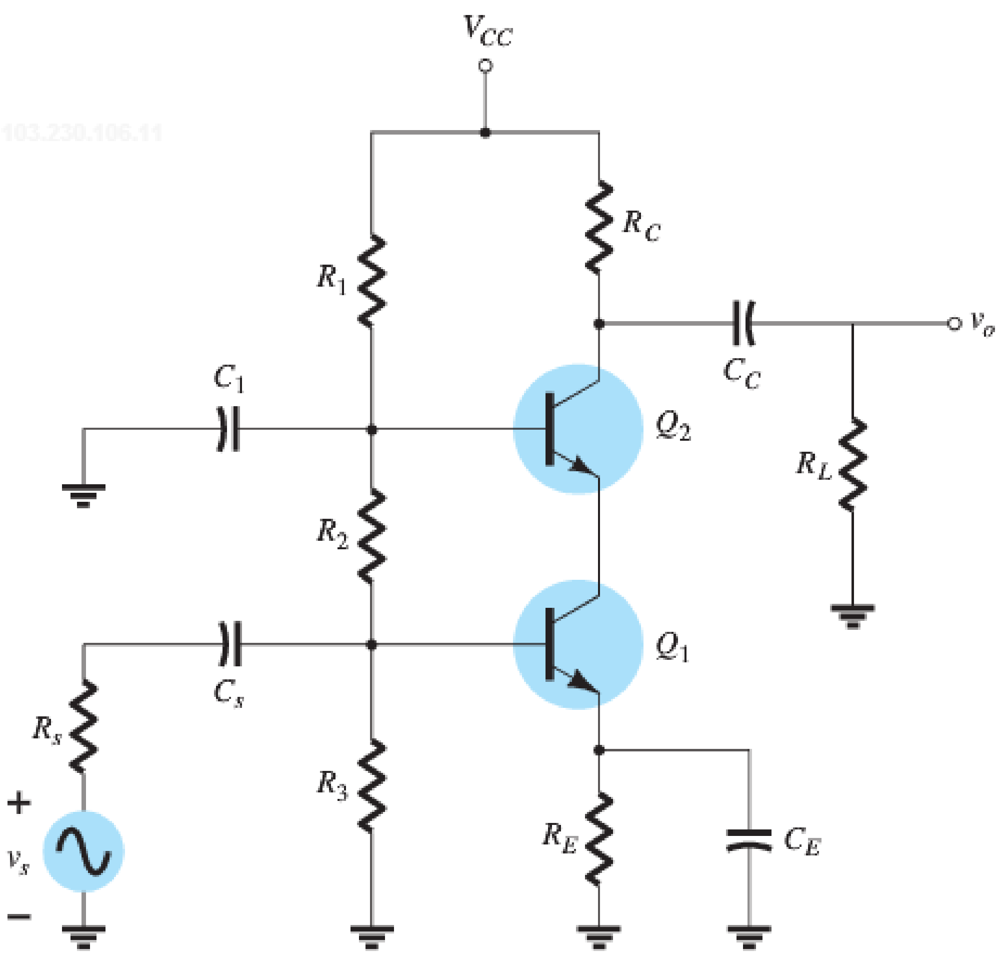
$$\boxed{V_{BE_D} = V_{BE_1} + V_{BE_2}}$$

$$\boxed{I_{B_1} = \frac{V_{CC} - V_{BE_D}}{R_B + (\beta_D + 1)R_E}}$$

$$\boxed{I_{C_2} \cong I_{E_2} = \beta_D I_{B_1}}$$

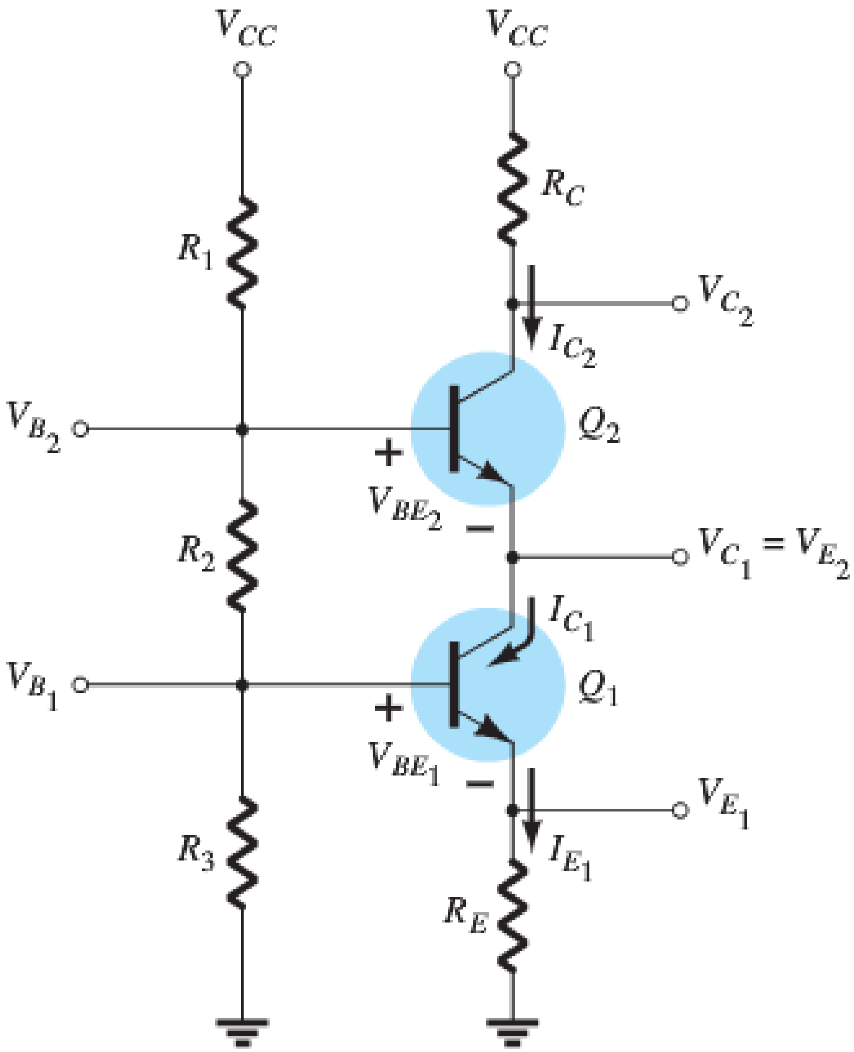
$\boxed{V_{CE_2} = V_{CC} - V_{E_2}}$ where $\boxed{V_{E_2} = I_{E_2}R_E}$

