Lecture #25

Chapter 5 of Jaeger, Chapter 2 of Spencer

Bipolar Junction Transistors

Outline/Learning Objectives:

- Describe the physical structure of the bipolar junction transistor (BJT).
- Identify the npn and pnp BJT circuit diagram symbols.
- Describe qualitatively and quantitatively the physical operating principles of the BJT.
- Describe qualitatively and quantitatively the i-v characteristics (output and transfer) of the BJT.
- Determine the regions of operation (cutoff, forward-active, and saturation).
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Selected problems:

- 5.32, 5.61, 5.65, 5.73, 5.74, 5.82, 5.91, 5.95, 5.98
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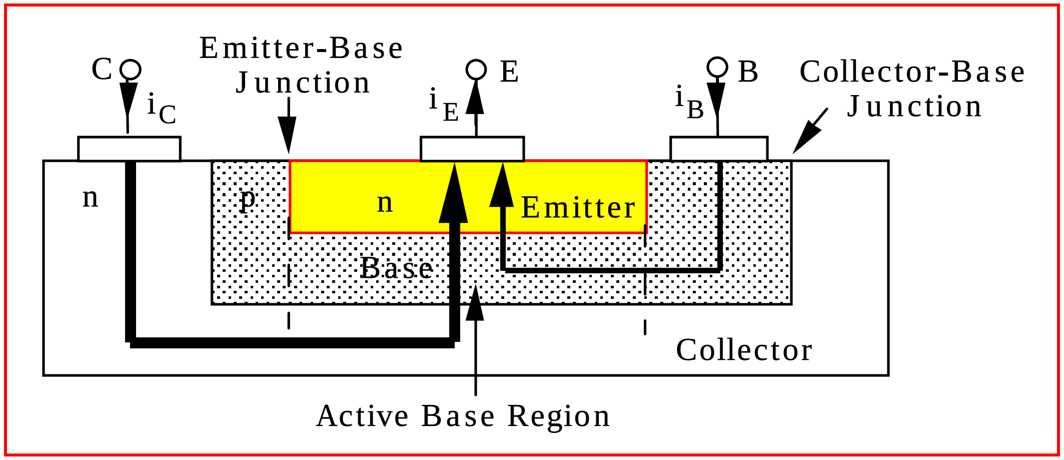
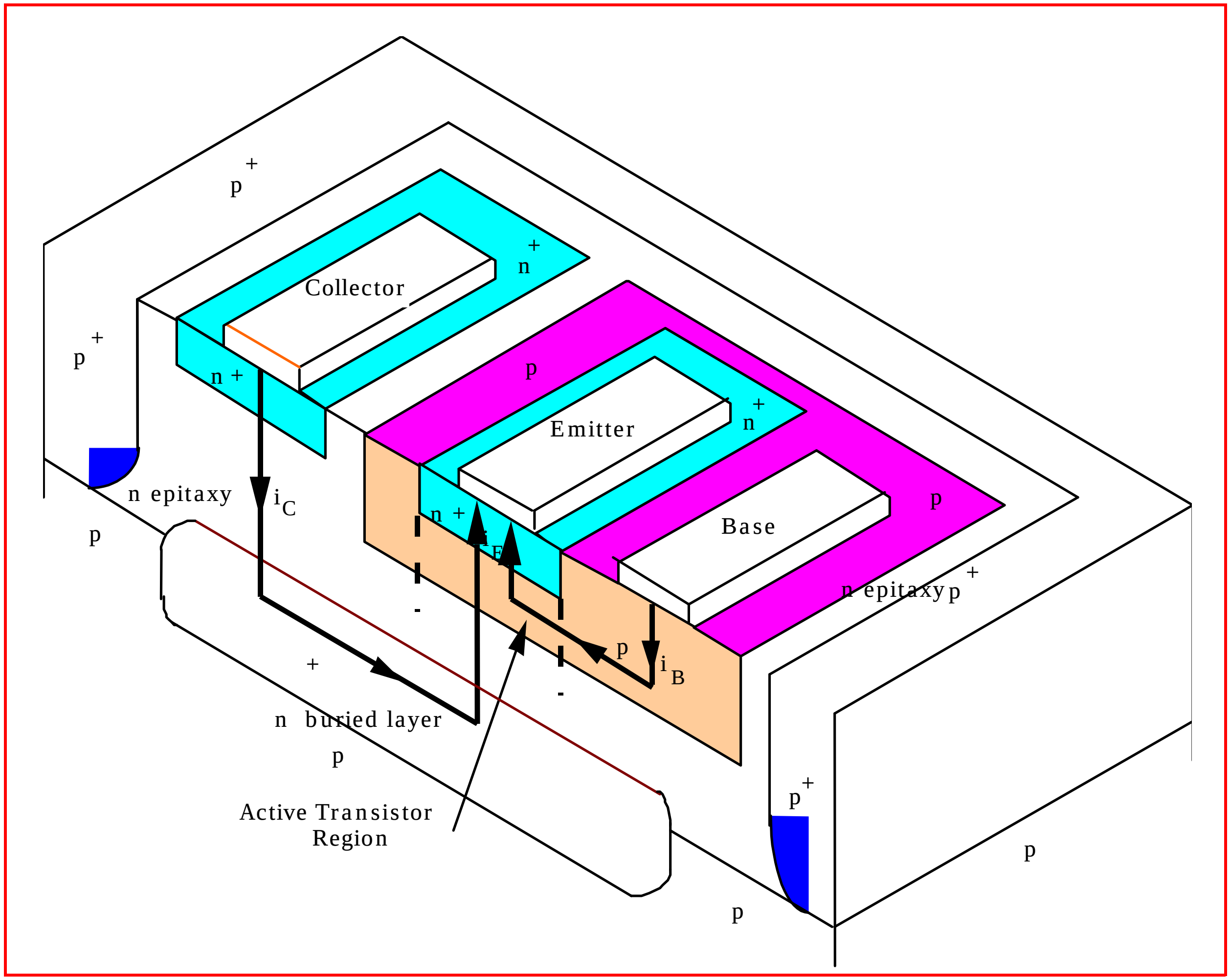
Physical Structure of the BJT

