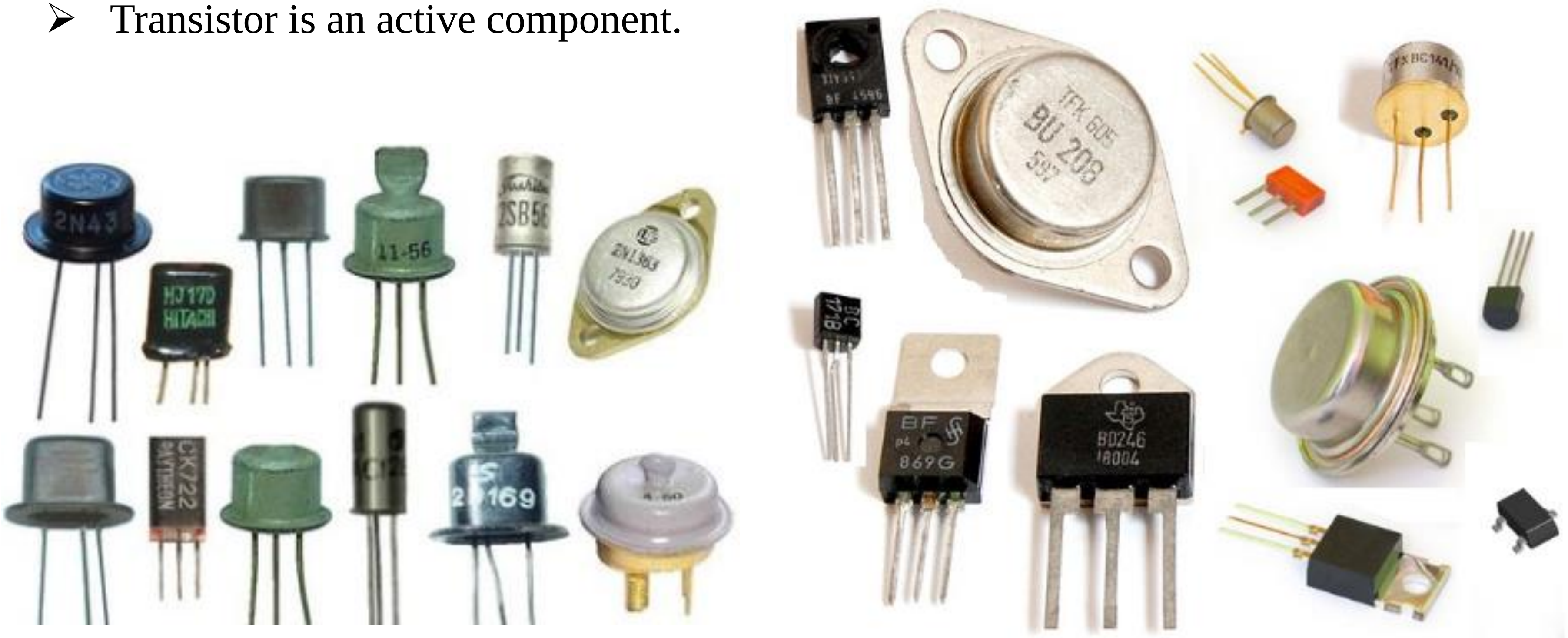
The Transistor

Transistor: It is a three-terminal, solid-state semiconductor device used to control the electric current or voltage between two of the terminals by applying an electric current or voltage to the third terminal.

- Transistor is an active component.



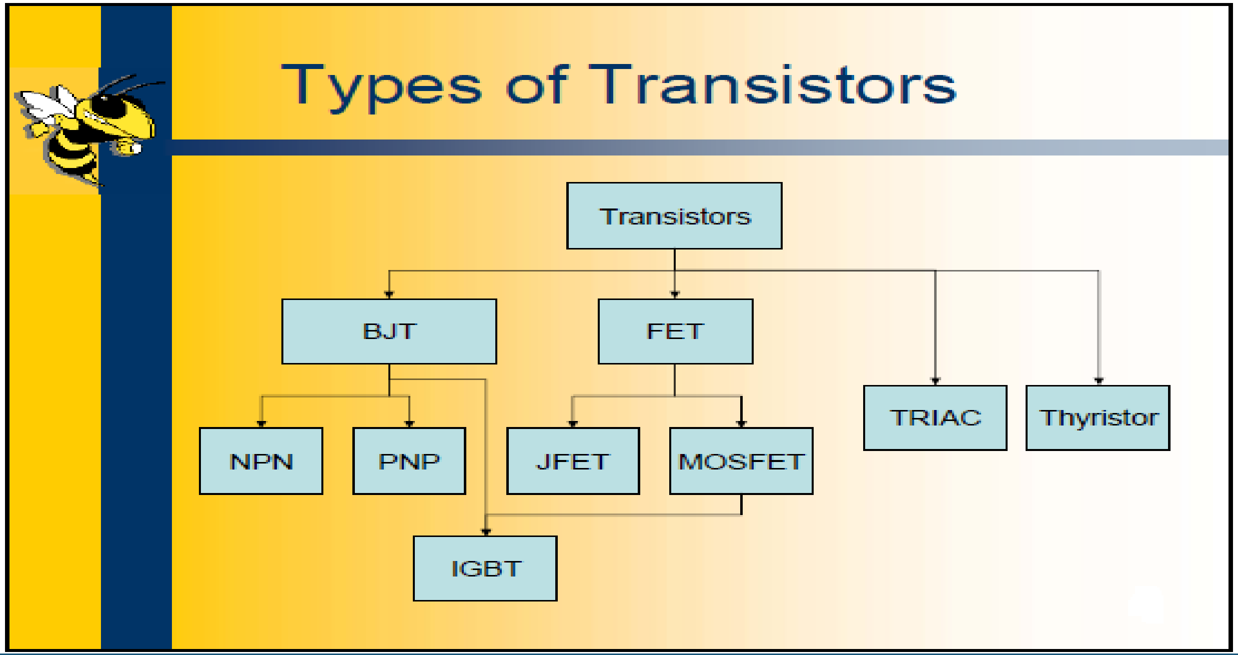
Examples of Different Transistors Packages

Week No -3

- Using the transistor as a switch
- Regions of operation
- Transistor as a switch (cut off and saturation)

Over view

It is very important to study the transistor as a switch because it is now used in each field of industrial to control the operation of electronic circuit and control the speed of DC and AC motors.



Power Electronic devices that can switch on or off

- Power Transistors (BJT)
- IGBTs
- MOSFETs

The **IGBT** is now the most commonly used for drives

Bipolar Junction Transistors

The Bipolar Junction Transistor (BJT):

The BJT is the most common transistor. It consists of three sections of semiconductors: an emitter, a base and a collector .In an npn-type BJT, the emitter and the collector are made of n-type semiconductors and the base is made of a p- type semiconductor

Introduction

The basic of electronic system nowadays is semiconductor device. The famous and commonly use of this device is BJTs (Bipolar Junction Transistors). It can be use as amplifier and logic switches. BJT consists of three terminal:

→ Collector: C
→ Base : B
→ Emitter : E

Two types of BJT : pnp and npn

Transistor Construction

3 layer semiconductor device consisting:

- **2 n- and 1 p-type layers of material → npn transistor**
- **2 p- and 1 n-type layers of material →pnp transistor**

The term bipolar reflects the fact that holes and electrons participate in the injection process into the oppositely polarized material

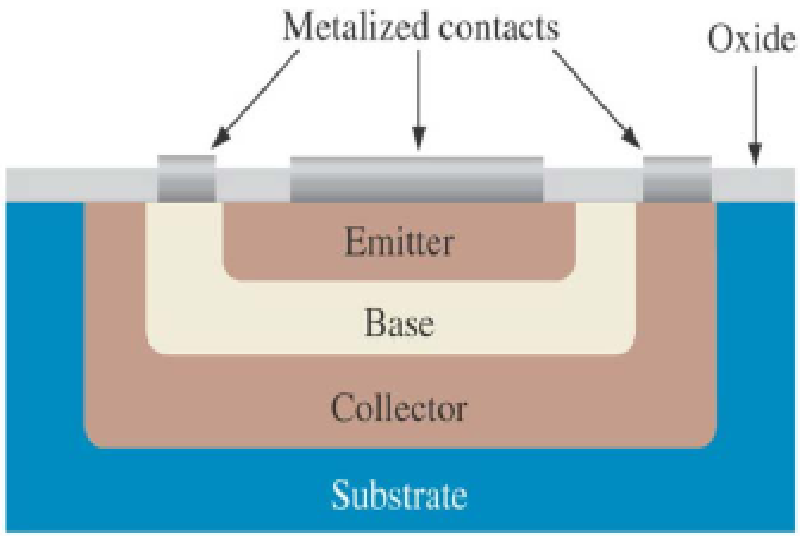
A single pn junction has two different types of bias:

- **forward bias**
- **reverse bias**

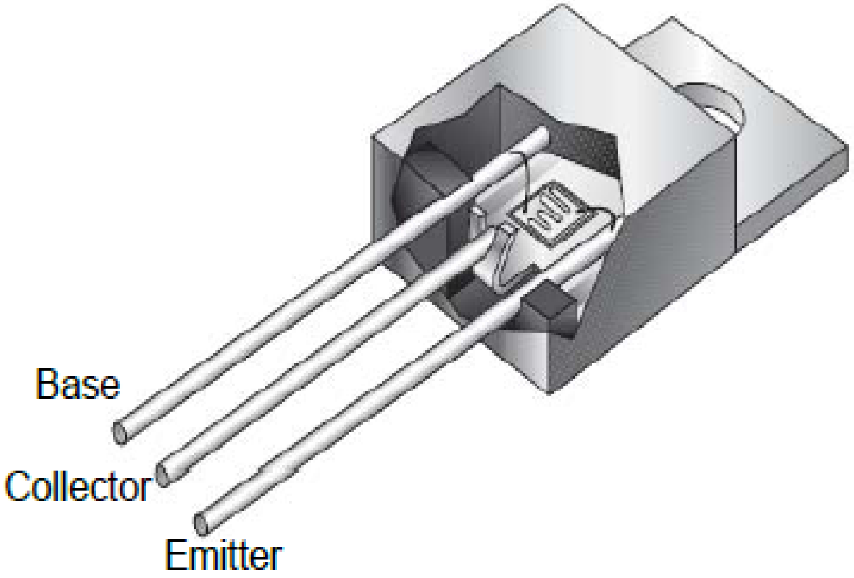
Thus, a two-pn-junction device has four types of bias.

Bipolar Junction Transistor (BJT)

- It is constructed with *three* doped semiconductor regions separated by *two* PN junctions.
- The three regions are called **emitter**, **base**, and **collector**.
- The base is lightly doped and very narrow compared with the heavily doped emitter and moderately doped collector.
- It is used as an electrical signal amplifier or an electronic switch.
- Bipolar: refers to the use of both holes and electrons as current carriers.



Basic BJT construction



BJT package Example

Position of the terminals and symbol of BJT

- Base is located at the middle and more thin from the level of collector and emitter
- The emitter and collector terminals are made of the same type of semiconductor material, while the base of the other type of material

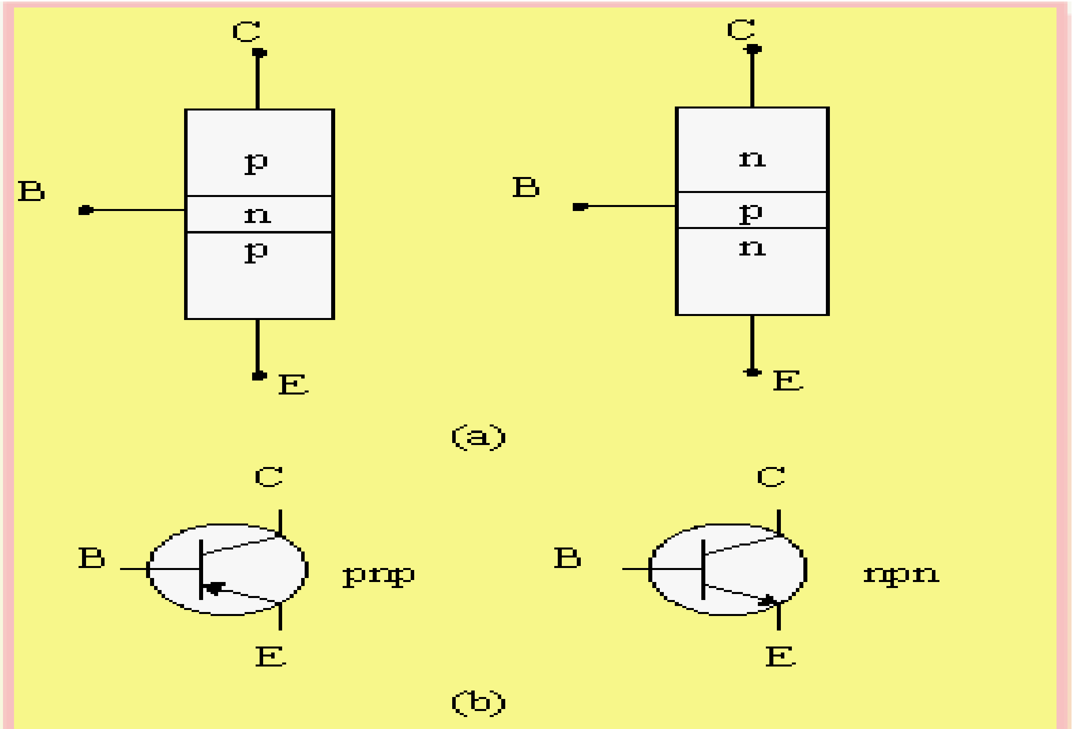
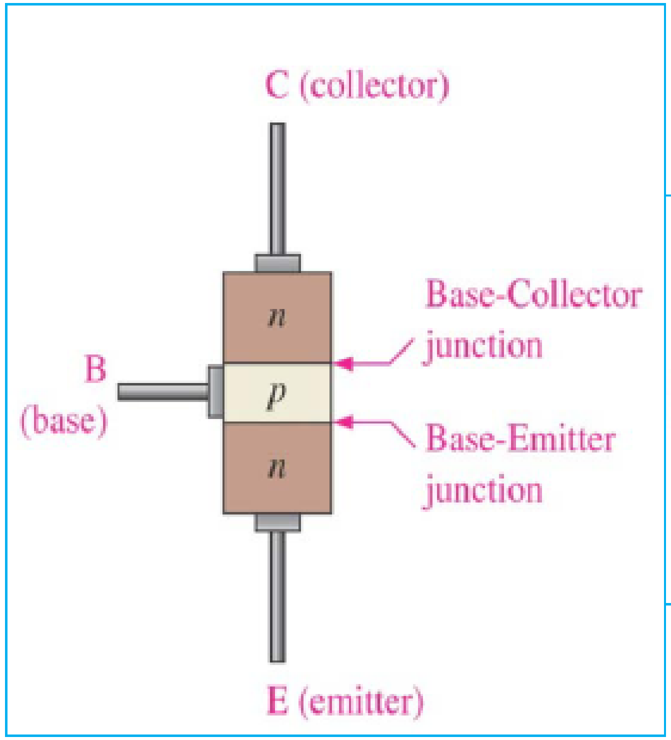
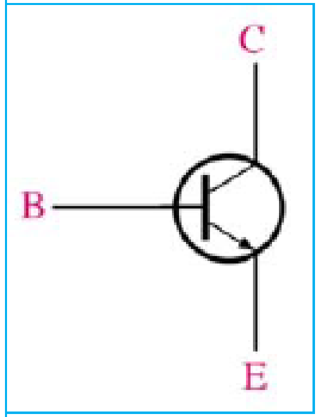