Multiple BJT Networks:
The Cascode Configuration



- It ties the collector of one transistor to the emitter of the other.
- A network with a high gain and a reduced Miller capacitance (to be discussed later)

The Cascode Configuration: DC Analysis



$$I_{R_1} \cong I_{R_2} \cong I_{R_3} \gg I_{B_1} \text{ or } I_{B_2}$$

$$\boxed{V_{B_1} = \frac{R_3}{R_1 + R_2 + R_3} V_{CC}}$$

$$\boxed{V_{B_2} = \frac{(R_2 + R_3)}{R_1 + R_2 + R_3} V_{CC}}$$

$$\boxed{V_{E_1} = V_{B_1} - V_{BE_1}}$$

$$\boxed{V_{E_2} = V_{B_2} - V_{BE_2}}$$

$$\boxed{I_{C_2} \cong I_{E_2} \cong I_{C_1} \cong I_{E_1} = \frac{V_{B_1} - V_{BE_1}}{R_E}}$$

$$\boxed{V_{C_1} = V_{B_2} - V_{BE_2}}$$

$$\boxed{V_{C_2} = V_{CC} - I_{C_2} R_C}$$

$$\boxed{I_{R_1} \cong I_{R_2} \cong I_{R_3} = \frac{V_{CC}}{R_1 + R_2 + R_3}}$$

$$\boxed{I_{B_1} = \frac{I_{C_1}}{\beta_1}}$$

$$\boxed{I_{B_2} = \frac{I_{C_2}}{\beta_2}}$$

CURRENT MIRRORS

- A dc network in which the current through a load is controlled by a current at another point in the network

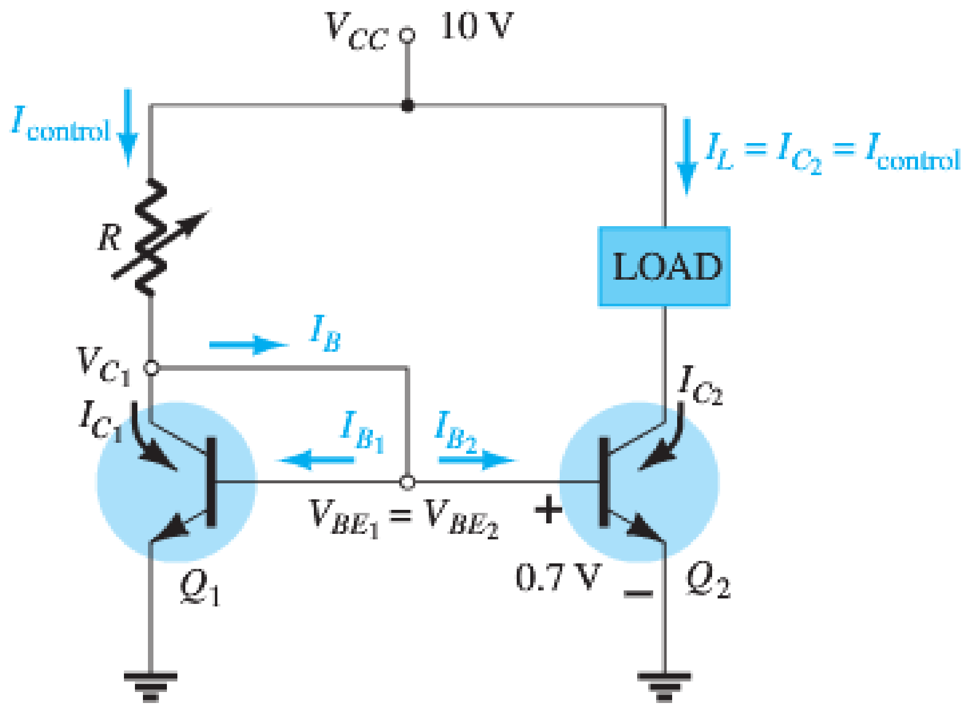


FIG. 4.74

Current mirror using back-to-back BJTs.

CURRENT MIRRORS

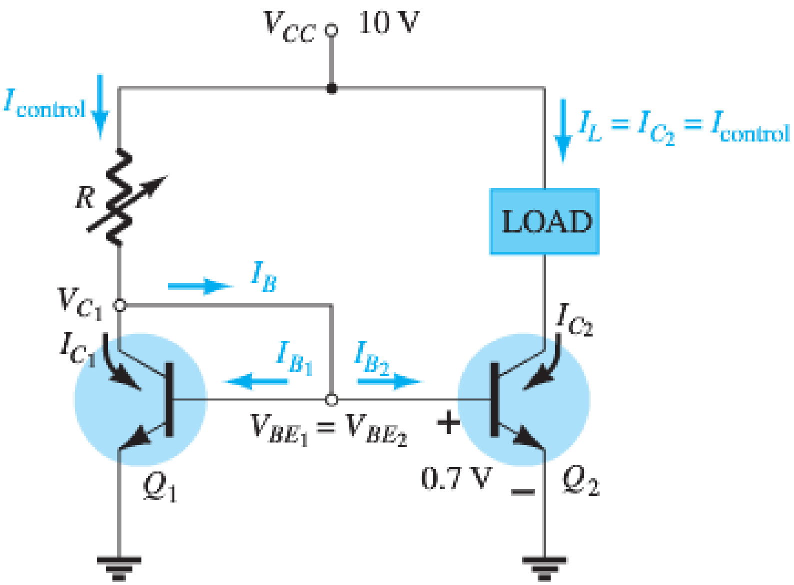


FIG. 4.74

Current mirror using back-to-back BJTs.

