Bipolar Junction Transistors

Topic 3 (Chapter 3)

OBJECTIVES

- Basic construction and operation
- Biasing
- Characteristics of an npn or pnp transistor
- Important parameters that define the response of a transistor
- Testing a transistor and identify the three terminals

TRANSISTOR INVENTION

- On December 23, 1947, Dr. S. William Shockley, Walter H. Brattain, and John Bardeen demonstrated the amplifying action of the first transistor at the Bell Telephone Laboratories

- The original transistor (a point-contact transistor)

FIG. 3.2

The first transistor. (Courtesy of AT&T Archives and History Center.)

Dr. William Shockley (seated); Dr. John Bardeen (left); Dr. Walter H. Brattain. (Courtesy of AT&T Archives and History Center.)

Dr. Shockley	Born: London, England, 1910 PhD Harvard, 1936
Dr. Bardeen	Born: Madison, Wisconsin, 1908 PhD Princeton, 1936
Dr. Brattain	Born: Amoy, China, 1902 PhD University of Minnesota, 1928

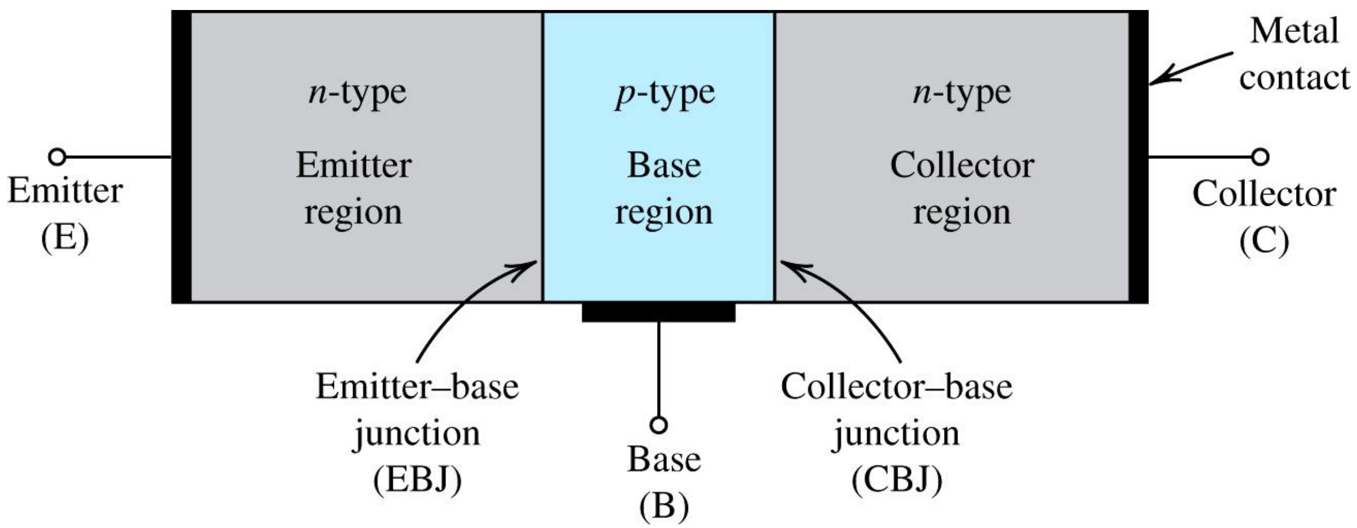
All shared the Nobel Prize in 1956 for this contribution.

Bipolar Junction Transistor (BJT)

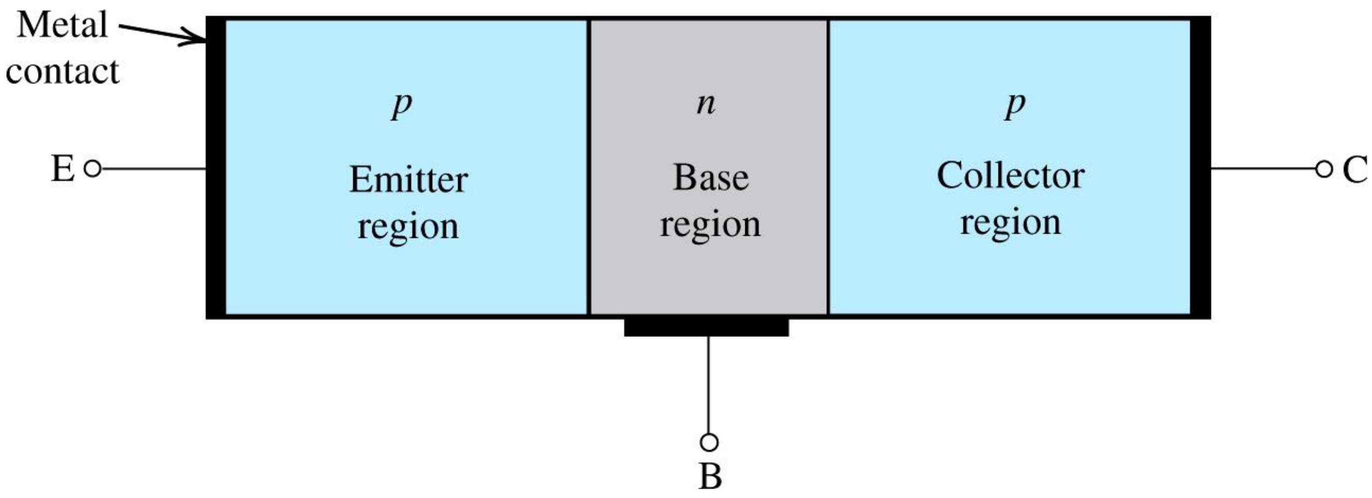
- A semiconductor device that can amplify (enlarge) electronic signals such as radio and television signals
- The transistor has led to many other semiconductor inventions including the integrated circuit (IC)
  - Backbone of modern civilization
- Bipolar means “two polarities” - electrons and holes

BJT Device Structure

NPN



PNP



The Structure of BJT Transistors in ICs

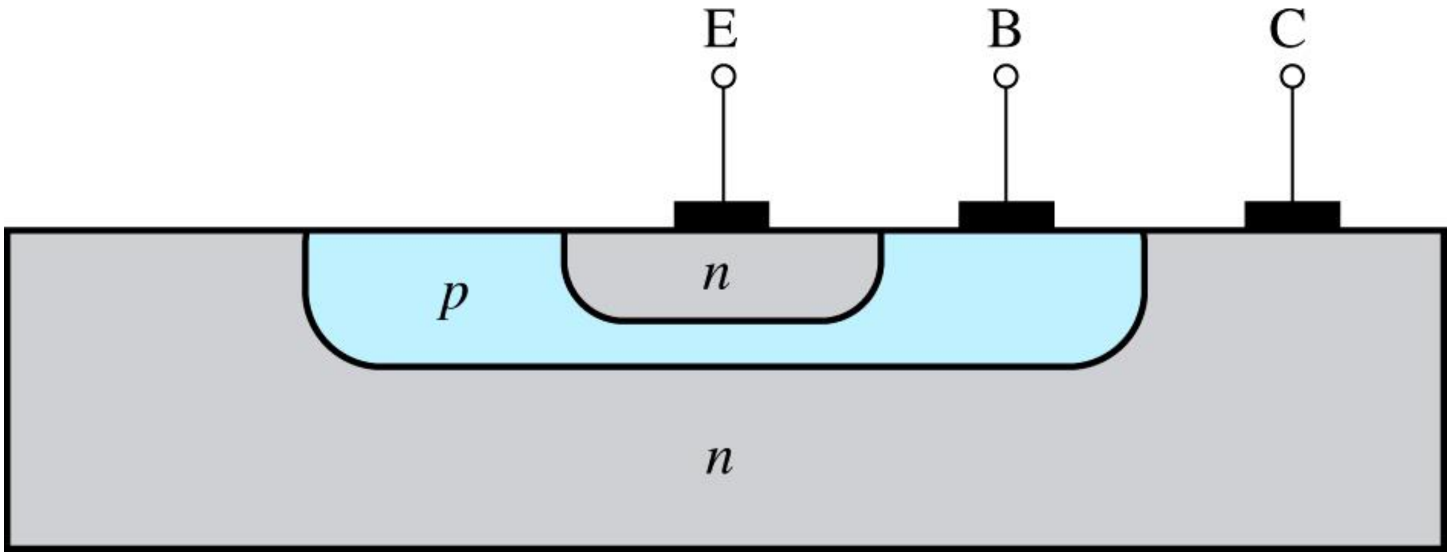
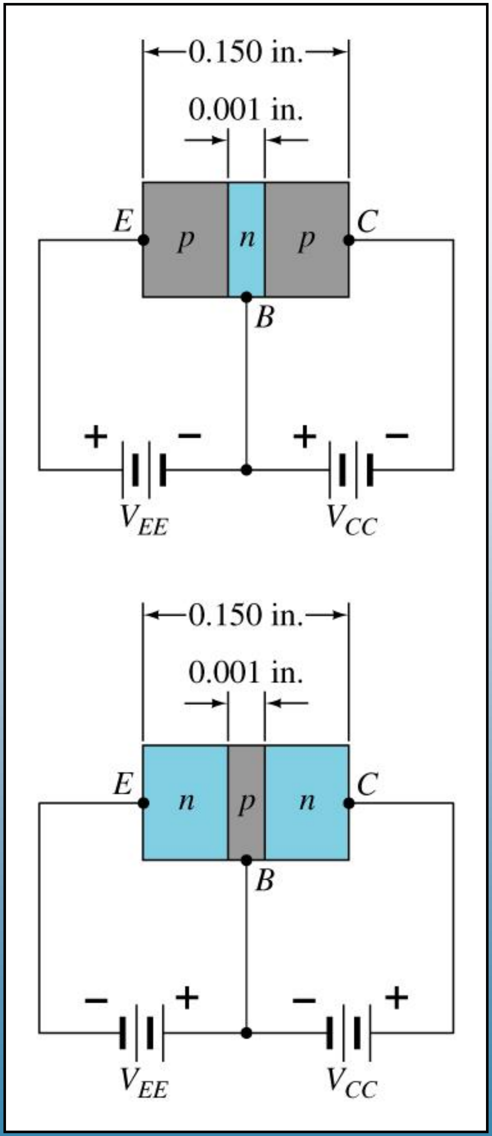


Figure: A more realistic (but still simplified) cross section of an *npn* BJT

- The collector virtually surrounds the emitter region
- The device is *not* symmetrical, and thus the emitter and collector cannot be interchanged.

