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EEE109: Bipolar Junction Transistor

Chapter 4

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- Discuss the physical structure and operation of the Bipolar Junction Transistor (BJT).
  - NPN
  - PNP
- Understand the DC analysis and design techniques of bipolar transistor circuits.
- Examine three basic applications of bipolar transistor circuits.
  - Inverter function
  - Logic function
  - Amplifier function

Basic Bipolar Junction Transistor

Understand the physical structure, operation, and characteristics of the bipolar junction transistors (BJT), including the npn and pnp devices.

Transistor Structure

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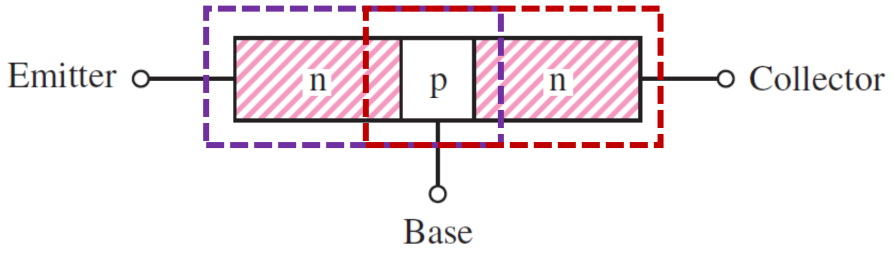
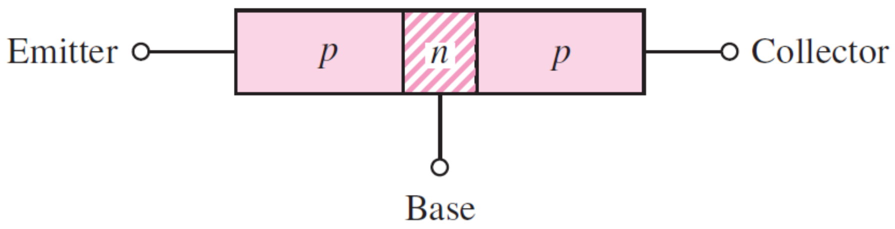
- The **Bipolar Junction Transistor** (BJT) has **three** separately doped regions and contains **two** pn junction
  - npn bipolar transistor
  - pnp bipolar transistor



- Chinese Name: 三极管, “三” means three. However, “bi” in bipolar means “two”. Why?



Current in the transistor is due to flow of both Electrons and Holes, two carriers results in the name **bipolar**

- Three terminals are emitter, based and collector
  - The width of the based must be very narrow 10^{-6}m

Transistor Structure

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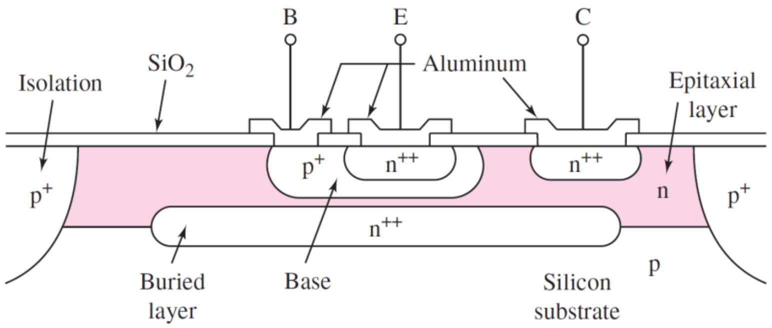
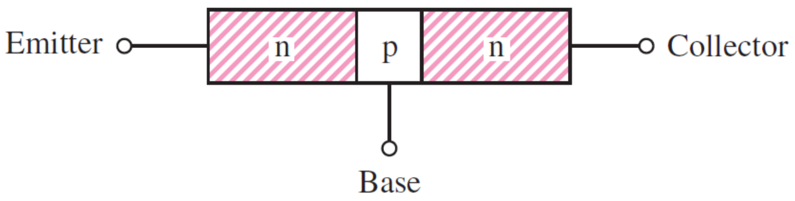
- Cross section of a conventional integrated circuit of npn bipolar Transistor
- The actual model is more complex and device is not even symmetrical!
- Although the block diagram is highly simplified, it is still useful for presenting the basic transistor characteristic



Real world

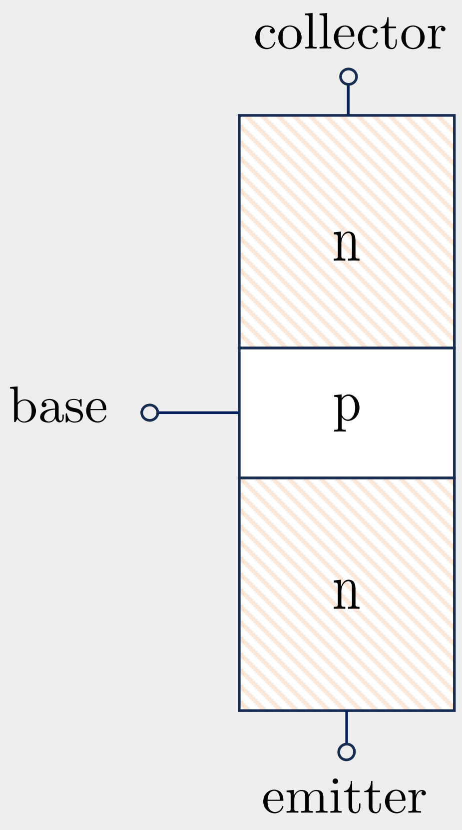


Fairytale

- Note: The trick to learning this chapter well is not to dig too deeply, because we are based on an simplified model.
- (有些地方目前不要挖掘太深，简化模型本来就够不精准，放过自己)

Four bias modes (NPN)

	NPN BJT Transistor
Saturation	• B-E and B-C junctions are forward-biased
Cut-off	• B-E and B-C junctions are reversed-biased
Forward-active mode	• B-E junction is forward biased • B-C junction is reversed-biased
Inverse-active mode	• B-E junction is reversed-biased • B-C junction is forward biased



Forward-active mode (NPN)

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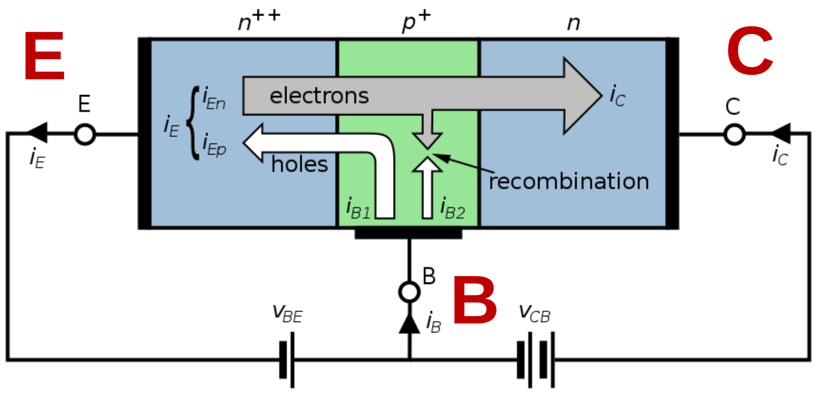
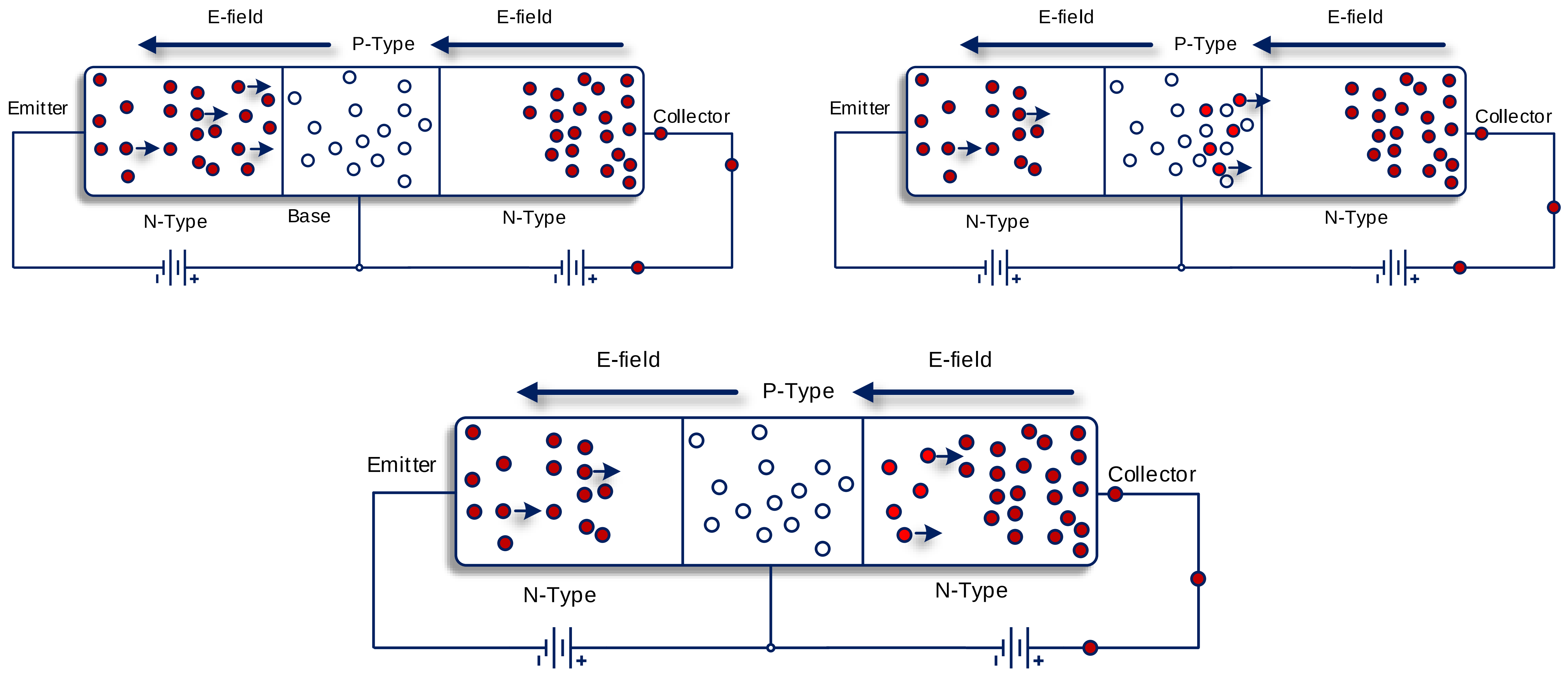
- The figure below shows an npn bipolar transistor biased in the forward-active mode.

