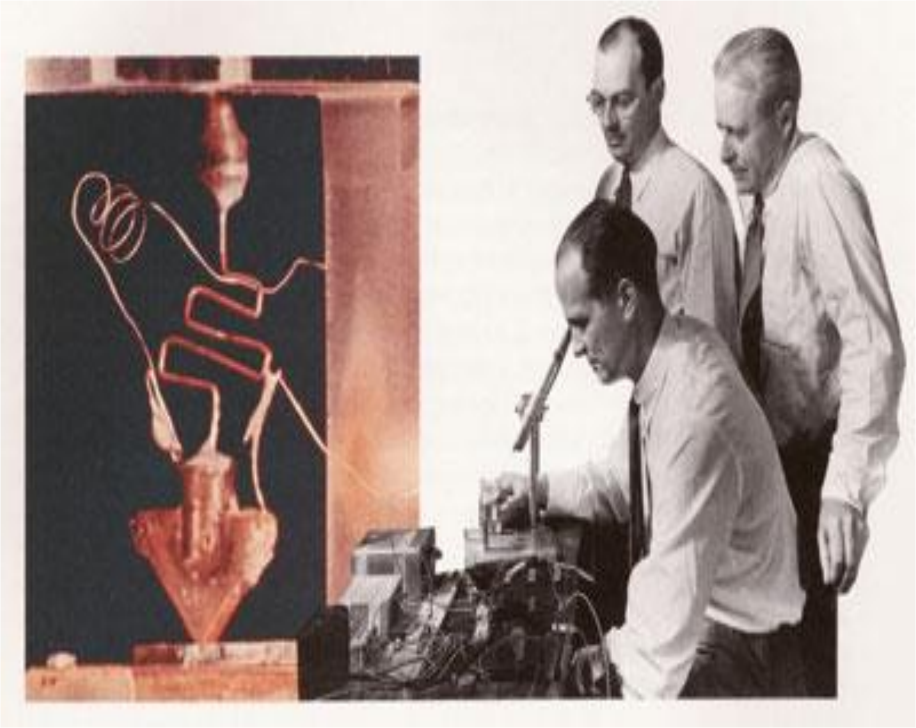
Bipolar Junction Transistors (BJT)

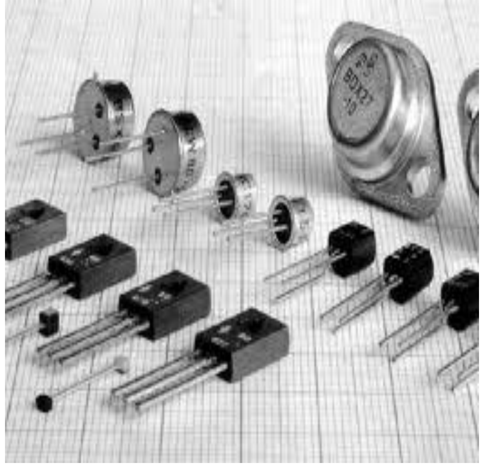
Transistors

- Evolution of electronics
  - In need of a device that was small, robust, reliable, energy efficient and cheap to manufacture
- 1947
  - **John Bardeen, Walter Brattain and William Shockley** invented transistor
- Transistor Effect
  - "when electrical contacts were applied to a crystal of germanium, the output power was larger than the input."

