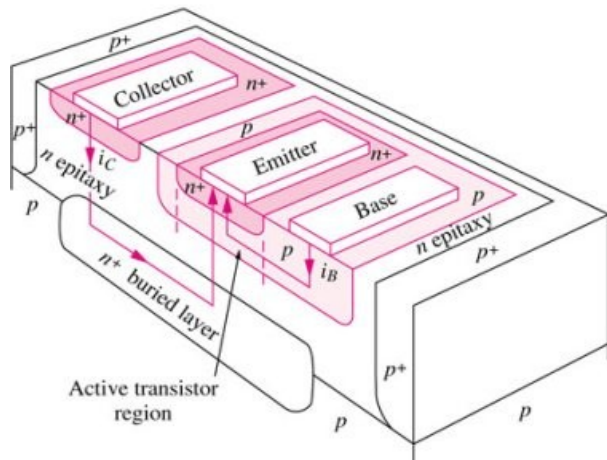
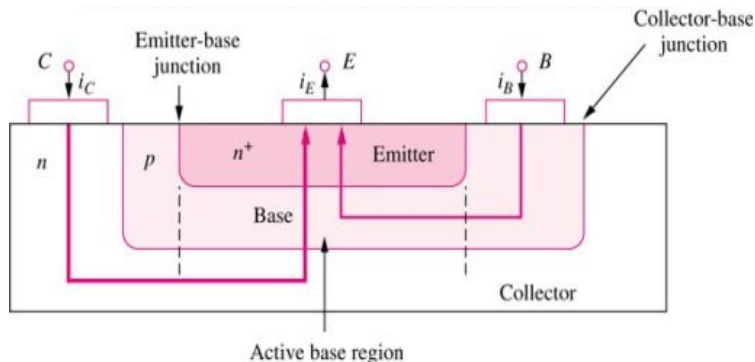


Bipolar Junction Transistors

Introduction

- Bipolar transistors are one of the main ‘building-blocks’ in electronic systems
- They are used in both analogue and digital circuits
- As an amplifier in analogue electronics and as a switch in computer
- They incorporate two pn junctions and are sometimes known as **bipolar junction transistors** or **BJTs**
- Here will refer to them simply as **bipolar transistors**

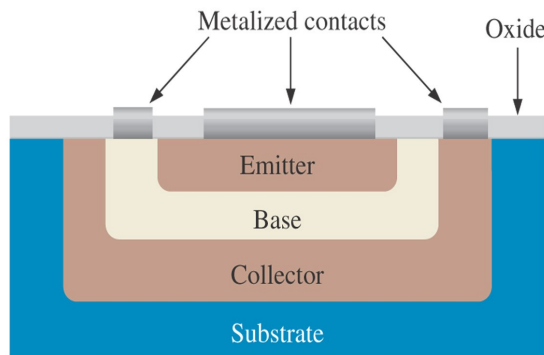
Physical Structure



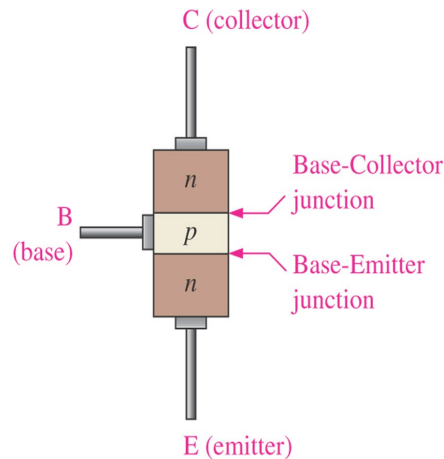
- The BJT consists of 3 alternating layers of n - and p -type semiconductor called **emitter** (E), **base** (B) and **collector** (C).
- The majority of current enters collector, crosses the base region and exits through the emitter. A small current also enters the base terminal, crosses the base-emitter junction and exits through the emitter.
- Carrier transport in the active base region directly beneath the heavily doped (n^+) emitter dominates the i - v characteristics of the BJT.

Architecture of BJTs

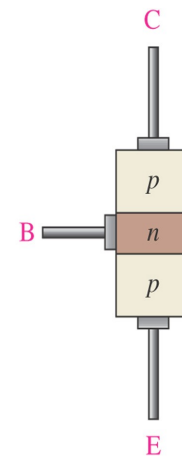
- The bipolar junction transistor (BJT) is constructed with three doped semiconductor regions separated by two pn junctions
- Regions are called **emitter**, **base** and **collector**



(a) Basic epitaxial planar structure



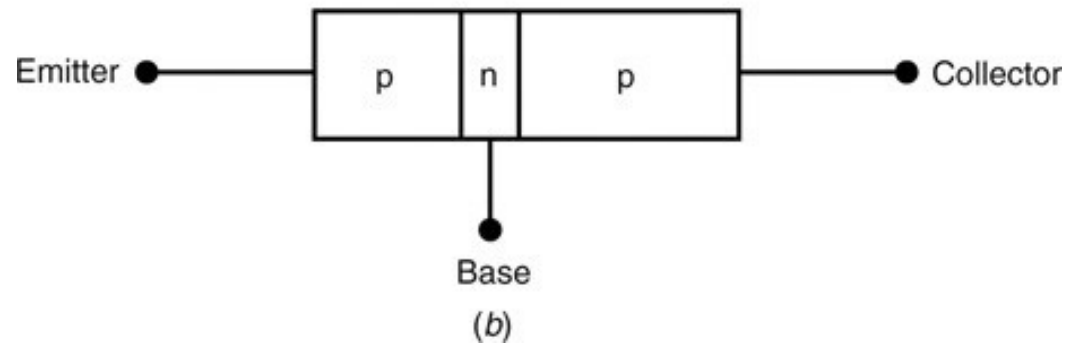
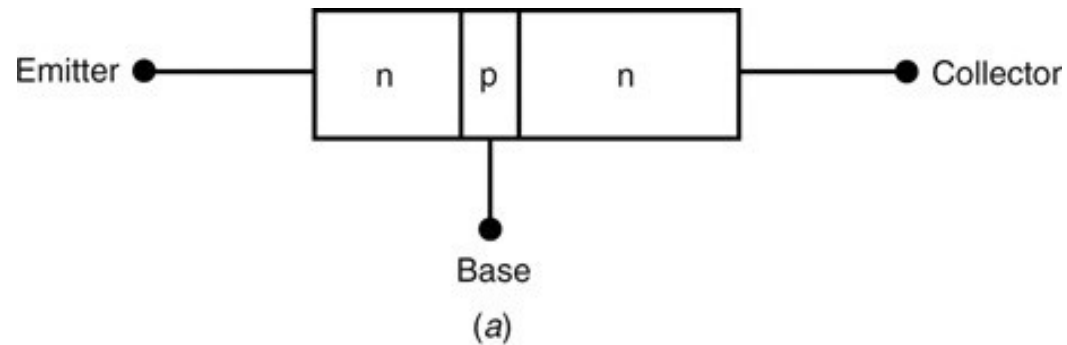
(b) npn



(c) pnp

Architecture of BJTs

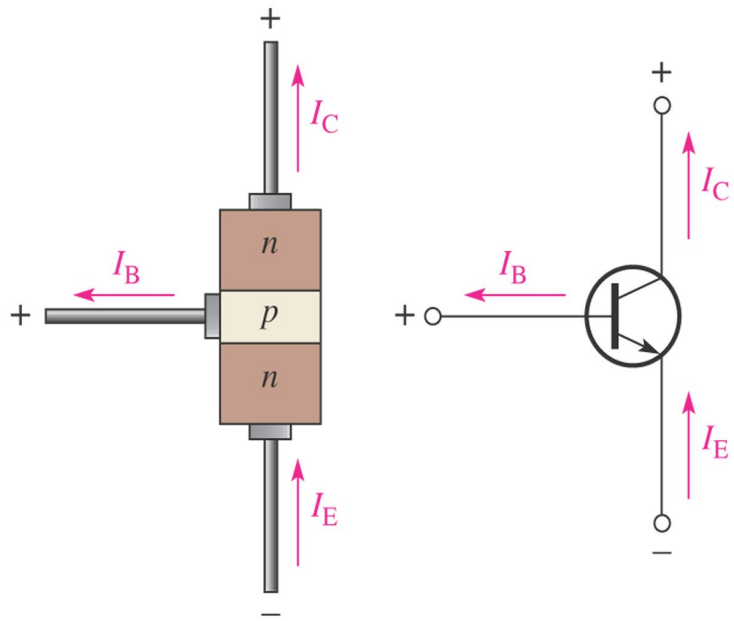
- The emitter region is heavily doped and its job is to emit carriers into the base.
- The base region is very thin and lightly doped.
- Most of the current carriers injected into the base from emitter pass on to the collector.
- The collector region is moderately doped and is the largest of all three regions.



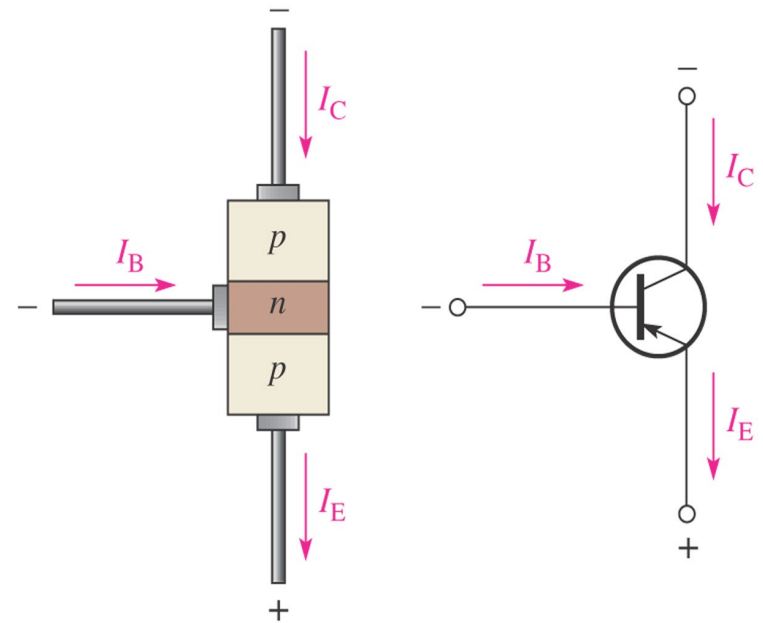
Architecture of BJTs

- There are two types of BJTs, the *npn* and *pnp*
- The two junctions are termed the *base-emitter* junction and the *base-collector* junction
- The term bipolar refers to the use of both holes and electrons as charge carriers in the transistor structure
- In order for the transistor to operate properly, the two junctions must have the correct dc bias voltages
 - the base-emitter (BE) junction is forward biased ($\geq 0.7\text{V}$ for Si, $\geq 0.3\text{V}$ for Ge)
 - the base-collector (BC) junction is reverse biased

FIGURE Transistor symbols.

