Fundamentals of Electronics
Week 7

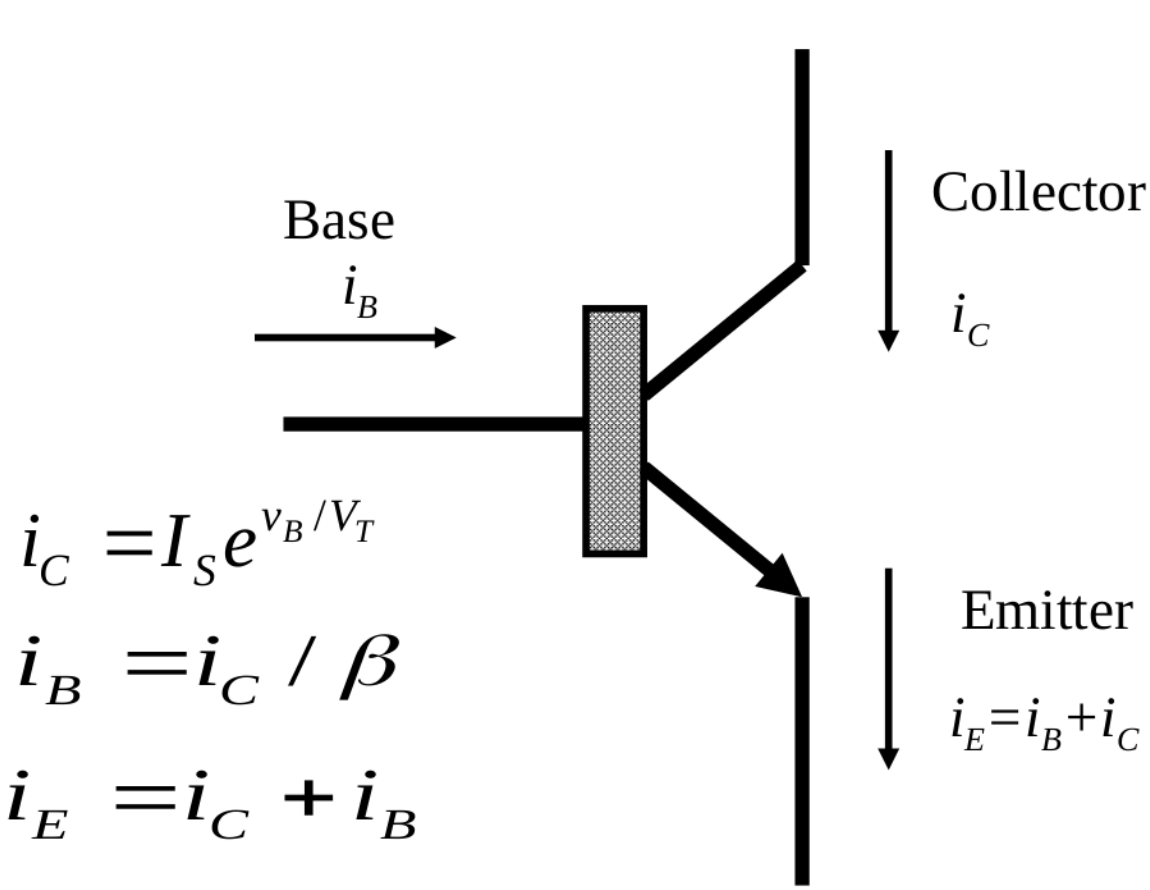
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Week 7 Agenda
BJT Basics

- Introduction to Transistors
- NPN Transistors
- Physical Properties
- Current Relationships in Active Mode
  - Base-Collector (beta)
  - Emitter-Collector (alpha)
- Circuit Models
- PNP Transistors
- Circuit Symbols

