Basic Bipolar Junction Transistor

Goal:

Physical structure, operation, and characteristics of the npn & pnp bipolar junction transistors (BJT)

- BJT --> 3 separately doped regions & 2 pn junctions, a 3 terminal device
- 1 pn junction: forward bias & reverse bias --> 2 modes of operation
- 2 pn junctions: 4 modes of operation depending on bias of each junction

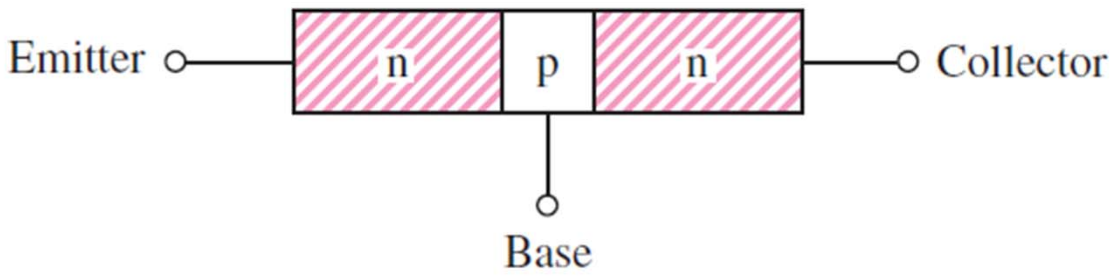
Basic principle:

The voltage between two terminals controls the current through the third terminal

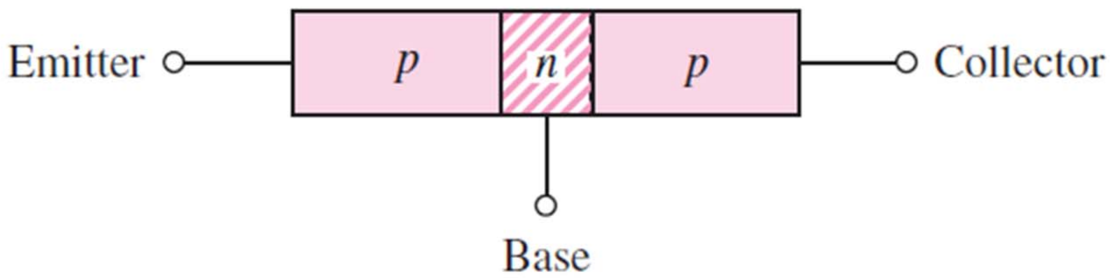
- Two pn junctions sufficiently close together are called interacting pn junctions, different from having back to back diodes.

- Bipolar: Because current is due to flow of both electrons and holes.

Transistor Structure:



npn bipolar transistor - thin p-region between 2 n-regions



pnp bipolar transistor - thin n-region between 2 p-regions

Three regions & terminals:

Emitter – outer layer, heavily doped

Base – inner layer, lightly doped

Collector – outer layer, intermediately doped

Actual structure of the bipolar transistor is complicated.

The device is not symmetrical electrically.

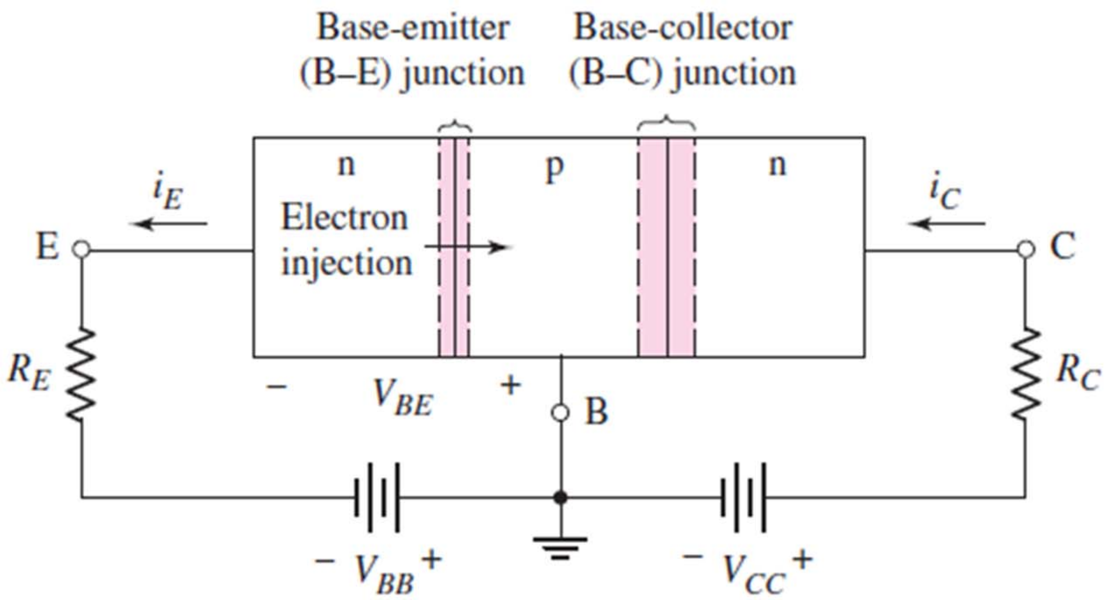
Asymmetry because:

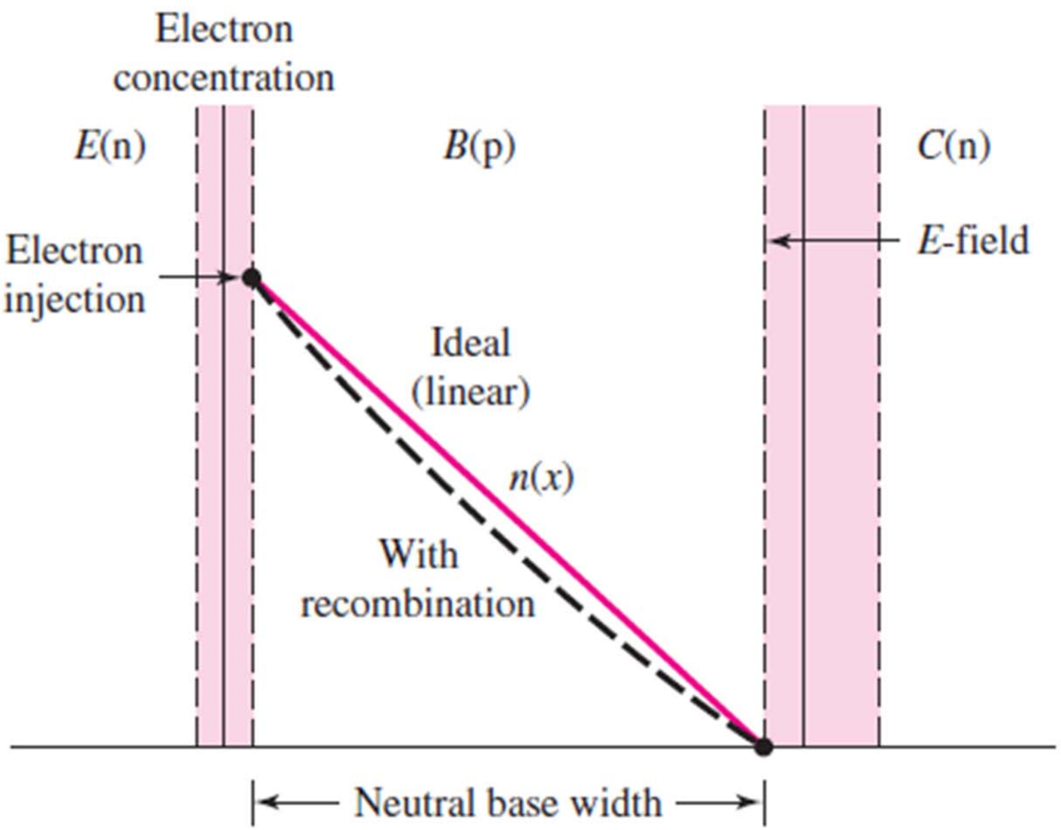
- The geometries of the emitter and collector regions are different
- Impurity doping concentrations in the three regions are different