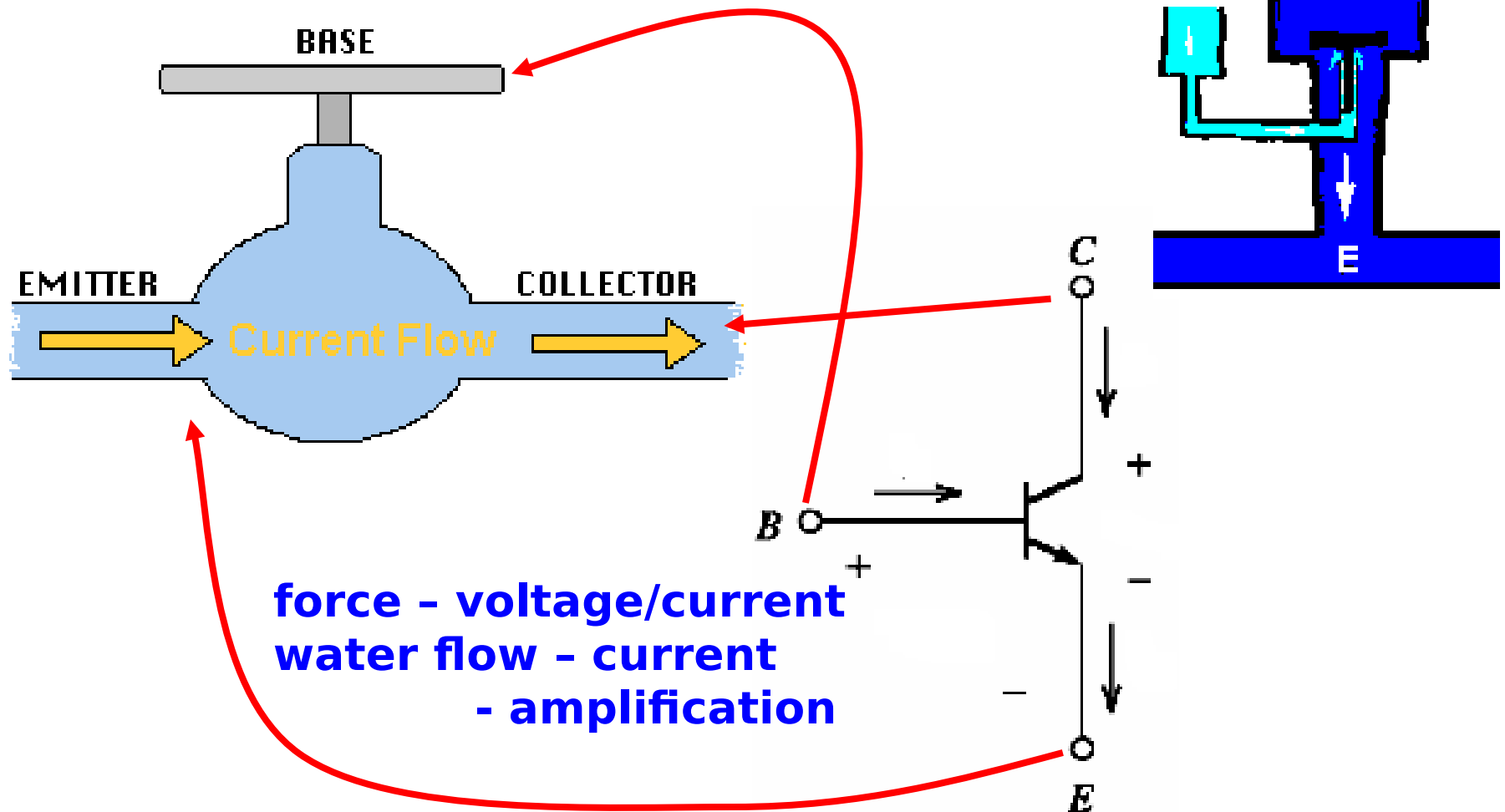


(a) *npn*



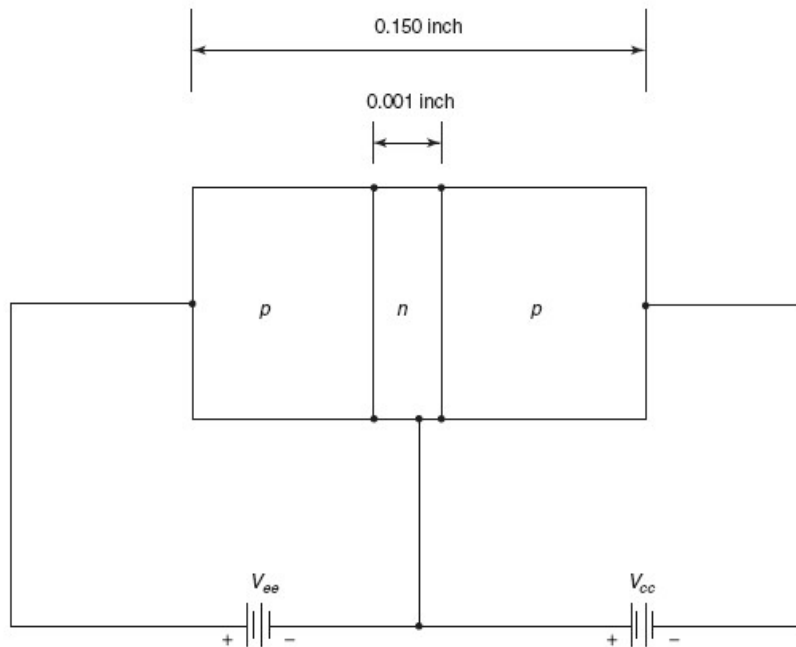
(b) *pnp*

Understanding of BJT

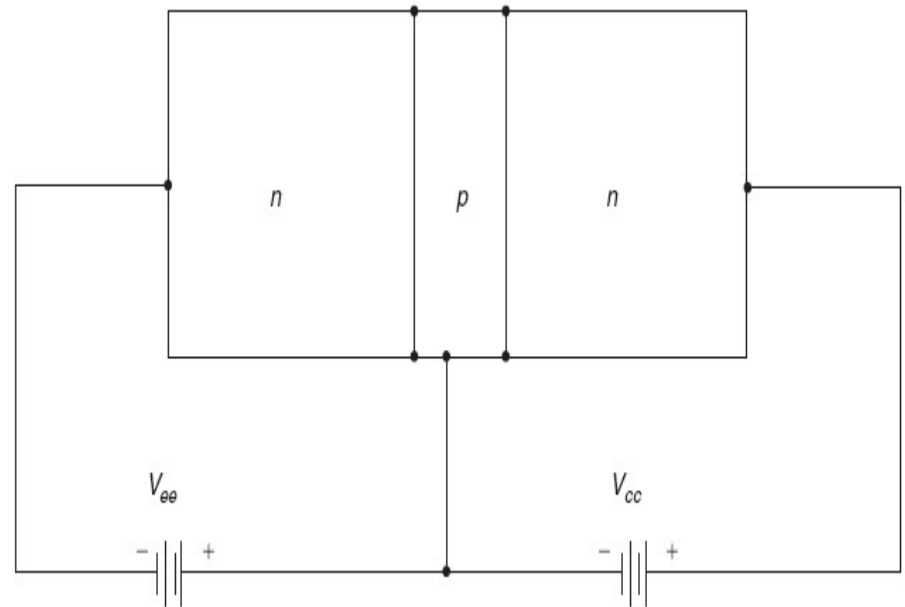


FORMATION OF p-n-p AND n-p-n JUNCTIONS

- ❖ When an *n-type thin semiconductor layer is placed between two p-type semiconductors*, the resulting structure is known as the *p-n-p transistor*.
- ❖ When a *p-type semiconductor is placed between two n-type semiconductors*, the device is known as the *n-p-n transistor*.



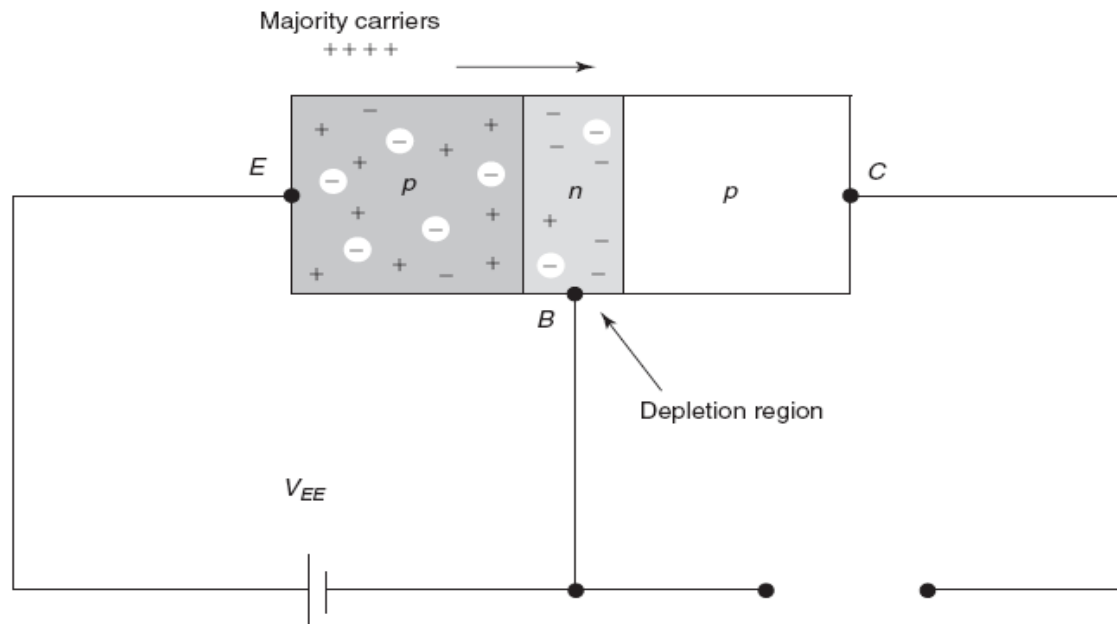
p-n-p transistor



n-p-n transistor

TRANSISTOR MECHANISM

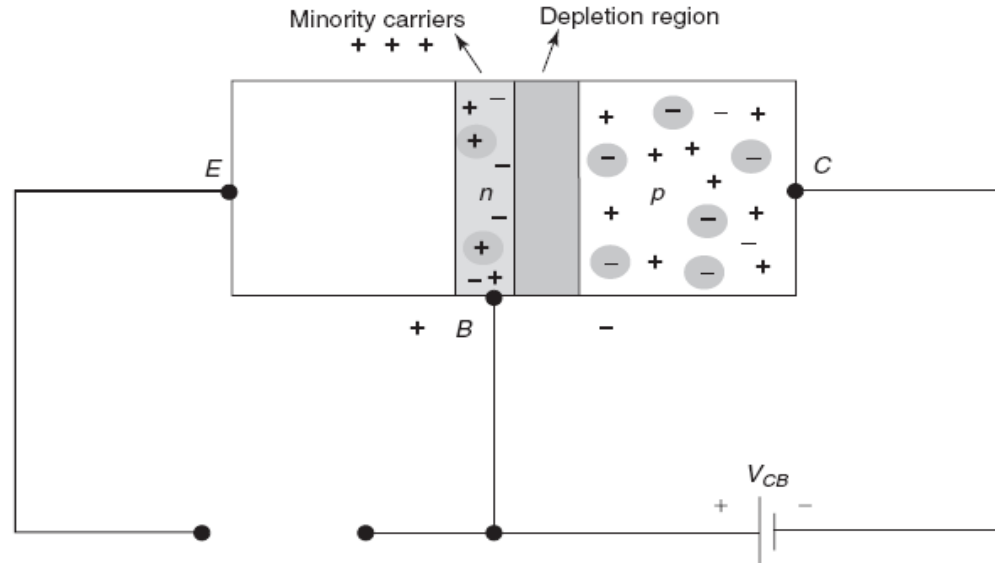
- ❖ The basic operation of the transistor is described using the *p–n–p transistor*.
- ❖ *The p–n junction of the transistor is forward-biased whereas the base-to-collector is without a bias.*
- ❖ The depletion region gets reduced in width due to the applied bias, resulting in a heavy flow of majority carriers from the *p-type to the n-type material gushing down the depletion region and reaching the base.*
- ❖ The forward-bias on the emitter–base junction will cause current to flow.



Forward-biased junction of a *p–n–p* transistor

TRANSISTOR MECHANISM

- ❖ For easy analysis, let us now remove the base-to-emitter bias of the p - n - p transistor.
- ❖ The flow of majority carriers is zero, resulting in a minority-carrier flow. Thus, one p - n junction of a transistor is reverse-biased, while the other is kept open.
- ❖ The operation of this device becomes much easier when they are considered as separate blocks. In this discussion, the drift currents due to thermally generated minority carriers have been neglected, since they are very small.

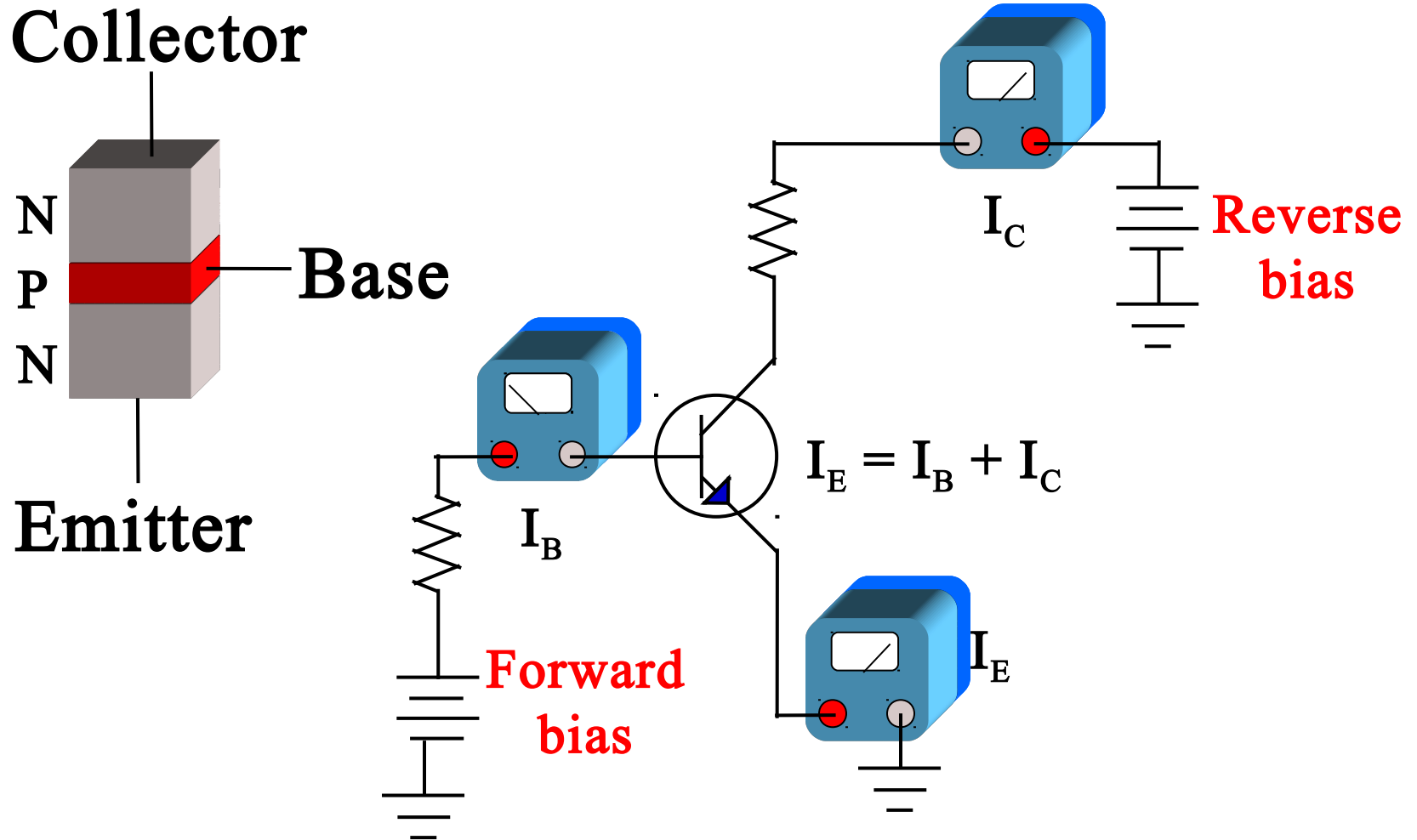


Reverse-biased junction of a p - n - p transistor

Proper Transistor Biasing

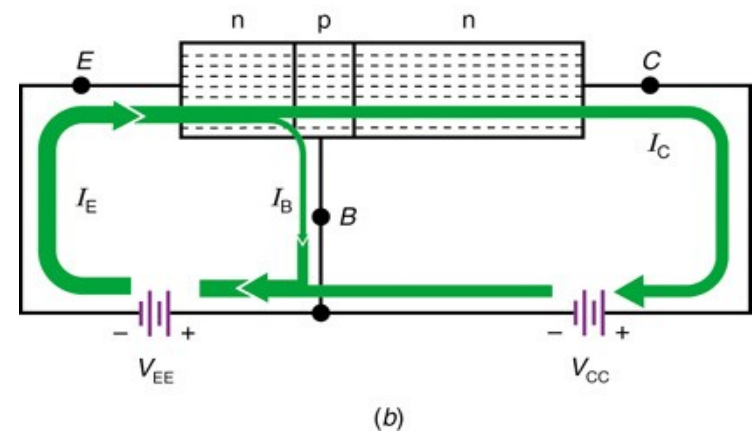
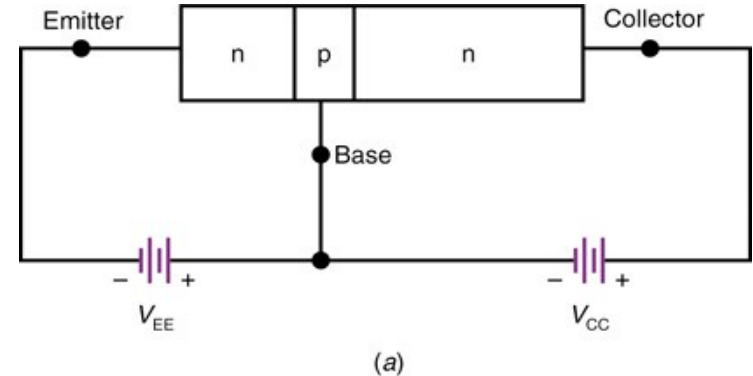
- For a transistor to function properly as an amplifier, the **emitter-base** junction must be forward-biased and the **collector-base** junction must be reverse-biased.
 - The common connection for the voltage sources are at the base lead of the transistor.
 - The emitter-base supply voltage is designated V_{EE} and the collector-base supply voltage is designated V_{CC} .
 - For silicon, the barrier potential for both EB and CB junctions equals 0.7 V
-

