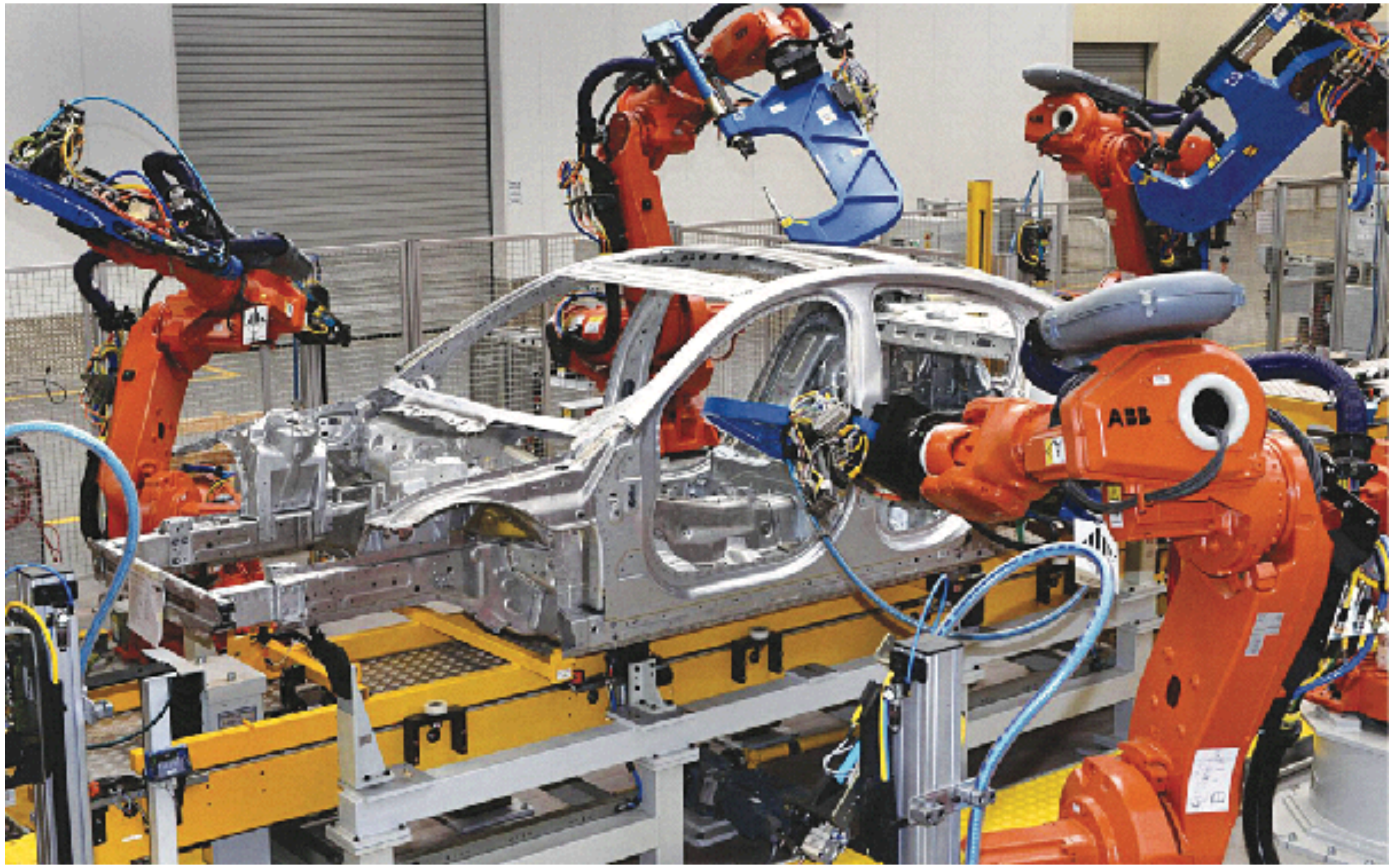
Electronics



Dr. Lana Damaj

Chapter 3

Chapter 2: Summary

- In addition to the exponential and constant-voltage models, an "ideal" model is sometimes used to analyze diode circuits. The ideal model assumes the diode turns on with a very small forward bias voltage.
- For many electronic circuits, the "input/output characteristics" are studied to understand the response to various input levels, e.g., as the input level goes from $-\infty$ to $+\infty$.
- Half-wave rectifiers pass the positive (negative) half cycles of the input wave- from and block the negative (positive) half cycles. If followed by a capacitor, a rectifier can produce a dc level nearly equal to the peak of the input swing.