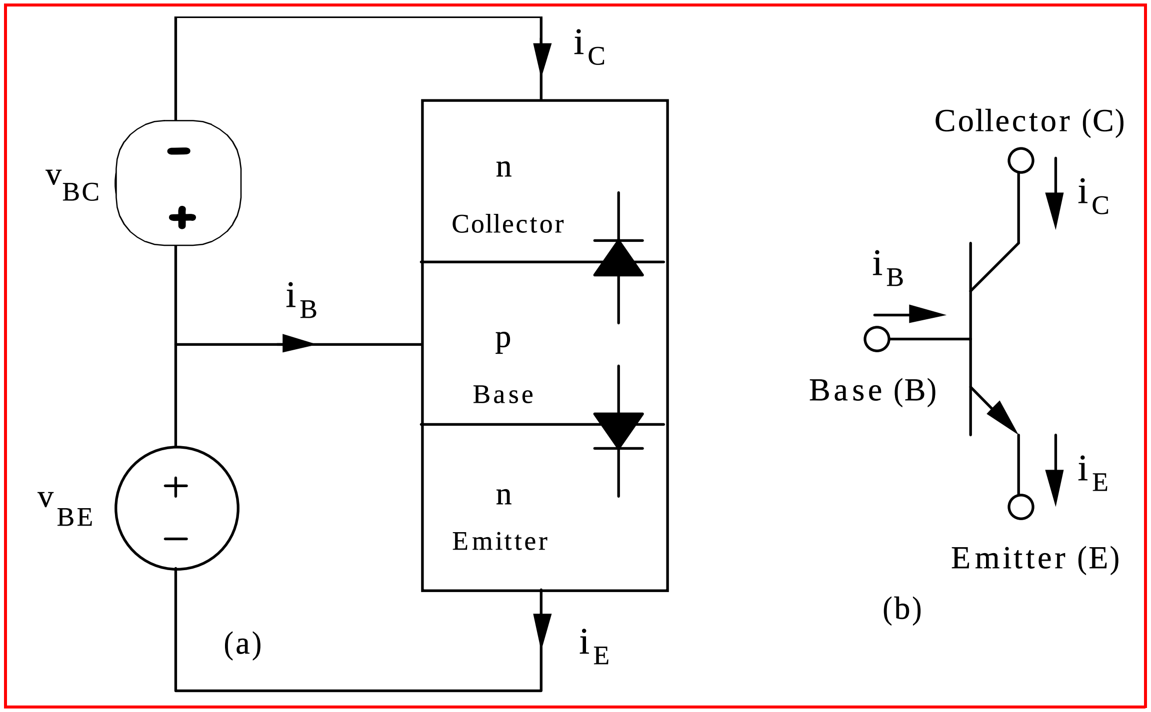


Simplified Cross-Section of an npn BJT

Currents are for "Normal" Operation



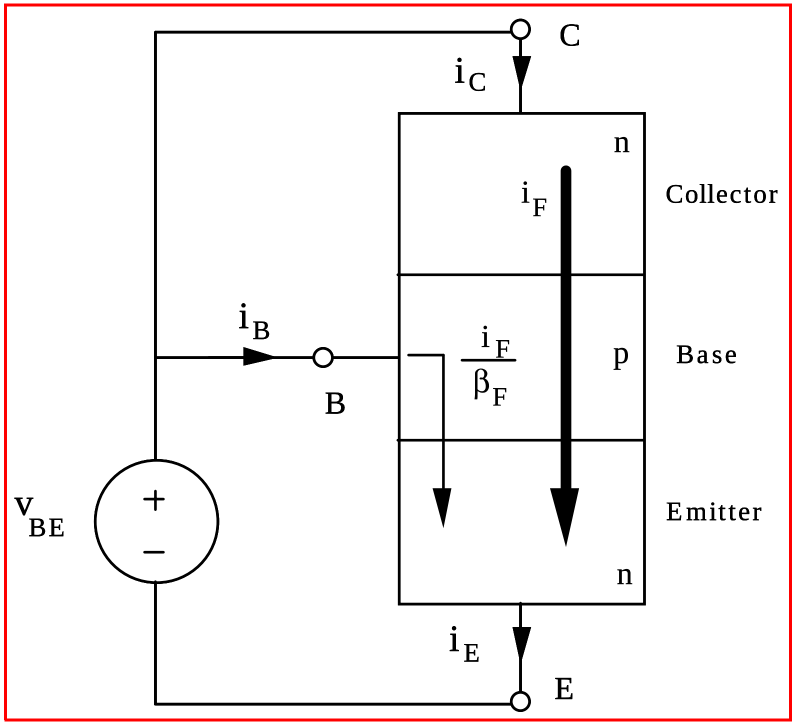
Idealized npn BJT and Circuit Symbol



Forward Characteristics

BE voltage --> i_E

i_E is composed of i_F & i_B



$$i_C = i_F = I_S\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right\}$$

with $10^{-18}A \le I_S \le 10^{-9}A$

I_S is proportional to the cross-sectional area of the active base region.

$$i_B = \frac{i_F}{\beta_F} = \frac{I_S}{\beta_F}\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right\}$$ with $20 \le \beta_F \le 500$.