Transistor Biasing

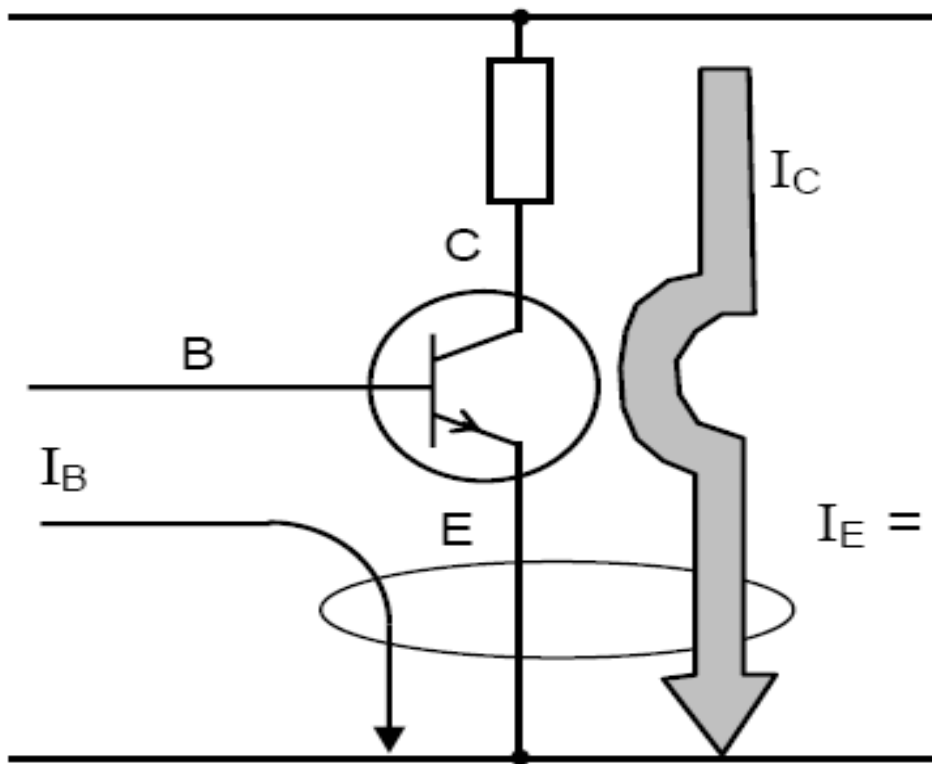


Proper Transistor Biasing

- Fig. shows transistor biasing for the *common-base* connection.
- Proper biasing for an npn transistor is shown in (a).
- The EB junction is forward-biased by the emitter supply voltage, V_{EE} .
- V_{CC} reverse-biases the CB junction.
- Fig. (b) illustrates currents in a transistor.
- CE voltage of an npn transistor must be positive
- Ratio of I_C to I_E is called DC alpha α_{dc}



Emitter, collector and base currents



(emitter current) = (base current) + (collector current)

$$I_E = I_B + I_C$$

$$I_E = I_C + I_B$$

Transistor Configurations

- common emitter (CE)
- common base (CB)
- common collector (CC).

Circuit Configuration

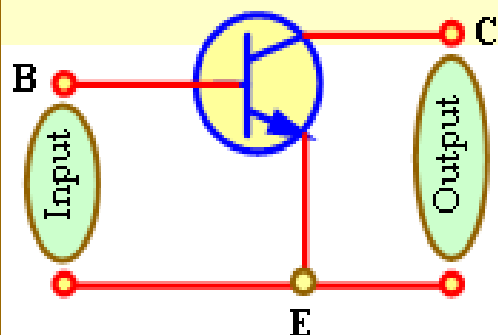


Figure 5a C-E Circuit

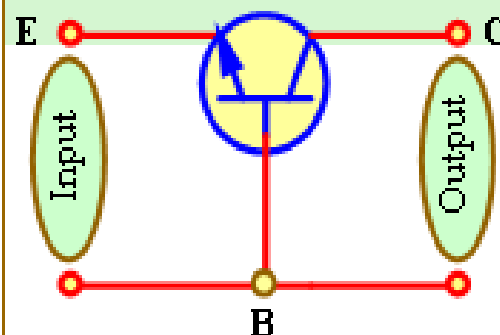


Figure 5b C-B Circuit

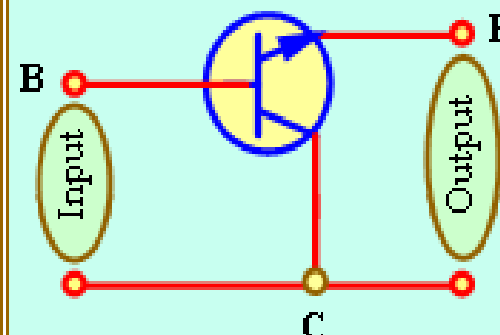


Figure 5c C-C Circuit

Current Gain

Medium (50)

Low (0.99)

Highest (60)

Voltage Gain

High (100 to 500)

Highest (200 to 2000)

Low (less than 1)

Power Gain

Highest (200 to 20,000)

Medium (200 to 1000)

Low (20 to 80)

R_{IN}

Medium ($1k\Omega$ to $5k\Omega$)

Very low (15Ω to 150Ω)

High ($2k\Omega$ to $500k\Omega$)

R_{OUT}

High (40Ω to $60k\Omega$)

Very high ($250k\Omega$ to $1M\Omega$)

Very low (25Ω to $1k\Omega$)

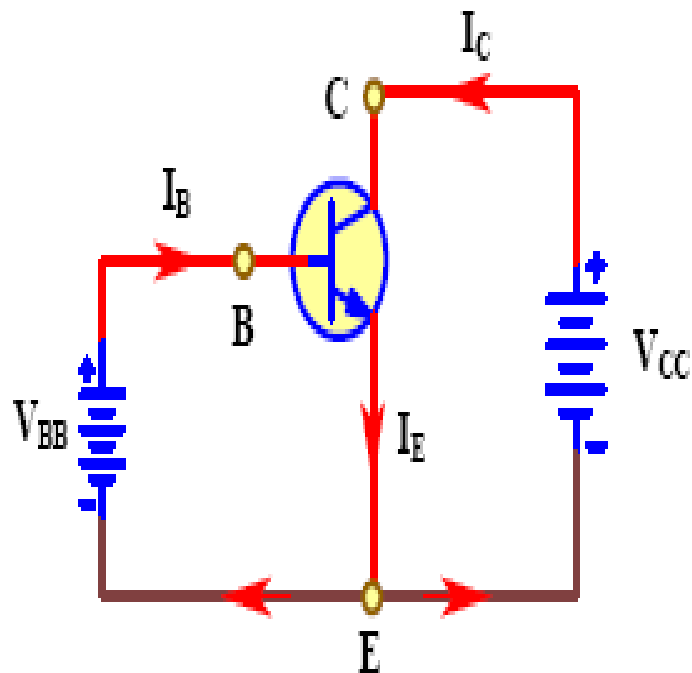
Phase shift

180°

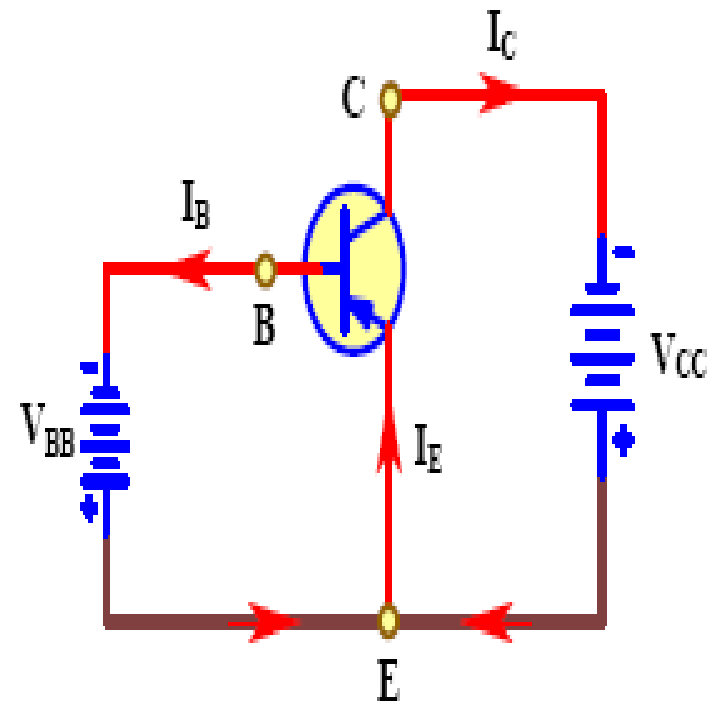
0°

0°

Currents in CE Circuit



(a) Currents in C-E (NPN) circuit



(b) Currents in C-E (PNP) circuit

Operating Regions

- Since emitter lead is common, this connection is called common-emitter connection
- Collector current I_C is controlled solely by the base current, I_B .
- By varying I_B , a transistor can be made to operate in any one of the following regions
 - Active
 - Saturation
 - Breakdown
 - Cutoff
- Ratio of I_C to I_B is called DC beta β_{dc}

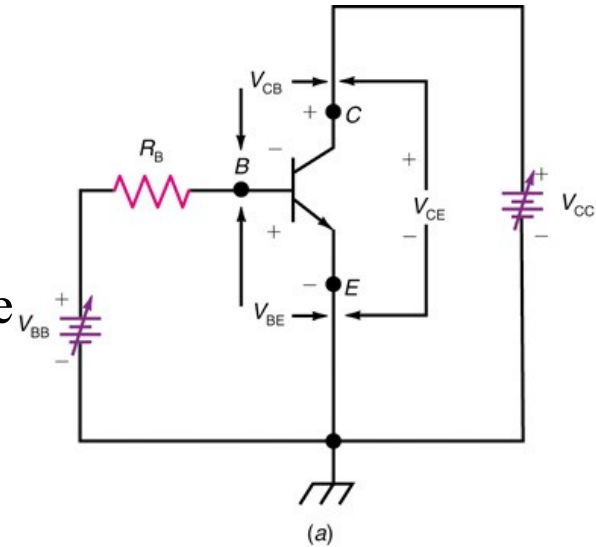
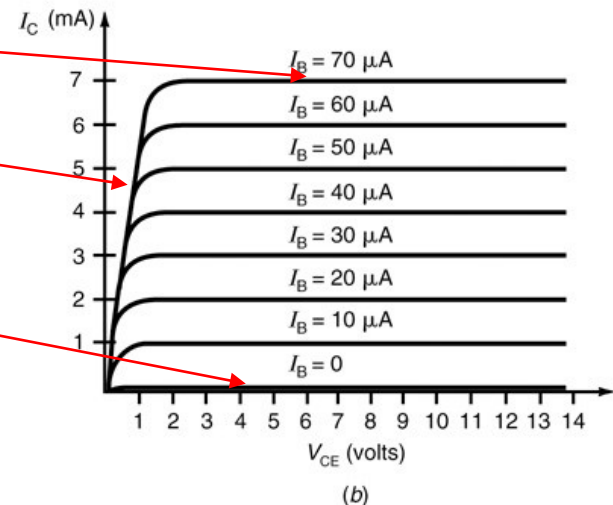


Fig. Common-emitter connection (a) circuit. (b) Graph of I_C versus V_{CE} for different base current values.