$$V_R \approx \frac{V_p - V_{D,on}}{R_L} \cdot \frac{T_{in}}{C_1}$$

- Full-wave rectifiers convert both positive and negative input cycles to the same polarity at the output. If followed by a smoothing capacitor and a load resistor.

$$V_R \approx \frac{1}{2} \cdot \frac{V_p - 2V_{D,on}}{R_L C_1 f_{in}}$$

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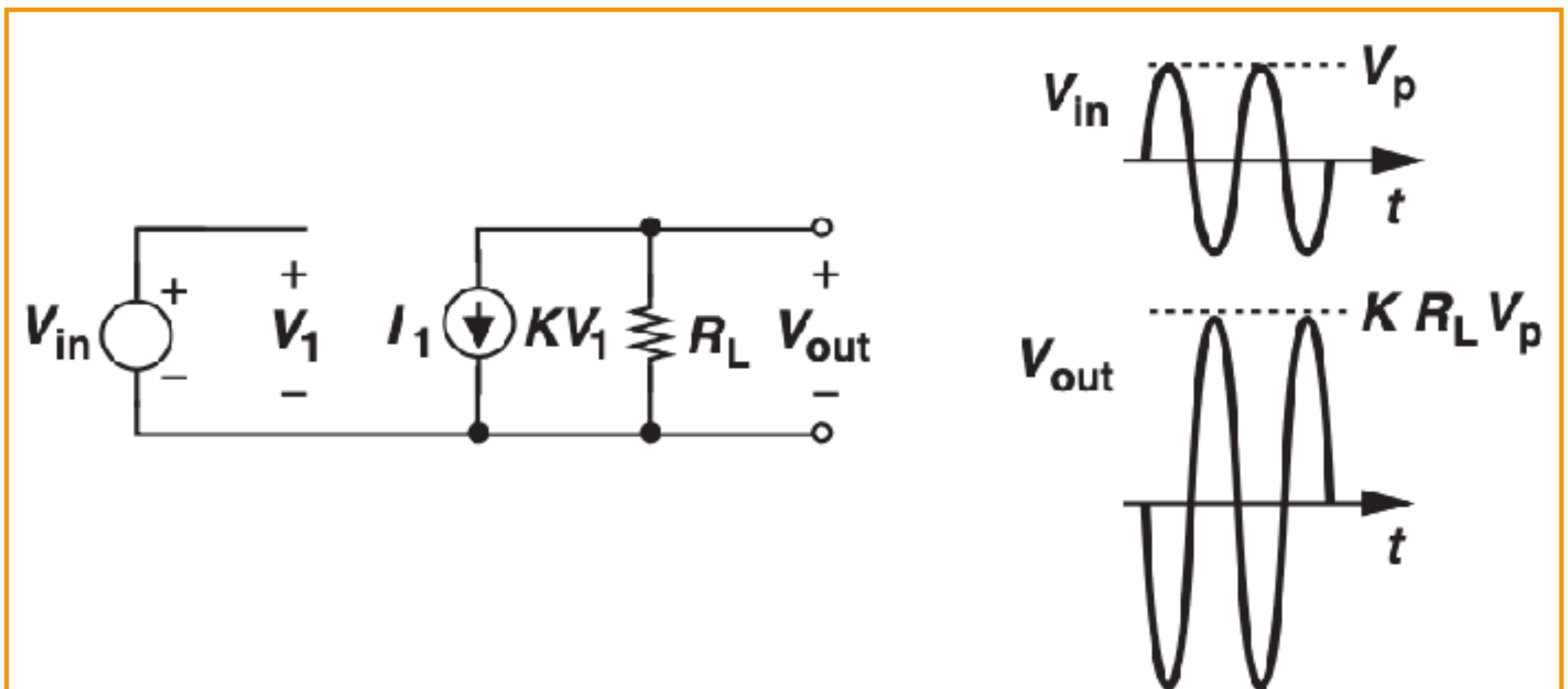
Chapter 3: Bipolar transistor