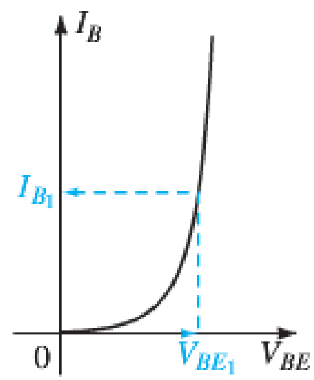


FIG. 4.75

Base characteristics

Assume identical transistors will result in $V_{BE_1} = V_{BE_2}$ and $I_{B_1} = I_{B_2}$

$$I_B = I_{B_1} + I_{B_2}$$
$$I_{B_1} = I_{B_2}$$
$$I_B = I_{B_1} + I_{B_1} = 2I_{B_1}$$

$$I_{\text{control}} = I_{C_1} + I_B = I_{C_1} + 2I_{B_1}$$
$$I_{C_1} = \beta_1 I_{B_1}$$
$$I_{\text{control}} = \beta_1 I_{B_1} + 2I_{B_1} = (\beta_1 + 2)I_{B_1}$$
$$I_{\text{control}} \cong \beta_1 I_{B_1}$$

$$\boxed{I_{B_1} = \frac{I_{\text{control}}}{\beta_1}}$$

$$\boxed{I_{\text{control}} = \frac{V_{CC} - V_{BE}}{R}}$$

The resistor R can be used to set the control current

$$\underbrace{I_L \uparrow I_{C_2} \uparrow I_{B_2} \uparrow V_{BE_2} \uparrow V_{CE_1} \uparrow, I_R \downarrow, I_B \downarrow, I_{B_2} \downarrow I_{C_2} \downarrow I_L \downarrow}_{\textit{Note}}$$

EXAMPLE 4.27 Calculate the mirrored current I in the circuit of Fig. 4.76.