- **B-E** junction is forward biased
  - Electrons is attracting from emitter to base region
  - Electrons concentration in base is increasing sharply



- **B-C** junction is reversed biased
  - Electrons concentration at the interface (B-C) of the junction is nearly zero
  - Then the electrons in the base region is attracting to collector region by a combination force with **diffusion** and **electric field force**.

Forward-active mode (NPN)



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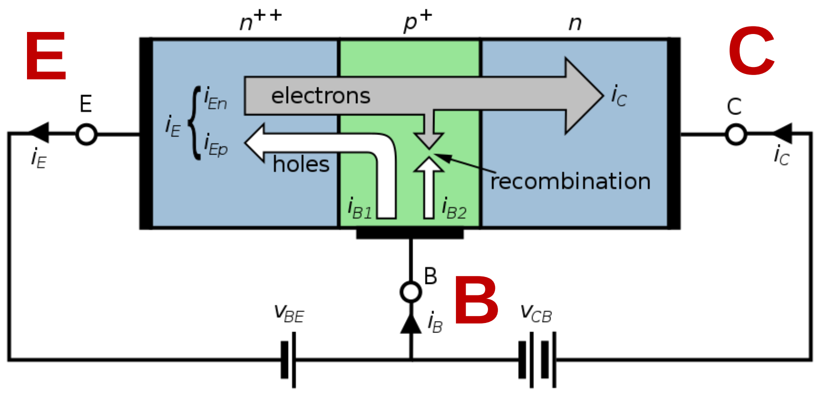


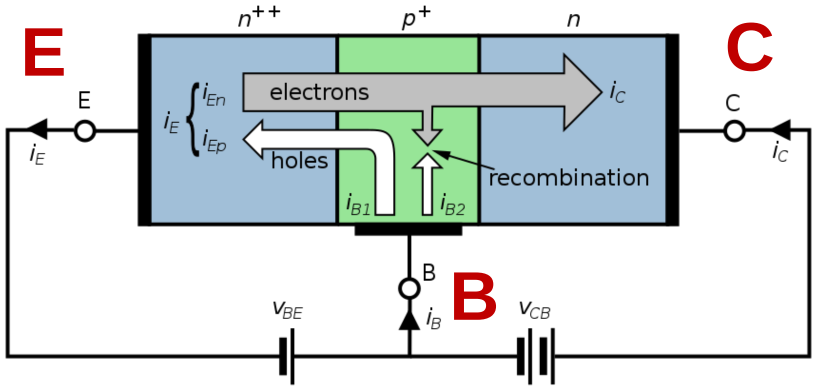
- **B-C** junction is reversed biased
  - Electrons concentration at the interface (B-C) of the junction is nearly zero
  - Then the electrons in the base region is attracting to collector region by a combination force with **diffusion** and **electric field force**.

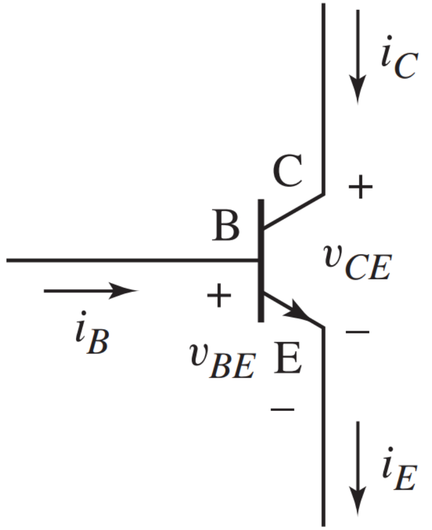
Transistor current (active region)

- The current in a BJT consists of three parts
  1. Emitter current (results of Electrons Moving)
  2. Collector current (results of Electrons Moving)
  3. Based Current (results of Holes Moving)

Emitter Current = **Collector Current** + Based Current

Major Part





Emitter Current

- The B-E junction is forward biased, the current through this junction to be exponential function of B-E voltage, consider that $V_{BE} >> V_T$ (V_T is thermal voltage = 0.026V)

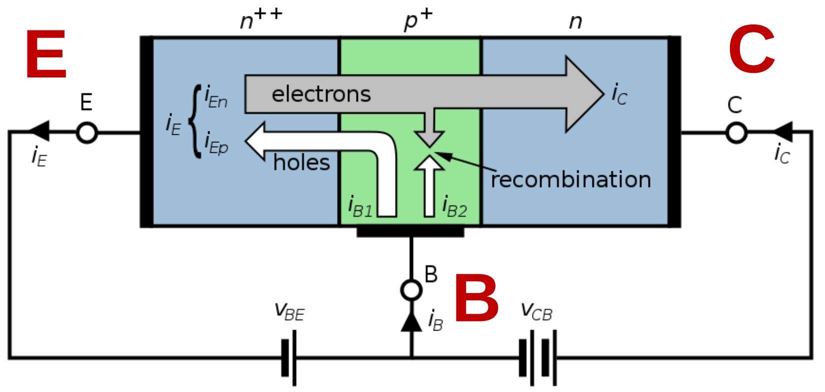
$$i_E = i_{EO}\left(e^{\frac{v_{BE}}{V_T}} - 1\right) \cong i_{EO}e^{\frac{v_{BE}}{V_T}}$$

It is the current equation of the diode

(这个就是二极管的电流公式)

- The electrons flow from the emitter into the base

- The emitter current is out of the emitter terminal

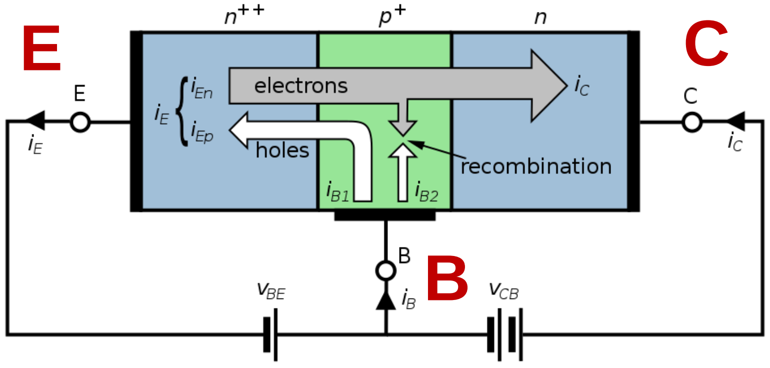


Collector Current

- The number of the injected electrons reaching the collector is the major component of collector current, which is coming from the emitter current (流进C端的电流主要是从E端来的, 看下图箭头, 想象成河流分支)

- Therefore, collector current is dependent on the emitter current.

- **B-E** voltage affects the collector current, but B-C can not.