Discrete Component BJT Construction



pnp

npn

Transistor pictures from a datasheet..

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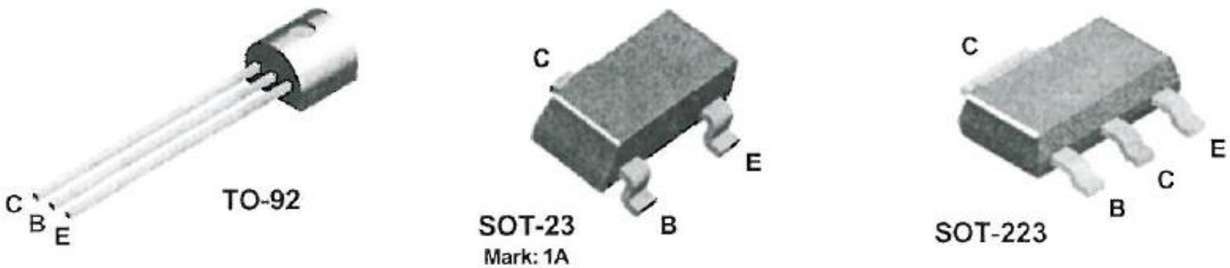
2N3904 / MMBT3904 / PZT3904

2N3904 MMBT3904 PZT3904



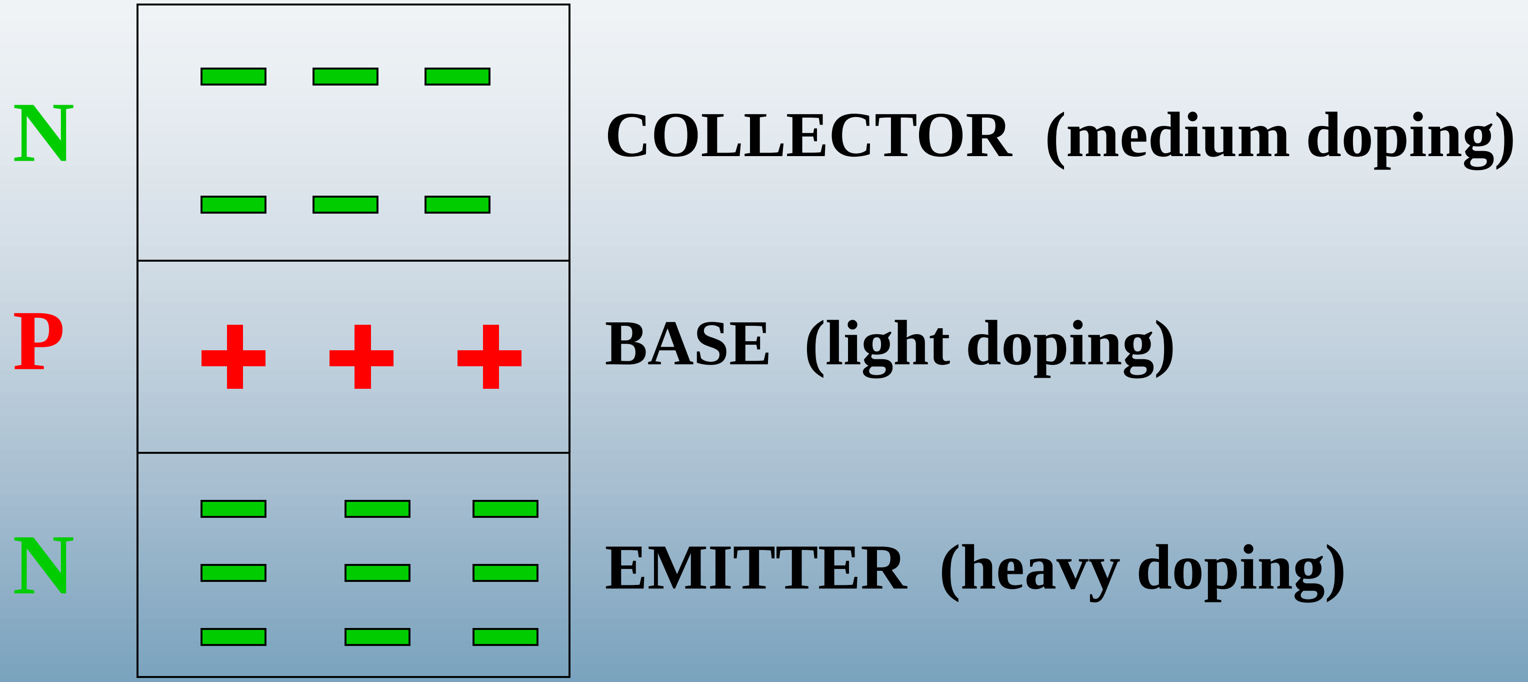
NPN General Purpose Amplifier

This device is designed as a general purpose amplifier and switch. The useful dynamic range extends to 100 mA as a switch and to 100 MHz as an amplifier.