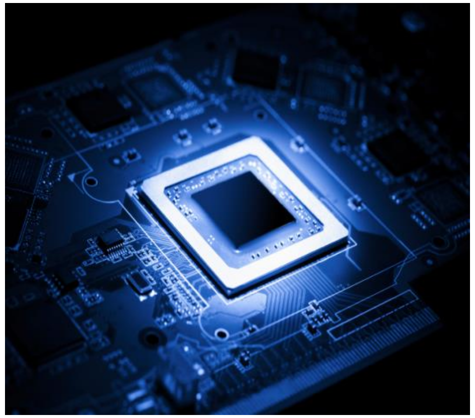


Transistors

First Transistor



Different types and sizes

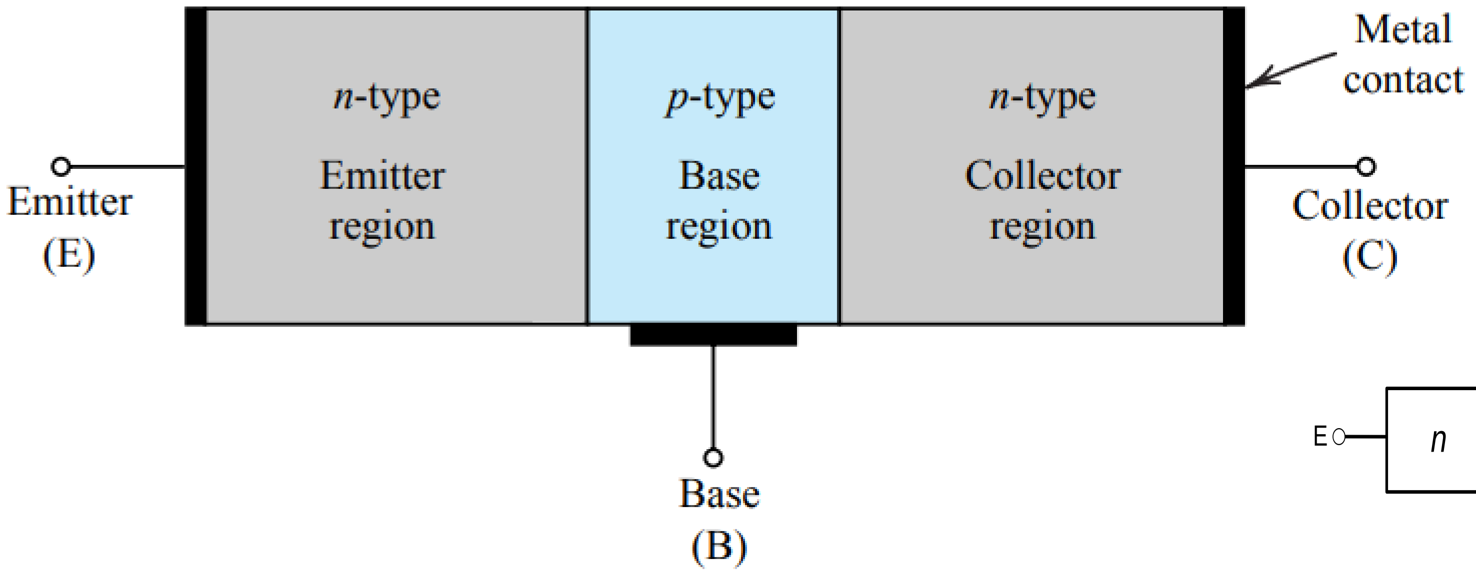


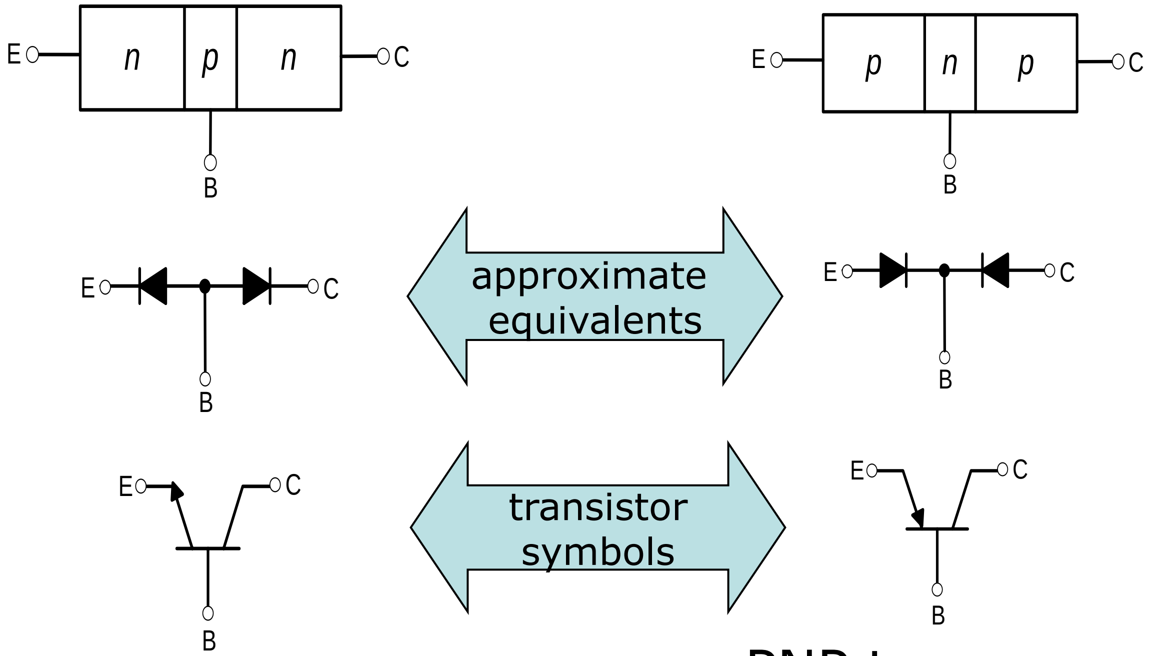
Modern Electronics

General Applications

BJT Device Structure

- A transistor has three doped regions: Emitter, Base, Collector



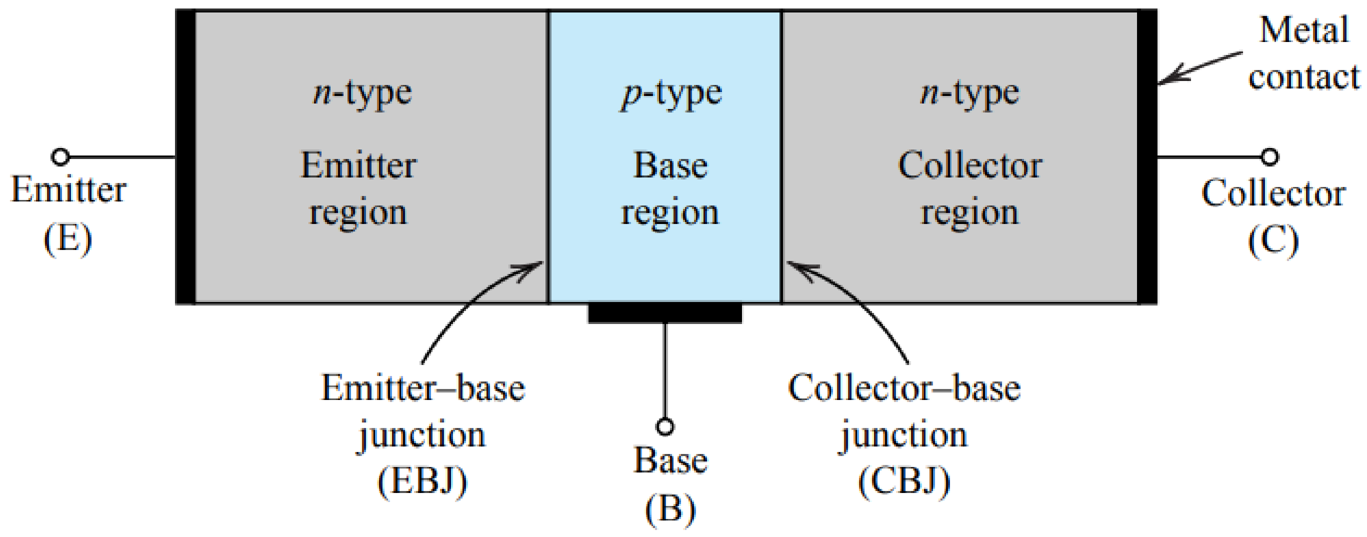


NPN type

PNP type

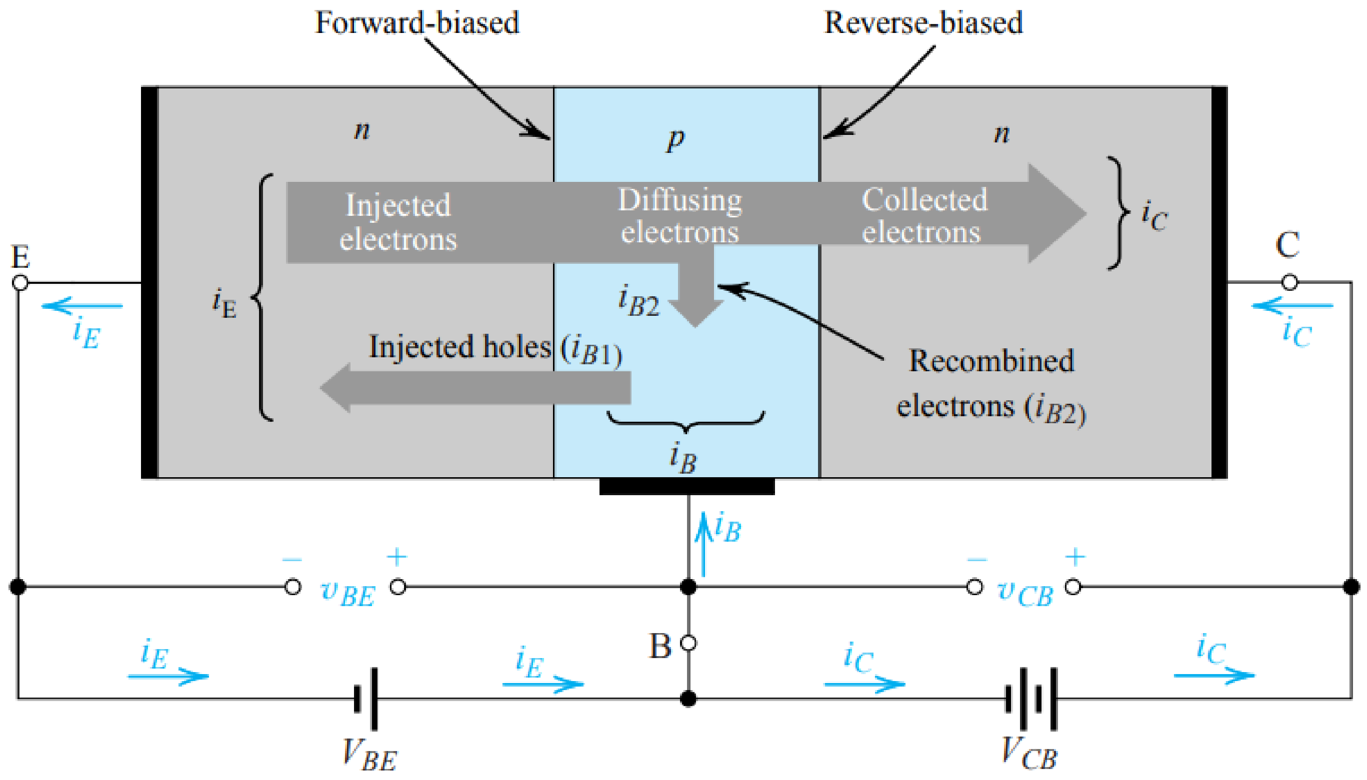
Unbiased Transistor

- A transistor has three doped regions: Emitter, Base, Collector
- **Doping Levels -** the emitter is heavily doped; the base is lightly doped; the collector is intermediately doped
- As a result of diffusion - two depletion layers
- the barrier potential is approx. 0.7 V at 25°C for silicon



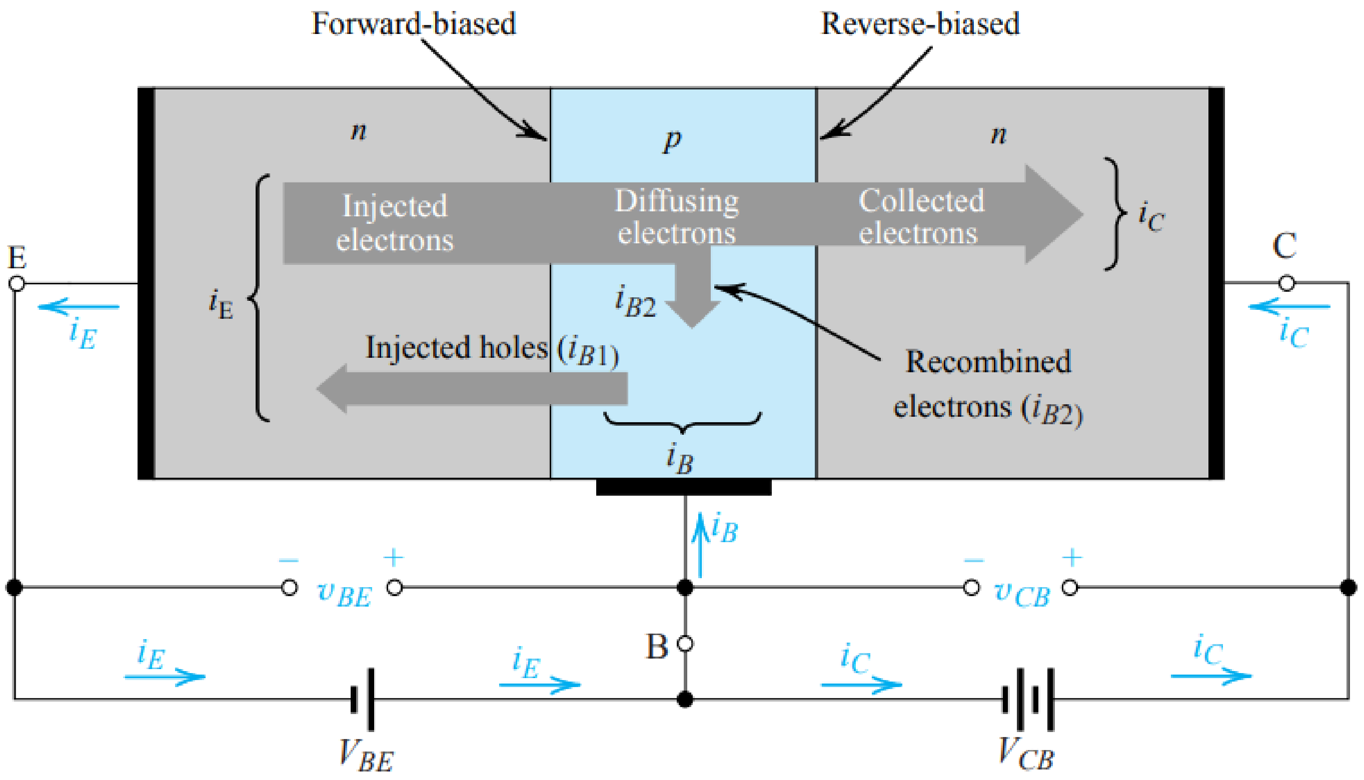
BJT Operation

- V_{BE} forward-biases the emitter diode
- V_{CB} reverse-biases the collector



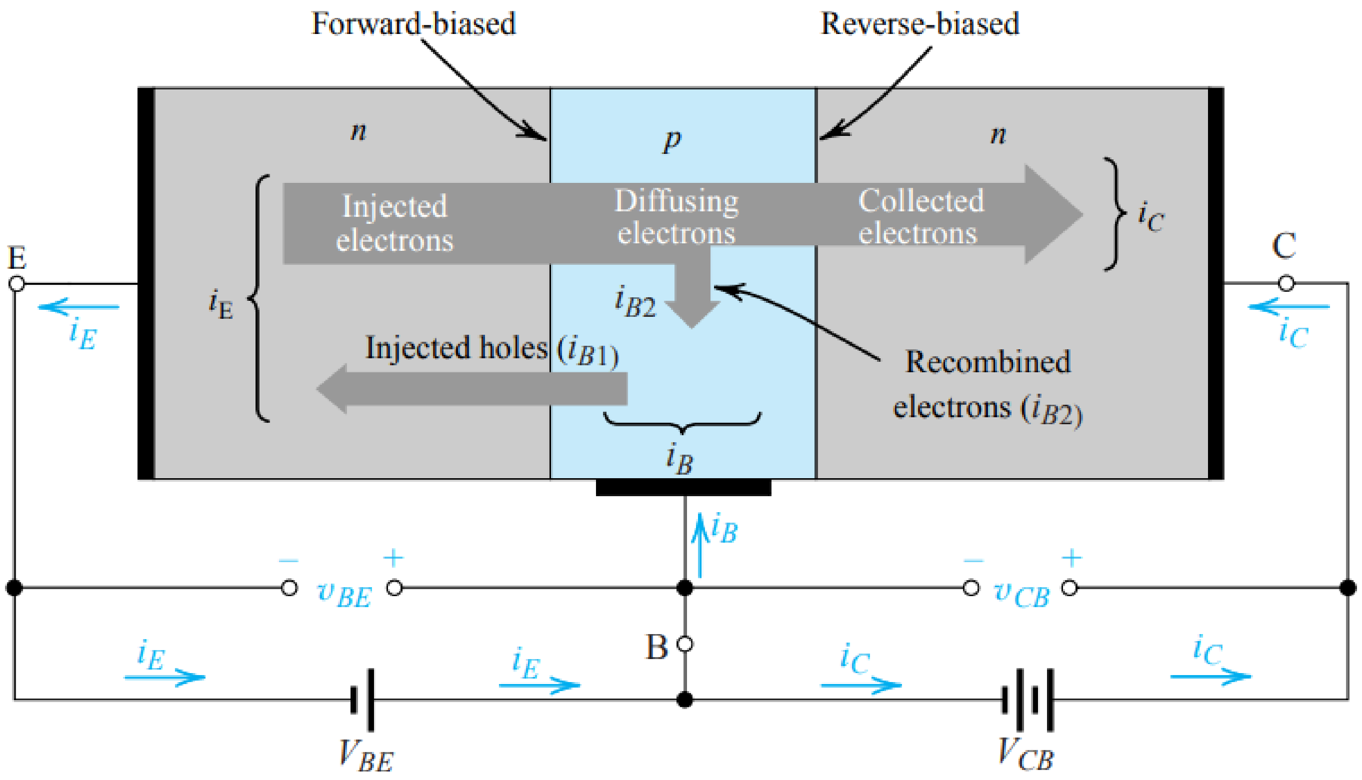
BJT Operation

- Heavily doped emitter emits or injects its free electrons into the base
- Holes diffuse from the base into the emitter
- Current through EB junction is Emitter current, i_E



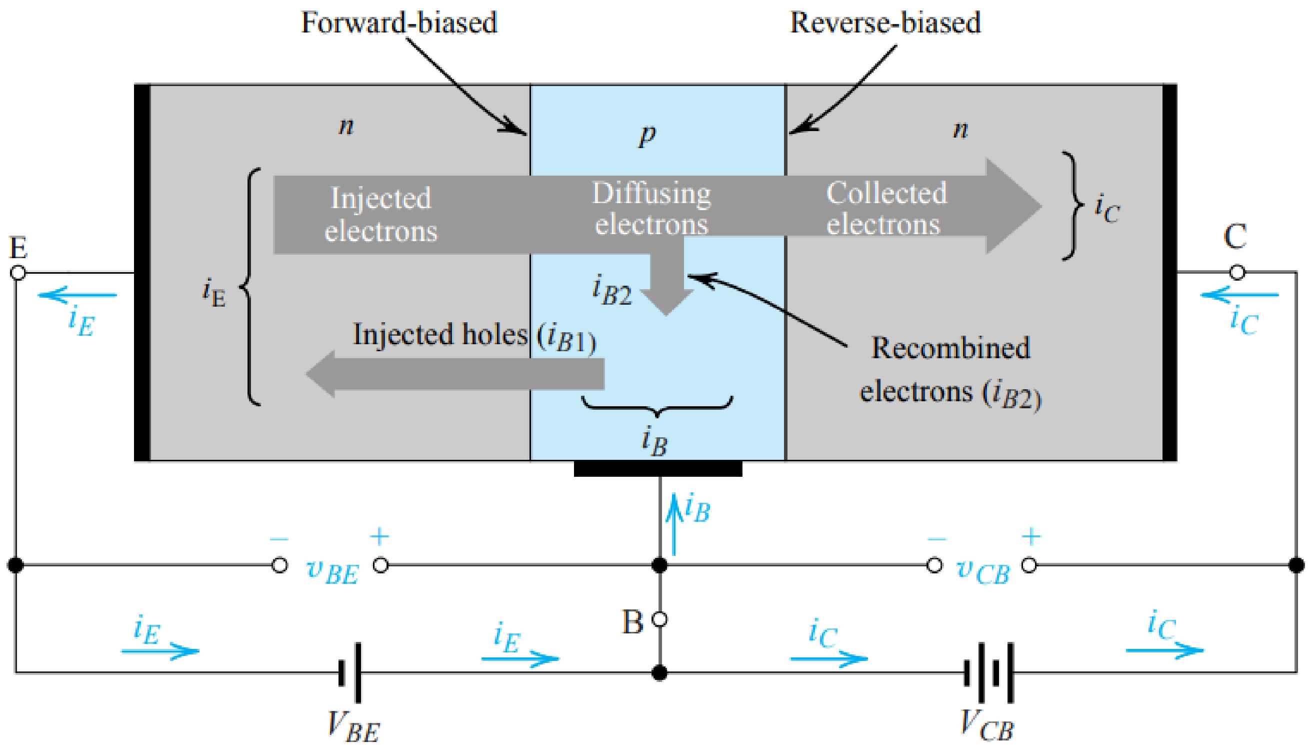
BJT Operation

- Lightly doped base passes emitter-injected electrons on to the collector.
- Only a few free electrons will recombine with holes in the lightly doped base
- Resulting in Base current, i_B



BJT Operation

- Most diffusing electrons will reach boundary of collector-base depletion region
- Because collector is more positive than base, these electrons are swept into collector
- Resulting in Collector current, i_C