npn Transistor: Forward-Active Mode Operation

Forward-active operating mode: Base–emitter (B–E) junction is forward biased, Base–collector (B–C) junction is reverse biased

Transistor Currents





Emitter Current:

Base-emitter voltage

$$i_E = I_{EO}[e^{v_{BE}/V_T} - 1] \cong I_{EO}e^{v_{BE}/V_T}$$

Thermal voltage

I_{EO}, directly proportional to the active B-E cross-sectional area. Miniscule valued electrical parameter of the junction can vary from transistor to transistor.

Collector Current:

- The number of electrons reaching the collector per unit time is proportional to the number of electrons injected into the base

- Number of electrons injected into the base is a function of B-E voltage

The collector current is proportional to e^{v_{BE}/V_T} and independent of the reverse-based B-C voltage, like a constant current source.

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

Collector current is slightly smaller than the emitter current, and

$$i_C = \alpha i_E$$

$$I_S = \alpha I_{EO}$$

Parameter α is called the common-base current gain whose value is always slightly less than unity

Base Current:

Flow of holes from Base to Emitter:

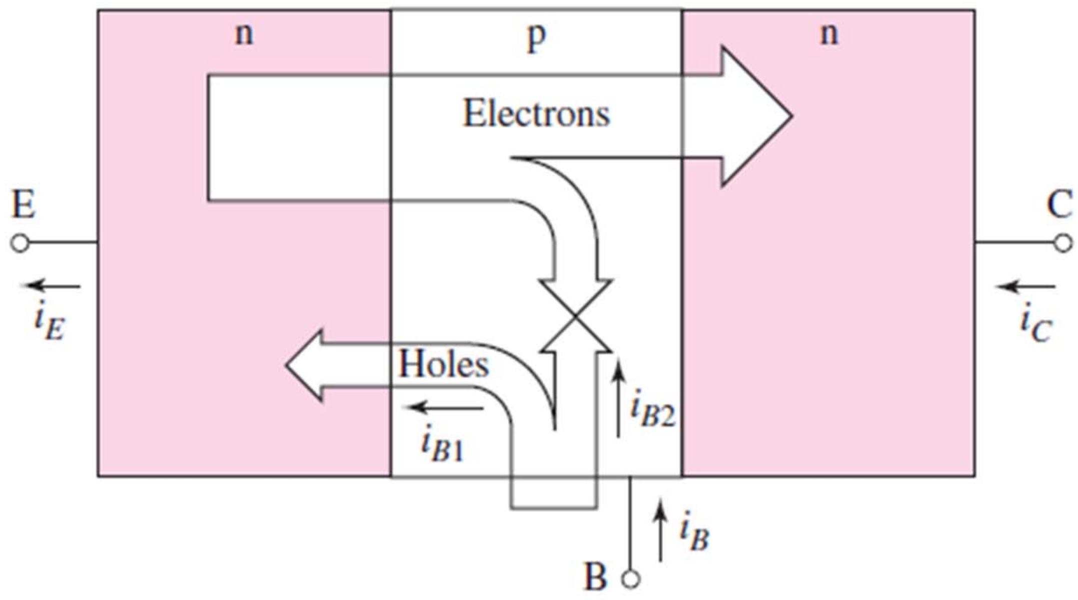
$$i_{B1} \propto e^{v_{BE}/V_T}$$

Flow of holes into base compensating the recombination with a few electrons from emitter:

$$i_{B2} \propto e^{v_{BE}/V_T}$$

Sum -

$$i_B \propto e^{v_{BE}/V_T}$$



Concentration of holes in p region << Concentration of electrons in n region

Emitter current / collector current >> Base current

Common-Emitter Current Gain

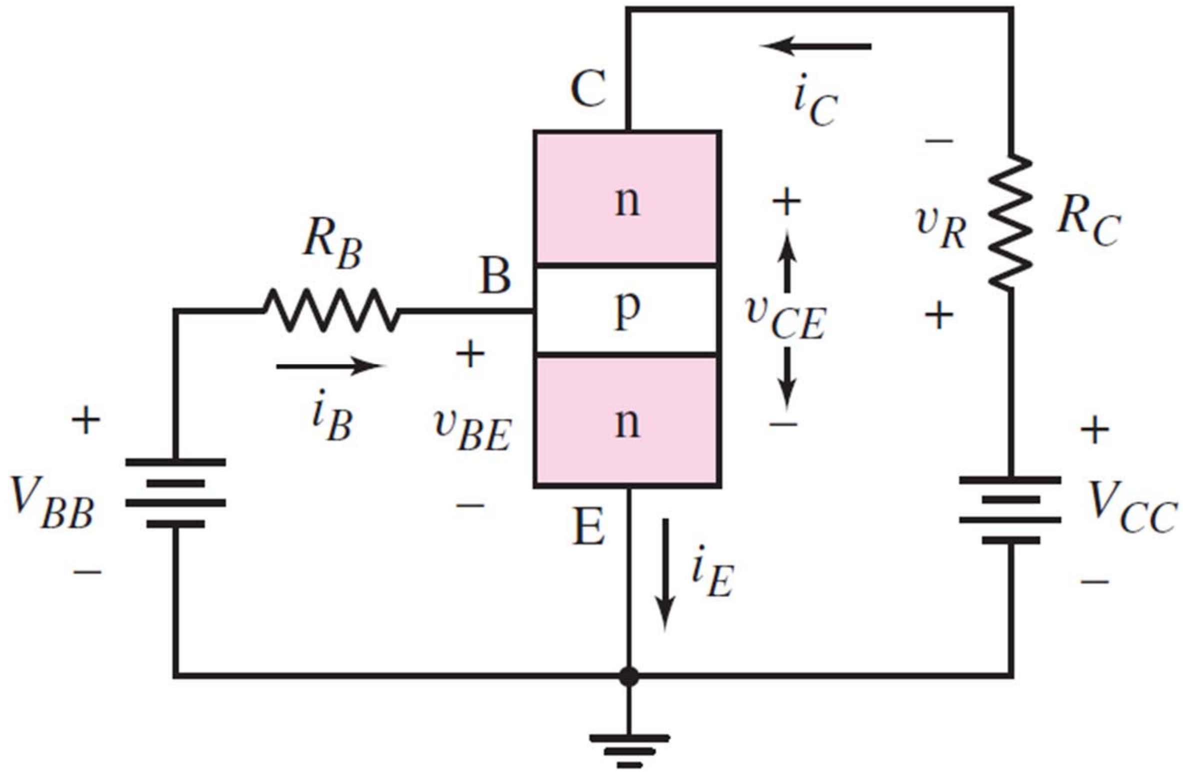
Emitter, collector and base current all are proportional to the B-E voltage. So

