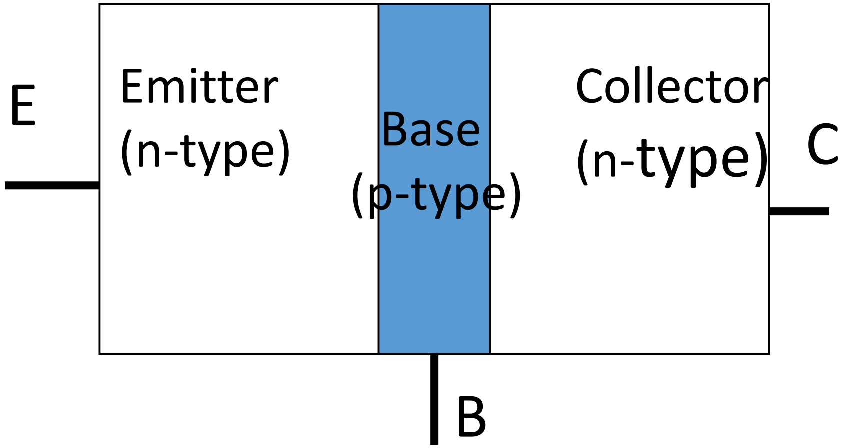
EEE109: Electronic Circuits

The Bipolar Junction Transistor

Contents

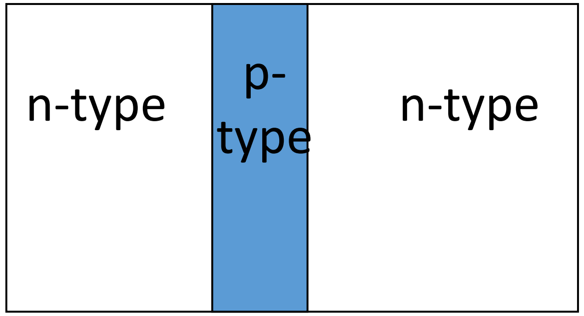
- Discuss the physical structure and operation of the bipolar junction transistor.
- Understand the dc analysis and design techniques of bipolar transistor circuits.
- Examine three basic applications of bipolar transistor circuits.
- Investigate various dc biasing schemes of bipolar transistor circuits, including integrated circuit biasing.
- Consider the dc biasing of multistage or multi-transistor circuits.

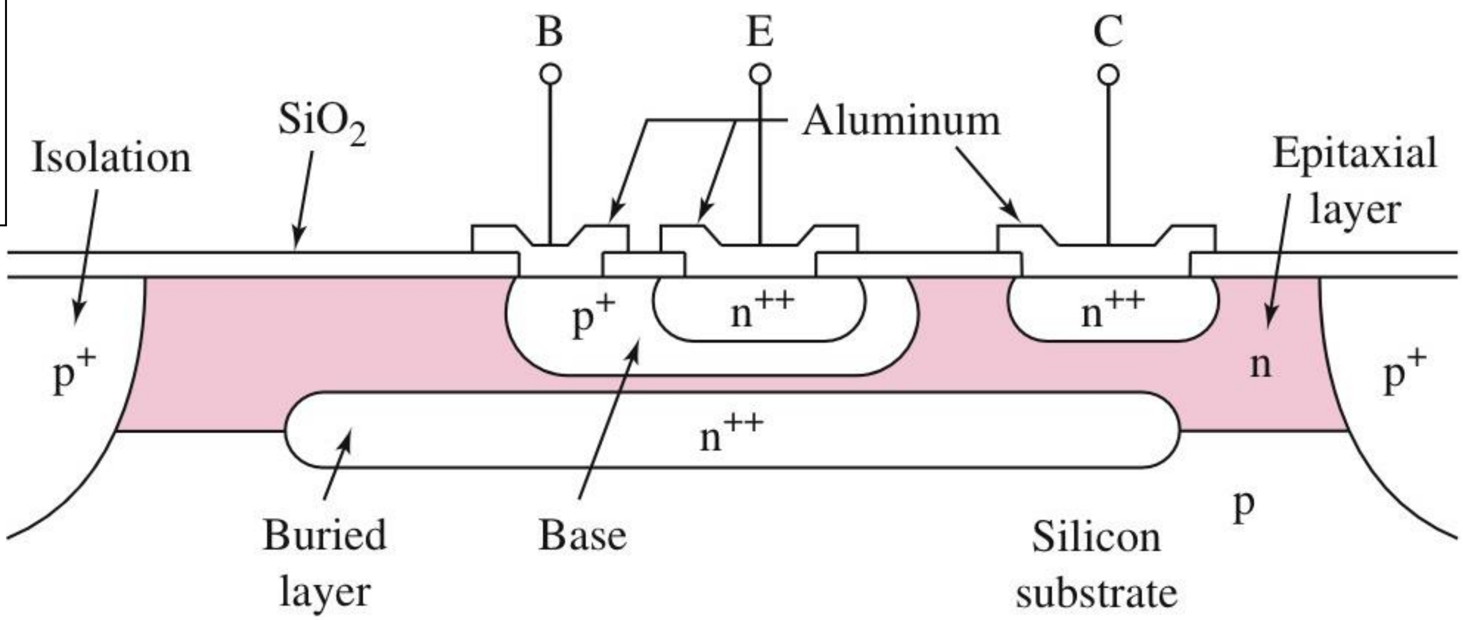
Bipolar Junction Transistors (BJTs)



- The bipolar junction transistor is a semiconductor device constructed with three doped regions.
- These regions essentially form two 'back-to-back' p-n junctions in the same block of semiconductor material (silicon).
- The most common use of the BJT is in linear amplifier circuits (linear means that the output is proportional to input). It can also be used as a switch (in, for example, logic circuits).

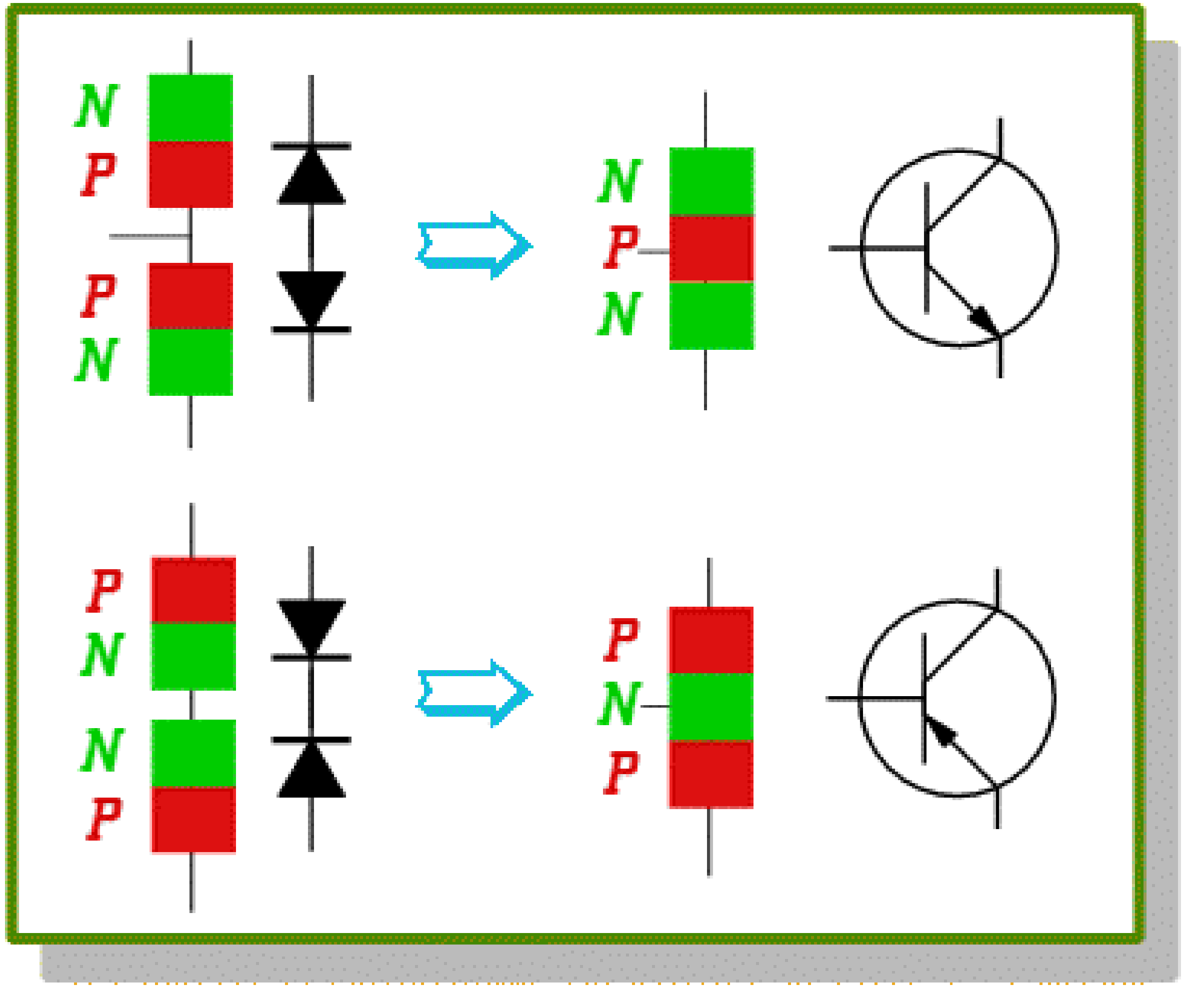
Cross Section of Integrated Circuit npn Transistor

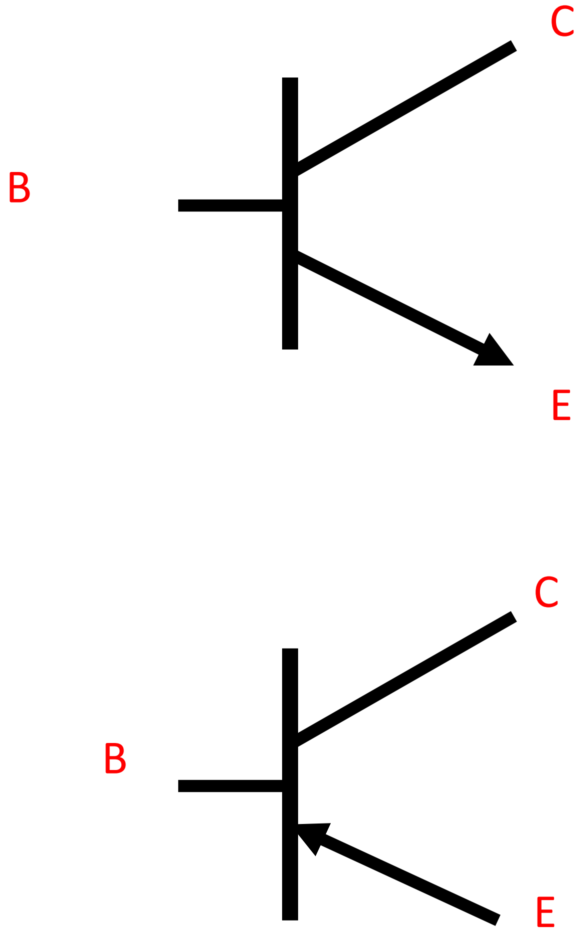




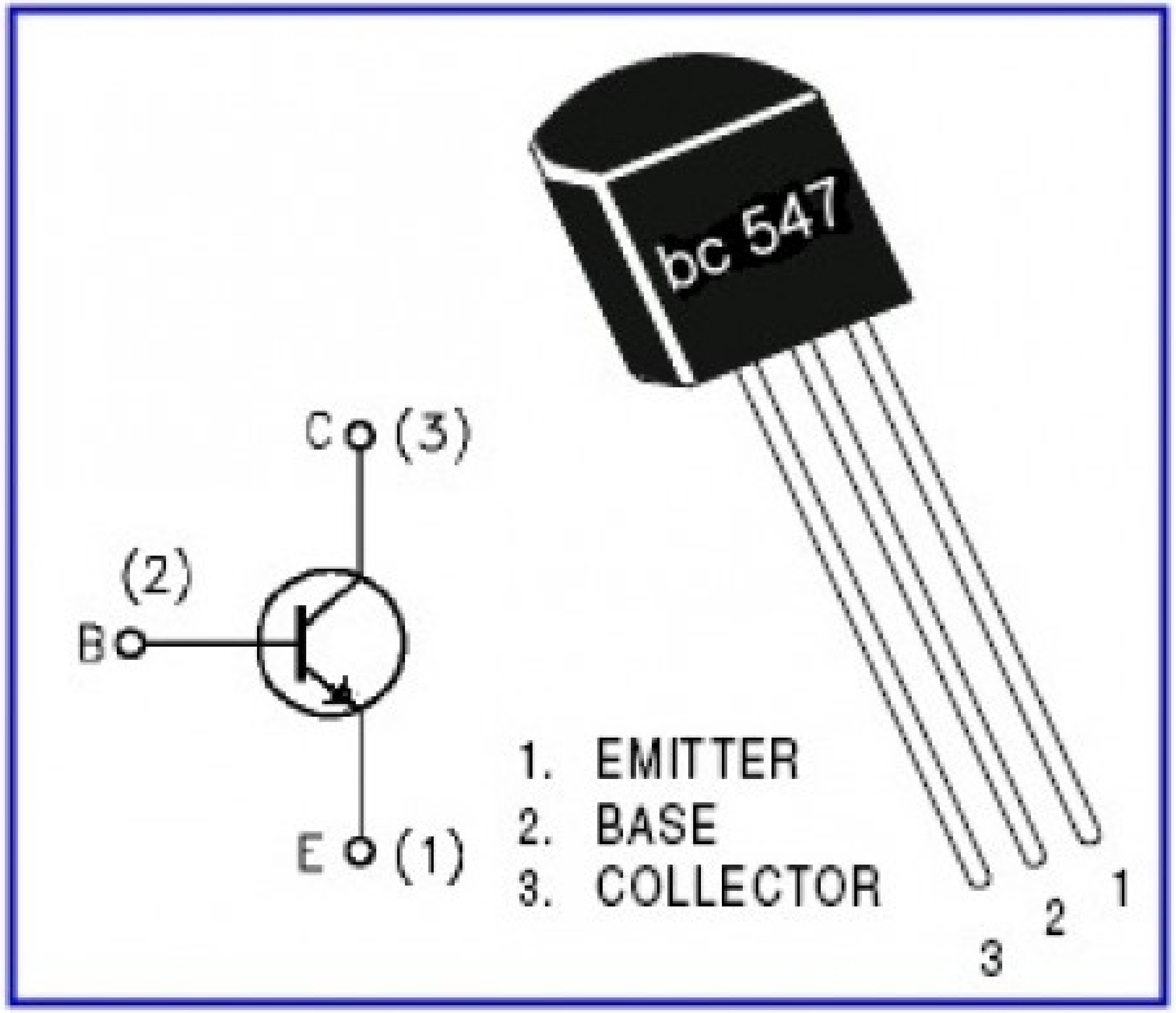
Impurity doping concentrations in the three regions are substantially different.

npn BJT Symbol





The direction of the arrow on the emitter is reversed



BC 547 NPN transistor 45V 100mA hFE 150

Specifications:
BIPOLAR TRANSISTOR, NPN, 45V, TO-92
Transistor Polarity: NPN
Collector Emitter Voltage V(br)ceo: 45V
Transition Frequency Typ ft: 300MHz
Power Dissipation Pd: 625mW
DC Collector Current: 100mA
DC Current Gain hFE: 150
Straight-lead housing

See more information on how to understand the specfication:

https://www.electronics-notes.com/articles/electronic_components/transistor/transistors-specifications.php

Common Configuration

- NPN Transistor Most Common Configuration

- Base, Collector, and Emitter
  - Base is a very thin region with **less dopants**
  - Base collector junction reversed biased
  - Base emitter junction forward biased

  Current flow analogy:
  - If current flows into the base, a **much larger current** can flow from the collector to the emitter
  - If a signal to be amplified is applied as a current to the base, a valve between the collector and emitter opens and closes in response to signal fluctuations

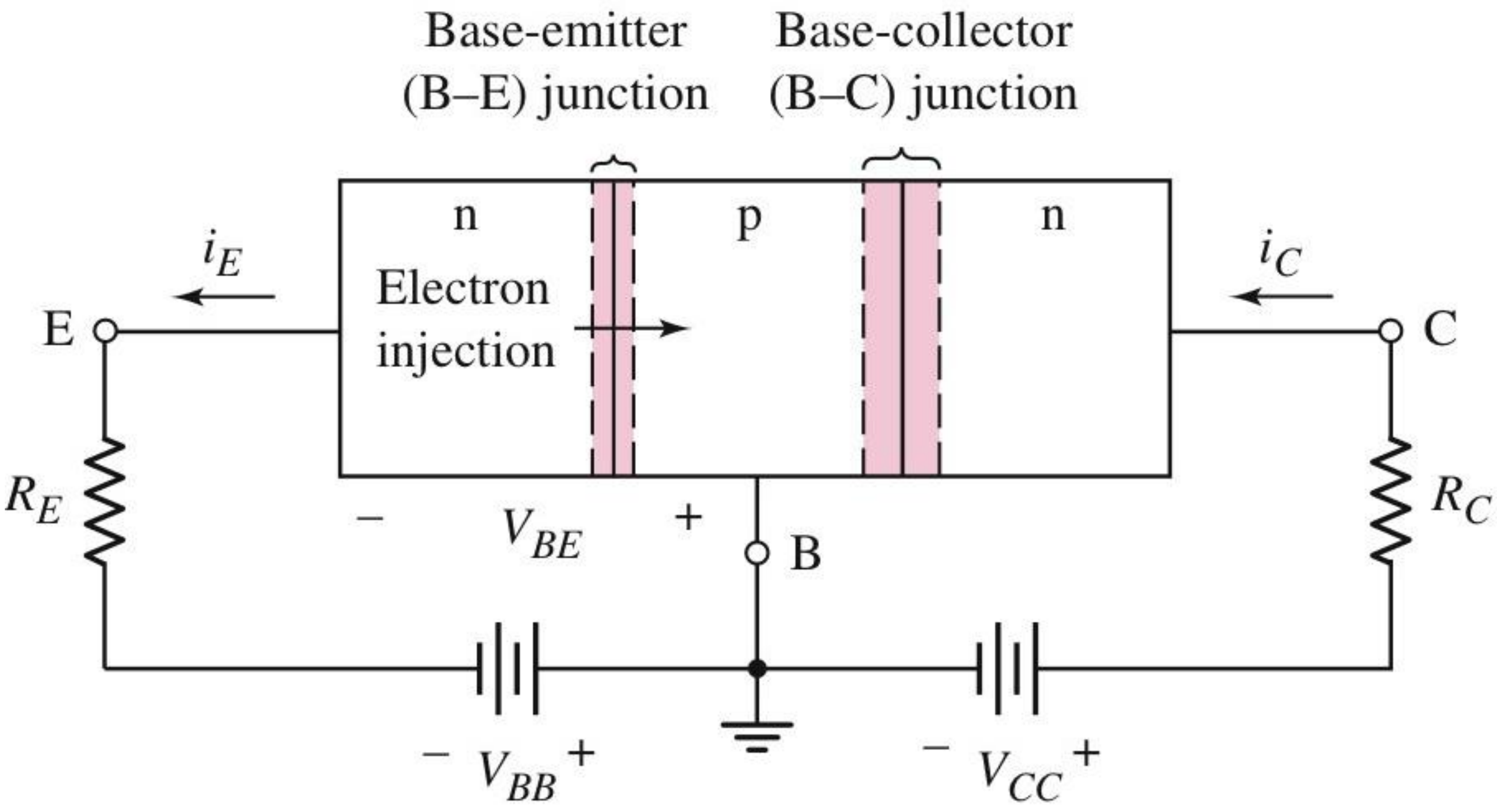
- PNP Transistor essentially the same except for directionality