Current Flow in BJT

- Three different currents in a transistor: emitter current i_E, base current i_B, and collector current i_C.
- Collector current, i_C $\quad i_C = I_S e^{v_{BE}/V_T}$
- Base current, i_B

$$i_B = \frac{i_C}{\beta} \qquad i_B = \frac{I_S}{\beta} e^{v_{BE}/V_T}$$

β Common Emitter current gain

- Emitter current, $i_E = i_C + i_B$

$$i_E = \frac{\beta + 1}{\beta} i_C \qquad \alpha = \frac{\beta}{\beta + 1} \qquad \beta = \frac{\alpha}{1 - \alpha}$$

$$i_C = \alpha i_E \qquad I_B << I_C \qquad I_C \approx I_E$$

Transistor Currents

- dc alpha α_{dc} - dc collector current divided by the dc emitter current

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

- Collector current almost equals the emitter current, the dc alpha is slightly less than 1
- dc beta β_{dc} of a transistor - ratio of the dc collector current to the dc base current

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

- dc beta is also known as the current gain because a small base current controls a much larger collector current.
- The current gain is typically 100 to 300

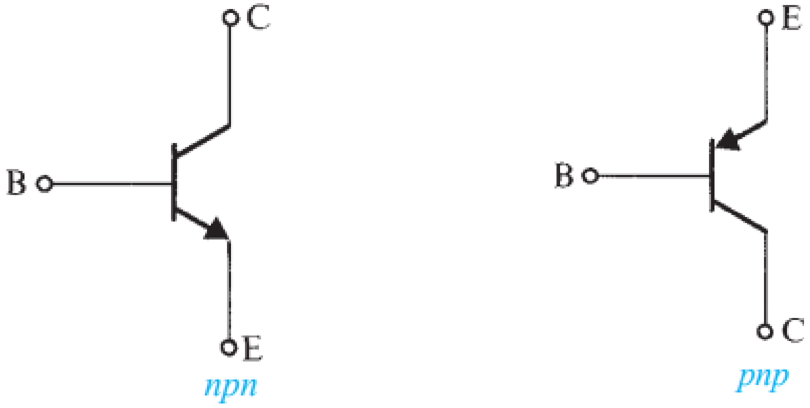
$$\alpha = \frac{\beta}{\beta + 1}, \qquad \beta = \frac{\alpha}{1 - \alpha}$$

Modes of operation

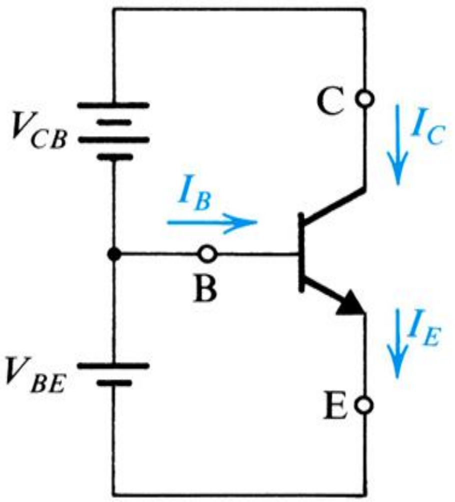
MODE	Emitter Base Junction (EBJ)	Collector Base Junction (CBJ)	Applications
Cut-off	Reverse Biased	Reverse Biased	Switch
Forward Active	Forward Biased	Reverse Biased	Amplifier
Reverse Active	Reverse Biased	Forward Biased	Mostly not operated in this mode
Saturation	Forward Biased	Forward Biased	Switch

Circuit Symbols and Conventions

- BJT circuit symbol



- *npn* transistor biased in active mode



npn transistor will operate in active mode as long as the collector voltage does not fall below that of the base by approximately 0.4 V

V_{CB} < 0.4 V transistor leaves active mode and enters saturation mode

Circuit Symbols and Conventions

The Collector-Base Reverse Current (I_{CB0})

- Previously, small reverse current was ignored.
  - This is carried by thermally-generated minority carriers.

- The **collector-base junction current** (I_{CBO}) is the reverse current flowing from collector to base with the emitter open-circuited.
  - Usually in nanoampere range

- I_{CBO} depends on temperature, approx. doubling for every 10^0C rise

Summary of BJT current-voltage relationship

$$i_C = I_S e^{v_{BE}/V_T}$$

$$i_B = \frac{i_C}{\beta} = \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T}$$

$$i_E = \frac{i_C}{\alpha} = \left(\frac{I_S}{\alpha}\right) e^{v_{BE}/V_T}$$

Note: For the *pnp* transistor, replace v_{BE} with v_{EB}.

$$i_C = \alpha i_E \qquad i_B = (1-\alpha) i_E = \frac{i_E}{\beta+1}$$

$$i_C = \beta i_B \qquad i_E = (\beta+1) i_B$$

$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \frac{\beta}{\beta+1}$$

$$V_T = \text{thermal voltage} = \frac{kT}{q} \simeq 25\ \text{mV at room temperature}$$

Problem #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

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

Problem #2

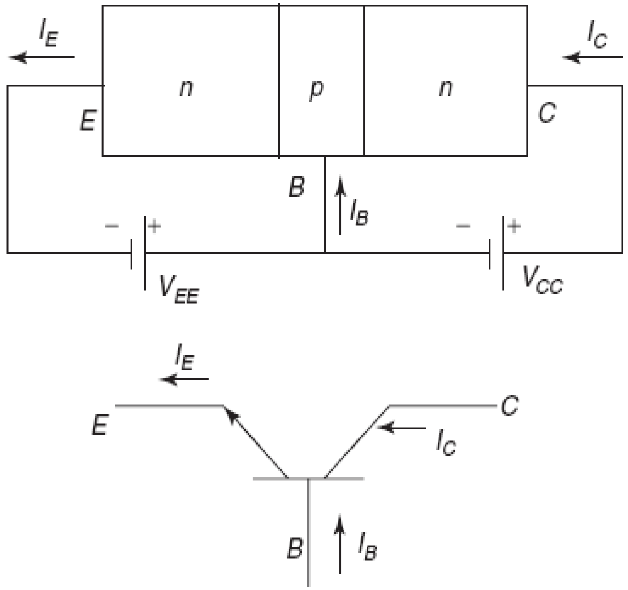
A transistor has a current gain of 175. If the base current is 0.1 mA, what is the collector current?

Solution

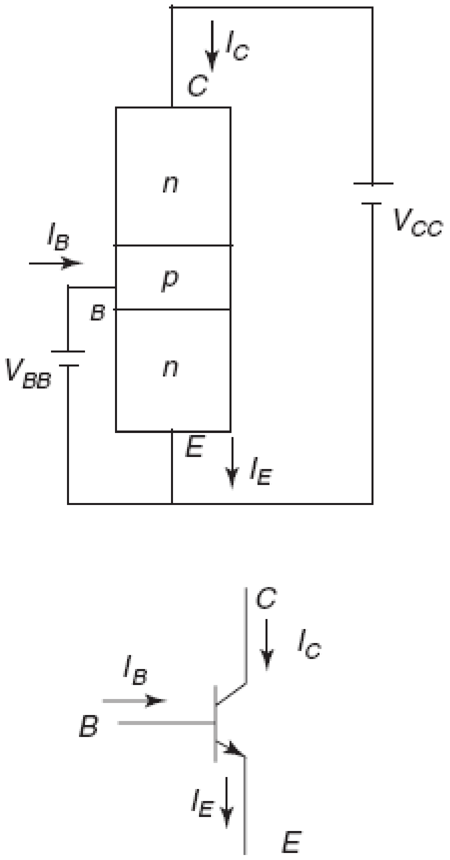
$$I_C = 175(0.1 \text{ mA}) = 17.5 \text{ mA}$$

BJT Configurations

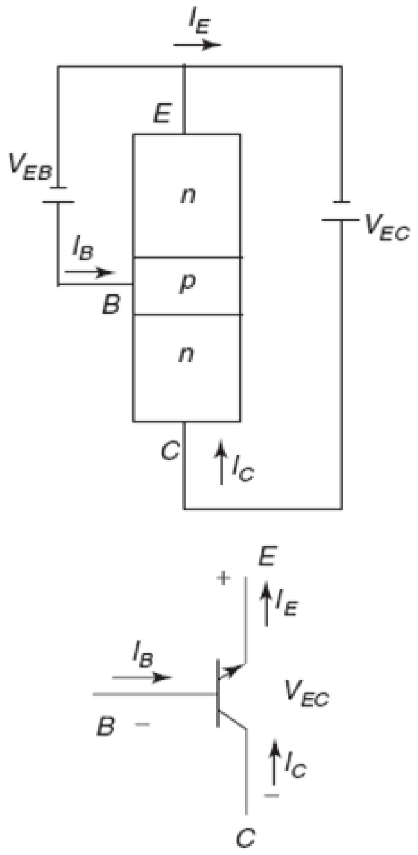
Common-base configuration of *npn transistor*



Common-emitter configuration of *npn transistor*



Common-collector configuration of *npn* transistor



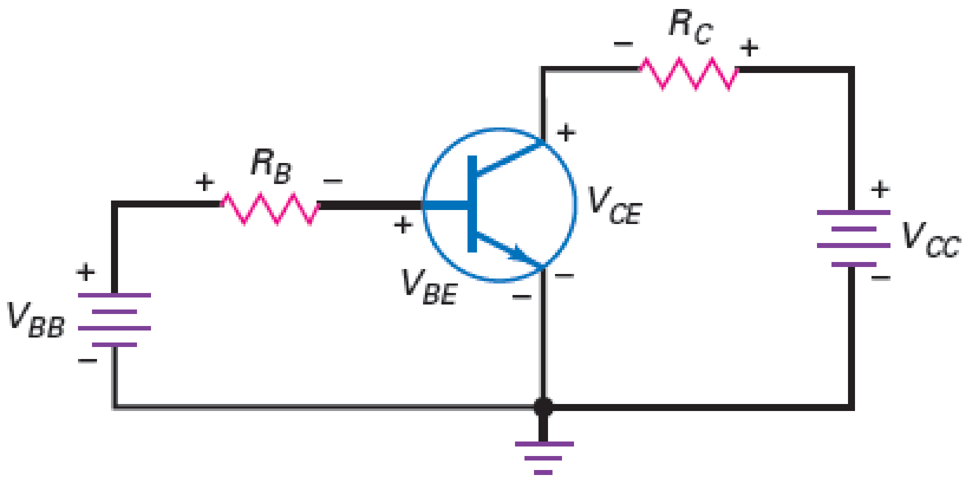
Transistor Characteristics

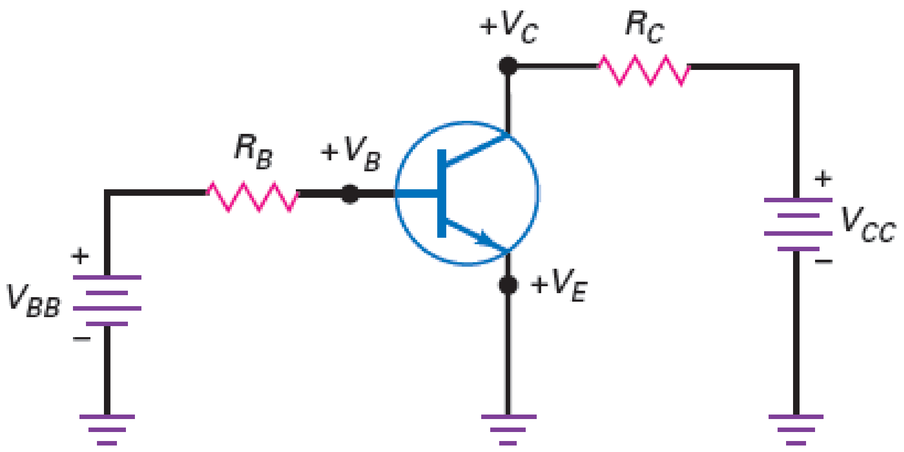
Common Emitter Characteristics

Transistor Characteristics

Common Emitter Configuration

- V_{BB} source forward-biases the emitter diode with R_B as a current-limiting resistance.
- By changing V_{BB} or R_B, the base current can be changed.
- Changing the base current will change the collector current.
- The base current controls the collector current.





