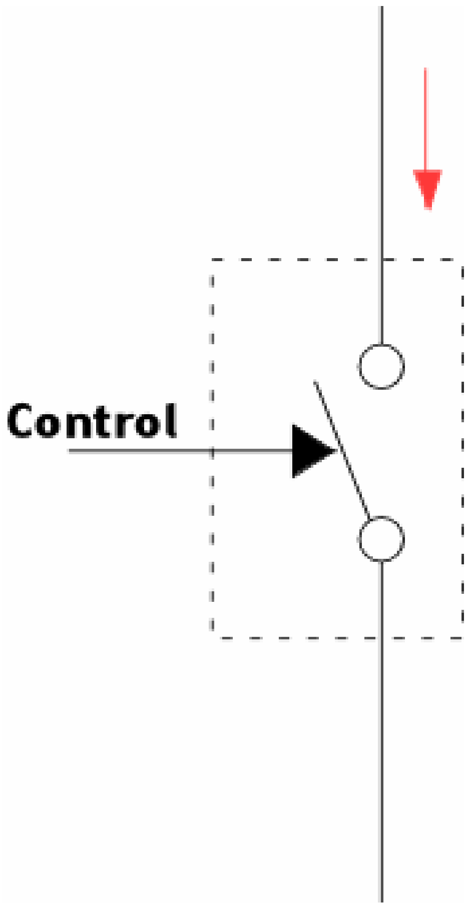
Chapter 5
Bipolar Junction Transistors (BJTs)

Sedra/Smith, Sections 5.1-5.9

Outline of Chapter 5

- 1- Introduction to The Bipolar Junction Transistor
- 2- Active Mode Operation of BJT
- 3- DC Analysis of Active Mode BJT Circuits
- 4- BJT as an Amplifier
- 5- BJT Small Signal Models
- 6- CEA, CEA with R_E, CBA, & CCA
- 7- Integrated Circuit Amplifiers

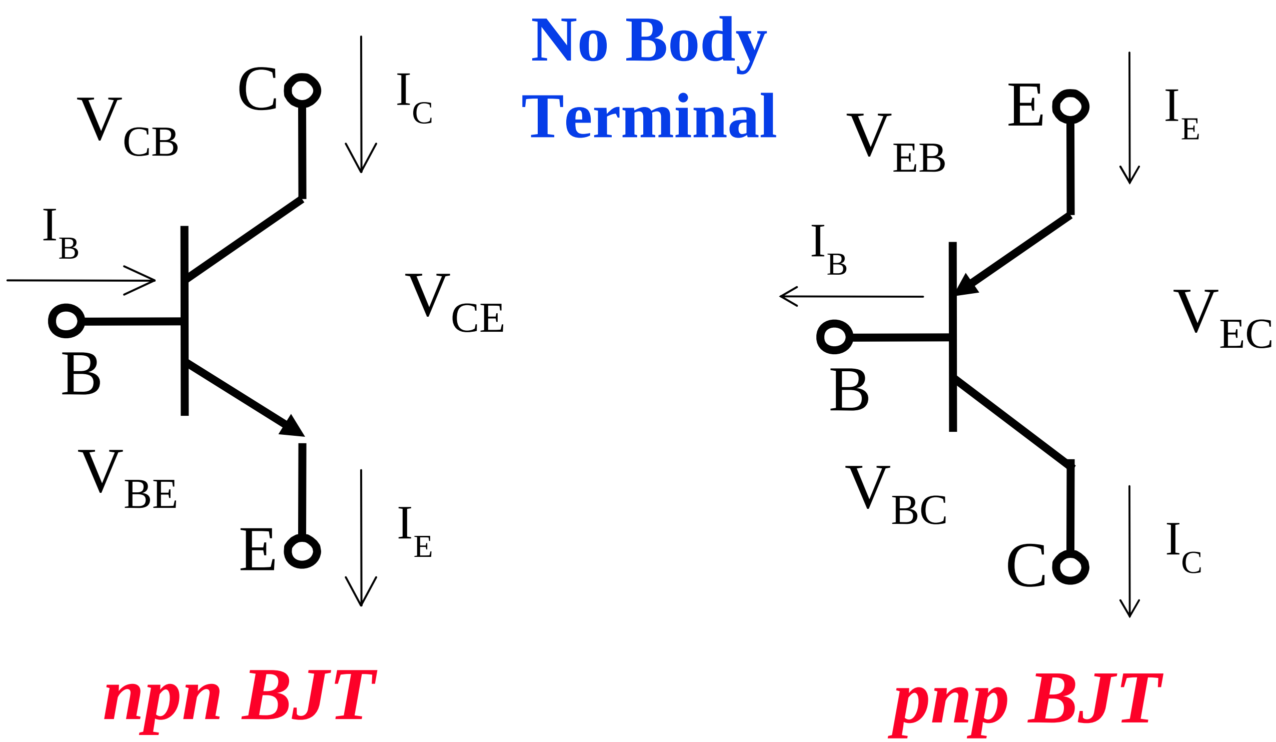
Transistors



- A ***three*** terminal device is required to implement current switches and amplifiers.
  - need voltage control terminal
  - used to control current flow through other two terminals
- All four ideal amplifier configurations (section 1) employ dependent sources.
- A small Control “voltage” can allow a large change in “current”.

Bipolar Junction Transistor (BJT)

- 3 terminal device in which the voltage across 2 terminals controls the current flowing in/out of a 3rd terminal:



BJT Active Mode Terminal Equations

- Voltage across 2 terminals (base/emitter) controls current at the 3rd (collector):

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

npn

$$i_C = I_S \exp\left(\frac{v_{EB}}{V_T}\right)$$

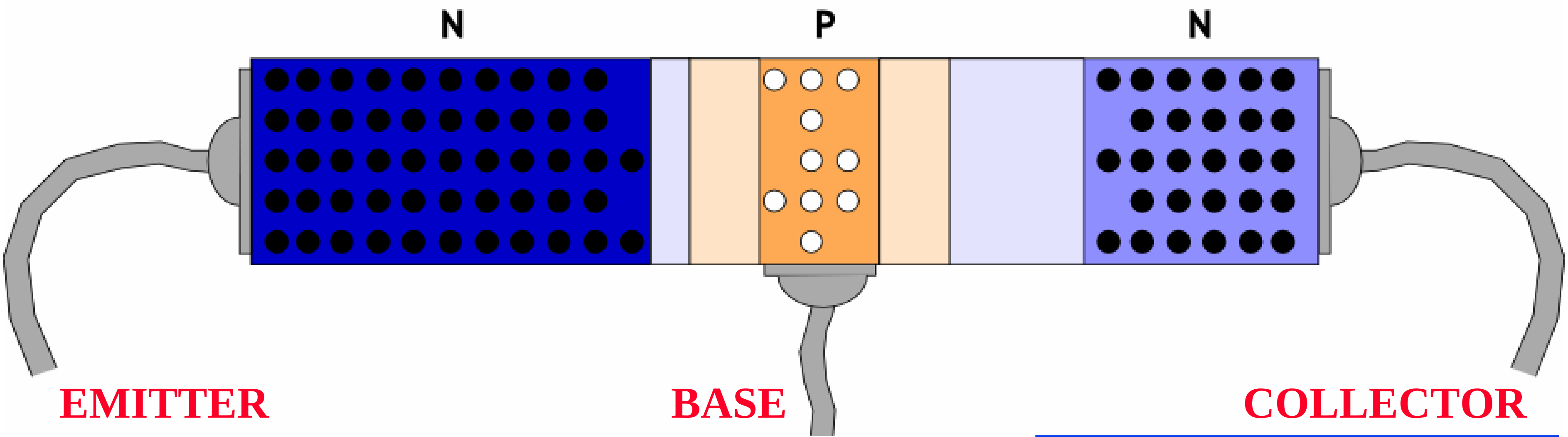
pnp

- Additional observation (applies to both transistor types) – total input current equals total output current:

$$i_E = i_C + i_B$$

In MOSFETs i_D=i_S and i_G=0

The npn BJT Operational Modes



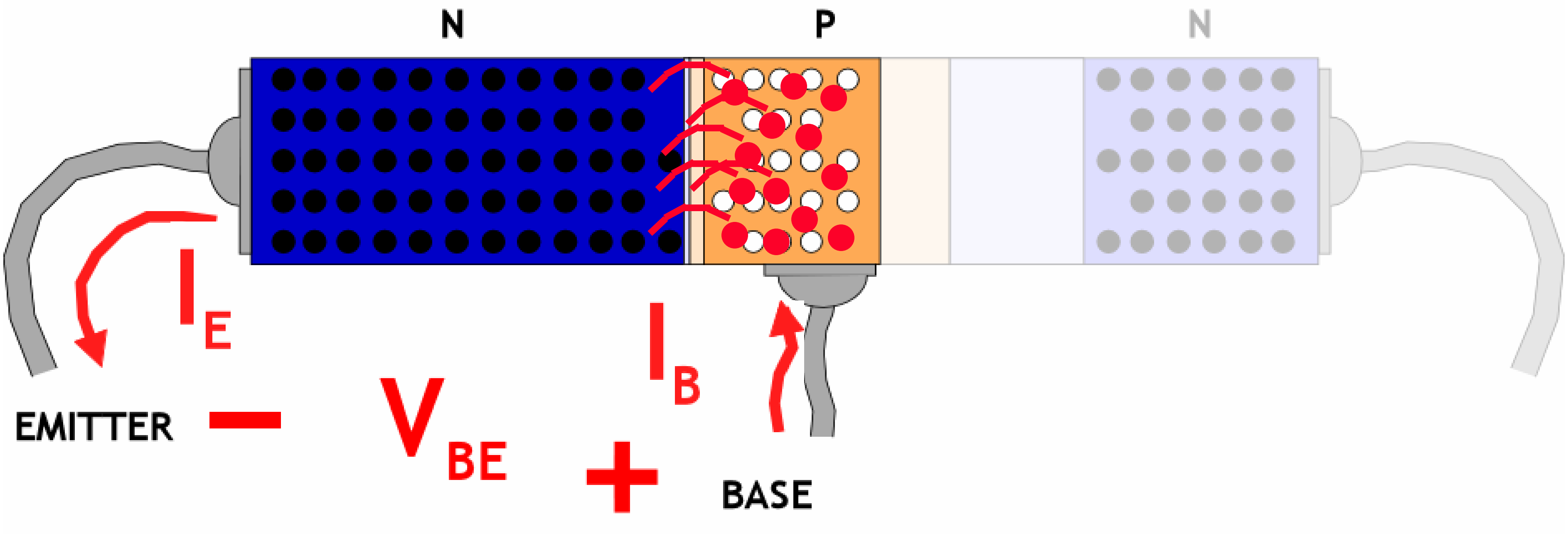
Notes the difference with MOSFETs

4 Modes of operation

	B-E Junction	B-C Junction
Cutoff	reverse	reverse
Active	forward	reverse
Saturation	forward	forward
Reverse Active	reverse	forward

Amplifier

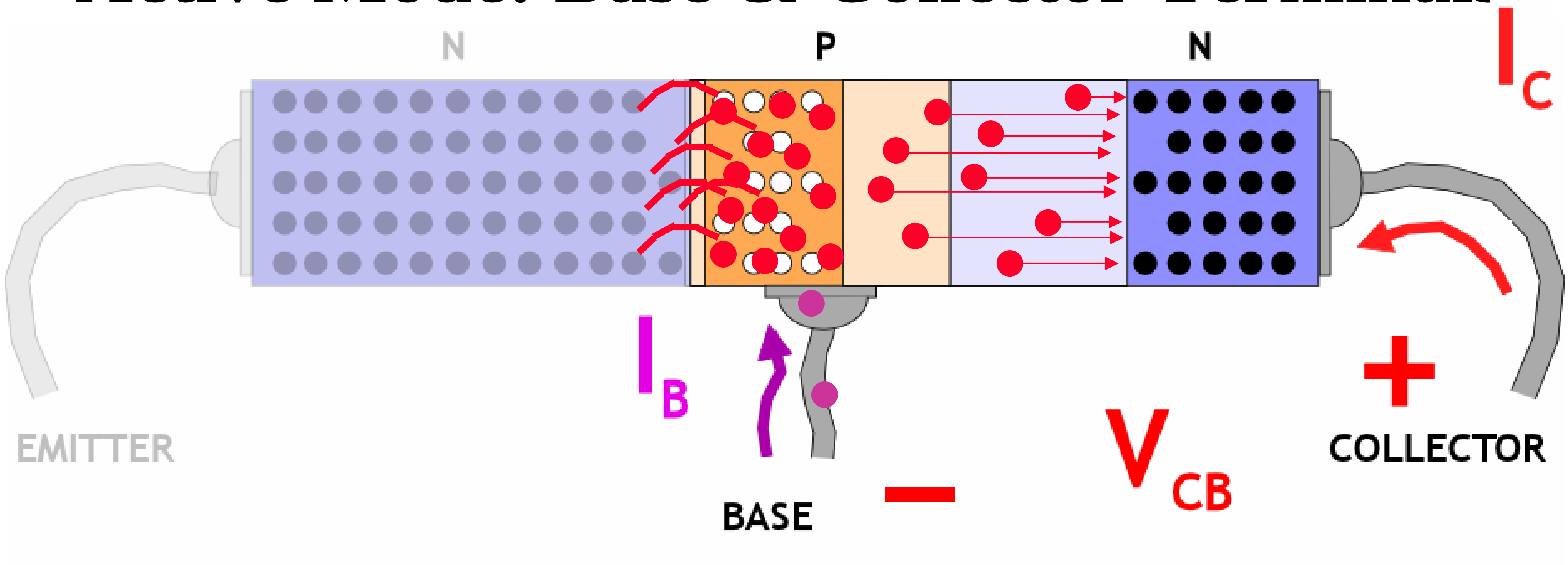
Active Mode: Base & Emitter Terminals



- Between the Base and the Emitter, have a pn junction; thus looks like a diode
- Across this junction in active mode, DC operating voltage is ~ 0.7V, just like a diode

- When the current begins to flow, a LARGE number of electrons from the emitter region enter the base region.

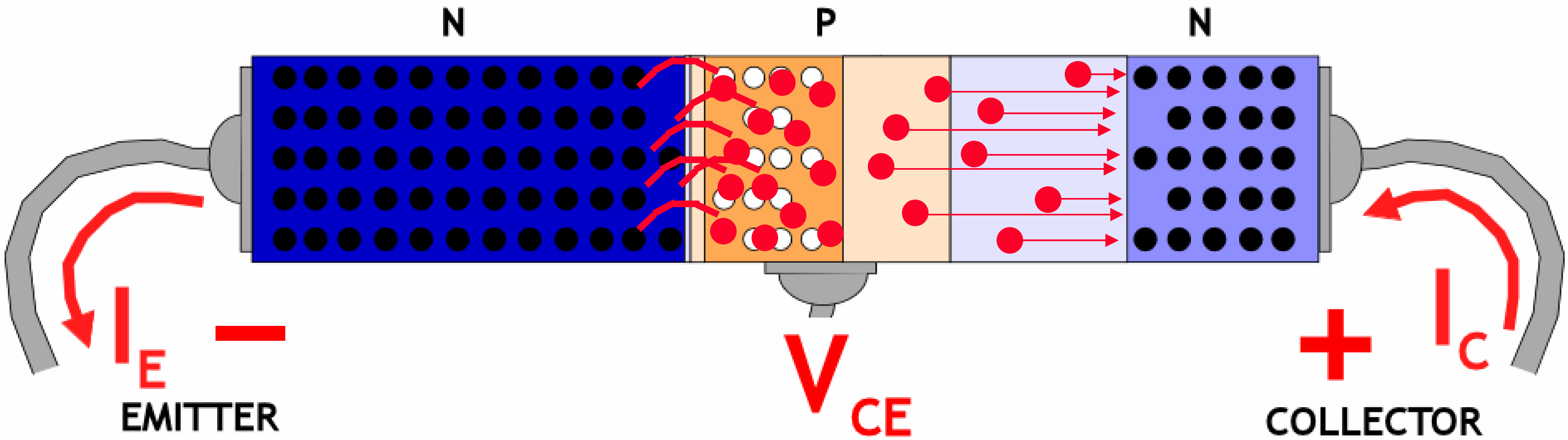
Active Mode: Base & Collector Terminals



- Between the Collector and the Base is a pn junction as well,
- In active mode, this junction is either reversed biased, or zero bias ($V_{CB} = 0$).