Modes of Operation

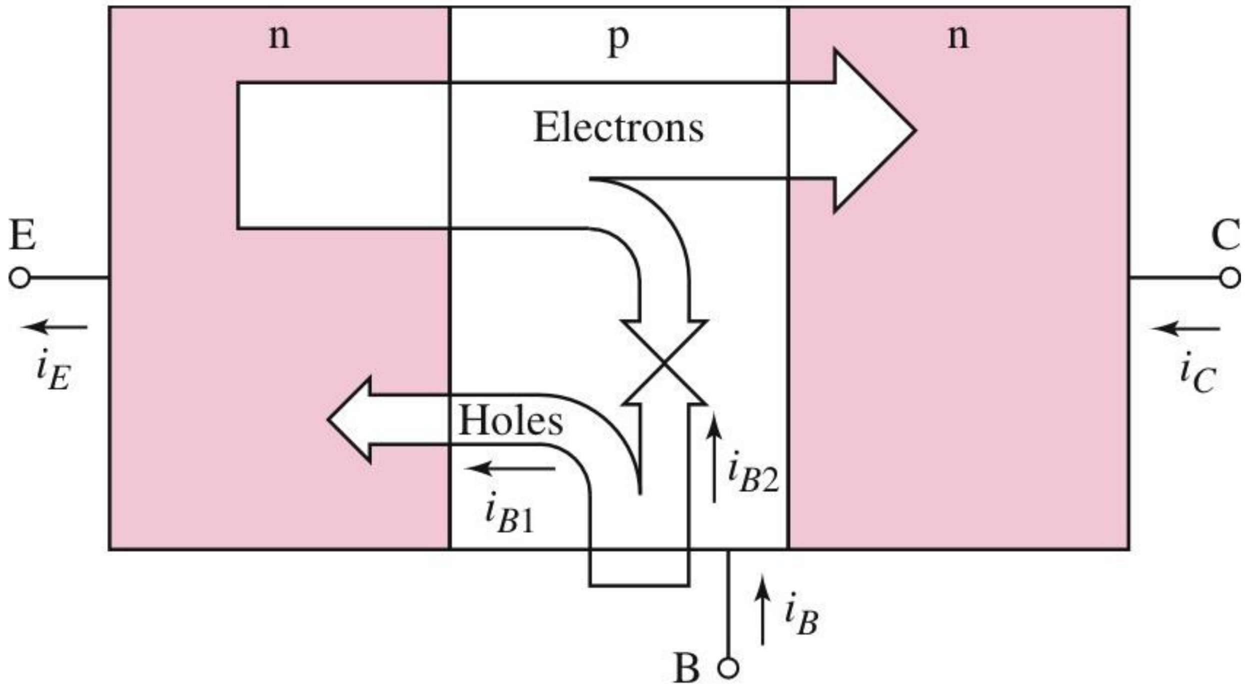
Modes of Operation

- Forward-Active
  - B-E junction is forward biased
  - B-C junction is reverse biased
- Saturation
  - B-E and B-C junctions are forward biased
- Cut-Off
  - B-E and B-C junctions are reverse biased
- Inverse-Active (or Reverse-Active)
  - B-E junction is reverse biased
  - B-C junction is forward biased

npn BJT in Forward-Active



Electrons and Holes in npn BJT



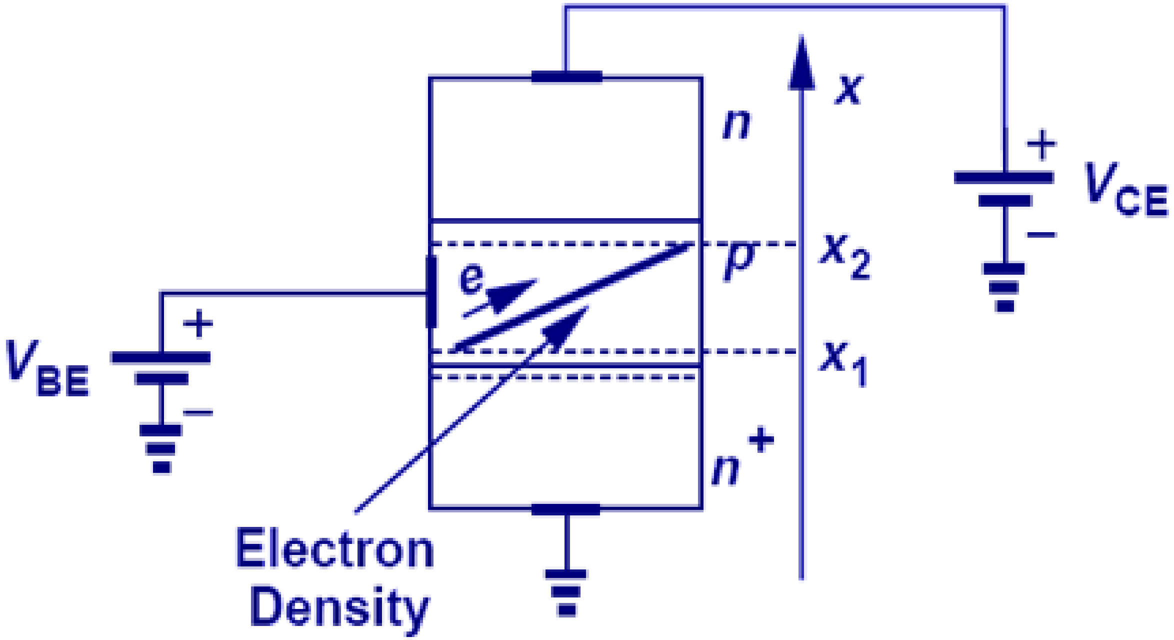
Carrier Transport in the Base Region

- Since the width of the quasi-neutral

  base region ($W_B = x_2 - x_1$) is much smaller than the minority-carrier diffusion length, very few of the carriers injected (from the emitter) into the base recombine before they reach the collector-junction depletion region.

  → Minority-carrier diffusion current is ~constant in the quasi-neutral base

- The minority-carrier concentration at the edges of the collector-junction depletion region are ~0.

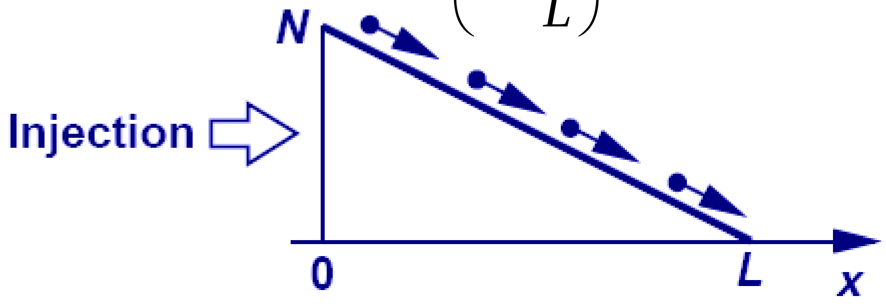


Diffusion Example Redux

- Linear concentration profile

  → constant diffusion current

$$p = N\left(1 - \frac{x}{L}\right)$$



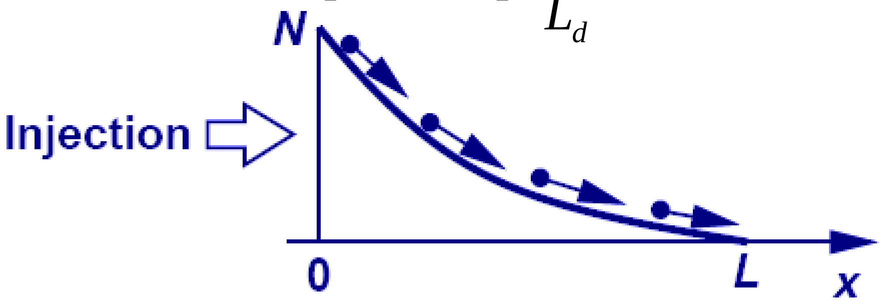
$$J_{p,diff} = -qD_p \frac{dp}{dx}$$

$$= qD_p \frac{N}{L}$$

- Non-linear concentration profile

  → varying diffusion current

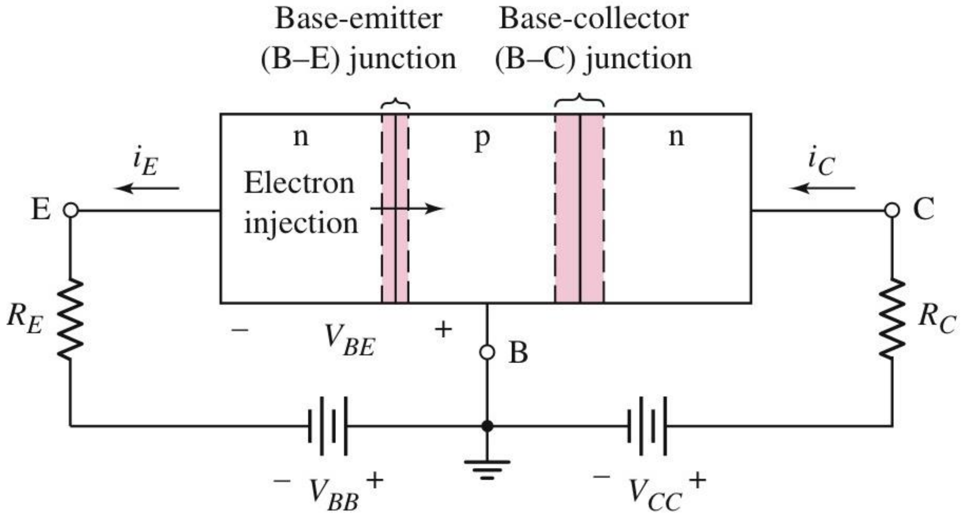
$$p = N \exp \frac{-x}{L_d}$$

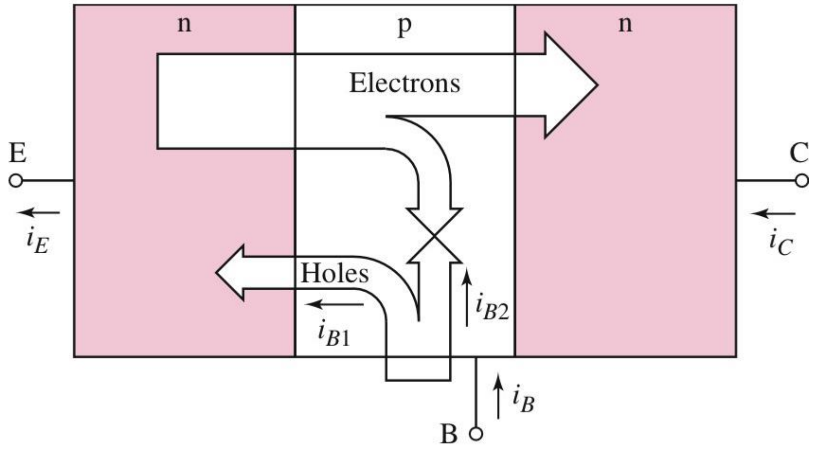


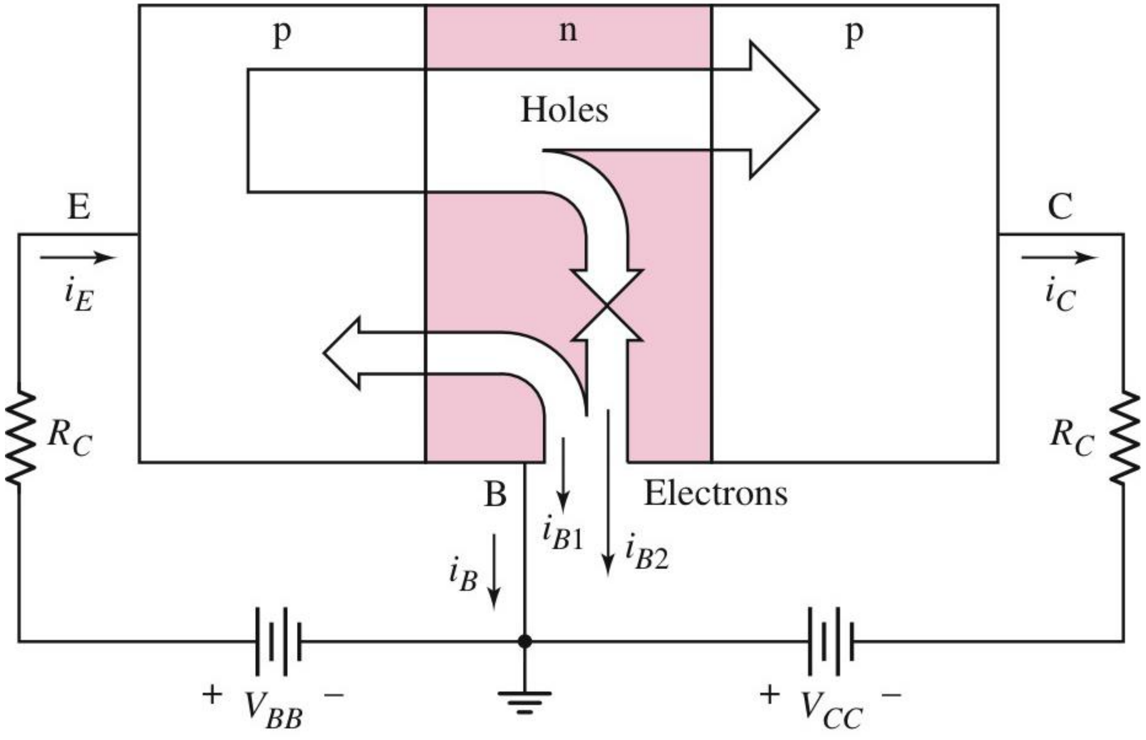
$$J_{p,diff} = -qD_p \frac{dp}{dx}$$

$$= \frac{qD_p N}{L_d} \exp \frac{-x}{L_d}$$

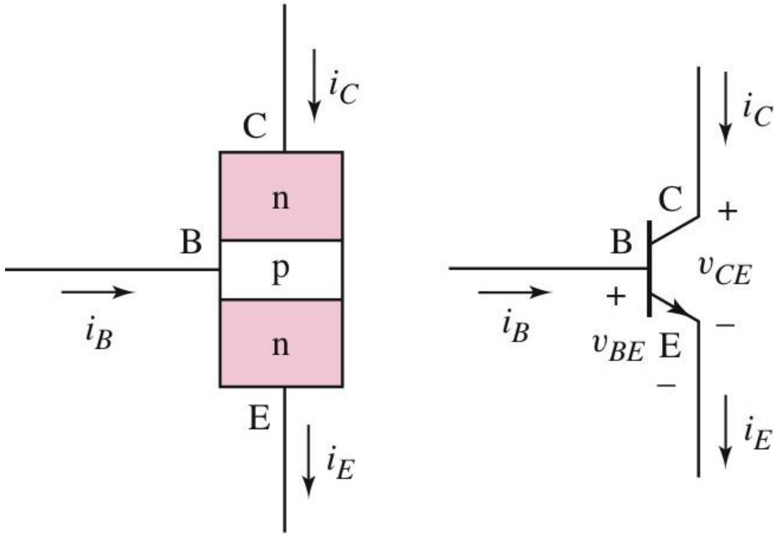
Electrons and Holes in pnp BJT



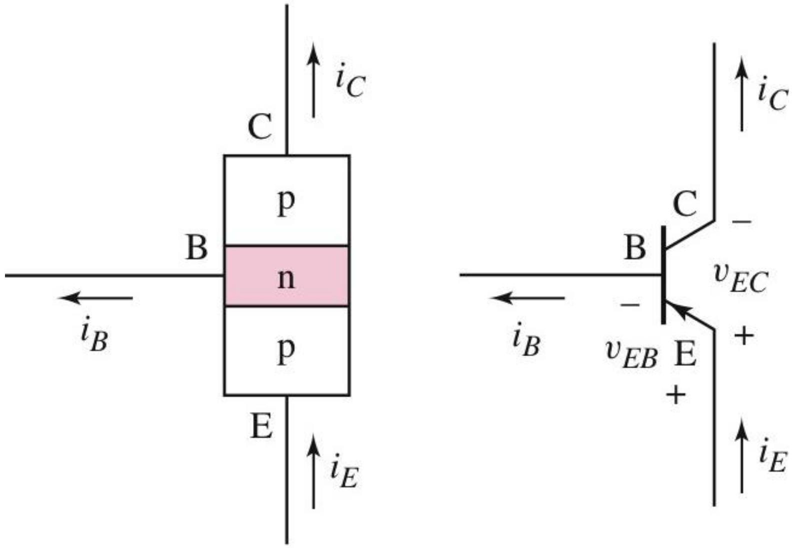




Circuit Symbols and Current Conventions

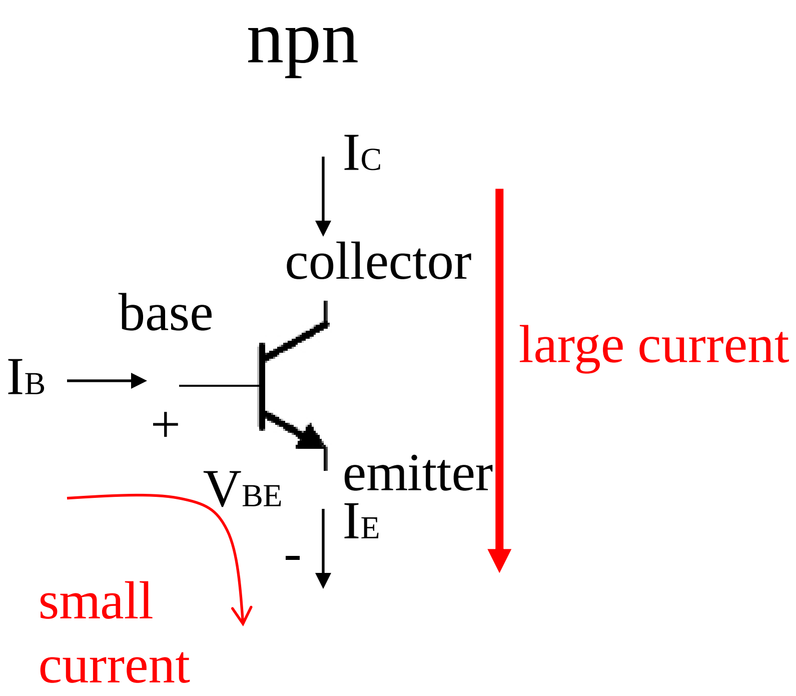


(a) (b)

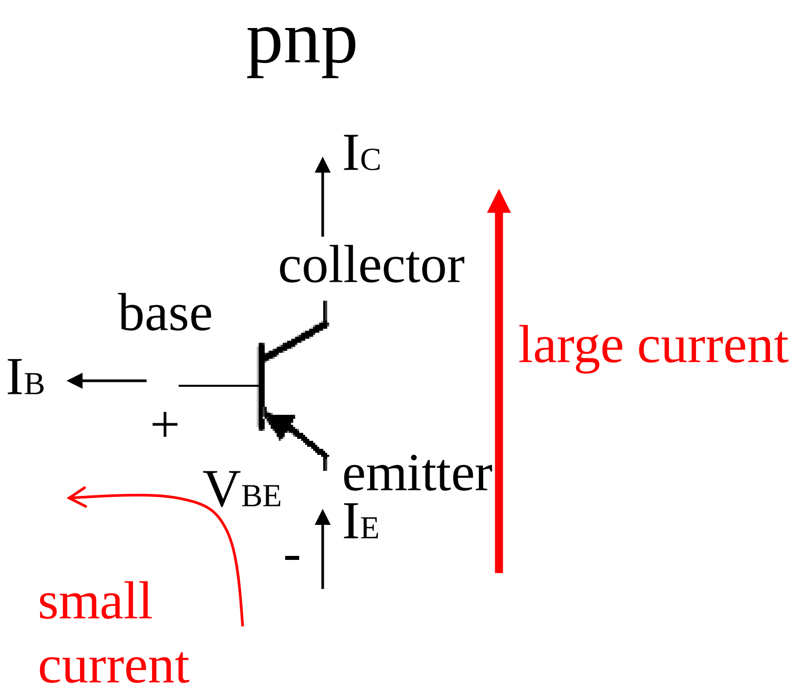


(a) (b)