Transistor Characteristics

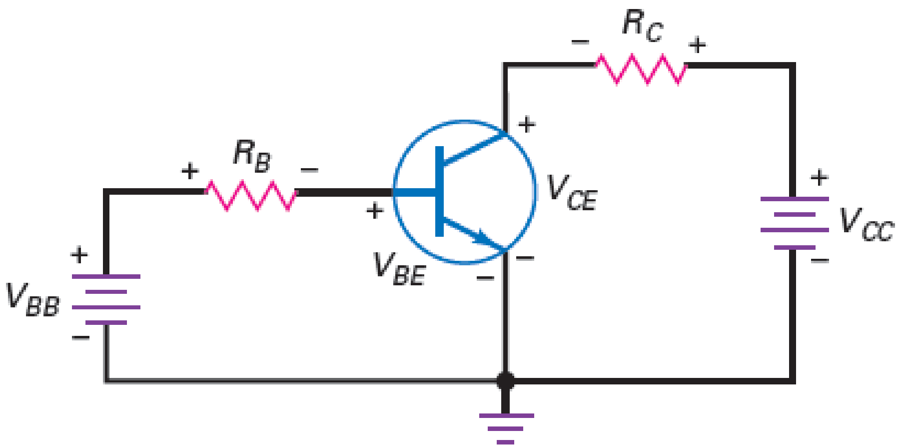
Common Emitter Configuration

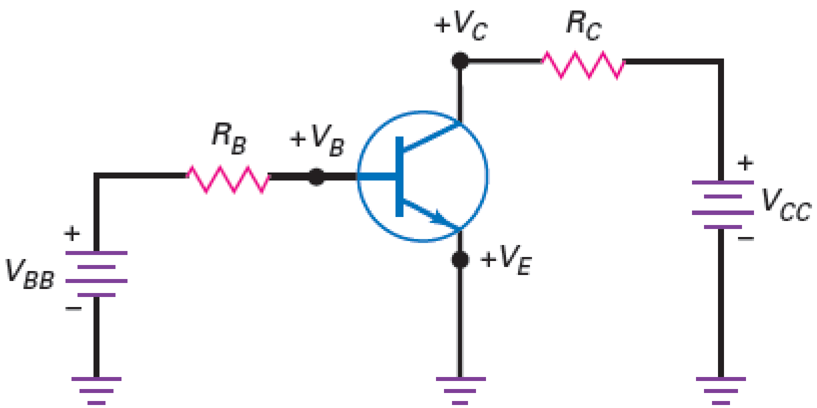
- Source voltage V_{CC} reverse-biases the collector diode through R_C.
- The collector must be positive to collect most of the free electrons injected into the base.

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

V_E is zero in CE connection

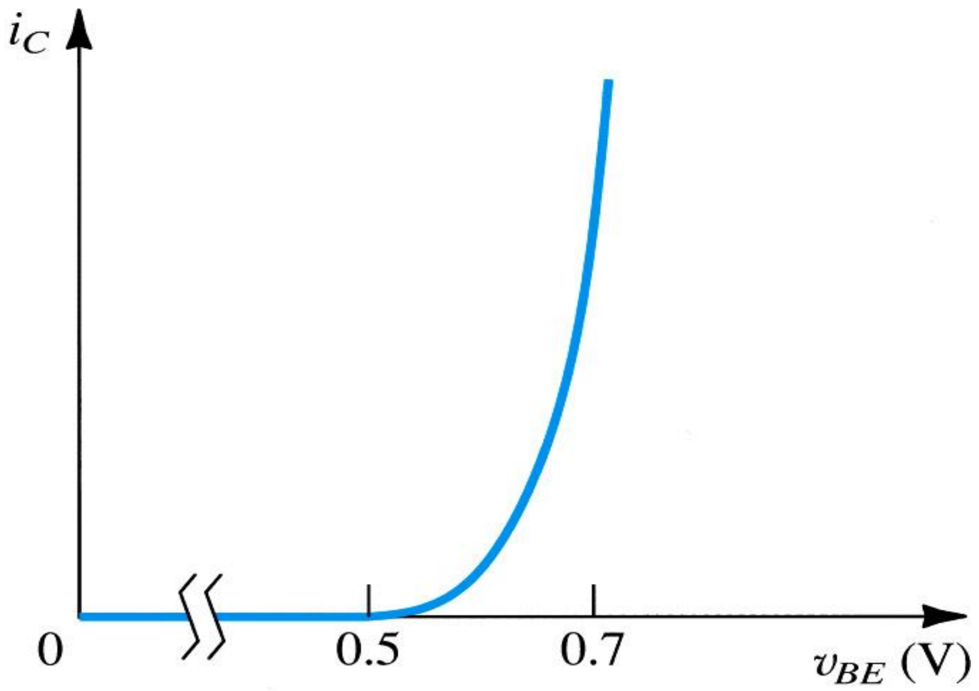
$$V_{CE} = V_C$$
$$V_{CB} = V_C - V_B$$
$$V_{BE} = V_B$$





Graphical Representation of transistor *i*-*v* Characteristics

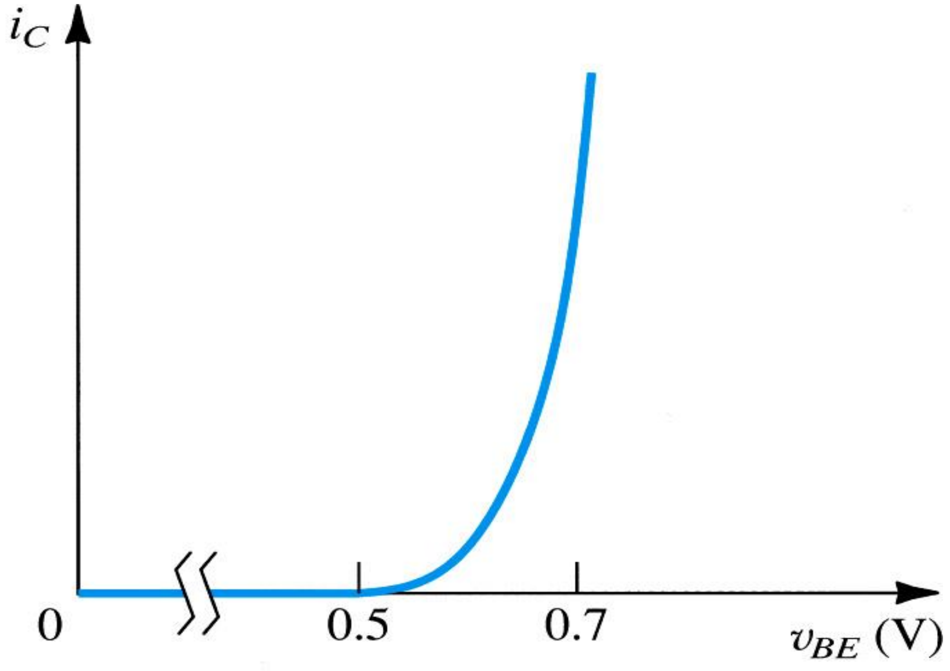
Common Emitter Characteristics



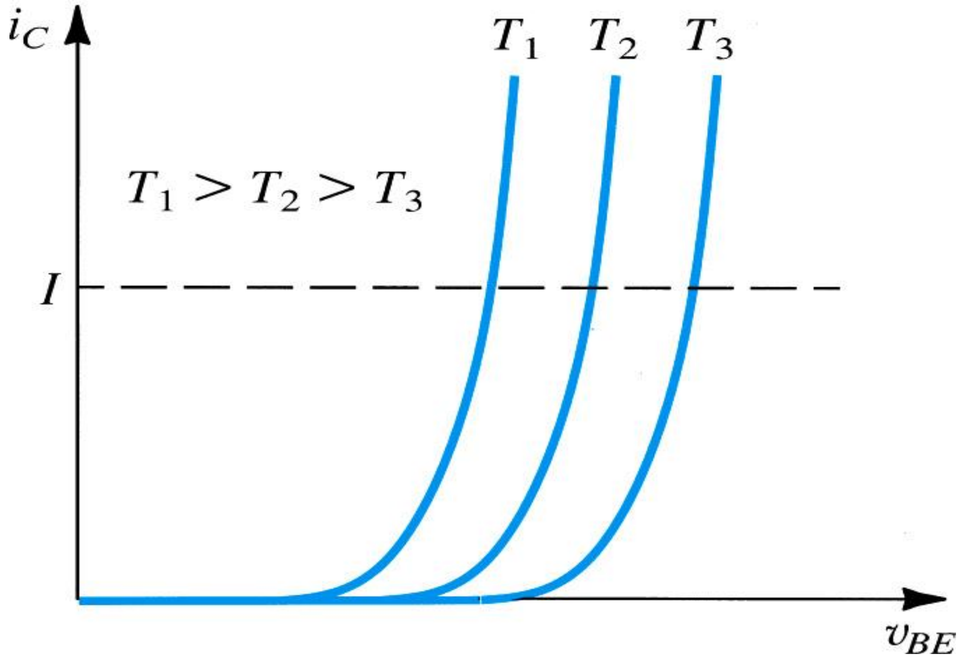
The i_C-v_{BE} characteristic for an npn transistor.

Graphical Representation of transistor *i*-*v* Characteristics

Common Emitter Characteristics



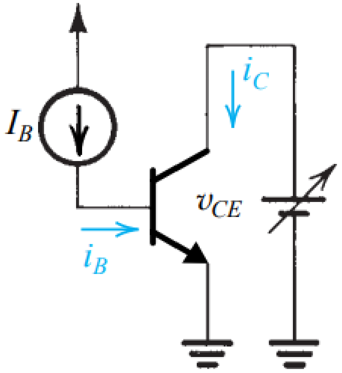
The i_C-v_{BE} characteristic for an npn transistor