$$\frac{i_C}{i_B} = \beta$$

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

The parameter β is the common-emitter current gain.

50 < β < 300, varies widely



Emitter is common! – Earlier base was common!

$$\boldsymbol{v_{BE}} \rightarrow \text{cut in voltage}$$

$$\boldsymbol{v_{CE} = v_{CB} + v_{BE} \rightarrow v_{BC} = v_{BE} - v_{CE}}$$

$$\boldsymbol{V_{CC} = v_{CE} + i_C R_C}$$

$$\boldsymbol{V_{BB} = v_{BE} + i_B R_B}$$

$$\boldsymbol{V_{BB} = 0 \rightarrow i_B = 0 \rightarrow i_C = 0 \;\&\; i_E = 0}$$

Current Relationships

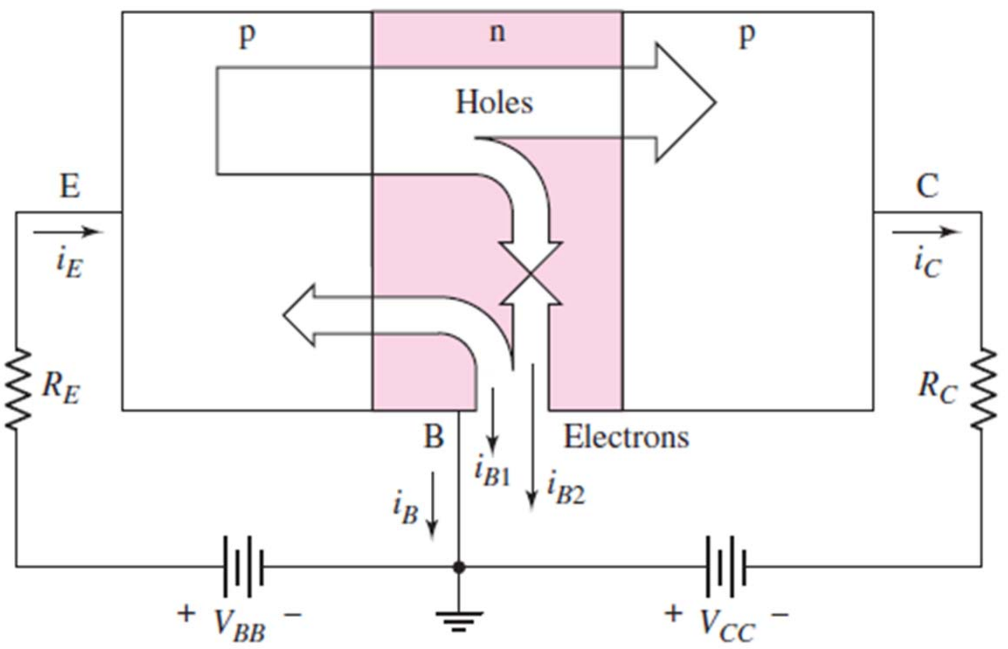
KCL: $$i_E = i_C + i_B$$

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

$$i_C = \left(\frac{\beta}{1+\beta}\right) i_E$$

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

pnp Transistor: Forward-Active Mode Operation



Emitter, base and collector current are proportional to v_{EB}

$$i_E = I_{EO} e^{v_{EB}/V_T} \qquad i_C = \alpha i_E = I_S e^{v_{EB}/V_T}$$

1st component of base current:

Flow of Electrons from Base to Emitter

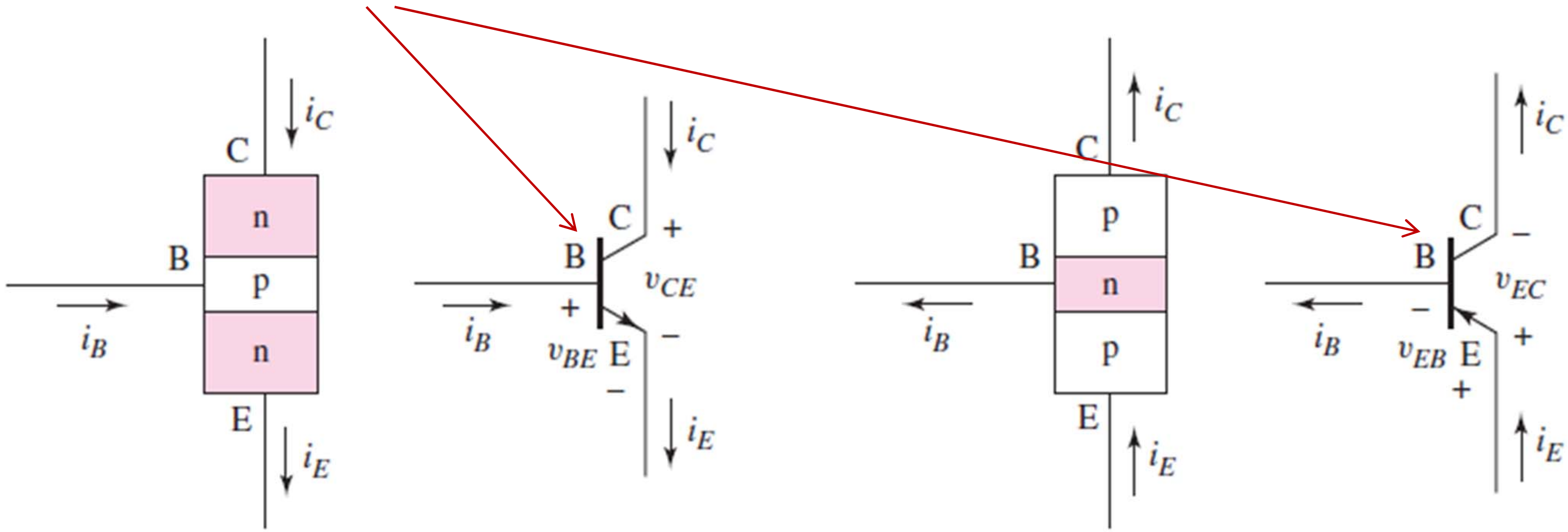
2nd component of base current:

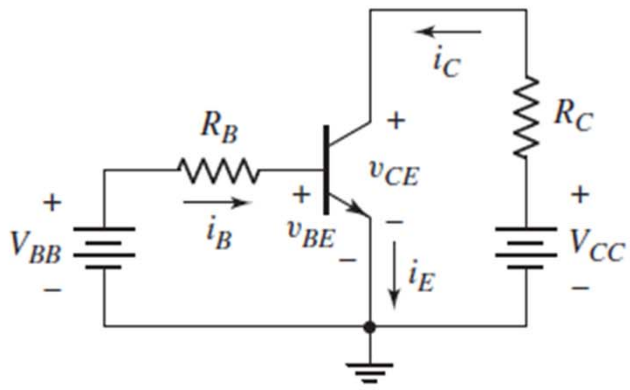
Flow of electrons into base compensating the recombination with a few holes from emitter

$$i_B = I_{BO} e^{v_{EB}/V_T} = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{EB}/V_T}$$

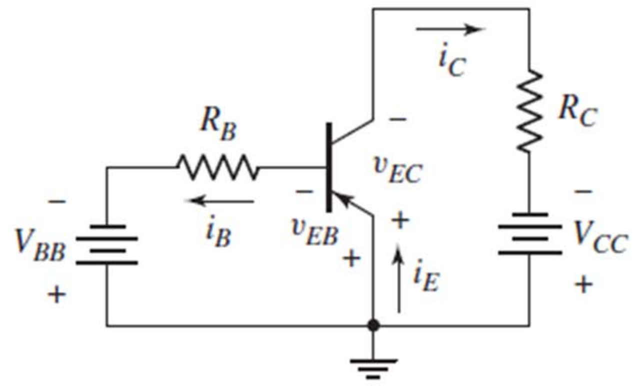
The relation between currents are similar to the npn case.

Circuit Symbols and Conventions

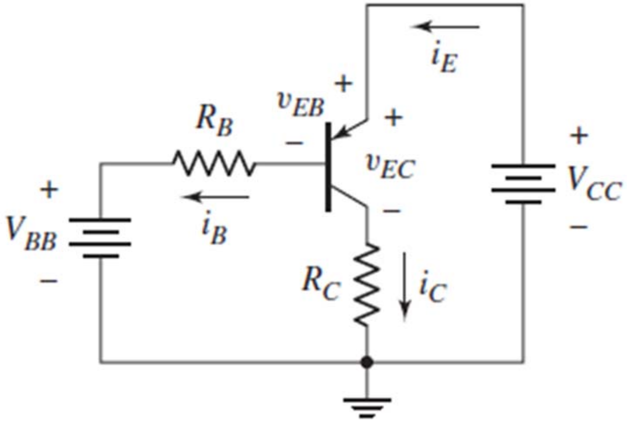




npn-CE



pnp-CE



pnp- common collector

Summary of the bipolar current–voltage relationships in the active region

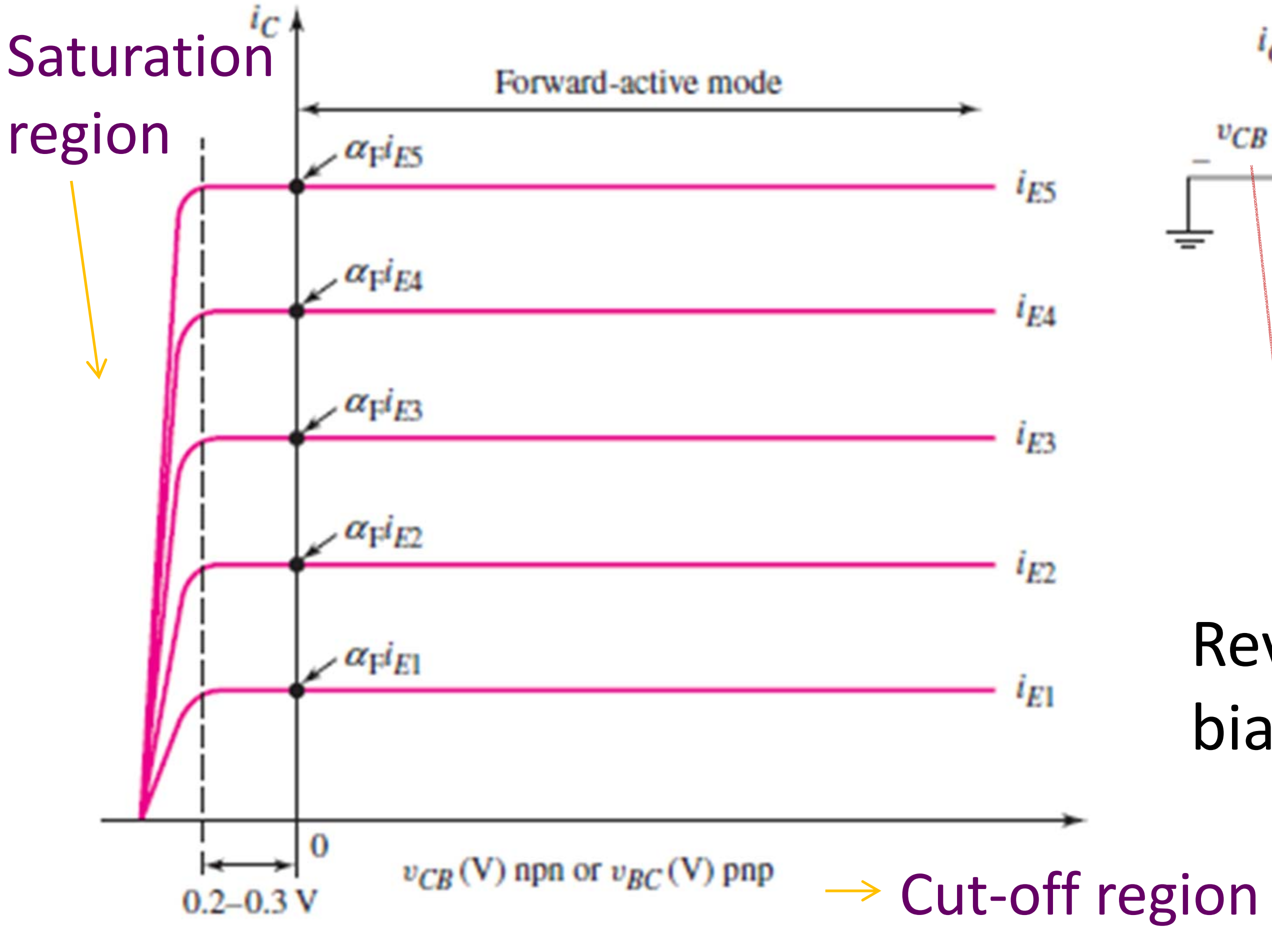
npn	pnp
$i_C = I_S e^{v_{BE}/V_T}$	$i_C = I_S e^{v_{EB}/V_T}$
$i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{BE}/V_T}$	$i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{EB}/V_T}$
$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{BE}/V_T}$	$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{EB}/V_T}$