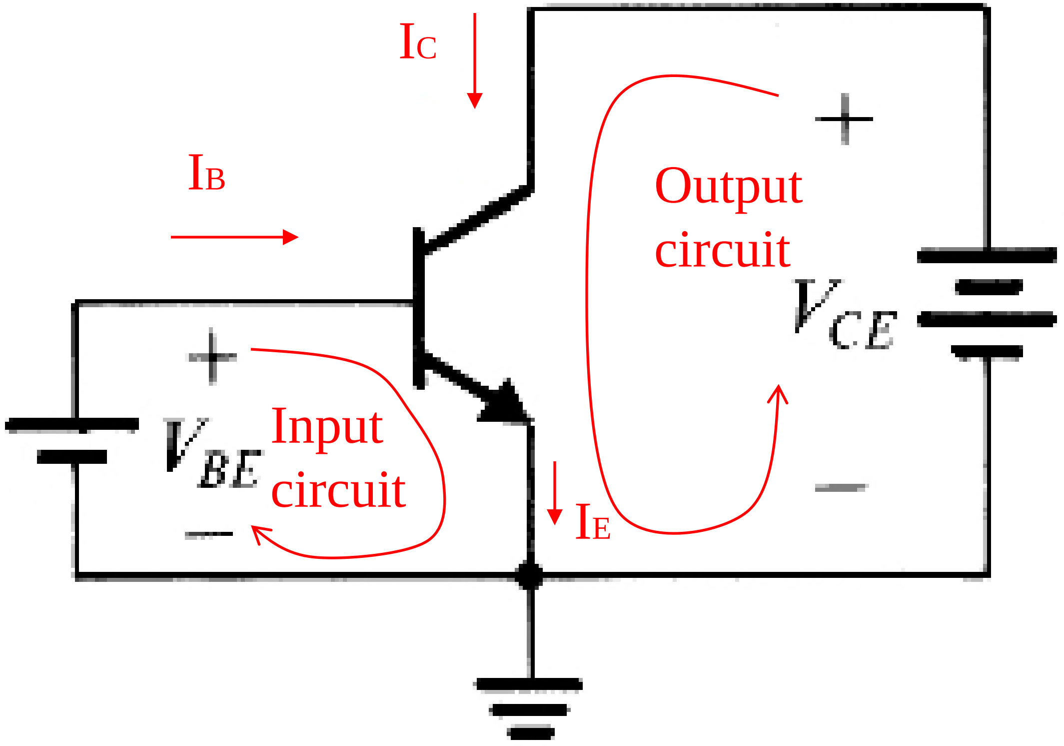
Summary of npn Transistor Behavior



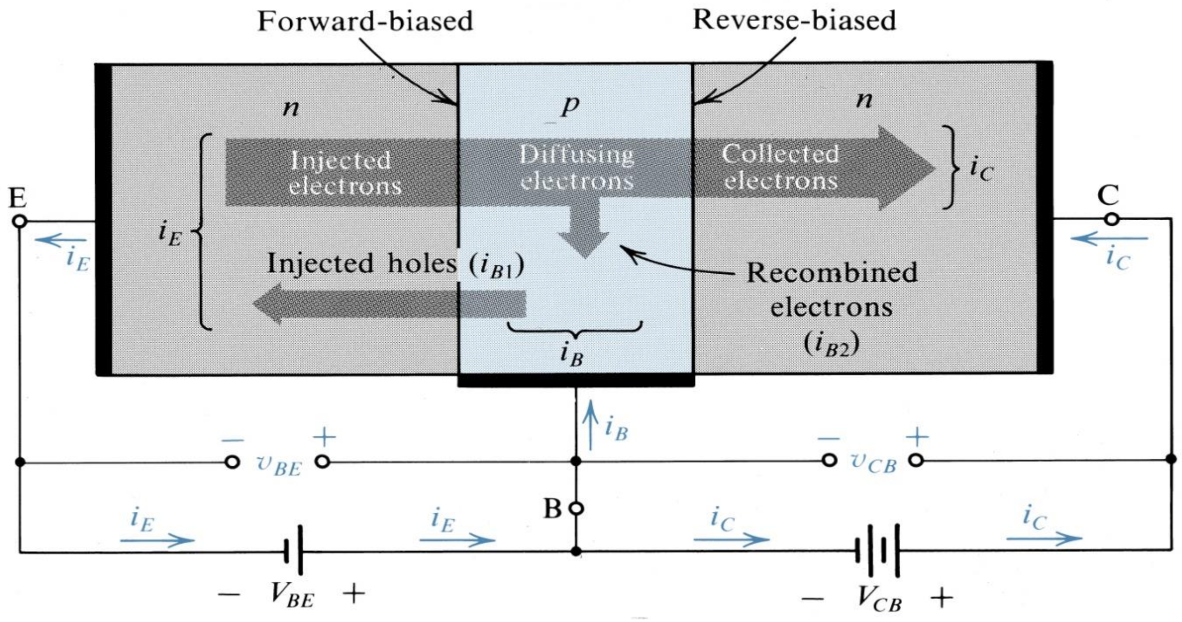
Summary of pnp Transistor Behavior



Graphical Representation of Transistor Characteristics



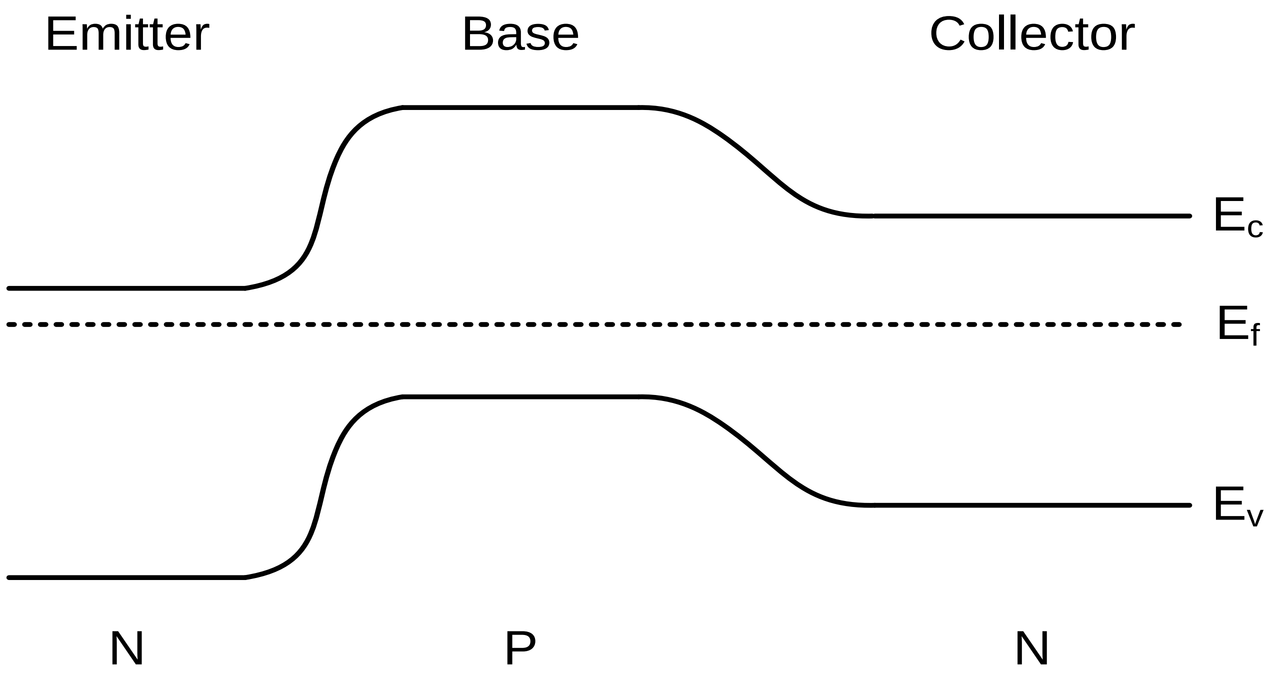
BJT in Active Mode



- Operation
  - Forward bias of EBJ injects electrons from emitter into base (small number of holes injected from base into emitter)
  - Most electrons shoot through the base into the collector across the reverse bias junction (think about band diagram)
  - Some electrons recombine with majority carrier in (P-type) base region

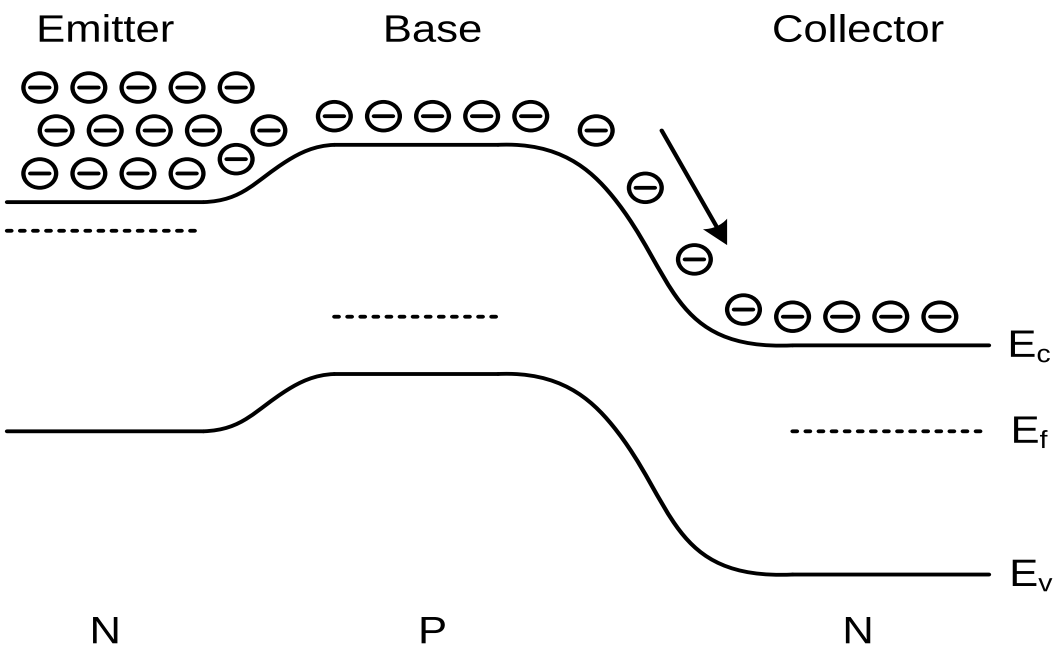
Band Diagrams (In equilibrium)

- No current flow
- Back-to-back PN diodes



Band Diagrams (Active Mode)

- EBJ forward biased
  - Barrier reduced and so electrons diffuse into the base
  - Electrons get **swept across** the base into the collector
- CBJ reverse biased
  - **Electrons roll down the hill (high E-field)**



Current Relationships and IV Characteristics

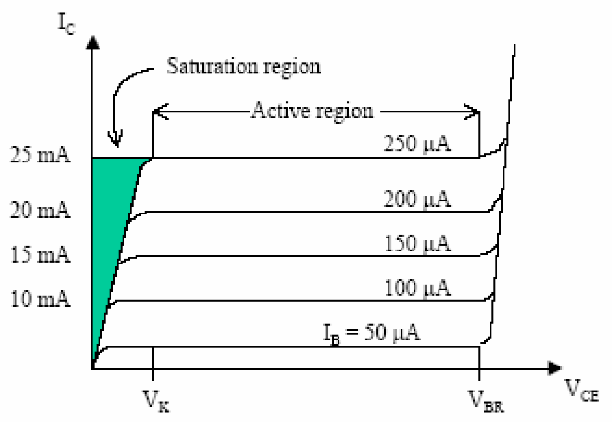
Collector Current

- Electrons that diffuse across the base to the CBJ junction are swept across the CBJ depletion region to the collector b/c of the higher potential applied to the collector.

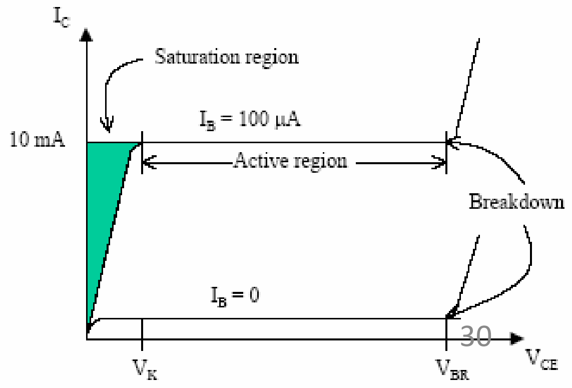
$$i_C = I_s e^{v_{BE}/V_T} \text{ where the saturation current is } I_S = qA_E D_n n_{p0}/W$$

and we can rewrite the saturation current as:

$$\boxed{I_S = \frac{qA_E D_n n_i^2}{N_A W}}$$



- Note that i_C is independent of v_{CB} (potential bias across CBJ) ideally
- Saturation current is
  - inversely proportional to W and directly proportional to A_E
    - Want short base and large emitter area for high currents
  - dependent on temperature due to n_i^2 term



Base Current

- Base current i_B composed of two components:
  - holes injected from the base region into the emitter region

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

  - holes supplied due to recombination in the base with diffusing electrons and depends on minority carrier lifetime τ_b in the base

$$i_{B2} = \frac{Q_n}{\tau_b}$$

And the Q in the base is

$$Q_n = \frac{qA_E W n_i^2}{N_A} e^{v_{BE}/V_T}$$

So, current is

$$i_{B2} = \frac{qA_E W n_i^2}{N_A \tau_b} e^{v_{BE}/V_T}$$

- Total base current is

$$i_B = \left(\frac{qA_E D_p n_i^2}{N_D L_P} + \frac{qA_E W n_i^2}{N_A \tau_b} \right) e^{v_{BE}/V_T}$$

Beta

- Can relate i_B and i_C by the following equation

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

and β is

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

  - Beta is constant for a particular transistor
  - On the order of 100-200 in modern devices (but can be higher)
  - Called the common-emitter current gain
- For high current gain, want small W, low N_A, high N_D

Current Relationships

Common-emitter
current gain: β

Common-base
current gain: α

$$i_E = i_C + i_B$$

$$i_C = \beta i_B$$

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

$$i_C = \alpha i_E$$

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

Current Relationships

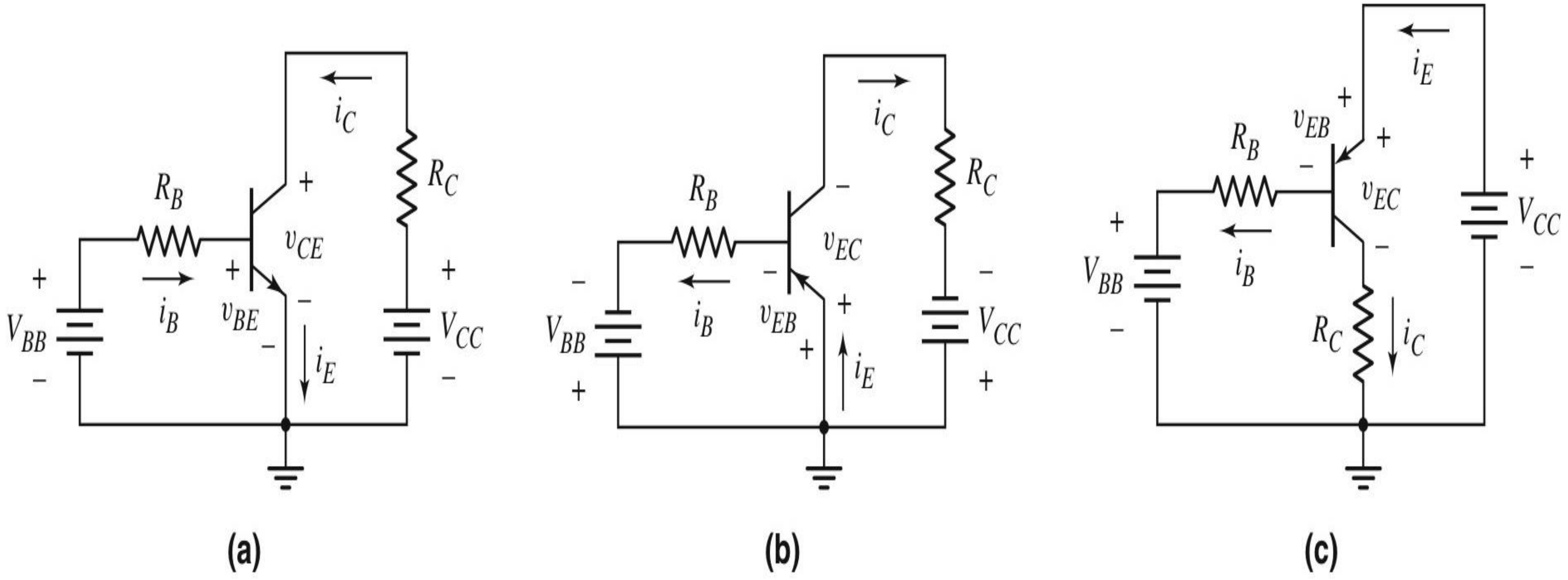
- Common-base current Gain **α** :
  - α is the fraction of electrons that diffuse across the narrow Base region
  - 1- α is the fraction of electrons that recombine with holes in the Base region to create base current
- The common-emitter current Gain **β** is expressed in terms of the **β** (beta) of the transistor (often called h_{fe} by manufacturers).
- β is Temperature and Voltage dependent.
- β can vary a lot among transistors (common values for signal BJT: 20 - 200).