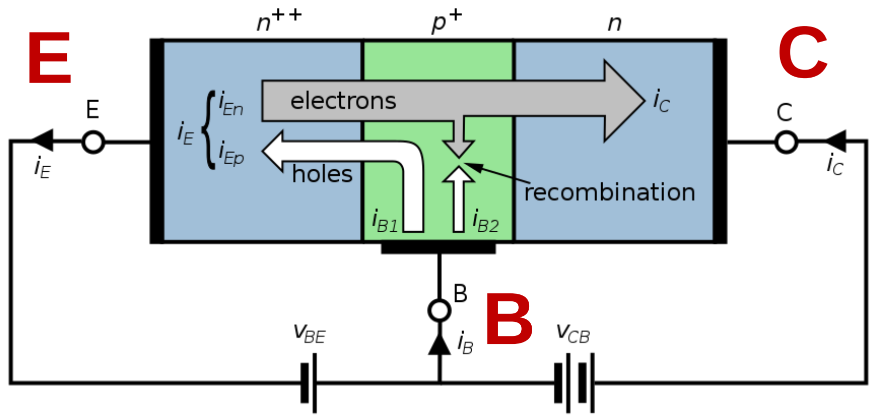


$$i_c = \alpha i_E$$

α is the common-base current gain, it must less than 1 (but very close to it)

Base Current

- The base current consists of two parts
- B-E junction is forward biased
  - Holes from the base are injected in to the emitter due the electric filed, I_{B1}



- A few holes recombine with the electrons coming from the emitter, the recombination current is I_{B2}

$$i_B = i_{B1} + i_{B2}$$

- But the base current is extremely **small**

Common-emitter current gain β

- In the BJT, **B-E** voltage can affect the collector current and base current. It means that collector current and base current are linearly related (线性相关). The ratio of collector and base current is defined:

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

- β is the common-emitter current gain, usually $50 < \beta < 300$.
- Be caution, you should remember this ratio must greater than 1.
- Some factors may affect this ratio, such as the temperature.

Current relationship in BJT

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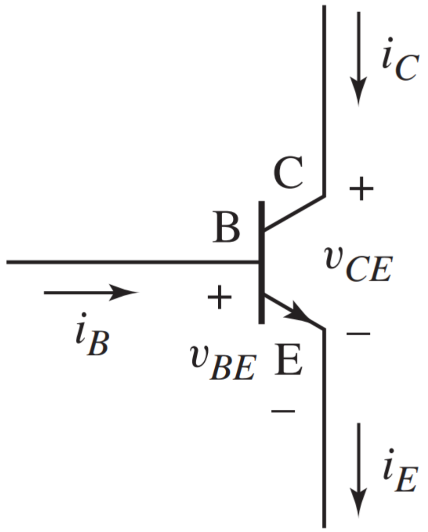
- If we treat the BJT as a single node, by KCL

$$i_E = i_B + i_C$$



- If the npn BJT is biased in the forward active-mode

$$i_C = \beta i_B \qquad i_C = \alpha i_E$$

- With above three equations, we can derive $i_E = (i_C/\beta) + i_C$

$$i_C = \left(\frac{\beta}{1+\beta}\right) i_E = \alpha i_E \quad \Rightarrow \quad \boxed{\alpha = \frac{\beta}{1+\beta} \rightarrow \beta = \frac{\alpha}{1-\alpha}}$$

Forward-active mode (PNP)

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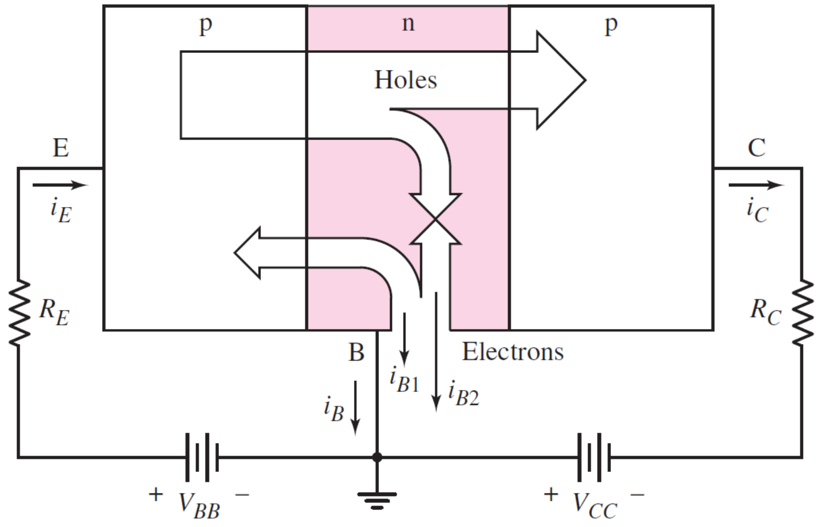
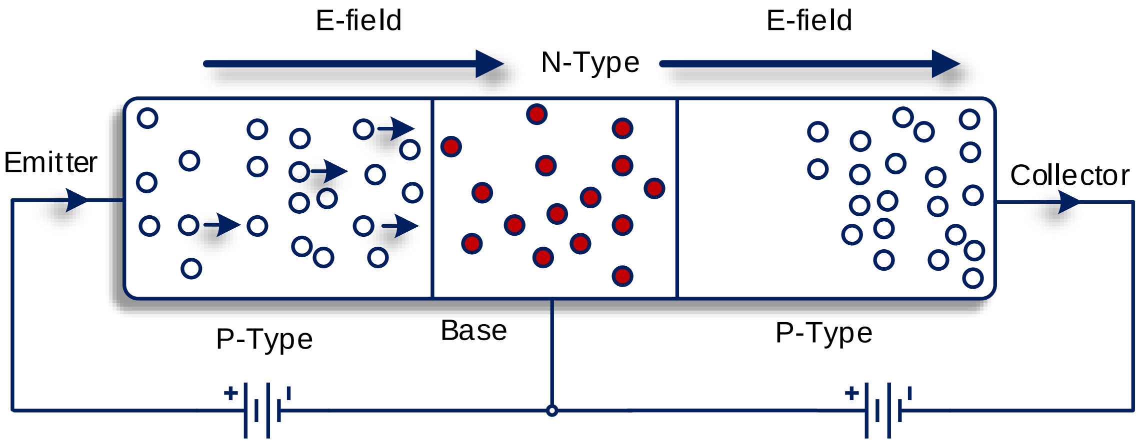
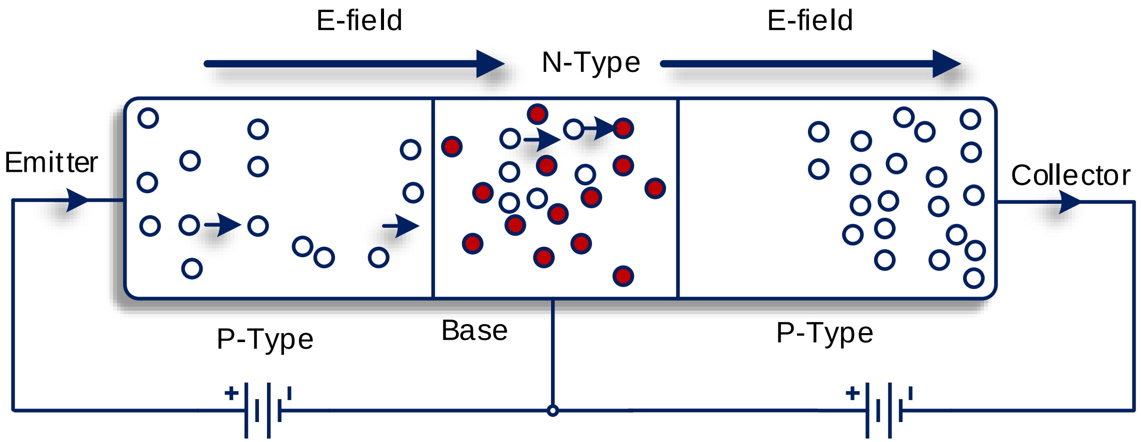
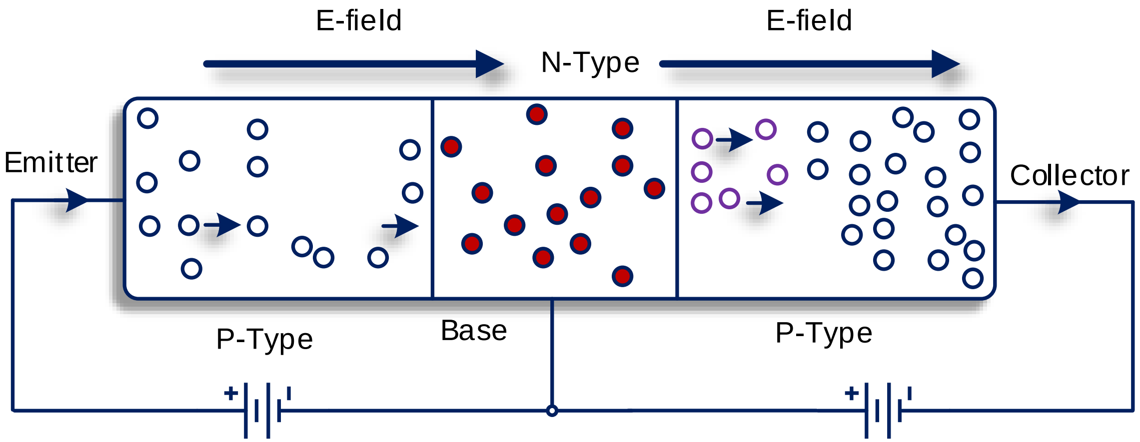
- Still consider the transistor biased in forward-active mode
- B-E junctions is forward biased
  - Holes are flow from the emitter in the based
- B-C junction is reversed bias
  - Hole concentration at the interface (B-C) of the junction is nearly zero
  - Then the Hole in the base region is attracting to collector region by a combination force with **diffusion** and **electric field** force.