Figure shown (a) Position of the terminals (b) type of BJT

Types of BJTs

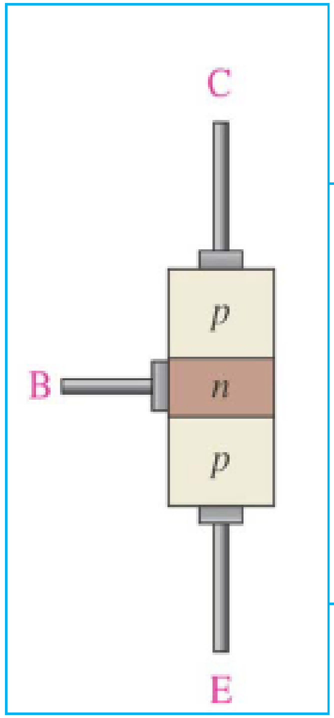
npn

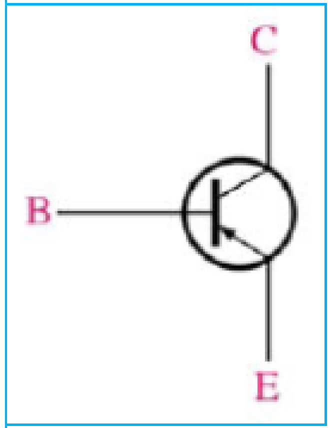




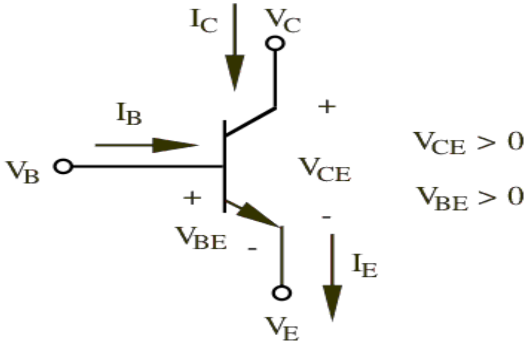
npn Symbol

pnp





pnp Symbol

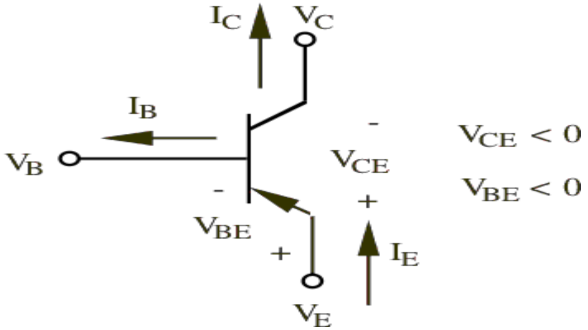


$$V_{BE} \square 0.7 \text{ V}$$

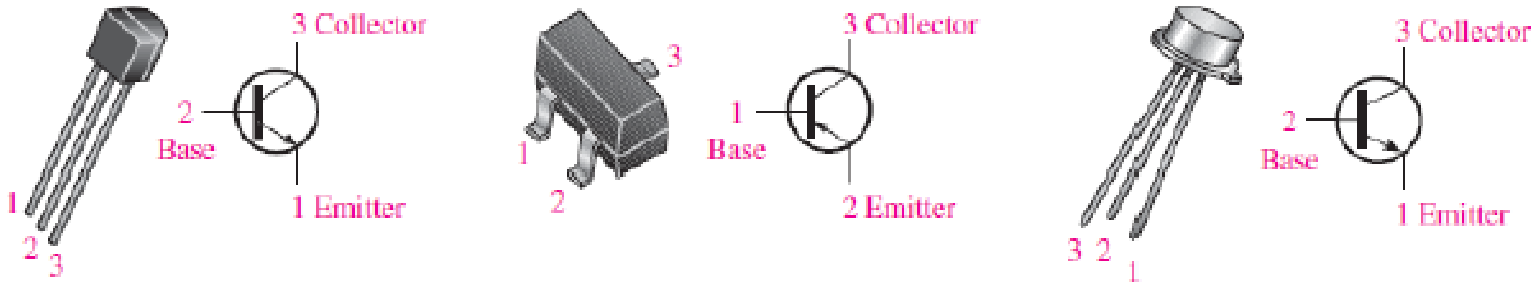
$$I_E = I_C + I_B$$

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

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

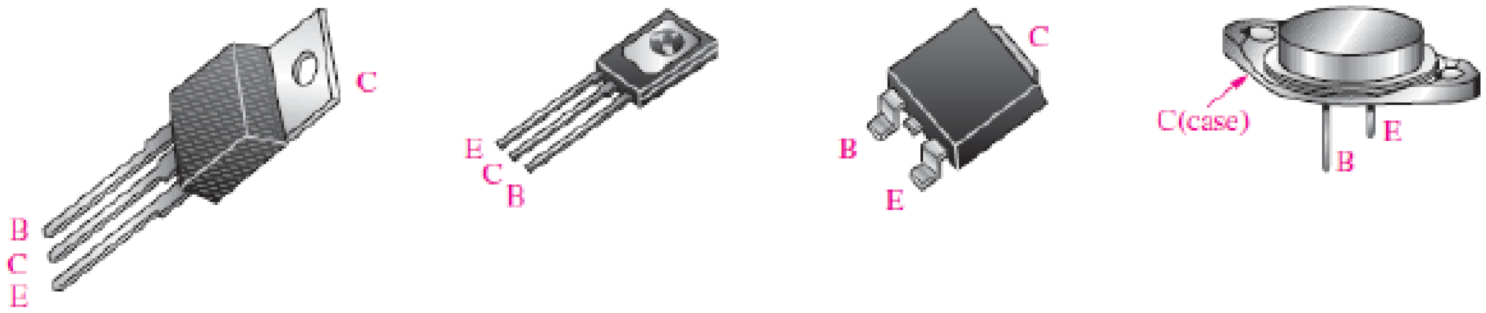


Examples of BJTs



(a) TO-92 (b) SOT-23 (c) TO-18. Emitter is closest to tab.

General-purpose/small-signal transistors

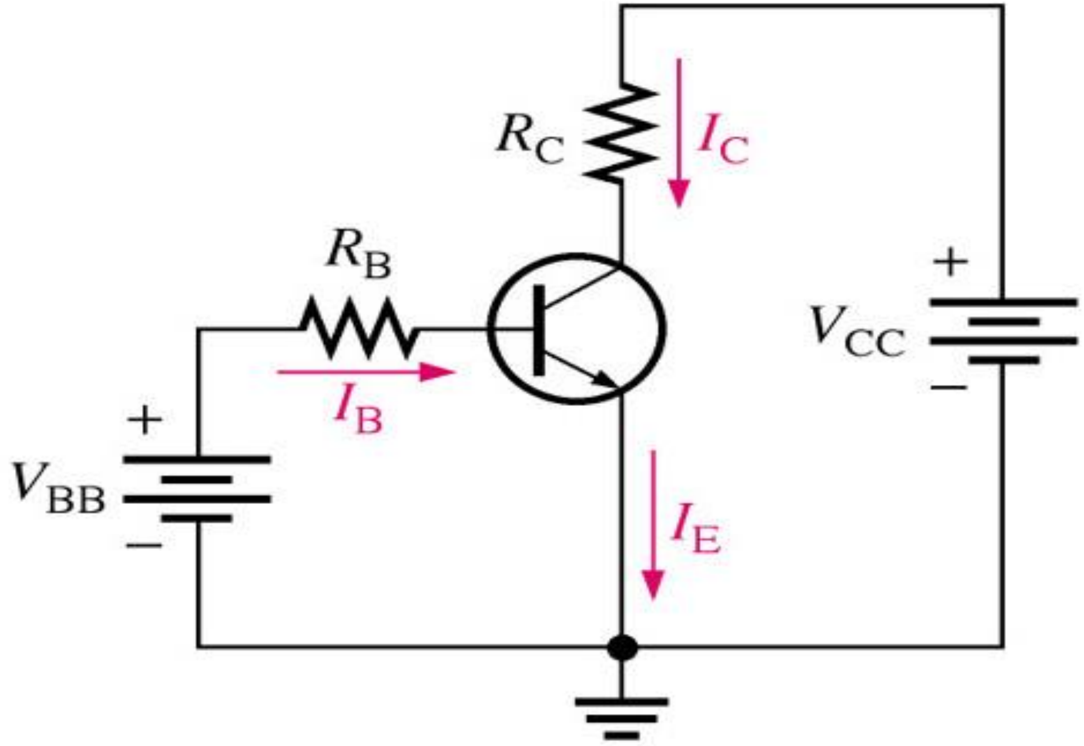


(a) TO-220 (b) TO-225 (c) D-Pack (d) TO-3

Power transistors

Basic Transistor Operation

Look at this one circuit as two separate circuits, the base-emitter(left side) circuit and the collector-emitter(right side) circuit. Note that the emitter leg serves as a conductor for both circuits.