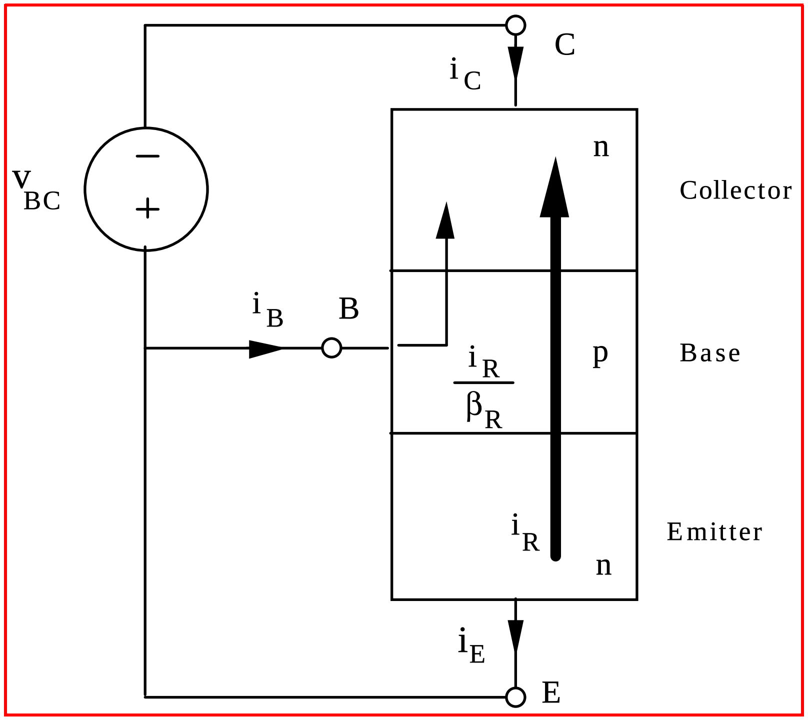
$$i_E = i_C + i_B = \left(I_S + \frac{I_S}{\beta_F}\right)\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right\} = \frac{I_S}{\alpha_F}\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right\}$$ with $0.95 \le \alpha_F < 1$.

$$\alpha_F = \frac{\beta_F}{\beta_F + 1}$$ and $$\beta_F = \frac{\alpha_F}{1 - \alpha_F}$$.

$i_C = \beta_F i_B$, $i_E = i_B + i_C = (\beta_F + 1)i_B$ and $i_C = \alpha_F i_E$.

Reverse Characteristics

BC voltage --> i_R & i_R/β_R



$$i_R = I_S\left\{\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right\}$$ and $i_E = -i_R$

$$i_B = \frac{i_R}{\beta_R} = \frac{I_S}{\beta_R}\left\{\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right\}$$

$0 < \beta_R \le 20$ and β_R is the reverse CE current gain.

$$i_C = i_E - i_B = -\left(I_S + \frac{I_S}{\beta_R}\right)\left\{\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right\} = \frac{-I_S}{\alpha_R}\left\{\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right\}$$ with $0 < \alpha_R \le 0.95$.

$$\alpha_R = \frac{\beta_R}{\beta_R + 1}$$ and $$\beta_R = \frac{\alpha_R}{1 - \alpha_R}$$.

α_F or α_R	$\beta_F = \frac{\alpha_F}{1-\alpha_F}$ or $\beta_R = \frac{\alpha_R}{1-\alpha_R}$
0.1	0.11
0.5	1
0.9	9
0.99	499

Full Transport Model Equations - Arbitrary Bias Conditions

$$i_C = I_S\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right)\right\} - \frac{I_S}{\beta_R}\left\{\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right\}.$$

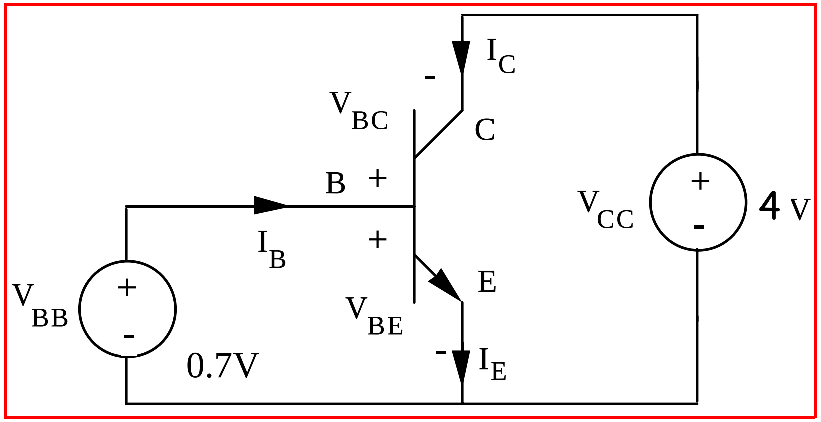
$$i_E = I_S\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right)\right\} + \frac{I_S}{\beta_F}\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right\}.$$

$$i_B = \frac{I_S}{\beta_F}\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right\} + \frac{I_S}{\beta_R}\left\{\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right\}.$$

Require 4 parameters - I_S, β_F, β_R and T to characterize an individual BJT.