BJT characteristics

- Current Gain:
 - α is the fraction of electrons that diffuse across the narrow Base region
 - $1 - \alpha$ is the fraction of electrons that recombine with holes in the Base region to create base current
- The current Gain is expressed in terms of the β (beta) of the transistor (often called h_{fe} by manufacturers).
- β (beta) is Temperature and Voltage dependent.
- It can vary a lot among transistors (common values for signal BJT: 20 - 200).

$$I_C = \alpha I_E$$

$$I_B = (1 - \alpha) I_E$$

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1 - \alpha}$$

Transistor Currents

- $I_E = I_B + I_C$

- $I_C = I_E - I_B$

$$I_B = I_E - I_C$$

- $\beta_{dc} = \frac{I_C}{I_B}$

- $\alpha_{dc} = \frac{I_C}{I_E}$

- $\alpha_{dc} = \frac{\beta_{dc}}{1 + \beta_{dc}}$

$$\beta_{dc} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}$$

Operating Regions

- Active Region
 - Collector curves are nearly horizontal
 - I_C is greater than I_B ($I_C = \beta_{dc} \times I_B$)
- Saturation
 - I_C is not controlled by I_B
 - Vertical portion of the curve near the origin
- Breakdown
 - Collector-base voltage is too large and collector-base diode breaks down
 - Undesired collector current
- Cutoff
 - $I_B = 0$
 - Small collector current flows $I_C \approx 0$

Example

- A transistor has the following currents:

$$I_E = 15 \text{ mA}$$

$$I_B = 60 \text{ } \mu\text{A}$$

Calculate α_{dc} and β_{dc}

- $I_C = I_E - I_B = 14.94 \text{ mA}$

- $\alpha_{dc} = 0.996$

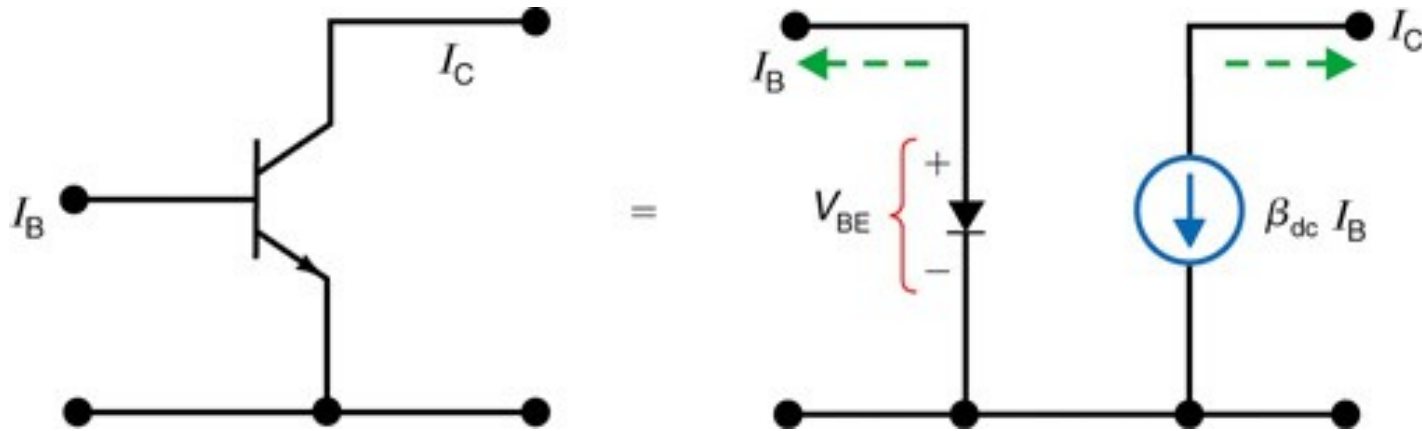
- $\beta_{dc} = 249$

Transistor Operation Regions

Operation Region	Bias	Application
CUT OFF REGION	I_B and I_C are 0 (base-emitter junction is reverse biased)	Open Switch (OFF)
SATURATION REGION	Base emitter junction is forward biased; I_B flows	Closed Switch (ON)
ACTIVE REGION	B-E junction is forward biased but C-E junction is reverse biased;	Amplifier

Operating Regions

- Fig. shows the **dc equivalent** circuit of a transistor operating in the active region.
- The base-emitter junction acts like a forward-biased diode with current, I_B .
- Usually, the second approximation of a diode is used.
- If the transistor is silicon, assume that V_{BE} equals 0.7 V.



Transistor can act as a Switch

A switching circuit

i) Transistor as an OFF switch

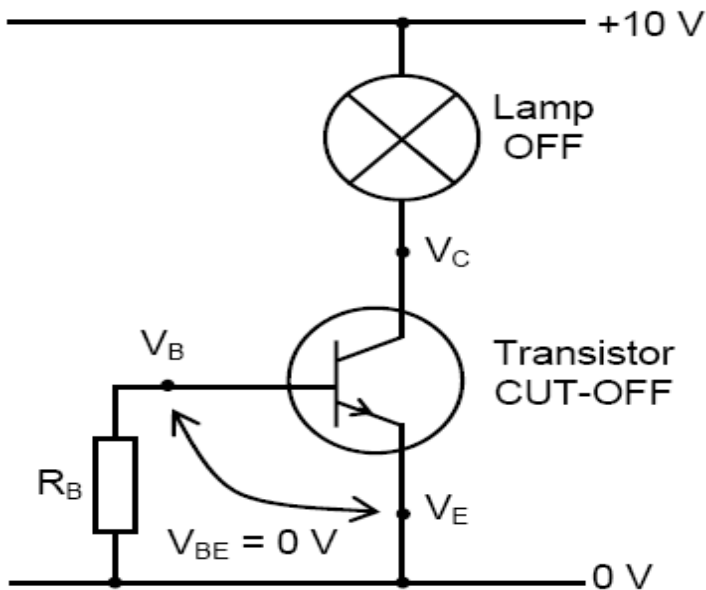


Fig. 5.25(a) – Transistor in CUT-OFF Condition (no current)

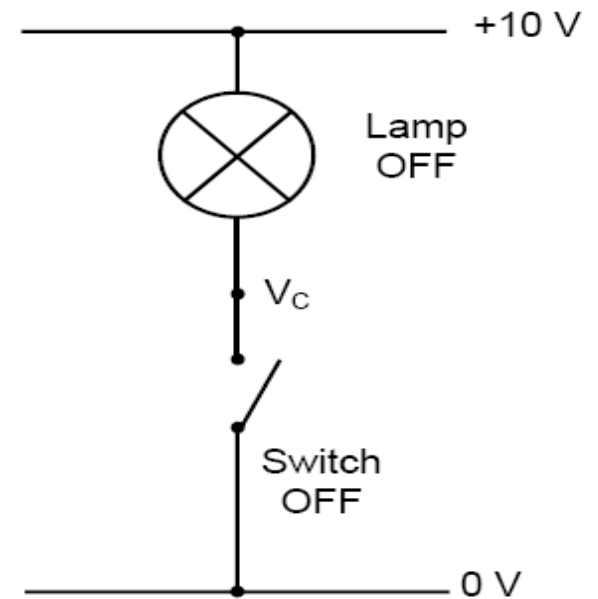


Fig. 5.25(b) – Transistor compared to switch

ii) Transistor as an ON switch

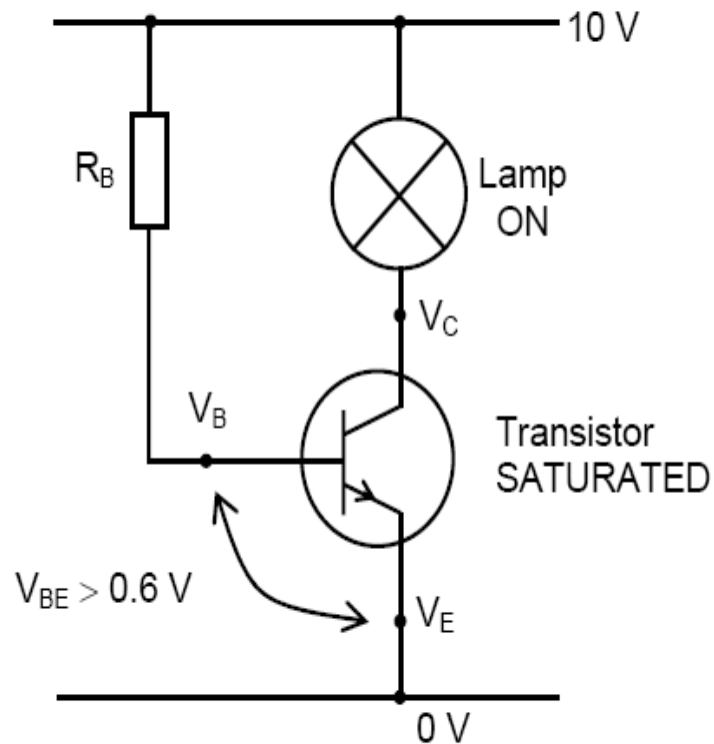


Fig. 5.26(a) – Transistor in SATURATED Condition (maximum current)

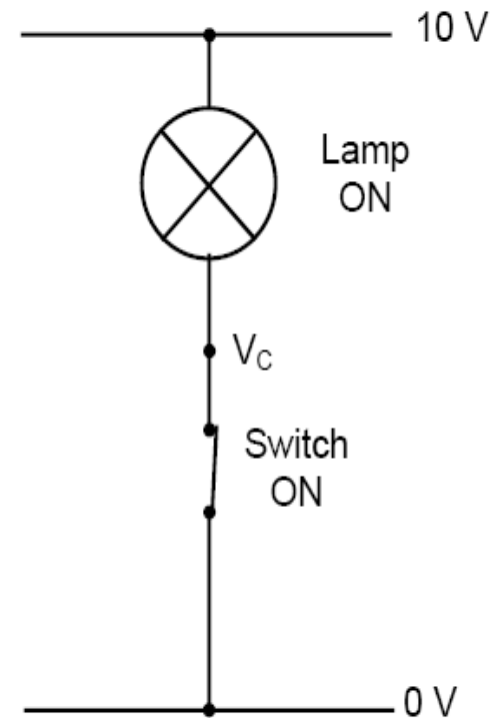
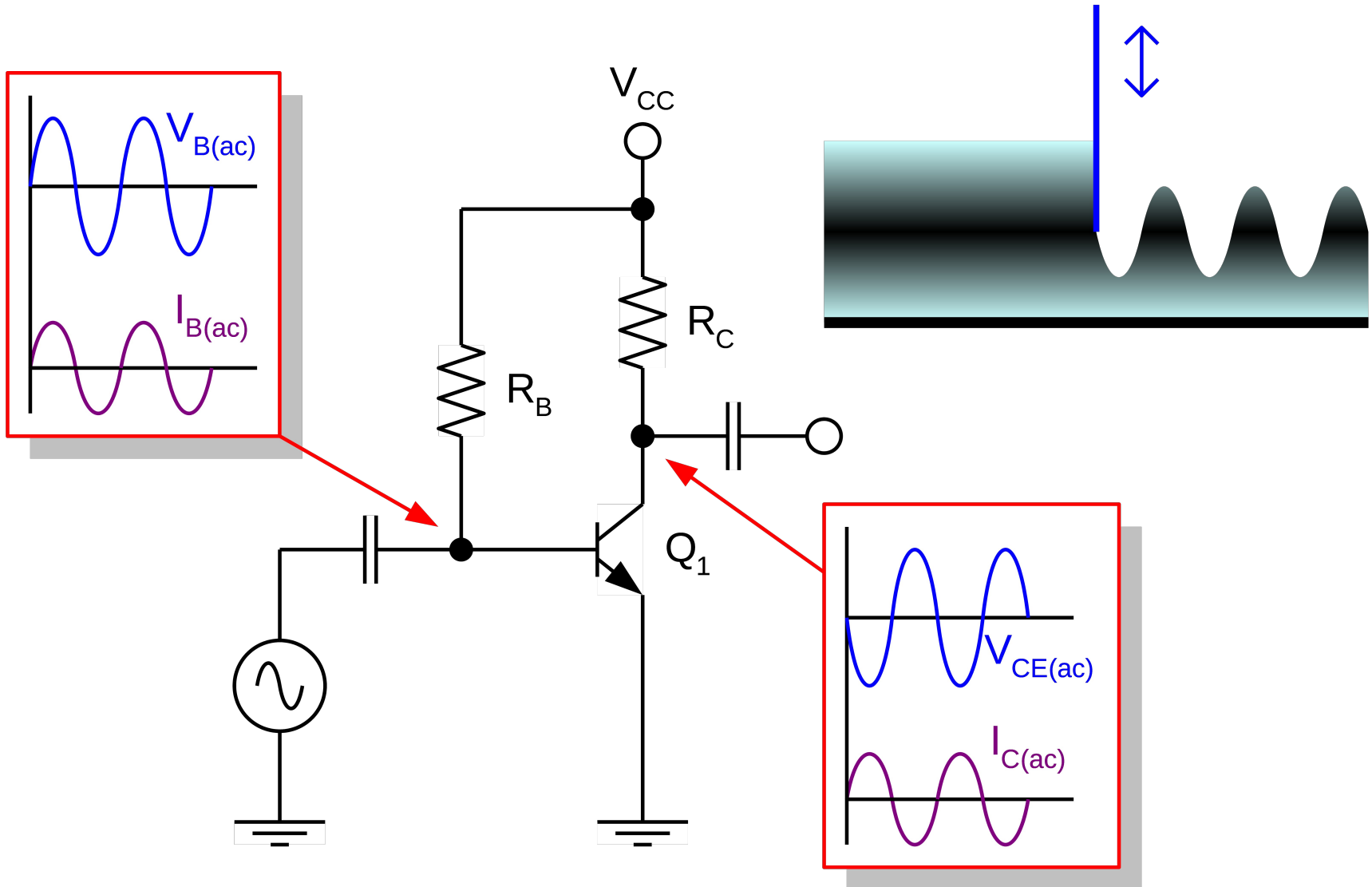


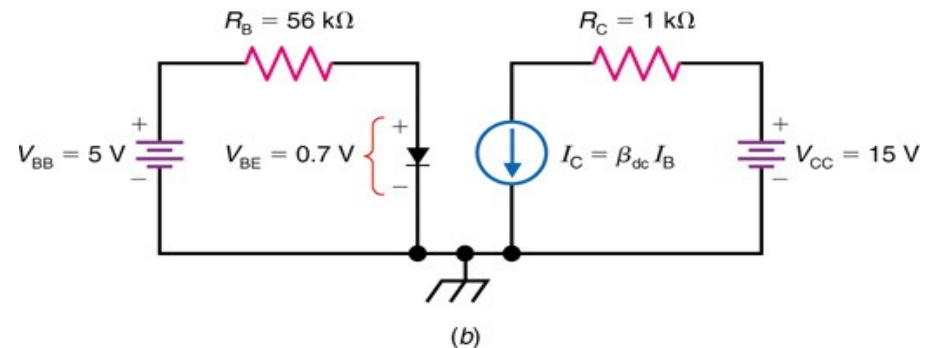
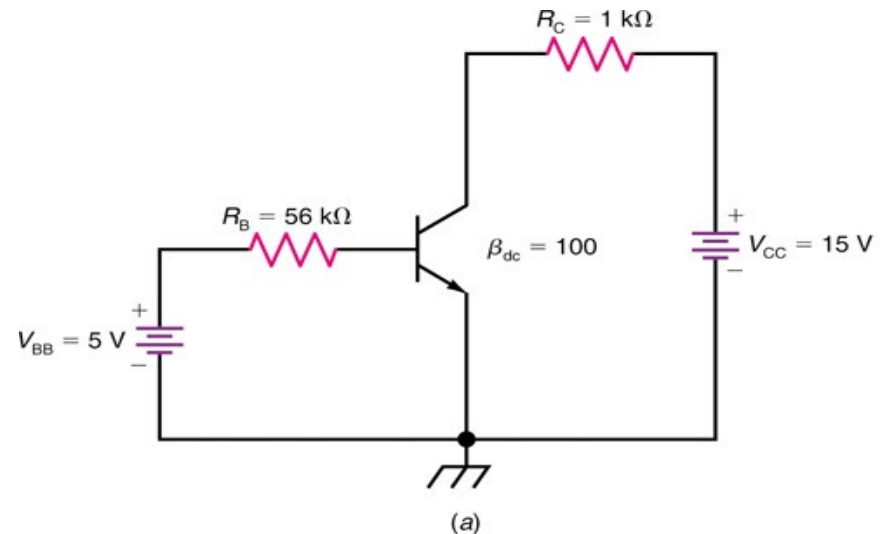
Fig. 5.26(b)

Typical amplifier operation.