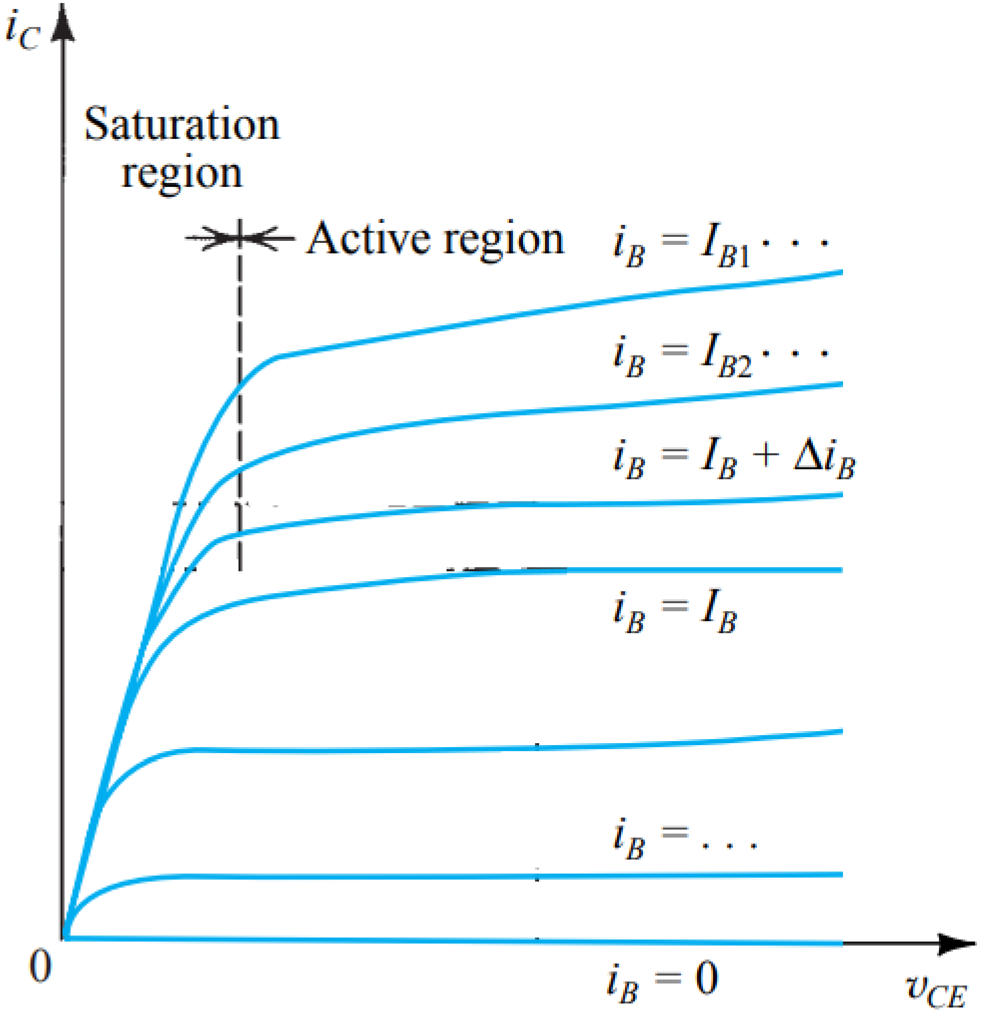


Effect of temperature on the i_C-v_{BE} characteristic

Graphical Representation of transistor *i*-*v* Characteristics

Common Emitter Characteristics

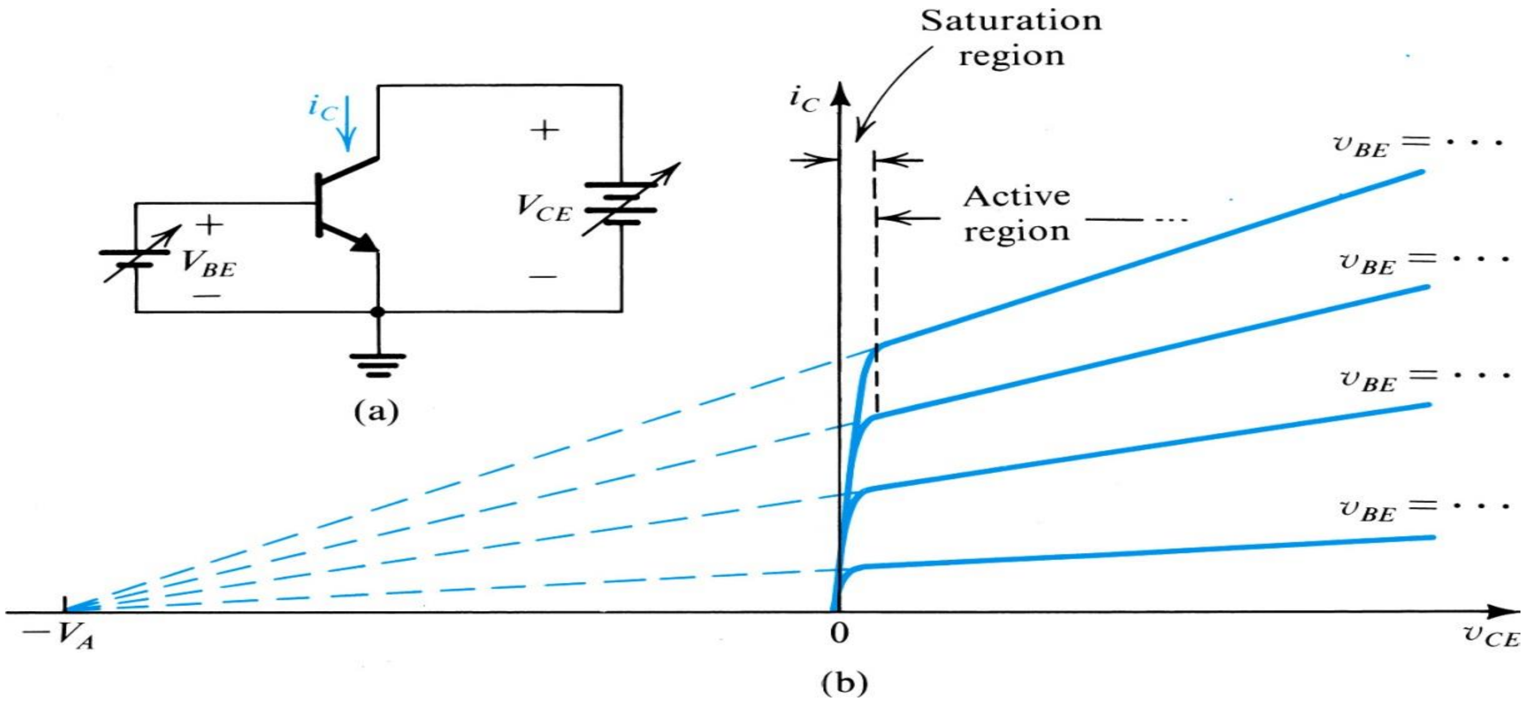




The i_C-v_{CE} characteristic for an npn transistor.

Dependence of i_C on Collector Voltage – The Early Effect

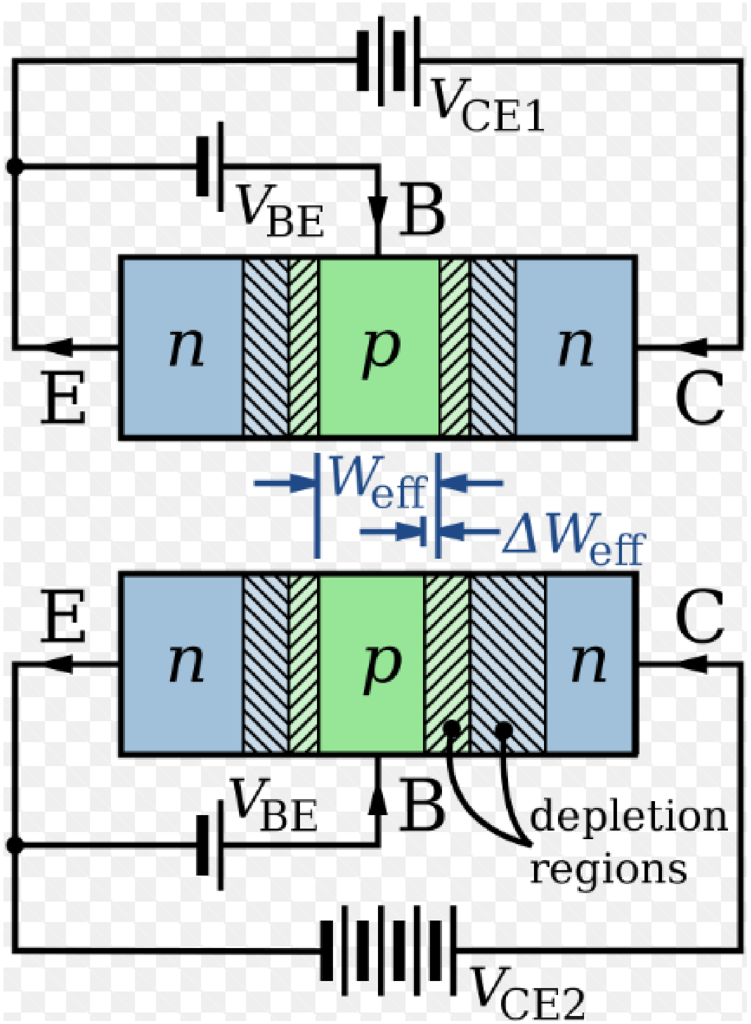
- When operated in active region, practical BJT's show some dependence of collector current on collector voltage.
- As such, i_C-v_{CE} characteristic is not "straight".



V_A - Early Voltage (50 – 100 V)

Early Effect

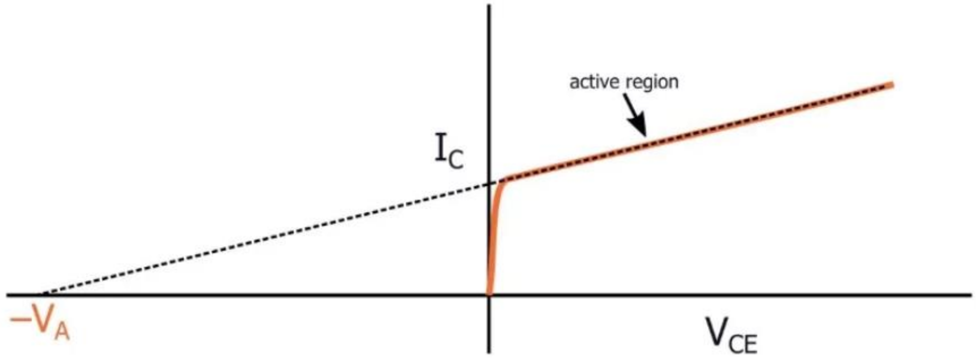
- **<u>Early effect</u>** <u>or base width modulation:</u> is the variation in the width of the base due to a variation in the applied base-to-collector voltage.
- For example a greater reverse bias across the collector- base junction increases the collector-base depletion width.



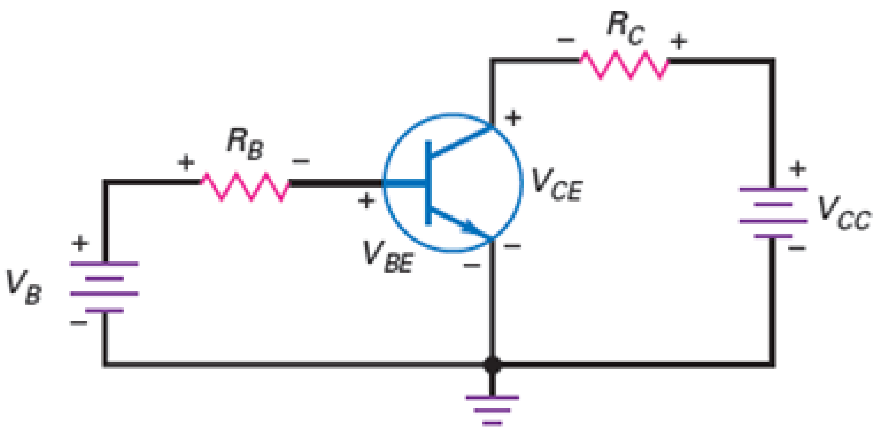
Consequences of Early Effect

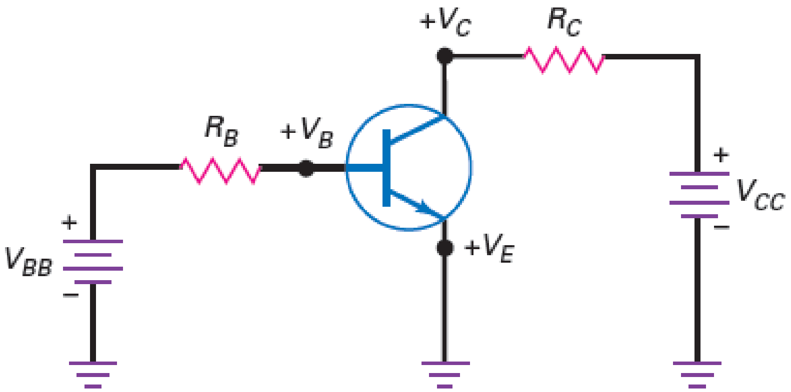
- Reverse saturation current increases, increasing the collector current. $I_C = I_S e^{\frac{V_{BE}}{V_T}}$
- Less chance for recombination in the base.
- Charge gradient is increased and hence the minority carriers injected inside the emitter will increase.
- For extremely large voltages, base width = 0 , causing voltage breakdown in transistor resulting in **punchthrough**.

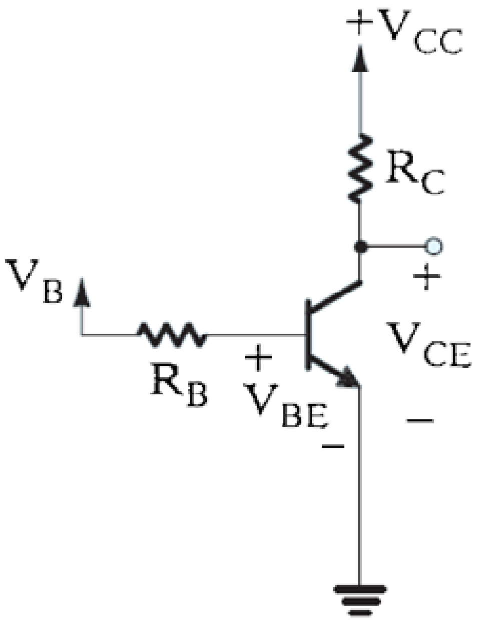
$$I_C = I_S e^{\frac{V_{BE}}{V_T}} \left(1 + \frac{V_{CE}}{V_A}\right)$$



Transistor Operating Point







Applying KVL

$$V_B = I_B R_B + V_{BE}$$

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

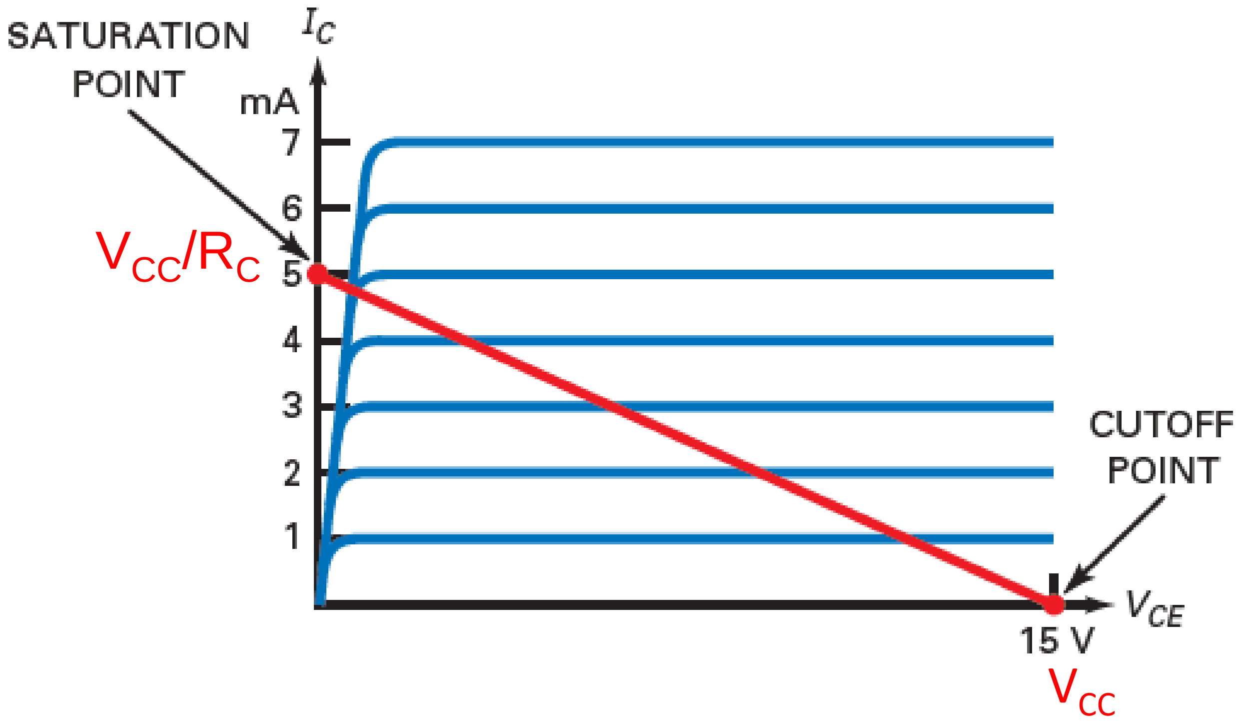
$$V_{CC} = I_C R_C + V_{CE}$$

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

$$P_D = V_{CE} I_C$$

DC Load Line

- In graphical analysis of nonlinear electronic circuits, a **load line** is a **line** drawn on the characteristic curve, a graph of the current vs the voltage
- It is used to determine the correct **DC** operating **point**, often called the **Q point**.