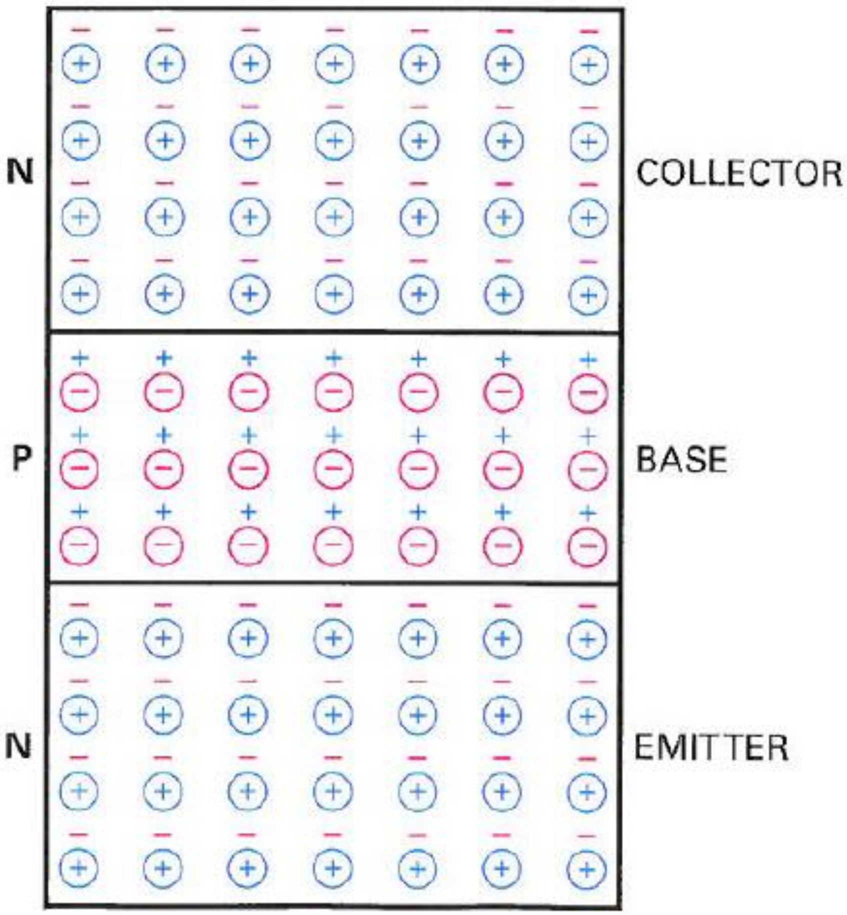
Unbiased transistor

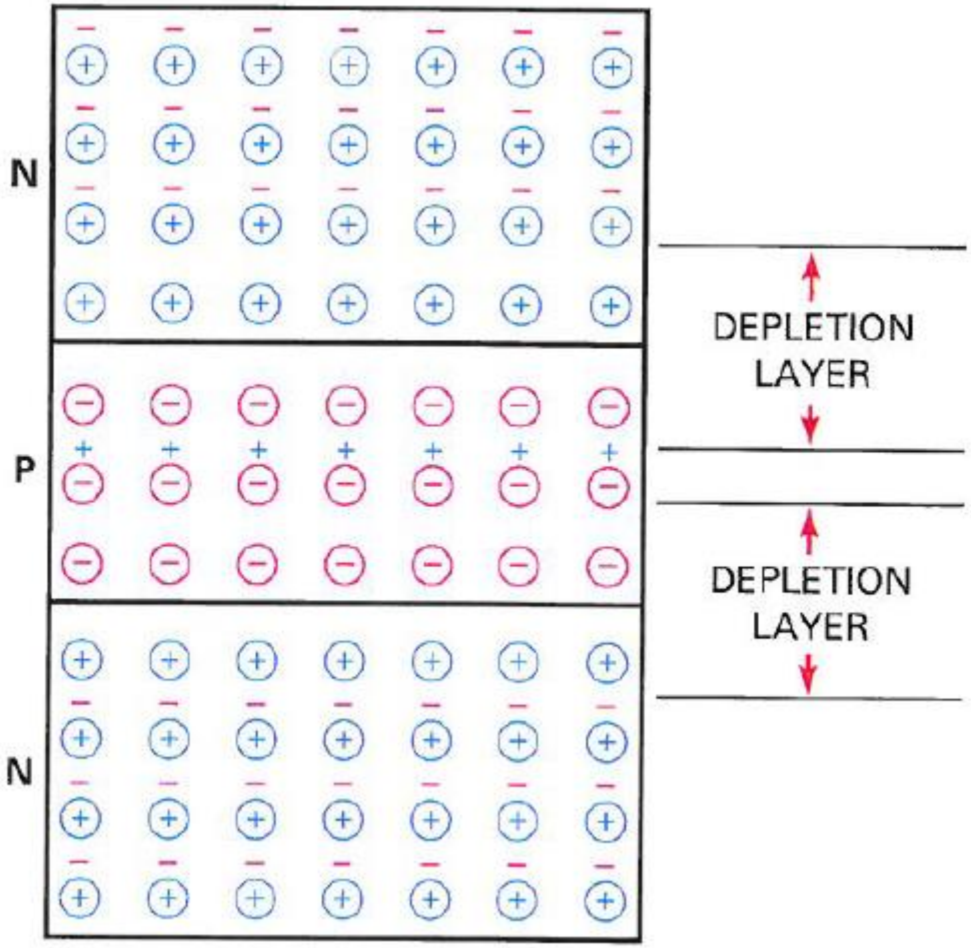
- **Three** doped regions: emitter, base, and collector
- **Two** pn junctions: emitter-base and base-collector
  - Like two back-to-back connected diodes
- NPN or PNP
- Silicon or germanium

The bipolar junction transistor has 3 doped regions.



Unbiased Transistor



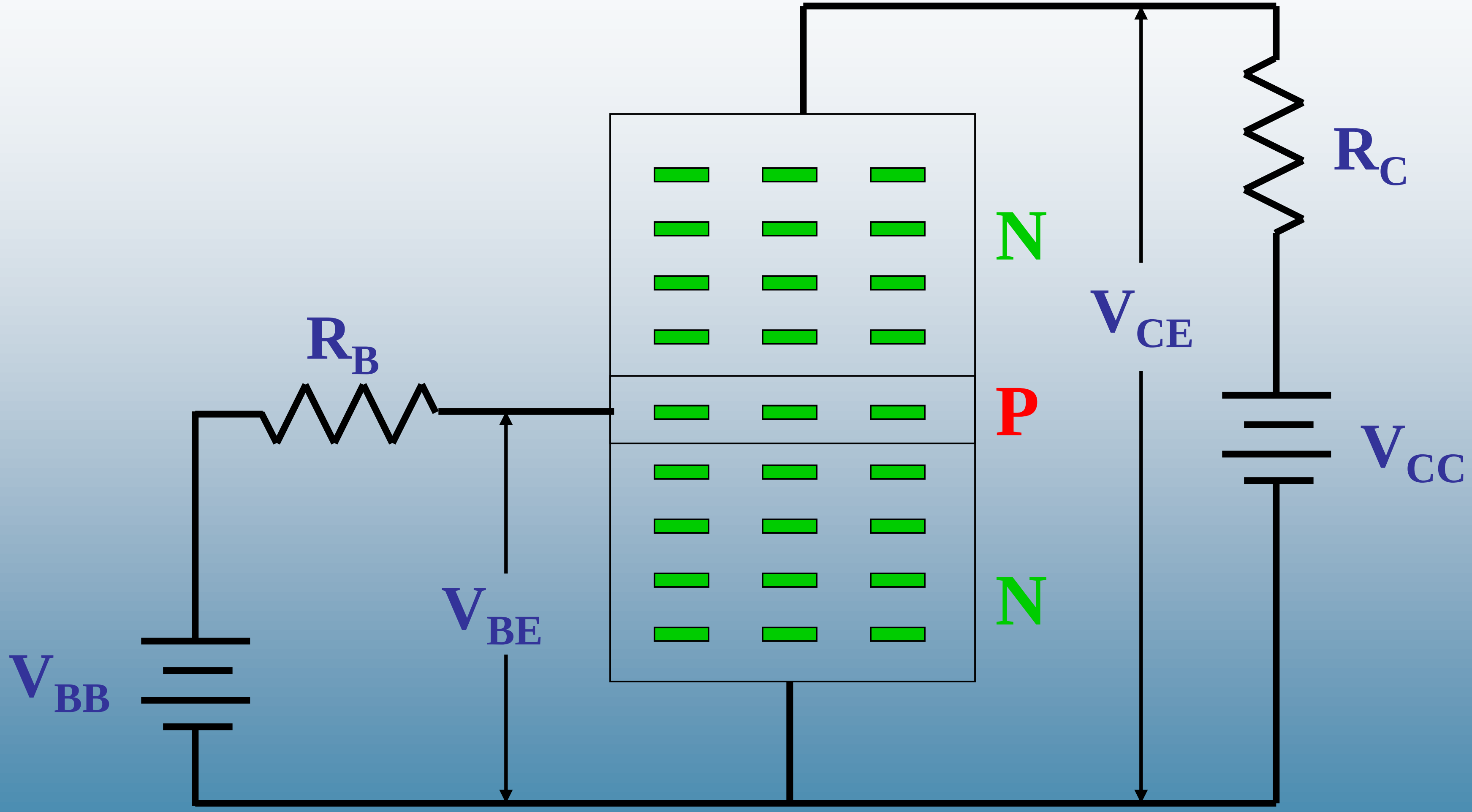


Before Diffusion **After Diffusion**

Biased transistor

- <u>Forward</u> bias the emitter diode
- <u>Reverse</u> bias the collector diode

In a properly biased NPN transistor, the emitter electrons diffuse into the base and then go on to the collector.



Purposes of Different Transistor Regions

- The heavily doped emitter emits or injects its free electrons into the base
- The lightly doped base also has a well-defined purpose: to pass emitter-injected electrons on to the collector
- The collector is so named because it collects or gathers most of the electrons from the base

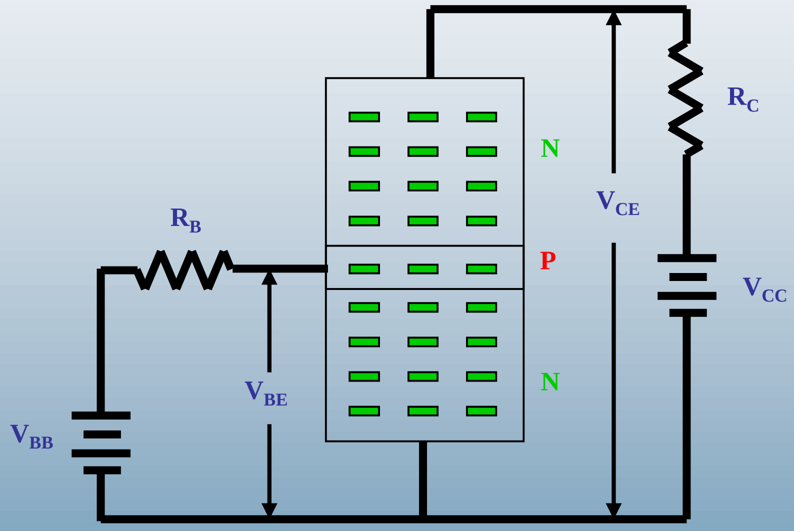
Electron Movement

- If V_{BE} is greater than the emitter-base barrier potential (0.7 V for Si), emitter electrons will enter the base region
- These electrons can flow in either of two directions.
  1. They can flow out of the base through the base terminal
  2. They can flow into the collector

Which way the free electrons in the base region go?