Transistor as 3–Terminal Device



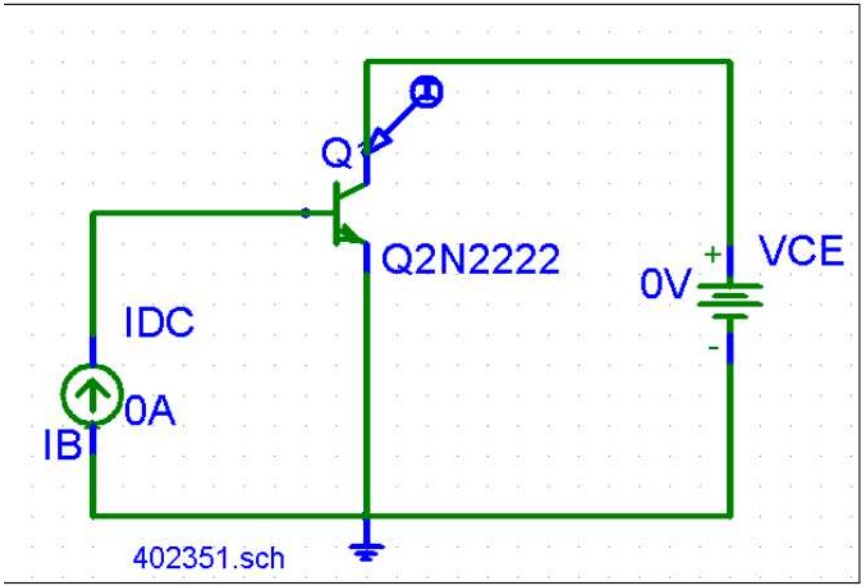
$$i_C = I_S e^{v_B / V_T}$$

$$i_B = i_C / \beta$$

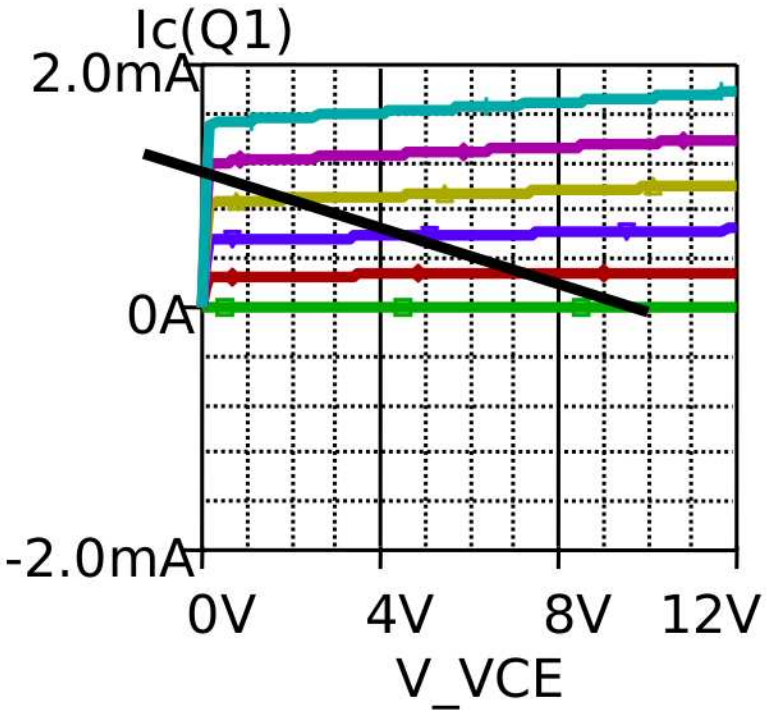
$$i_E = i_C + i_B$$

A Look Ahead: I–V Curves

- Test Circuit
  - Active Mode
  - Saturation
  - Cutoff

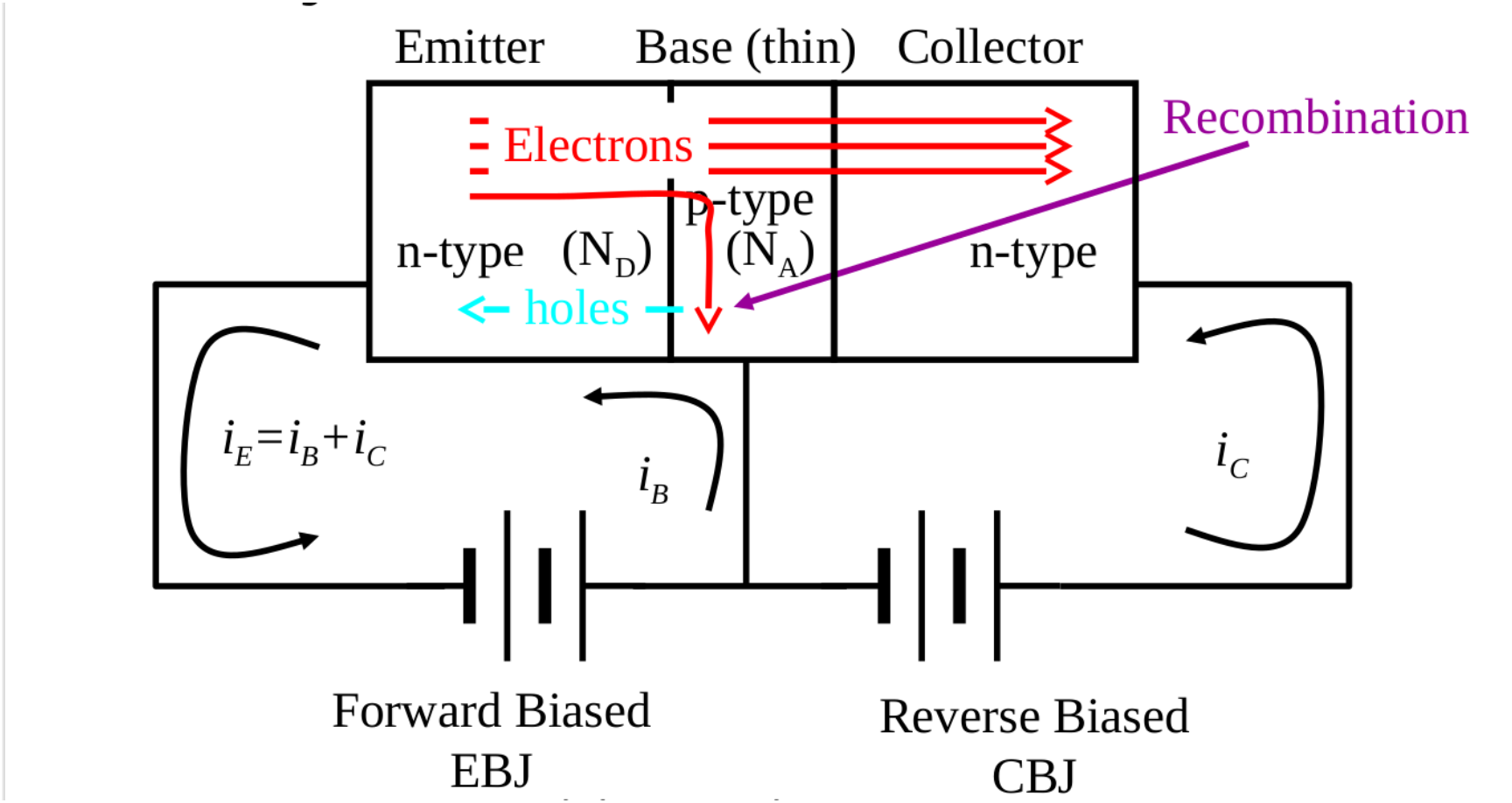


- I-V Curves
  - i_B=[0:2:10] microamperes



3 Modes: Active, Saturation, Cutoff

Physical Model: Active Mode

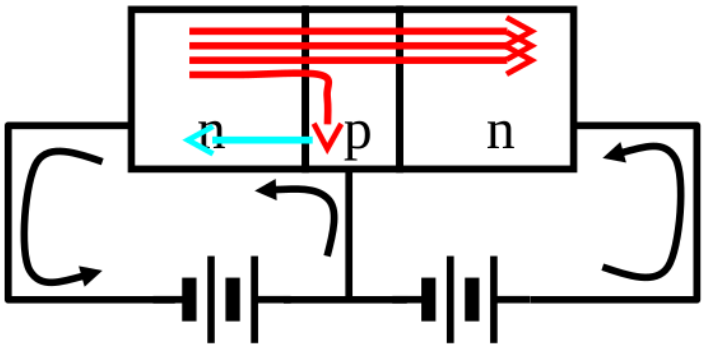


Modes of Operation

- Active Mode (Next Few Slides)
  - EBJ Forward Biased
  - CBJ Reverse Biased
- Other Modes (Discussed Later)
  - Saturation Mode