Forward-active mode (PNP)







Emitter and collector Current

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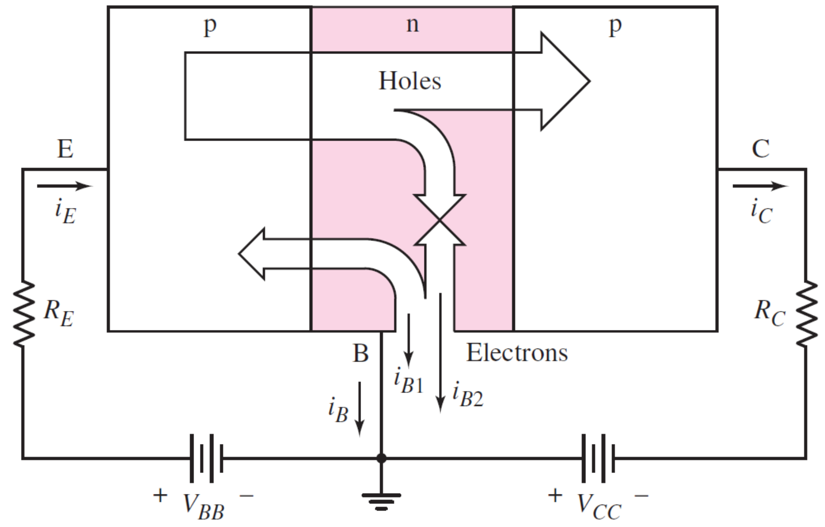
- The B-E junction is forward biased, the current through this junction to be exponential function of B-E voltage, sider that $V_{EB} >> V_T$

$$i_E = i_{EO}\left(e^{\frac{v_{EB}}{V_T}} - 1\right) \cong i_{EO}e^{\frac{v_{EB}}{V_T}}$$



- The collector current is an exponential function of the E-B voltage

$$i_c = \alpha i_E = i_{EO}e^{\frac{v_{EB}}{V_T}}$$

Base current (PNP)

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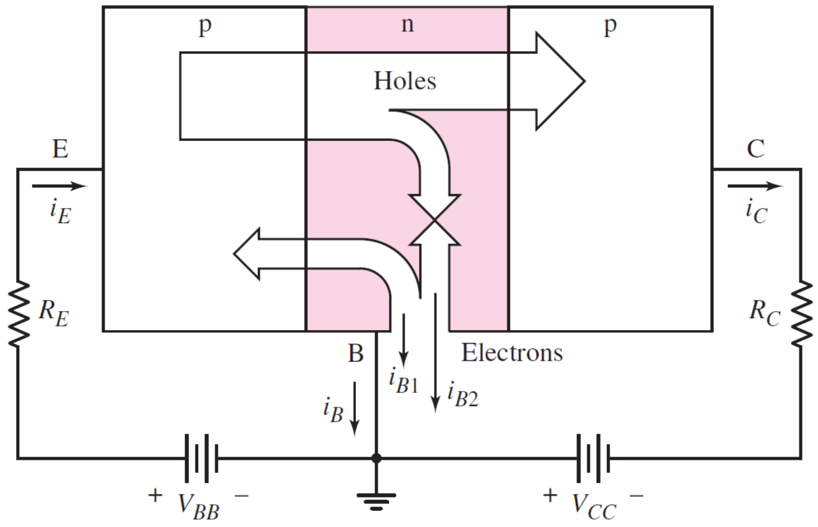
- E-B junction is forward biased
  - Electrons from the base are injected in to the emitter due the electric filed, I_{B1}
- A few Electrons recombine with the holes coming from the emitter, this current is recombination current, I_{B2}

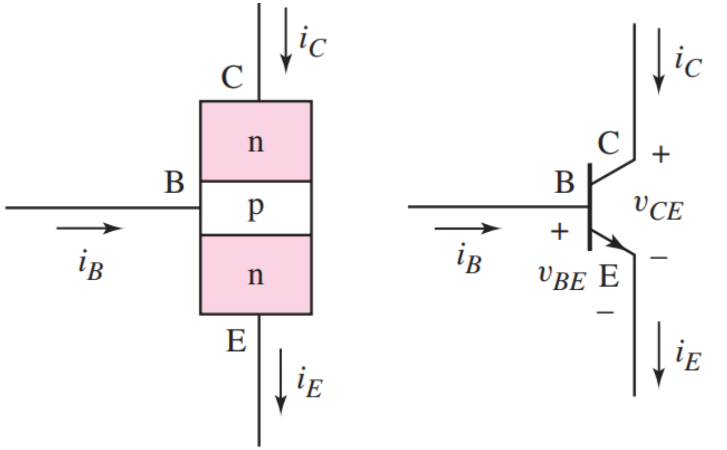
$$i_B = i_{B1} + i_{B2}$$

- But the base current is extremely **small**

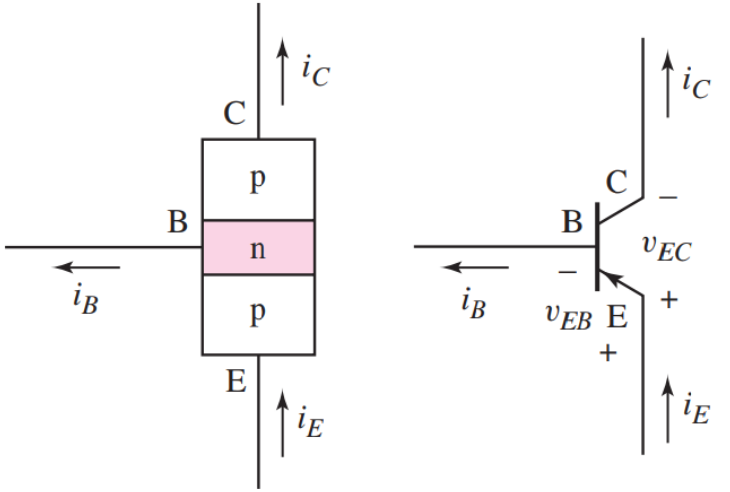


Circuit symbol

- For npn device
  - Direction of the emitter current: out of the emitter
  - Collector current: caused by the movement of Electron (电子运动产生电流)



- For pnp device
  - Direction of the emitter current: into the emitter
  - Collector current: caused by the movement of Hole (空穴运动产生电流)



Summary of BJT Equation

NPN	PNP
$i_E = i_{EO} e^{\frac{v_{BE}}{V_T}}$	$i_E = i_{EO} e^{\frac{v_{EB}}{V_T}}$
$i_c = \alpha i_E = i_{EO} e^{\frac{v_{BE}}{V_T}}$	$i_c = \alpha i_E = i_{EO} e^{\frac{v_{EB}}{V_T}}$
$i_B = i_C / \beta$	$i_B = i_C / \beta$

For both transistors
$i_E = i_B + i_C \quad i_E = (1+\beta)\, i_B \quad i_C = \beta i_B \quad i_C = \alpha i_B$
$\alpha = \dfrac{\beta}{1+\beta} \rightarrow \beta = \dfrac{\alpha}{1-\alpha}$

Reinforce Your Learning (Exercise)

- An npn transistor is based in the forward-active mode. The base current is I_B = 5μA and the collector current is I_c = 0.62mA. Determine I_E, β, and α.