- **Most continue on to the collector**
  - **Why?**
    - **The base is *lightly doped* and *very thin***
    - **The light doping means that the free electrons have a long lifetime in the base region**
    - **The very thin base means that the free electrons have only a short distance to go to reach the collector**
    - **The positive voltage (reverse voltage) applied to the collector pulls them towards the collector**
    - **For these reasons, almost all the emitter-injected electrons pass through the base to the collector.**
  - **Only a few free electrons will recombine with holes in the lightly doped base**
    - **As valence electrons, they flow through the base resistor to the positive side of the V_{BB} supply**

Summary of Carrier Flow in a Biased NPN Transistor



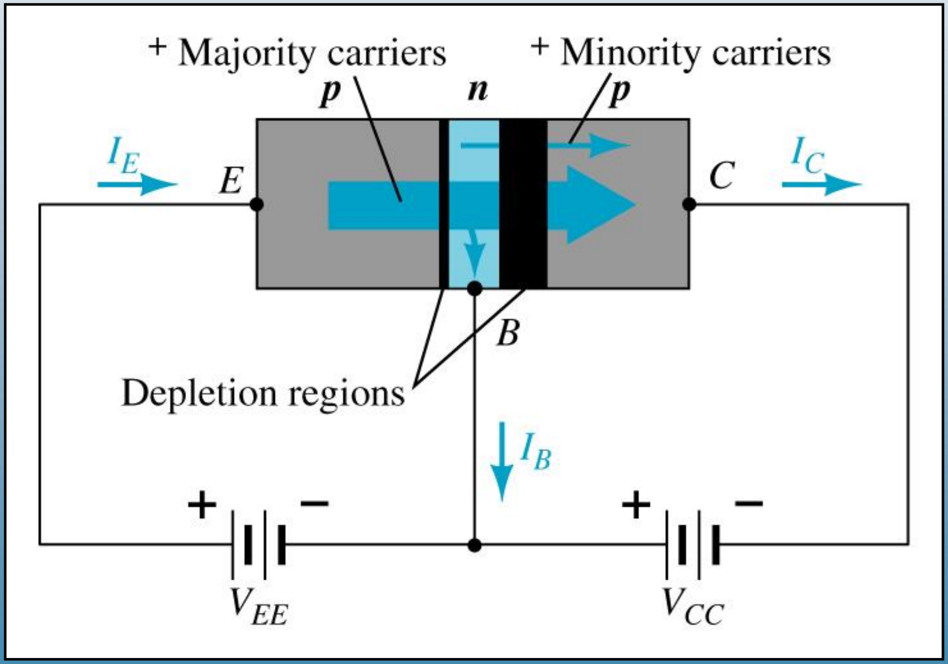
- V_{BB} forward biases the emitter diode
  - Forces the free electrons in the emitter to enter the base
- The thin and lightly doped base gives almost all these electrons enough time to diffuse into the collector
- These electrons flow through the collector, through R_C and into the positive terminal of the V_{CC} voltage source

Transistor Operation

With the external sources, V_{EE} and V_{CC}, connected as shown:

The emitter-base junction is forward biased

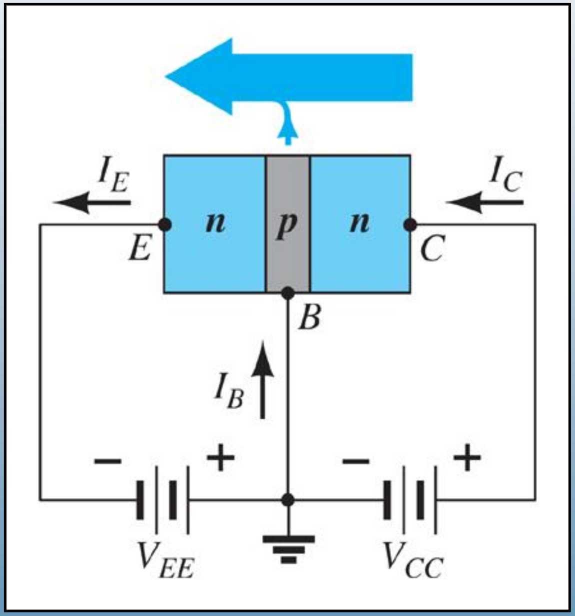
The base-collector junction is reverse biased



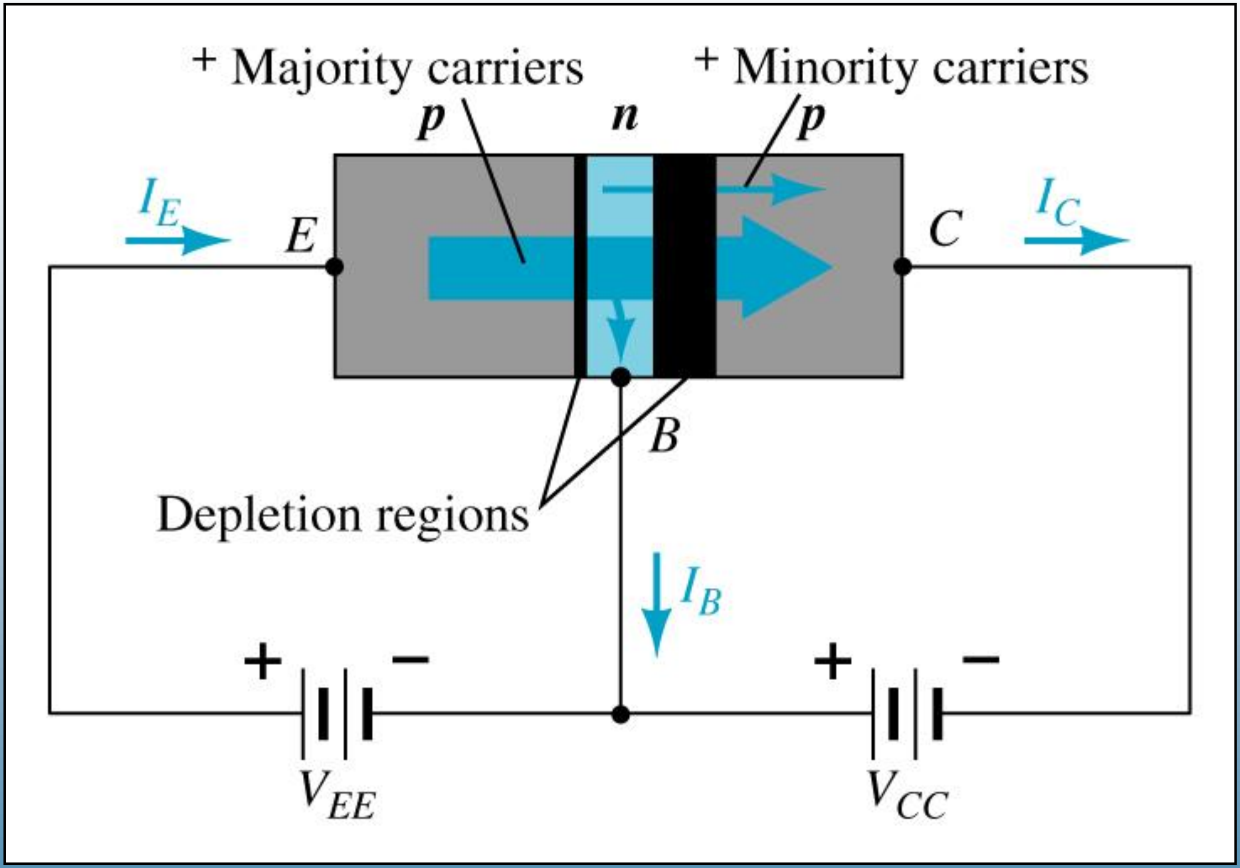
Currents in a Transistor

Emitter current is the sum of the collector and base currents:

$$I_E = I_C + I_B$$



Carrier flow in a pnp transistor



Emitter current is the sum of the collector and base currents:

$$I_E = I_C + I_B$$

The collector current is comprised of two currents:

$$I_C = I_{C\,(majority)} + I_{CO\,(minority)}$$

Transistor Connections

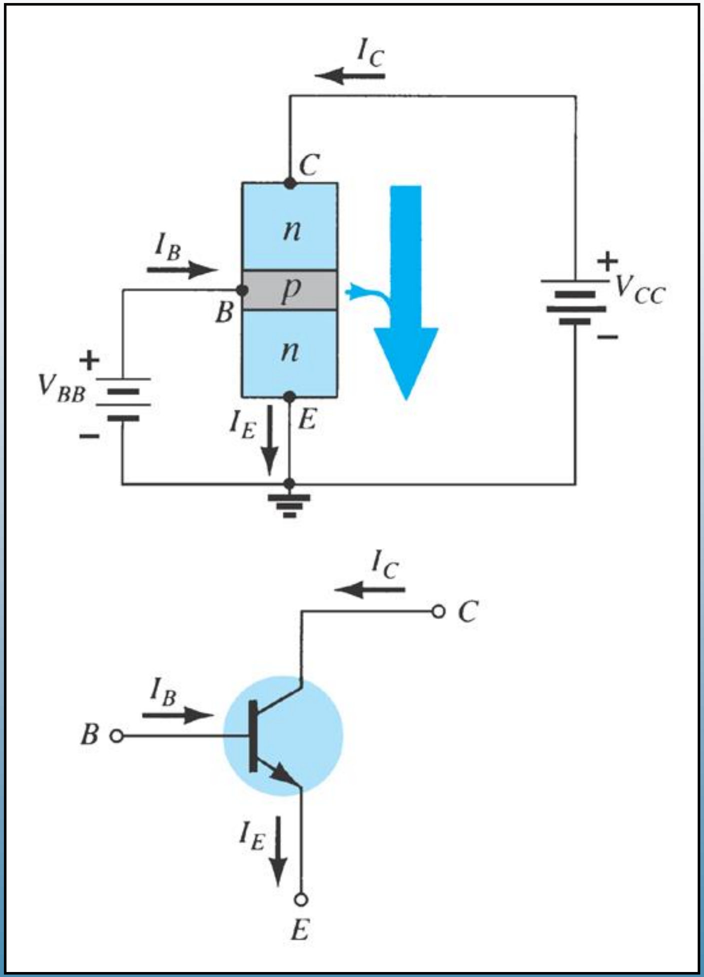
There are three useful way to connect a transistor:

- CE (common emitter) – most widely used
- CC (common collector)
- CB (common base)

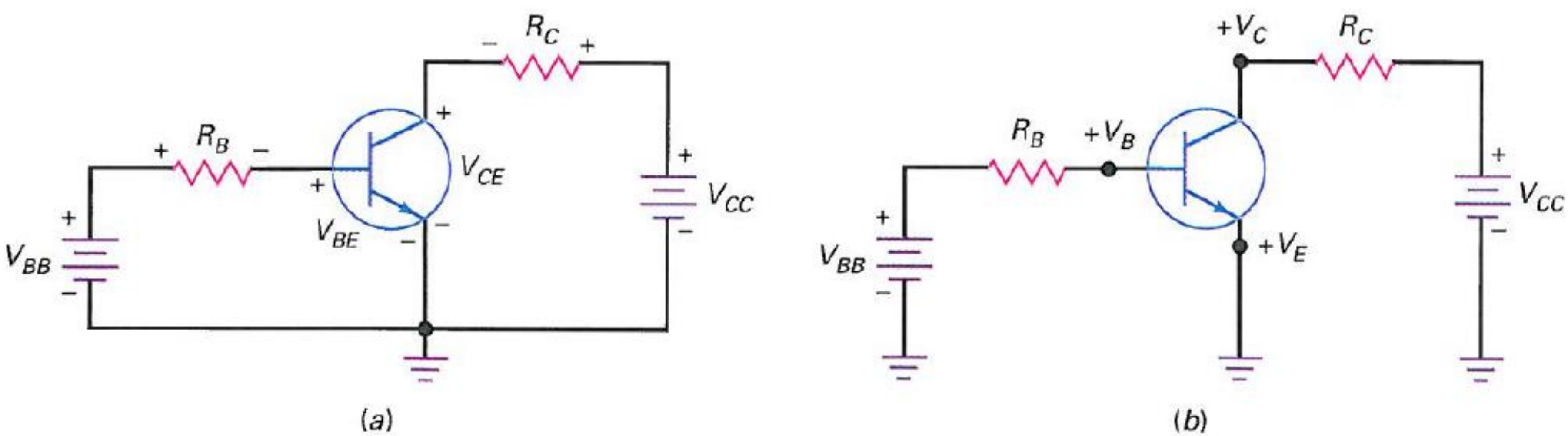
Common-Emitter Configuration

The emitter is common to both input (base-emitter) and output (collector-emitter) circuits.

The input is applied to the base and the output is taken from the collector.



The CE connection

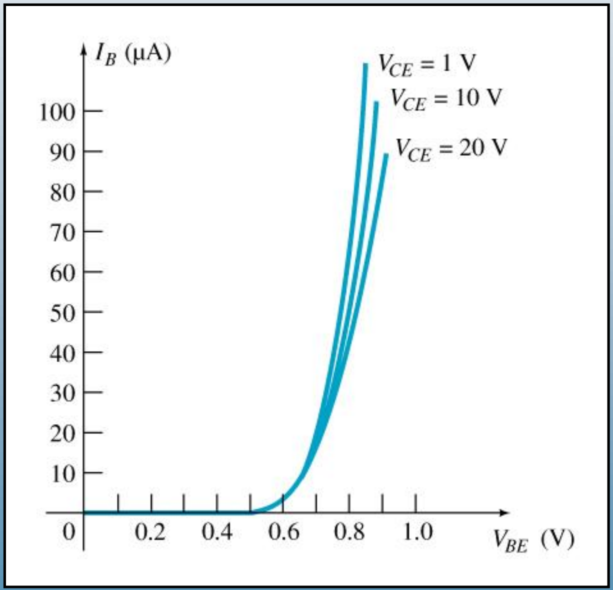


$$V_{CE} = V_C - V_E$$
$$V_{CB} = V_C - V_B$$
$$V_{BE} = V_B - V_E$$

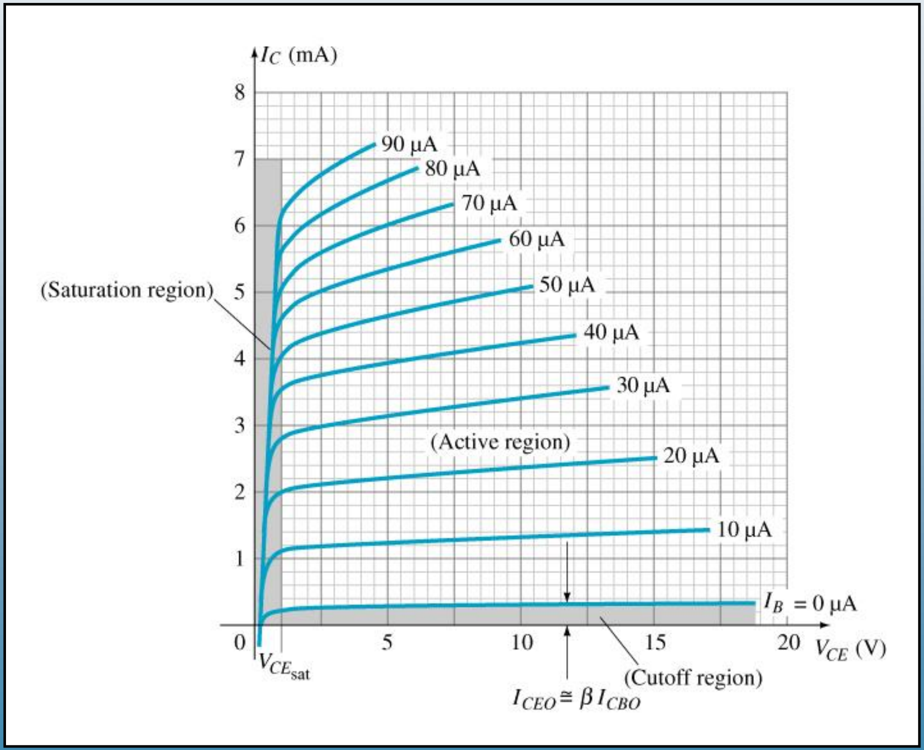
- The emitter is **grounded** or **common**
- The base-emitter acts like a **diode**
- The base-collector acts like a dependent **current source** equal to $\beta_{dc} I_B$

CE Transistor Characteristics

- To fully describe the behavior of a BJT, two sets of characteristics are required:
  1. Driving point or input characteristics
  2. Output side or output characteristics



Base or Input Characteristics



Collector or Output Characteristics

Common-Emitter Amplifier Currents

Ideal Currents

$$I_E = I_C + I_B \qquad I_C = \alpha I_E$$

Actual Currents

$$I_C = \alpha I_E + I_{CBO}$$

where I_{CBO} = minority collector current

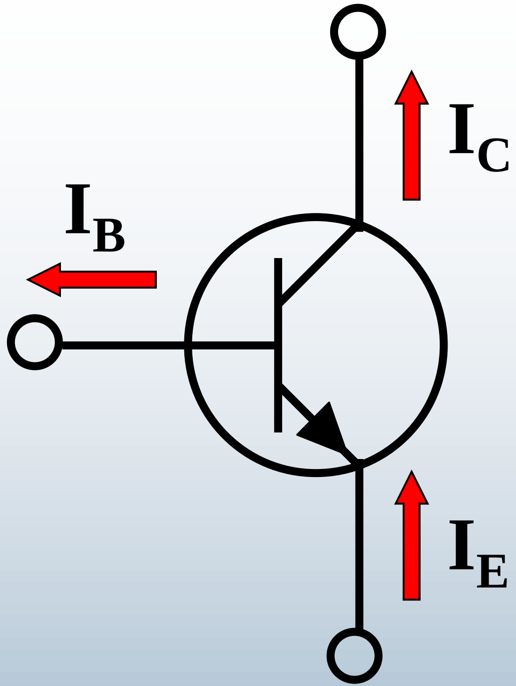
I_{CBO} is usually so small that it can be ignored, except in high power transistors and in high temperature environments.

When $I_B = 0$ μA the transistor is in cutoff, but there is some minority current flowing called I_{CEO}.

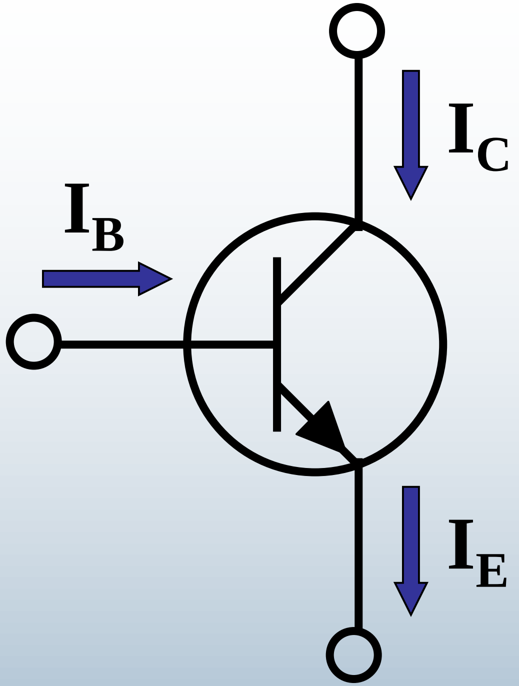
$$I_{CEO} = \left.\frac{I_{CBO}}{1-\alpha}\right|_{I_B = 0\ \mu A}$$

Transistor Current Gain

- The ratio of collector current to base current is **current gain** (β_{dc} or h_{FE})
- Current gain is typically **100** to **300**



Electron flow



Conventional flow

$I_E = I_C + I_B$ $\qquad$ $I_C \cong I_E$ $\qquad$ $I_B << I_C$

$$\alpha_{dc} = \frac{I_C}{I_E} \qquad \beta_{dc} = \frac{I_C}{I_B}$$

Beta (β)

β represents the amplification factor of a transistor.