Transistor Biasing

- Fig. (a) shows the simplest way to bias a transistor, called **base bias**.
- V_{BB} is the base supply voltage, which is used to forward-bias the base-emitter junction.
- R_B is used to provide the desired value of base current.
- V_{CC} is the collector supply voltage, which provides the reverse-bias voltage required for the collector-base junction.
- The collector resistor, R_C , provides the desired voltage in the collector circuit



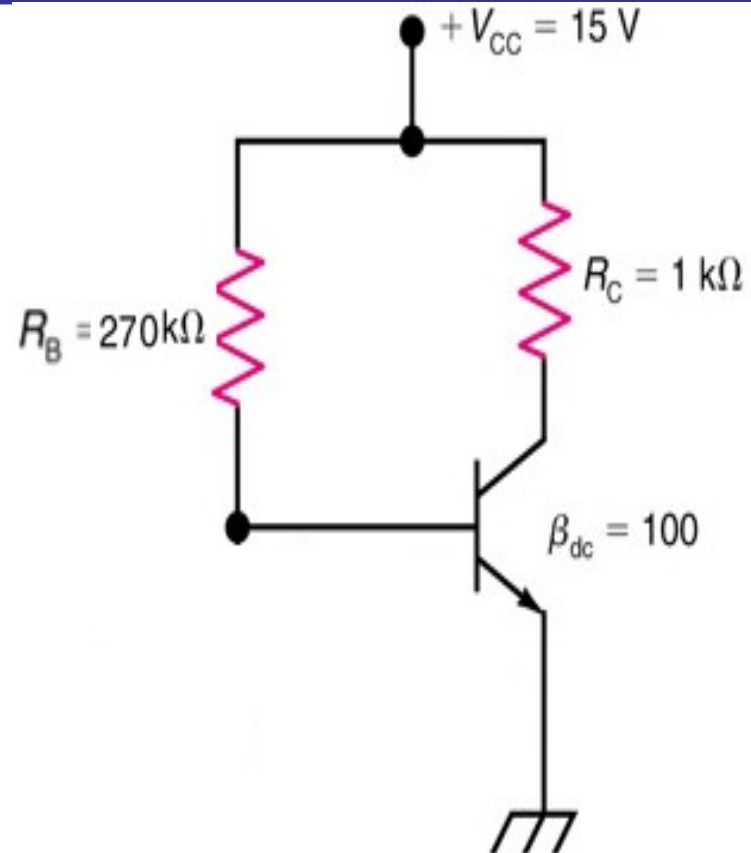
Transistor Biasing: Base Biasing

- A more practical way to provide base bias is to use one power supply.

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

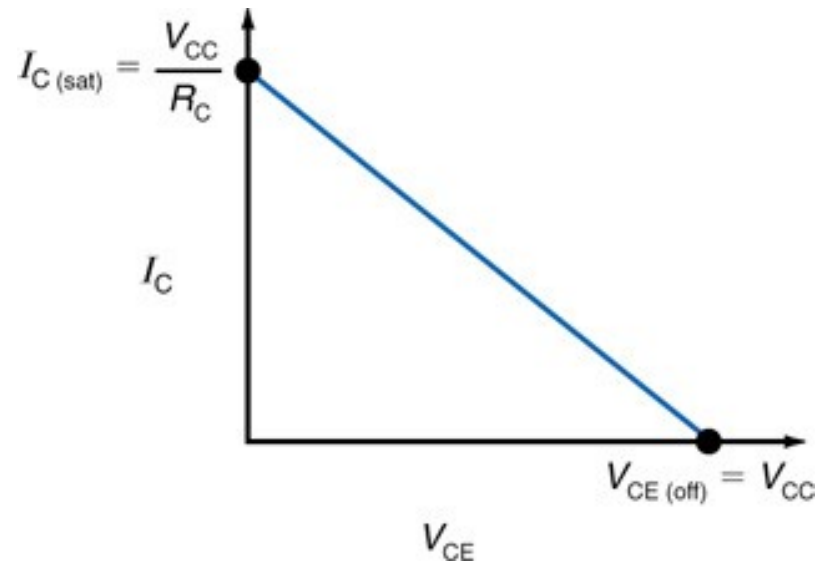
$$I_C \approx \beta_{dc} \times I_B$$

$$V_{CE} \approx V_{CC} - I_C R_C$$



Transistor Biasing

- The **dc load line** is a graph that allows us to determine all possible combinations of I_C and V_{CE} for a given amplifier.
- For every value of collector current, I_C , the corresponding value of V_{CE} can be found by examining the dc load line.
- A sample dc load line is shown in Fig.



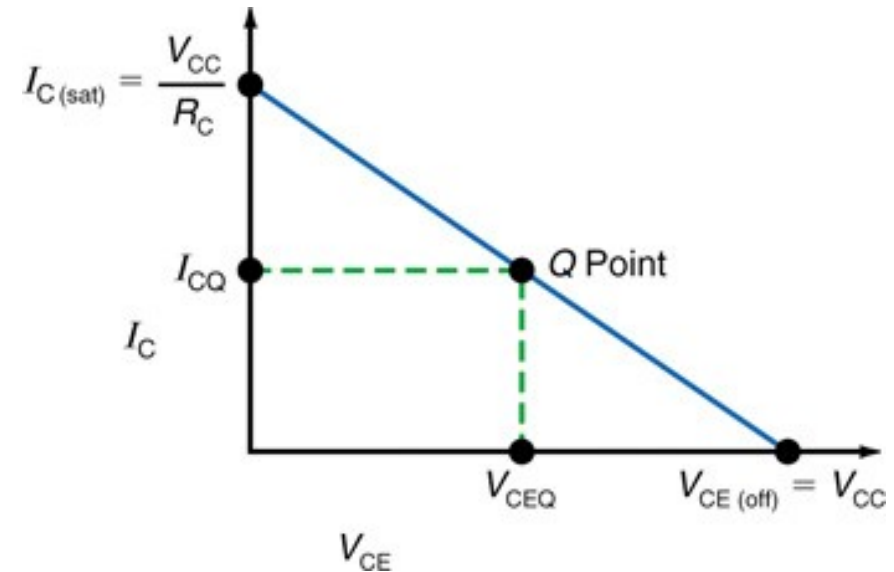
Transistor Biasing

Midpoint Bias

- Without an ac signal applied to a transistor, specific values of I_C and V_{CE} exist at a specific point on a dc load line
 - This specific point is called the Q point (quiescent currents and voltages with no ac input signal)
 - An amplifier is biased such that the Q point is near the center of dc load line
 - $I_{CQ} = \frac{1}{2} I_{C(sat)}$
 - $V_{CEQ} = \frac{1}{2} V_{CC}$
 - Base bias provides a very unstable Q point, because I_C and V_{CE} are greatly affected by any change in the transistor's beta value
-

Transistor Biasing

Fig. illustrates a **dc load line** showing the end points I_C (sat) and V_{CE} (off), as well as the Q point values I_{CQ} and V_{CEQ} .



Biasing of BJT

➤ Biasing refers to the application of D.C. voltages to setup the operating point in such a way that output signal is undistorted throughout the whole operation.

➤ Also once selected properly, the Q point should not shift because of change of I_C due to

(i) β variation due to replacement of the transistor of same type

(ii) Temperature variation

Stabilization

➤ The process of making operating point independent of temperature changes or variation in transistor parameters is known as stabilization.

➤ Stabilization of operating point is necessary due to

❖ Temperature dependence of I_C

❖ Individual variations

❖ Thermal runaway

Stabilization

Temperature dependence of I_C & Thermal runaway

$$I_C = \beta I_B + (\beta + 1)I_{CBO}$$

- I_{CBO} is strong function of temperature. A rise of 10°C doubles the I_{CBO} and I_C will increase $(\beta + 1)$ times of I_{CBO}
- The flow of I_C produce heat within the transistor and raises the transistor temperature further and therefore, further increase in I_{CBO}
- This effect is cumulative and in few seconds, the I_C may become large enough to burn out the transistor.
- The self destruction of an unstabilized transistor is known as thermal runaway.

Stability Factor

- The rate of change collector current I_C with respect to the collector leakage current I_{CBO} is called stability factor, denoted by S .

$$S = \left(\frac{dI_C}{dI_{CBO}} \right)$$

Lower the value of S , better is the stability of the transistor.

Stability Factor

➤ The rate of change collector current I_C with respect to the collector leakage current I_{CBO} at constant β and I_B is called stability factor, denoted by S .

$$I_C = \beta I_B + (\beta + 1)I_{CBO} \quad (1)$$

Differentiating equation (1) w.r.t I_C

$$1 = \beta \left(\frac{dI_B}{dI_C} \right) + (\beta + 1) \frac{dI_{CBO}}{dI_C}$$

$$1 = \beta \left(\frac{dI_B}{dI_C} \right) + \frac{(\beta + 1)}{S}$$

$$S = \frac{(\beta + 1)}{1 - \beta \left(\frac{dI_B}{dI_C} \right)}$$

Different biasing schemes

- (i) Fixed bias (base resistor biasing)
- (ii) Collector base bias
- (iii) Emitter bias
- (iv) Voltage divider bias

General Formula

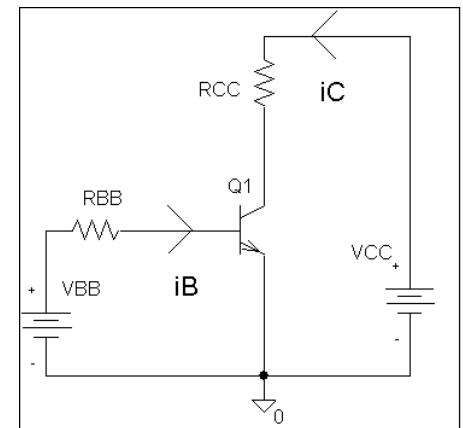
$$S = \frac{1 + \frac{R_B}{R_E}}{1 + (1 - \alpha) \left(\frac{R_b}{R_E} \right)}$$

Deriving BJT Operating points in Active Region –An Example

In the CE Transistor circuit shown earlier $V_{BB} = 5V$, $R_{BB} = 107.5 \text{ k}\Omega$, $R_{CC} = 1 \text{ k}\Omega$, $V_{CC} = 10V$. Find I_B, I_C, V_{CE}, β and the transistor power dissipation using the characteristics as shown below

By Applying KVL to the base emitter circuit

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



By using this equation along with the i_B / v_{BE} characteristics of the base emitter junction, $I_B = 40 \mu A$

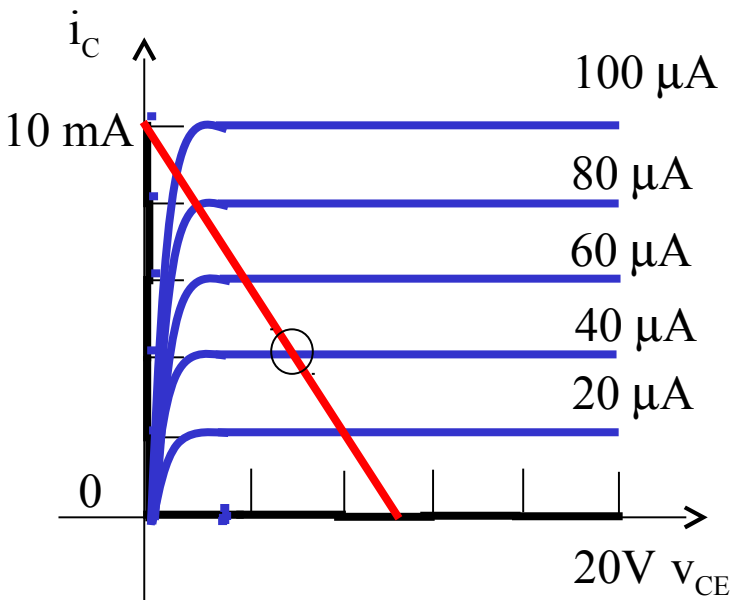
Deriving BJT Operating points in Active Region –An Example (2)

By Applying KVL to the collector emitter circuit

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

By using this equation along with the i_C / v_{CE} characteristics of the base collector junction, $i_C = 4 \text{ mA}$, $V_{CE} = 6 \text{ V}$

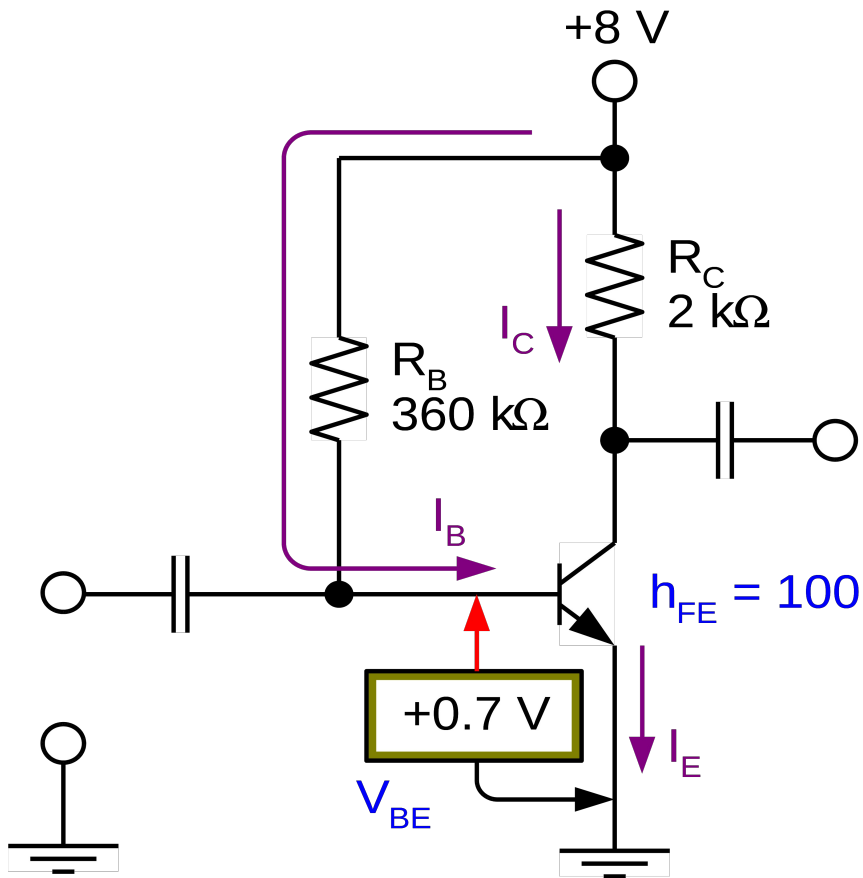
$$\beta = \frac{I_C}{I_B} = \frac{4 \text{ mA}}{40 \mu\text{A}} = 100$$