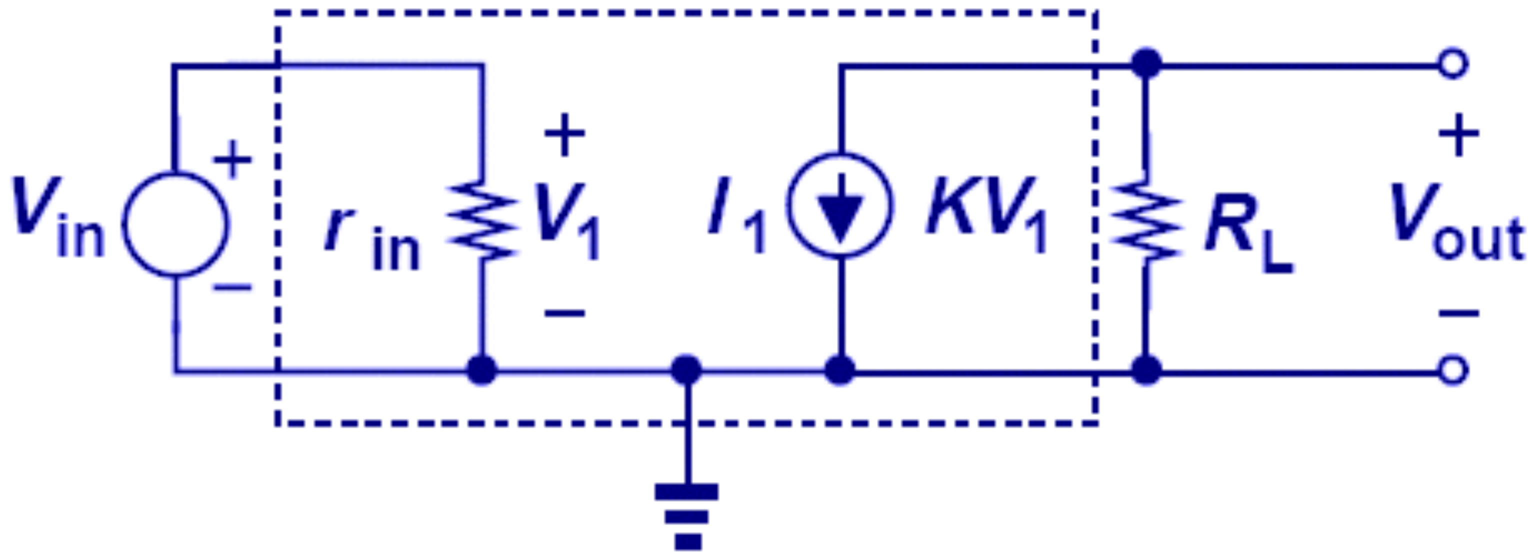
- General Considerations
- Structure of Bipolar Transistor
- Operation of Bipolar Transistor in Active Mode
- Bipolar Transistor Models
- The PNP Transistor

GENERAL CONSIDERATIONS

- In its simplest form, the bipolar transistor can be viewed as a voltage-dependent current source.
- We first show how such a current source can form an amplifier and hence why bipolar devices are useful and interesting.
- Consider the voltage-dependent current source depicted in Fig. below, where I_1 is proportional to V_1: $I_1 = KV_1$. Note that K has a dimension of resistance.
- $V_{out} = -R_L K V_1$, where $V_1 = V_{in}$.
- The amplification factor or "voltage gain" of the circuit, A_V, is defined as $A_v = V_{out}/V_{in} = -KR_L$
- 

GENERAL CONSIDERATIONS

- Example 1: Consider the circuit shown in Fig. below, where the voltage-controlled current source exhibits an "internal" resistance of r_{in}. Determine the voltage gain of the circuit.