In DC mode:

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

In AC mode:

$$\beta_{ac} = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE}=constant}$$

β_{ac} is sometimes referred to as h_{fe}, a term used in transistor modeling calculations

Beta (β)

Determining β from a Graph

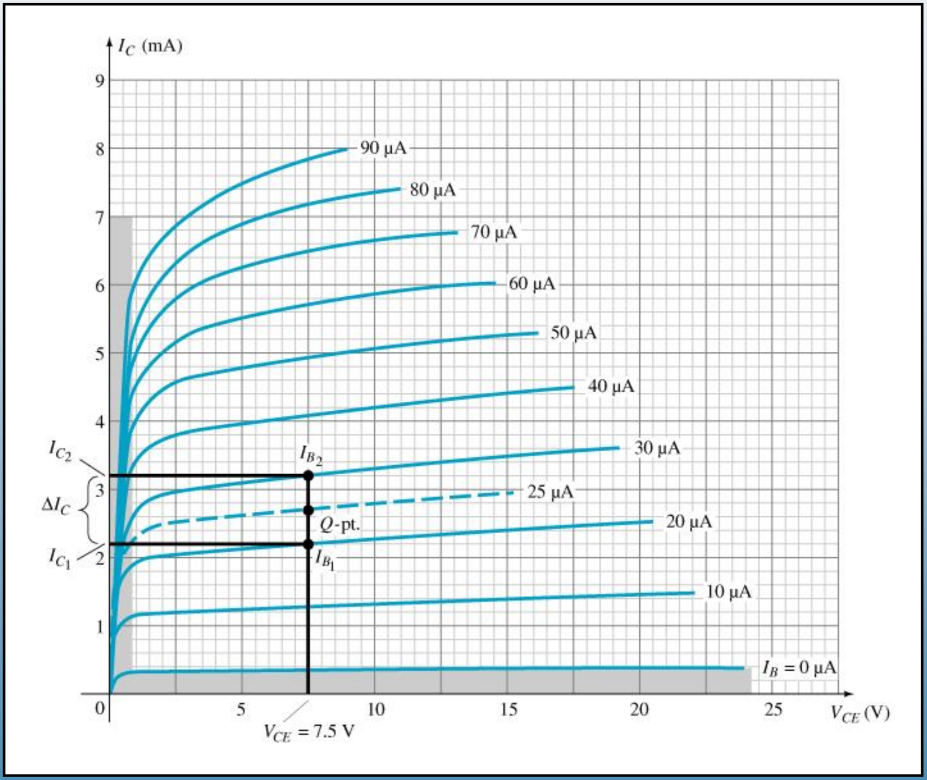
$$\beta_{AC} = \frac{(3.2\ mA - 2.2\ mA)}{(30\ \mu A\ -\ 20\ \mu A)}$$

$$= \frac{1\, mA}{10\ \mu A}\Big|_{V_{CE}=7.5V}$$

$$= 100$$

$$\beta_{DC} = \frac{2.7\ mA}{25\ \mu A}\Big|_{V_{CE}=7.5V}$$

$$= 108$$



Example 6-1

A transistor has a collector current of 10 mA and a base current of 40 μA. What is the current gain of the transistor?

SOLUTION Divide the collector current by the base current to get:

$$\beta_{dc} = \frac{10 \text{ mA}}{40 \ \mu\text{A}} = 250$$

Example 6-2

A transistor has a current gain of 175. If the base current is 0.1 mA, what is the collector current?

SOLUTION Multiply the current gain by the base current to get:

$$I_C = 175(0.1\ \text{mA}) = 17.5\ \text{mA}$$

Example 6-3

A transistor has a collector current of 2 mA. If the current gain is 135, what is the base current?

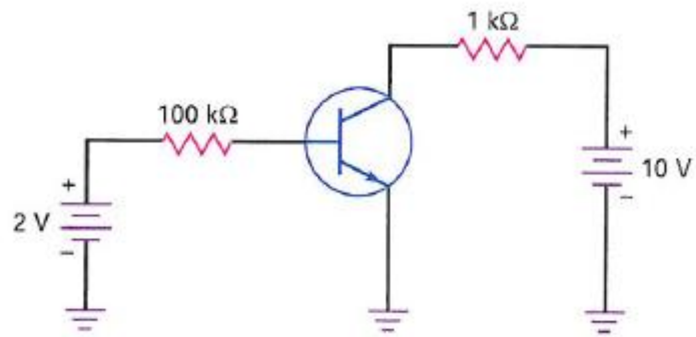
SOLUTION Divide the collector current by the current gain to get:

$$I_B = \frac{2\ \text{mA}}{135} = 14.8\ \mu\text{A}$$

Example 6-4

MultiSim

Use the second approximation to calculate the base current in Fig. 6-8*b*. What is the voltage across the base resistor? The collector current if $\beta_{dc} = 200$?



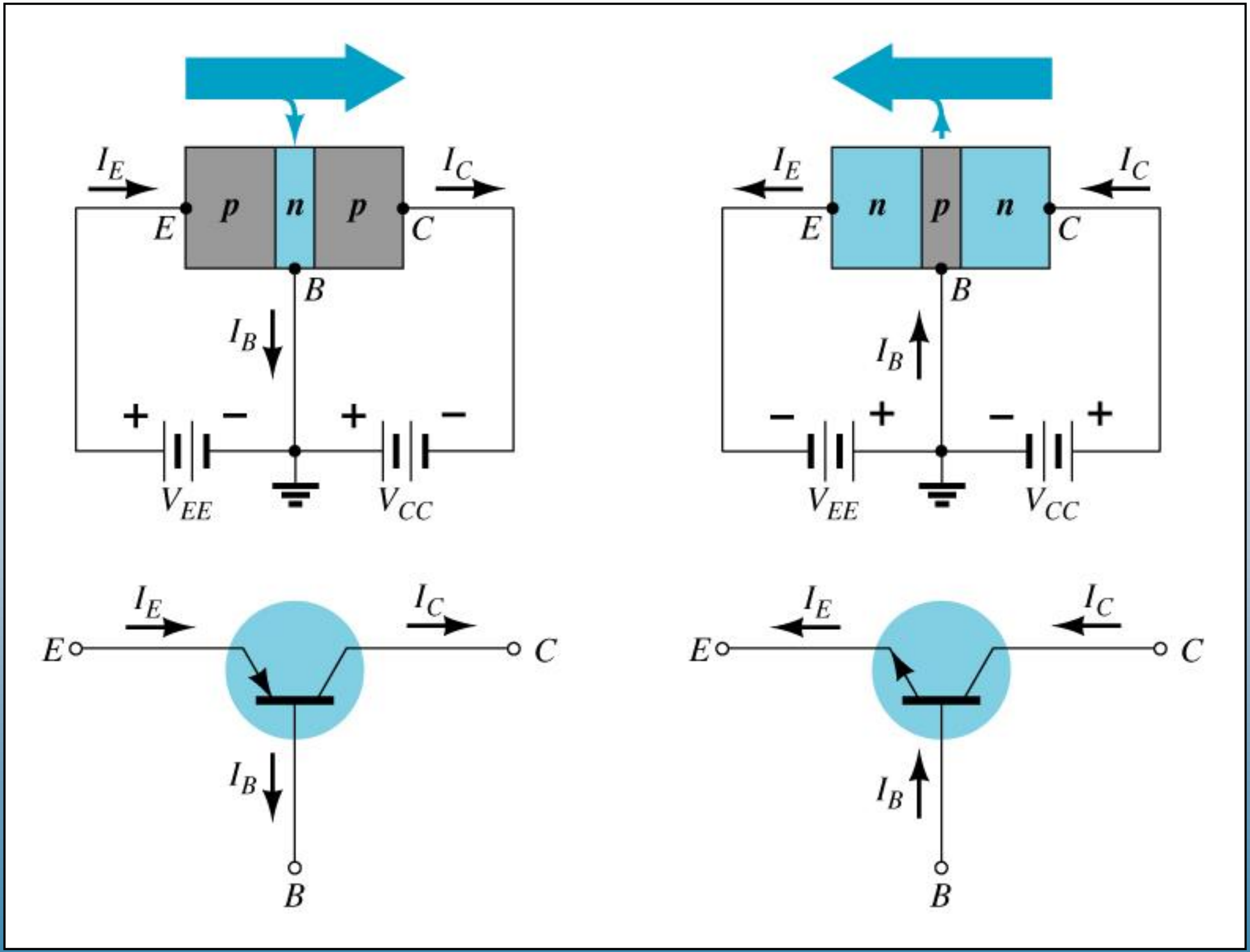
(*b*)

$$V_{BB} - V_{BE} = 2\text{ V} - 0.7\text{ V} = 1.3\text{ V}$$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{1.3\text{ V}}{100\text{ k}\Omega} = 13\ \mu\text{A}$$

$$I_C = \beta_{dc} I_B = (200)(13\ \mu\text{A}) = 2.6\text{ mA}$$

Common-Base Configuration



The base is common to both input (emitter–base) junction and output (collector–base) junction of the transistor.