    Both Forward Biased
  - Cutoff Mode
    Both Reverse Biased

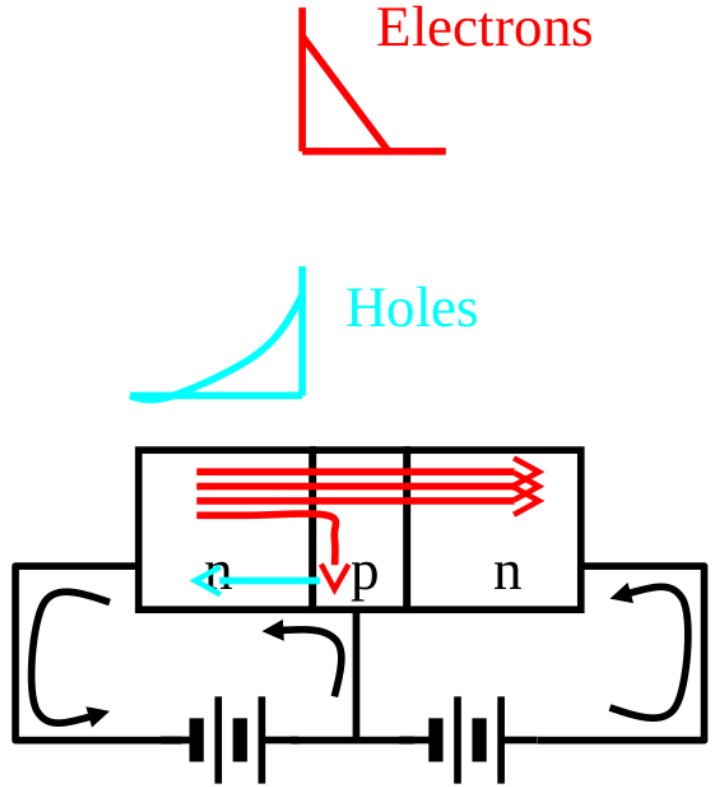
Physical Principles: Active Mode (1)

- External Circuit Provides Emitter Current
  - Electrons to Emitter
  - holes to Base
- Increased Majority Carriers Cover Charge in EBJ Depletion Region
- Barrier Voltage Reduces
- Electrons Move to Base
  - Become Minority Carriers



Physical Principles: Active Mode (2)

- Electron Density is Linear in *x* in Thin Base
  - Max at EBJ
  - Zero at CBJ
- Electrons Diffuse Across Base to Collector
- Holes Become Part of Emitter Current
  - Diffuse to Electrode and External Circuit