Example

Determine i_C, i_E and i_B if $I_S = 10^{-15}A$, $V_T = 25mV$, $\beta_F = 100$ and $\beta_R = 2$.



$V_{BB} = V_{BE} = 0.7V$ and

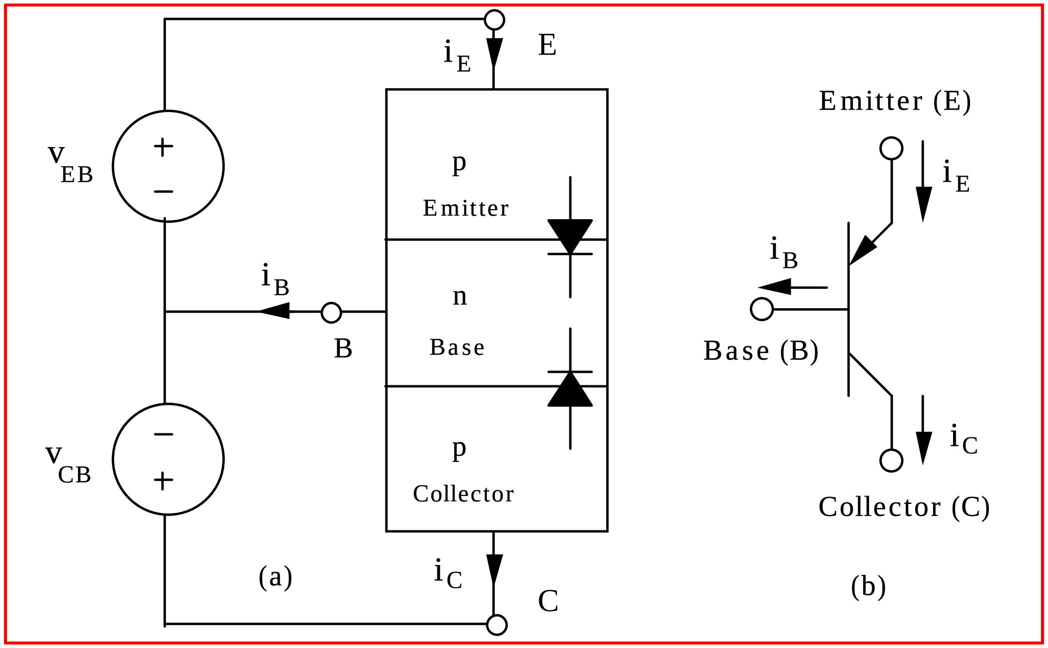
$V_{BC} = V_{BB} - V_{CC} = -3.3V$

$$I_C = I_S\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right)\right\} - \frac{I_S}{\beta_R}\left\{\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right\} = \mathbf{1.45mA}$$

$$I_E = I_S\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right)\right\} + \frac{I_S}{\beta_F}\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right\} = \mathbf{1.46mA}$$

$$I_B = \frac{I_S}{\beta_F}\left\{\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right\} + \frac{I_S}{\beta_R}\left\{\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right\} = \mathbf{14.5\mu A}$$