Operating Regions

Active

Operating range of the amplifier.

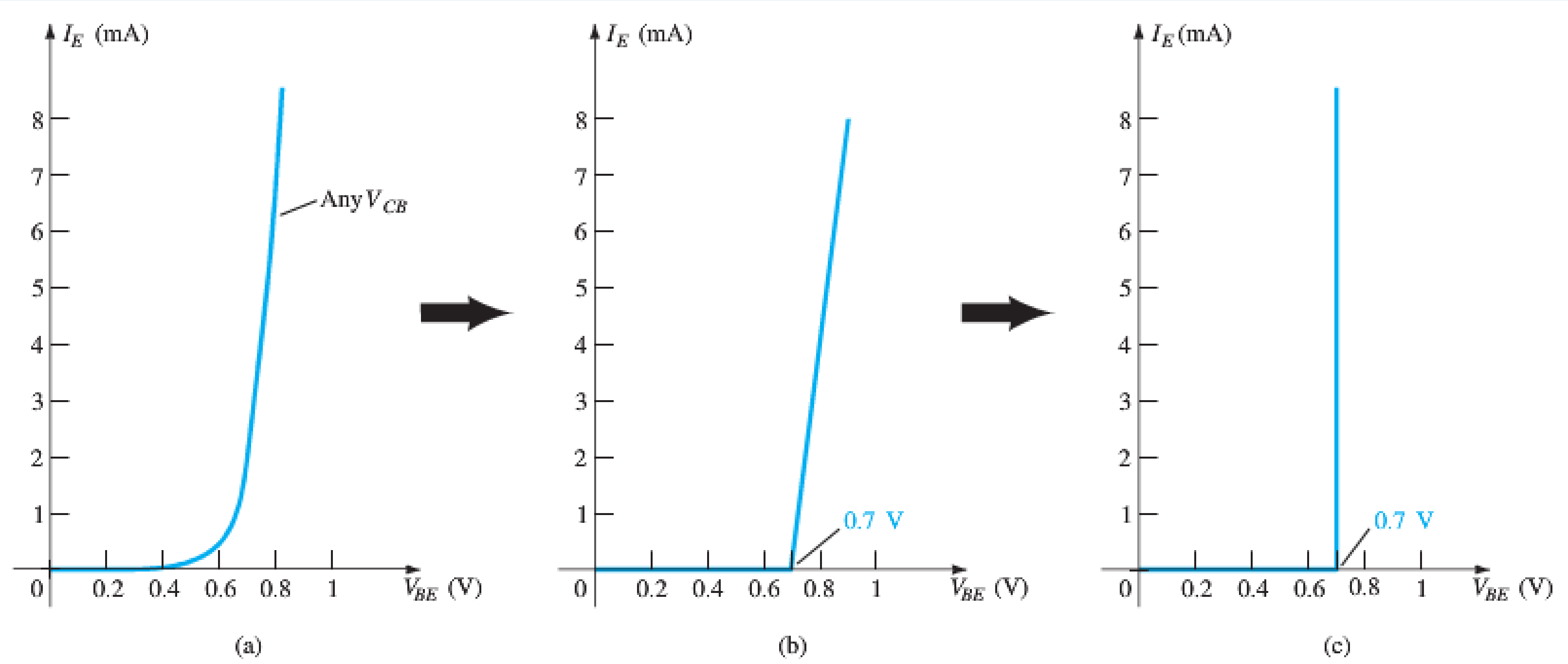
Cutoff

The amplifier is basically off. There is voltage, but little current.

Saturation

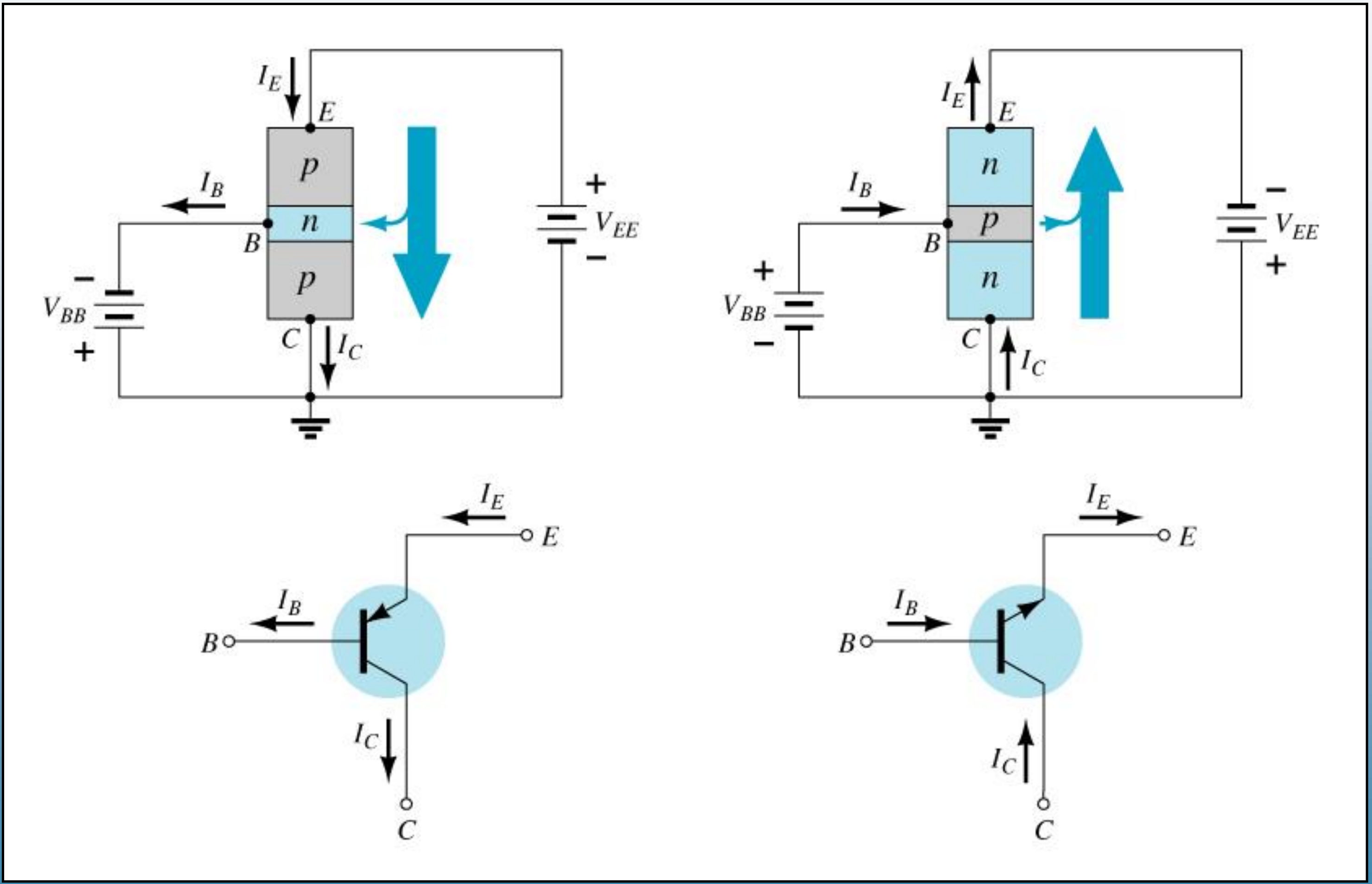
The amplifier is fully on. There is current, but little voltage.

Developing the equivalent model for the base-to-emitter region



Common-Collector Configuration

The input is on the base and the output is on the emitter.



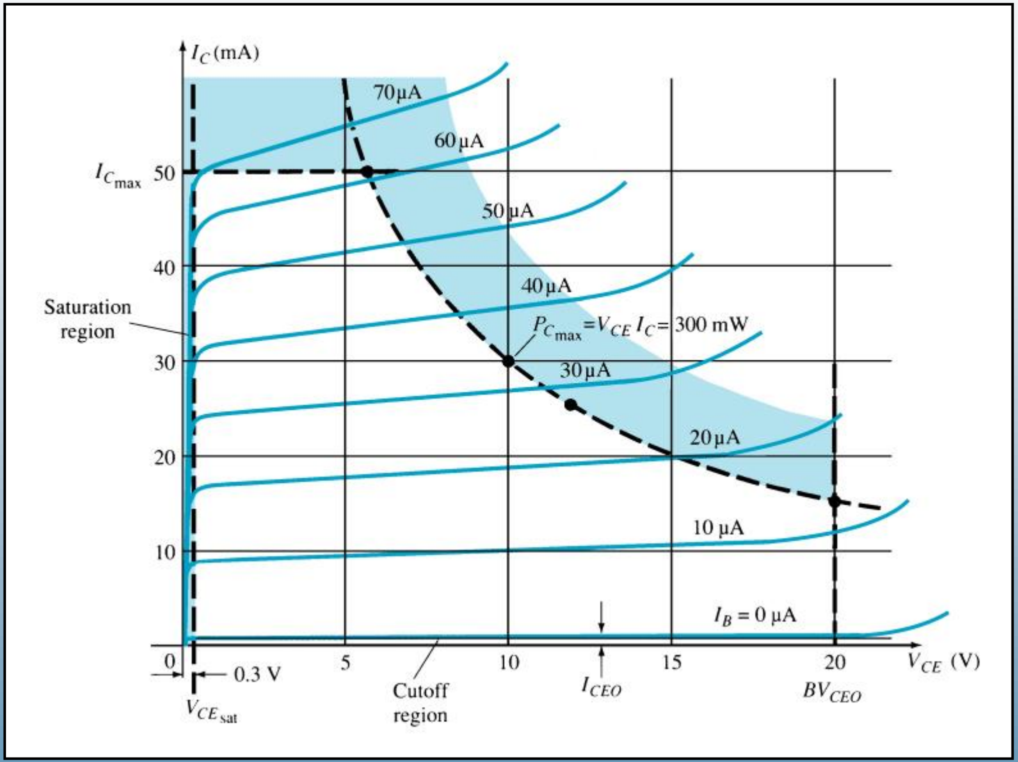
Operating Limits

V_{CE} is maximum and I_C is minimum in the cutoff region.

$$I_{C(max)} = I_{CEO}$$

I_C is maximum and V_{CE} is minimum in the saturation region.

$$V_{CE(max)} = V_{CE(sat)} = V_{CEO}$$



The transistor operates in the active region between saturation and cutoff.