Equations for Active Mode

- Minority Carriers in Base (same as diode)
- Electron Current in Base

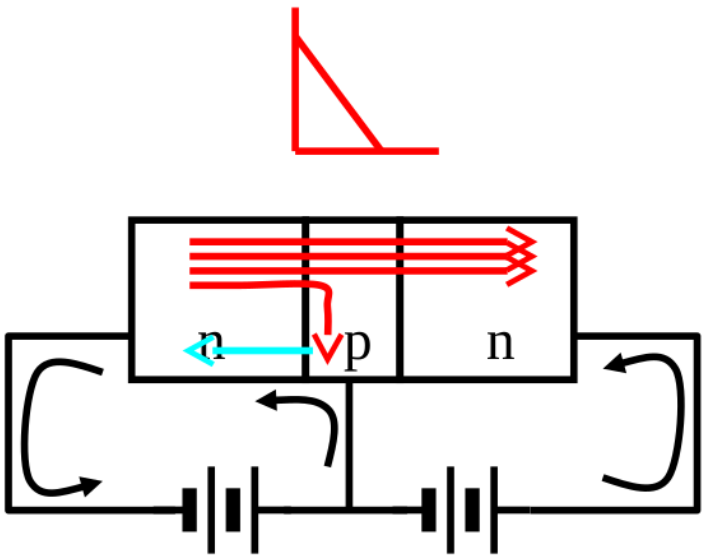
$$n_p(0) = n_{po} e^{v_{BE}/V_T}$$

$$n_p(W) = 0$$

$$I_n = A_E(-q)D_n \frac{dn_p(x)}{dx}$$

$$= A_E(-q)D_n \frac{-n_p(0)}{W}$$

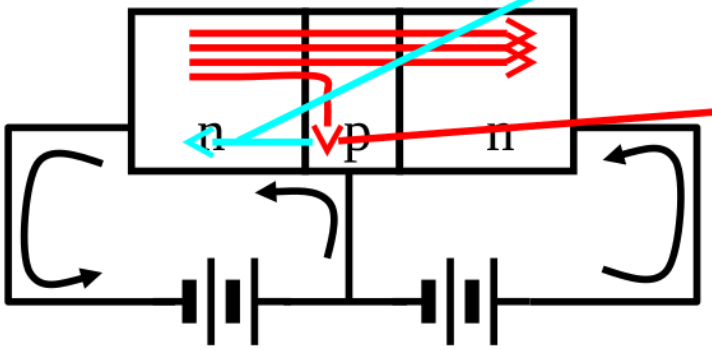
$$= \frac{A_E q D_n n_i^2}{N_A W} e^{v_{BE}/V_T} = I_S e^{v_{BE}/V_T}$$



Currents in Active Mode

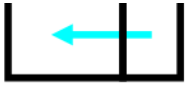
- Collector Current

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



- Base Current
  - Holes as Minority Carriers in Emitter
    - Proportional to Hole Density.
    - Limited by Electrons Recombining in the Base (i_{B1})
  - Electron Curent (i_{B2})
    - Minority Carriers in Base Recombine with Holes
    - Replenished from Emitter and External Circuit

Base Current (1)



- Hole Current
  - Density of Holes at the EBJ

    $$\frac{n_i^2}{N_D} e^{v_{BE}/V_T}$$

  - Diffusion Length in Emitter = L_p
  - Hole Current

$$i_{B1} = \frac{A_E q D_p n_i^2}{N_D L_P} e^{v_{BE}/V_T}$$

- Electrons Recombining with Holes in Base (replenished from emitter)

$$i_{B2} = \frac{\text{Coulombs in Base}}{\text{Minority Carrier Time}} \frac{Q_n}{\tau_B}$$

Charge In Base (area of Triangle)



$$Q_n = A_E q \frac{W}{2} n_p(0)$$

$$i_{B2} = \frac{1}{2} \frac{A_E q W n_i^2}{\tau_B N_A} e^{v_{BE}/V_T}$$

Base Current (2)

$$i_B = \frac{A_E q D_p n_i^2}{N_D L_P} e^{v_{BE}/V_T} + \frac{1}{2} \frac{A_E q W n_i^2}{\tau_B N_A} e^{v_{BE}/V_T}$$

$$i_B = i_C / \beta$$

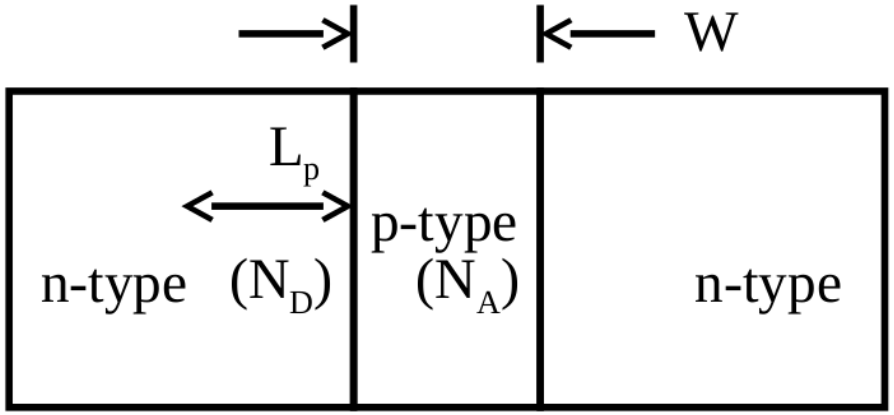
Recall: $$i_C = \frac{A_E q D_n n_i^2}{N_A W} e^{v_{BE}/V_T} = I_S e^{v_{BE}/V_T}$$

$$\frac{1}{\beta} = \frac{D_p N_A W}{D_n N_D L_P} + \frac{1}{2} \frac{W^2}{D_n \tau_B}$$

Base Current (3)

We Want this Small

$$\frac{1}{\beta} = \frac{D_p N_A W}{D_n N_D L_P} + \frac{1}{2}\frac{W^2}{D_n \tau_B}$$