Transistor power dissipation = $V_{CE} I_C = 24 \text{ mW}$

We can also solve the problem without using the characteristics if β and V_{BE} values are known

Example



$$I_B = \frac{V_{CC} - 0.7V}{R_B} = \frac{8V - 0.7V}{360k\Omega} = 20.28\mu A$$

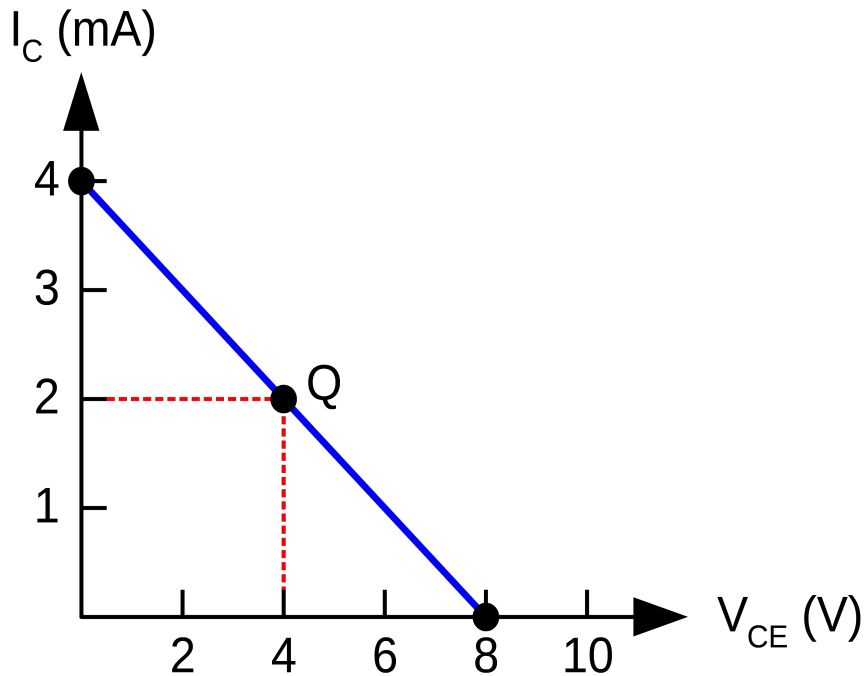
$$I_C = h_{FE} I_B = (100) (20.28\mu A) = 2.028mA$$

$$V_{CE} = V_{CC} - I_C R_C = 8V - (2.028mA) (2k\Omega) = 3.94V$$

The circuit is midpoint biased.

Example

Construct the dc load line for the circuit shown in Fig, and plot the Q-point from the values obtained in previous Example. Determine whether the circuit is midpoint biased.

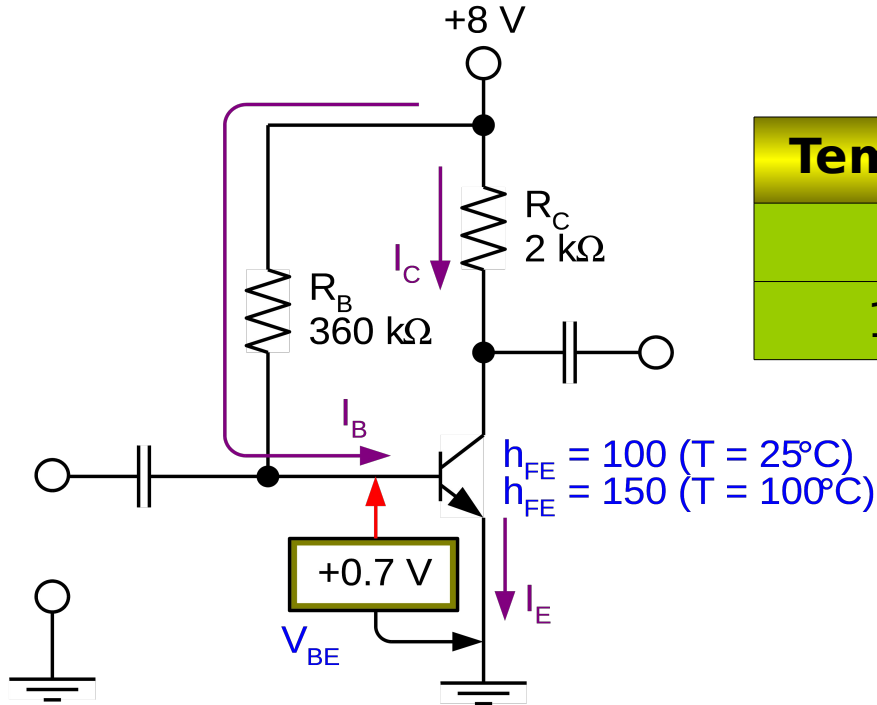


$$I_{C(\text{sat})} = \frac{V_{CC}}{R_C} = \frac{8\text{V}}{2\text{k}\Omega} = 4\text{mA}$$

$$V_{CE(\text{off})} = V_{CC} = 8\text{V}$$

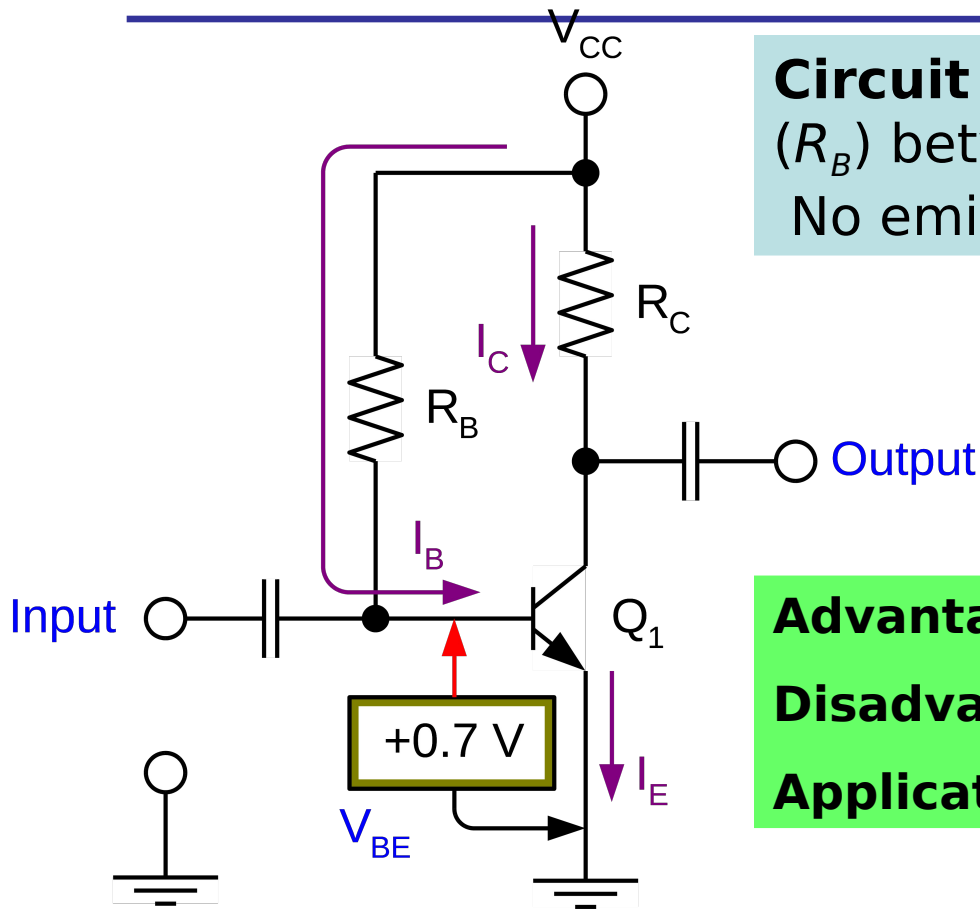
Example (Q-point shift.)

The transistor in Fig. has values of $h_{FE} = 100$ when $T = 25^\circ\text{C}$ and $h_{FE} = 150$ when $T = 100^\circ\text{C}$. Determine the Q-point values of I_C and V_{CE} at both of these temperatures.



Temp($^\circ\text{C}$)	I_B (μA)	I_C (mA)	V_{CE} (V)
25	20.28	2.028	3.94
100	20.28	3.04	1.92

Base bias characteristics. (1)



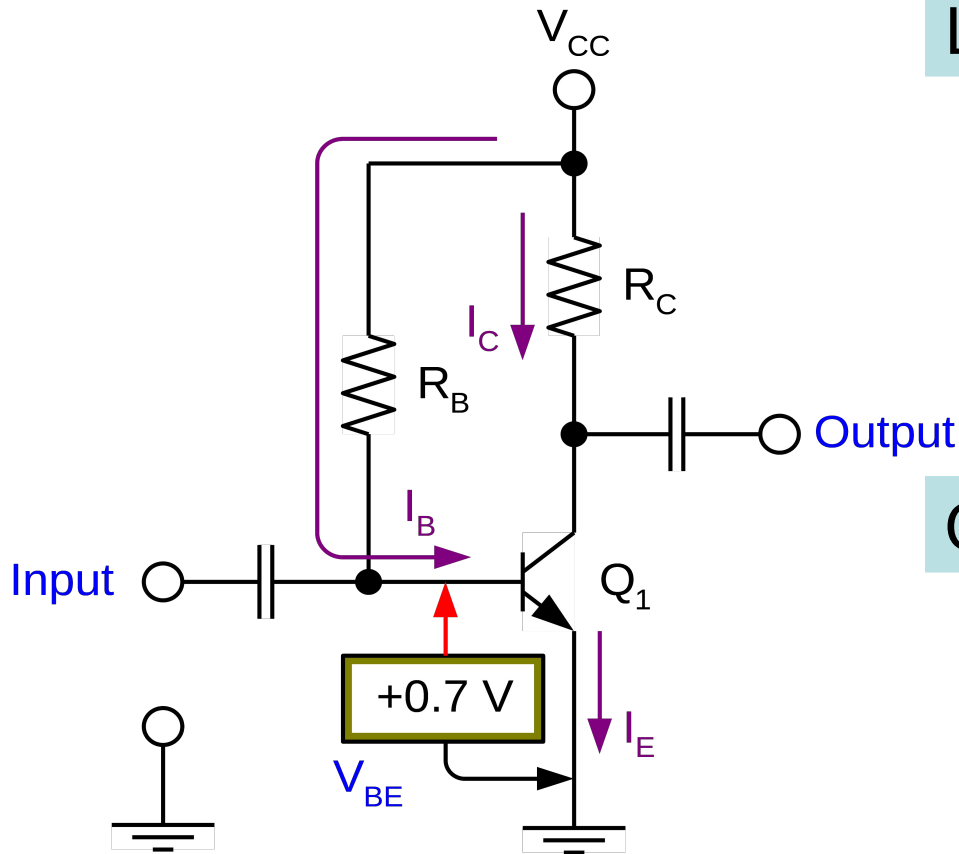
Circuit recognition: A single resistor (R_B) between the base terminal and V_{CC} . No emitter resistor.

Advantage: Circuit simplicity.

Disadvantage: Q-point shift with temp.

Applications: Switching circuits only.

Base bias characteristics. (2)



Load line equations:

$$I_{C(\text{sat})} \cong \frac{V_{CC}}{R_C}$$

$$V_{CE(\text{off})} = V_{CC}$$

Q-point equations:

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

$$I_C = h_{FE} I_B$$

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

Fig 7.14 Voltage divider bias. (1)

Assume that $I_2 > 10I_B$.