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

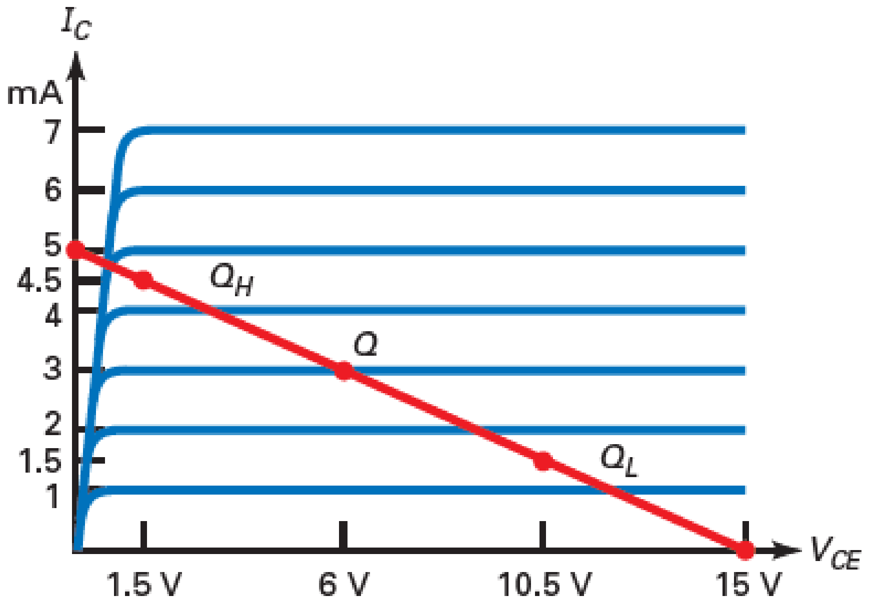
$$I_C = \frac{V_{CC}}{R_C} - \frac{V_{CE}}{R_C}$$

Operating Point (Q-Point)

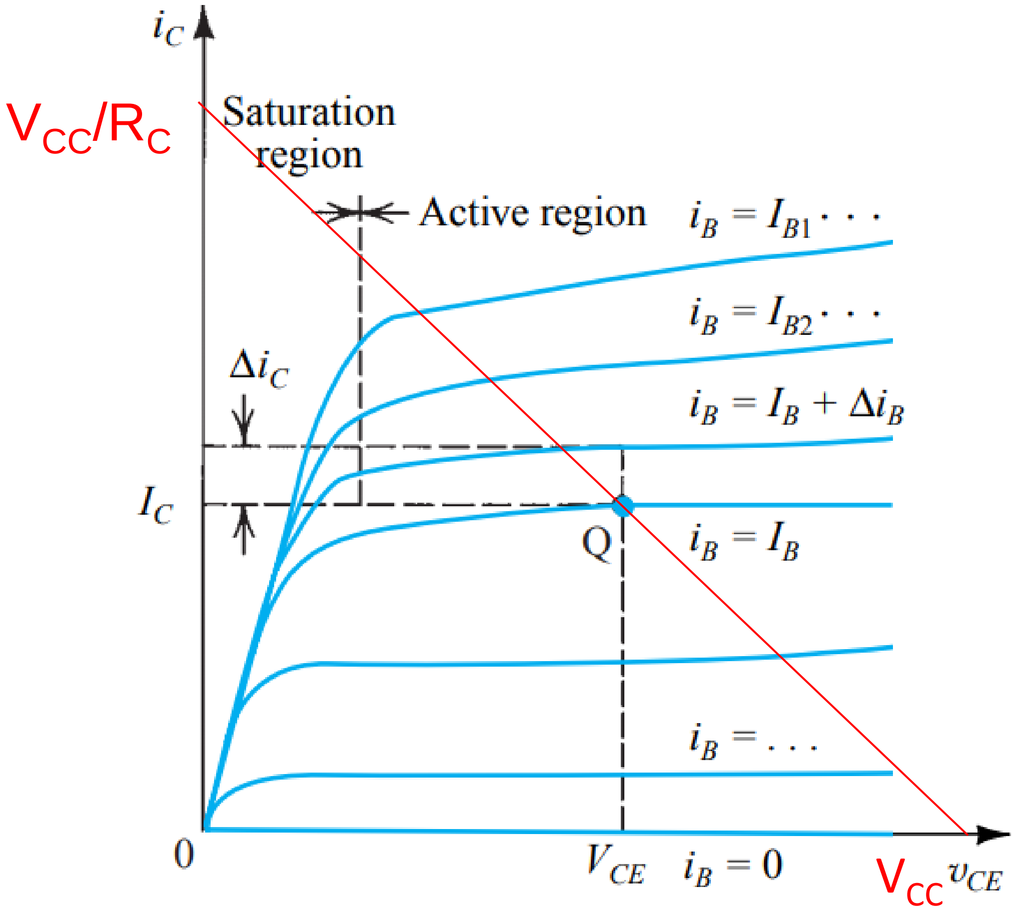
$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

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

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



Operating Point (Q-Point)

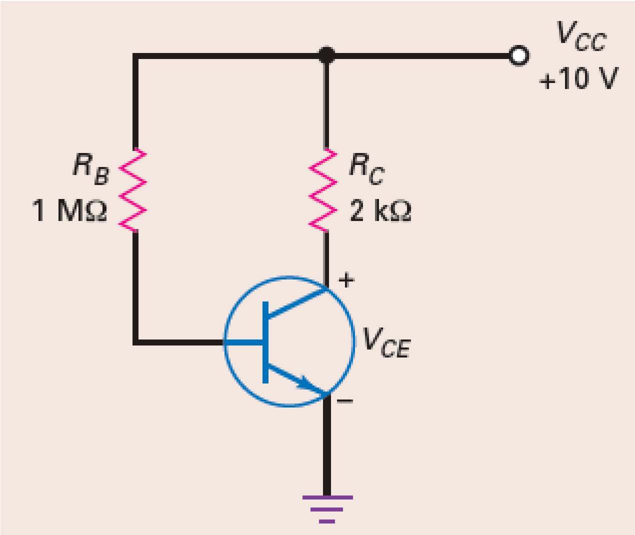


$$V_{CC} = I_C R_C + V_{CE}$$

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

Problem #3

The transistor shown below has $\beta_{dc} = 300$. Calculate I_B, I_C, V_{CE}, and P_D.



Solution

$I_B = 9.3\ \mu A$
$I_C = 2.79\ mA$
$V_{CE} = 4.42\ V$
$P_D = 12.3\ mW$

FAIRCHILD SEMICONDUCTOR®

October 2011

2N3904 / MMBT3904 / PZT3904
NPN General Purpose Amplifier

Features

- 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.

Absolute Maximum Ratings* T_a = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
V_{CBO}	Collector-Base Voltage	60	V
V_{EBO}	Emitter-Base Voltage	6.0	V
I_C	Collector Current - Continuous	200	mA
T_J, T_{stg}	Operating and Storage Junction Temperature Range	-55 to +150	°C

* These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

NOTES:

1) These ratings are based on a maximum junction temperature of 150 degrees C.

2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations.

Thermal Characteristics T_a = 25°C unless otherwise noted

Symbol	Parameter	Max.			Units
		2N3904	*MMBT3904	**PZT3904	
P_D	Total Device Dissipation Derate above 25°C	625 5.0	350 2.8	1,000 8.0	mW mW/°C
$R_{\theta JC}$	Thermal Resistance, Junction to Case	83.3			°C/W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	200	357	125	°C/W

* Device mounted on FR-4 PCB 1.6" X 1.6" X 0.06".

** Device mounted on FR-4 PCB 36 mm X 18 mm X 1.5 mm; mounting pad for the collector lead min. 6 cm^2.

Electrical Characteristics T_a = 25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Max.	Units
OFF CHARACTERISTICS					
$V_{(BR)CEO}$	Collector-Emitter Breakdown Voltage	I_C = 1.0mA, I_B = 0	40		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10∝A, I_E = 0	60		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10∝A, I_C = 0	6.0		V
I_{BL}	Base Cutoff Current	V_{CE} = 30V, V_{EB} = 3V		50	nA
I_{CEX}	Collector Cutoff Current	V_{CE} = 30V, V_{EB} = 3V		50	nA
ON CHARACTERISTICS*					
h_{FE}	DC Current Gain	I_C = 0.1mA, V_{CE} = 1.0V I_C = 1.0mA, V_{CE} = 1.0V I_C = 10mA, V_{CE} = 1.0V I_C = 50mA, V_{CE} = 1.0V I_C = 100mA, V_{CE} = 1.0V	40 70 100 60 30	 300 	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10mA, I_B = 1.0mA I_C = 50mA, I_B = 5.0mA		0.2 0.3	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10mA, I_B = 1.0mA I_C = 50mA, I_B = 5.0mA	0.65	0.85 0.95	V V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	I_C = 10mA, V_{CE} = 20V, f = 100MHz	300		MHz
C_{obo}	Output Capacitance	V_{CB} = 5.0V, I_E = 0, f = 1.0MHz		4.0	pF
C_{ibo}	Input Capacitance	V_{EB} = 0.5V, I_C = 0, f = 1.0MHz		8.0	pF
NF	Noise Figure	I_C = 100∝A, V_{CE} = 5.0V, R_S = 1.0kΩ, f = 10Hz to 15.7kHz		5.0	dB
SWITCHING CHARACTERISTICS					
t_d	Delay Time	V_{CC} = 3.0V, V_{BE} = 0.5V I_C = 10mA, I_{B1} = 1.0mA		35	ns
t_r	Rise Time			35	ns
t_s	Storage Time	V_{CC} = 3.0V, I_C = 10mA, I_{B1} = I_{B2} = 1.0mA		200	ns
t_f	Fall Time			50	ns

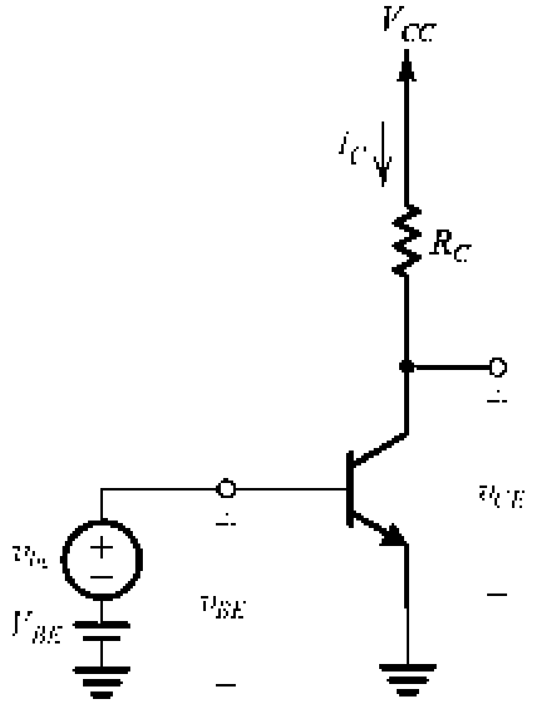
* Pulse Test: Pulse Width ≤ 300∝s, Duty Cycle ≤ 2.0%