$$N_A << N_D$$

$$W << L_P$$

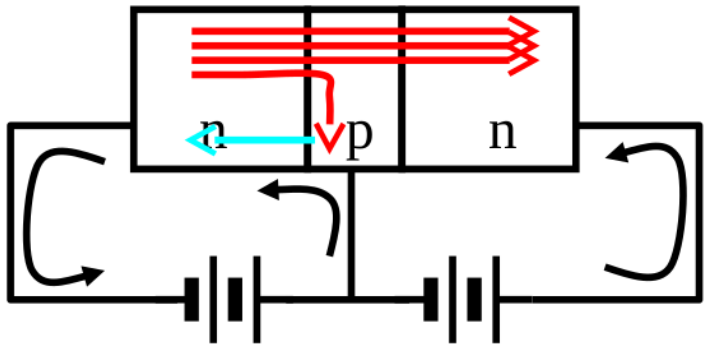
$$W << \sqrt{D_n \tau_B}$$

Typical Result: β is between 100 and 200

Emitter Current

$$i_E = i_C + i_B$$

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



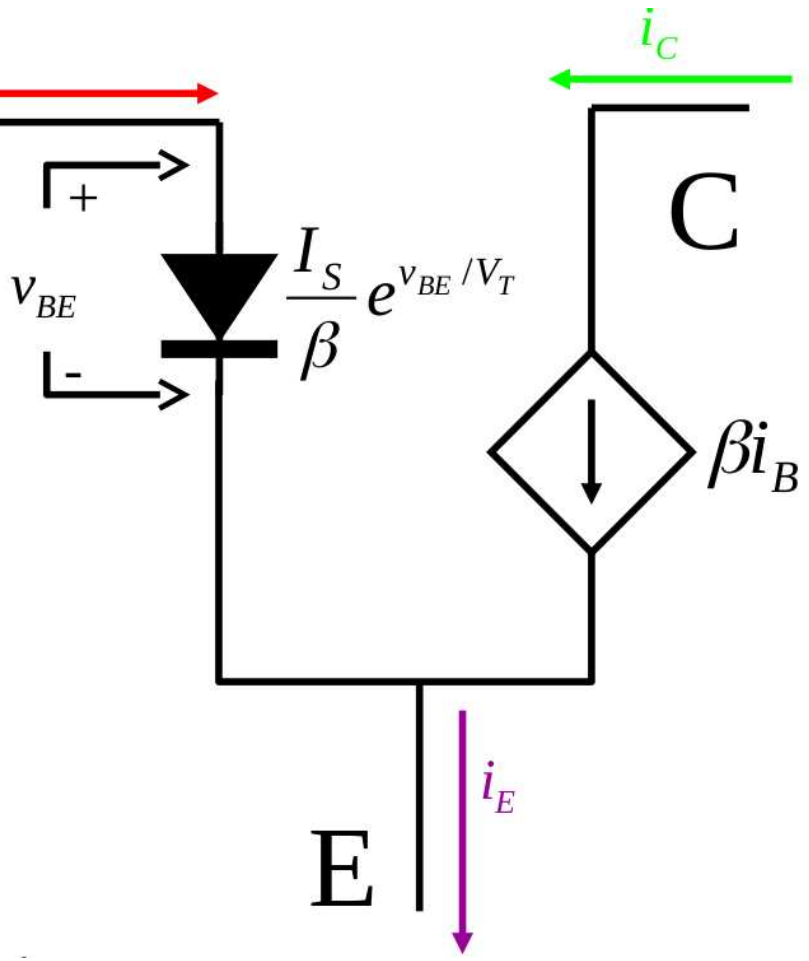
$$\alpha = \frac{\beta}{\beta + 1} \approx 1$$

BJT Models

- Overall Structure
  - Diode and Controlled Source
- Basic Models
  - Tee *vs.* Pi
- Mathematical Representation
  - Current *vs.* Voltage Control
- Applicability
  - DC, or AC

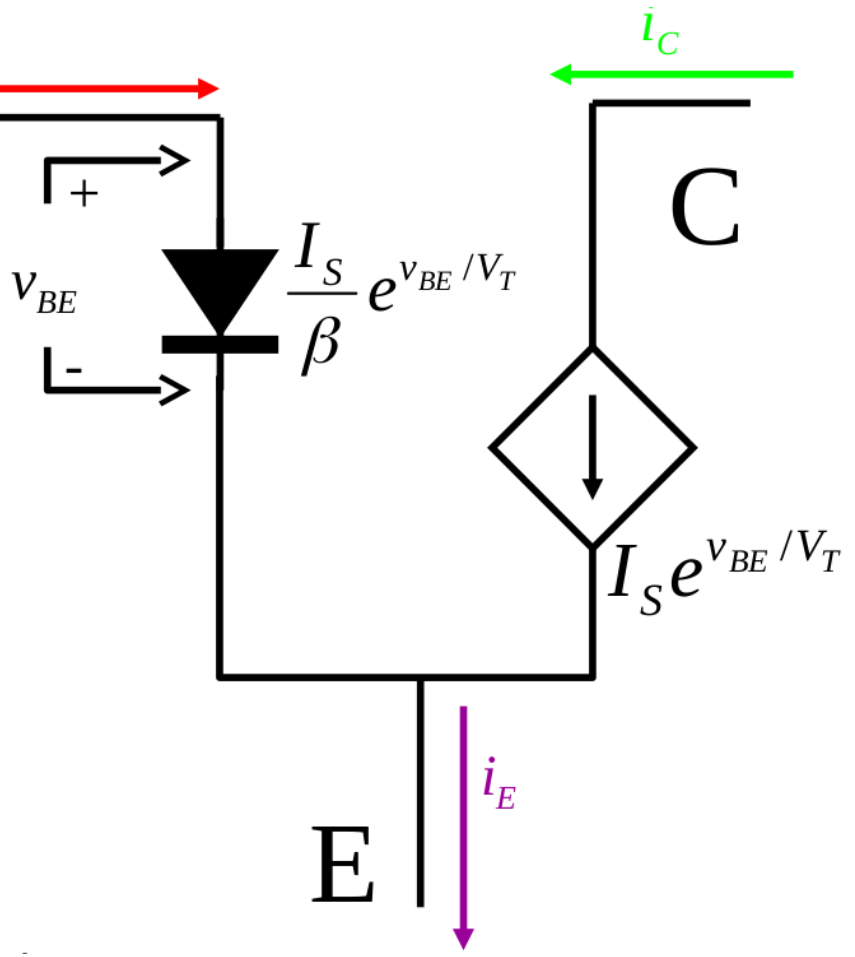
A Pi Model

- Base-Emitter Diode has Saturation Current reduced by 1/β
- Collector Current Depends on Base Current.
- Emitter Current Calculated from Other Two
- Note that $i_E > i_C$