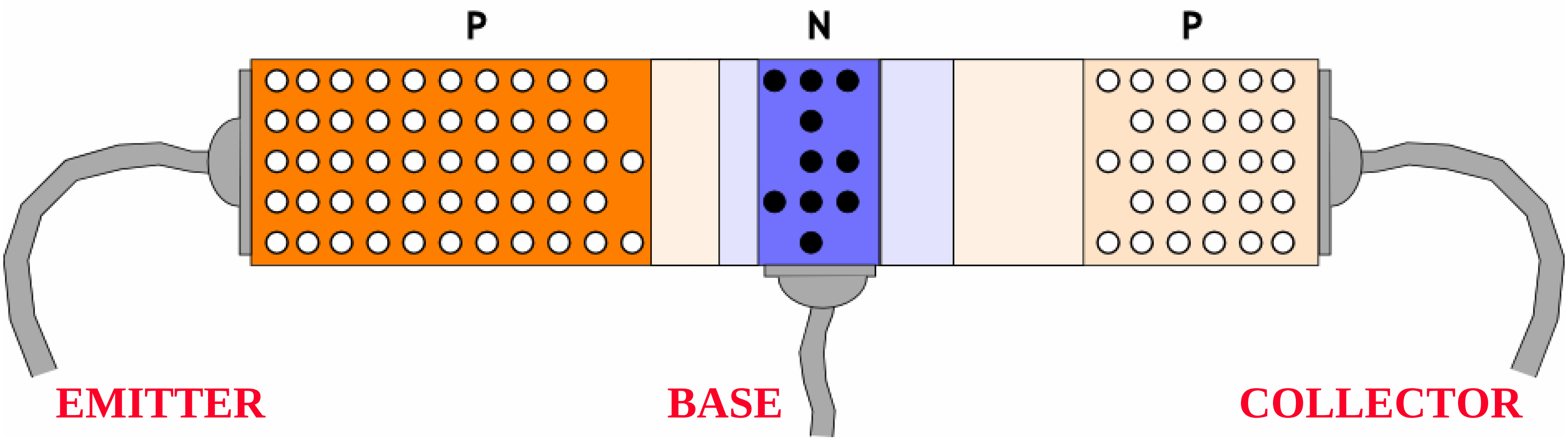
- Since the Base-region is so thin, the carriers from the emitter region are swept into the collector region.

Active Mode: Collector & Emitter Terminals



- Between the Collector and the Emitter a LARGE current flows,
- Controlled by a small voltage: V_{BE}.

The pnp Bipolar Junction Transistor



4 Modes of operation

	B-E Junction	B-C Junction
Cutoff	reverse	reverse
Active	forward	reverse
Saturation	forward	forward
Reverse Active	reverse	forward

Collector Current

- Based on device operational principles, we write a diode-like equation for the current flowing in the collector:

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

- I_S is the ***current-scale factor*** or ***saturation current***
  - Proportional to area of the base-emitter junction
  - Inversely proportional to base region width
  - Inversely proportional to doping level in base
  - Between 10^{-12} and 10^{-18}A, typically, in ICs
  - Strongly dependent on temperature (doubles every 5°C increase)

Base Current

- Base current has two components
  - hole diffusion current from base to emitter
  - electron recombination in base
- The base current also has a diode-like expression for current, but is a fraction of the collector current. It is given in terms of a parameter called the ***common-emitter current gain*, β**, and the collector current:

$$I_B = \frac{I_C}{\beta}$$

Transistor β

- Transistor Beta (β)
  - Always treated as a fixed constant in EC1
  - In reality, dependent on I_C, V_{CB}, temperature, and operating frequency
  - β is typically between 100 and 200
  - A large β represents an efficient BJT

- Variations in β
  - For large I_C, recombination increases (β decreases)
  - For elevated temperatures, number of free holes in base region increases (β decreases)
  - As V_{CB} increases, effective base width (W) decreases (β increases)

Emitter Current

- Emitter current: $$I_E = I_C + I_B$$

- In terms of I_C and the *common-base current gain*, α: $$I_C = \alpha I_E; \qquad \alpha = \frac{\beta}{\beta+1} \approx 1$$

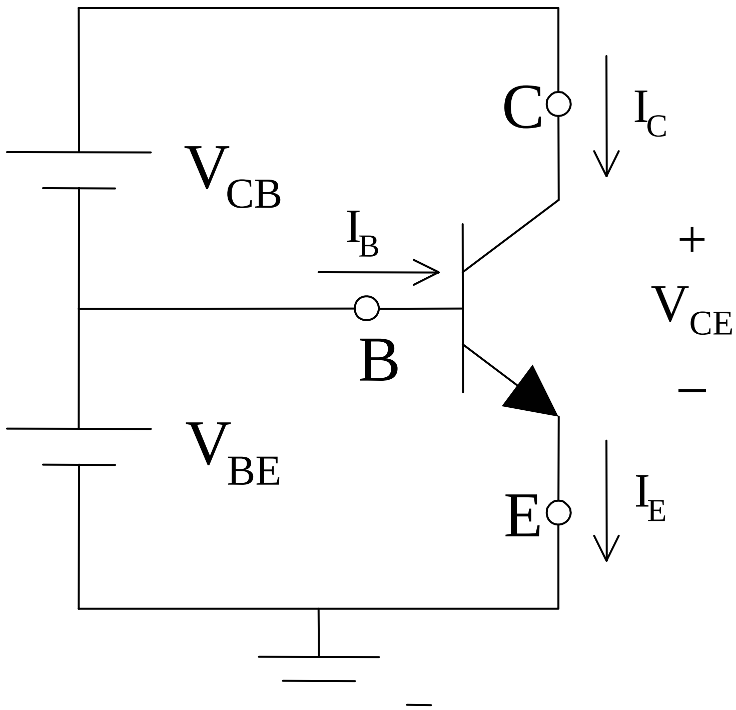
$$I_E = I_C + I_B = I_C + \frac{I_C}{\beta} = \left(\frac{\beta+1}{\beta}\right) I_C$$

- In terms of I_B: $I_E = I_C + I_B = \beta I_B + I_B = (\beta+1) I_B$

$$I_E = (\beta+1) I_B$$

Active Mode Biasing

- Conceptual biasing arrangement:

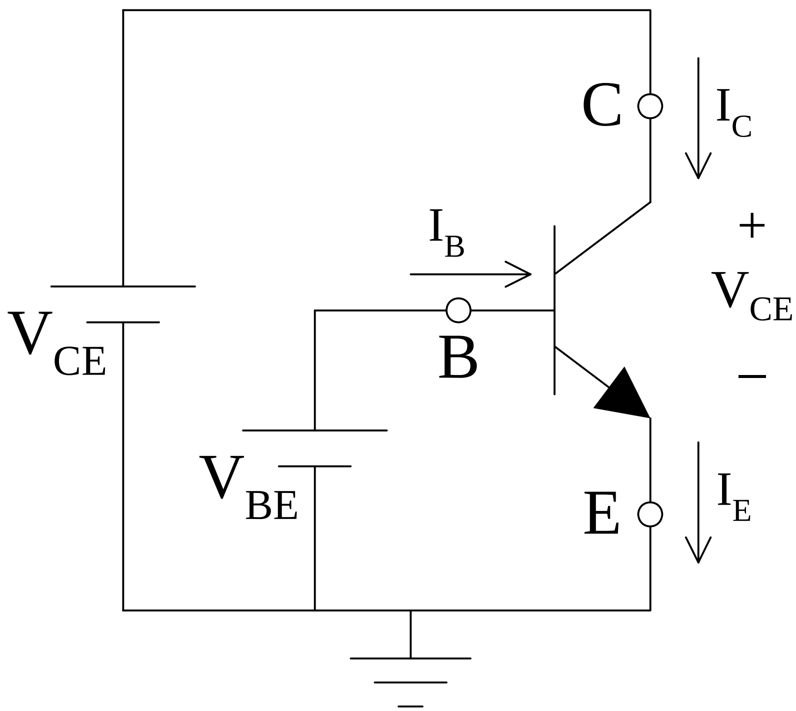


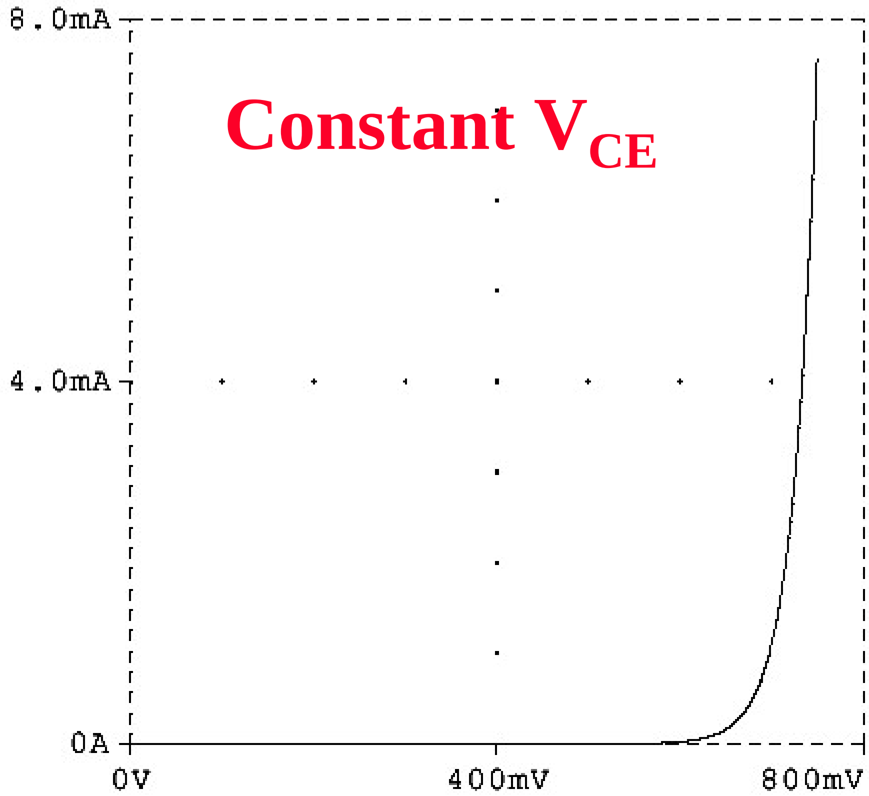
- $V_{BE} = 0.7V$ (forward bias B-E junction)
- B-C junction kept from forward-bias conduction
  - In principle, $V_{CB} \geq -0.5V$ when cut-in voltage of 0.5 is assumed
  - In simplified cases $V_{CB} \geq 0V$ is sometimes assumed

$$V_C \geq V_B > V_E; \quad V_{BE} \approx 0.7V$$

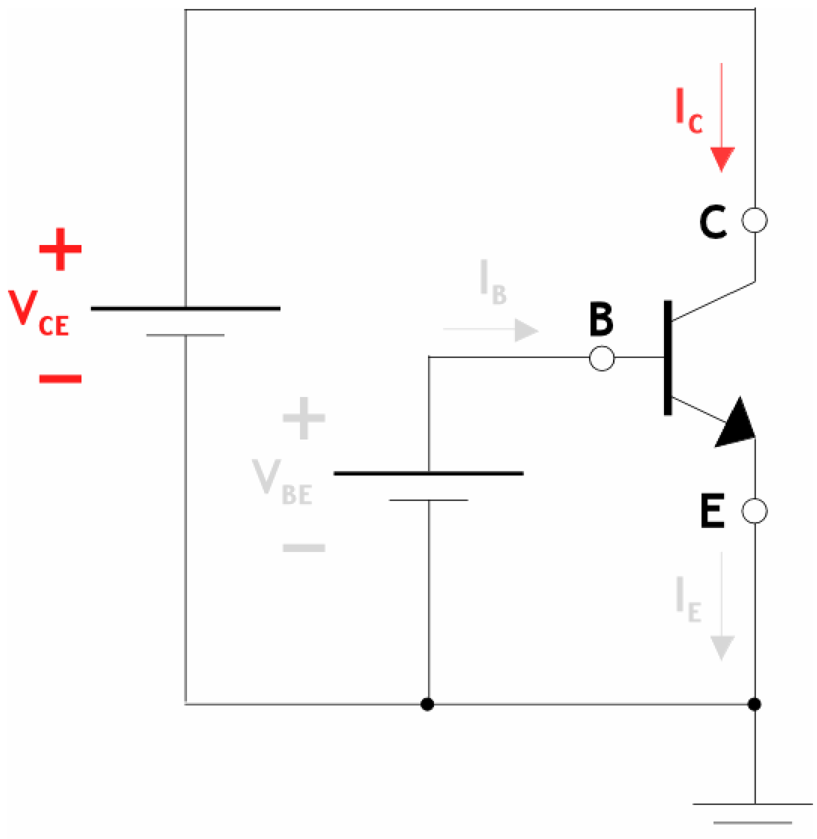
I_C vs V_{BE} for Constant V_{CE}

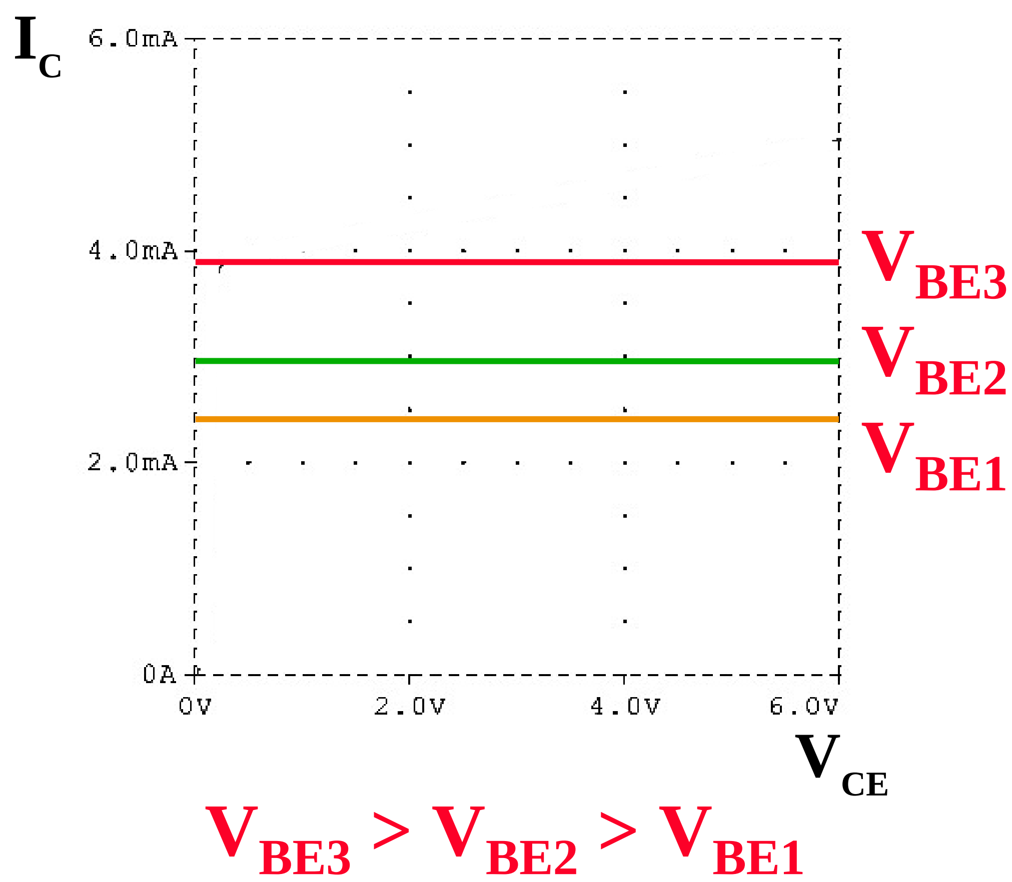
For constant V_{CE}, I_C vs. V_{BE} follows a diode I-V curve, consistent with I_C vs V_{BE} relationship: $I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$