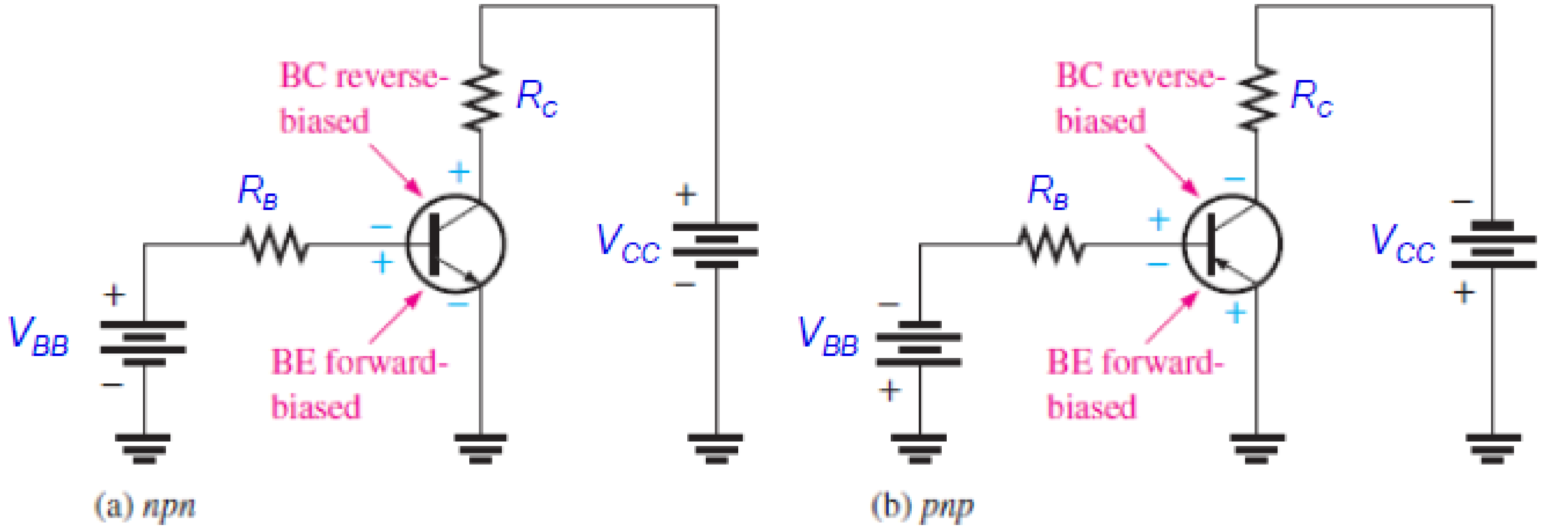


(a) *npn*

Common Emitter BJT Circuit

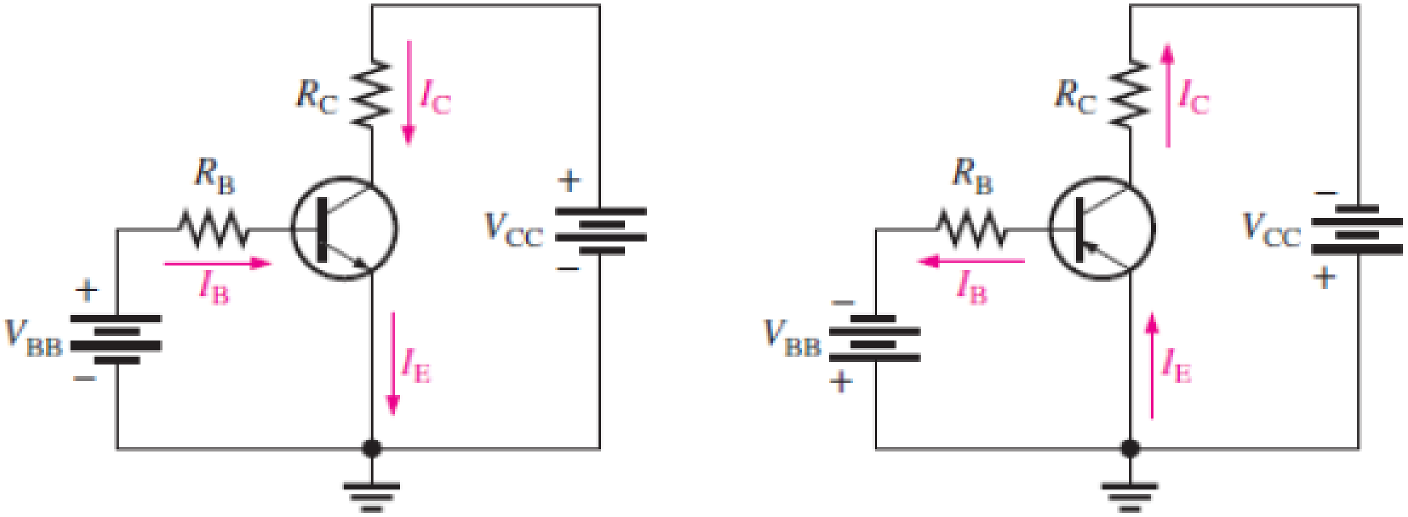
- In order for a **BJT** to operate properly as an amplifier, the two **pn** junctions must be correctly biased with external **dc** voltages.
- The operation of **pnp** is similar to the **npn** except that the roles of electrons and holes, bias voltage polarities, and current directions are all reversed.

Forward-Reverse Bias for BJT Operation as an amplifier



- The BE junction in both cases is forward-biased .
- The BC junction in both cases is reversed-biased.

BJT Currents



(a) *npn* (b) *pnp*

For Conventional current direction (holes current) we have:

$$I_E = I_B + I_C$$

I_B is very small due to light doping

$$I_E \simeq I_C$$

Collector current is much greater than base current and hence the current gain

Transistor Characteristics and Parameters

There are three key dc voltages and three key dc currents to be considered. Note that these measurements are important for troubleshooting.

I_B: dc base current

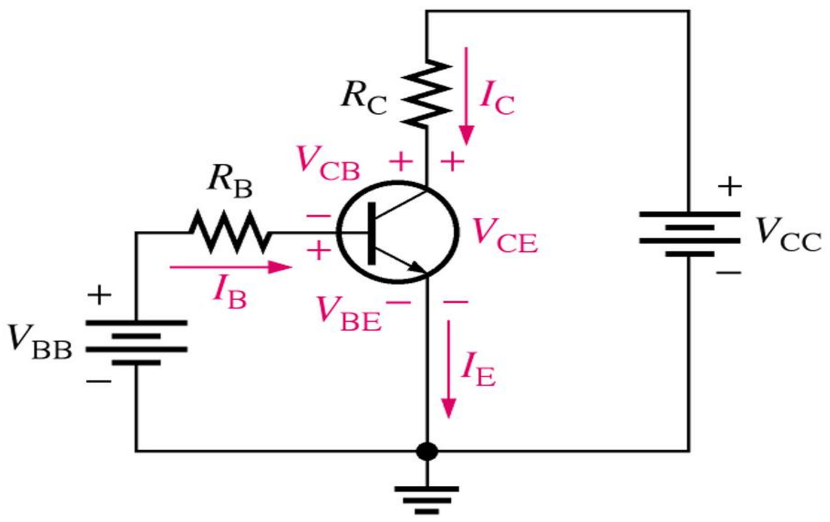
I_E: dc emitter current

I_C: dc collector current

V_{BE}: dc voltage across base-emitter junction

V_{CB}: dc voltage across collector-base junction

V_{CE}: dc voltage from collector to emitter



PNP And NPN Transistors

BJT Parameters

DC Beta (β_{DC}) and DC Alpha (α_{DC})

- The **dc current gain** of a transistor (β_{DC}) is the ratio of dc collector current (I_C) to the dc base current (I_B).

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

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

- In data sheets, the hybrid ***h***-parameters are used for transistors where $h_{FE} = \beta_{DC}$.

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

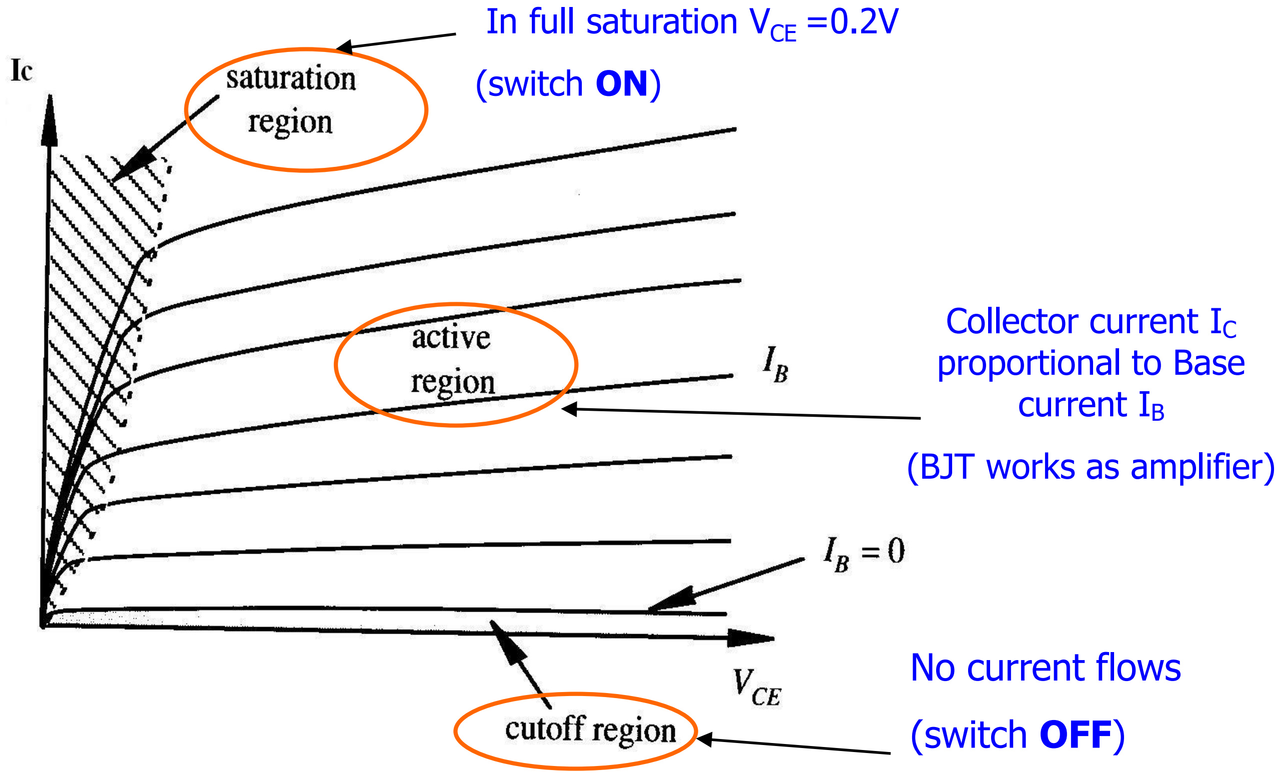
$$\alpha_{DC} = \frac{I_C}{I_E}$$

Typical values of α_{DC} from 0.95 to 0.99 or less than 1.

BJT Operation

- Emitter is grounded and input voltage is applied to Base.
- Base-Emitter starts to conduct when V_{BE} is about 0.7V, I_C flows with $I_C = \beta_{DC} I_B$
- As I_B further increases, V_{BE} slowly increases to 0.7V, IC rises exponentially.
- As I_C rises, voltage drop across R_C increases and V_{CE} drops toward ground (transistor in saturation, no more linear relation between I_C and I_B)

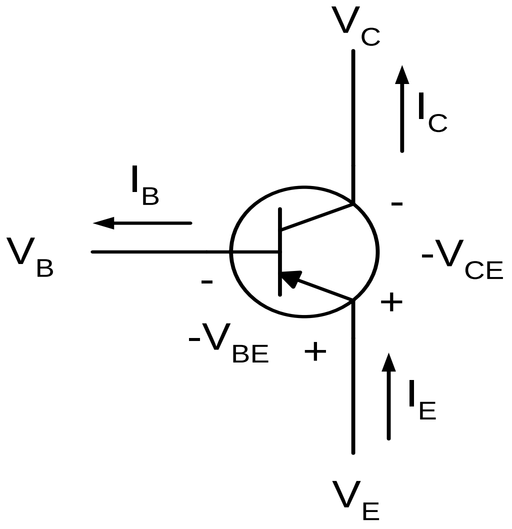
Common Emitter Characteristics



BJT Operation

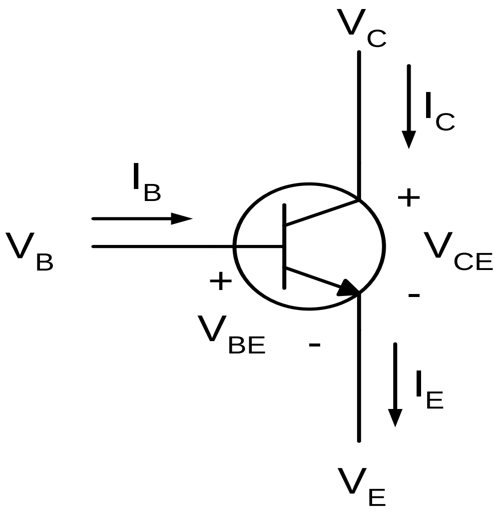
- Electrons diffuse from **E**mitter to **B**ase (from *n* to *p*) With $V_C > V_B > V_E$
- Depletion layer on the Base-Collector junction → no flow of electron allowed.
- The Base is thin and Emitter region is heavily doped → electrons have enough momentum to cross Base into Collector.
- Small base current I_B controls large current I_C through β_{DC} which functioning as a current gain of the amplifier.
- β_{DC} is temperature and voltage dependent.