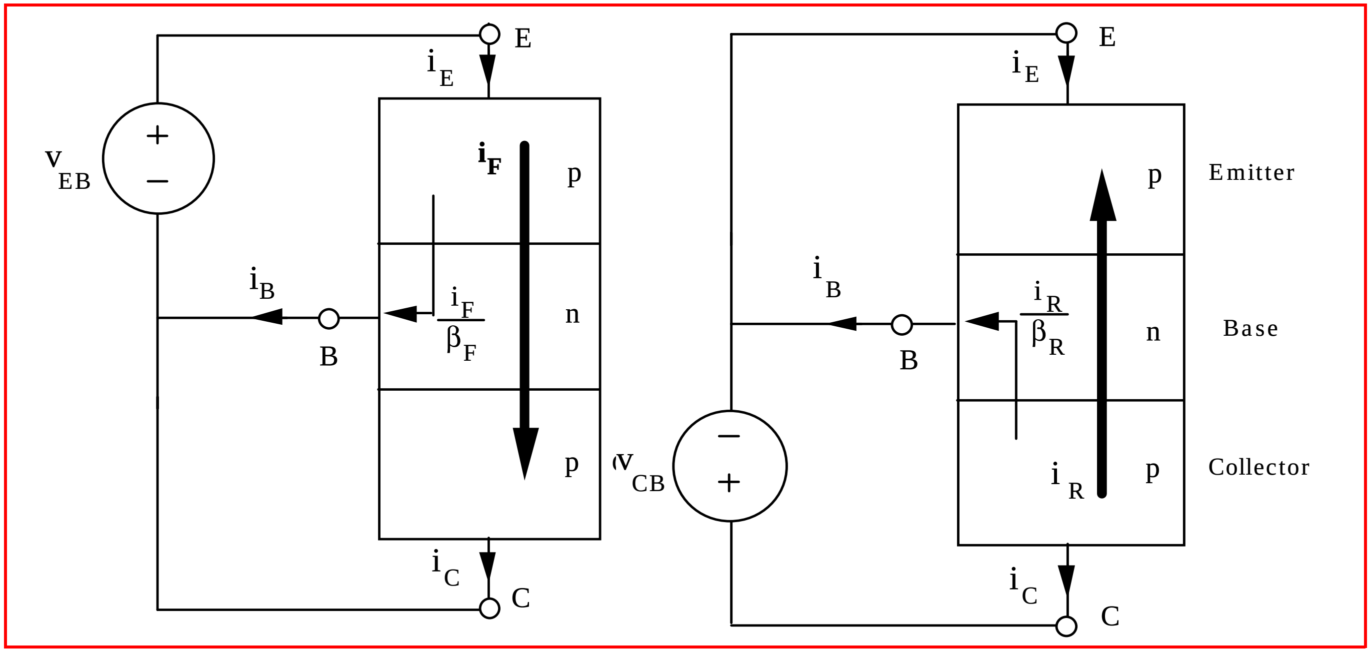
PNP Transistor



$$i_C = I_S\left\{\exp\left(\frac{v_{EB}}{V_T}\right) - \exp\left(\frac{v_{CB}}{V_T}\right)\right\} - \frac{I_S}{\beta_R}\left\{\exp\left(\frac{v_{CB}}{V_T}\right) - 1\right\}.$$

$$i_E = I_S\left\{\exp\left(\frac{v_{EB}}{V_T}\right) - \exp\left(\frac{v_{CB}}{V_T}\right)\right\} + \frac{I_S}{\beta_F}\left\{\exp\left(\frac{v_{EB}}{V_T}\right) - 1\right\}.$$

$$i_B = \frac{I_S}{\beta_F}\left\{\exp\left(\frac{v_{EB}}{V_T}\right) - 1\right\} + \frac{I_S}{\beta_R}\left\{\exp\left(\frac{v_{CB}}{V_T}\right) - 1\right\}.$$



Operating Regions of the Bipolar Transistor

Each pn junction may be independently biased.

Have 4 regions of operation.

Both pn junctions reverse biased - cut-off region.

Both pn junctions forward biased - saturation region (closed switch).

BE junction forward and BC junction reverse biased - forward active region (normal mode). Have high current, high voltage and high power gains. ECL logic switch between cut-off and forward active (fastest bipolar logic).

BE junction reverse and BC junction forward biased - reverse active region (inverse-active mode). Have low common emitter gain and this mode is not often used. It is used in TTL circuits and for some analog switching applications.

Base-Emitter Junction	**Base-Collector Junction**	
	Forward Bias	Reverse Bias
Forward Bias	**Saturation Region (Closed Switch)**	Forward-Active Region (good amplifier)
Reverse Bias	Reverse-Active Region (poor amplifier)	**Cut-Off Region (open switch)**