$$I_C = \alpha I_E$$

$$I_B = (1-\alpha) I_E$$

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$$

Common-Emitter Configurations

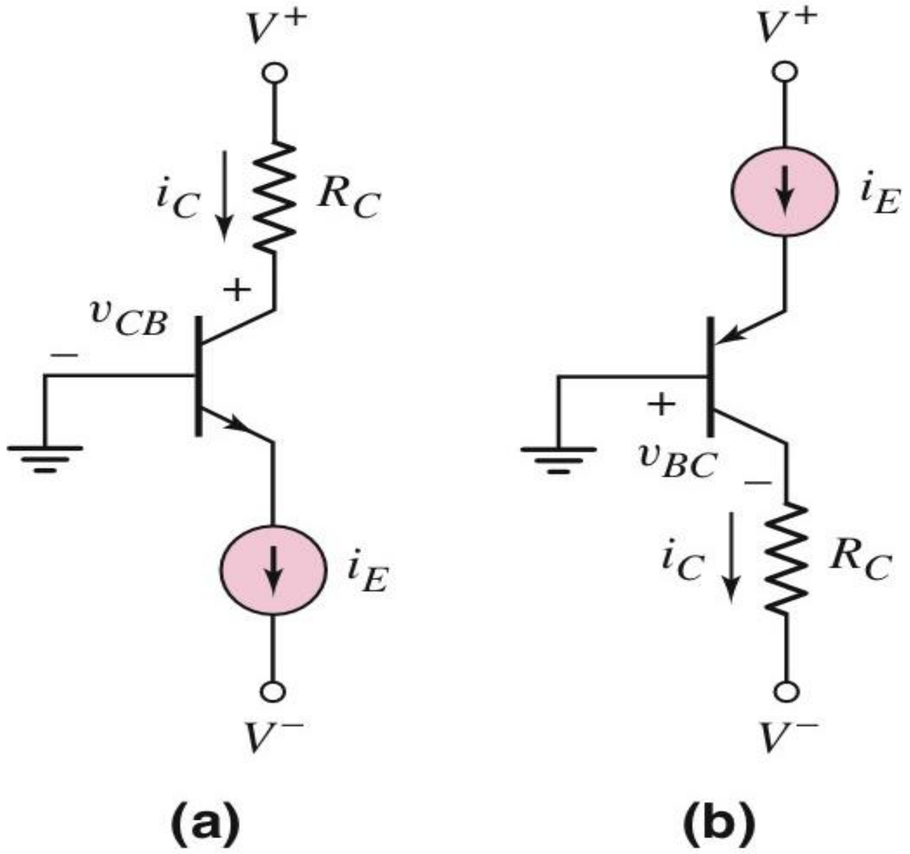


(a) CE circuit with npn transistor

(b) CE circuit with pnp transistor

(c) CE circuit with pnp transistor with a positive voltage source

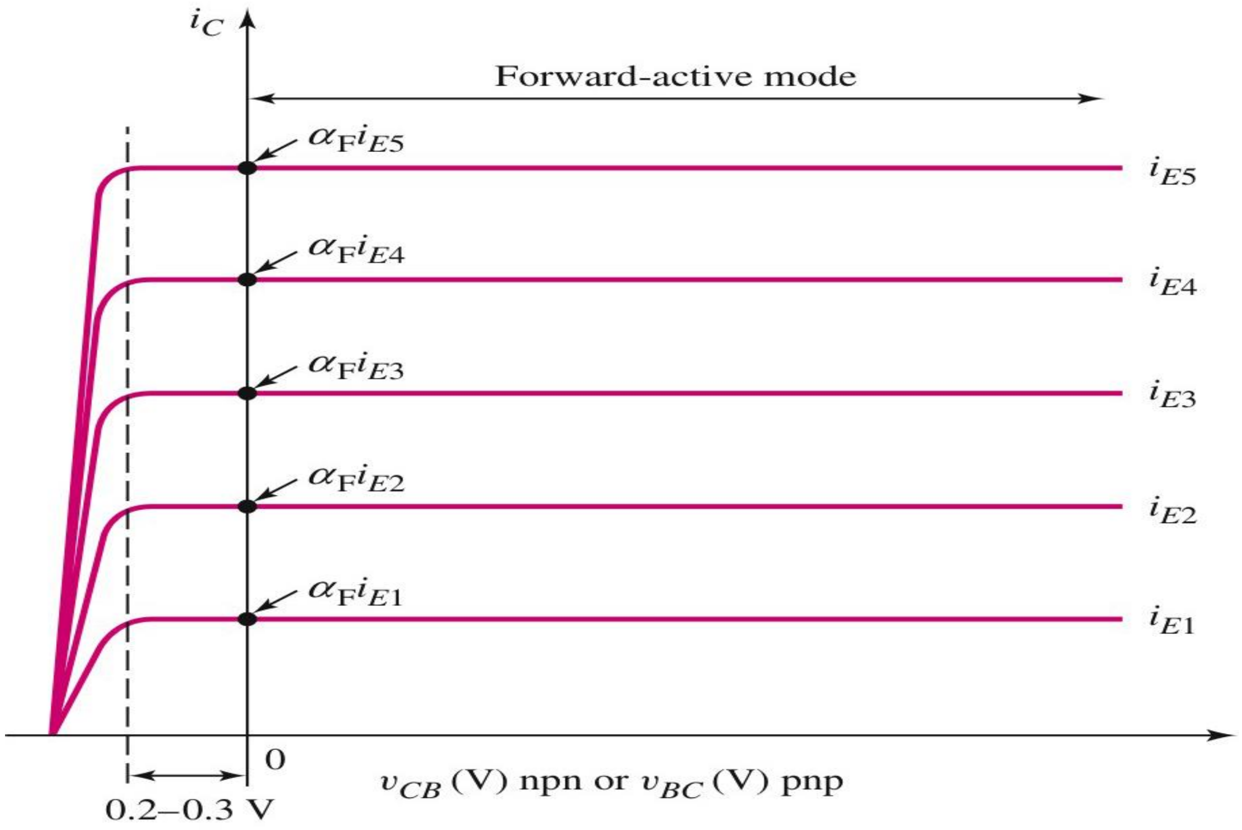
Common-Base Configuration



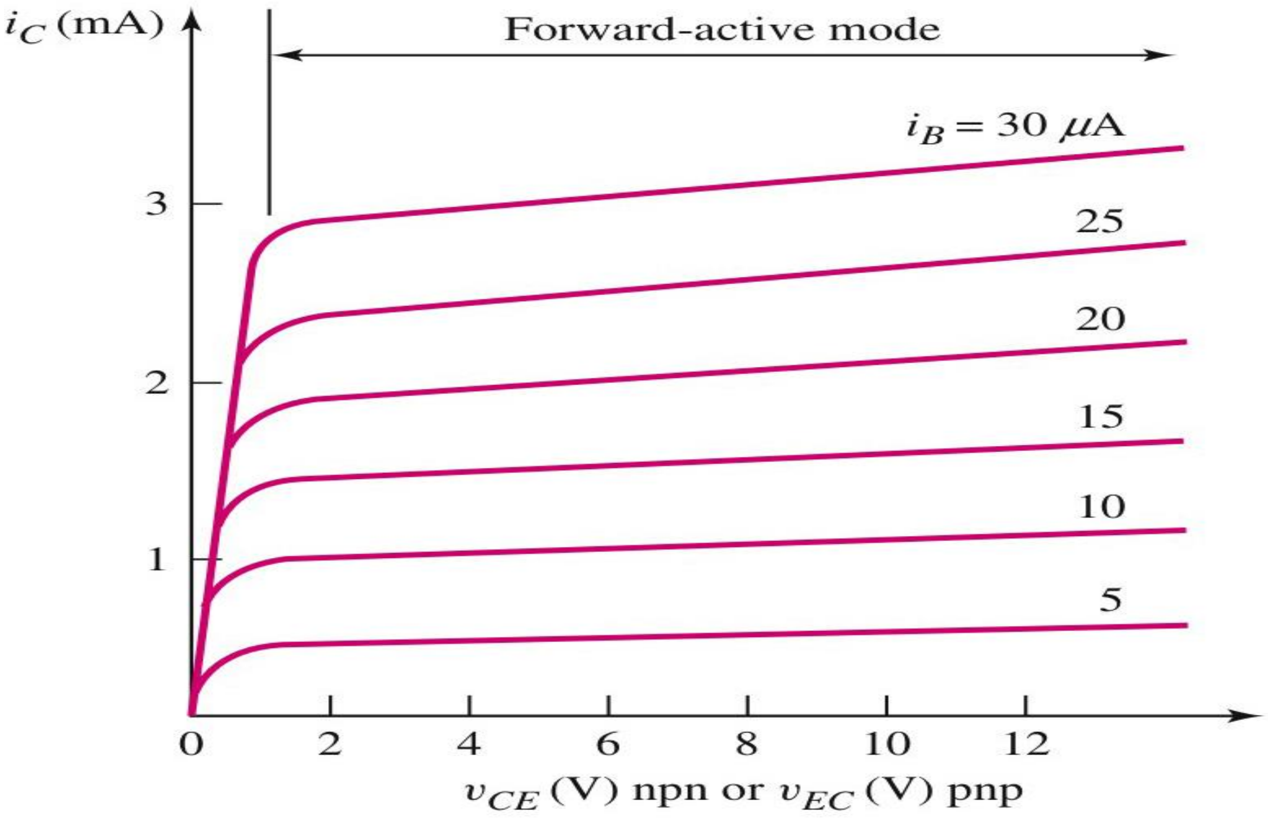
The common-base device is nearly an ideal constant current source.

Common-base current gain: α

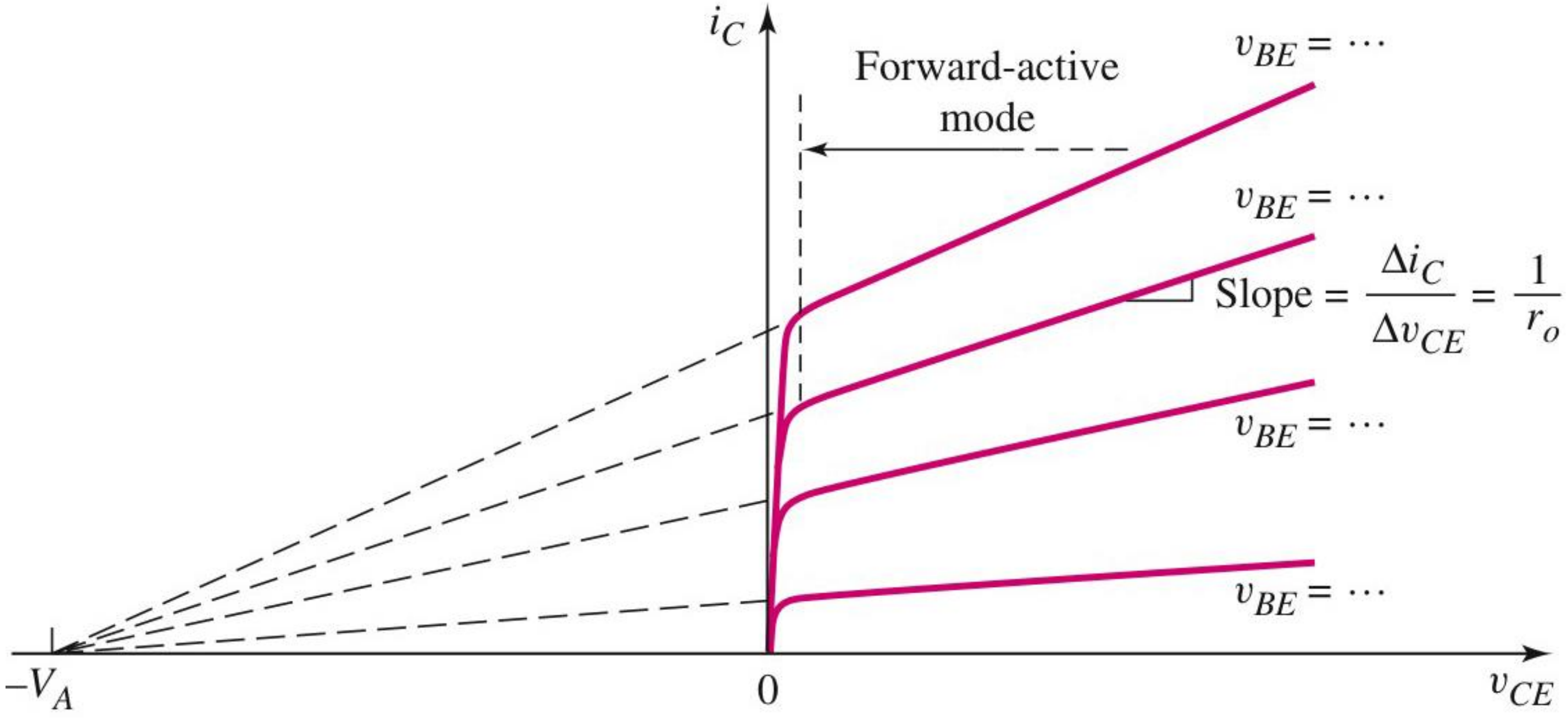
Current-Voltage Characteristics of a Common-Base Circuit



Current-Voltage Characteristics of a Common-Emitter Circuit



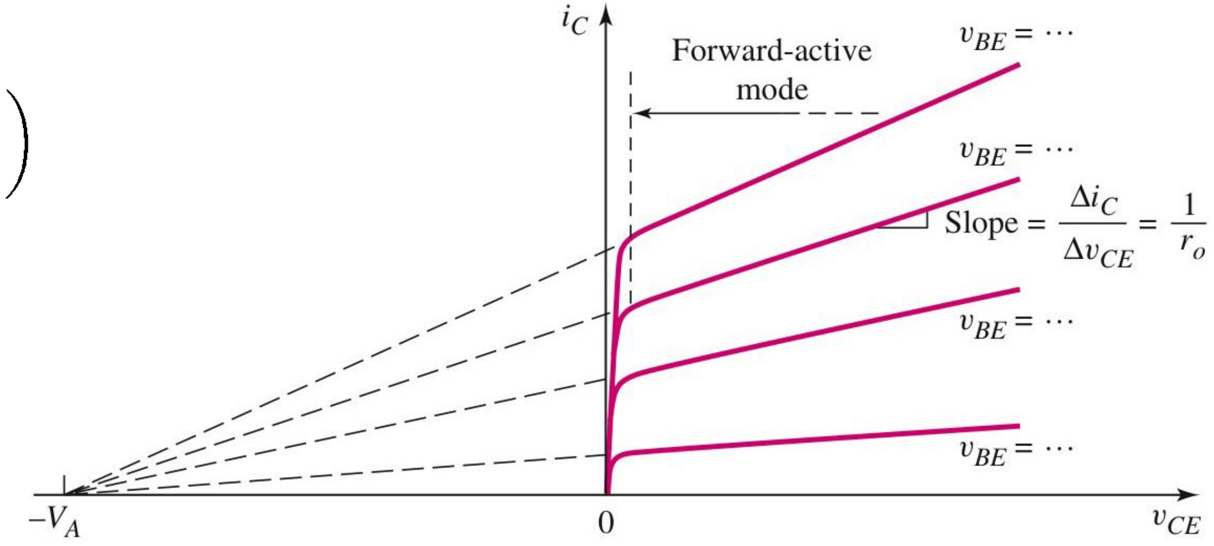
Early Voltage/Finite Output Resistance



Base-width modulation – Early Effect!

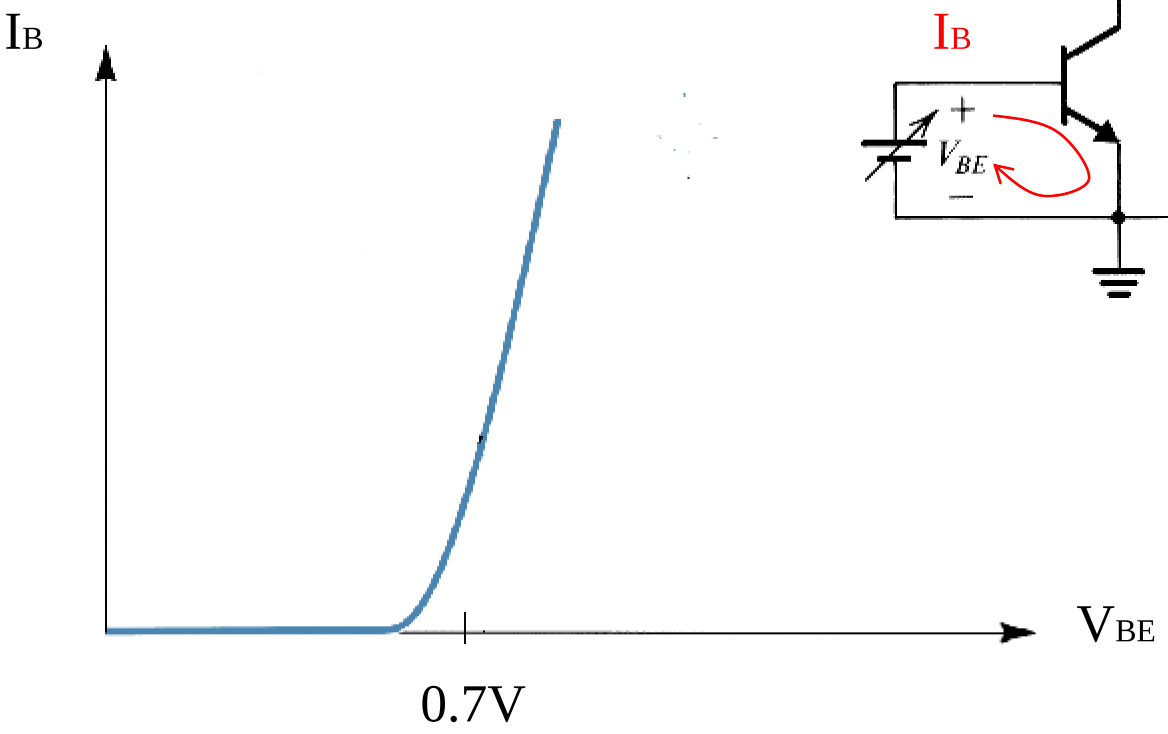
Early Effect

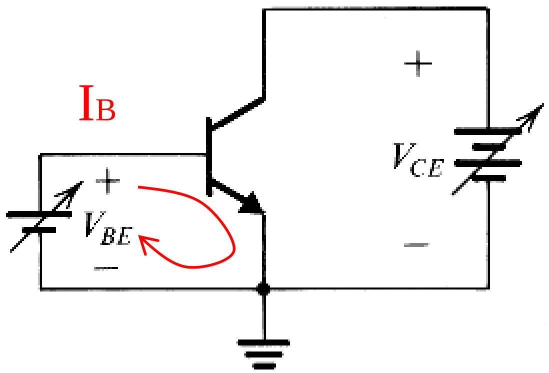
$$I_C = I_S e^{V_{BE}/V_T}\left(1 + \frac{V_{CE}}{V_A}\right)$$



- Early Effect
  - Current in active region depends (slightly) on v_{CE}
  - V_A is a parameter for the BJT (50 to 100) and called the Early voltage
  - Due to a decrease in effective base width W as reverse bias increases
  - Account for Early effect with additional term in collector current equation
  - Nonzero slope means the output resistance is NOT infinite, but…
    - I_C is collector current at the boundary of active region

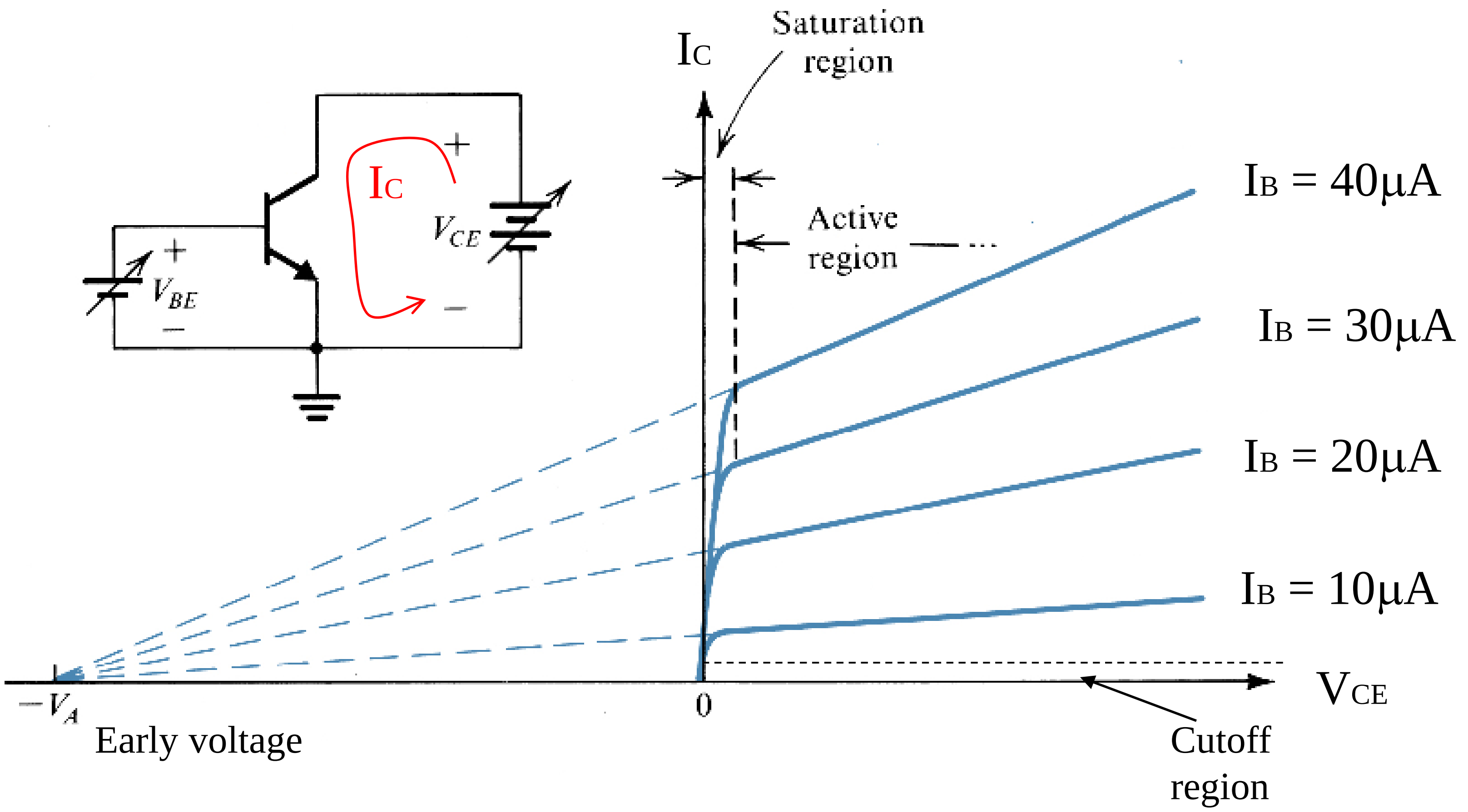
Summary: Input characteristics





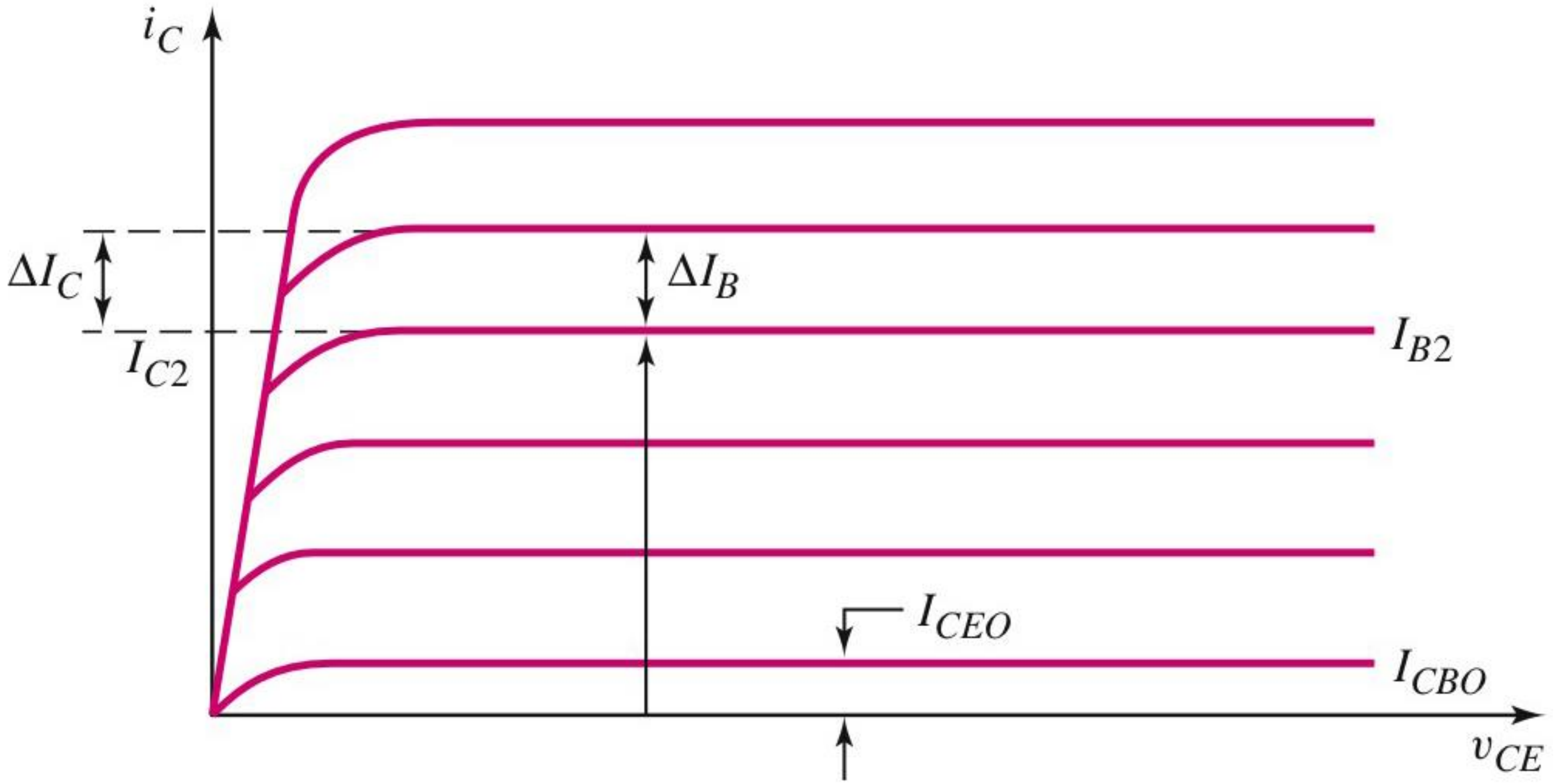
- Acts as a diode
- $V_{BE} \approx 0.7V$