PNP And NPN Transistors



Apply voltage LOW
to base to turn ON

$$V_{CE} = V_C - V_E$$
$$V_{BE} = V_B - V_E$$
$$I_E = I_C + I_B$$

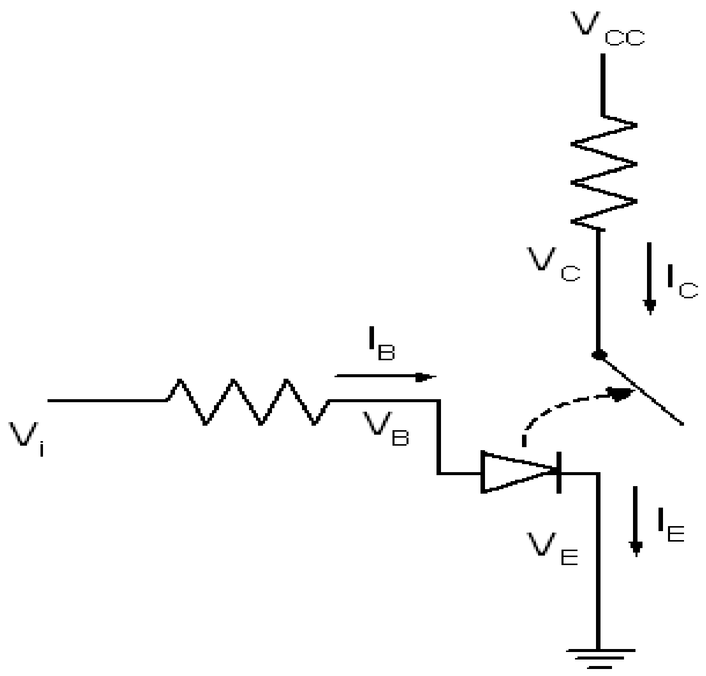


Apply voltage HIGH
to base to turn ON

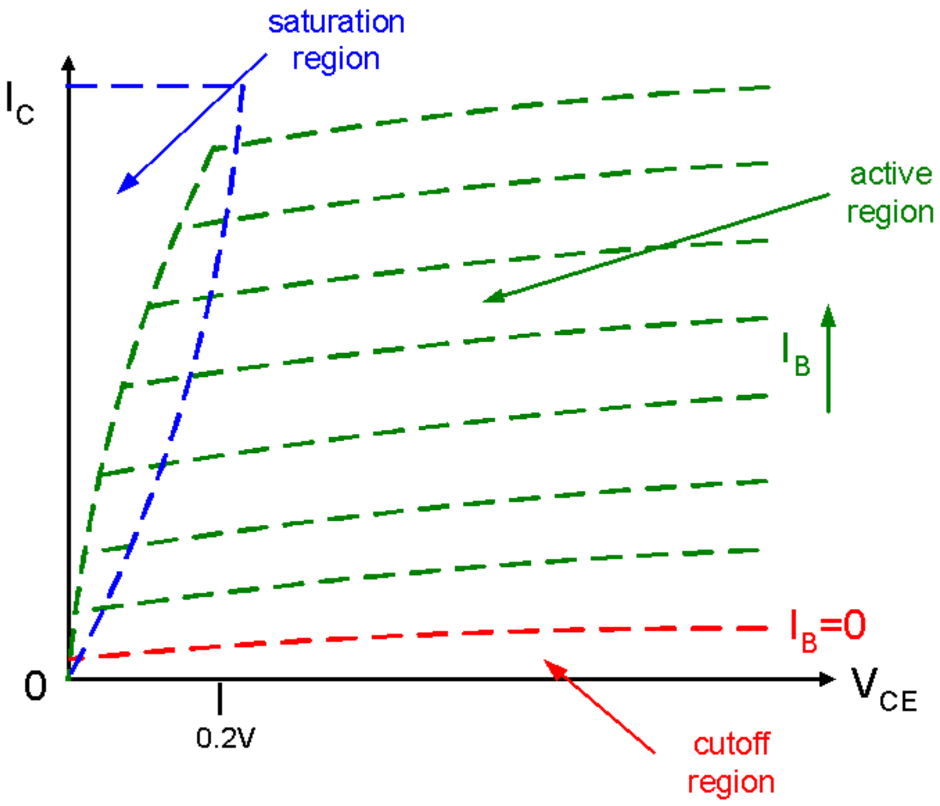
Active region	Saturation region	Cut-off region
• I_E increased, I_C increased • BE junction forward bias and CB junction reverse bias • Refer to the graf, $I_C \approx I_E$ • I_C not depends on V_{CB} • Suitable region for the transistor working as amplifier	• BE and CB junction is forward bias • Small changes in V_{CB} will cause big different to I_C • The allocation for this region is to the left of V_{CB} = 0 V.	• Region below the line of I_E=0 A • BE and CB is reverse bias • no current flow at collector, only leakage current

Diode Model of the npn BJT

- The diode is controlled by the voltage at B.
- When the diode is completely on, the switch is closed. This is the saturation region.
- When the diode is completely off, the switch is open. This is the cutoff region.
- When the diode is in between we are in the active region.



NPN Common Emitter Characteristics



$I_C = \beta I_B$

$V_{BE} = 0.7\ V$

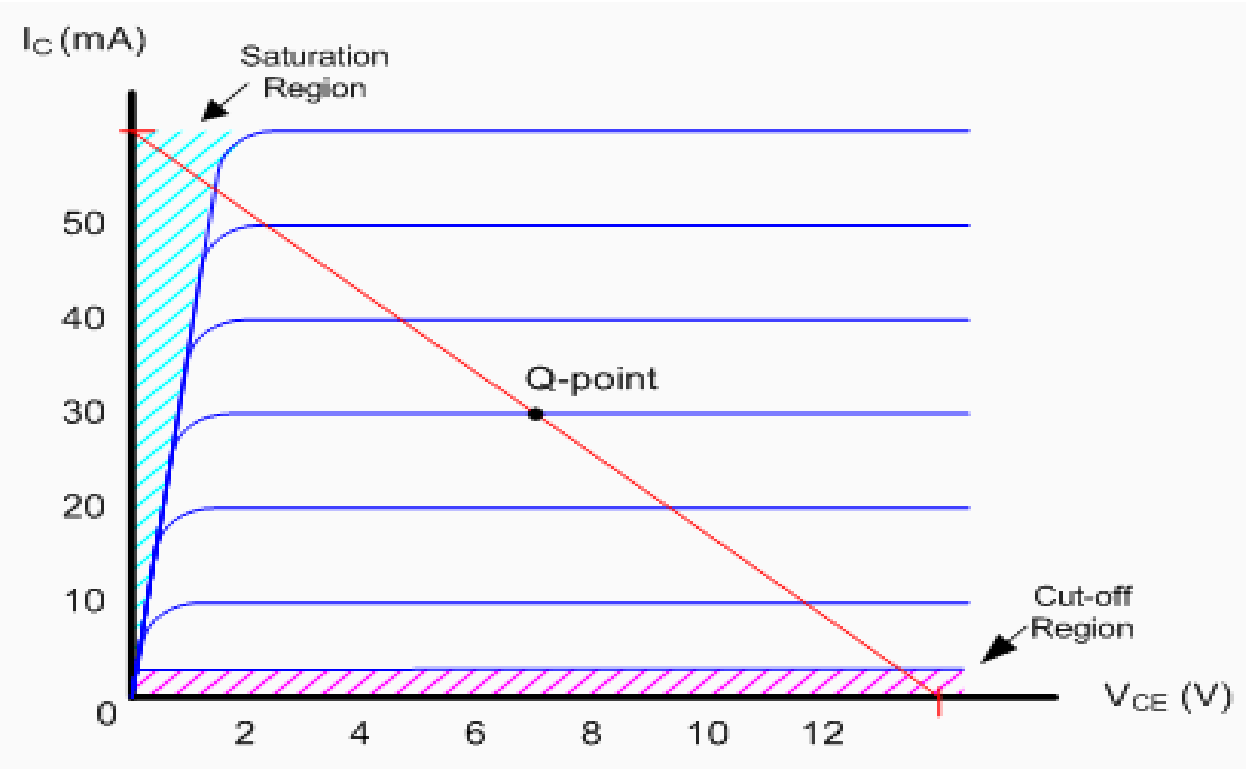
$$\alpha = \frac{I_C}{I_E}$$

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

$$0.9 < \alpha < 0.999$$

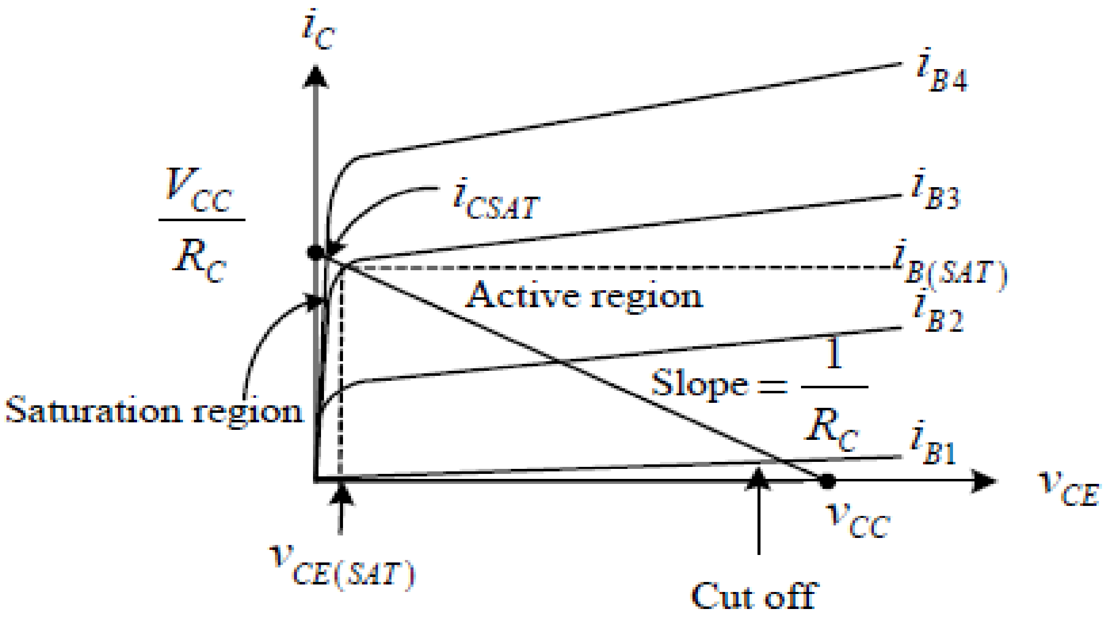
$$10 < \beta < 1000$$

$V_{BE} < 0.6\ V$



IC (mA)
Saturation Region
50
40
30
20
10
0
Q-point
Cut-off Region
VCE (V)
2
4
6
8
10
12

I −V output characteristics of BJT



Common Emitter configuration

Characteristics of Transistors

Cutoff Region

Not enough voltage at B for the diode to turn on.
No current flows from C to E and the voltage at C is V_{cc}.

Saturation Region

The voltage at B exceeds 0.7 volts, the diode turns on and the maximum amount of current flows from C to E.
The voltage drop from C to E in this region is about 0.2V but we often assume it is zero in this class.

Active Region

As voltage at B increases, the diode begins to turn on and small amounts of current start to flow through into the doped region. A larger current proportional to I_B, flows from C to E.
As the diode goes from the cutoff region to the saturation region, the voltage from C to E gradually decreases from V_{cc} to 0.2V.

$$I_C = \beta I_B$$

$$10 < \beta < 1000$$

Beta analysis of the operating point

If we assume that the BJT is operating in the active mode,

we can write:

$$I_C = \alpha \ I_E$$

Applying KCL to the transistor yield $I_E = I_C + I_B$

Substituting for I_E:

$$\frac{I_C}{\alpha} = I_C + I_B$$

$$\left(\frac{1}{\alpha} - 1\right) \cdot I_C = I_B$$

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

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

We define: $\beta = \frac{\alpha}{1-\alpha}$

Then:

$$I_C = \beta \cdot I_B$$

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

The variable β is another way of expressing the large signal forward current gain. In common-emitter configurations, it is more convenient to use than α.

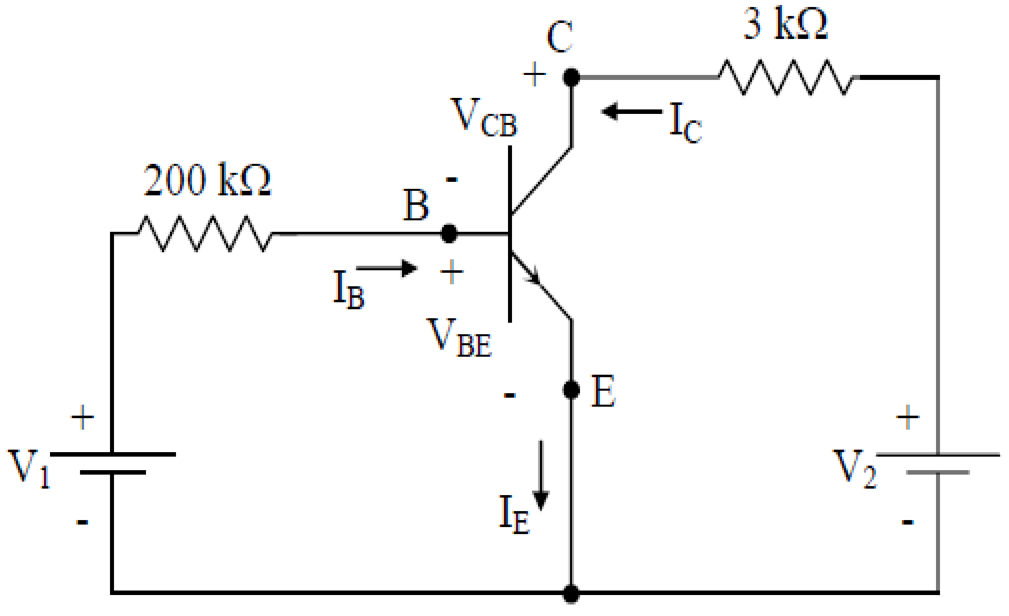
The following examples show how beta can be used to calculate the operating point of a BJT.

Example 1: Find I_C and V_{CB} in the circuit shown in **Figure. Ignore reverse saturation currents and Let V1=5 V, V2=10 V and** $\beta = 100$

Ans.