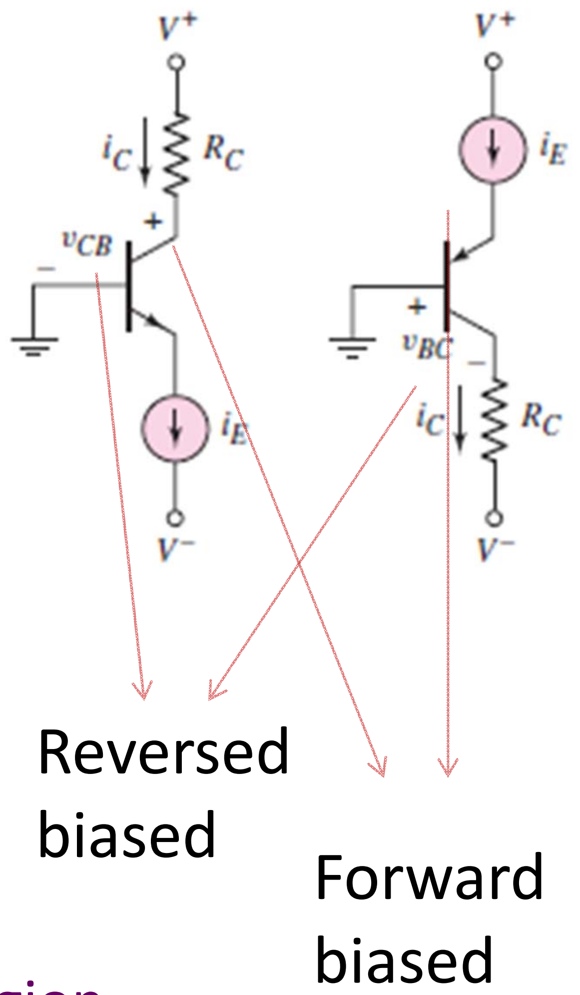
For both transistors

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

Current-Voltage Characteristics

Common base circuit config -

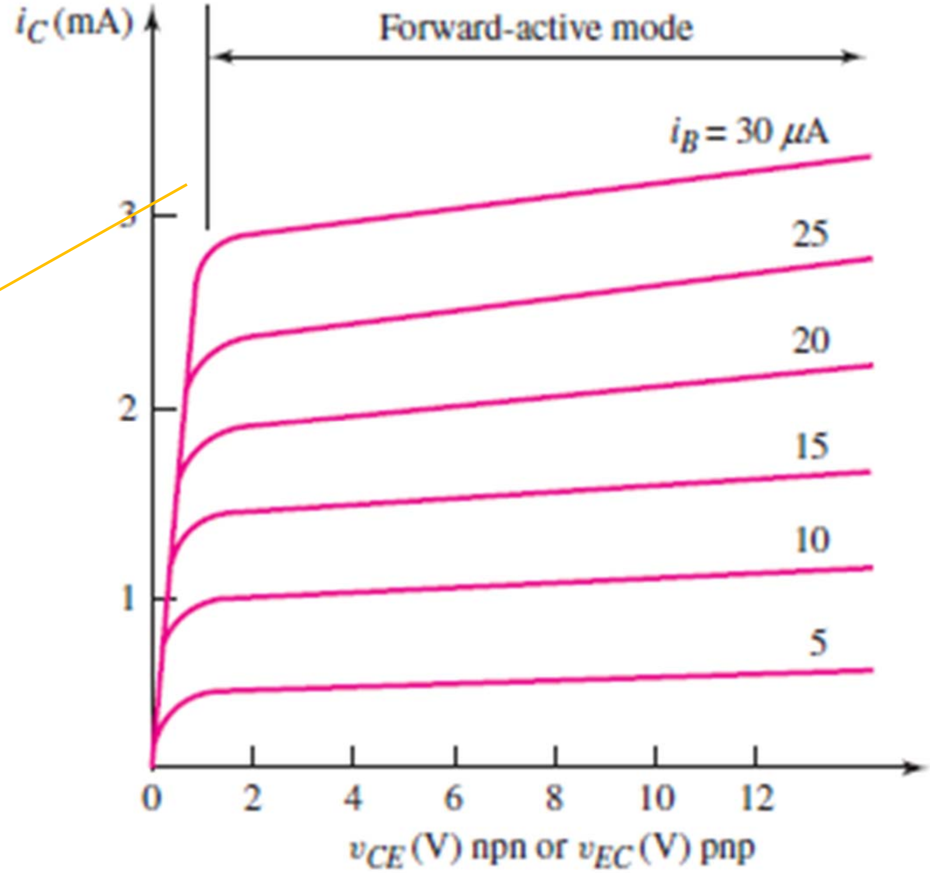




These characteristics show that the common-base device is nearly an ideal constant-current source