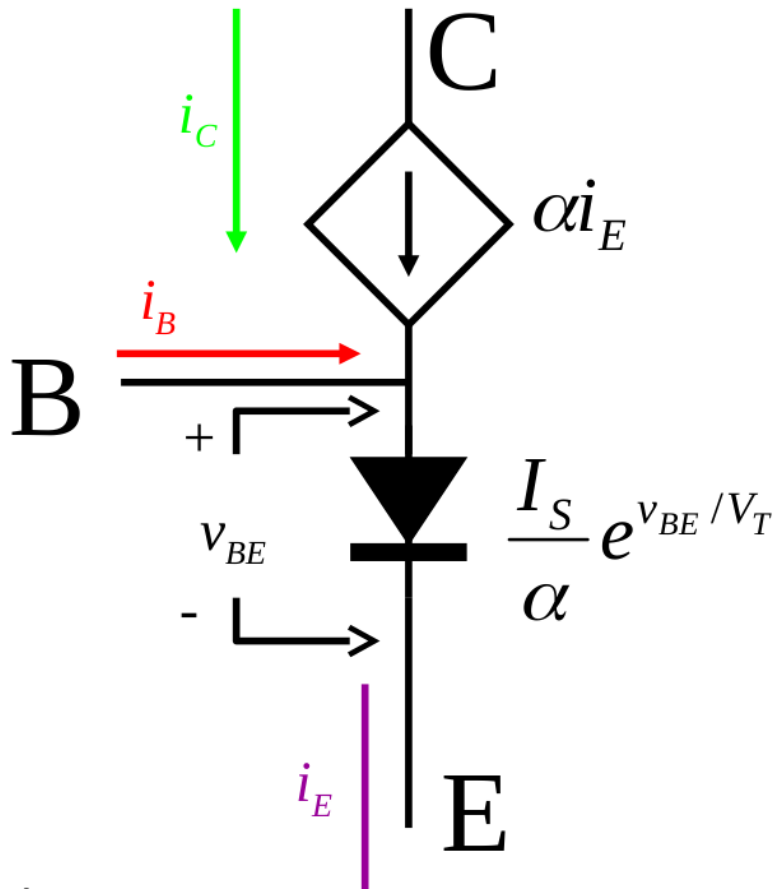
Another Pi MOdel

- Base-Emitter Diode has Saturation Current reduced by 1/β
- Collector Current Depends on Base-Emitter Voltage.
- Emitter Current Calculated from Other Two
- Note that $i_E > i_C$



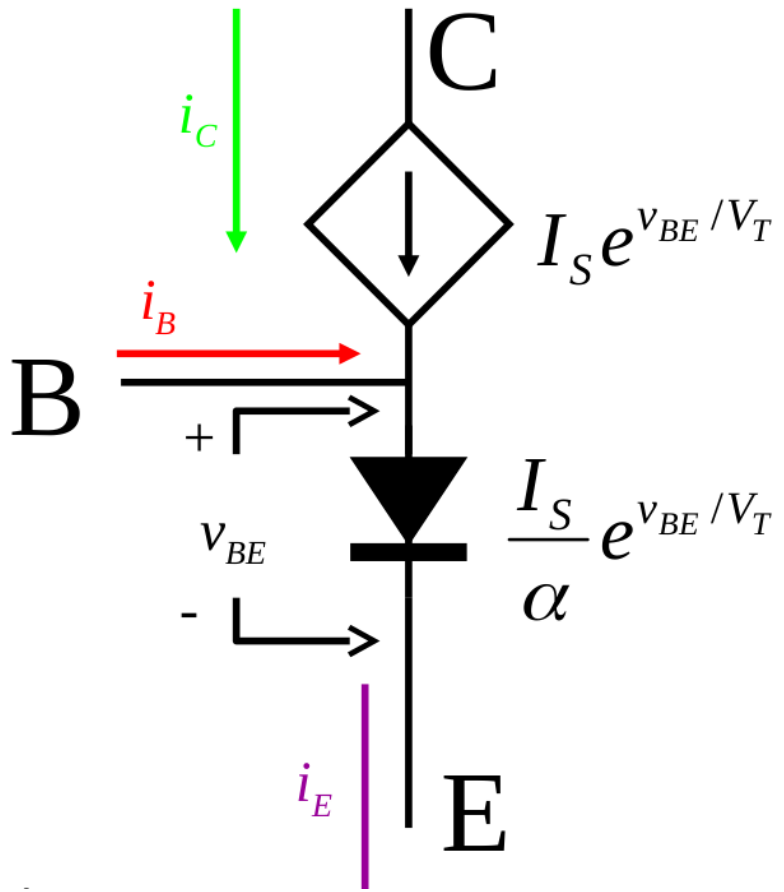
A Tee Model

- Base-Emitter Diode has Saturation Current increased by $1/\alpha$
- Collector Current Depends on Emitter Current.
- Base Current Calculated from Other Two
- Note that $i_E > i_C$