I_C=2.15 mA

V_{CB} =2.85 V

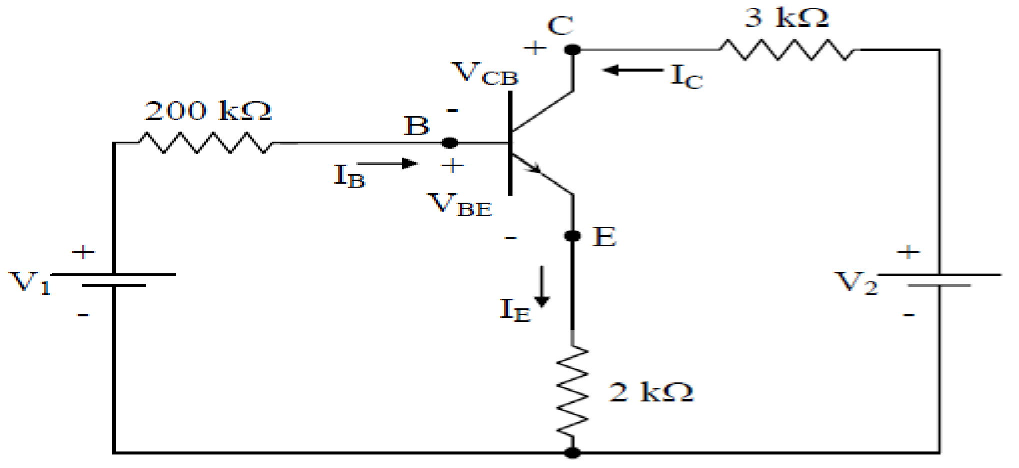


npn-type BJT in
Common-emitter Configuration

Example 2: Find I_C and V_{CB} in the circuit shown in

Figure. Ignore reverse saturation currents and

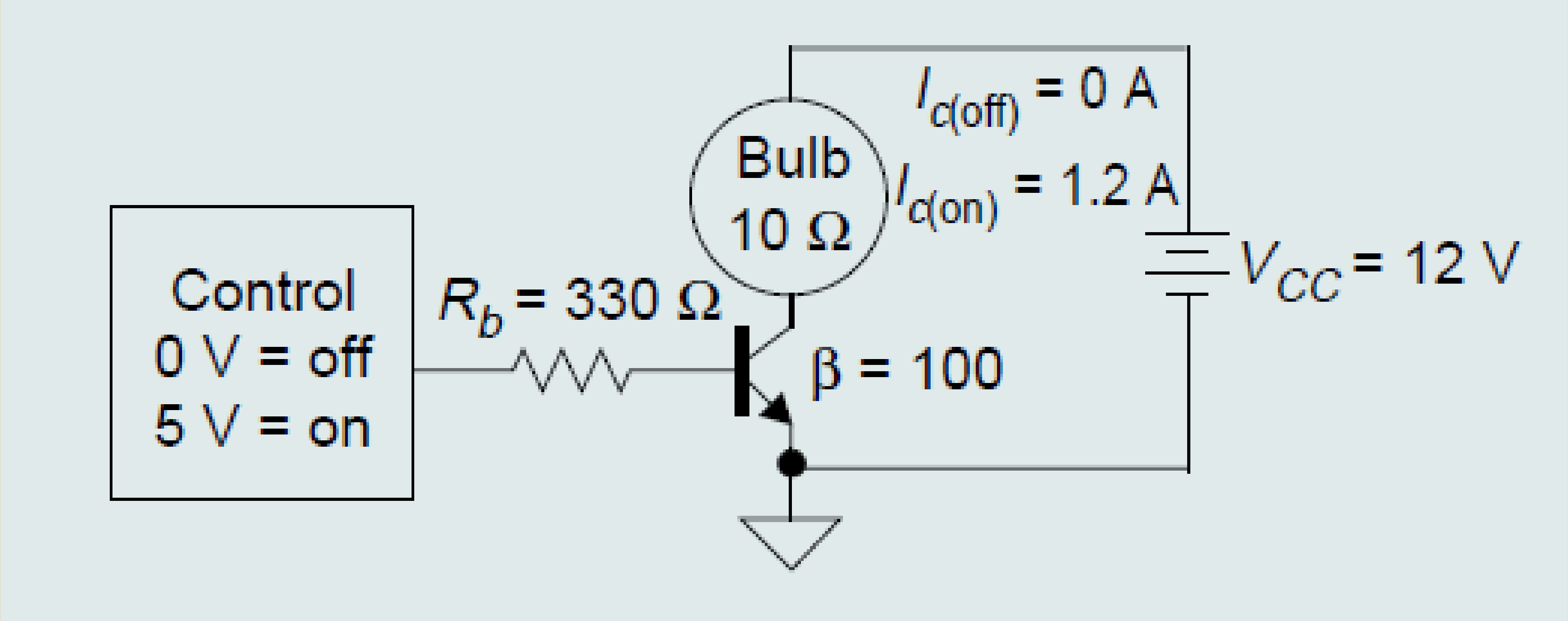
let $V1=5V$, $V2=10V$ and $\beta = 100$



npn-type BJT in Common-emitter Configuration, with Emitter Resistance

EXAMPLE

Design the transistor switching circuit shown in Figure



Step 1. Calculate the collector current when the bulb is in the on state. The supply voltage is divided by the resistance of the load (bulb).

$I_C = I_L = V_{CC}/R_L = 12\ V/10\ \Omega = 1.2\ A$

Step 2. Using beta, calculate the needed base current.

$I_B = I_C/\beta = 1.2\ A/100 = 12\ mA$

Step 3. Calculate the value of V_{RB}.

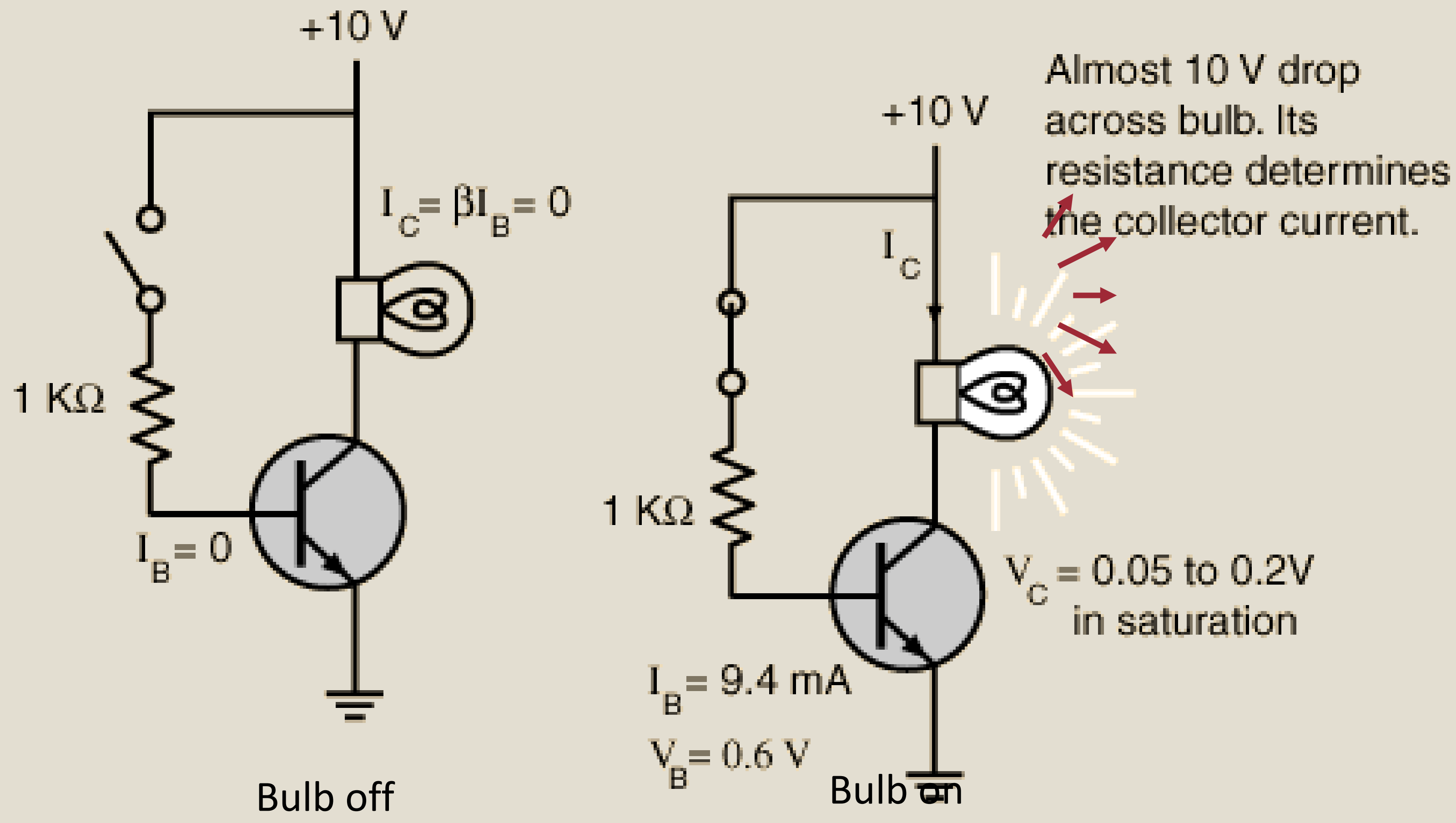
$V_{RB} = V_{control} - V_{BE} = 5\ V - 0.7\ V = 4.3\ V$

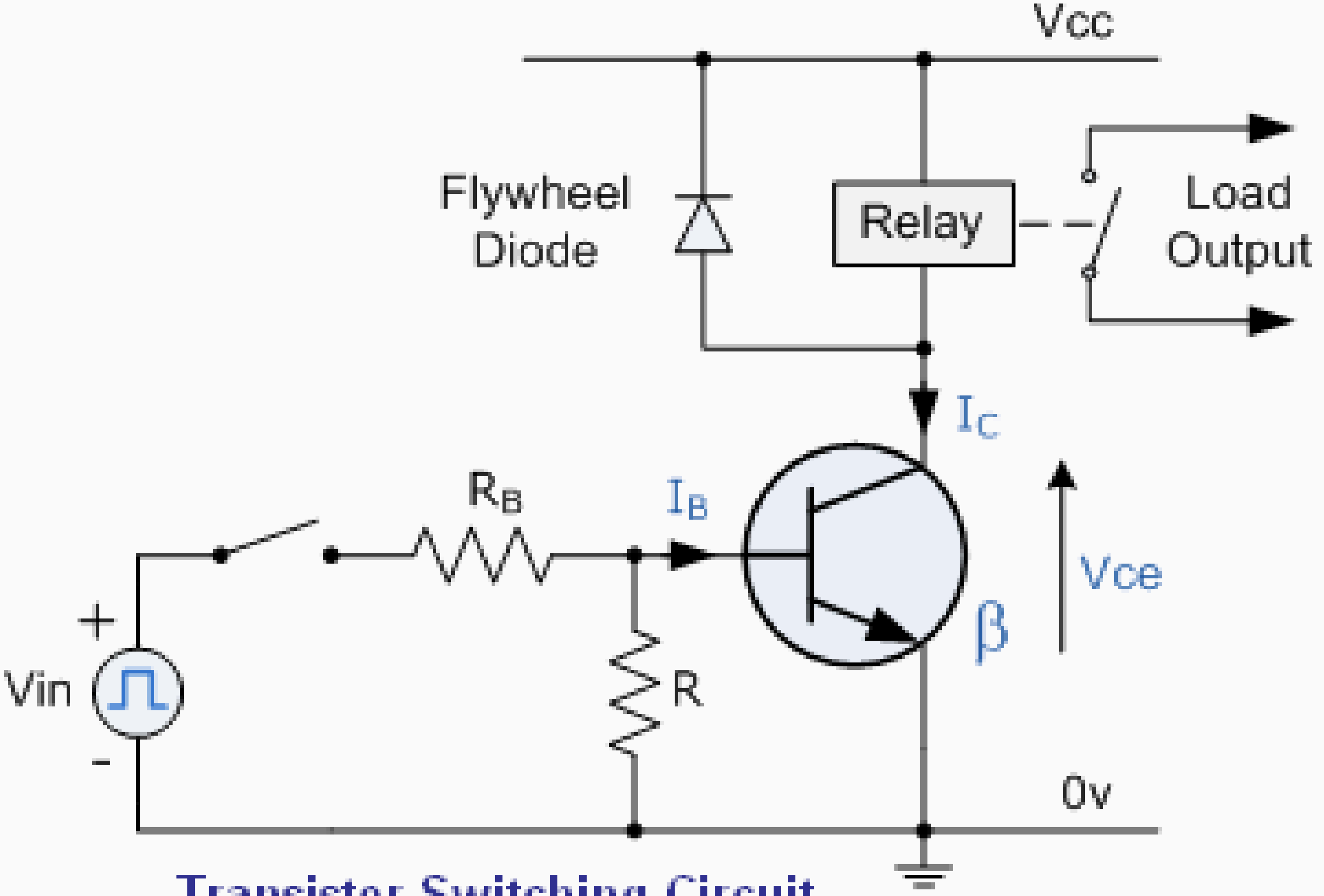
Step 4. Calculate the value of R_b.