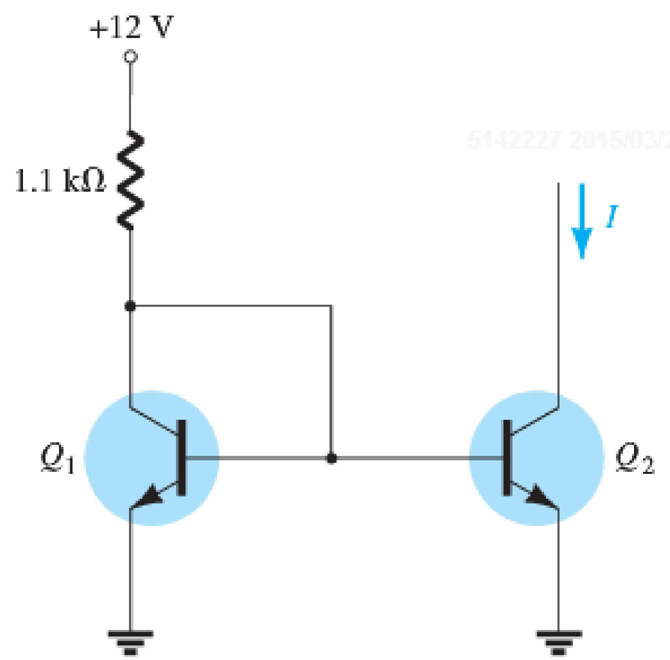


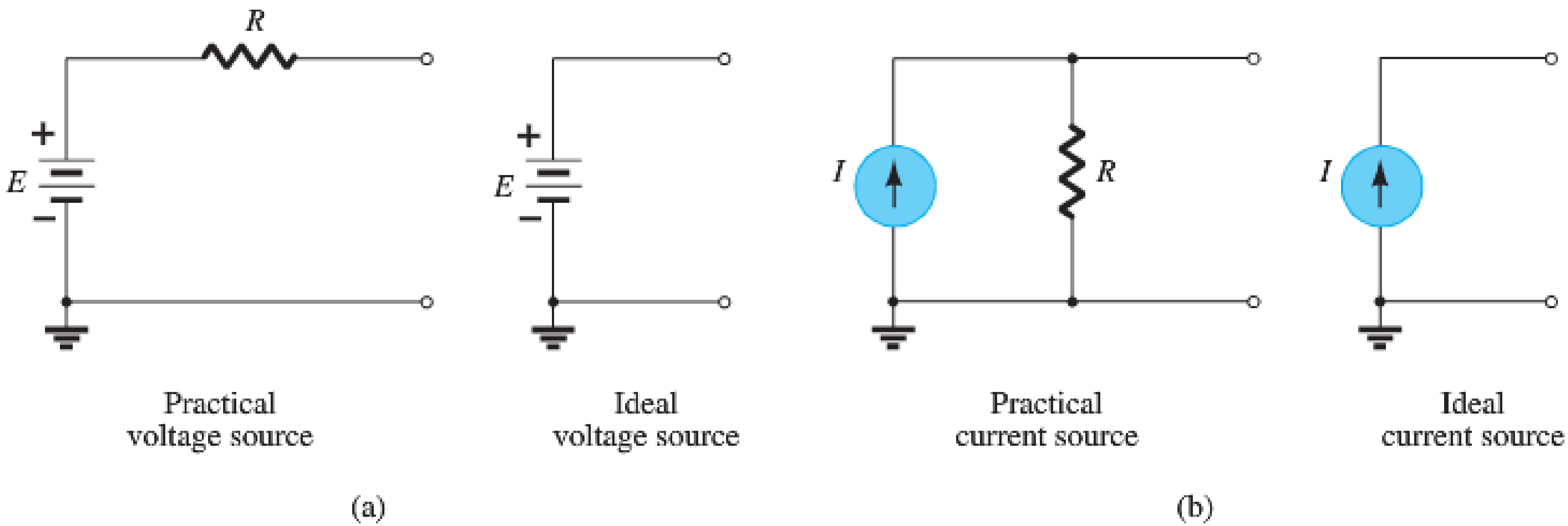
FIG. 4.76

Current mirror circuit for Example 4.27.

Solution: Eq. (4.75):

$$I = I_{\text{control}} = \frac{V_{CC} - V_{BE}}{R} = \frac{12\text{ V} - 0.7\text{ V}}{1.1\text{ k}\Omega} = \mathbf{10.27\text{ mA}}$$

CURRENT SOURCE CIRCUITS



- An ideal current source provides a constant current regardless of the load connected to it.
- Constant-current circuits can be built using bipolar devices, FET devices, and a combination of these components.

Bipolar Transistor Constant-Current Source

- Bipolar transistors can be connected in a number of ways to form constant-current sources

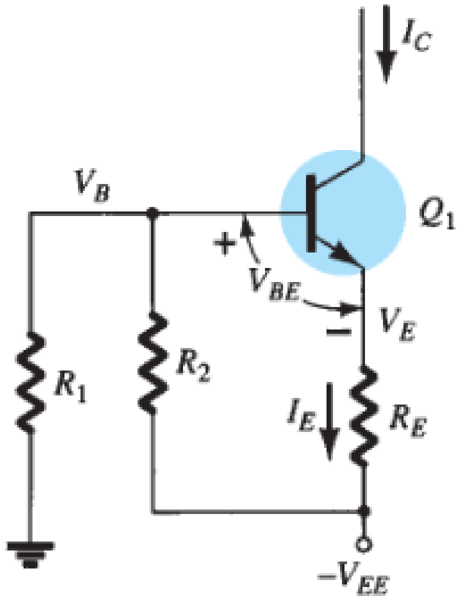


FIG. 4.81
Discrete constant-current source.

$$V_B = \frac{R_1}{R_1 + R_2}(-V_{EE})$$

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

$$I_E = \frac{V_E - (-V_{EE})}{R_E} \approx I_C$$

- I_C is the constant current provided by the circuit.

EXAMPLE 4.29 Calculate the constant current I in the circuit of Fig. 4.82.

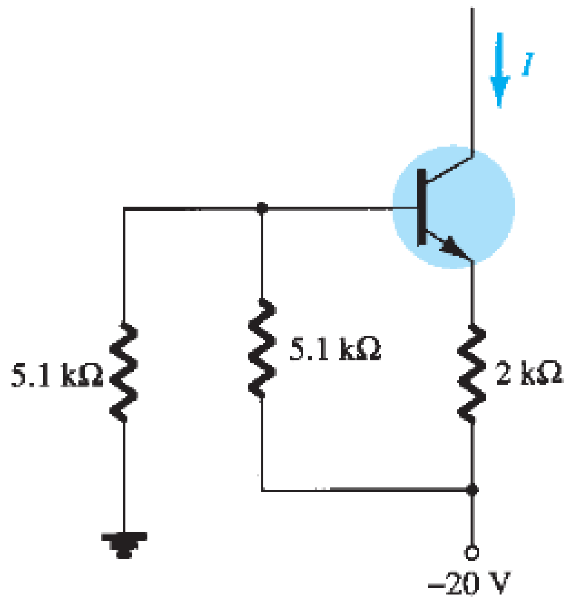


FIG. 4.82

Constant-current source for Example 4.29.

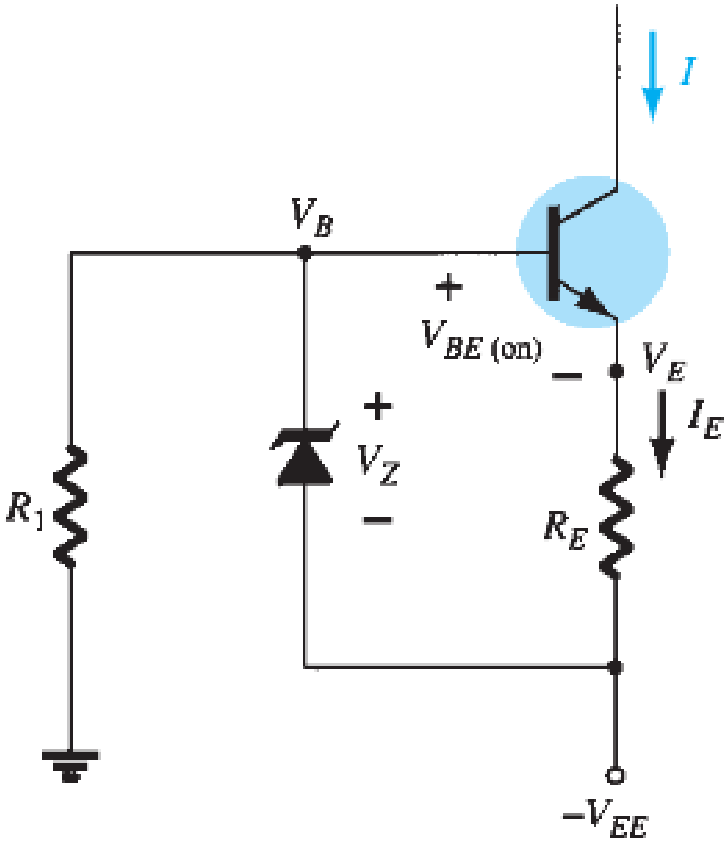
$$V_B = \frac{R_1}{R_1 + R_2}(-V_{EE}) = \frac{5.1\text{ k}\Omega}{5.1\text{ k}\Omega + 5.1\text{ k}\Omega}(-20\text{ V}) = -10\text{ V}$$