- **Solution**

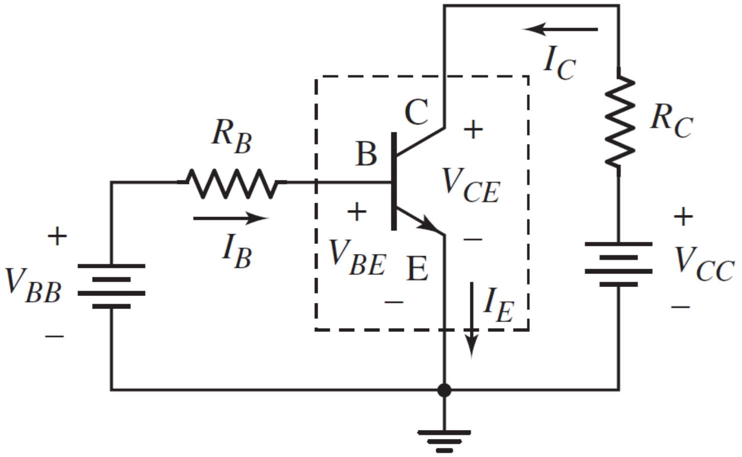
DC Analysis of Transistor Circuit

Understand and become familiar with the DC analysis and design techniques of bipolar transistor circuits

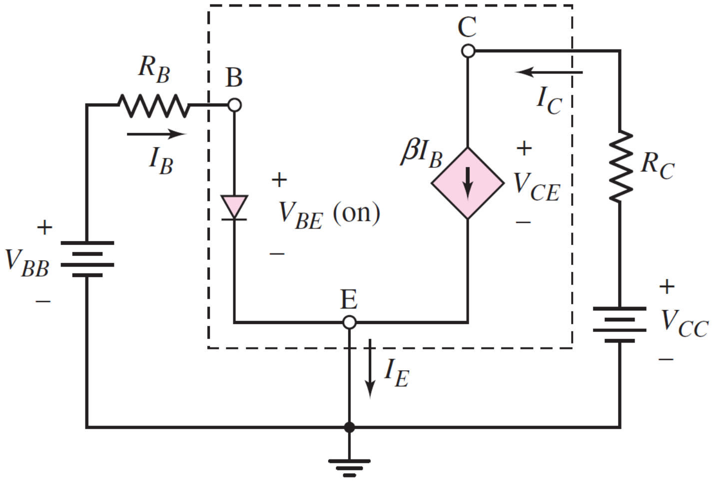
Common Emitter circuit

- In forward-active region
  - B-E junction is forward biased, voltage drop is $V_{BE(on)}$
  - B-C junction is reverse biased, it can be regarded as a dependent current source $I_C = \beta I_B$

Voltage controlled current source (VCCS): is a current source where the current is controlled by a voltage elsewhere in the circuit. Where? we will find it



Common-emitter circuit



DC equivalent circuit

Common Emitter circuit (NPN)

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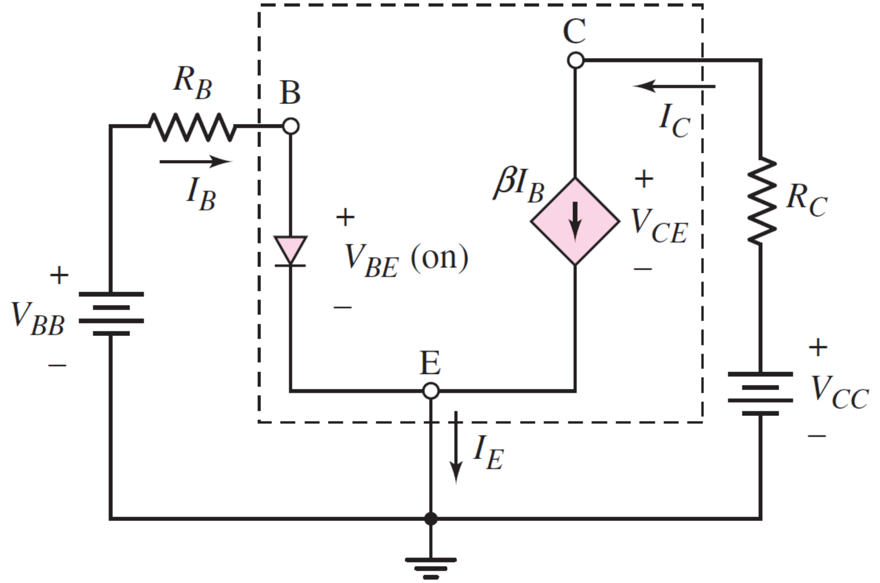
- The base current is

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

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



- The power dissipated on the transistor is

$$P_T = I_B V_{BE(on)} + I_C V_{CE}$$

BJT in saturation mode

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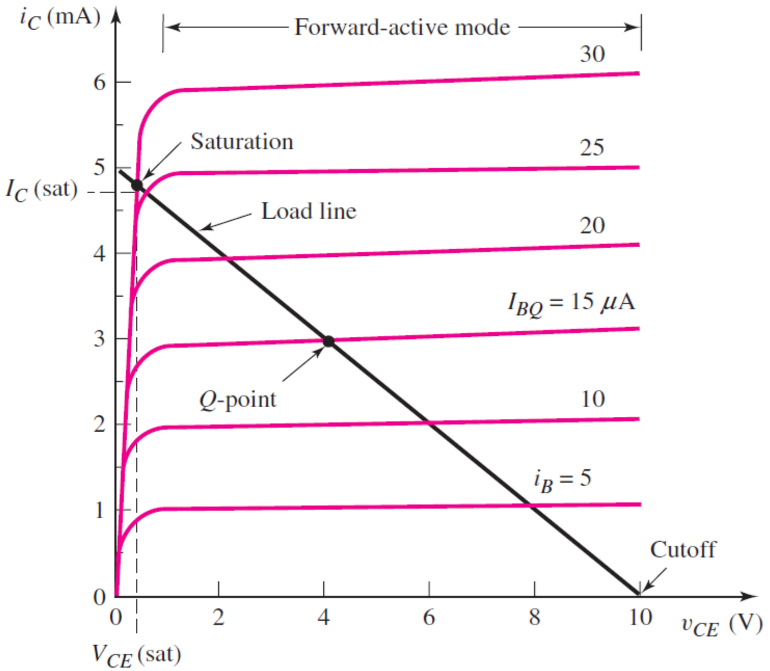
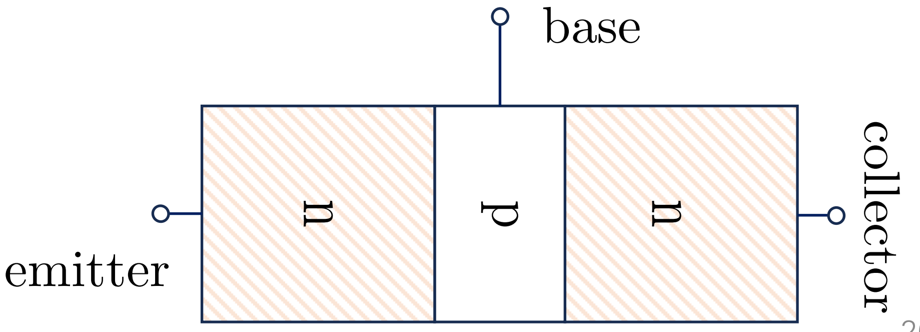
- For the C-E portion of the circuit

$$I_B = \frac{V_{BB} - V_{BE(on)}}{R_B} \qquad V_{CE} = V_{CC} - I_C R_C$$

- If we increase V_{BB}, I_B increase. To a point that I_c no longer increase, BJT switches to **Saturation mode**
  - B-C junction becomes forward biased
  - C-E voltage in saturation $V_{CE(sat)}$, constant value in range of **0.1 to 0.3V**





Common-Emitter Circuit (PNP)

- In forward-active region
  - B-E junction is forward biased, voltage drop is $V_{EB(on)}$
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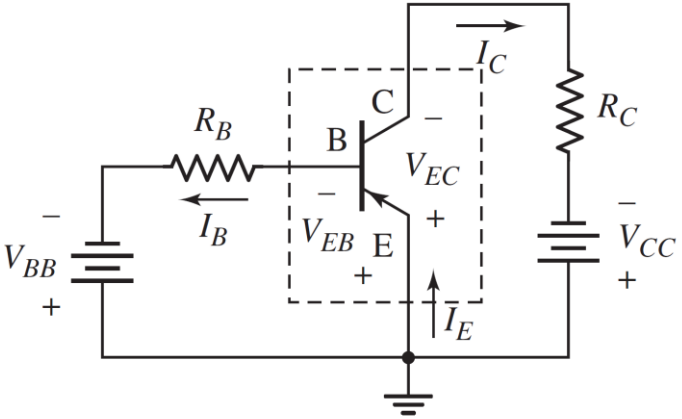
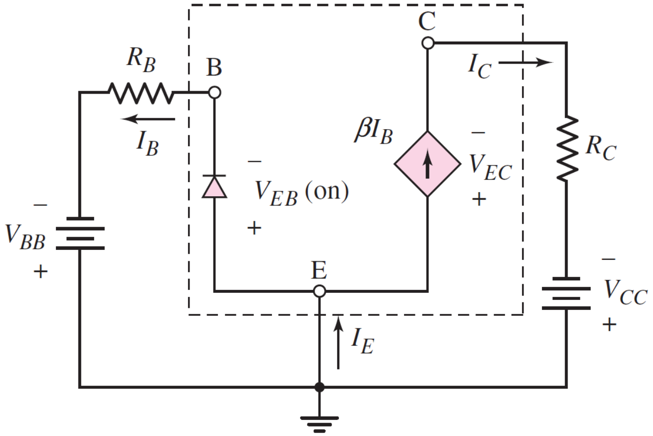