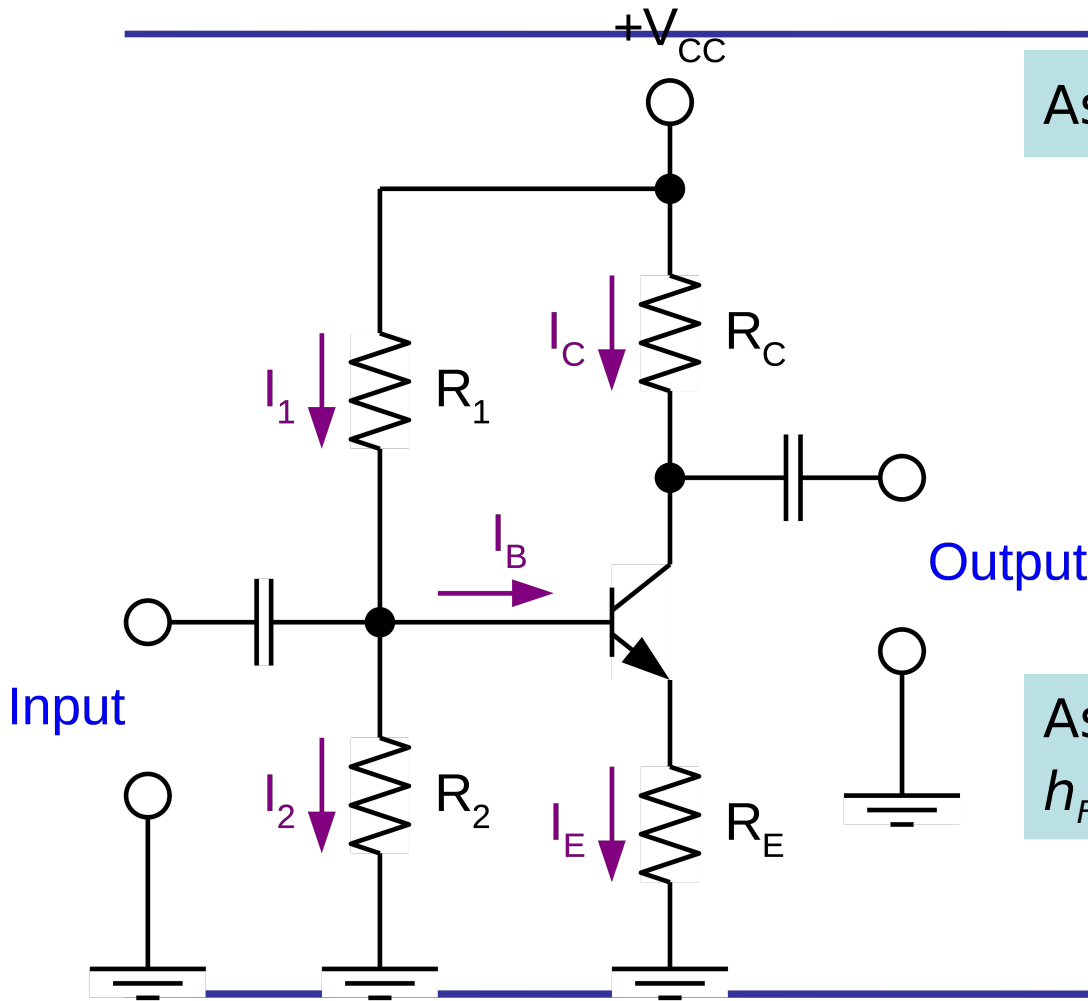
$$V_B = \frac{R_2}{R_1 + R_2} V_{CC}$$

$$V_E = V_B - 0.7V$$

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

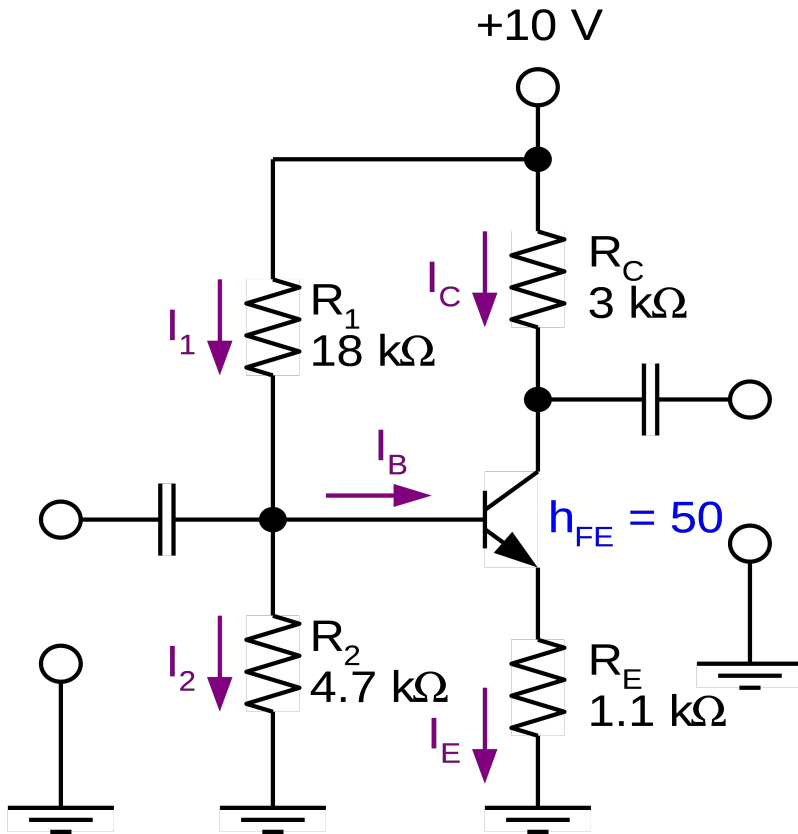
Assume that $I_{CQ} \cong I_E$ (or $h_{FE} \gg 1$). Then

$$V_{CEQ} = V_{CC} - I_{CQ}(R_C + R_E)$$



Example (1)

Determine the values of I_{CQ} and V_{CEQ} for the circuit shown in Fig.



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

$$= (10\text{V}) \frac{4.7\text{k}\Omega}{22.7\text{k}\Omega} = 2.07\text{V}$$

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

$$= 2.07\text{V} - 0.7\text{V} = 1.37\text{V}$$

Because $I_{CQ} \cong I_E$ (or $h_{FE} \gg 1$),

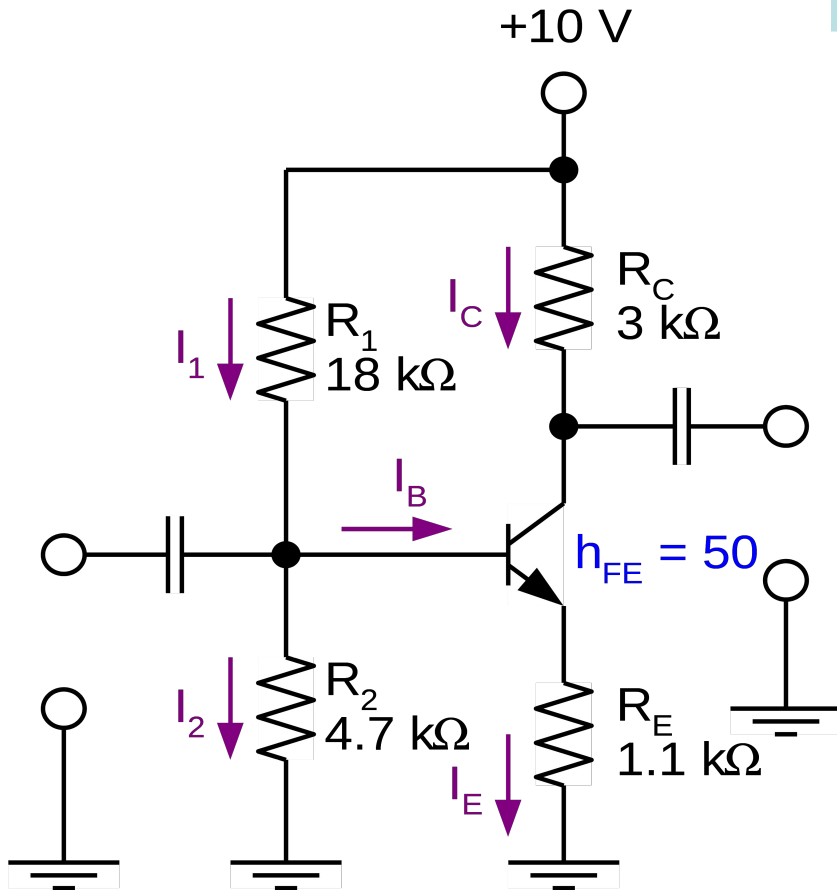
$$I_{CQ} \cong \frac{V_E}{R_E} = \frac{1.37\text{V}}{1.1\text{k}\Omega} = 1.25\text{mA}$$

$$V_{CEQ} = V_{CC} - I_{CQ} (R_C + R_E)$$

$$= 10\text{V} - (1.25\text{mA}) (4.1\text{k}\Omega) = 4.87\text{V}$$

Example (2)

Verify that $I_2 > 10 I_B$.

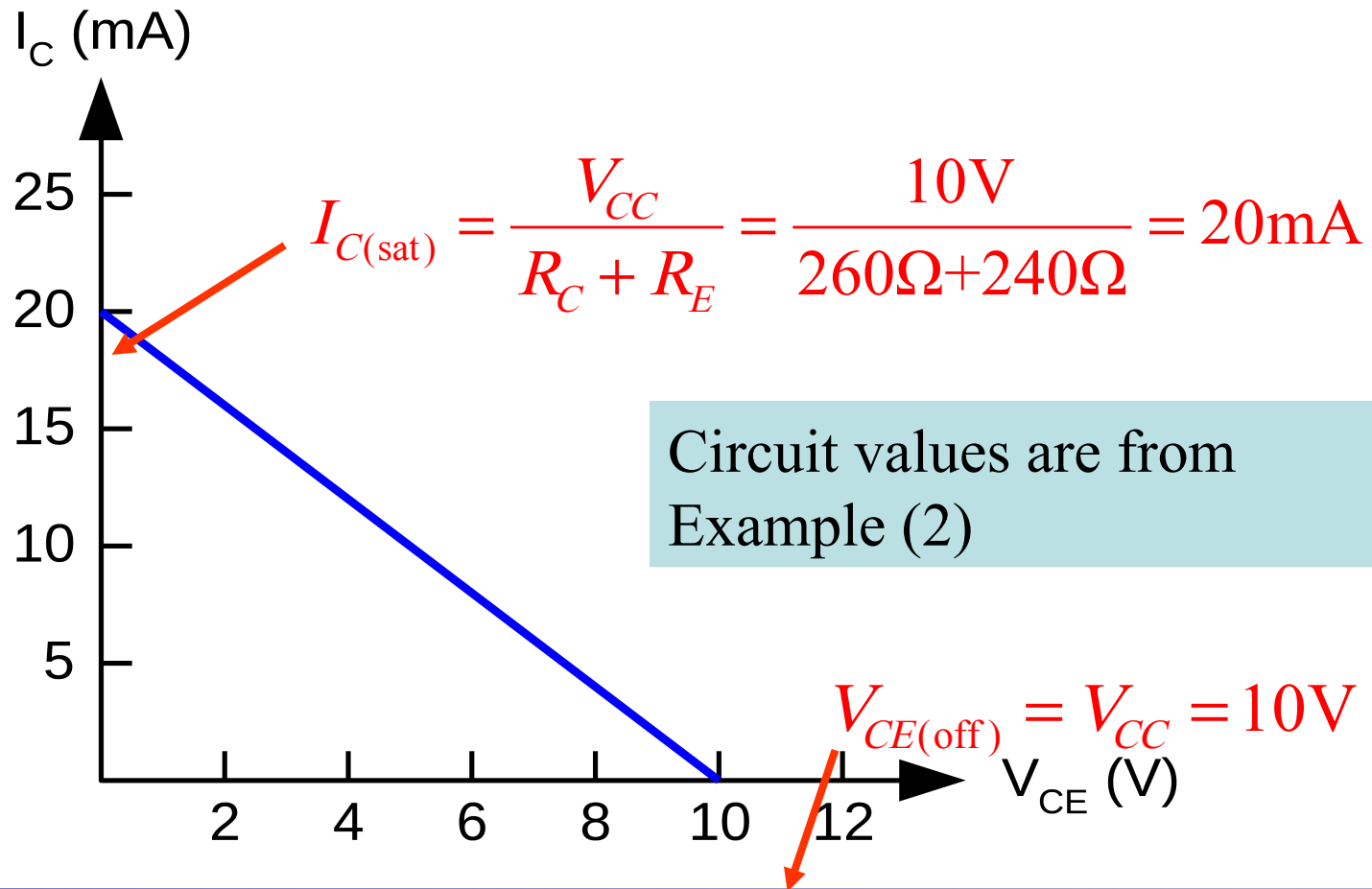


$$I_2 = \frac{V_B}{R_2} = \frac{2.07\text{V}}{4.7\text{k}\Omega} = 440.4\mu\text{A}$$

$$I_B = \frac{I_E}{h_{FE} + 1} = \frac{1.25\text{mA}}{50 + 1} = 24.51\mu\text{A}$$

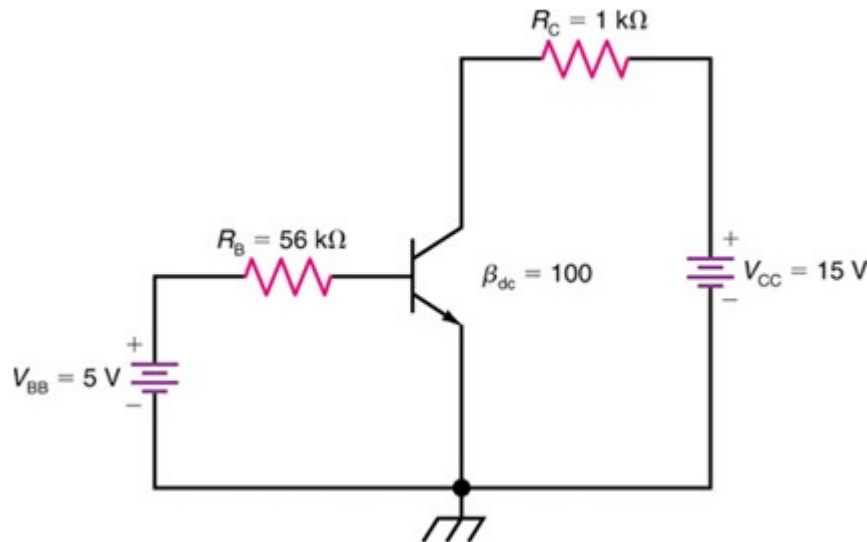
$$\therefore I_2 > 10 I_B$$

Load line for voltage divider bias circuit.