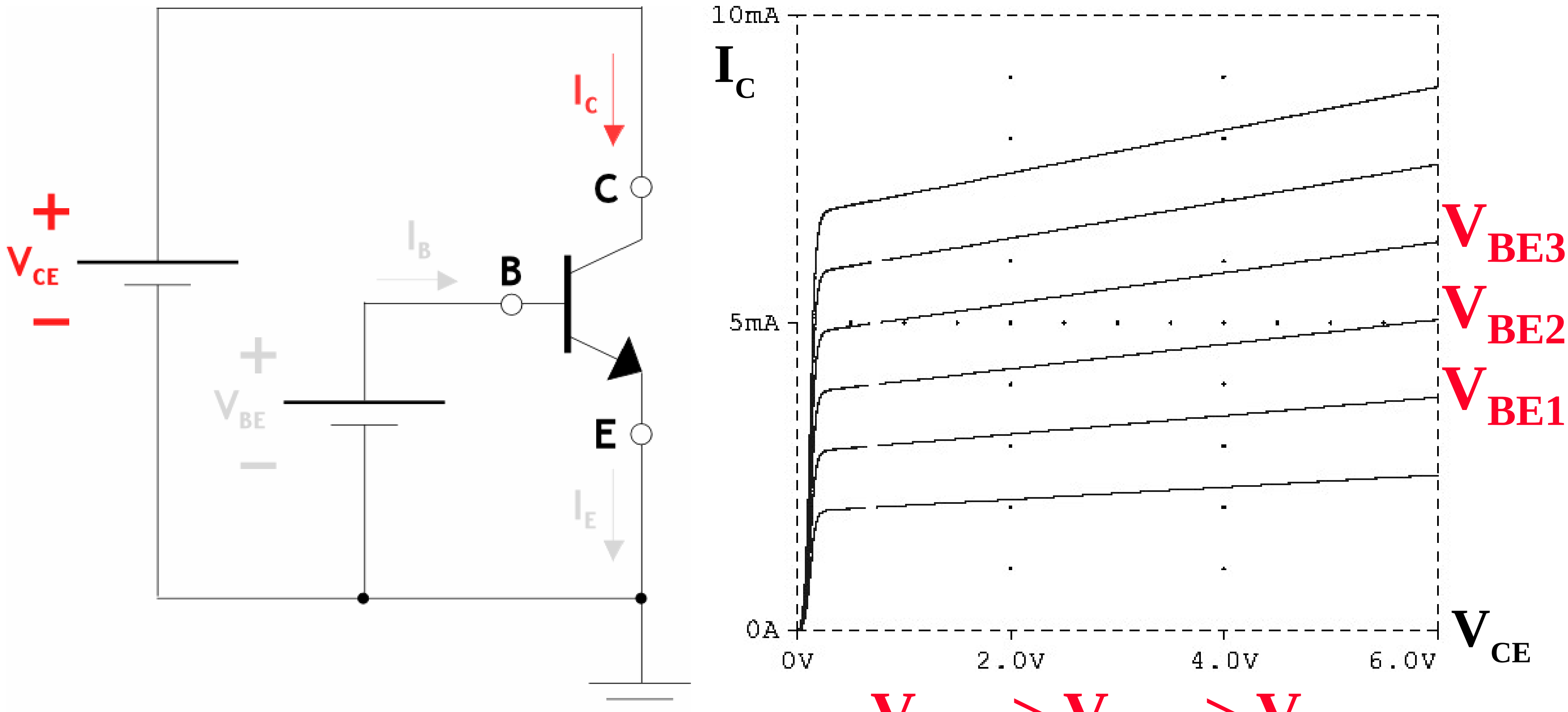
Ideal I_C vs V_{BE}/V_{CE} Curve





Ideal I_C vs. V_{CE} curve indicates ***no dependence*** on V_{CE}

Real I_C vs V_{BE}/V_{CE} Curve

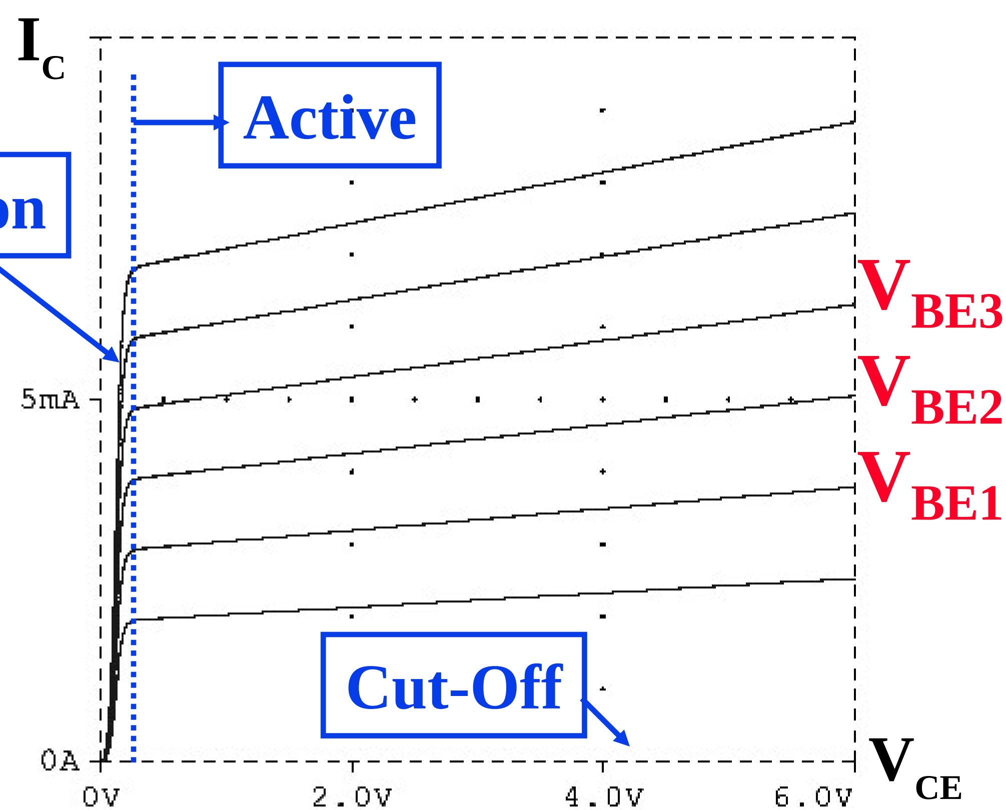


$V_{BE3} > V_{BE2} > V_{BE1}$

Real I_C vs. V_{CE} curve indicates ***dependence*** on V_{CE}

npn BJT Family of Curves

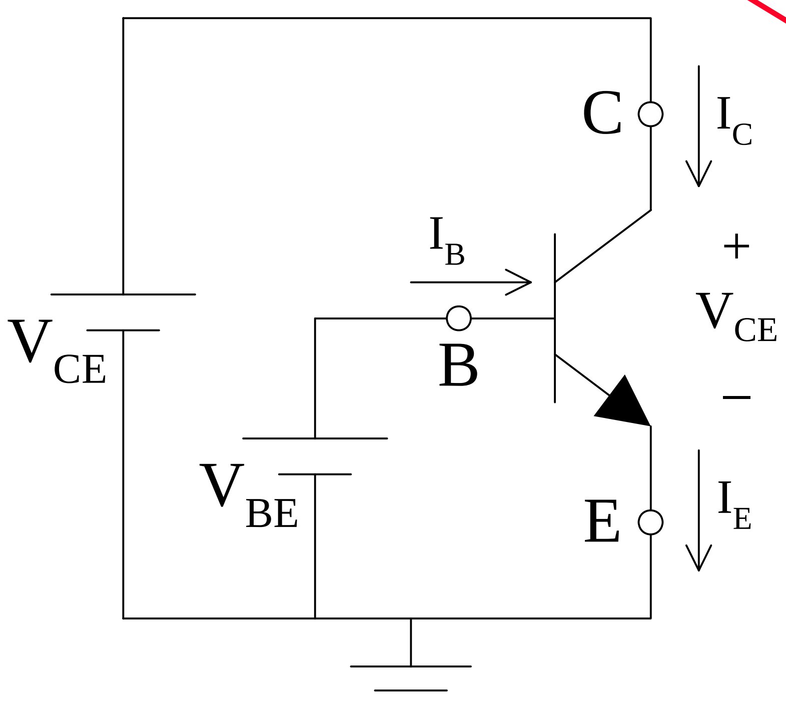
- Family of curves describes I_C vs. V_{BE}/V_{CE}.
- 3 Modes of operation:
  - ***Active***
  - ***Saturation***
  - ***Cutoff***
- Active mode for analog applications
- Saturation/cutoff for digital applications



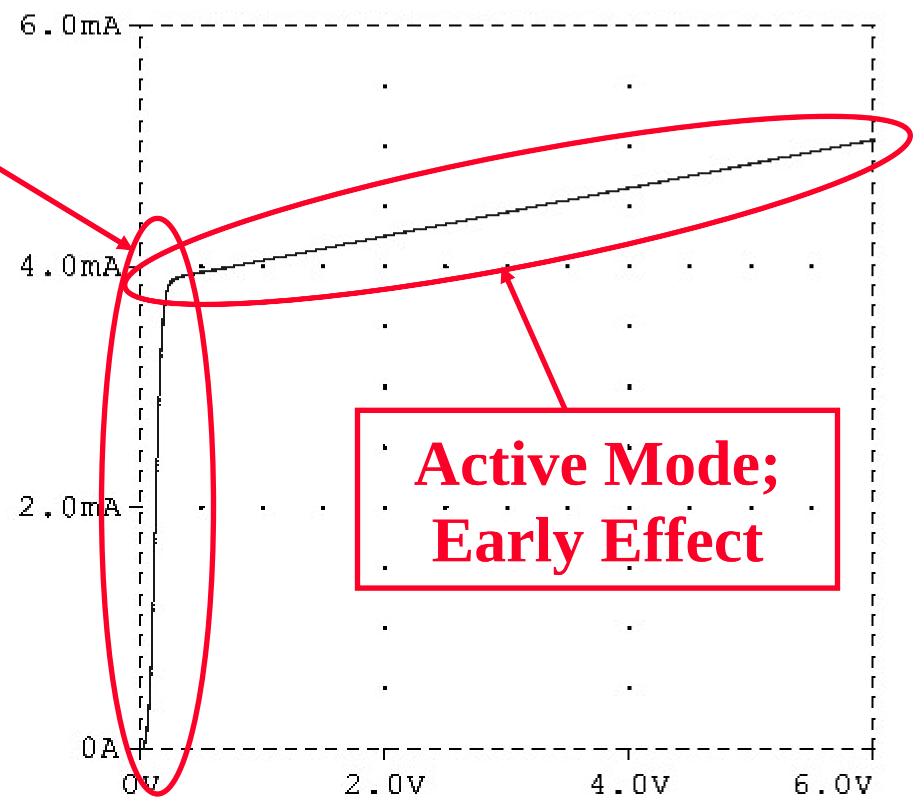
$V_{BE3} > V_{BE2} > V_{BE1}$

I_C vs V_{CE} for Constant V_{BE}

- For constant V_{BE} and small V_{CE}, BJT in saturation:



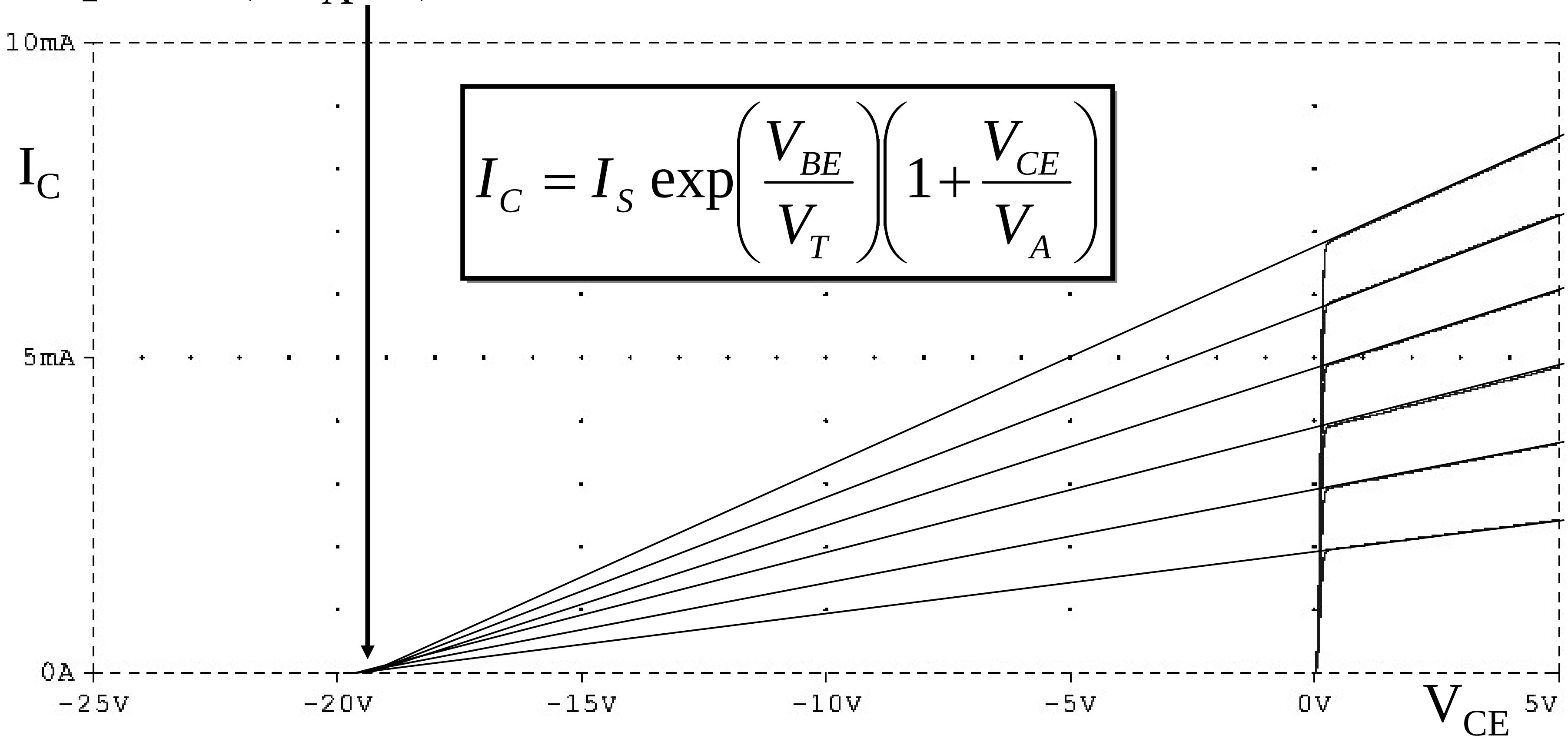
Linear dependence on I_C vs. V_{CE} for constant V_{BE} defined as the Early Effect