$$V_E = V_B - 0.7\text{ V} = 10\text{ V} - 0.7\text{ V} = -10.7\text{ V}$$

$$I = I_E = \frac{V_E - (-V_{EE})}{R_E} = \frac{-10.7\text{ V} - (-20\text{ V})}{2\text{ k}\Omega}$$

$$= \frac{9.3\text{ V}}{2\text{ k}\Omega} = \mathbf{4.65\text{ mA}}$$

Transistor/Zener Constant-Current Source



$$I \approx I_E = \frac{V_Z - V_{BE}}{R_E}$$

- Provides an improved constant-current source
- The constant current depends on the Zener diode voltage and the emitter resistor R_E
- The voltage supply V_{EE} has no effect on the value of I.

EXAMPLE 4.30 Calculate the constant current I in the circuit of Fig. 4.84.

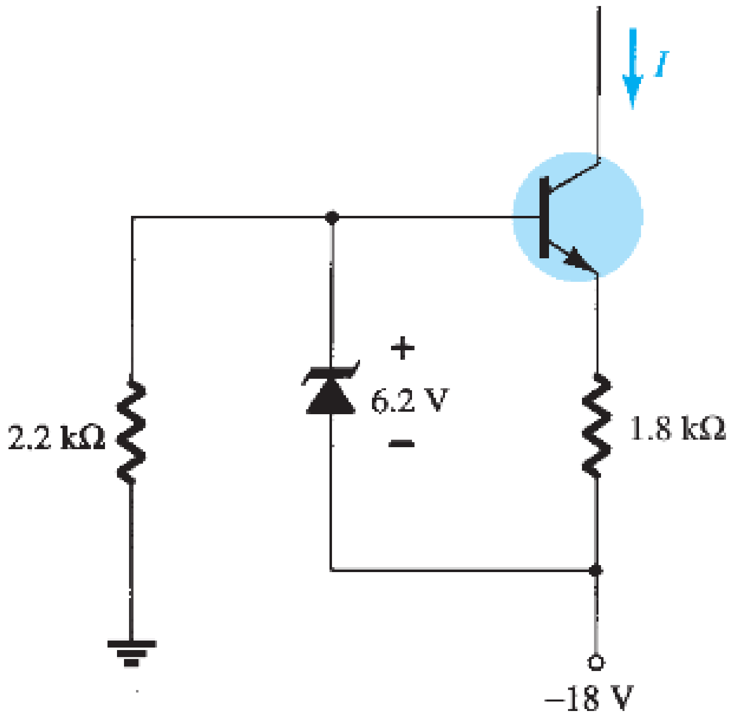
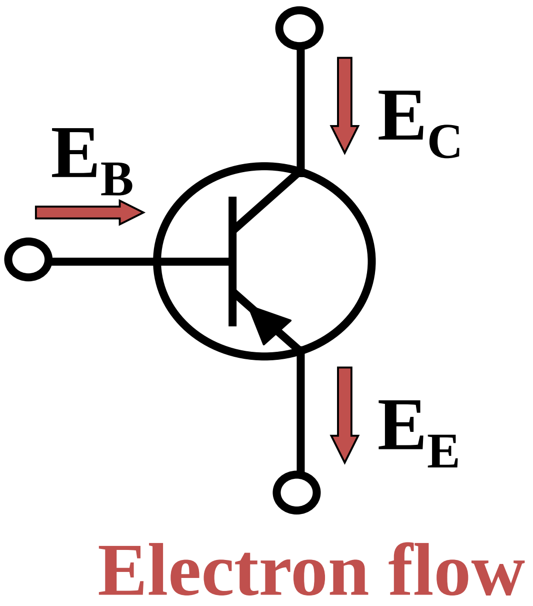


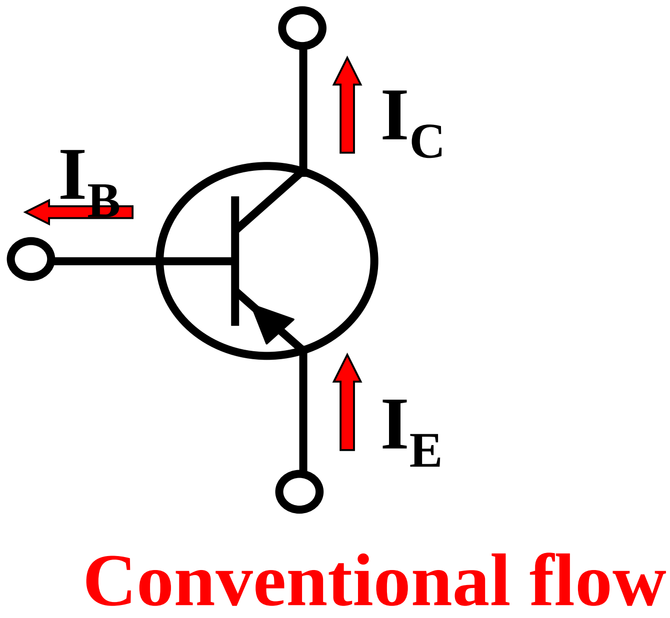
FIG. 4.84
Constant-current circuit for Example 4.30.