Summary: Output characteristics

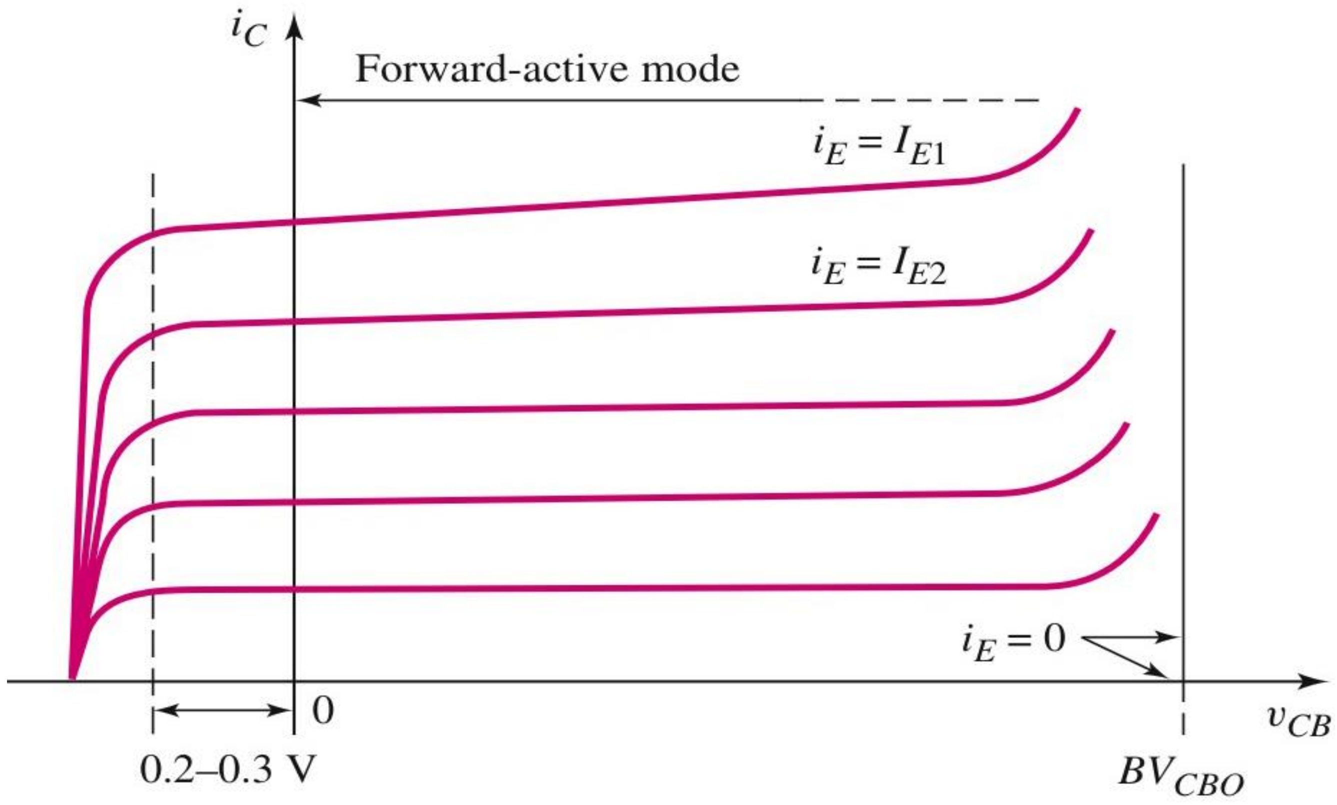


- At a fixed I_B, I_C is not dependent on V_{CE}
- Slope of output characteristics in linear region is near 0 (scale exaggerated)

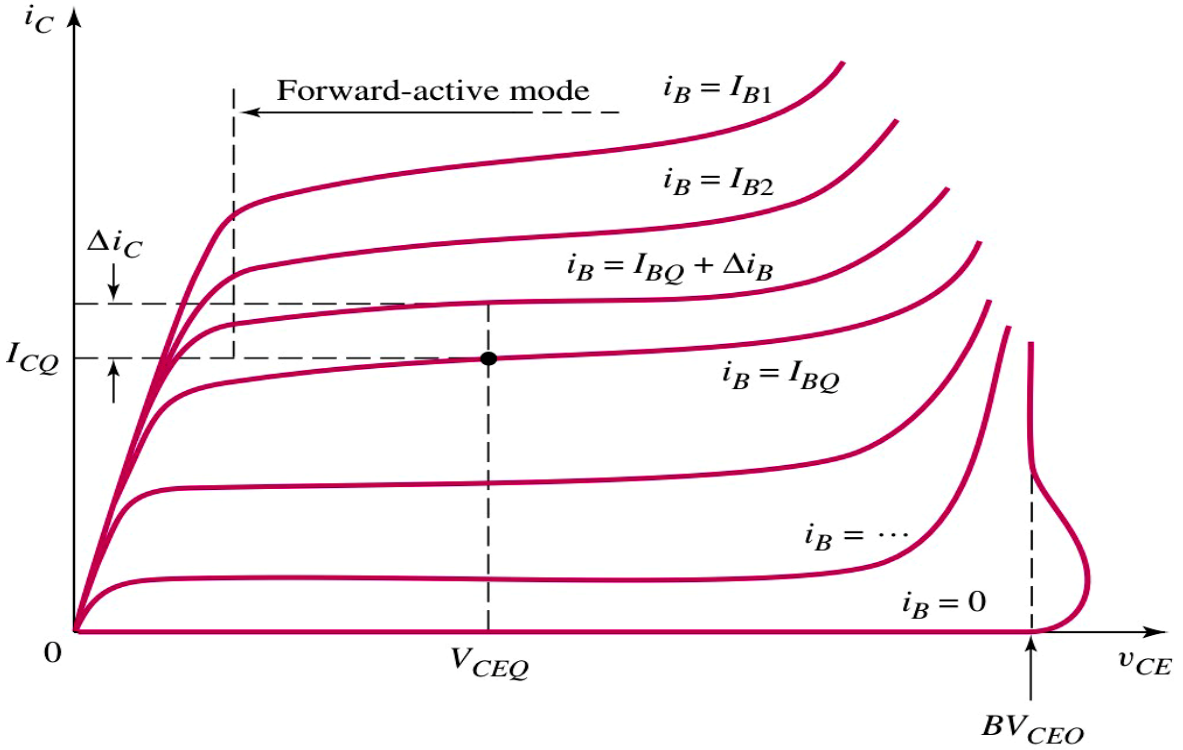
Effects of Leakage Currents on I-V Characteristics



Effect of Collector-Base Breakdown on Common Base I-V Characteristics



Effect of Collector-Base Breakdown on Common Emitter I-V Characteristics



Breakdown Voltages

- The basic limitation of the max. voltage in a transistor is the same as that in a *pn* junction diode.
- However, the voltage breakdown depends not only on the nature of the junction involved but also on the external circuit arrangement.
- In **Common Base** configuration, the maximum voltage between the collector and base with the emitter open, BV_{CBO} is determined by the avalanche breakdown voltage of the CBJ.
- In **Common Emitter** configuration, the maximum voltage between the collect and emitter with the base open, BV_{CEO} can be much smaller than BV_{CBO}.

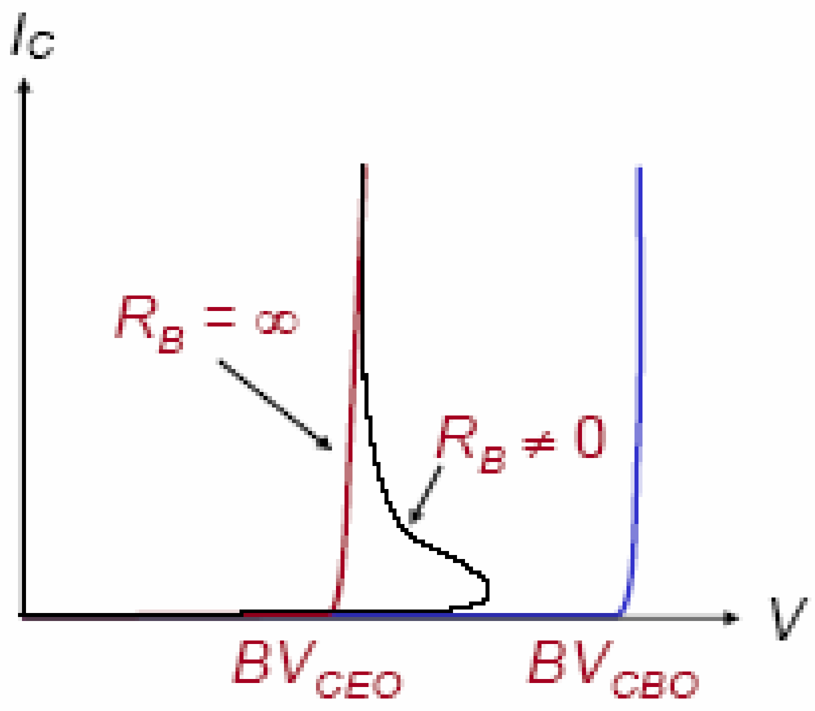
Breakdown Voltages

In general, BV_{CEO} is related to BV_{CBO} by the following expression,

$$BV_{CEO} = BV_{CBO}\sqrt[n]{1-\alpha} \approx BV_{CBO}/\sqrt[n]{\beta}$$

The typical value of n is between 2 to 4 in silicon.

In general, the actual breakdown voltage is between BV_{CEO} and BV_{CBO}, depending on the external resistance seen by the base, R_B.



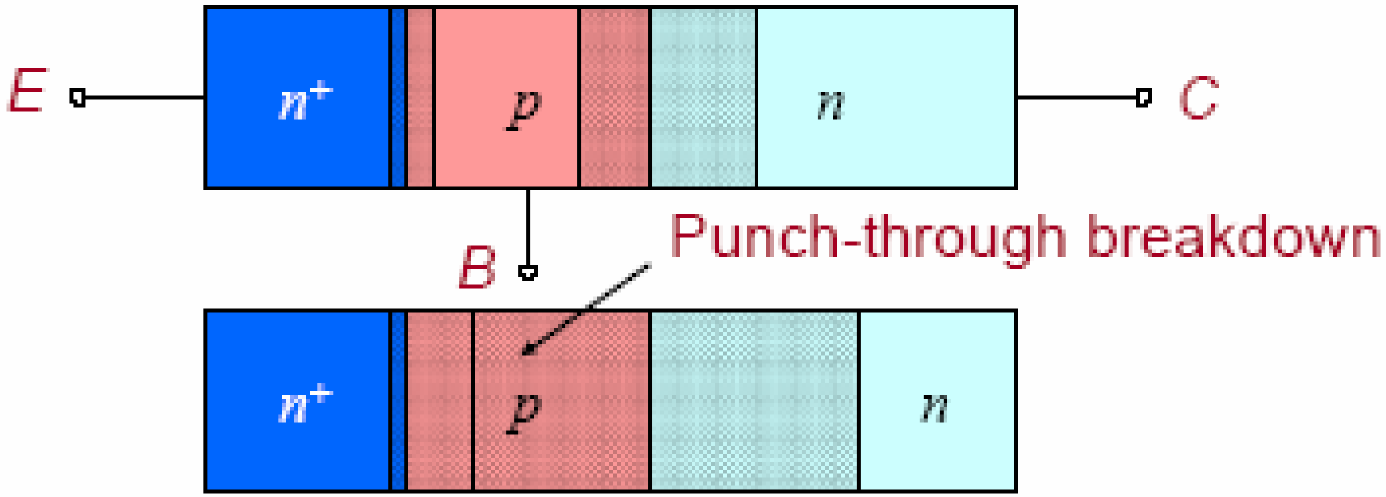
Breakdown Voltages

For a planar abrupt p^+n junction, the avalanche breakdown voltage is given by

$$BV = \frac{\varepsilon_s \varepsilon_0 E_{crit}^2}{2qN_D}$$

where E_{crit} is the critical electric field, and N_D is the doping concentration for the low doping region.

Breakdown Voltages



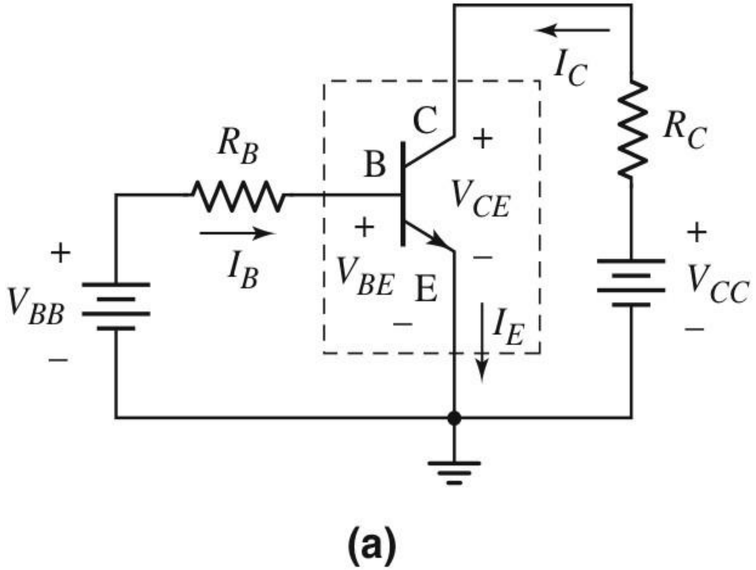
- As V_{CB} (or V_{CE}) increases, the depletion region will continue to spread into the base region.
- If the base become completely depleted, the depletion region from the collector and emitter touch each other, resulting in a short between the n+ and n regions.

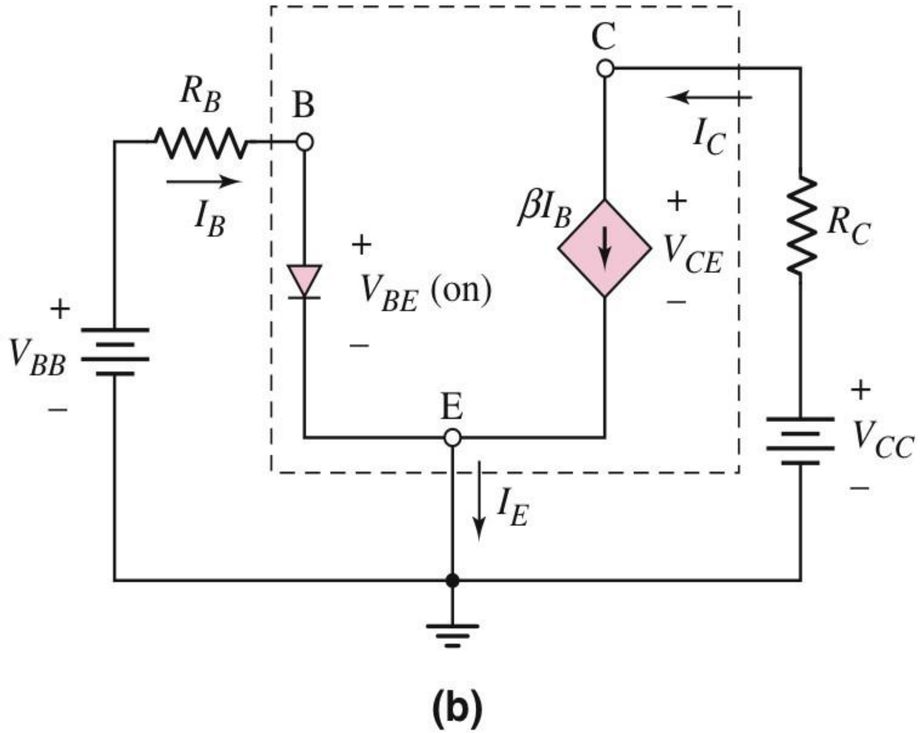
Operation region summary

Operation Region	*I_B or V_{CE} Char.*	*BC and BE Junctions*	*Mode*
Cutoff	I_B = Very small	Reverse & Reverse	Open Switch
Saturation	V_{CE} = Small	Forward & Forward	Closed Switch
Active Linear	V_{CE} = Moderate	Reverse & Forward	Linear Amplifier
Break-down	V_{CE} = Large	Beyond Limits	Overload