Power Dissipation

Common-base:

$$P_{C\max} = V_{CB} I_C$$

Common-emitter:

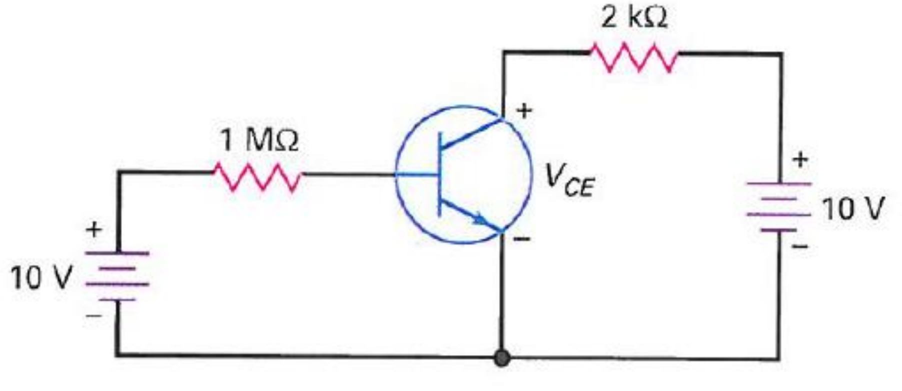
$$P_{C\max} = V_{CE} I_C$$

Common-collector:

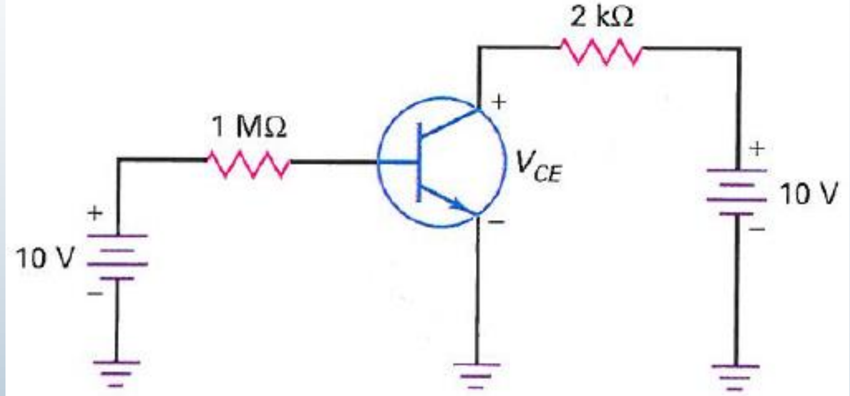
$$P_{C\max} = V_{CE} I_E$$

Example 6–5

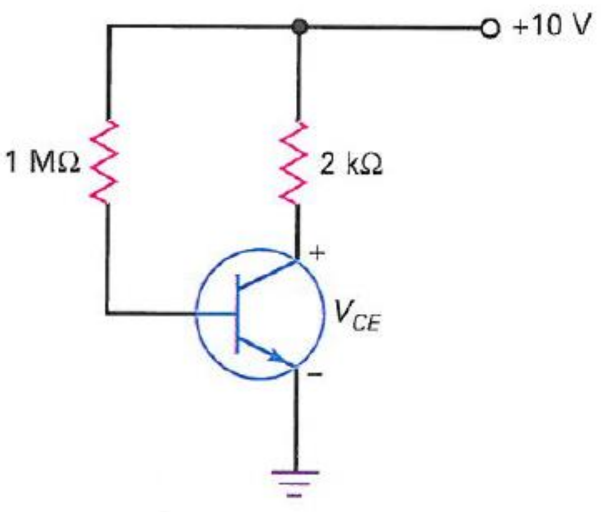
The transistor of Fig. 6-11a has $\beta_{dc} = 300$. Calculate I_B, I_C, V_{CE}, and P_D.



(a)



(b)



(c)

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{10\text{ V} - 0.7\text{ V}}{1\text{ M}\Omega} = 9.3\ \mu\text{A}$$

$$I_C = \beta_{dc} I_B = (300)(9.3\ \mu\text{A}) = 2.79\text{ mA}$$

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (2.79\text{ mA})(2\text{ k}\Omega) = 4.42\text{ V}$$

$$P_D = V_{CE} I_C = (4.42\text{ V})(2.79\text{ mA}) = 12.3\text{ mW}$$

Transistor Specification Sheet

MAXIMUM RATINGS

Rating	Symbol	2N4123	Unit
Collector-Emitter Voltage	V_{CEO}	30	Vdc
Collector-Base Voltage	V_{CBO}	40	Vdc
Emitter-Base Voltage	V_{EBO}	5.0	Vdc
Collector Current – Continuous	I_C	200	mAdc
Total Device Dissipation @ $T_A = 25°C$ Derate above 25°C	P_D	625 5.0	mW mW°C
Operating and Storage Junction Temperature Range	T_j, T_{stg}	–55 to +150	°C

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	$R_{\theta JC}$	83.3	°C W
Thermal Resistance, Junction to Ambient	$R_{\theta JA}$	200	°C W

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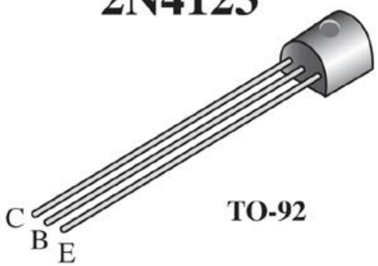
2N4123



TO-92

General Purpose Transistor NPN Silicon

Transistor Specification Sheet

ELECTRICAL CHARACTERISTICS ($T_A = 25^\circ$C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
OFF CHARACTERISTICS				
Collector-Emitter Breakdown Voltage (1) ($I_C = 1.0$ mAdc, $I_E = 0$)	$V_{(BR)CEO}$	30		Vdc
Collector-Base Breakdown Voltage ($I_C = 10$ µAdc, $I_E = 0$)	$V_{(BR)CBO}$	40		Vdc
Emitter-Base Breakdown Voltage ($I_E = 10$ µAdc, $I_C = 0$)	$V_{(BR)EBO}$	5.0	–	Vdc
Collector Cutoff Current ($V_{CB} = 20$ Vdc, $I_E = 0$)	I_{CBO}	–	50	nAdc
Emitter Cutoff Current ($V_{BE} = 3.0$ Vdc, $I_C = 0$)	I_{EBO}	–	50	nAdc
ON CHARACTERISTICS				
DC Current Gain(1) ($I_C = 2.0$ mAdc, $V_{CE} = 1.0$ Vdc) ($I_C = 50$ mAdc, $V_{CE} = 1.0$ Vdc)	h_{FE}	50 25	150 –	–
Collector-Emitter Saturation Voltage(1) ($I_C = 50$ mAdc, $I_B = 5.0$ mAdc)	$V_{CE(sat)}$	–	0.3	Vdc
Base-Emitter Saturation Voltage(1) ($I_C = 50$ mAdc, $I_B = 5.0$ mAdc)	$V_{BE(sat)}$	–	0.95	Vdc

Transistor Specification Sheet

SMALL-SIGNAL CHARACTERISTICS

Current-Gain – Bandwidth Product (I_C = 10 mAdc, V_{CE} = 20 Vdc, f = 100 MHz)	f_T	250		MHz
Output Capacitance (V_{CB} = 5.0 Vdc, I_E = 0, f = 100 MHz)	C_{obo}	–	4.0	pF
Input Capacitance (V_{BE} = 0.5 Vdc, I_C = 0, f = 100 kHz)	C_{ibo}	–	8.0	pF
Collector-Base Capacitance (I_E = 0, V_{CB} = 5.0 V, f = 100 kHz)	C_{cb}	–	4.0	pF
Small-Signal Current Gain (I_C = 2.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	h_{fe}	50	200	–
Current Gain – High Frequency (I_C = 10 mAdc, V_{CE} = 20 Vdc, f = 100 MHz) (I_C = 2.0 mAdc, V_{CE} = 10 V, f = 1.0 kHz)	h_{fe}	2.5 50	– 200	–
Noise Figure (I_C = 100 µAdc, V_{CE} = 5.0 Vdc, R_S = 1.0 k ohm, f = 1.0 kHz)	NF	–	6.0	dB

(1) Pulse Test: Pulse Width = 300 µs. Duty Cycle = 2.0%