$R_b = V_R B/I_B = 4.3\ V/12\ mA = 358\ \Omega$ **(Use the next lower standard value, 330 Ω.)**

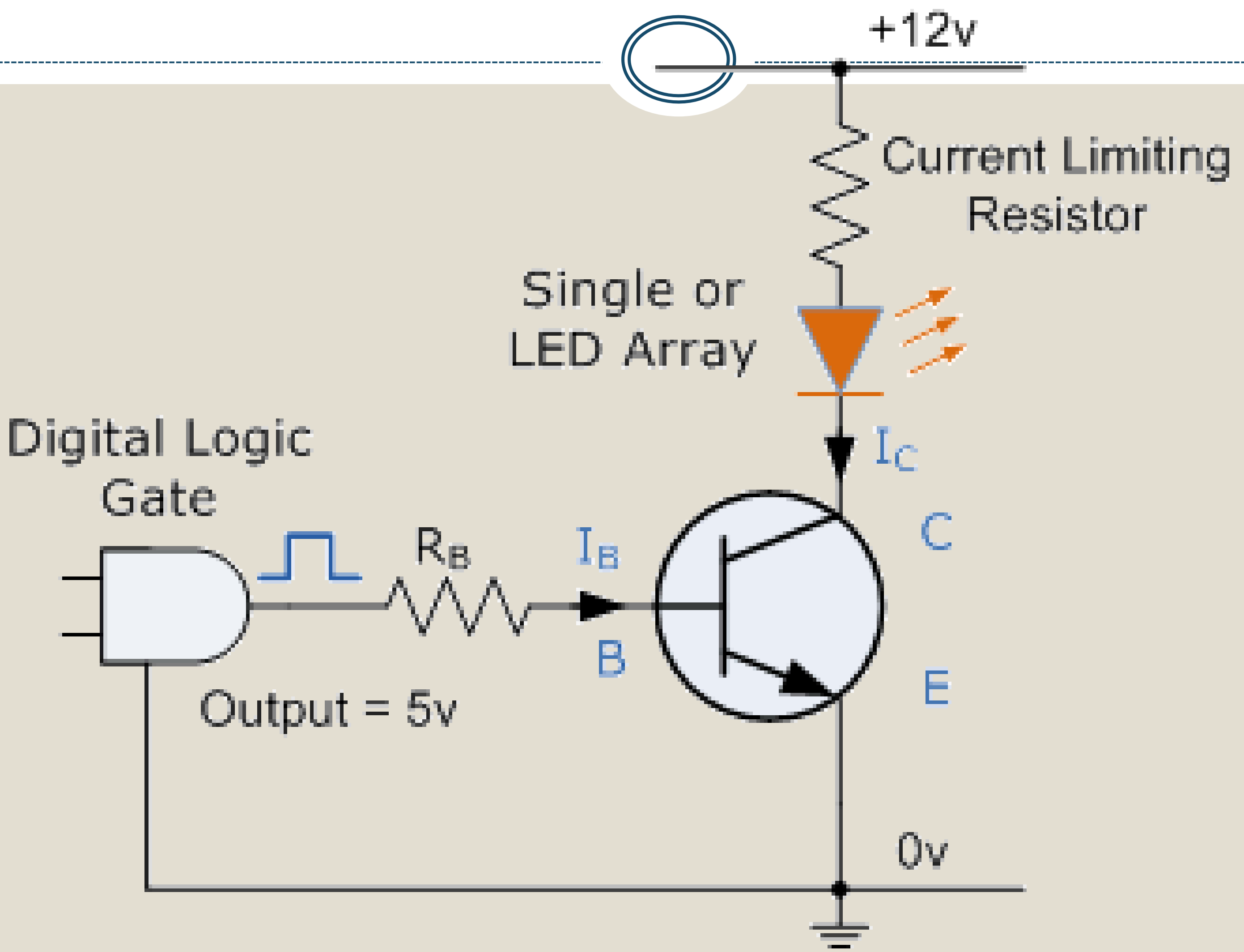
Step 5. Draw the switching circuit. (The switching circuit is shown in Figure.)

Using the transistor as a switch



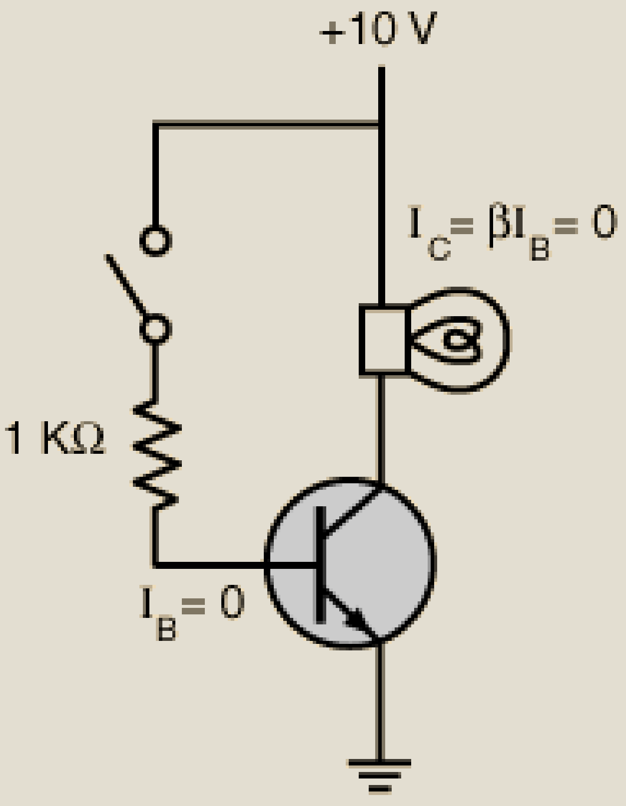


Transistor Switching Circuit

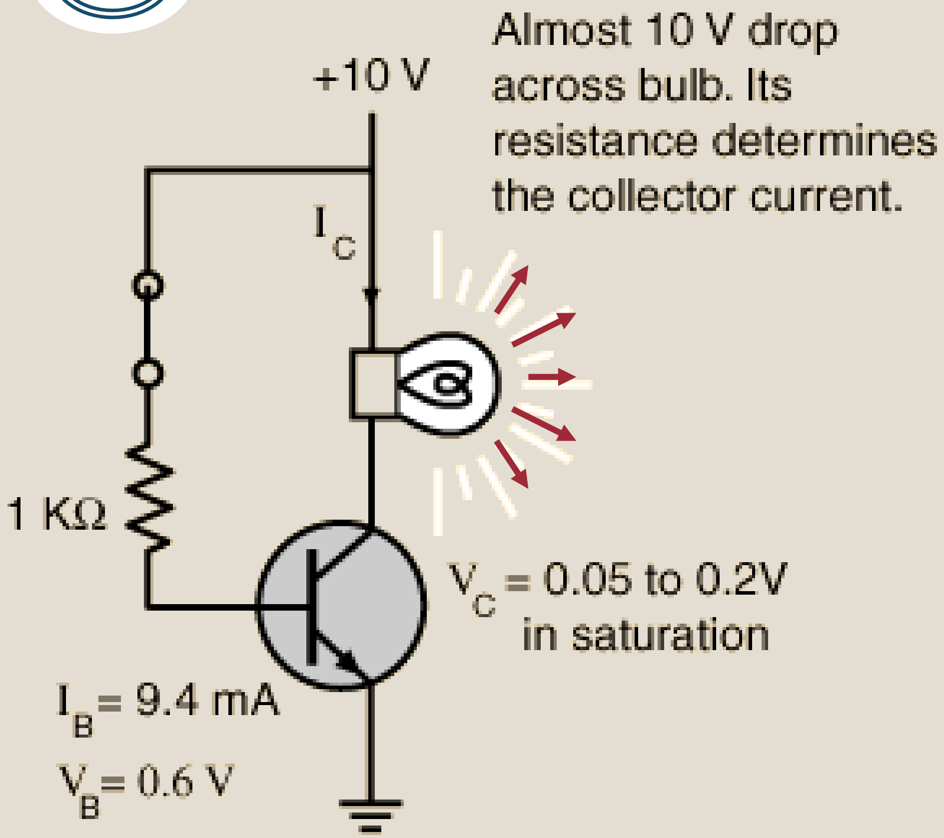


+12v
Current Limiting
Resistor
Single or
LED Array
Digital Logic
Gate
I_C
C
R_B
I_B
B
E
Output = 5v
0v

Using the transistor as a switch



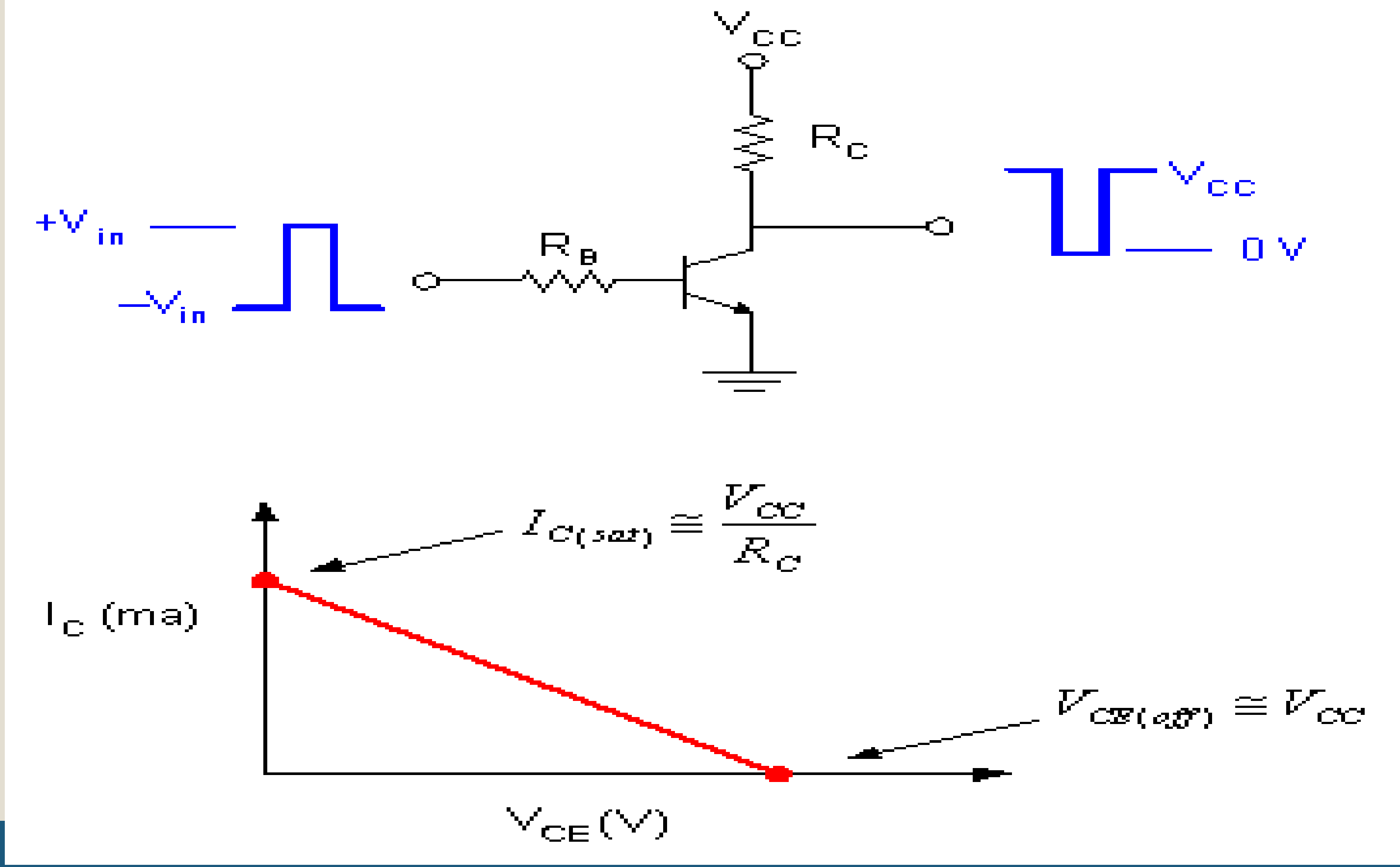
Bulb off



Bulb on

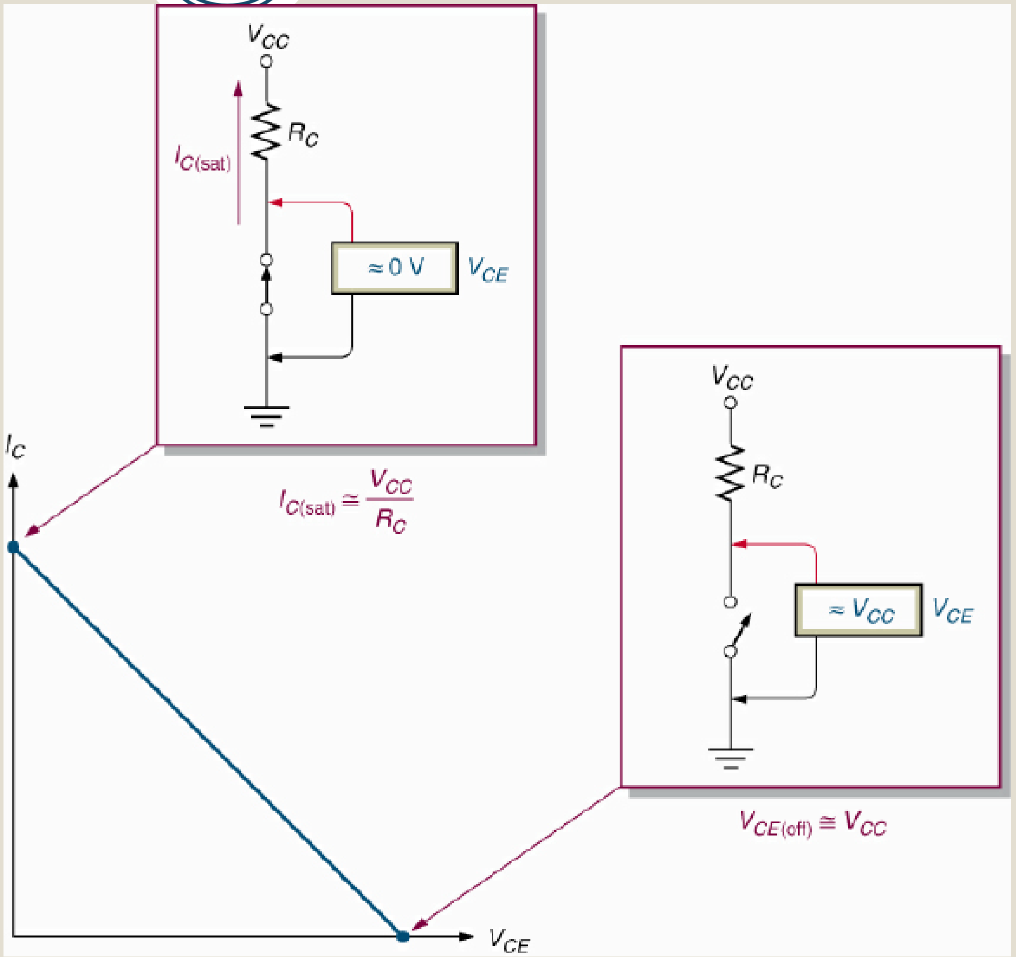
The BJT as a Switch

- The BJT can be used as a switch by driving it back and forth between saturation (closed) and cutoff (open).