Common-emitter circuit



DC equivalent circuit

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Common-Emitter Circuit (PNP)

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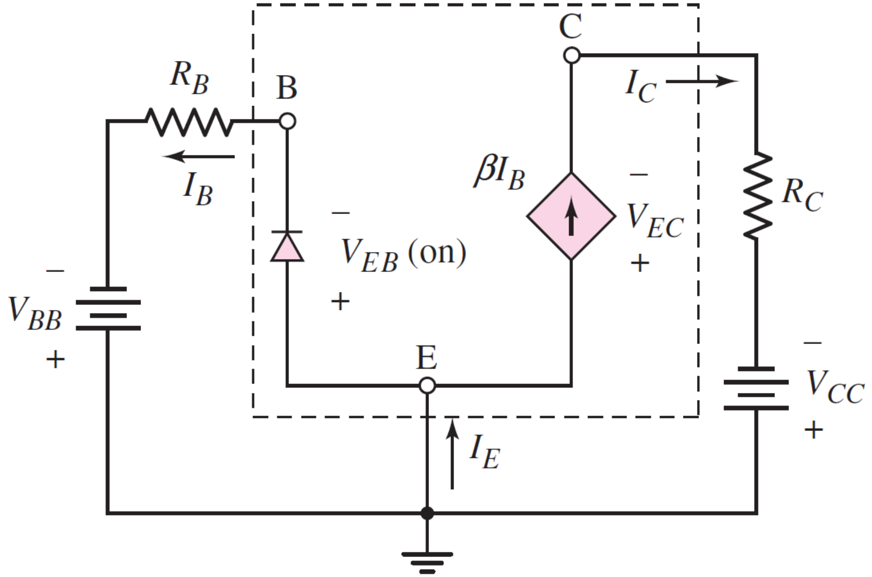
- The base current is

$$I_B = \frac{-V_{EB(on)} + V_{BB}}{R_B}$$

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



- The power dissipated is

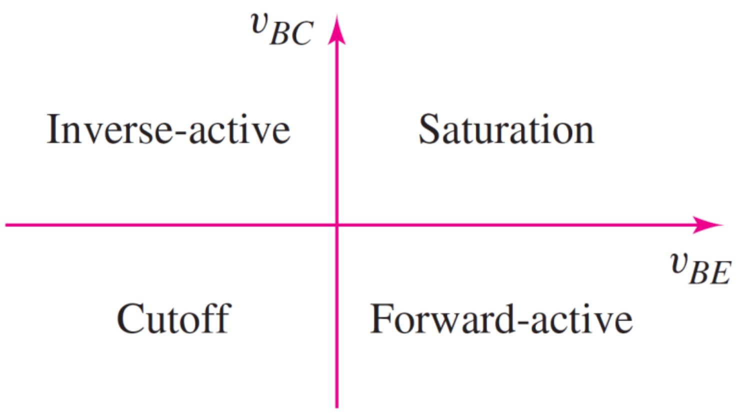
$$P_T = I_B V_{BE(on)} + I_C V_{EC}$$

Problem-Solving Technique

- As usual, we still need to make assumptions. Assume the state of the transistor, then analyze the circuit to determine if we have a solution consistent with initial guess

1. Assume that the BJT is biased in the forward-active mode

$$V_{BE} = V_{BE(on)} \qquad I_B > 0 \qquad I_C = \beta I_B$$



2. Analyze the "linear" Circuit with this assumption

3. Evaluate the resulting state of transistor
   - If $V_{CE} > V_{CE(sat)}$, assumption is correct

4. If the initial assumption is incorrect, we need make a new assumption and return to Step 2

Reinforce Your Learning (Exercise)

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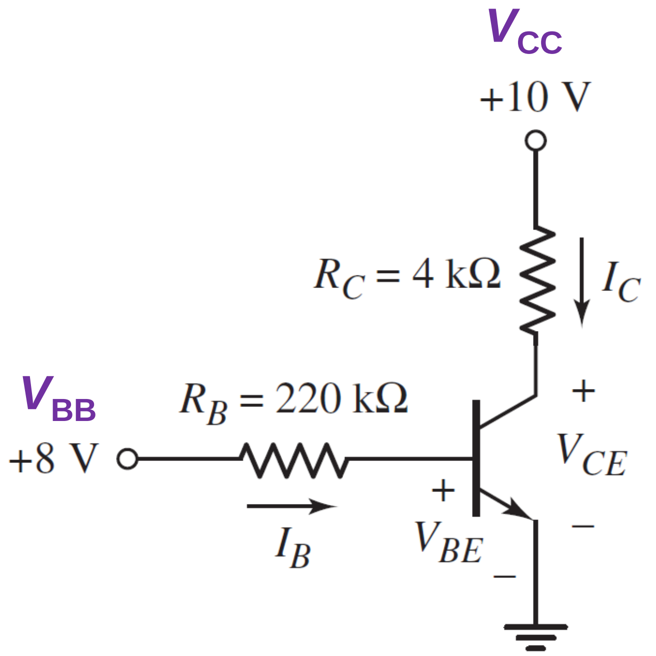
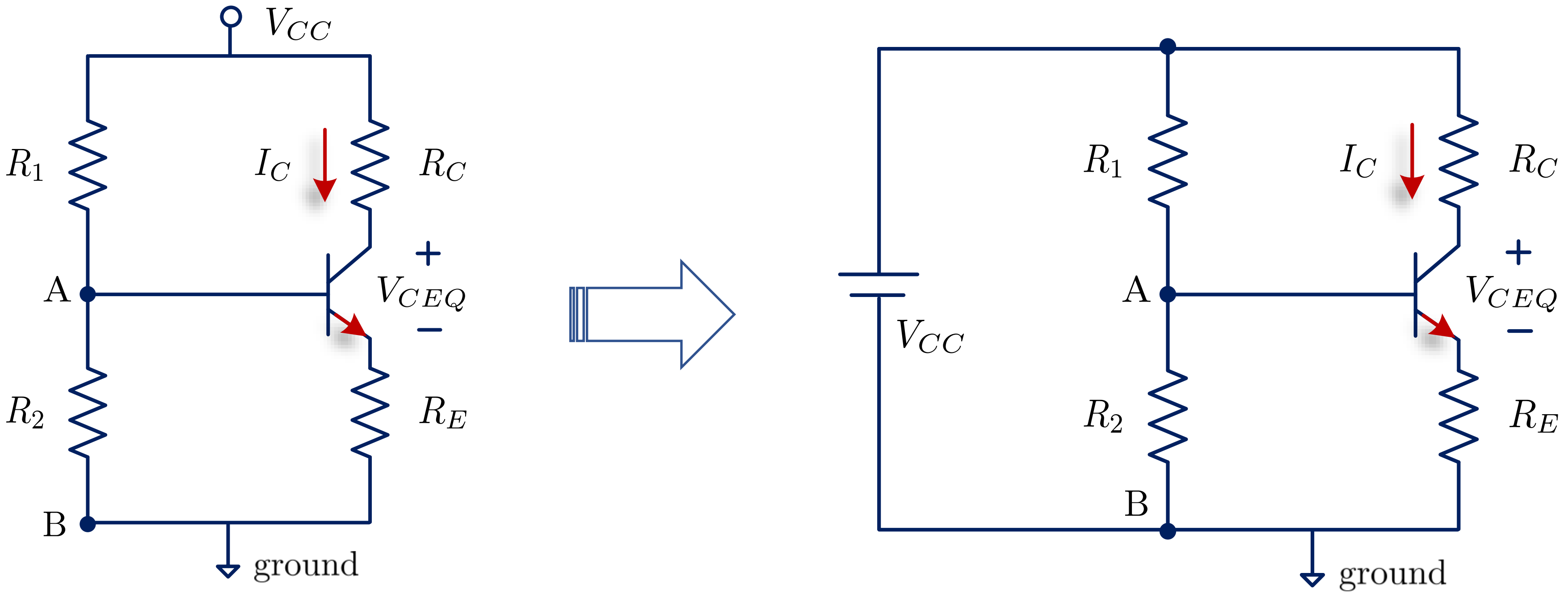
- Calculate the emitter currents and C-E voltages in a circuit. The transistor parameters are β = 100, and V_{BE}(ON) = 0.7V. If the transistor is biased in saturation, assume V_{CE}(sat)=0.2V.