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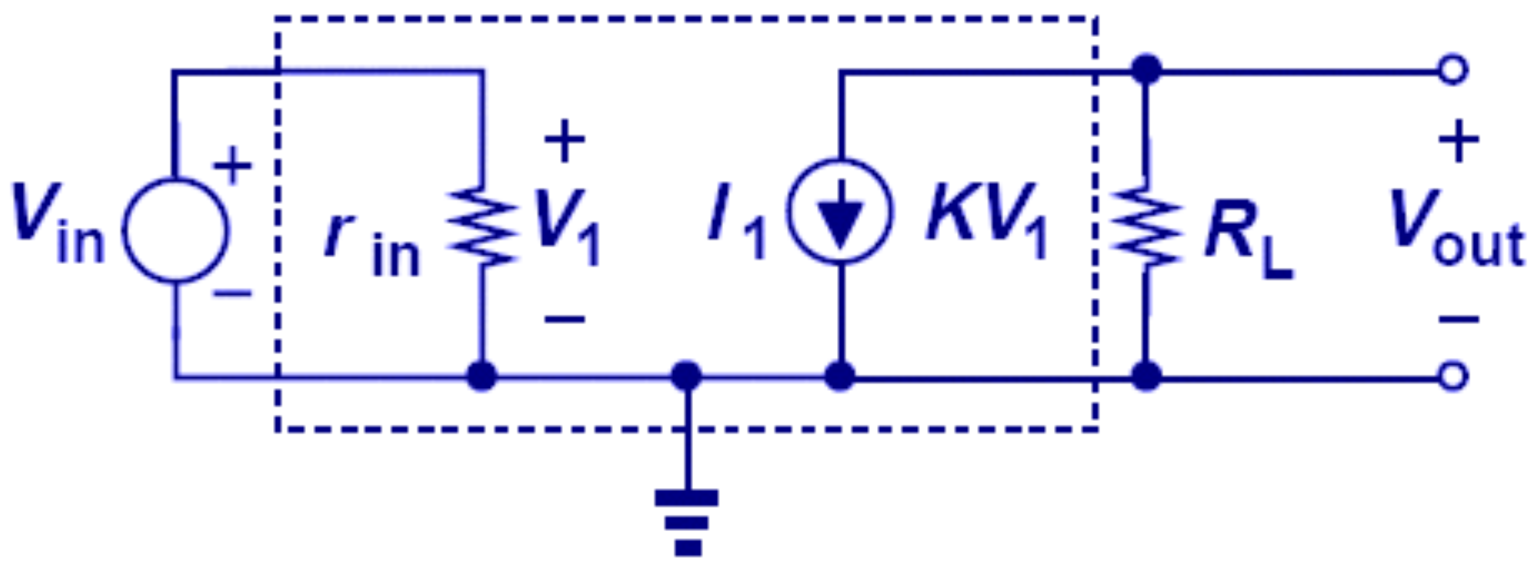
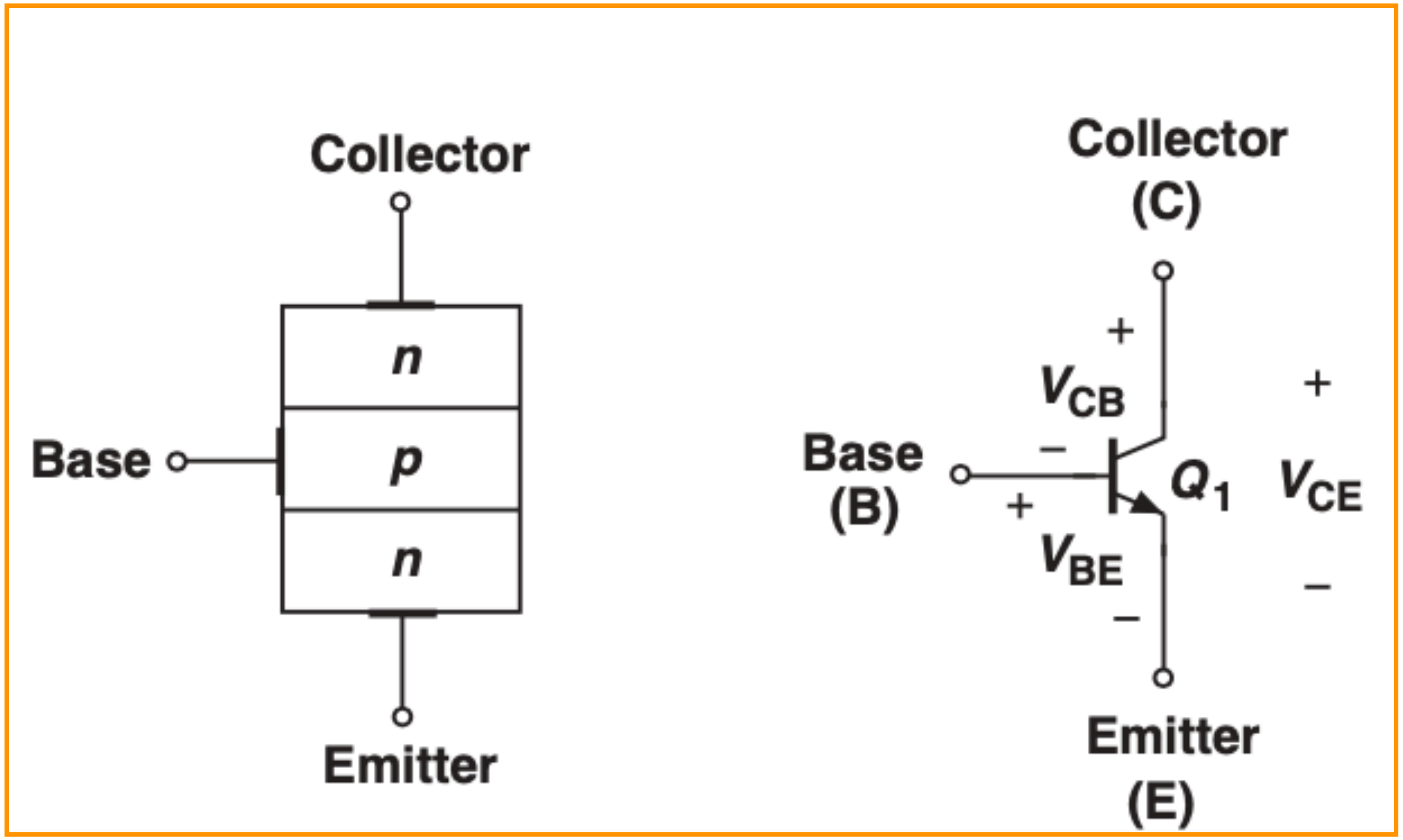