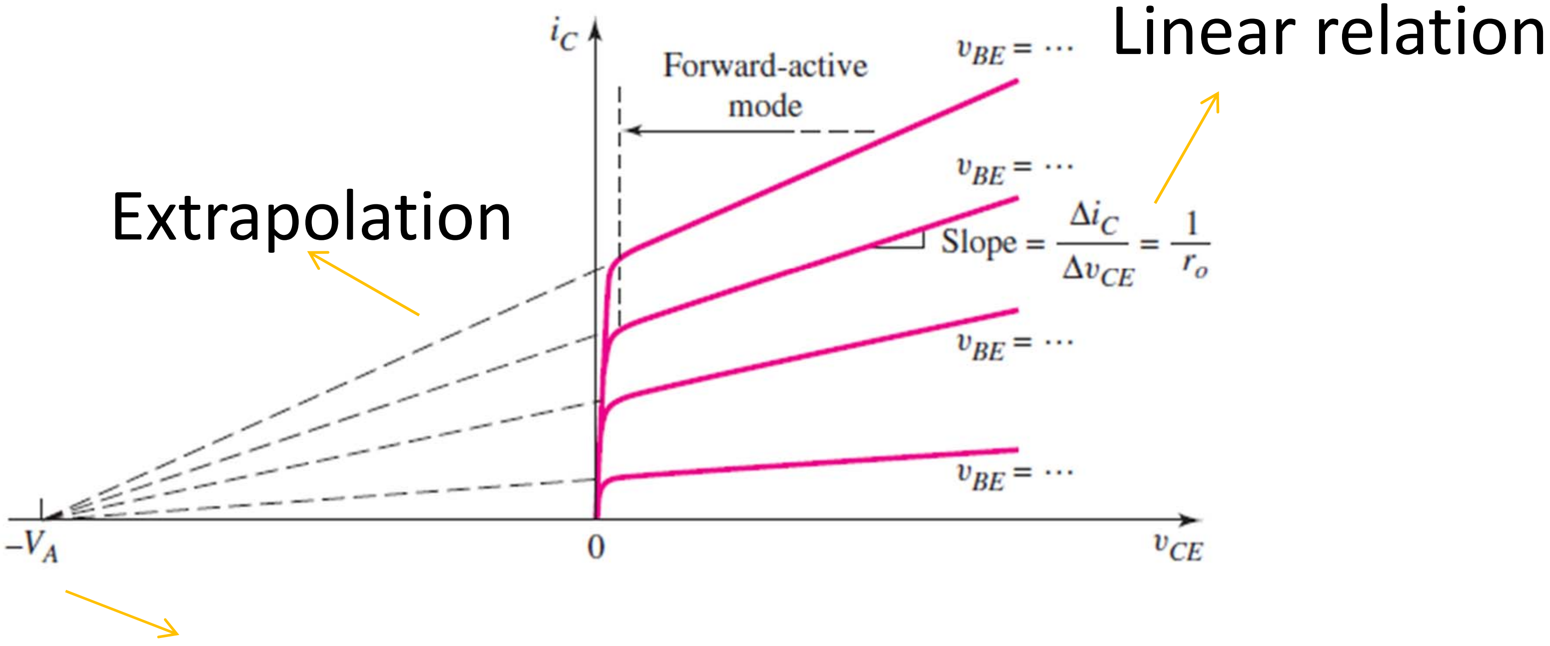
Common emitter circuit config -

v_{CE} must be greater than approximately v_{BE}(on).



Similar characteristics can be seen for a common collector configuration as well!

Early effect



All meet at the early voltage V_A!

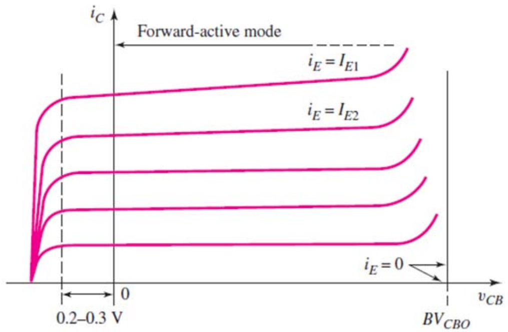
With v_{BE} constant, v_{CE} increase - reverse bias increases - depletion region increases - reduces base width - larger the minority carrier gradient - more diffusion - collector current increases. So …

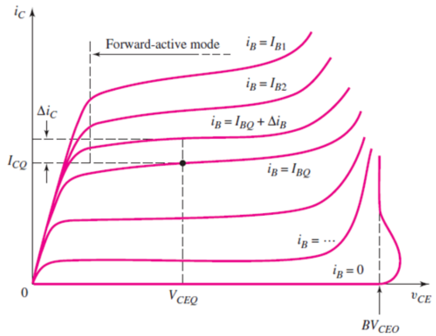
$$i_C = I_S(e^{v_{BE}/V_T}) \cdot \left(1 + \frac{v_{CE}}{V_A}\right)$$

$$\frac{1}{r_o} = \left.\frac{\partial i_C}{\partial v_{CE}}\right|_{v_{BE}=\text{const.}} \quad \rightarrow \quad r_o \cong \frac{V_A}{I_C} \qquad \boldsymbol{taking\ v_{CE} \ll V_A}$$

- The dependence of i_C on v_{CE} is not critical in the dc analysis or design of transistor circuits.
- Finite output resistance r_o may significantly affect characteristics of such circuits.

All seen for Ideal transistor. Non ideal transistors will have some leakage currents & breakdowns in reverse bias!





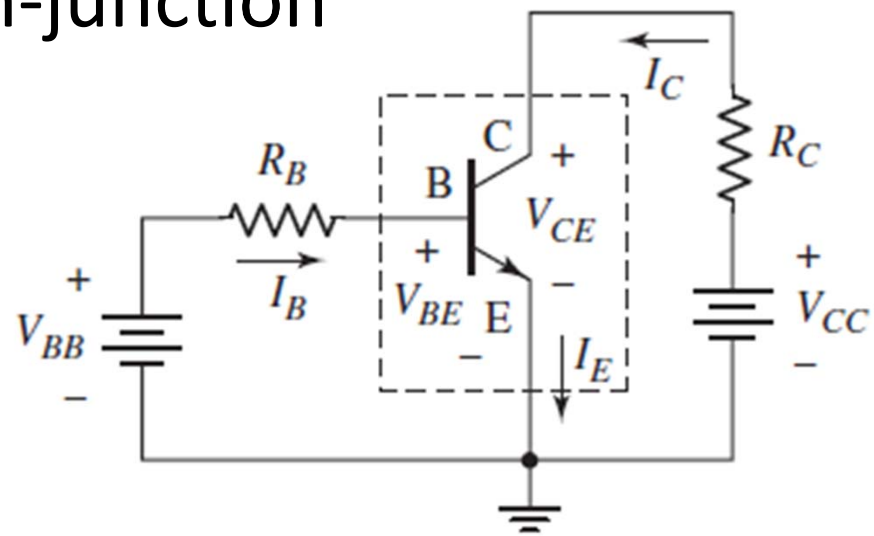
DC Analysis of Transistor Circuits

Goal:

dc analysis and design techniques of bipolar transistor circuits

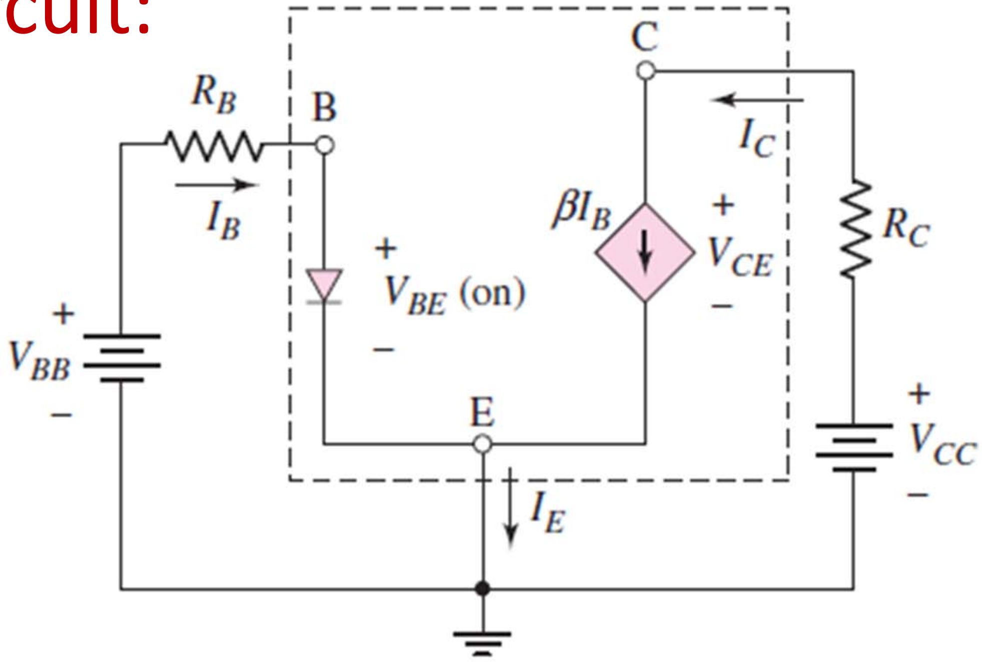
Common Emitter Circuit

Forward active mode, considering piecewise linear model for pn-junction



dc equivalent circuit:

npn



$$I_B = \frac{V_{BB} - V_{BE}(\text{on})}{R_B}$$

$V_{BB} > V_{BE}$ **otherwise cutoff**

$$I_C = \beta I_B \qquad V_{CE} = V_{CC} - I_C R_C$$

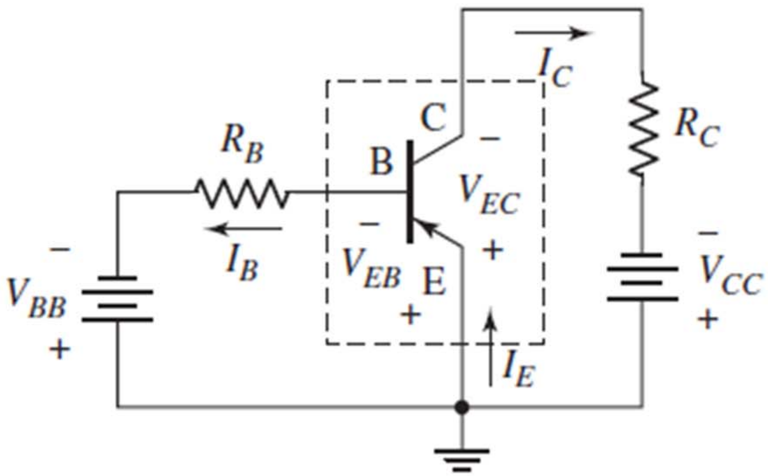
$V_{CE} > V_{BE}$ **so that BC junction reverse biased**

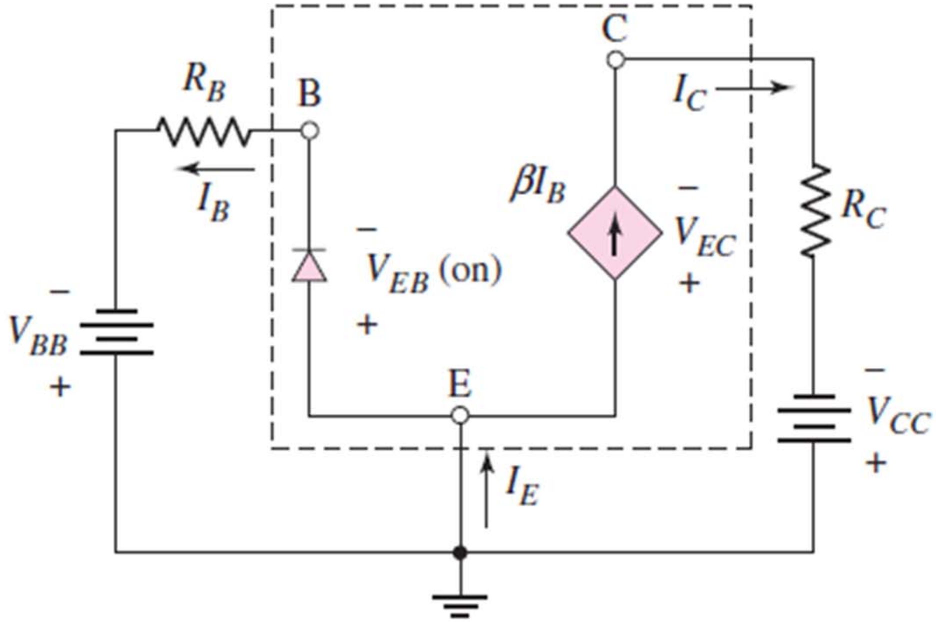
Power dissipated in the transistor: $P_T = I_B V_{BE}(\text{on}) + I_C V_{CE}$