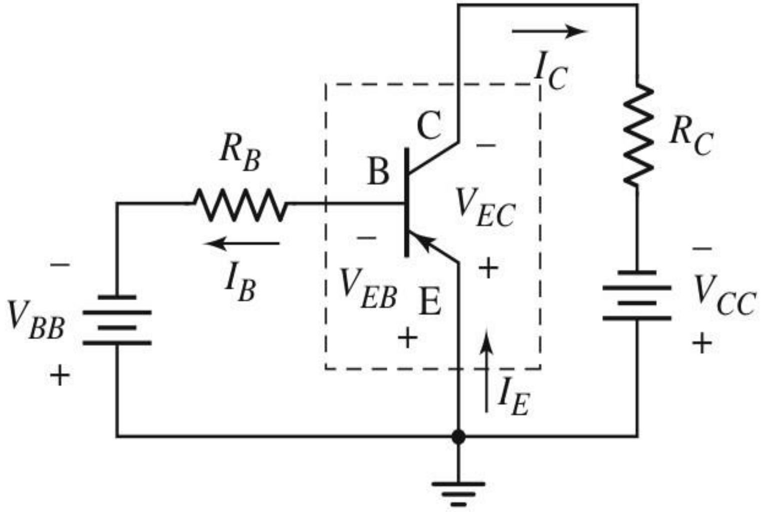
DC Equivalent Circuit

DC Equivalent Circuit for npn Common Emitter

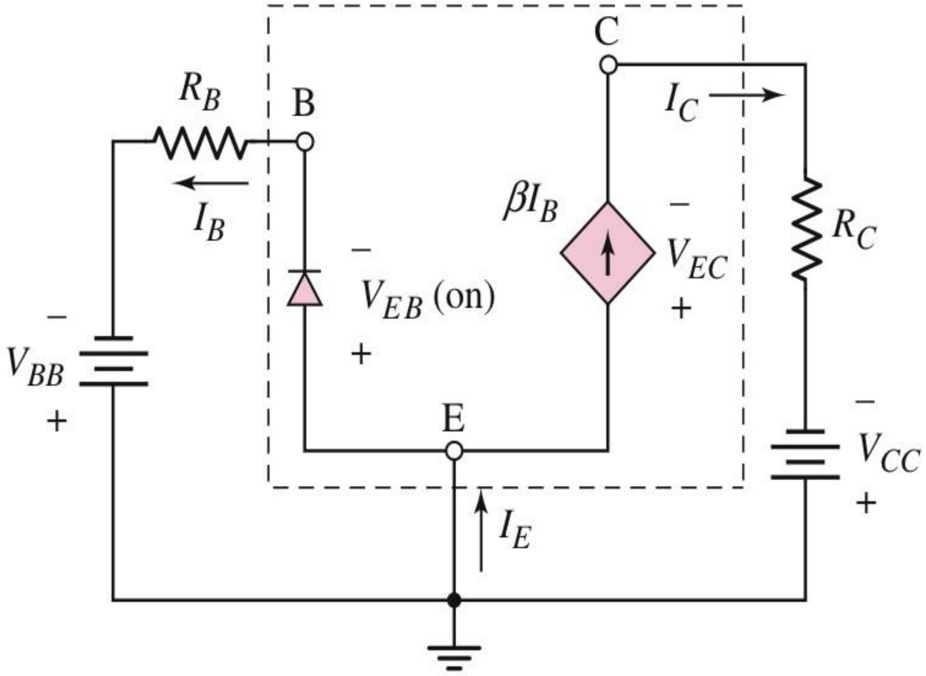




DC Equivalent Circuit for pnp Common Emitter

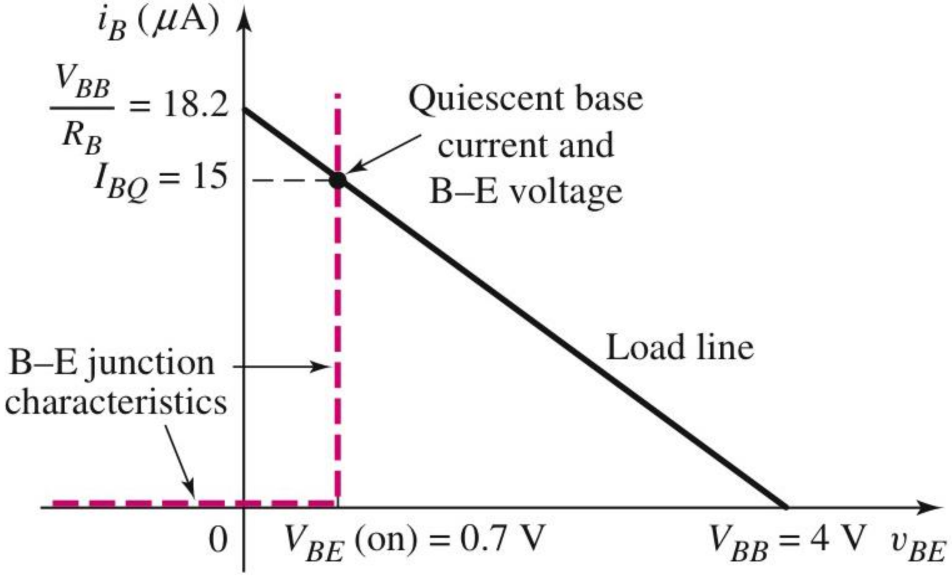


(a)



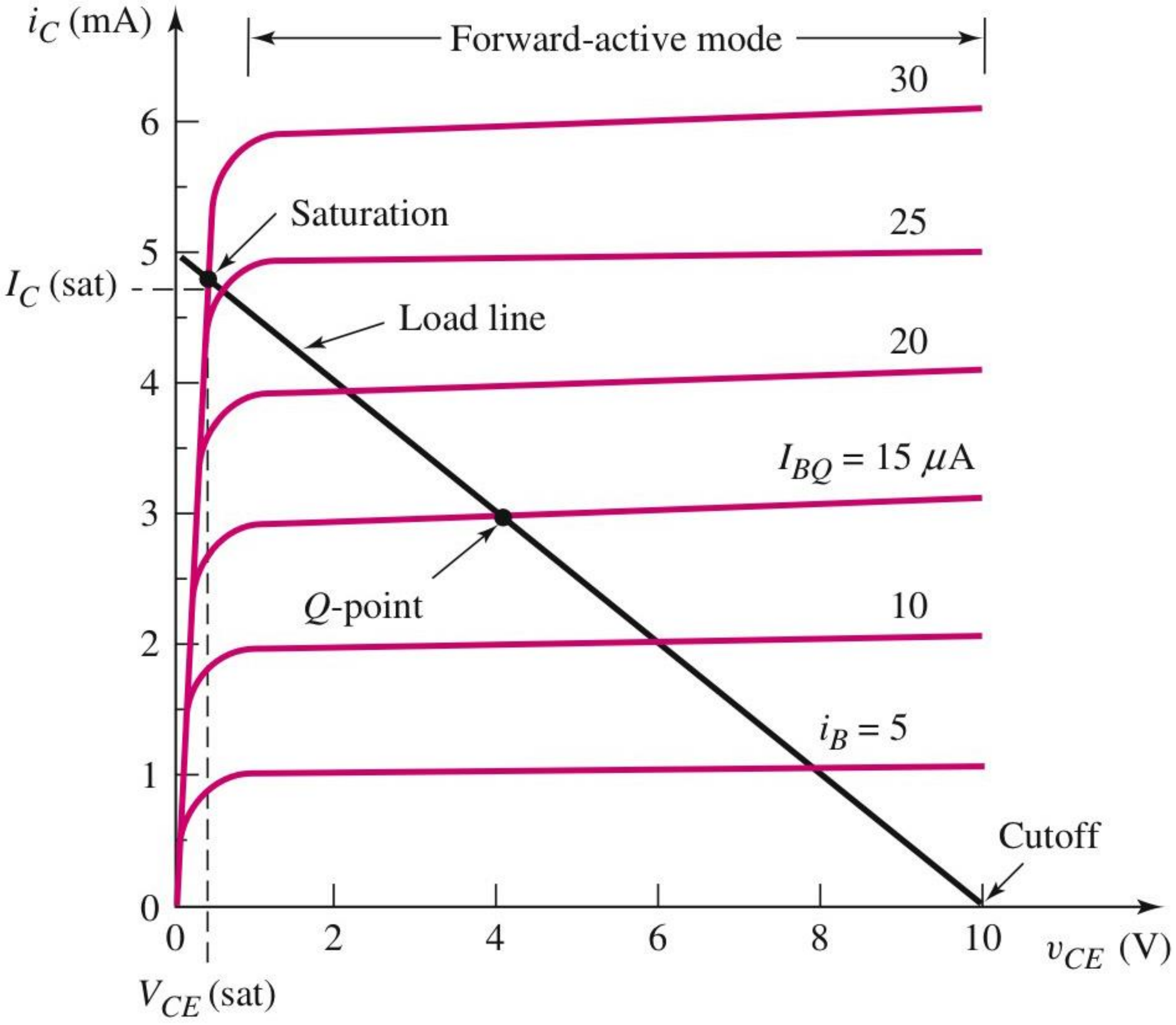
(b)

Load Line



i_B (μA)
$\frac{V_{BB}}{R_B} = 18.2$
$I_{BQ} = 15$
Quiescent base current and B–E voltage
Load line
B–E junction characteristics
0
V_{BE} (on) = 0.7 V
$V_{BB} = 4$ V
v_{BE}

(a)



i_C (mA)
Forward-active mode
30
25
20
$I_{BQ} = 15\ \mu$A
10
$i_B = 5$
Saturation
I_C (sat)
Load line
Q-point
Cutoff
0
1
2
3
4
5
6
0
2
4
6
8
10
v_{CE} (V)
V_{CE} (sat)

(b)

Problem-Solving Technique: Bipolar DC Analysis

1. Assume that the transistor is biased in forward active mode
   a. $V_{BE} = V_{BE}(on)$, $I_B > 0$, & $I_C = \beta I_B$
2. Analyze 'linear' circuit.
3. Evaluate the resulting state of transistor.
   a. If $V_{CE} > V_{CE}(sat)$, assumption is correct
   b. If $I_B < 0$, transistor likely in cutoff
   c. If $V_{CE} < 0$, transistor likely in saturation
4. If initial assumption is incorrect, make new assumption and return to Step 2.

Summary of DC Problem

- Bias transistors so that they operate in the linear region B-E junction forward biased, C-E junction reversed biased

- Use V_{BE} = 0.7 (npn), $I_C \approx I_E$, $I_C = I_B$

- Represent base portion of circuit by the Thevenin circuit

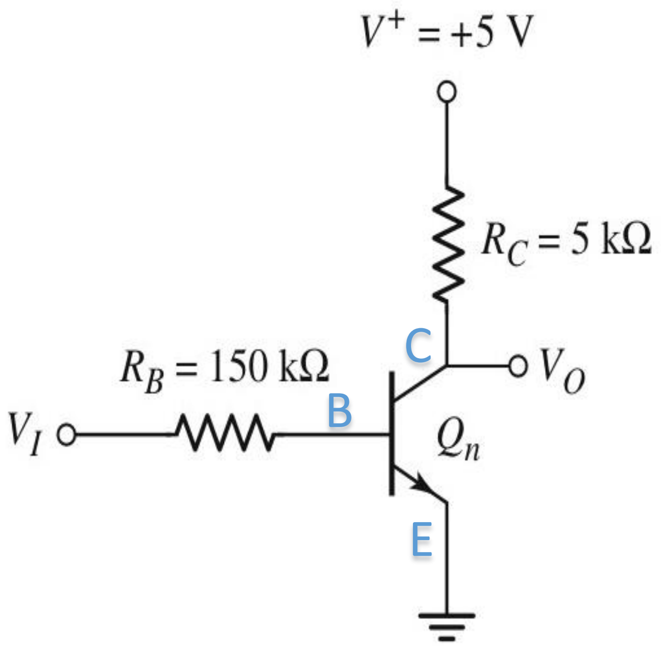
- Write B-E, and C-E voltage loops.

- For analysis, solve for I_C, and V_{CE}.

- For design, solve for resistor values (I_C and V_{CE} specified).

Voltage Transfer Characteristic

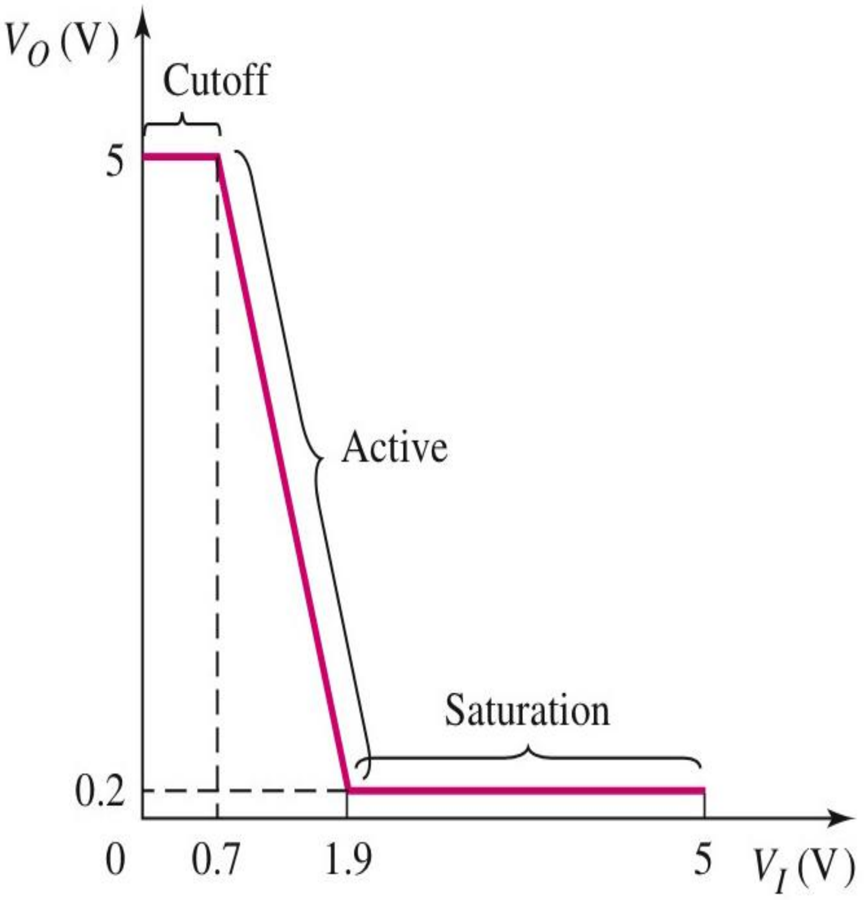
Voltage Transfer Characteristic for npn Circuit



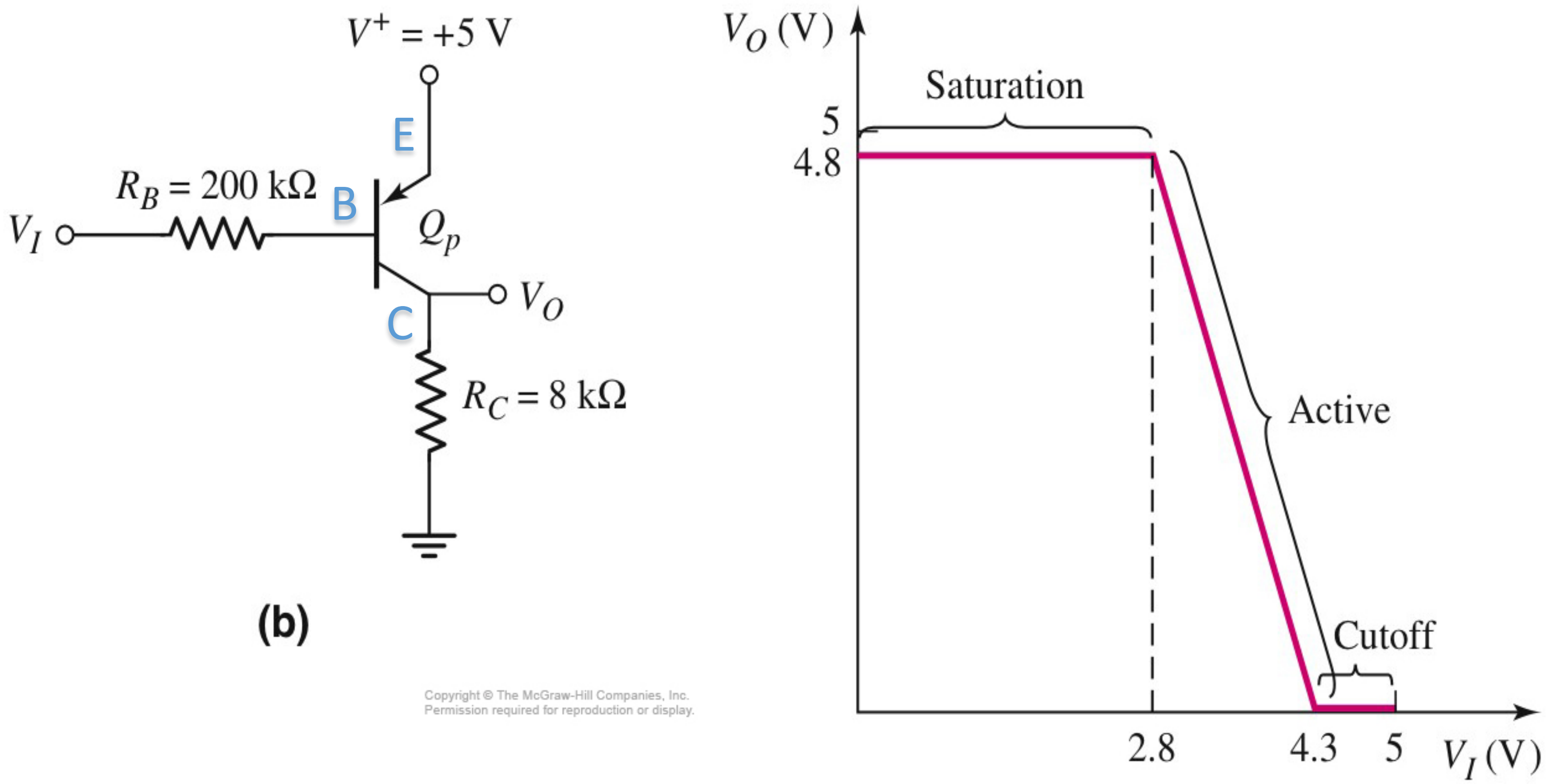
(a)