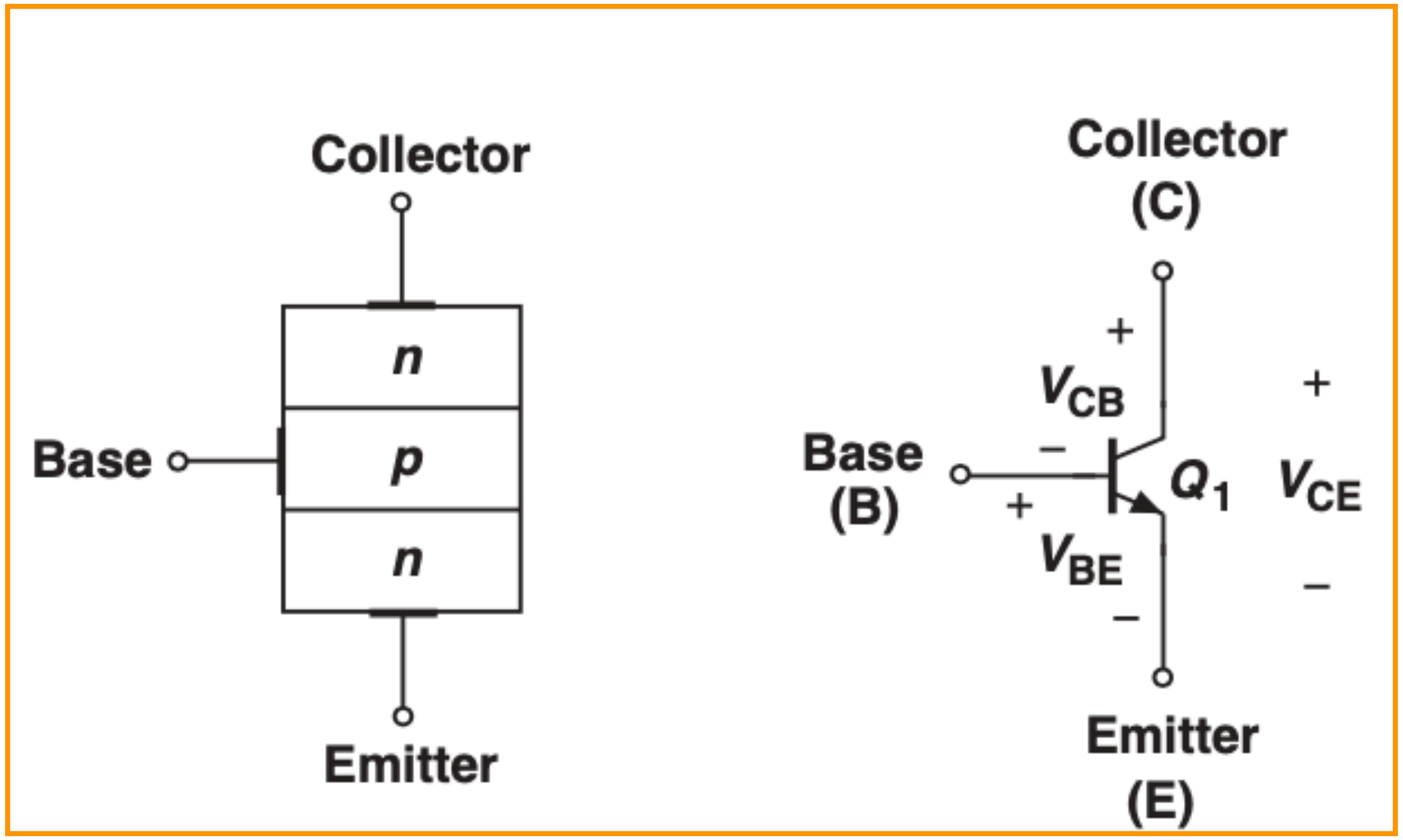
- Solution: $V_1 = V_{in}$, regardless the value of r_{in}
- $A_v = \dfrac{V_{out}}{V_{in}}$, where $V_{out} = -R_L K V_1$
- $\Longrightarrow A_v = -R_L K$