- **Solution** Try to assume the transistor is biased in the forward-active region



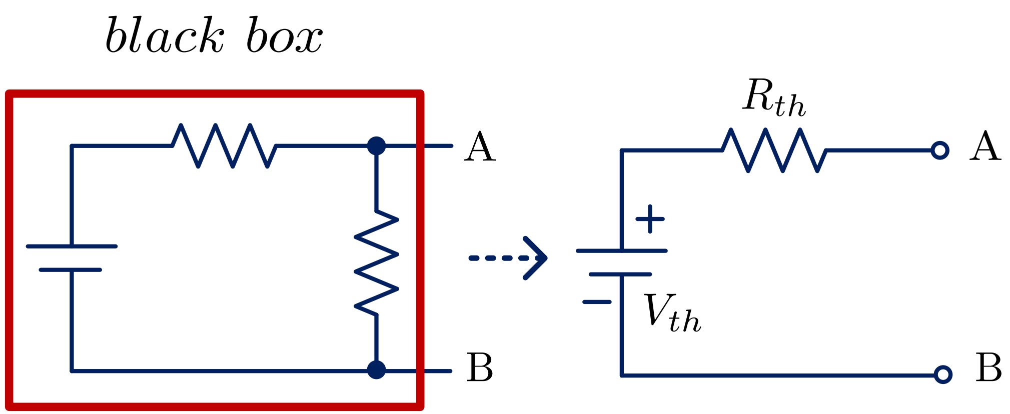
Voltage Divider Biasing

- The circuit below is a common-emitter circuit with an emitter resistor and voltage divider bias circuit in the base. R_1 and R_2 are the bias resistor. R_C is the collector resistor and R_E is the emitter resistor.
- The **Thevenin equivalent circuit** can be used to analyze this circuit



Thevenin Equivalent Circuit

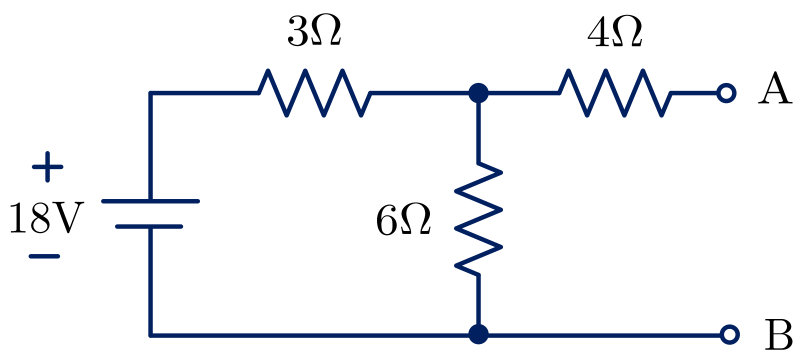
- Thevenin equivalent circuit is the content in EEE103. Let us review it together.



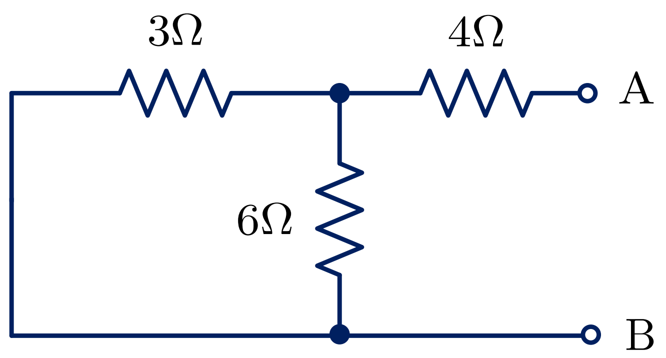
- Any combination of voltage and resistances with two terminals can be replaced by a single voltage source V_{th} and a single series resistor R_{th}

- V_{th} :The open-circuit voltage at the output of the original circuit;
- R_{th} :The resistance measured across output into the circuit, by replacing voltage source with short circuit and current source with open circuit

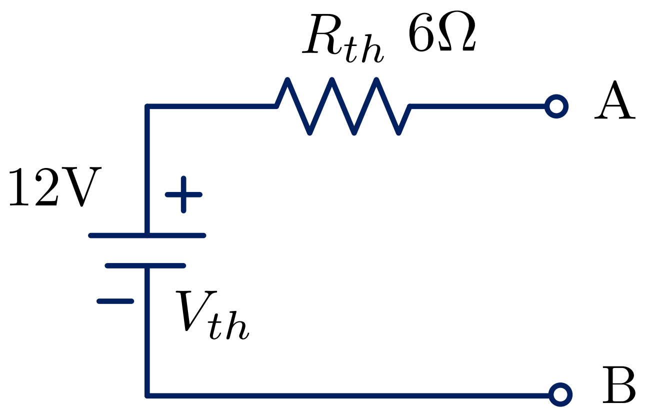
Example of Thevenin Circuit



$$V_{th} = V_{AB} = 18 \times \left(\frac{6}{6+3}\right) = 12V$$



$$R_{th} = 4 + (6 \parallel 3) = 6\Omega$$

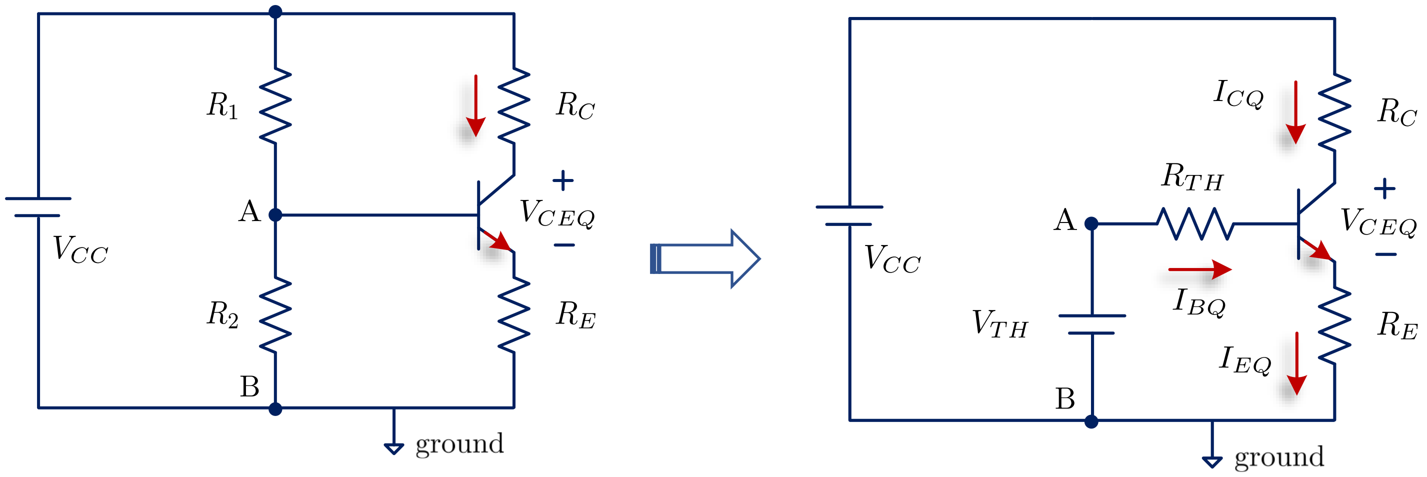


Thevenin Equivalent Circuit

- Thevenin equivalent circuit

$$V_{TH} = \frac{R_2}{R_1 + R_2} V_{CC}$$

$$R_{TH} = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2}$$



- Apply KVL around the B-E Loop

$$V_{TH} = I_{BQ} R_{TH} + V_{BE}(on) + I_{EQ} R_E$$

Q here for quiescent, indicating the value for **DC** component

$$I_{EQ} = (1+\beta) I_{BQ} \qquad I_{BQ} = \frac{V_{TH} - V_{BE}(on)}{R_{TH} + (1+\beta) R_E} \qquad I_{CQ} = \beta I_{BQ}$$

$$\Rightarrow \quad V_{CEQ} = V_{CC} - I_{CQ} R_C - I_{EQ} R_E$$

Assume transistor biased in active region

Reinforce Your Learning (Exercise)

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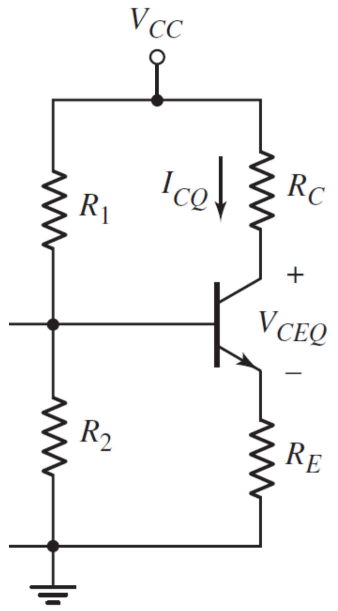
- Analyze a circuit using a voltage divider bias circuit. Determine the value of R_{th}, V_{TH}, I_{BQ}, I_{CQ} and V_{CEQ}. R_1 = 56kΩ, R_2 = 12.2kΩ, R_C = 2kΩ, R_E = 0.4kΩ, V_{CC} = 10V, $V_{BE}(on)$ = 0.7V, β = 100