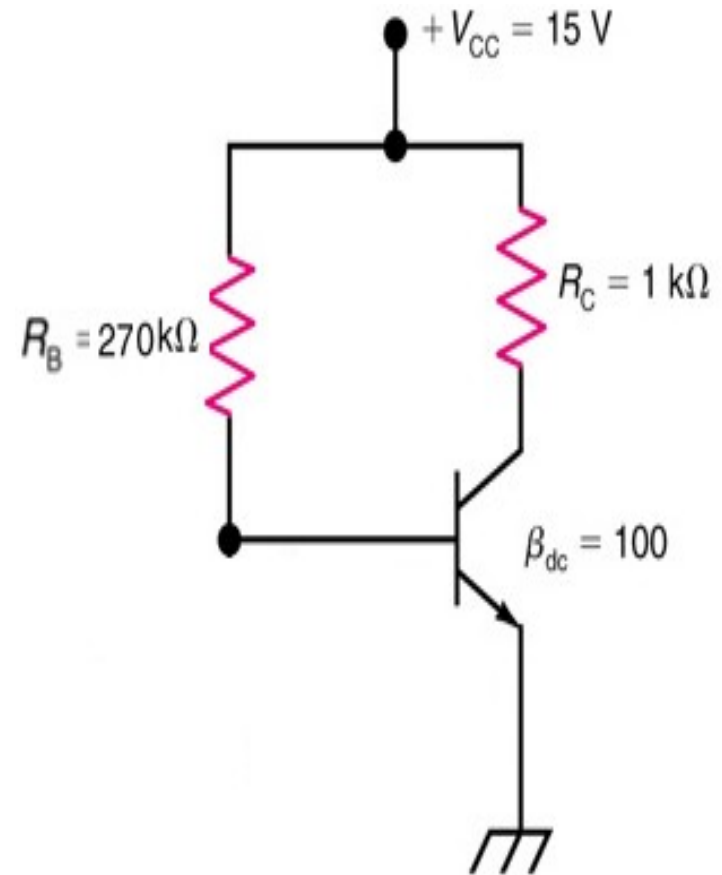
Base Bias - Example 1

- Solve for I_B , I_C and V_{CE}
- Construct a dc load line showing the values of $I_{C(sat)}$, $V_{CE(off)}$, I_{CQ} and V_{CEQ}



Base Bias - Example 2

- Solve for I_B , I_C and V_{CE}
- Construct a dc load line showing the values of $I_{C(sat)}$, $V_{CE(off)}$, I_{CQ} and V_{CEQ}



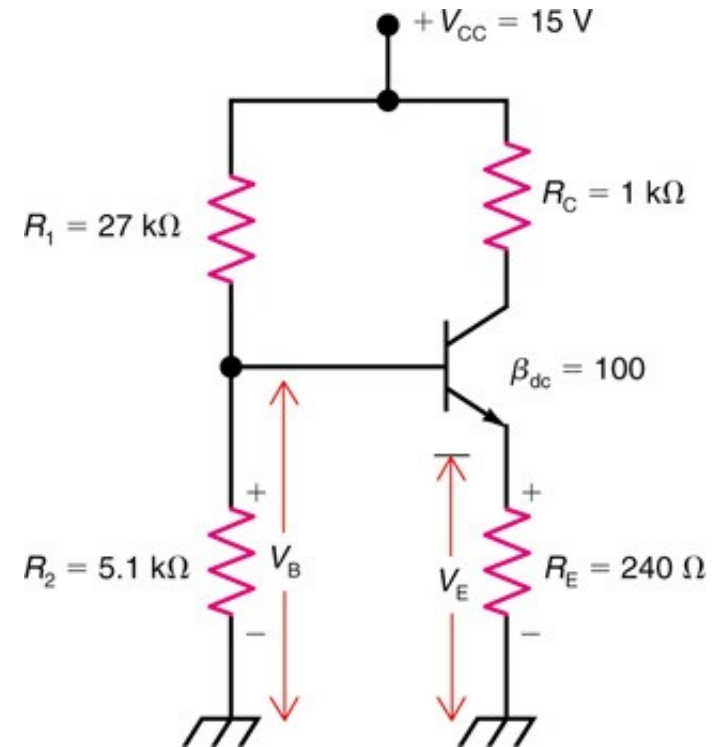
Transistor Biasing

- The most popular way to bias a transistor is with **voltage-divider bias**.
- The advantage of voltage-divider bias lies in its stability.
- An example of voltage-divider bias is shown in Fig.

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

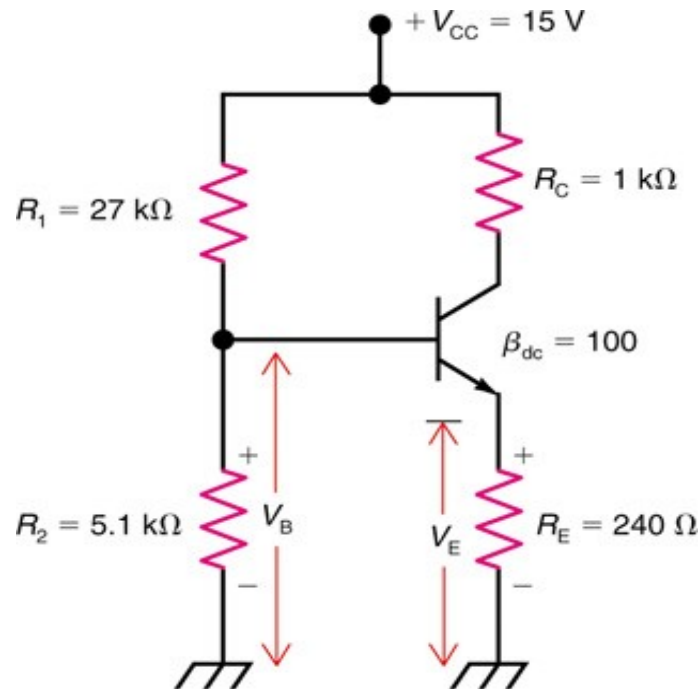
$$V_E = V_B - V_{BE}$$

$$I_E \approx I_C$$



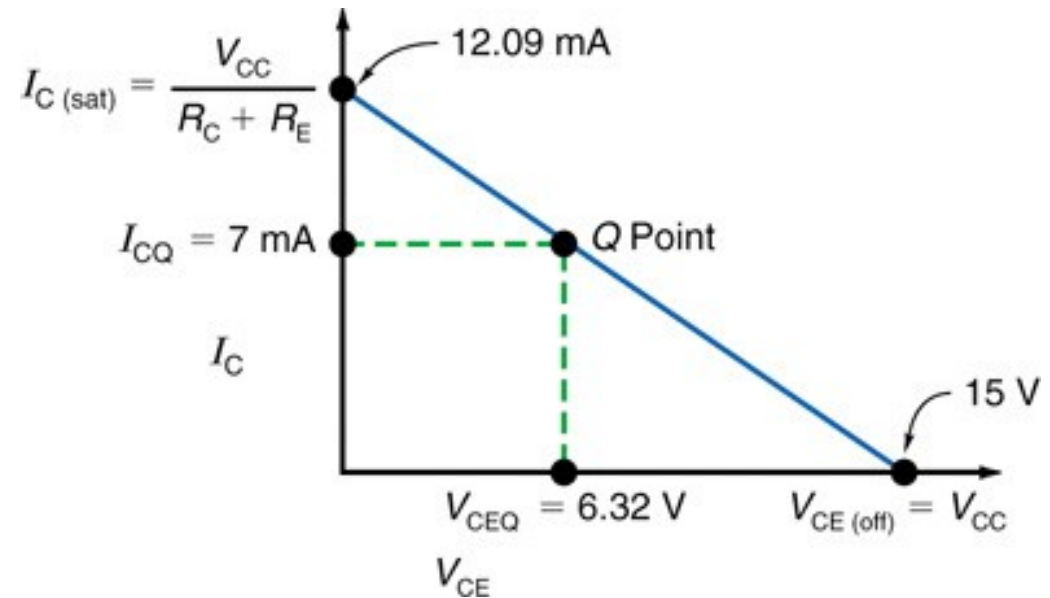
Voltage Divider Bias - Example

- Solve for V_B , V_E , I_E , I_C , V_C and V_{CE}
- Construct a dc load line showing the values of $I_{C(sat)}$, $V_{CE(off)}$, I_{CQ} and V_{CEQ}



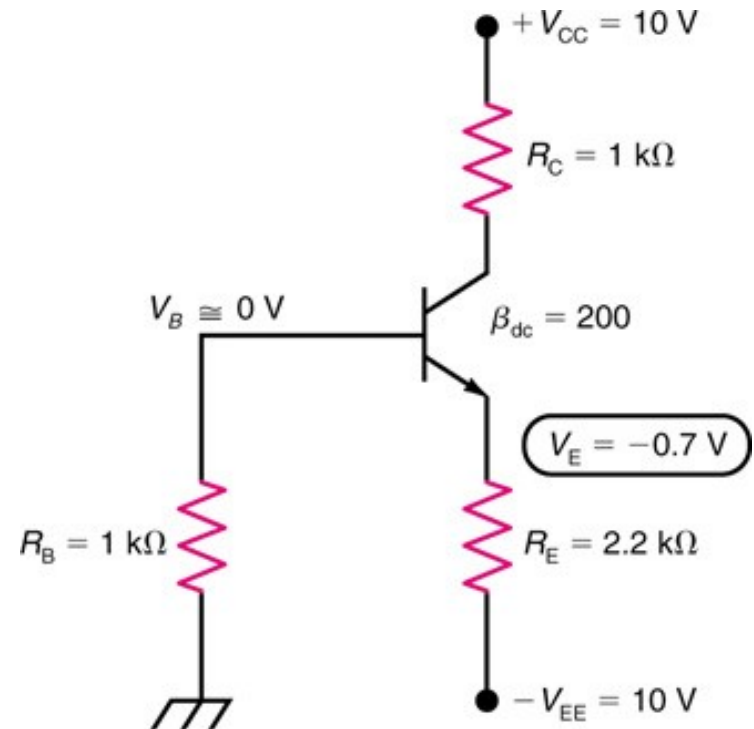
Transistor Biasing

- Fig. shows the **dc load line** for voltage-divider biased transistor circuit in previous slide
- End points and Q points are
 - $I_C (\text{sat}) = 12.09 \text{ mA}$
 - $V_{CE} (\text{off}) = 15 \text{ V}$
 - $I_{CQ} = 7 \text{ mA}$
 - $V_{CEQ} = 6.32 \text{ V}$



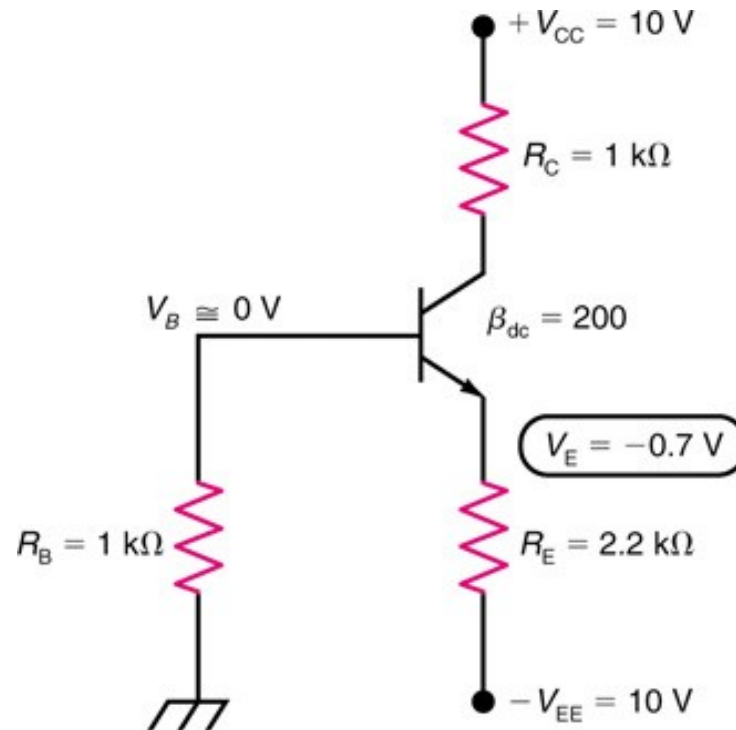
Transistor Biasing

- Both positive and negative power supplies are available
- **Emitter bias** provides a solid Q point that fluctuates very little with temperature variation and transistor replacement.

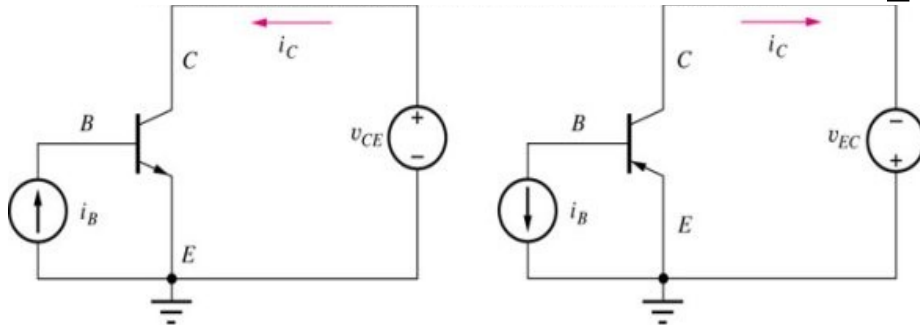


Emitter Bias - Example

- Solve for I_E , and V_C



i - v Characteristics Bipolar Transistor: Common-Emitter Output Characteristics

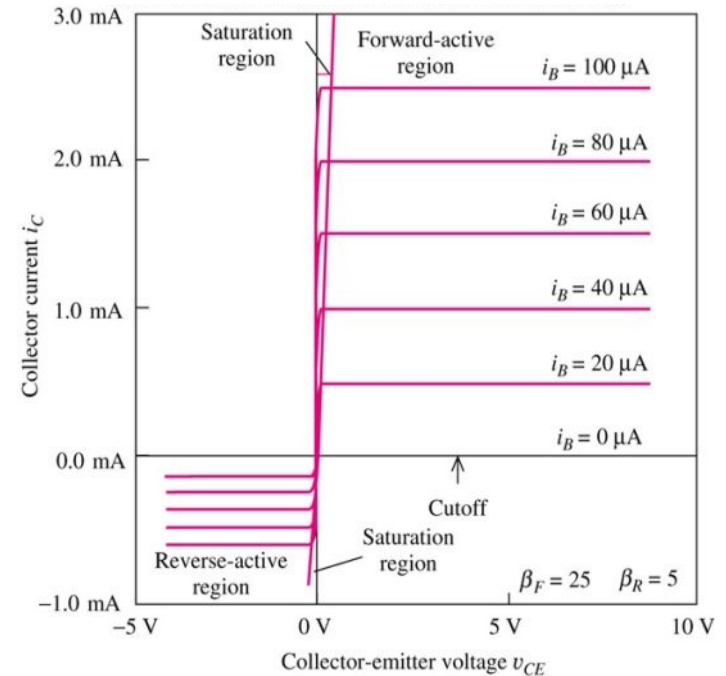


For $i_B=0$, the transistor is cutoff. If $i_B > 0$, i_C also increases.

For $v_{CE} > v_{BE}$, the *nnp* transistor is in the forward active region, $i_C = \beta_F i_B$ is independent of v_{CE} .

For $v_{CE} < v_{BE}$, the transistor is in saturation.

For $v_{CE} < 0$, the roles of collector and emitter are reversed.



Transistor Ratings

- A transistor, like any other device, has limitations on its operations.
- These limitations are specified in the manufacturer's data sheet.
- Maximum ratings are given for
 - Collector-base voltage
 - Collector-emitter voltage
 - Emitter-base voltage
 - Collector current
 - Power dissipation

Junction Breakdown Voltages

- If reverse voltage across either of the two *pn* junctions in the transistor is too large, the corresponding diode will break down.
- The emitter is the most heavily doped region, and the collector is the most lightly doped region.
- Due to these doping differences, the base-emitter diode has a relatively low breakdown voltage (3 to 10 V). The collector-base diode is typically designed to break down at much larger voltages.
- Transistors must therefore be selected in accordance with the possible reverse voltages in circuit.