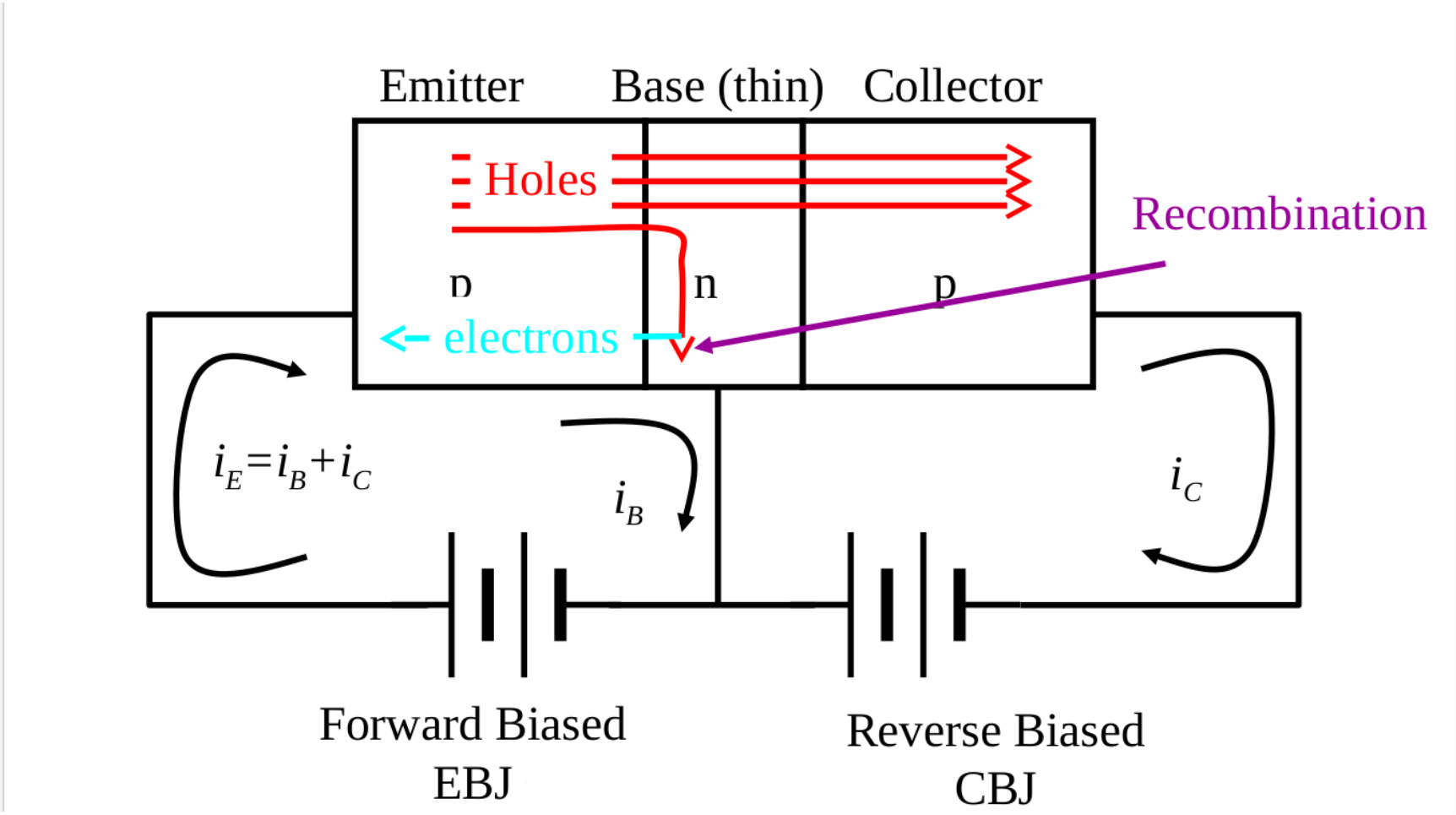


Another Tee Model

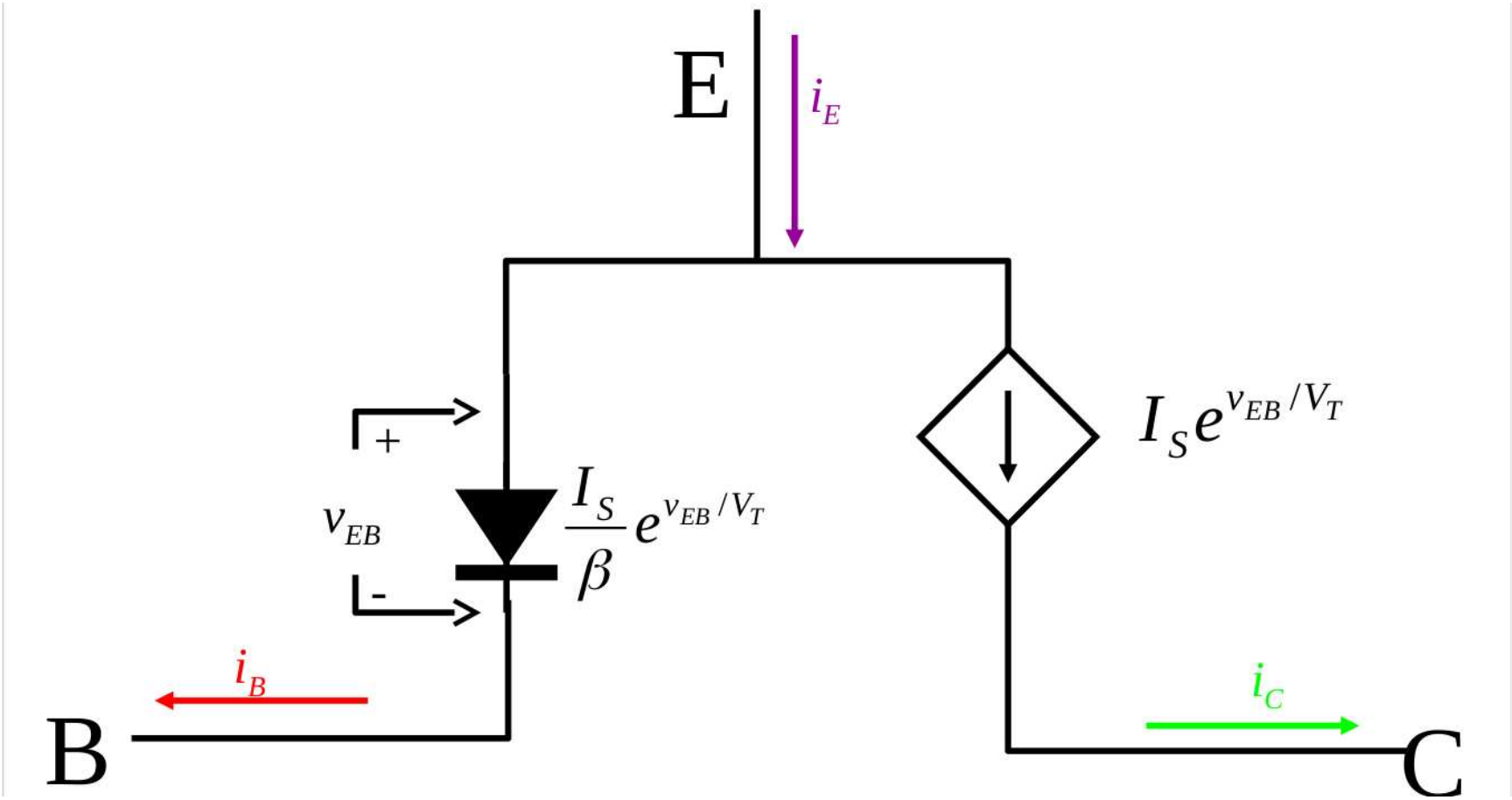
- Collector Current Depends on v_{BE}.
- Base-Emitter Diode has Saturation Current increased by $1/\alpha$
- Base Current Calculated from Other Two
- Note that $i_E > i_C$



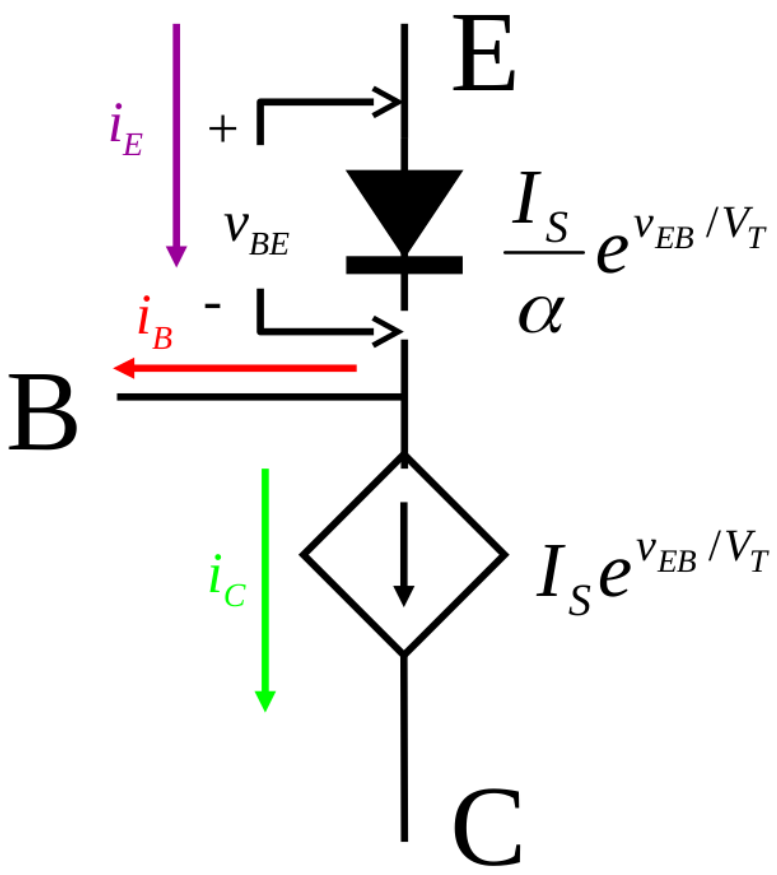
PNP Transistor



A Pi Model for PNP



A TEE Model for PNP



- Sign Convention
  - Positive Voltages at Top of Page
  - Emitter at Top
  - Currents Reversed
    - Into Emitter
    - Out of Collector
    - Out of Base
    - Still Positive
- Note Subscript Reversal
  - v_{EB} instead of v_{BE}

Helpful Hint

- Try to draw the circuit so positive voltages are at the top
- NPN collectors above emitters
- PNP collectors below emitters

Circuit Symbols