V_{CE}(sat) = 0.2 V

β = 120



Voltage Transfer Characteristic for pnp Circuit



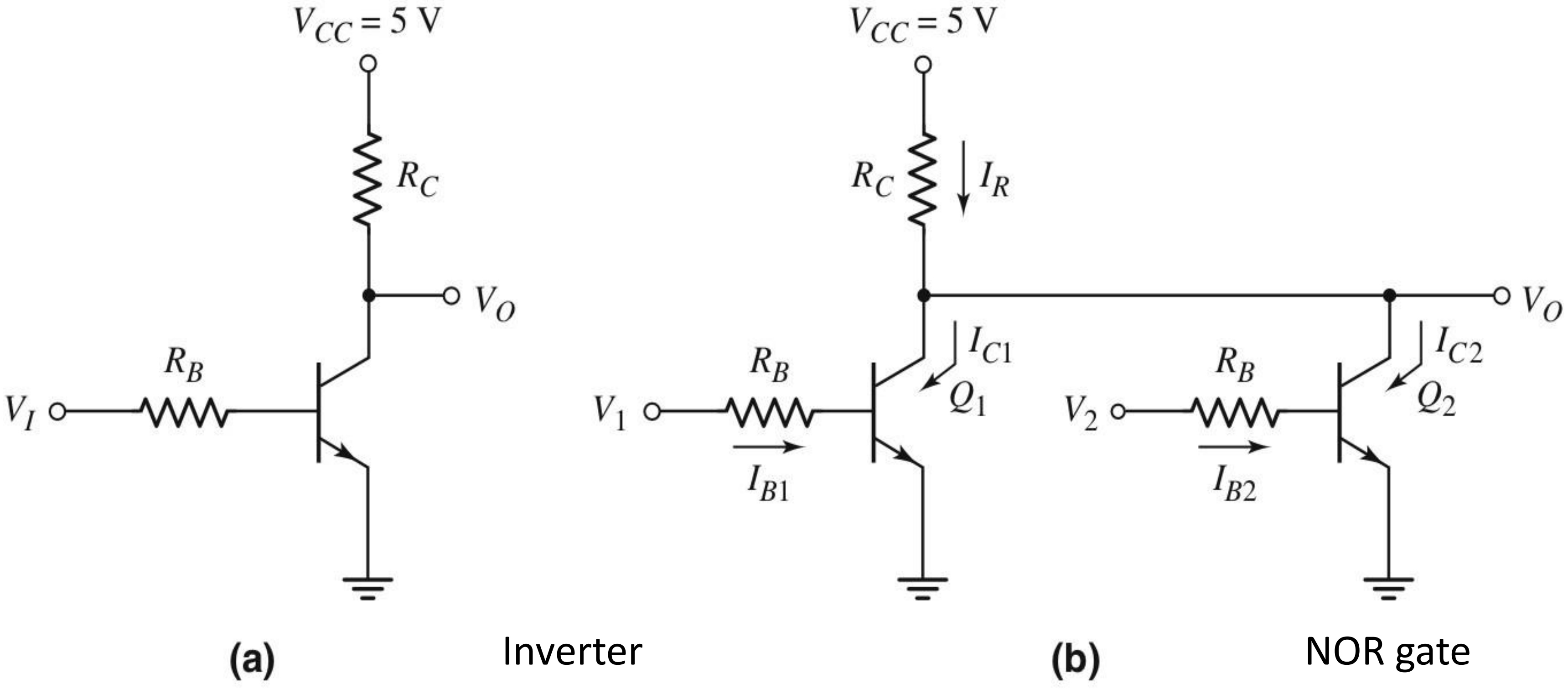
V_{EC}(sat) = 0.2 V

$V_{EB} < 0.7$V

β = 80

Digital Logic Circuit

Digital Logic



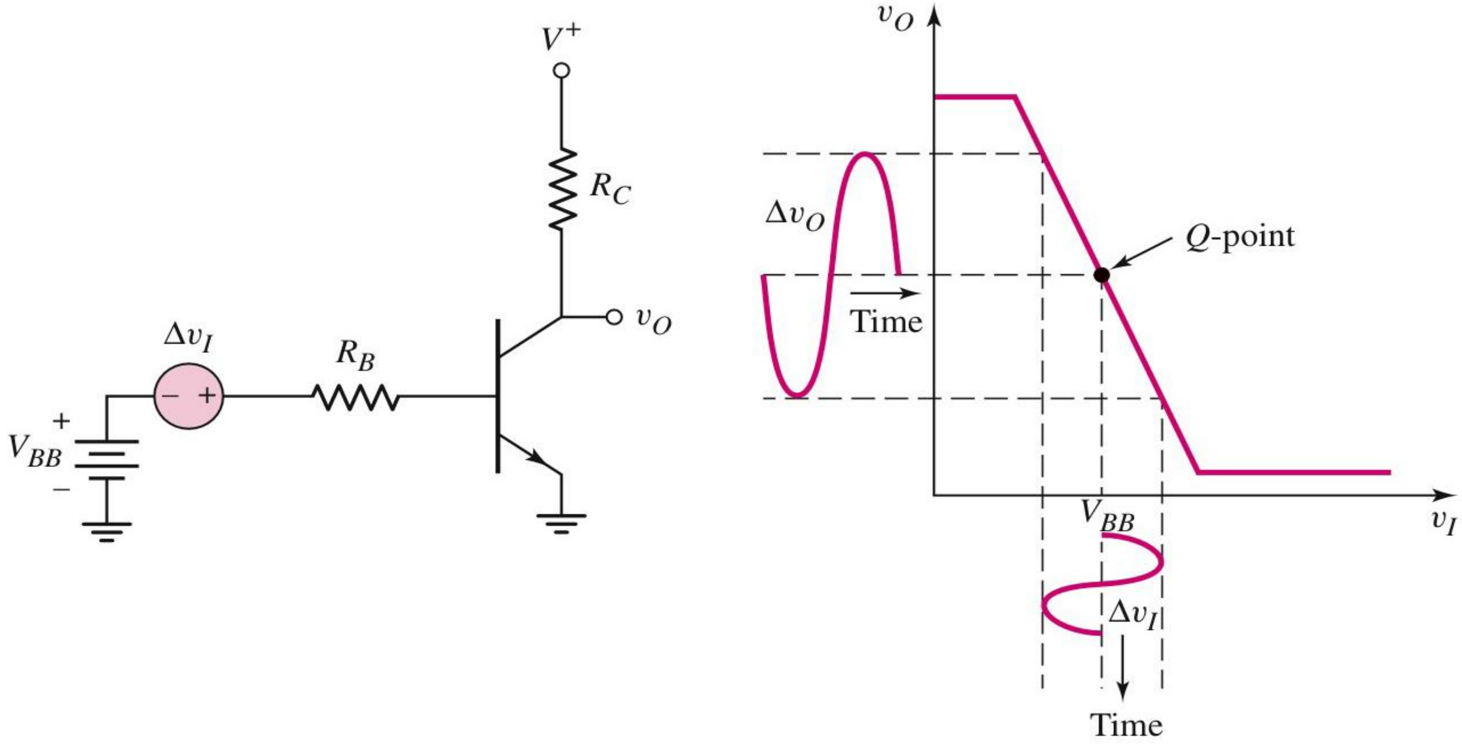
Inverter

NOR gate

INPUT		OUTPUT
A	B	A NOR B
0	0	1
0	1	0
1	0	0
1	1	0

V_1 (V)	V_2 (V)	V_O (V)
0	0	5
5	0	0.2
0	5	0.2
5	5	0.2

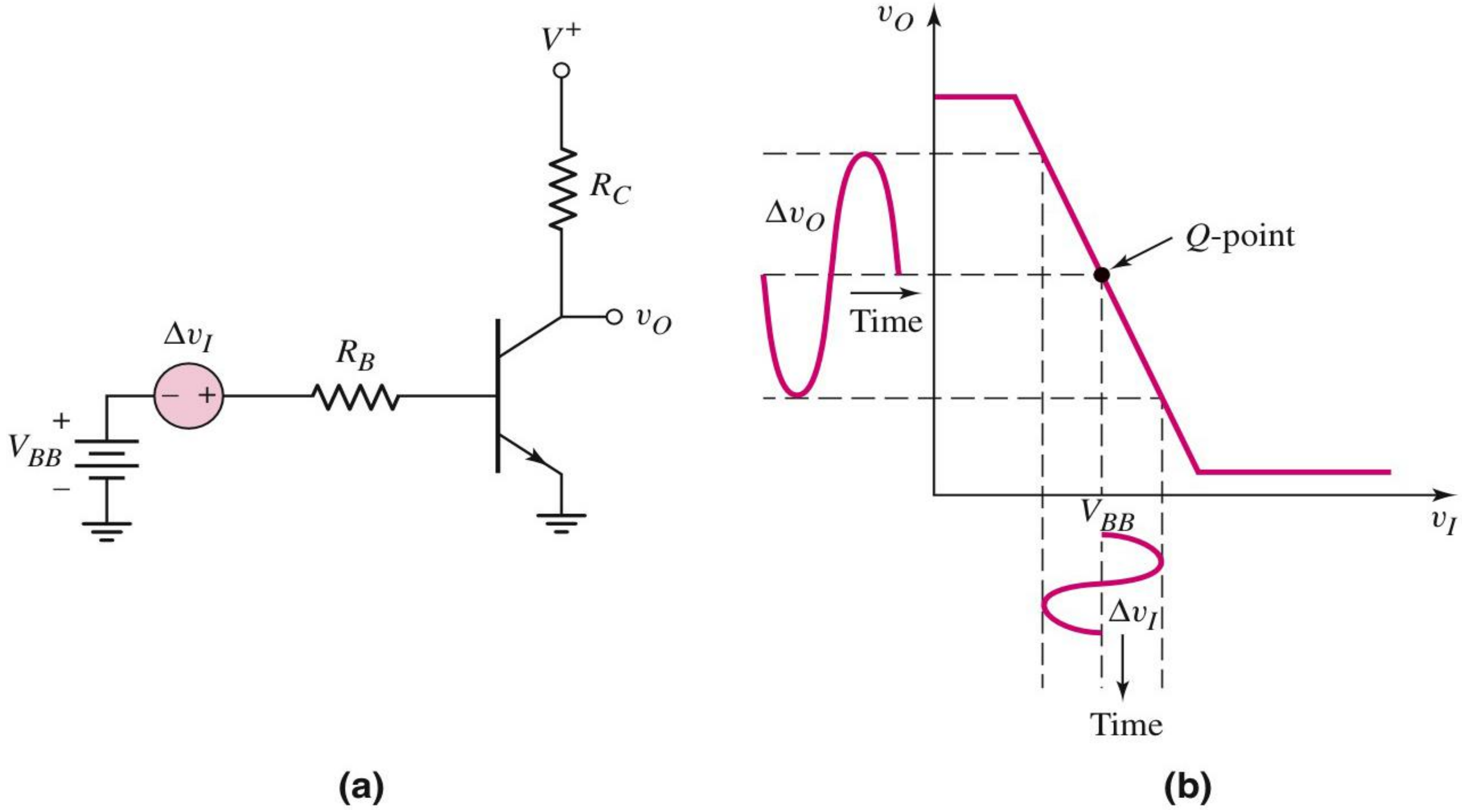
Bipolar Inverter as Amplifier



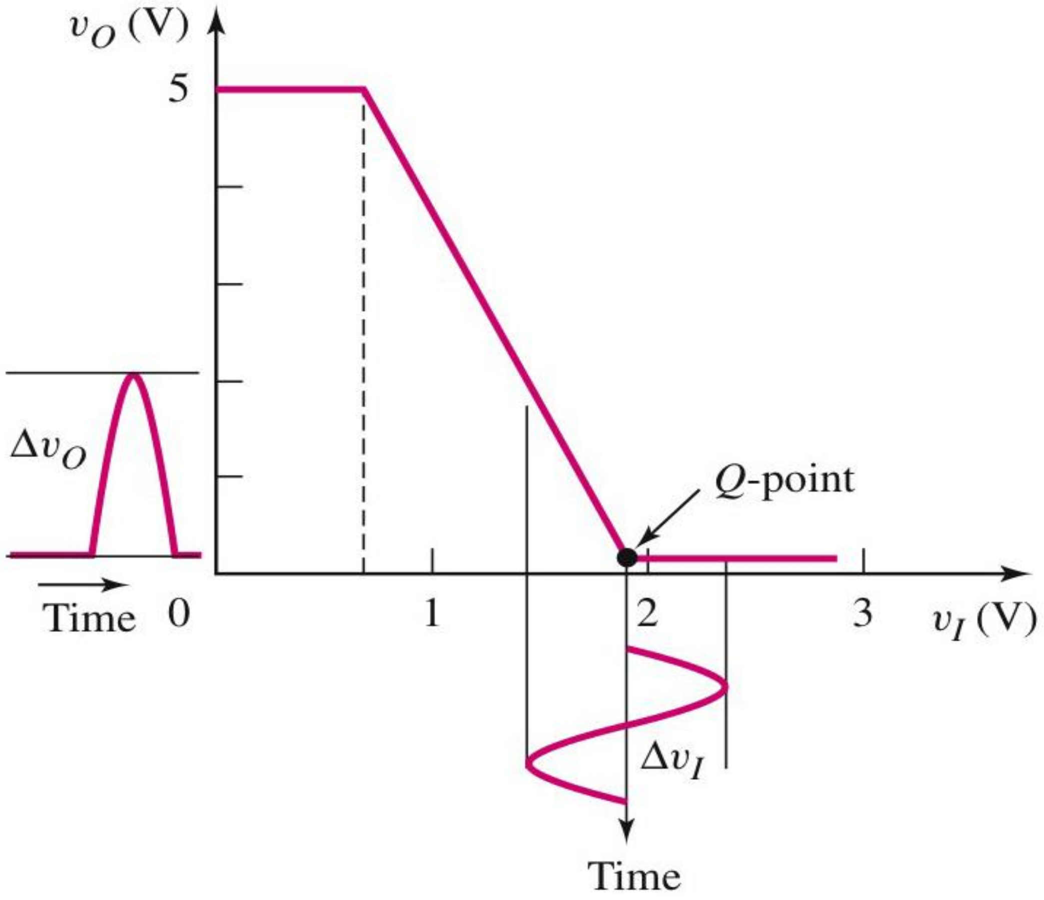
(a) (b)

Bipolar Transistor Biasing

Bipolar Inverter as Amplifier



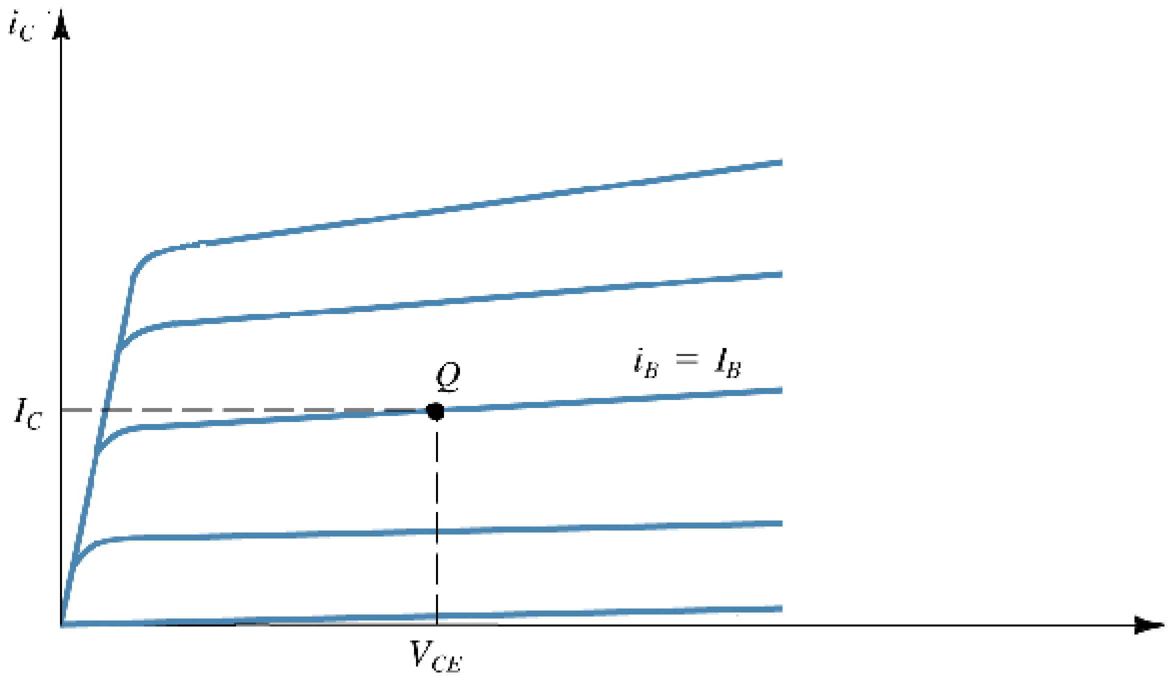
Effect of Improper Biasing on Amplified Signal Waveform



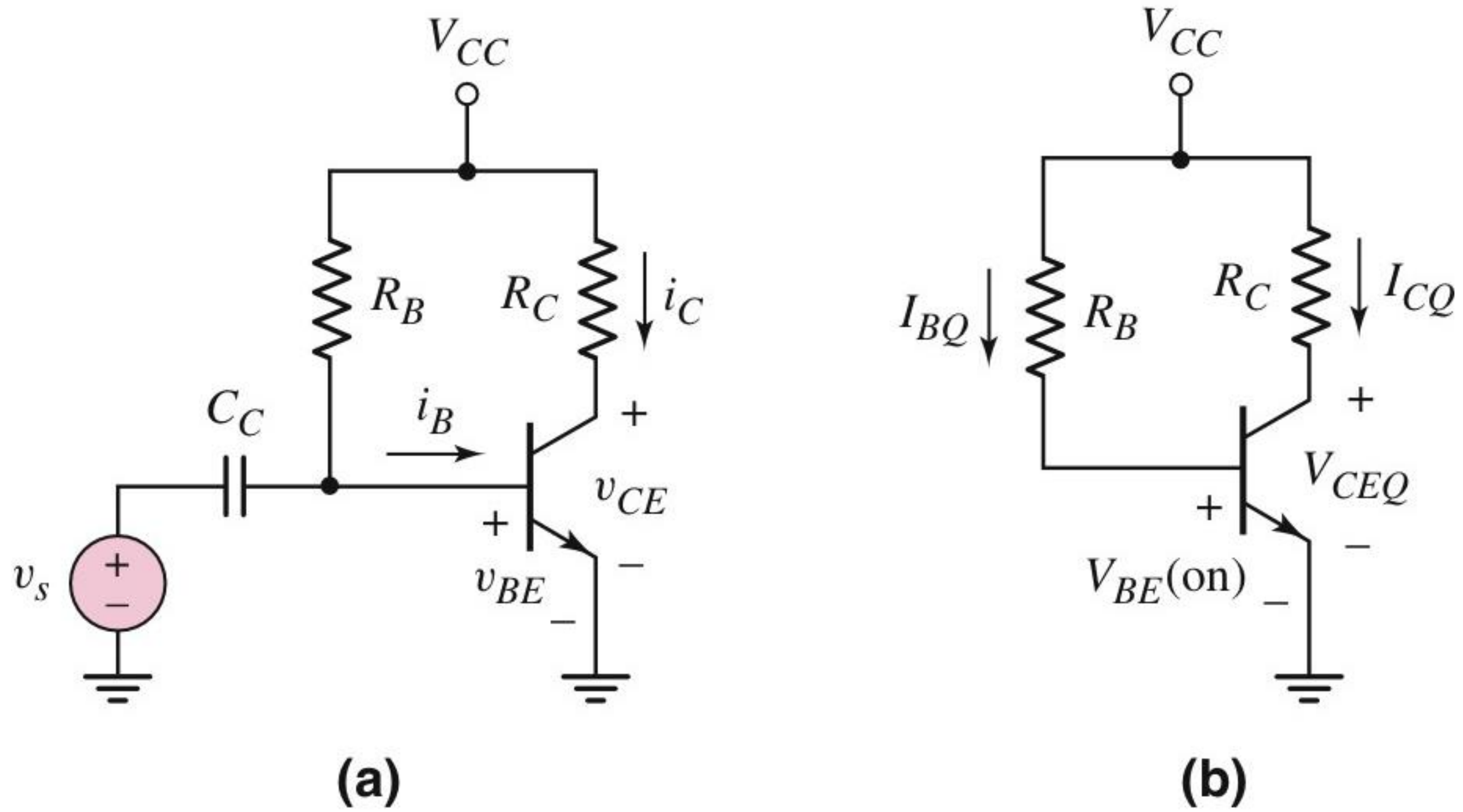
Biasing a Transistor

- We must operate the transistor in the linear region.
- A transistor's operating point (Q-point) is defined by

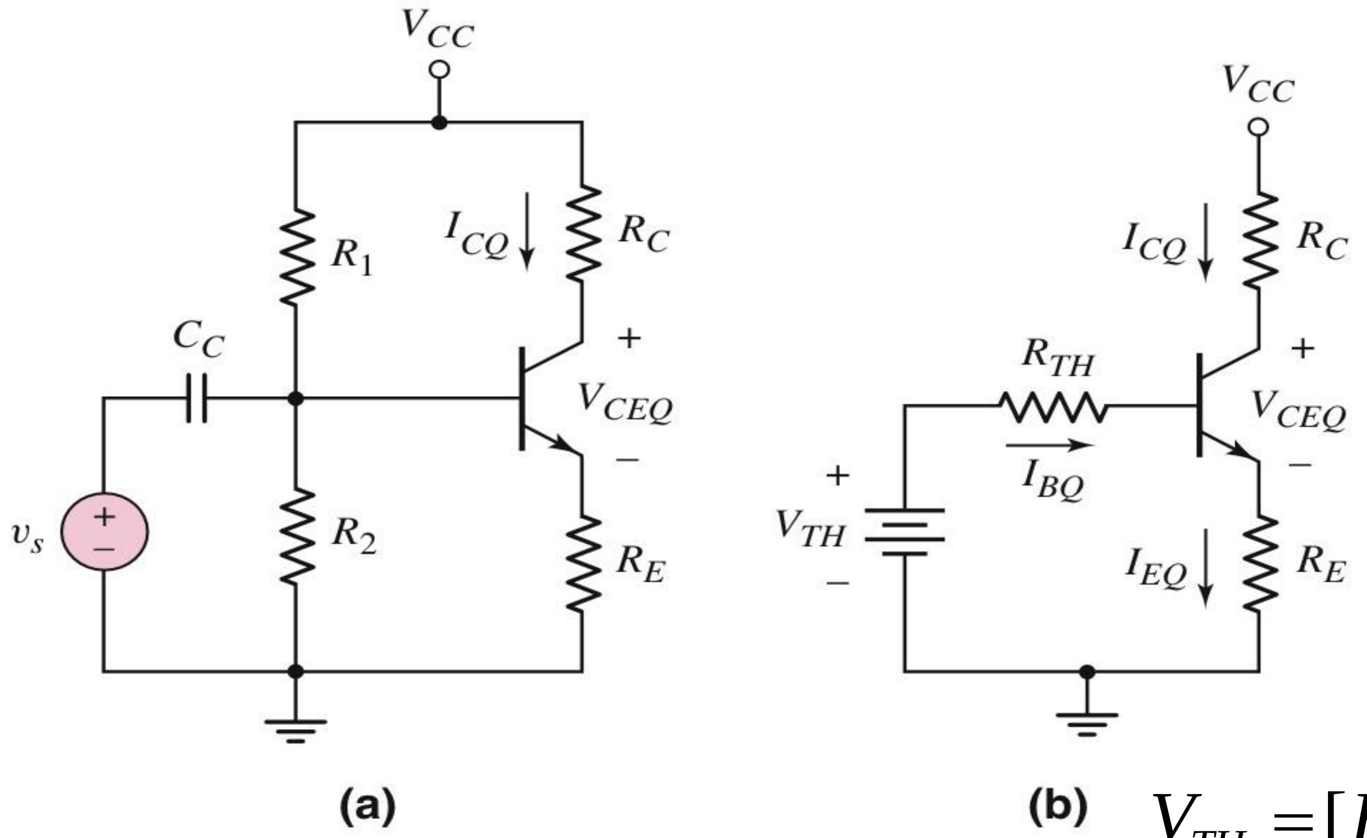
I_C, V_{CE}, and I_B.