Solution:

$$\text{Eq. (4.83):} \quad I = \frac{V_Z - V_{BE}}{R_E} = \frac{6.2\text{ V} - 0.7\text{ V}}{1.8\text{ k}\Omega} = 3.06\text{ mA} \cong \mathbf{3\text{ mA}}$$

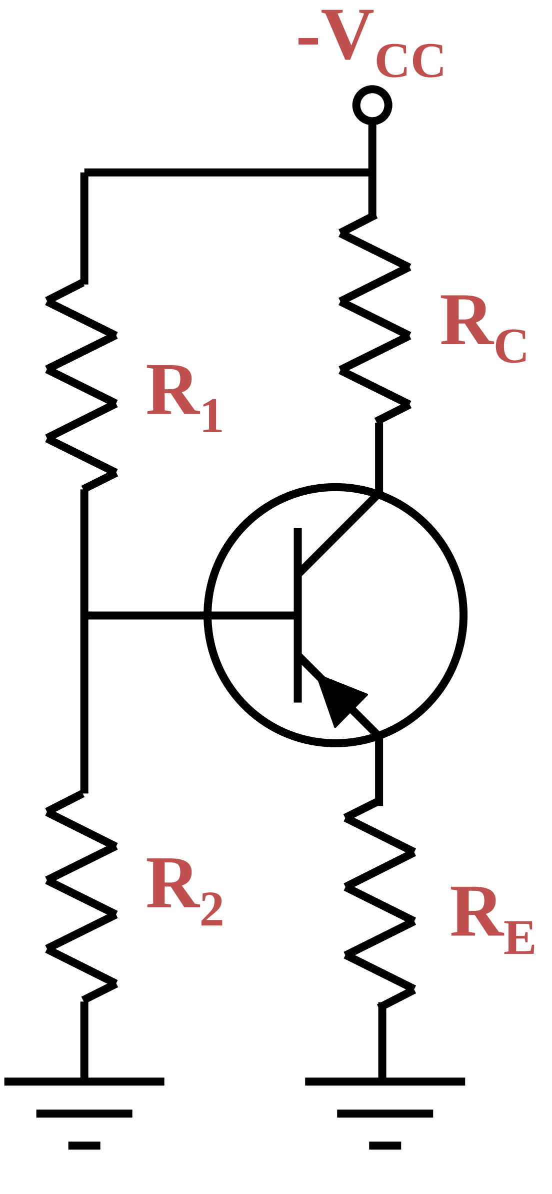
Biasing PNP Transistors



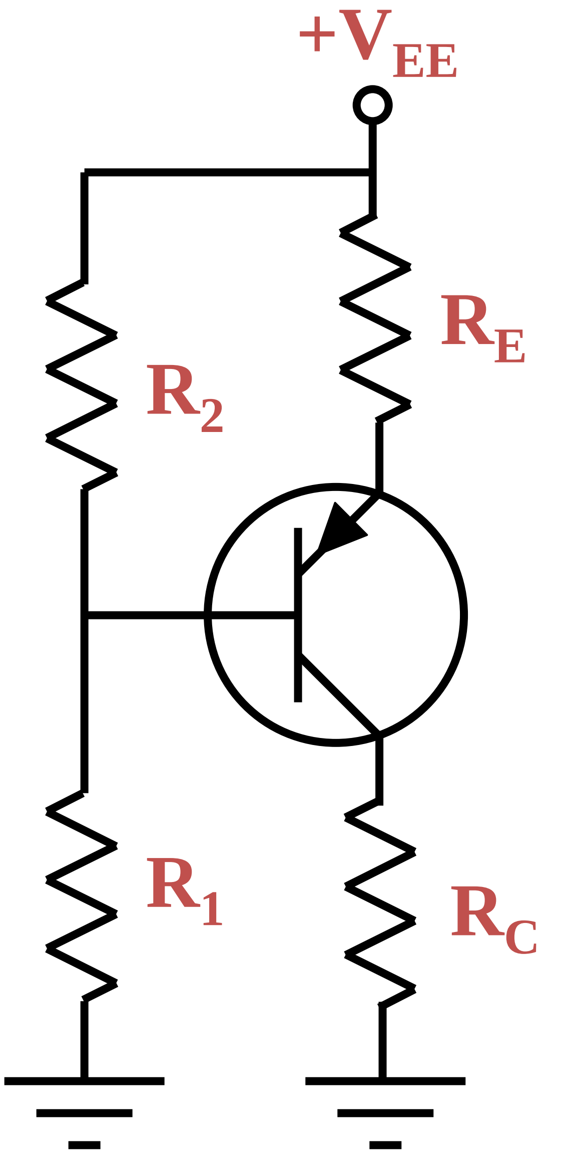


- The analysis for *pnp* transistor biasing circuits is the same as that for *npn* transistor circuits.
  - The only difference is that the currents are flowing in the opposite direction.