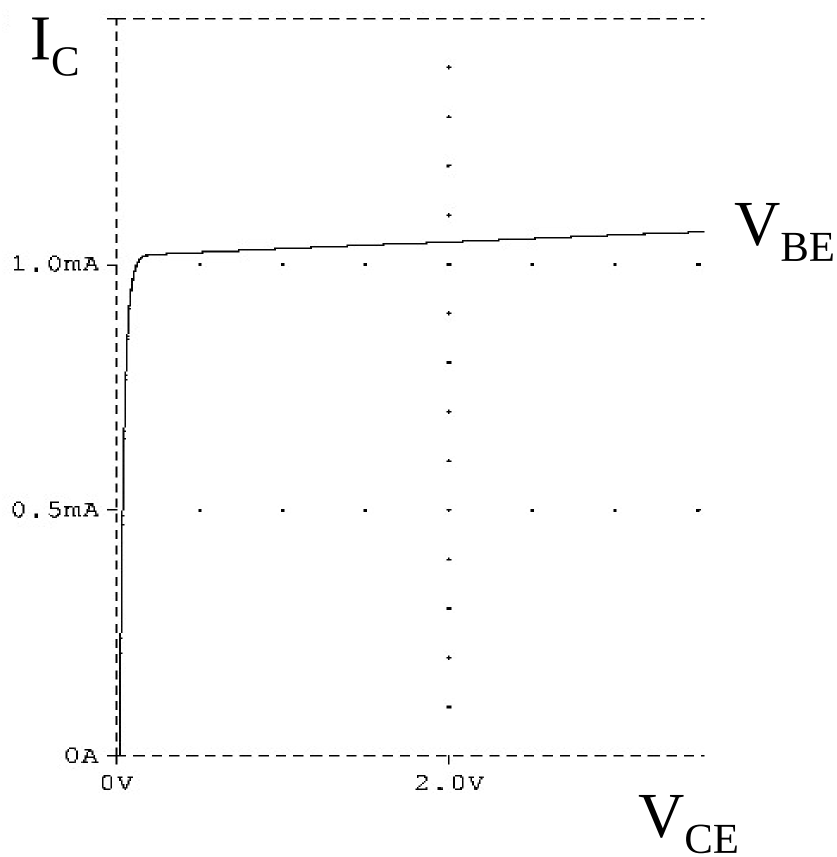
Modeling the Early Effect

- Extrapolated curves intersect at common point ($-V_A$, 0)
- V_A is the ***Early*** voltage
  - typically 50 to 100V

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



BJT Output Resistance



- Nonzero slope of I_C vs V_{CE} is a measure of the output resistance looking into the collector.
- Defined r_o as the BJT output resistance:

$$r_o \equiv \left[\left. \frac{\partial I_C}{\partial V_{CE}} \right|_{v_{BE}=const.} \right]^{-1} = \frac{V_A}{I_C}$$

$$r_o = \frac{V_A}{I_C}$$

Summary of npn Active Mode Characteristics

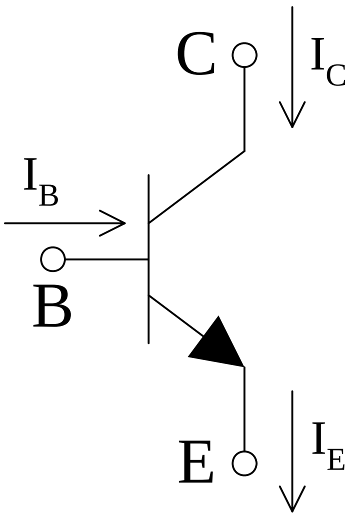
$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)\left(1+\frac{V_{CE}}{V_A}\right)$$

$$I_B = \frac{I_C}{\beta} \qquad r_o = \frac{V_A}{I_C}$$

$$I_C = \alpha I_E; \qquad \alpha = \frac{\beta}{\beta+1} \approx 1$$

$$I_E = (\beta+1)I_B$$

$$I_E = I_C + I_B$$



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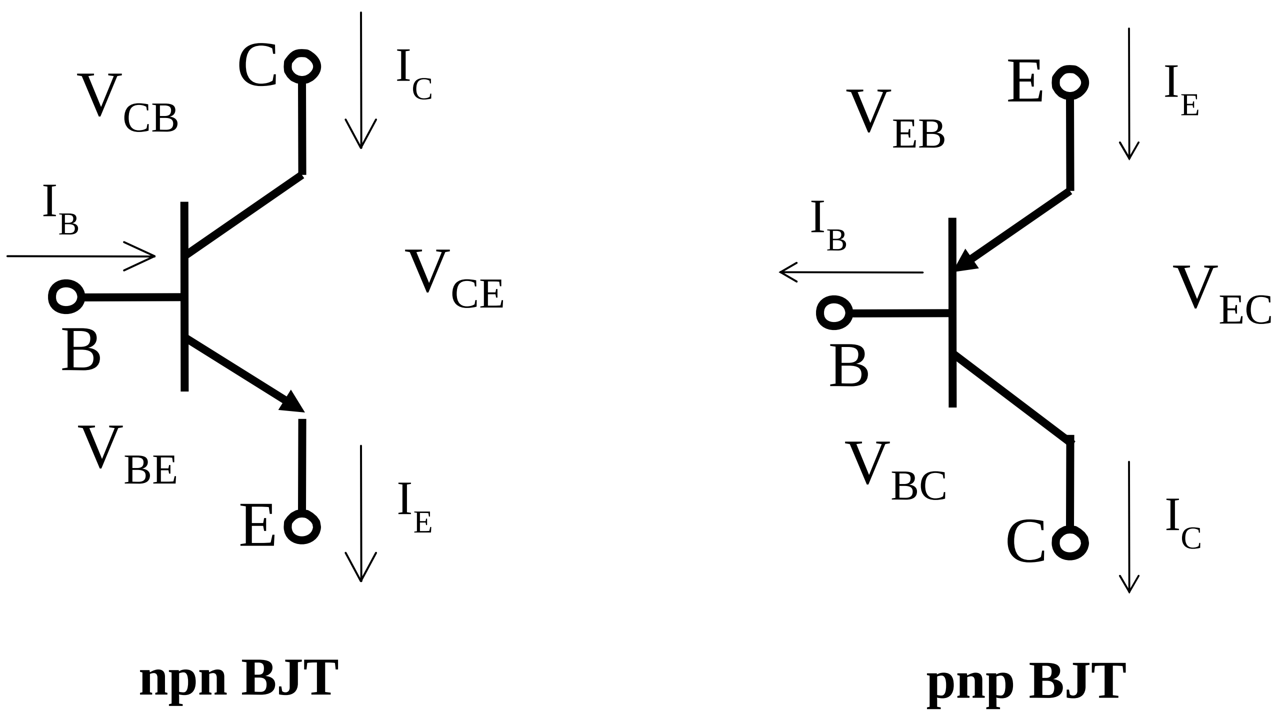
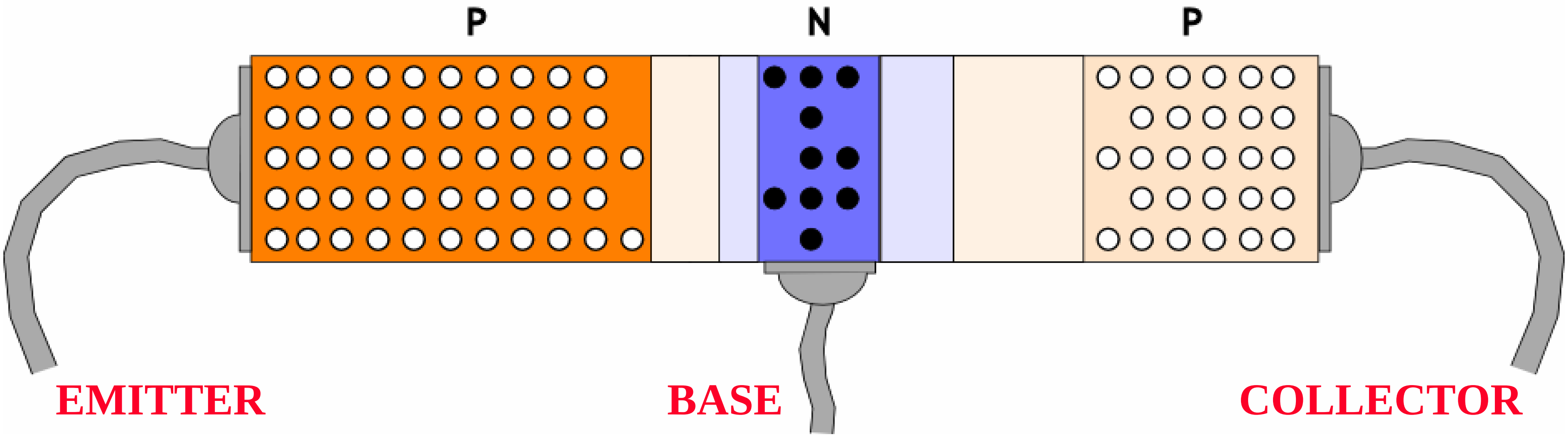