Single Base Resistor Biasing

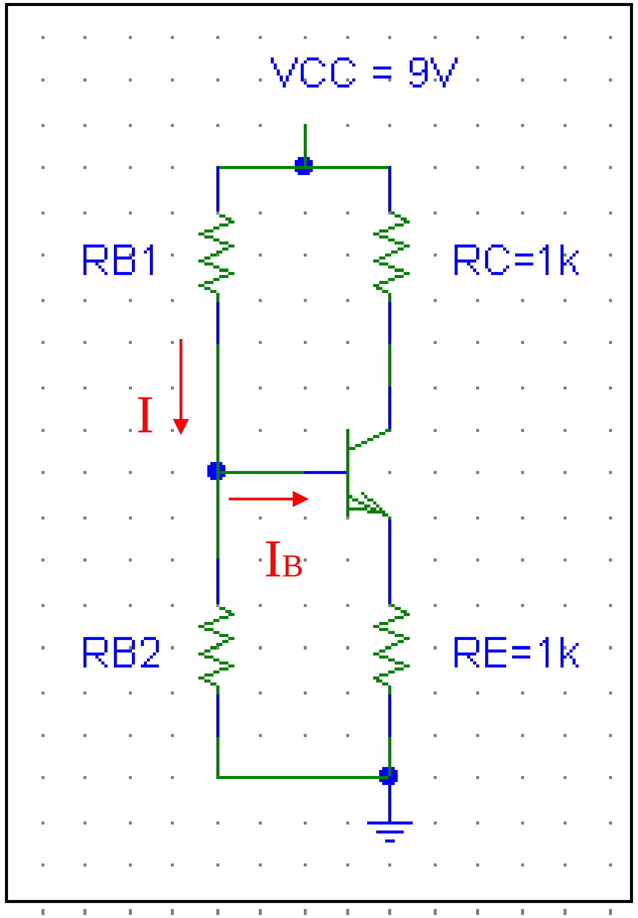


Common Emitter with Voltage Divider Biasing and Emitter Resistor



$$V_{TH} = [R_2 /(R_1 + R_2)V_{CC}$$

Example:



•Use a voltage divider, R_{B1} and R_{B2} to bias V_B to avoid two power supplies.

•Make the current in the voltage divider about 10 times I_B to simplify the analysis. Use $V_B = 3V$ and $I = 0.2mA$.

(a) R_{B1} and R_{B2} form a voltage divider.

Assume $I >> I_B$ $I = V_{CC}/(R_{B1} + R_{B2})$

$$.2mA = 9 /(R_{B1} + R_{B2})$$

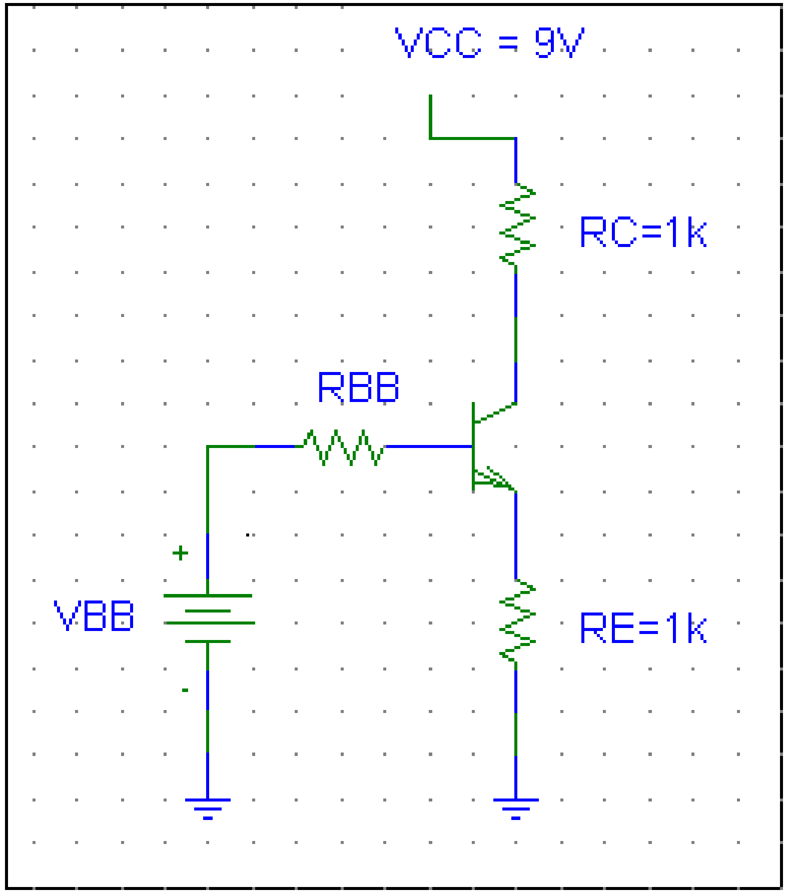
AND

$V_B = V_{CC}[R_{B2}/(R_{B1} + R_{B2})]$

$3 = 9 [R_{B2}/(R_{B1} + R_{B2})]$, Solve for R_{B1} and R_{B2}.

$R_{B1} = 30K\Omega$, and $R_{B2} = 15K\Omega$.

Example (Cont')



Find the operating point

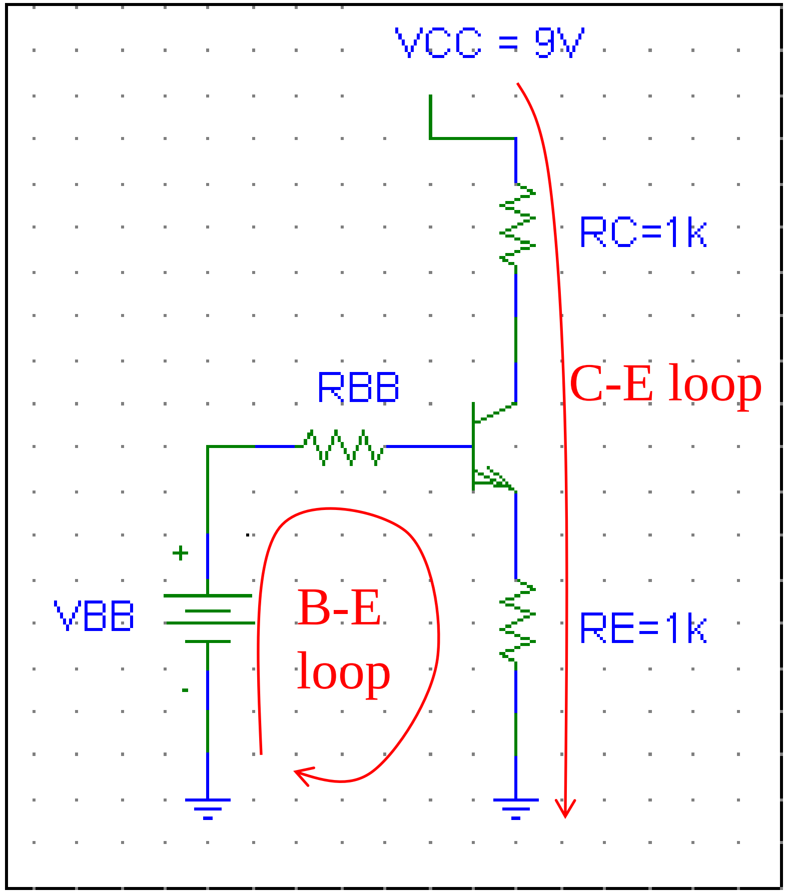
- Use the Thevenin equivalent circuit for the base

- Makes the circuit simpler

- $V_{BB} = V_B = 3V$

- R_{BB} is measured with voltage sources grounded
- $R_{BB} = R_{B1} \| R_{B2} = 30K\Omega \| 15K\Omega = 10K\Omega$

Example (Cont’)



Write B-E loop and C-E loop

B-E loop

$V_{BB} = I_B R_{BB} + V_{BE} + I_E R_E$

$I_E = 2.09$ mA

C-E loop

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

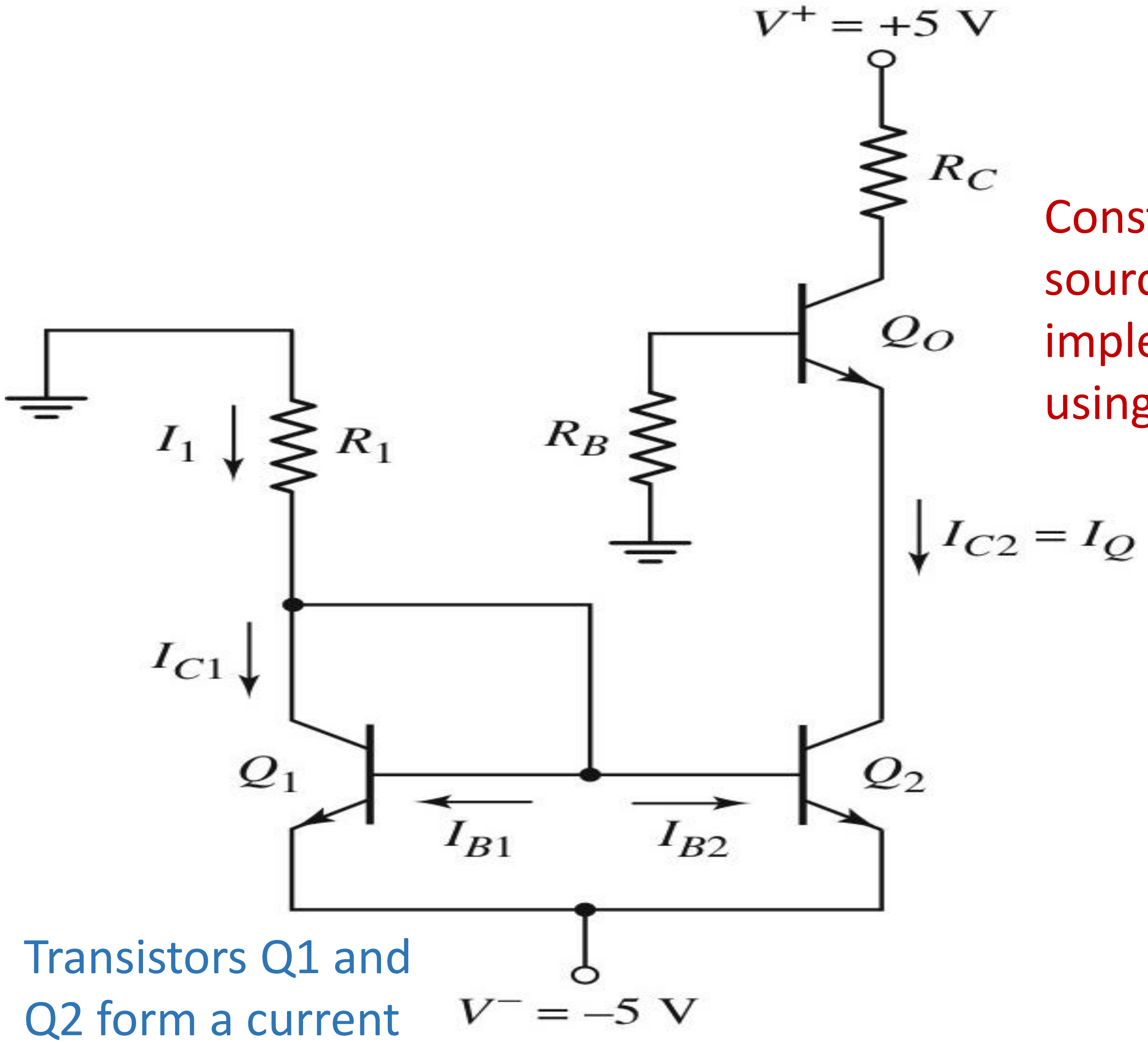
$V_{CE} = 4.8$ V

This is how all DC circuits are analyzed

and designed!

Integrated Circuit Biasing

$$I_C = I_Q = \frac{I_1}{1+\frac{2}{\beta}}$$

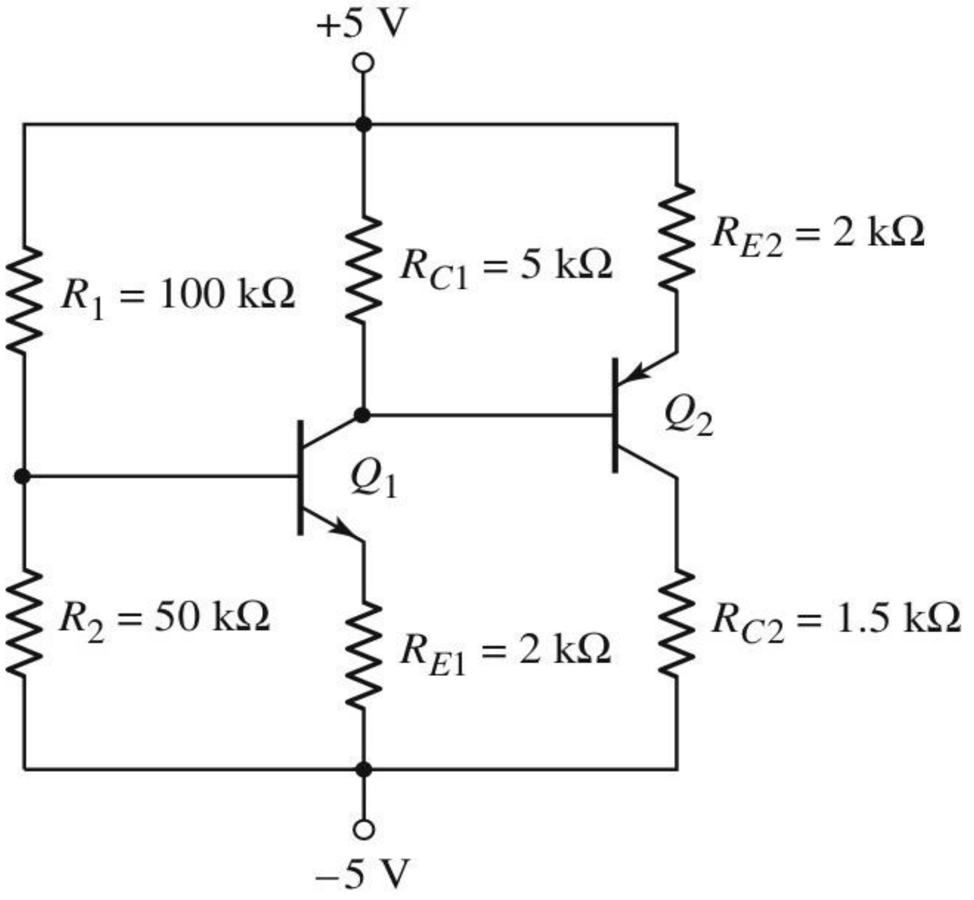


Constant current source implemented by using transistors.

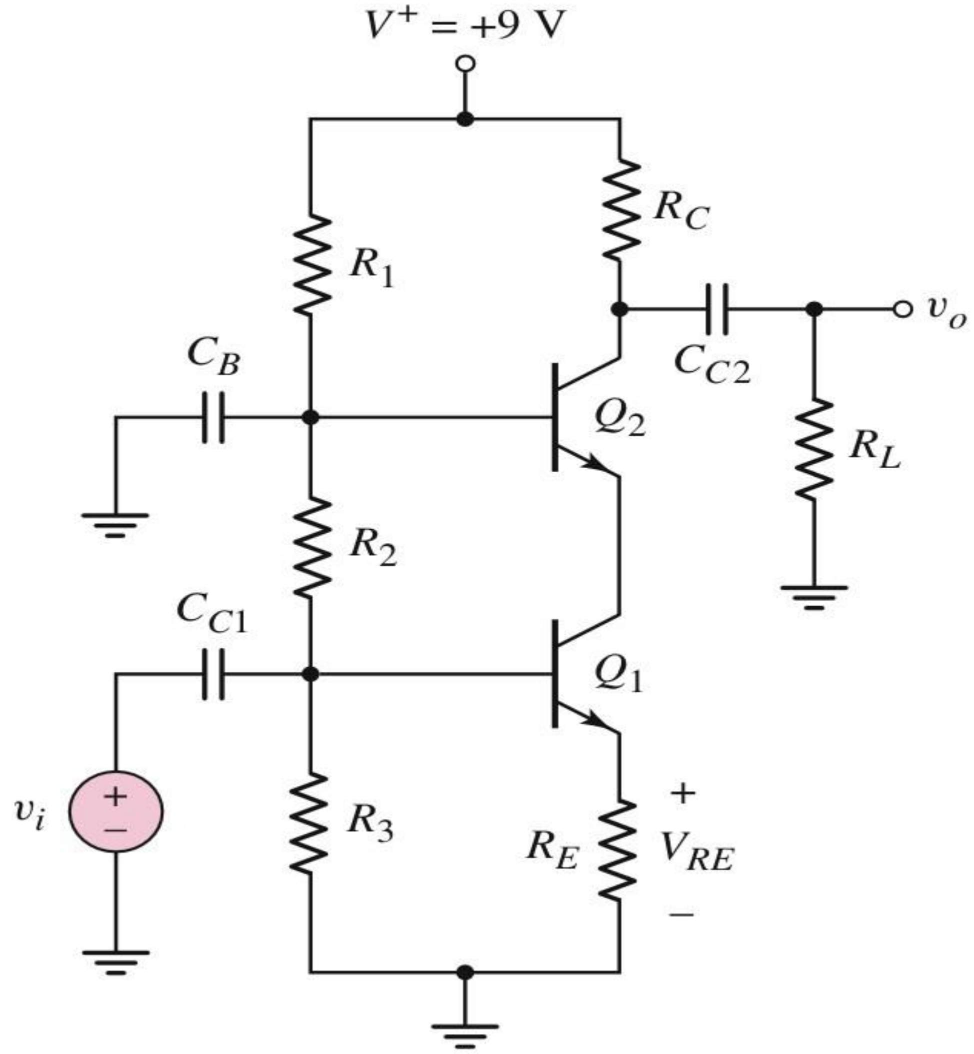
Transistors Q1 and Q2 form a current mirror.

Multistage Circuits

Multistage Cascade Transistor Circuit



Multistage Cascode Transistor Circuit



Comparison of Characteristics

- For MOSFET, the important feature is how V_{GS} controls I_D, shown as the **transfer characteristic**, I_D against V_{GS} .

- For a BJT the transfer characteristic is almost a straight line with slope β (transfer characteristics don't vary) so it is not necessary to examine it.

- For the BJT the **input characteristic** is examined (<u>I_B as a function of V_{BE}</u>) whereas no current flows into a MOSFET so it has the input characteristic is $I_G = 0$.

An enhancement MOSFET is "*on*" – "*active*" - if $V_{GS} > V_T$, where V_T is the **threshold voltage**.

Comparison of Characteristics

Bipolar

- I_B controls the collector current
- Control varies greatly from transistor to transistor as β varies by a large amount
- Input voltage threshold is $V_{BE} > 0.7$ volts.
- When conducting V_{BE} is almost constant at about 0.7V

MOSFET

- V_{GS} controls the drain current (strictly $V_{GS} - V_T$)
- Control varies greatly from transistor to transistor as V_T varies by a large amount
- Input voltage threshold is V_T - varies with transistor.
- $I_G = 0$ for all situations so is constant

Contents of Chapter

- Discuss the physical structure and operation of the bipolar junction transistor.
- Understand the dc analysis and design techniques of bipolar transistor circuits.
- Examine three basic applications of bipolar transistor circuits.
- Investigate various dc biasing schemes of bipolar transistor circuits, including integrated circuit biasing.
- Consider the dc biasing of multistage or multi-transistor circuits.