PNP Biasing with a negative supply



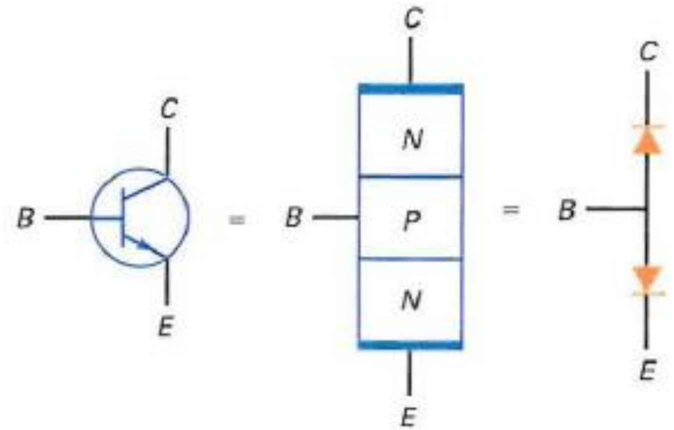
PNP Biasing with a positive supply



Troubleshooting a transistor

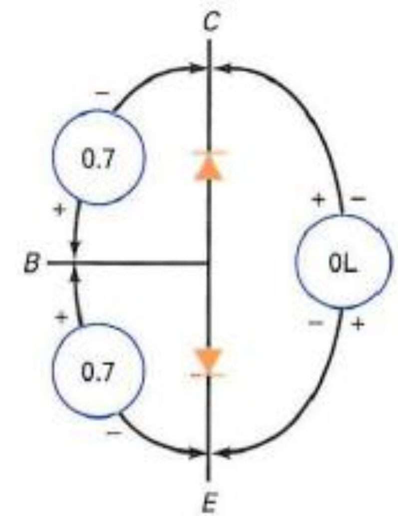
- **Ohmmeter resistance tests**
- **DMM resistance or h_{FE} function tests**
- **In-circuit voltage measurements**

Troubleshooting: Out-of- Circuit Tests

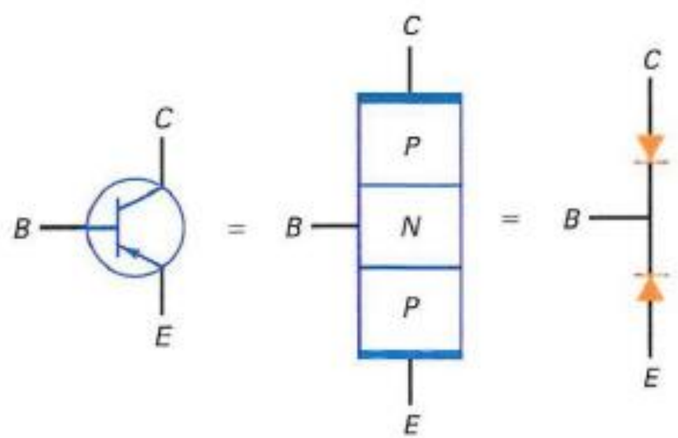


+	−	Reading
B	E	0.7
E	B	0L
B	C	0.7
C	B	0L
C	E	0L
E	C	0L

(a)

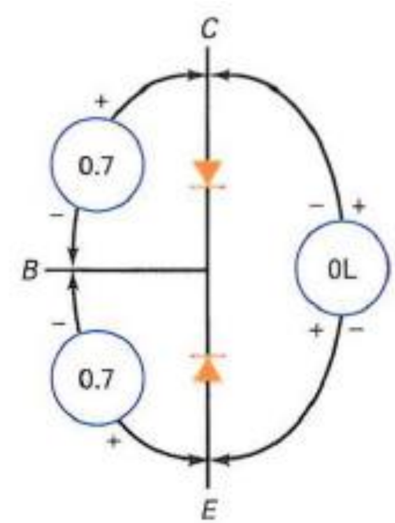


(b)



+	−	Readings
B	E	0L
E	B	0.7
B	C	0L
C	B	0.7
C	E	0L
E	C	0L

(a)



(b)

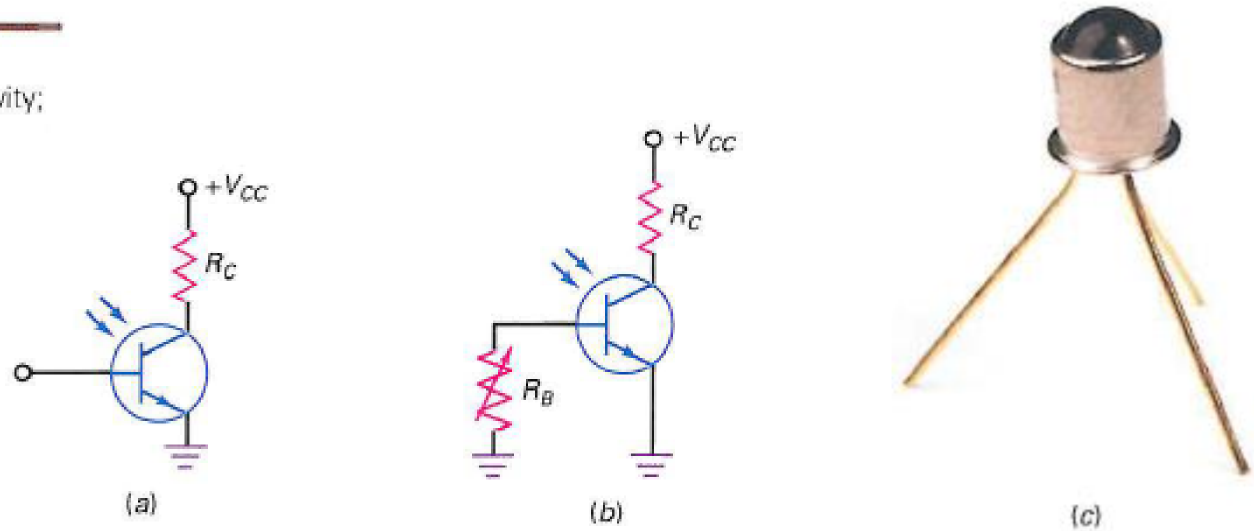
In- Circuit Test: Transistor curve tracer

Figure 7-19 Transistor curve tracer test courtesy of Tektronix.