- **Solution** Using the Thevenin equivalent circuit



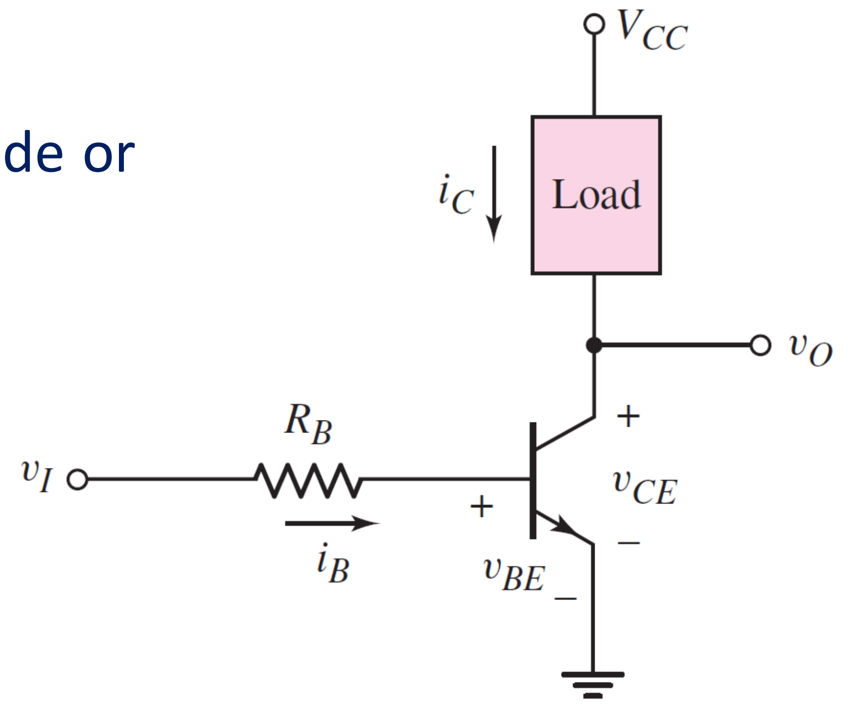
Basic Transistor Applications

Examine three applications of bipolar transistor circuits: a switch circuit, digital logic circuit, and an amplifier circuit.

Transistor Inverter circuit

- The bipolar circuit shown below is called an inverter
  - The transistor is switched between cutoff and saturation
- The load in this circuit could be a motor, a light-emitting diode or some other electrical device
- If $V_i < V_{BE}(ON)$
  - The transistor is cutoff, $i_c = 0$, $v_o = V_{CC}$
- If $V_i = V_{CC}$
  - The transistor is driven to saturation, $v_o = V_{CE}(sat)$

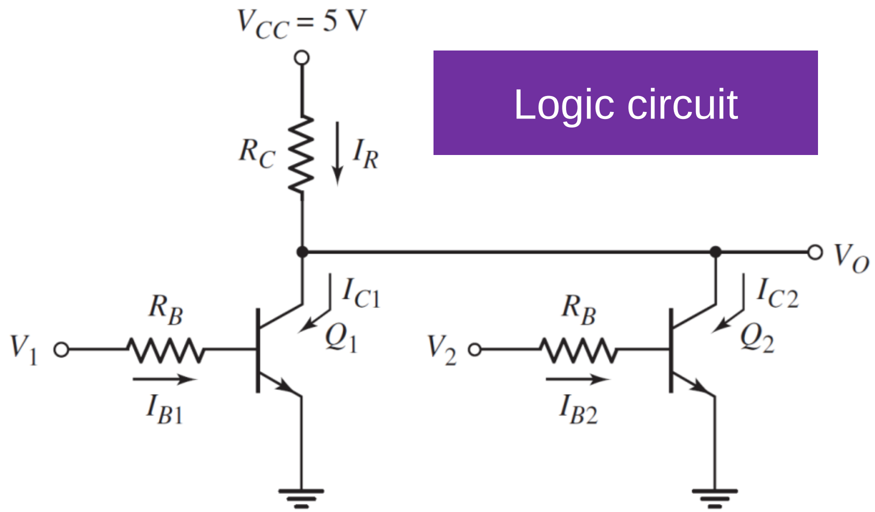
$$i_C = I_C(sat) = \frac{V_{CC} - V_{CE}(sat)}{R_C}$$



Inverter circuit

Digital Logic Circuit

- When $V_1 = V_2 = 0$ (Q$_1$ and Q$_2$ are cutoff. $V_o = V_{CC}$ high-level
- When $V_1 = 5$V and $V_2 = 0$V
  - Q$_1$ is in saturation, and Q$_2$ is cutoff
  - $V_o = V_{CE}(sat) = 0.2$V
- When $V_1 = 0$V and $V_2 = 5$V
  - Q$_1$ is in cutoff, and Q$_2$ is in saturation
  - $V_o = V_{CE}(sat) = 0.2$V
- When $V_1 = V_2 = 5$V
  - Q$_1$ and Q$_2$ is in saturation
  - $V_o = V_{CE}(sat) = 0.2$V



Logic circuit

Bipolar NOR logic circuit response		
V_1(V)	V_2(V)	V_O(V)
0	0	**5 High**
5	0	0.2 Low
0	5	0.2 Low
5	5	0.2 Low

Amplifier

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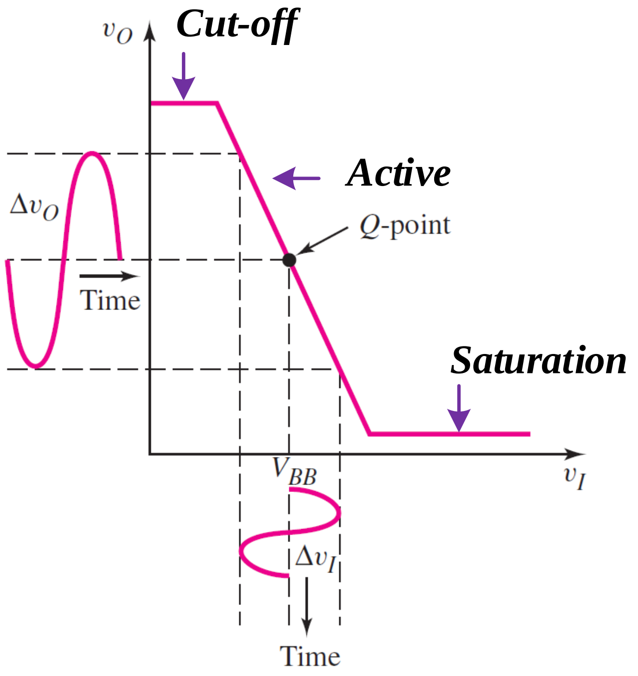
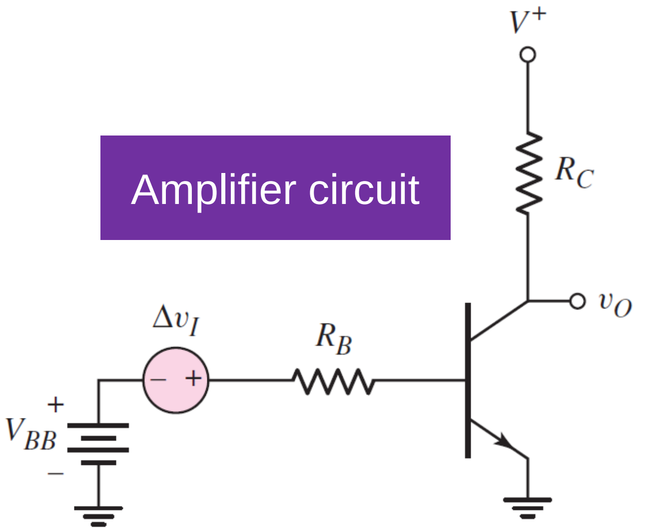
- The bipolar circuit can also be used to amplify a time-varying signal. In this circuit:
  - Δv_I is a time-varying voltage source (ac signal)
  - V_{BB} is a constant DC-voltage. The function is to bias the transistor in the active region



Transfer Characteristic

Amplifier circuit



- If the magnitude of the slope of the transfer characteristic is greater than 1, then the time-varying output signal will be greater than the time-varying input signal

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- The following circuit is a transistor inverter circuit. Determine the R_B such that V_o = 0.2V and I_C/I_B = 20 when V_I = 5V, and $V_{BE}(ON)$=0.7V

- **Solution**