$I_C \gg I_B, V_{CE} \gg V_{BE}$

$P_T \cong I_C V_{CE}$

pnp

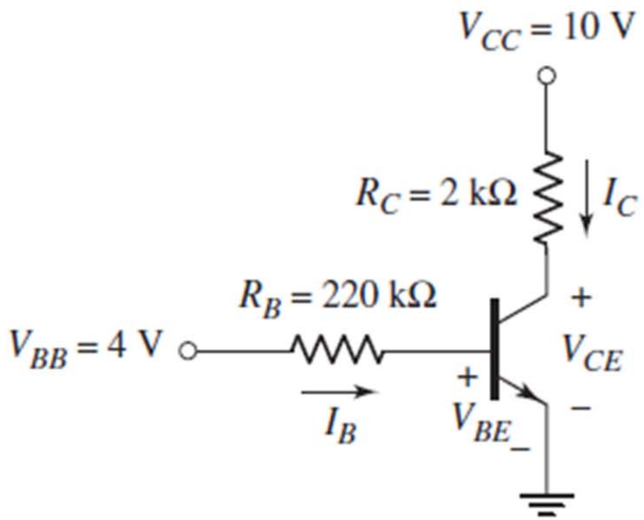




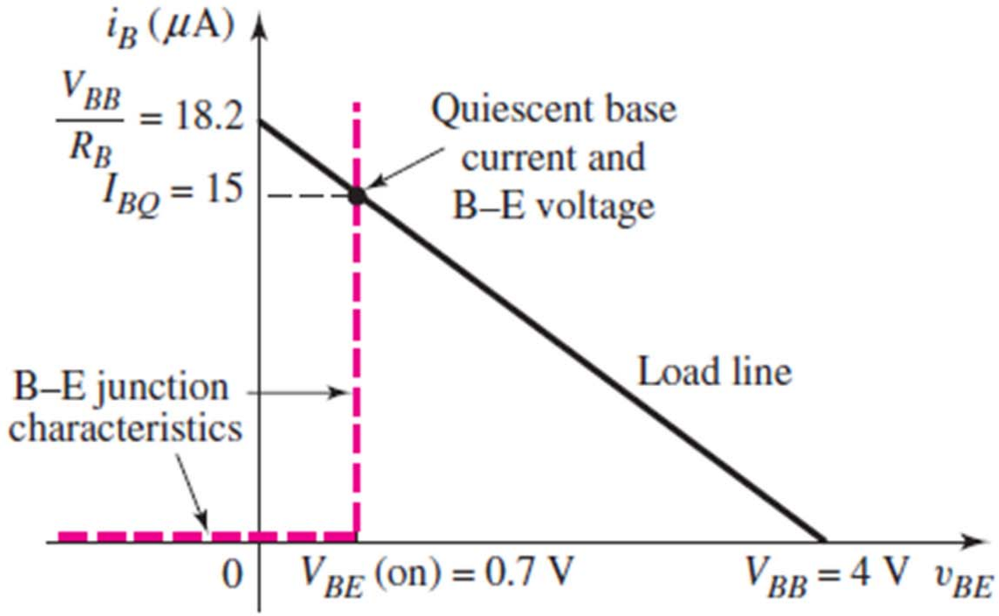
$$I_B = \frac{V_{BB} - V_{EB}(\text{on})}{R_B} \qquad I_C = \beta I_B \qquad V_{EC} = V_{CC} - I_C R_C$$

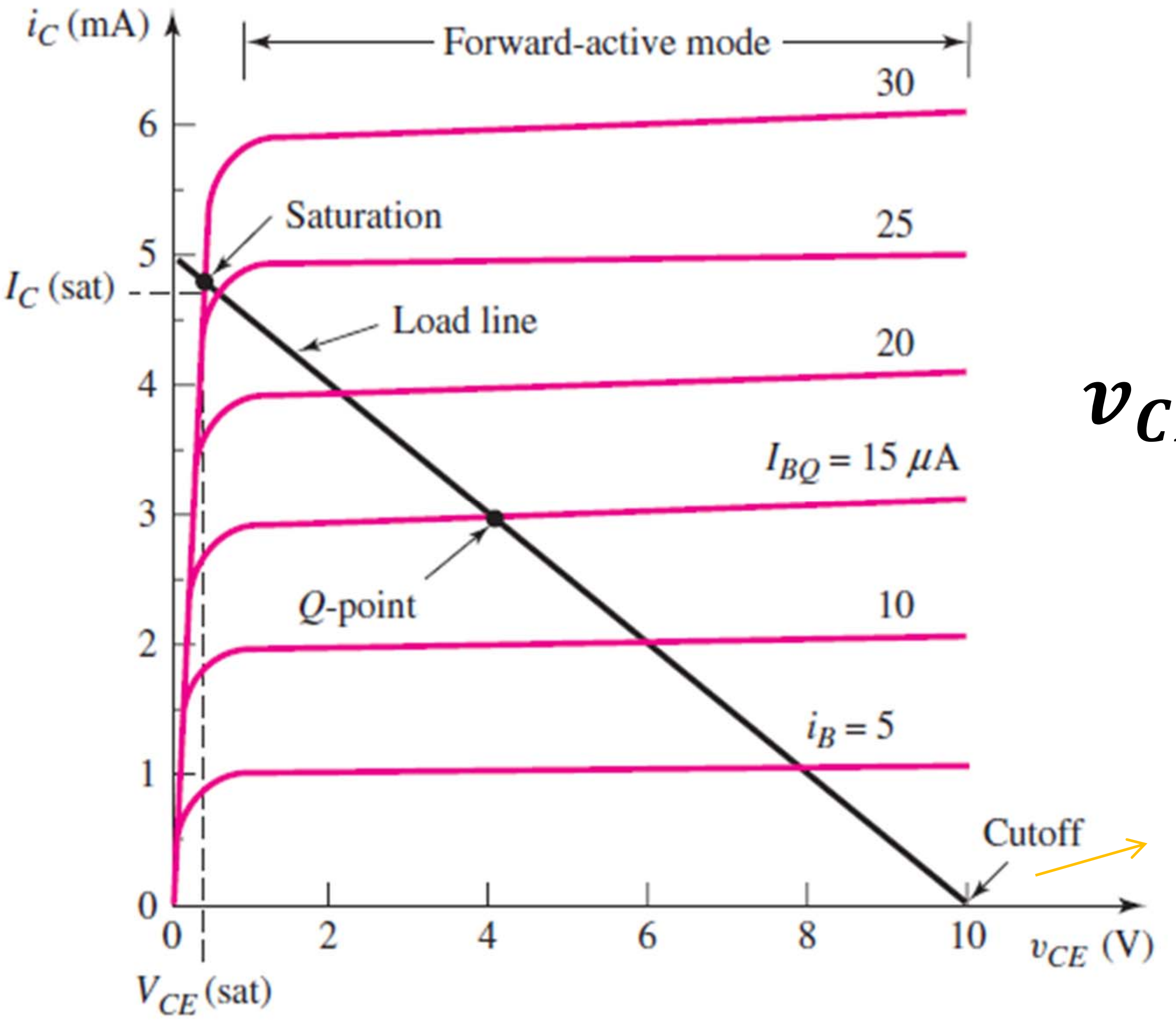
The pnp bipolar transistor will be reconfigured in a circuit so that positive voltage sources are used, yielding the common collector circuit.

Load line and modes of operation



$$V_{BB} = v_{BE} + I_B R_B$$





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

Also at I_B=0

At a point with IB increase IC cannot increase further. Here, the transistor is biased in saturation mode, B-C junction is forward bias, that is, B-E voltage is greater than C-E voltage.

$$I_C < \beta I_B$$