More Optoelectronic devices

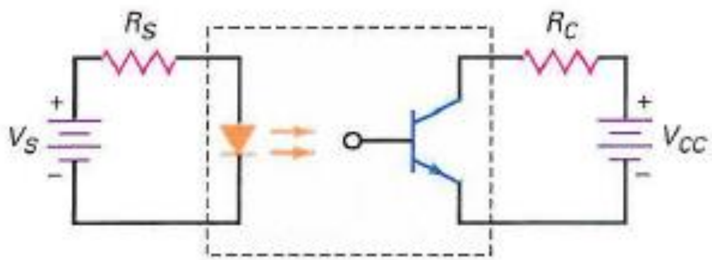
- A **phototransistor** has current gain and is more sensitive than a photodiode
- Combined with an LED, a phototransistor provides a more sensitive **optocoupler**

Figure 7-22 Phototransistor.
(*a*) Open base gives maximum sensitivity; (*b*) variable base resistor changes sensitivity; (*c*) typical phototransistor.

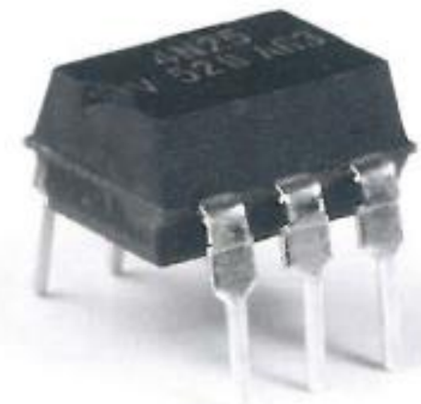


Optocoupler with LED and phototransistor

Figure 7-23 (*a*) Optocoupler with LED and phototransistor; (*b*) optocoupler *IC*.

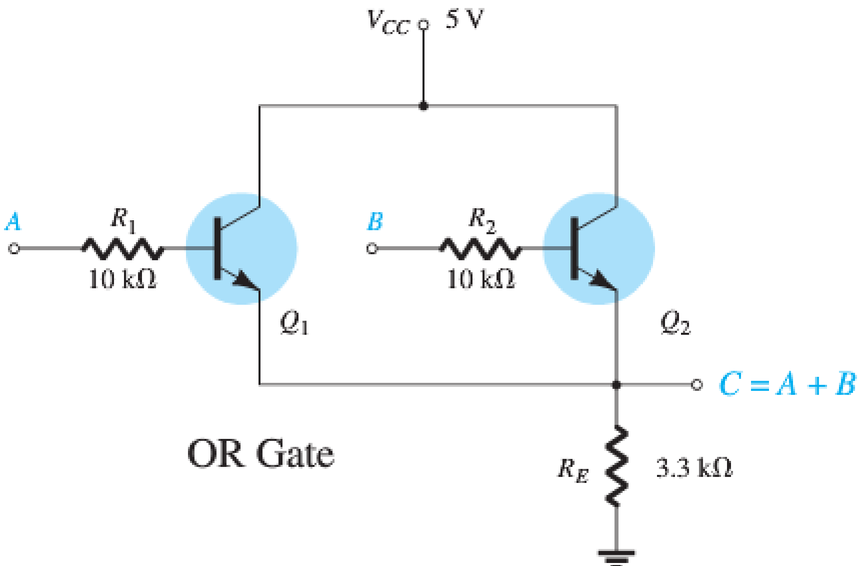


(*a*)



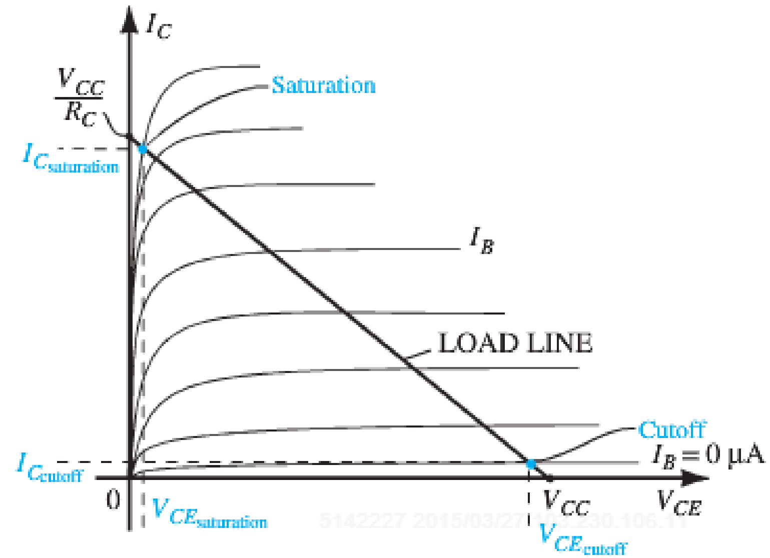
(*b*)

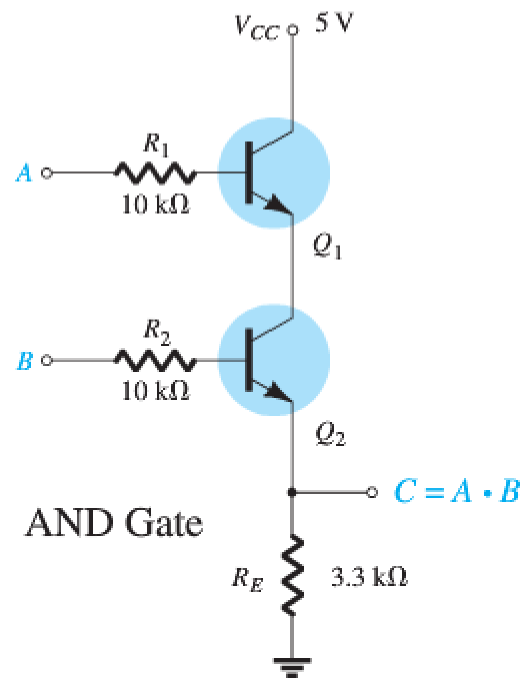
Logic Gates



A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

1 = high
0 = low





A	B	C
0	0	0
0	1	0
1	0	0
1	1	1