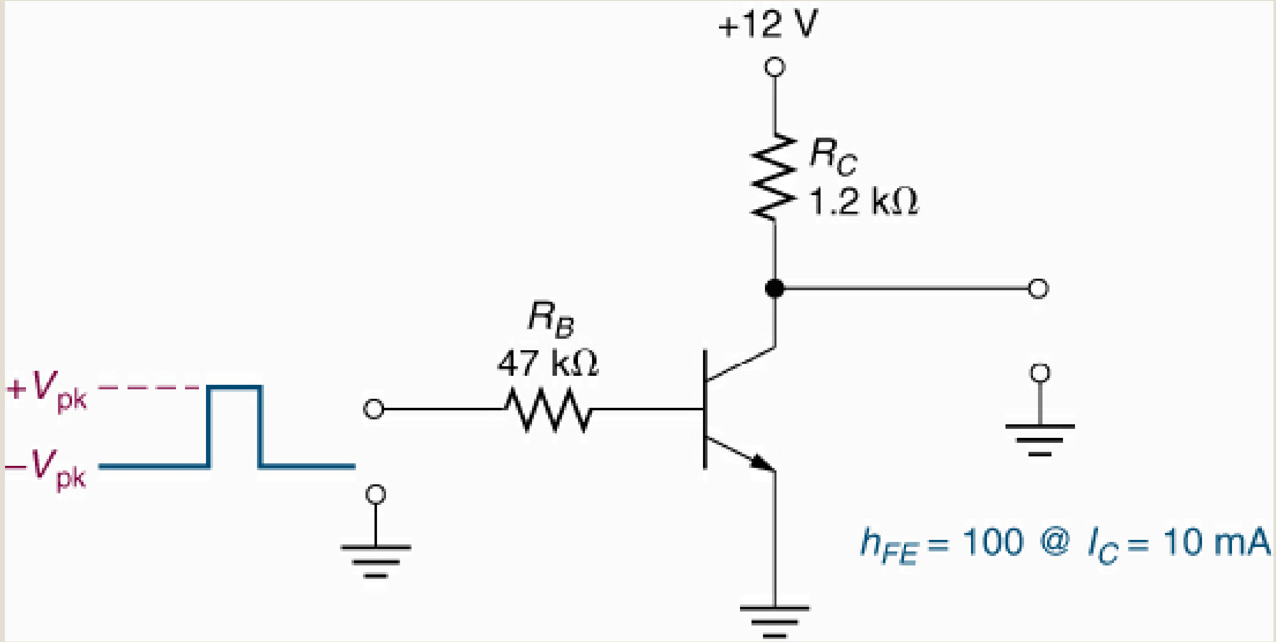
Open and Closed BJT Switch

- **When operated in saturation, the BJT acts as a closed switch.**
- **When operated in cutoff, the BJT acts as an open switch.**



Saturation

- **Transistor saturation can be guaranteed by designing the circuit so that:**
  - $+V_{pk} = V_{CC}$
  - I_B is greater than $I_{C(sat)} / h_{FE}$



Example 1

(a) For a given BJT: I_B = 50 μA and I_C = 3.65 mA . Find the dc current gain (β_{DC}), I_E , and α_{DC} .

(b) In a certain BJT: I_B = 50 μA and β_{DC} = 200. Find I_C , I_E , and α_{DC} . (HOME WORK)

SOLUTION

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.65 \text{ mA}}{50 \ \mu\text{A}} = \frac{3.65\times10^{-3}}{50\times10^{-6}} = 73$$

$$I_E = I_B + I_C = 50\times10^{-6} + 3.65\times10^{-3} = 3.7\times10^{-3} = 3.7 \text{ mA}$$

$$\alpha_{DC} = \frac{I_C}{I_E} = \frac{3.65 \text{ mA}}{3.7 \text{ mA}} = \frac{3.65\times10^{-3}}{3.7\times10^{-3}} = 0.986$$

DC Analysis of BJT Circuit

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

Also, by Ohm's law,

$$V_{R_B} = I_B R_B$$

Substituting for V_{R_B} yields

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

Solving for I_B,

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

The voltage at the collector with respect to the grounded emitter is

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

Since the drop across R_C is

$$V_{R_C} = I_C R_C$$

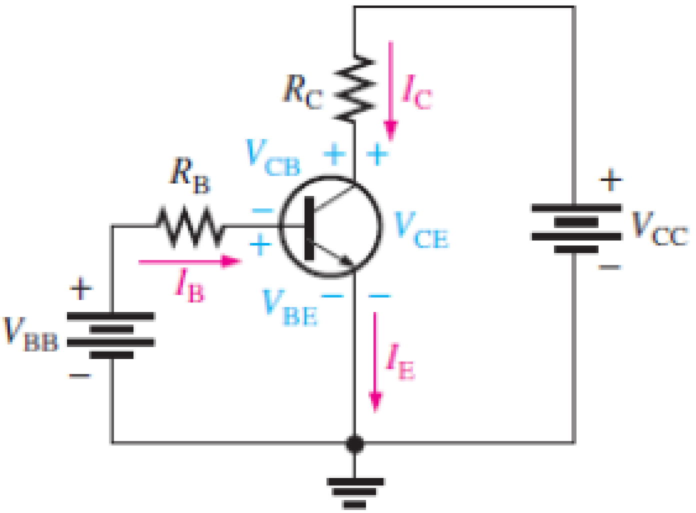
the voltage at the collector with respect to the emitter can be written as

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

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

The voltage across the reverse-biased collector-base junction is

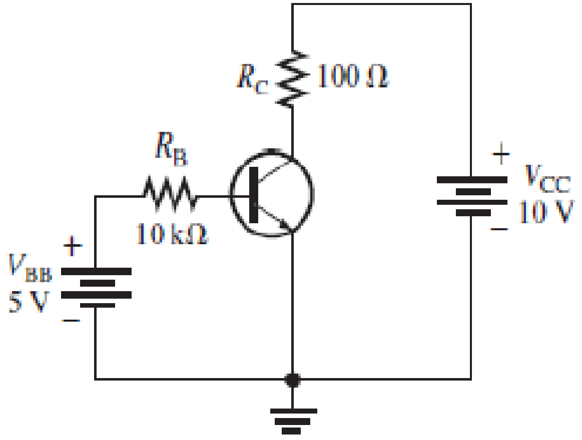
$$\boxed{V_{CB} = V_{CE} - V_{BE}}$$



DC Bias Circuit of *npn* Transistors

Example 2

1) For the given npn BJT circuit if $\beta_{DC} = 150$, find: I_B, I_C, I_E, V_{BE}, V_{CE}, and V_{CB}.
2) Repeat the problem if $\beta_{DC} = 90$, $R_B = 22\ k\Omega$, $R_C = 220\ \Omega$, $V_{BB} = 6V$, $V_{CC} = 9V$. (HOME WORK)



SOLUTION

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

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

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

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

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

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

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

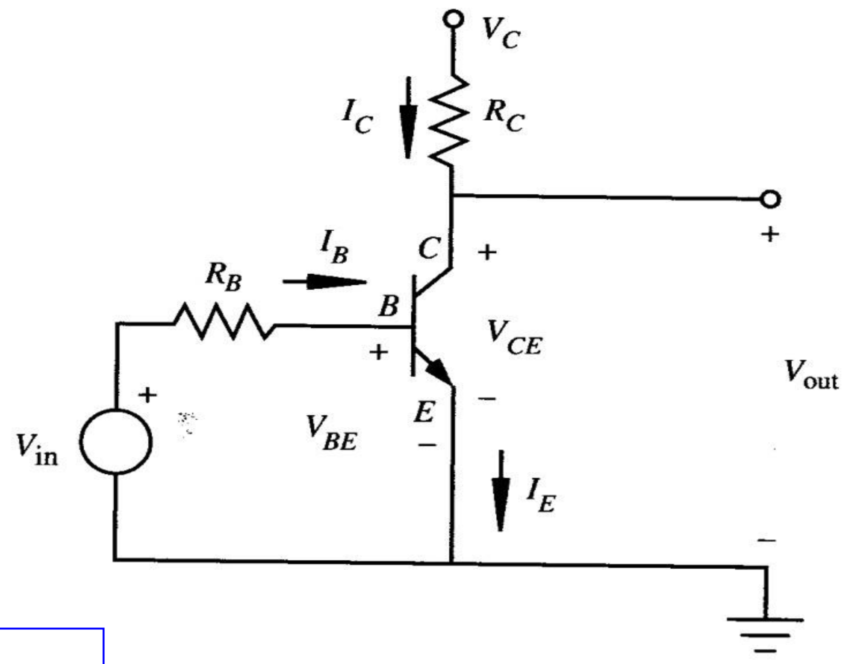
Since the collector is at a higher voltage than the base, the collector-base junction is reverse-biased.

BJT As Switch

OFF State

When $V_{in} < 0.7V$

- BE junction not forward biased
- **Cutoff state** of transistor
- $I_C = I_E = 0$
- $V_{out} = V_{CE} = V_C$
- V_{out} = High



ON State

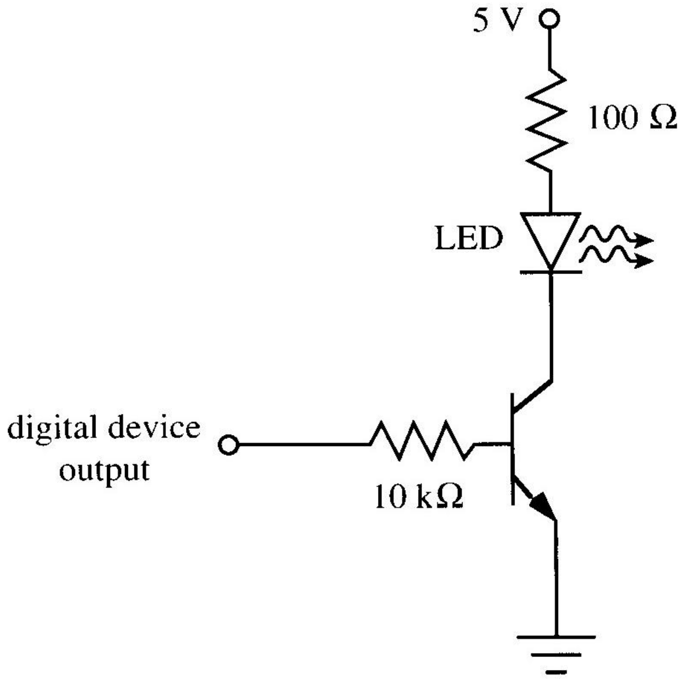
When $V_{in} > 0.7$

- BE junction forward biased (V_{BE} = 0.7V)
- $I_B = (V_{in} - V_{BE}) / R_B$
- **Saturation** region
- V_{CE} small (~0.2 V for saturated BJT)
- V_{out} = Low

Example 3

Practical LED Switch: For the given 2N3904 npn BJT circuit assuming the LED requires 20-40 mA to provide a bright display and has 2 voltage drop when forwarded biased. Find that the circuit works properly with ON and OFF states.

Solution



- When digital output is 0V, transistor is **OFF**.
- When digital output is 5V, the transistor is in **saturation** (**ON**), with base current:

$$I_B = (5V - 0.7V)/10K\Omega = 0.43\, mA$$

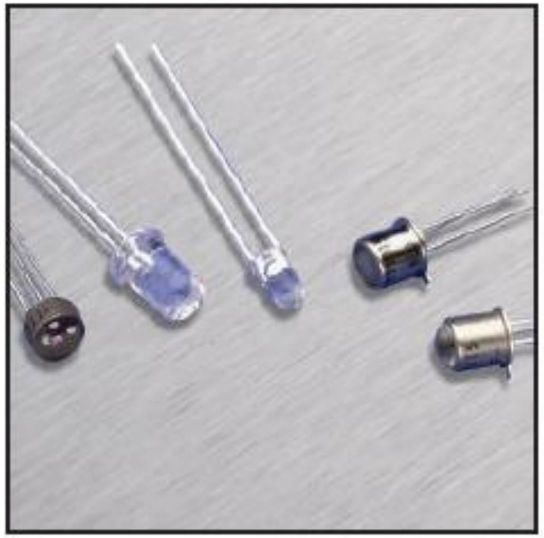
Collector current (LED current) is limited by collector resistor as:

$$I_C = (5V - 2V - 0.2V)/100\Omega = 28\, mA$$

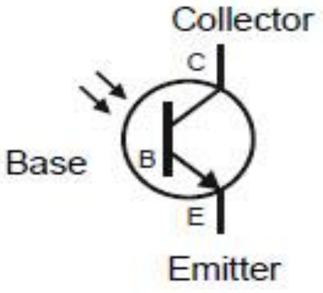
Hence: LED is lighted properly

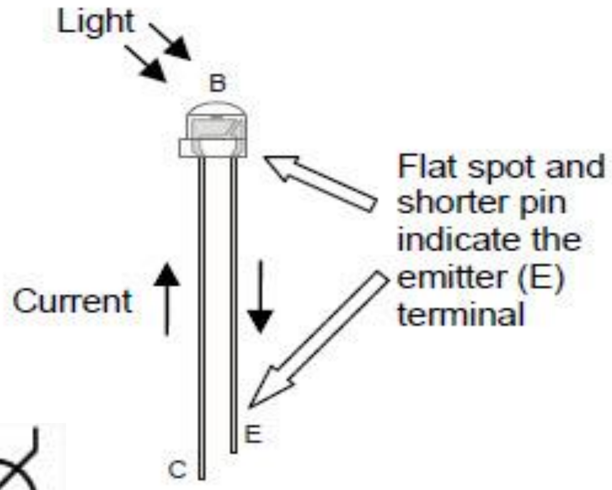
Phototransistors

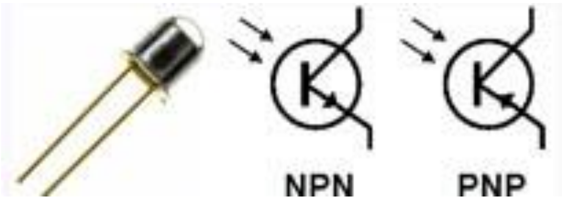
- **Phototransistors** are solid-state light detectors that possess internal gain.
- They are photodiode-amplifier combinations (2 or 3 terminals) integrated within a single silicon chip to overcome the major fault of photodiodes (unity gain).
- They can be used to provide either an analog or digital output signal.