The pnp BJT Operational Modes



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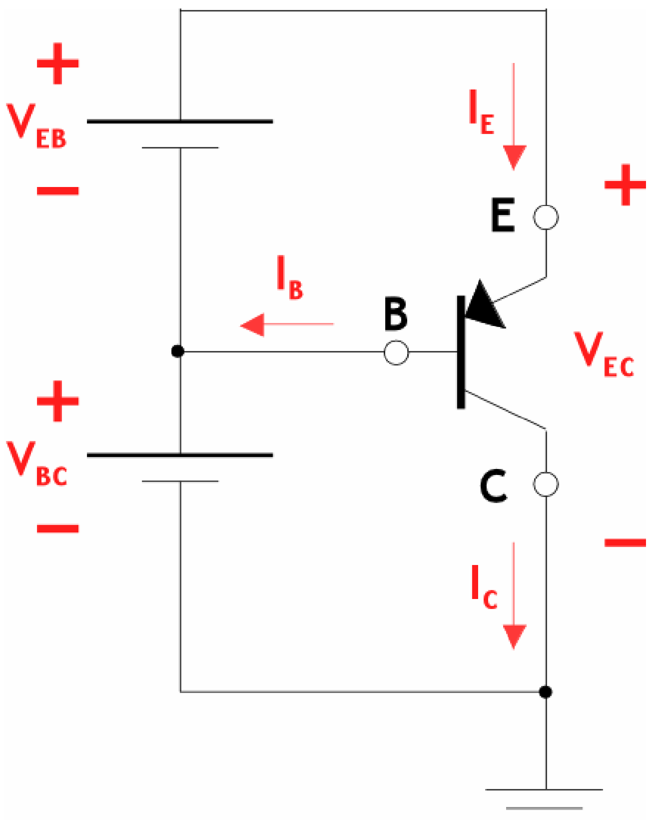

- V_{EB} = 0.7V (forward bias E-B junction)
- C-B junction kept from forward-bias conduction
  - In principal, $V_{BC} \geq$ -0.5V
  - $V_{BC} \geq$ 0V in simplified cases

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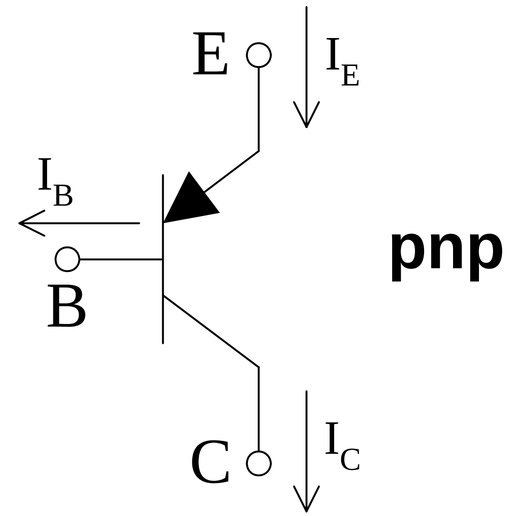

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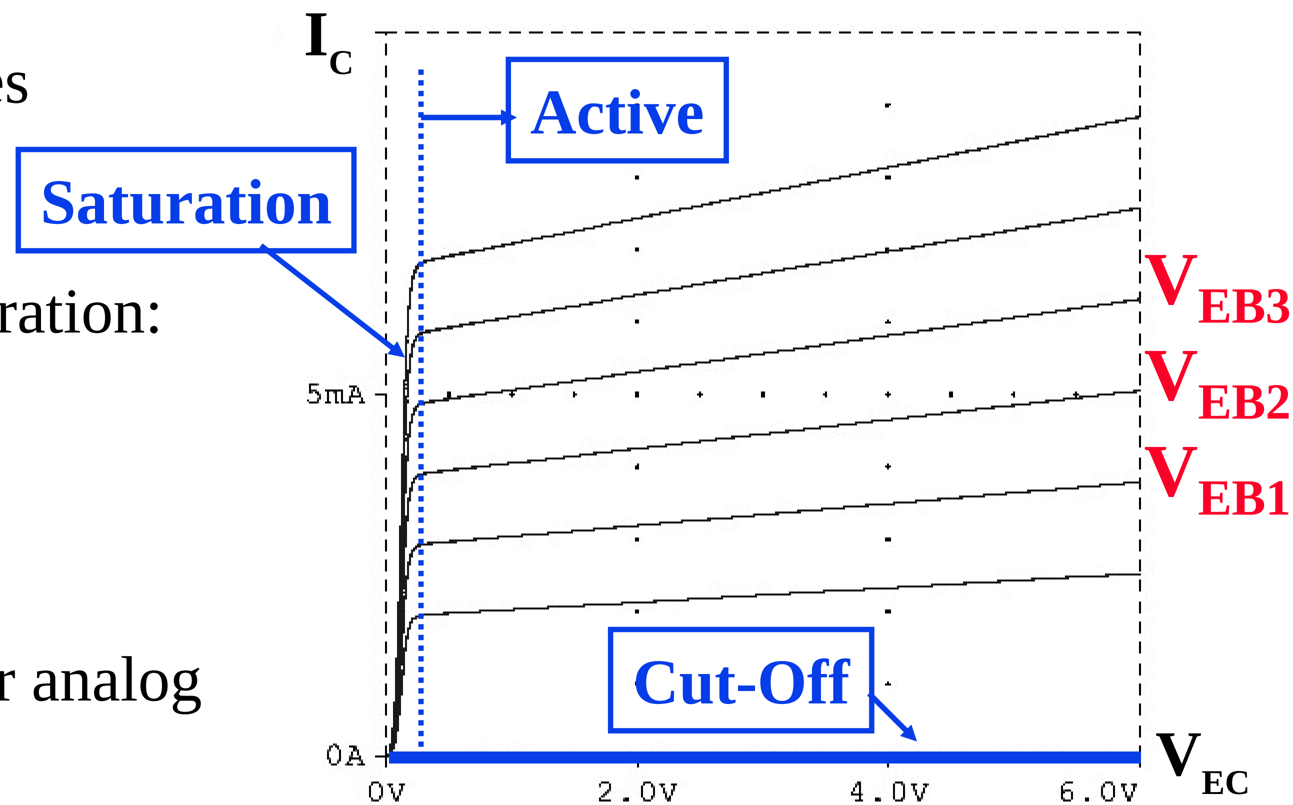

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