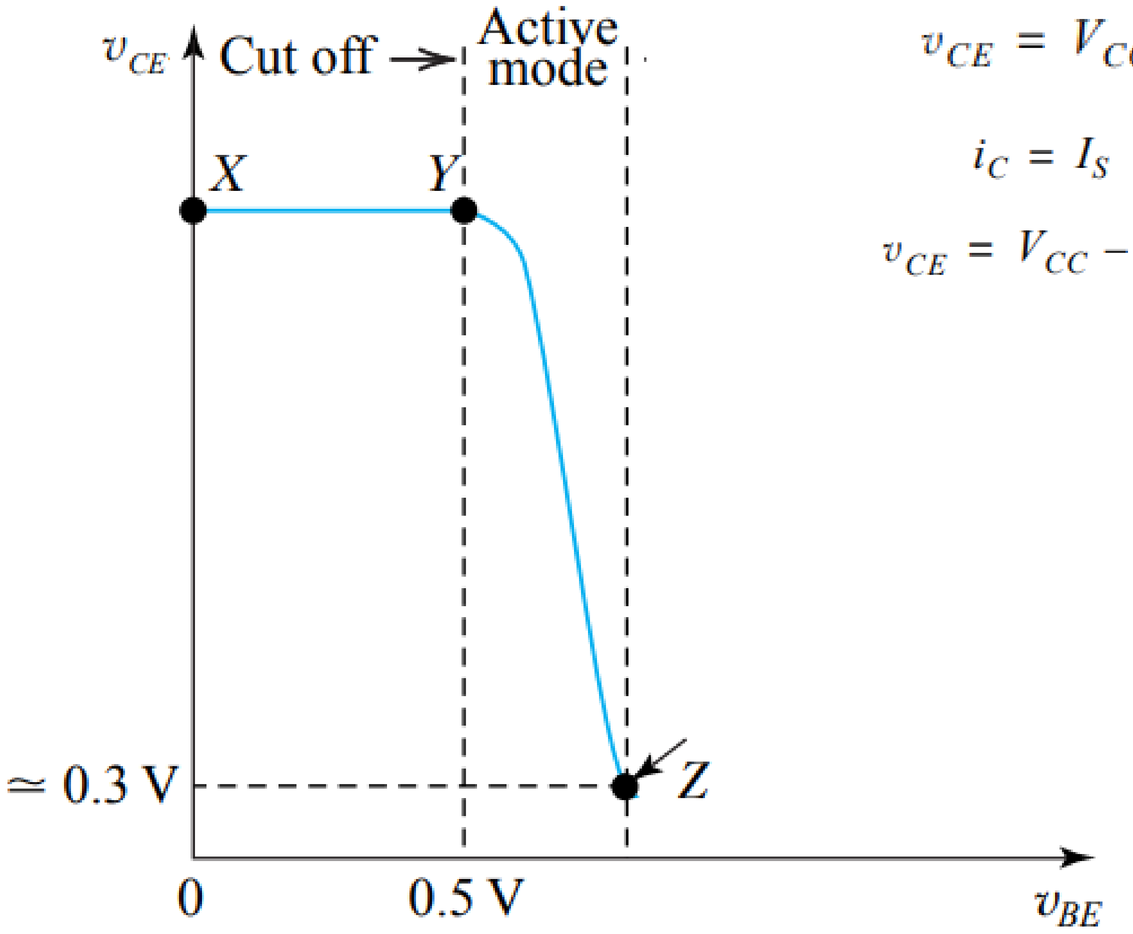
ON CHARACTERISTICS*					
h_{FE}	DC Current Gain	I_C = 0.1mA, V_{CE} = 1.0V I_C = 1.0mA, V_{CE} = 1.0V I_C = 10mA, V_{CE} = 1.0V I_C = 50mA, V_{CE} = 1.0V I_C = 100mA, V_{CE} = 1.0V	40 70 100 60 30	 300 	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10mA, I_B = 1.0mA I_C = 50mA, I_B = 5.0mA		0.2 0.3	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10mA, I_B = 1.0mA I_C = 50mA, I_B = 5.0mA	0.65	0.85 0.95	V V