NPN Phototransistors
0.25", small area, high speed
0.04", medium area, high sensitivity
0.05", large area, high sensitivity







Two and Three Terminal Phototransistors

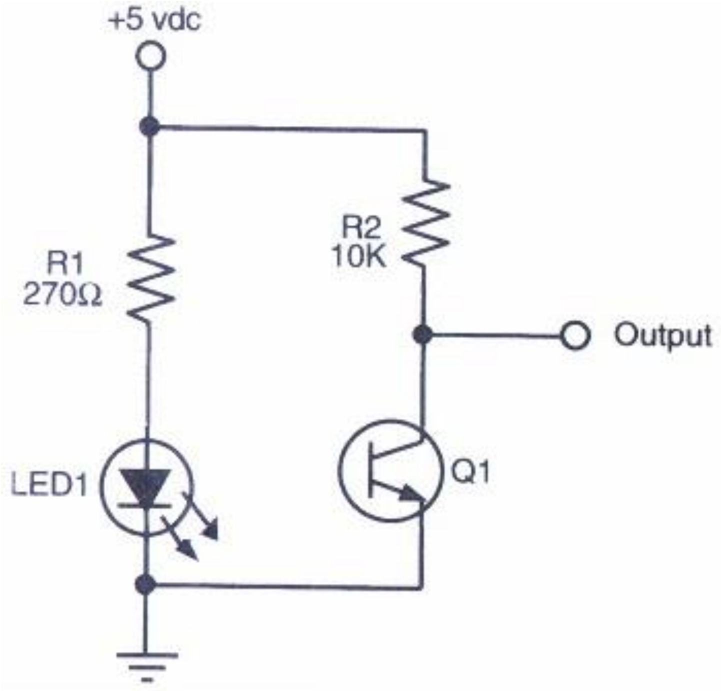
Features and Applications of Phototransistors

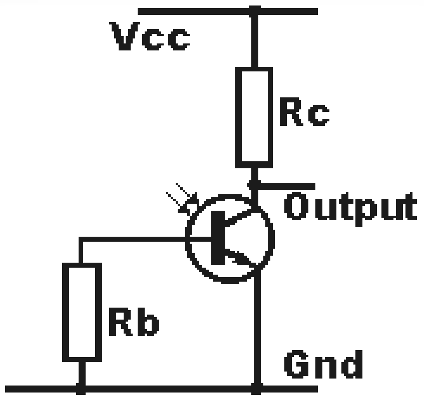
Features

- Low-cost visible and near-IR region.
- Available with gains from 100 to over 1500.
- Moderately fast response times.
- Available in a wide range of packages.
- Same general electrical characteristics as BJTs.

Applications

- Computer/business equipment: write-protect control and margin controls in printers.
- Industrial: security systems and safety shields.
- Consumers: coin counters, lottery card readers, audio/visual equipments, games, and camera shutter control.





Circuit Diagrams for Phototransistor Connections

Problems and Solutions

Question 1 Using ideal BJT switch of $\beta_{DC} = 200$, $V_{CC} = 10V$ and $I_B = 20\mu A$.

1) Find the value of base resistor R_B required to switch the load "ON" when the input terminal voltage exceeds 2.5V and $V_{BE} = 0.7V$.
2) Calculate R_C for point (1).
3) Find the minimum base current I_B required to turn the transistor "Fully-ON" (saturated) for a load that requires 200 mA when the input voltage is increased to 5.0V. Also calculate the new value of R_B.

Solution:

$$1)\ R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{2.5 - 0.7}{20 \times 10^{-6}} = 90\ \text{k}\Omega$$

2) For ideal BJT at saturation $V_{CE} = 0$ Volt

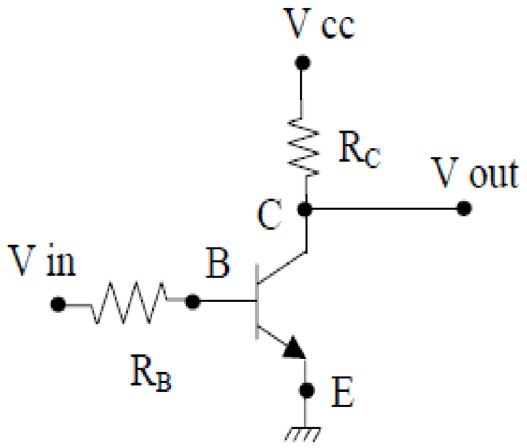
$$I_C = \beta_{DC} I_B = 200 \times 20 \times 10^{-6} = 4\ \text{mA}$$

$$R_C = \frac{V_{CC} - V_{CE}}{I_C} = \frac{10 - 0}{4 \times 10^{-3}} = 2.5\ \text{k}\Omega$$

3) At ON state, the load current is equal to I_C

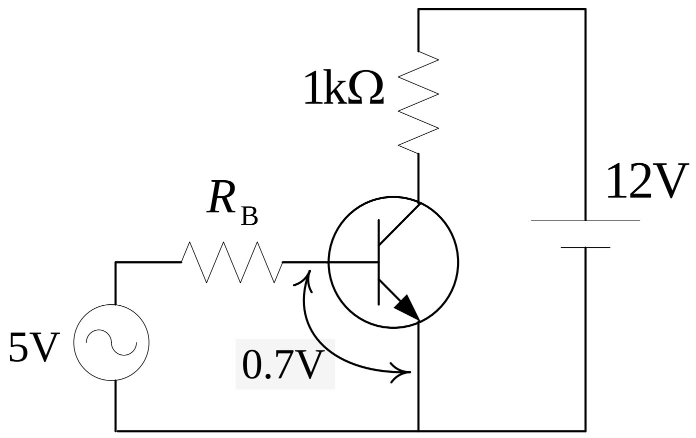
$$I_B = \frac{I_C}{\beta_{DC}} = \frac{200\ \text{mA}}{200} = 1\ \text{mA}$$

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{5 - 0.7}{1 \times 10^{-3}} = 4.3\ \text{k}\Omega$$



Question 2 The BJT in the given circuit has: $50 \le \beta_{DC} \le 150, V_{CC} = 12\text{V}$, $V_{BE} = 0.7\text{V}$, and $V_{CE} = 0.2\text{V}$. Find R_B that saturates the BJT with the so called Over Driven Factor (ODF) of at least 10.

Solution:



$$I_{Csat} = \frac{V_{CC} - V_{CE}}{R_C} = \frac{12 - 0.2}{1\times10^3} = 11.8 \text{ mA}$$

$$I_B = \frac{I_{Csat}}{\beta_{DC\,\min}} = \frac{11.8\times10^{-3}}{50} = 0.236 \text{ mA}$$

For OFD of at least10, we have:

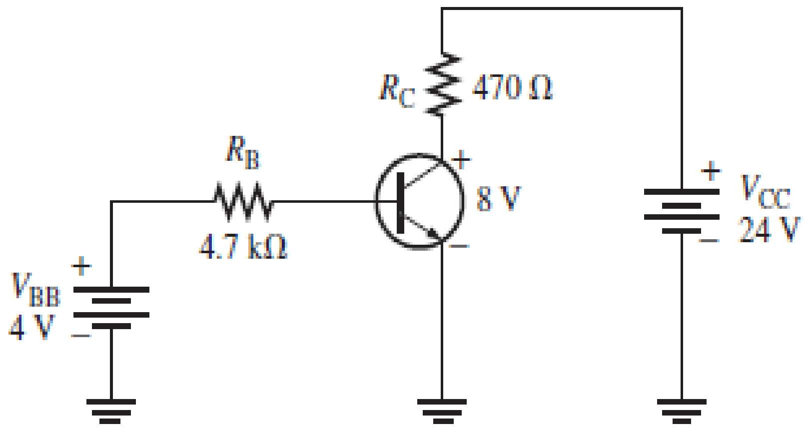
$$I_B' = 10\times I_B = 10\times0.236\times10^{-3} = 2.36 \text{ mA}$$

$$R_B = \frac{V_{in} - V_{BE}}{I_B'} = \frac{5-0.7}{2.36\times10^{-3}} = 1.82 \text{ k}\Omega$$

Question 3 Find for the given npn BJT circuit: I_B , I_C , I_E , V_{CB} , β_{DC} , α_{DC}

Solution:

We have $V_{BE} = 0.7$ V and form the circuit $V_{CE} = 8$ V



$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{4 - 0.7}{4.7 \times 10^3} = 0.7 \text{ mA}$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{24 - 8}{470} = 34 \text{ mA}$$

$$I_E = I_B + I_C = 0.7 \text{ mA} + 34 \text{ mA} = 34.7 \text{ mA}$$

$$V_{CB} = V_{CE} - V_{BE} = 8 - 0.7 = 7.3 \text{ V}$$

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{34 \text{ mA}}{0.7 \text{ mA}} = 48.57$$

$$\alpha_{DC} = \frac{I_C}{I_E} = \frac{34 \text{ mA}}{34.7 \text{ mA}} = 0.9798$$

Question 4

For the given BJT switch circuit: $\beta_{DC} = 100$, $V_{CC} = 5V$, $V_{BE} = 0.7V$, $V_{CE} = 0V$, $V_{LED} = 2V$ and $I_{LED} = 15mA$. Assuming the minimum average voltage of microcontroller I/O port V_{port} with logical "1" is about 4.2V.

1) Find the value of R_B and R_C.
2) Calculate the power dissipation on R_B and R_C.

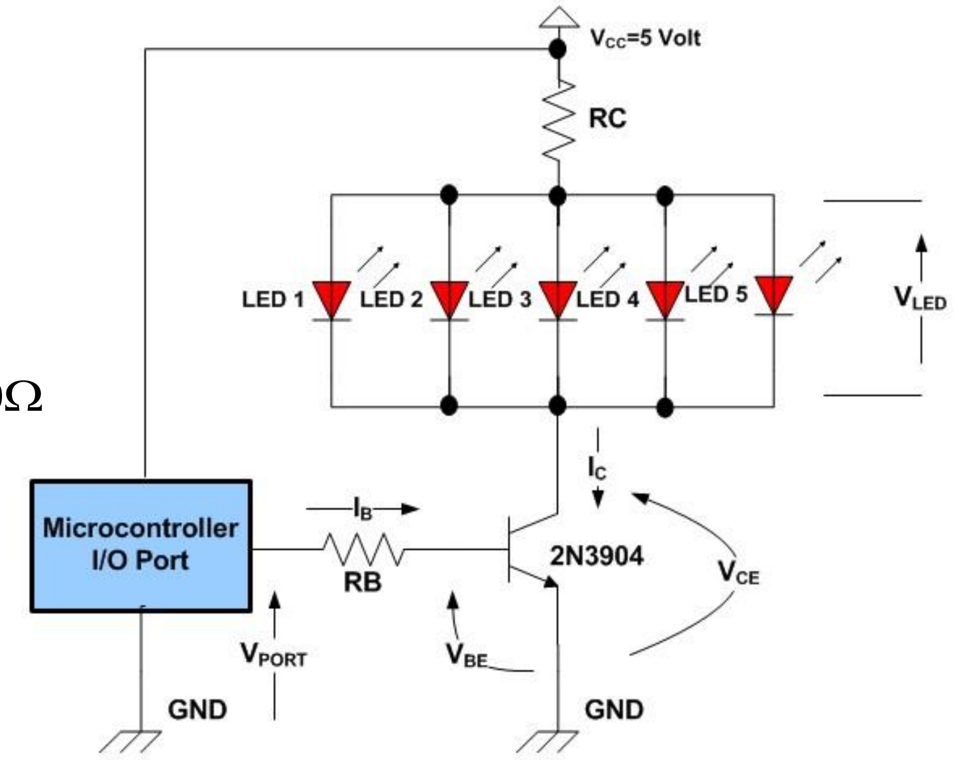
Solution:

1) $$I_C = 5\times I_{LED} = 5\times 15\times 10^{-3} = 75 \text{ mA}$$

$$I_B = \frac{I_C}{\beta_{DC}} = \frac{75 \text{ mA}}{100} = 0.75 \text{ mA}$$

$$R_B = \frac{V_{port} - V_{BE}}{I_B} = \frac{4.2 - 0.7}{0.75\times 10^{-3}} = 4.6 \text{ k}\Omega$$

$$R_C = \frac{V_{CC} - V_{LED} - V_{CE}}{I_C} = \frac{10 - 2 - 0}{75\times 10^{-3}} = 40\Omega$$



2) Power dissipation on $R_B = I_B^2 R_B$

$$= \left(0.75\times 10^{-3}\right)^2 \times 4.6\times 10^3 = 2.58 \text{ mW}$$

Power dissipation on $R_C = I_C^2 R_C$

$$= \left(75\times 10^{-3}\right)^2 \times 40 = 0.225 \text{ W}$$