BJT as an Amplifier

Common Emitter Amplifier

Voltage amplifier





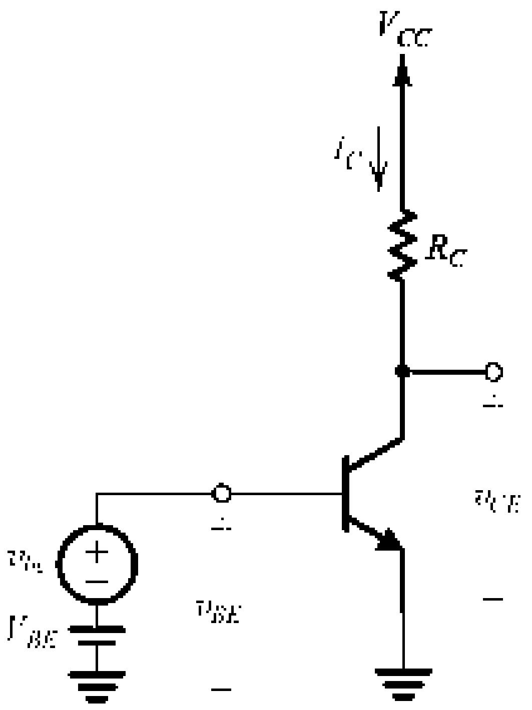
$$v_{CE} = V_{CC} - i_C R_C$$

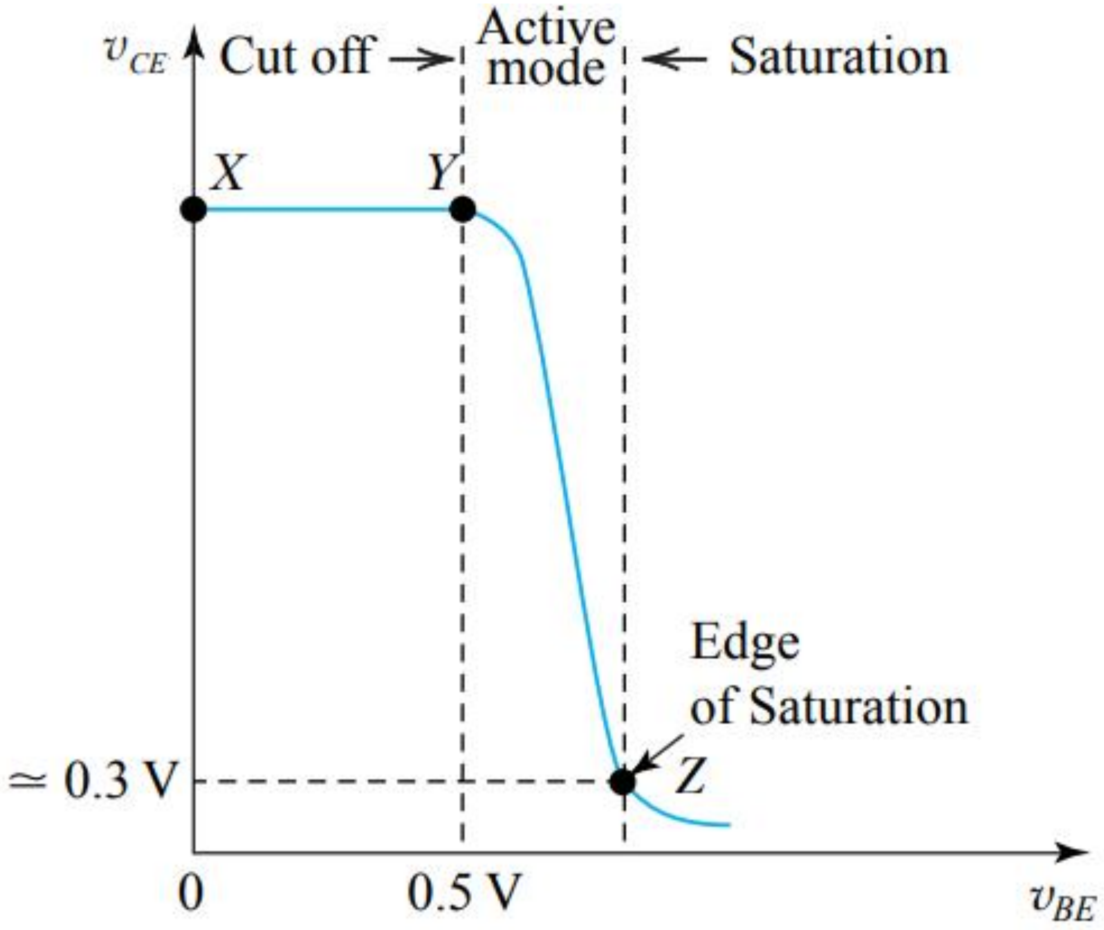
$$i_C = I_S \; e^{v_{BE}/V_T}$$

$$v_{CE} = V_{CC} - R_C I_S \; e^{v_{BE}/V_T}$$

Common Emitter Amplifier

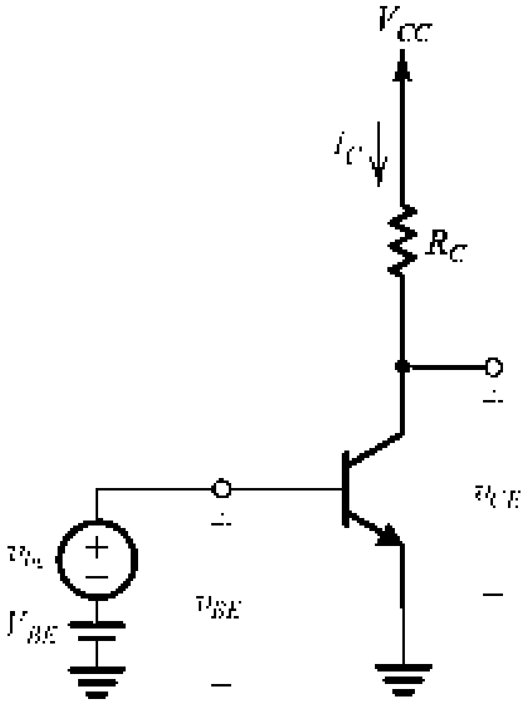
Voltage amplifier

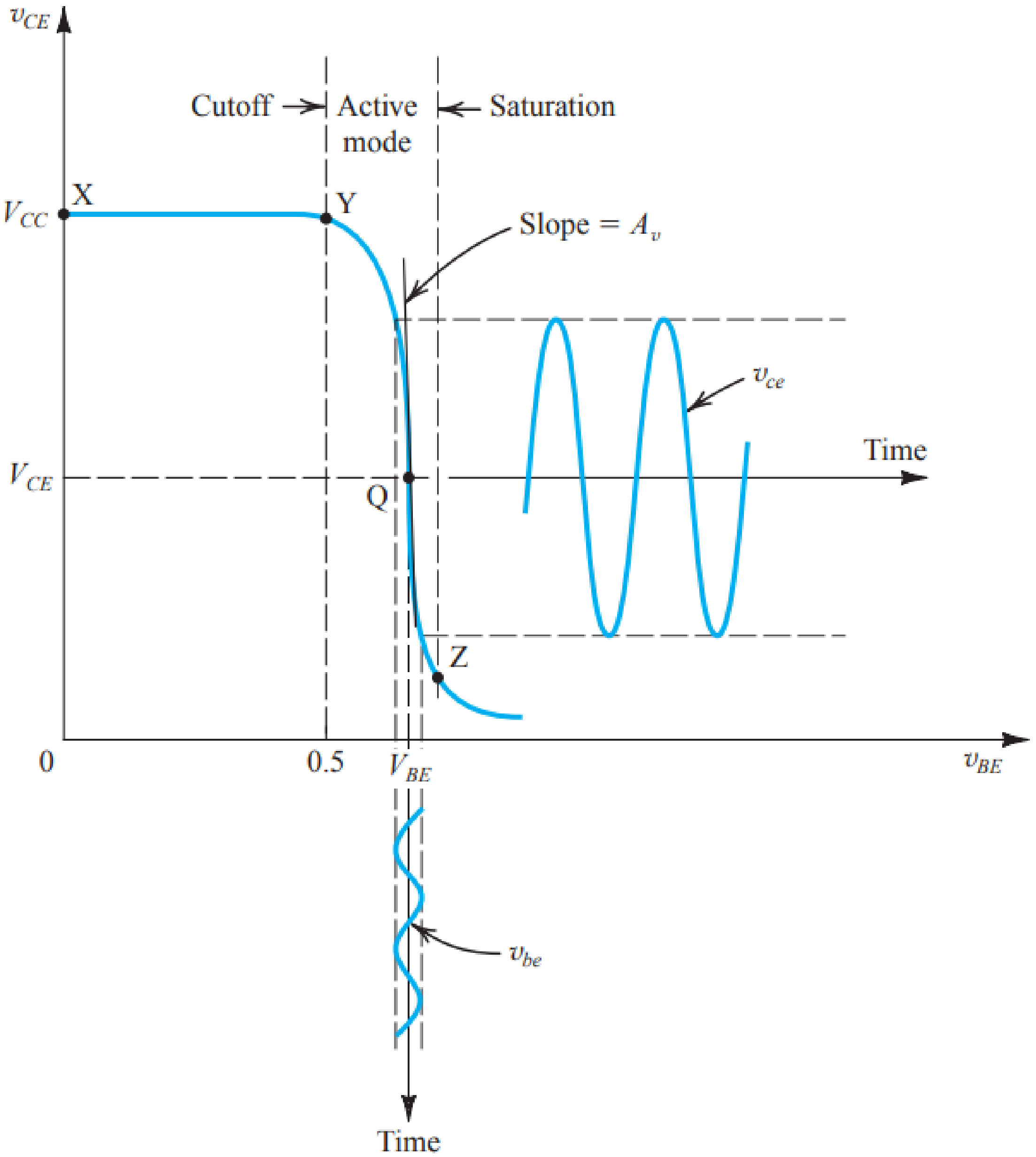




Common Emitter Amplifier

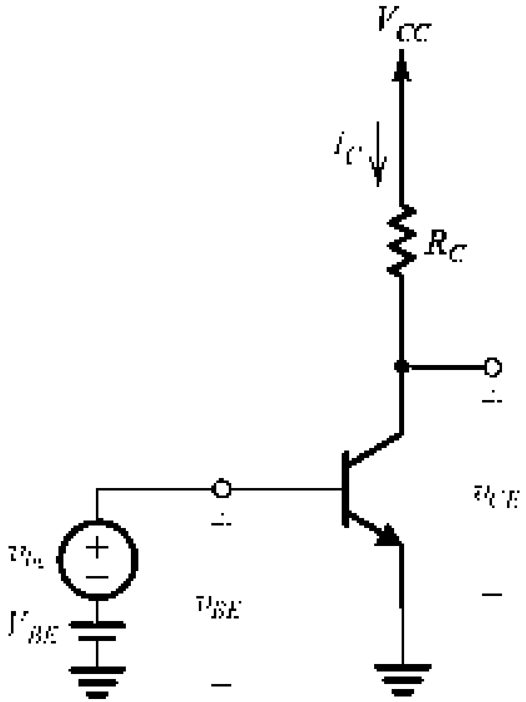
Voltage amplifier





Common Emitter Amplifier

Voltage amplifier



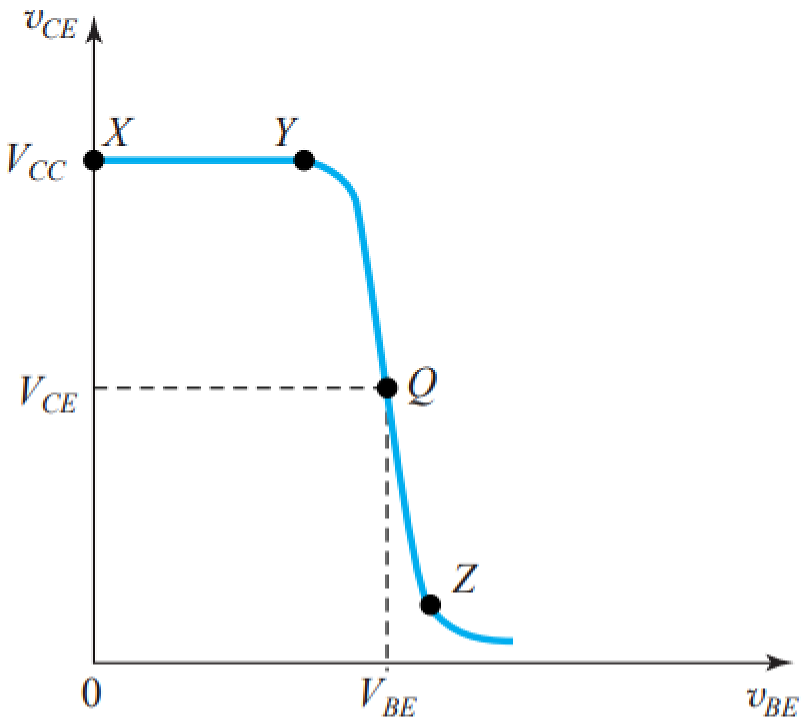
Voltage gain $A_v \equiv \left.\frac{dv_{CE}}{dv_{BE}}\right|_{v_{BE}=V_{BE}}$

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

$$v_{CE} = V_{CC} - R_C I_S \, e^{v_{BE}/V_T}$$

$$A_v = -\left(\frac{I_C}{V_T}\right) R_C$$

$$A_v = -\frac{I_C R_C}{V_T}$$



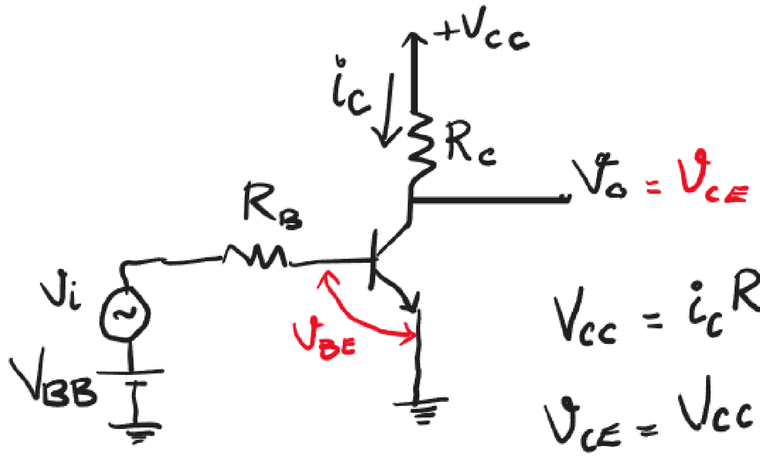
Common Emitter Amplifier

Voltage amplifier

BJT as Amplifier

i_e i_b i_c } Bias + Signal

I_c I_B I_E } i_C i_B i_E

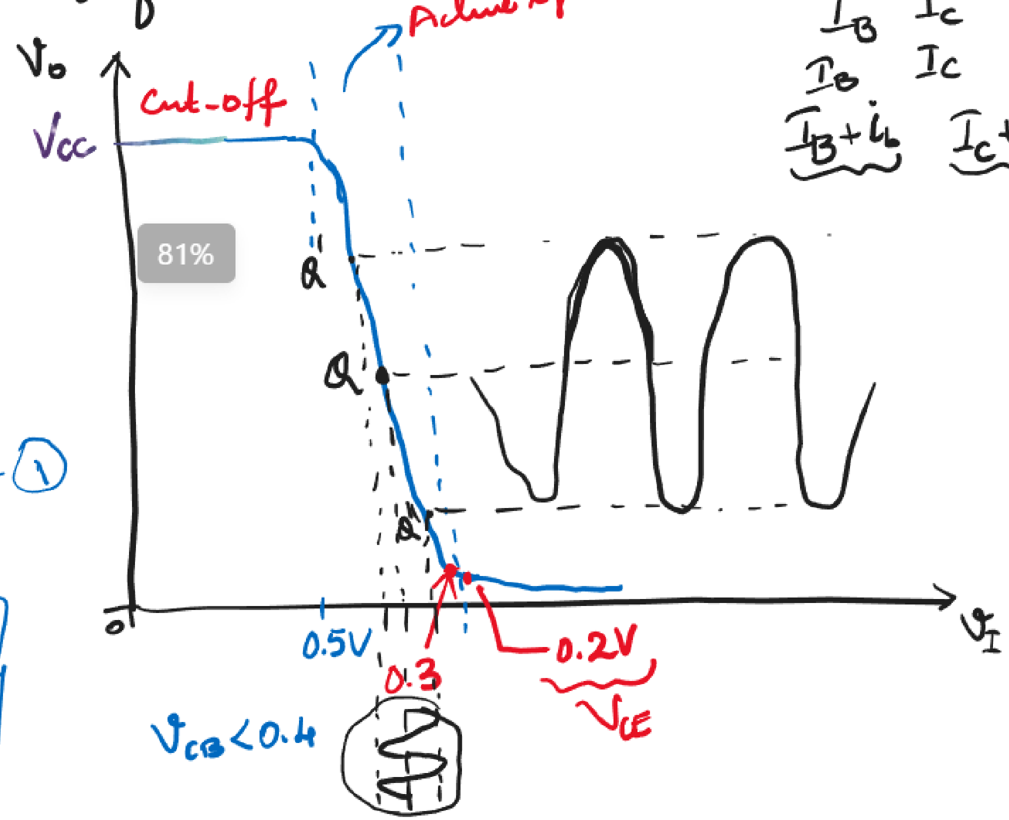


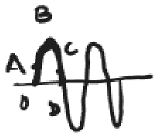
$V_{cc} = i_C R_c + v_{CE}$ — (1)

$v_{CE} = V_{cc} - i_C R_c$

$10 - 1 = 9V$
$10 - 4 = 6$
$10 - 6 = 4$
$10 - 10 = 0$

Transfer Charac.





V_{BB}

I_B I_c V_{CE}

I_B I_c

$I_B + i_b$ $I_c + i_c$

$V_{CE} + v_{ce}$

Common Emitter Amplifier

Voltage amplifier

$$v_o = v_{CE} = V_{cc} - i_C R_C \rightarrow (1)$$

$$i_C = I_s e^{v_{BE}/V_T}$$

$$\boxed{v_o = V_{cc} - R_C I_s e^{v_{BE}/V_T}}$$

Voltage gain, $A_v = \frac{\Delta V_o}{\Delta V_i}$

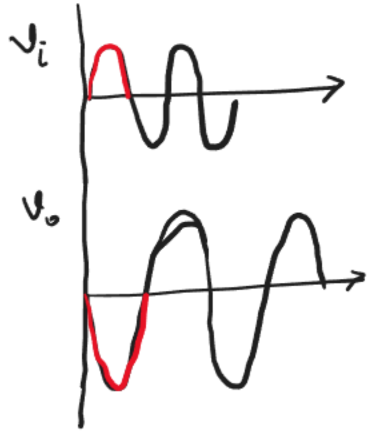
$$A_v = \left.\frac{dV_o}{dV_i}\right|_{v_i = v_{BE}}$$

$$A_v = 0 - \frac{1}{V_T} \cdot I_s e^{v_{BE}/V_T} \cdot R_c$$

$$= - \frac{R_C}{V_T} \cdot \underbrace{I_s e^{V_{BE}/V_T}}_{i_C}$$

$$= -\frac{i_C R_C}{V_T}$$

$$\boxed{A_v = -\frac{i_C R_C}{V_T}}$$



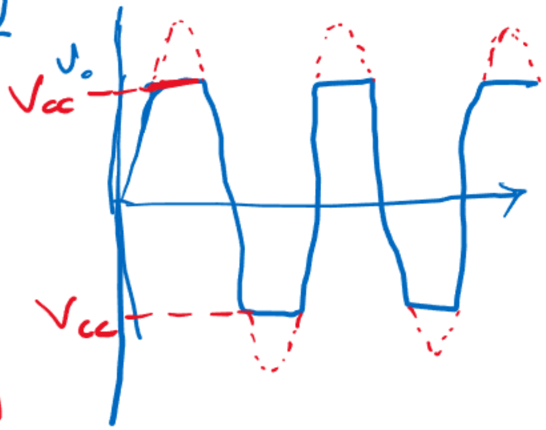
180° phase shift

CE ↗

$$A_v = -\frac{(V_{cc} - V_{CE})}{V_T}$$

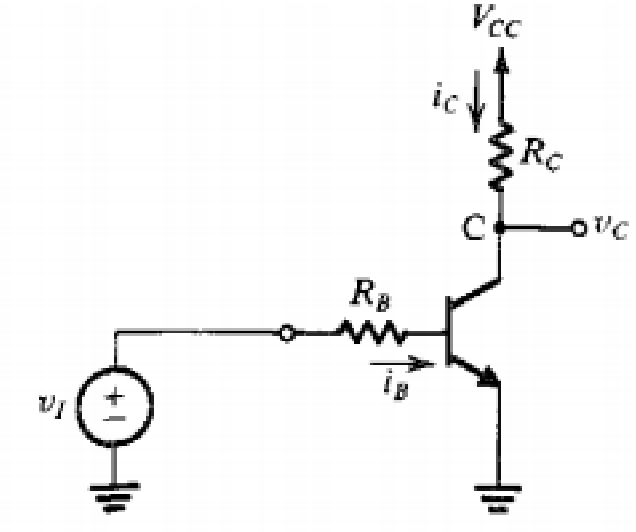
V_{CE} → 0.2V

$$\boxed{A_v \simeq -\frac{V_{cc}}{V_T}}$$



Signal Swing

Operation as Switch



$$i_B = \frac{v_I - V_{BE}}{R_B}$$

$$i_C = \beta i_B$$

$$v_C = V_{CC} - R_C i_C$$

$$I_{C(\mathrm{EOS})} = \frac{V_{CC} - 0.3}{R_C}$$

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

$$\beta_{\mathrm{forced}} \equiv \frac{I_{C\mathrm{sat}}}{I_B}$$

$$\beta_{\mathrm{forced}} < \beta_F$$

Operation as Switch

BJT as a Switch

$$v_I = i_B R_B + V_{BE}$$

$$i_B = \frac{v_I - V_{BE}}{R_B}$$

$$i_C = \beta i_B$$

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

EOS – Edge of Saturation

$$I_{C(EOS)} = \frac{V_{CC} - V_{CE}}{R_C} \quad V_{CE} = 0.3\,V$$

$$= \frac{V_{CC} - 0.3}{R_C}$$

$$I_{B(EOS)} = \frac{I_{C(EOS)}}{\beta}$$

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} \quad V_{CE(sat)} = 0.2\,V$$

(i) $V_{CE} = V_{CC}$ Cut off

(ii) $V_{CE} = V_{CC}/2$ Active

(iii) $V_{CE} = 0.2\,V$ Saturation

$$\beta_{forced} = \frac{I_{C(sat)}}{I_B}$$

$$\text{Overdrive factor} = \frac{I_B}{I_{B(EOS)}}$$