STRUCTURE OF BIPOLAR TRANSISTOR

- The bipolar transistor consists of three doped regions forming a sandwich.
- Shown in Fig. below is an example comprising of a *p* layer sandwiched between two *n* regions and called an "*npn*" transistor.
- The three terminals are called the "base," the "emitter," and the "collector."
- The emitter "emits" charge carriers and the collector "collects" them while the base controls the number of carriers that make this journey.



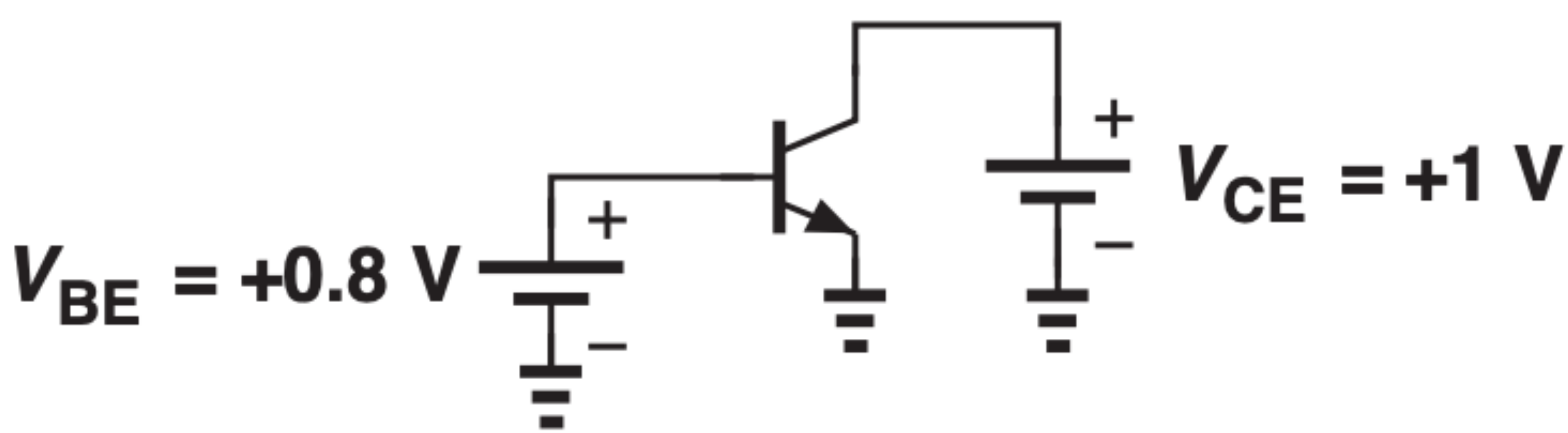
STRUCTURE OF BIPOLAR TRANSISTOR



- The device contains two *pn* junction diodes: one between the base and the emitter and another between the base and the collector.
- For example, if the base is more positive than the emitter, $V_{BE} > 0$, then this junction is forward-biased.
- While this simple diagram may suggest that the device is symmetric with respect to the emitter and the collector, in reality, the dimensions and doping levels of these two regions are quite different.
- In other words, *E* and *C* cannot be interchanged.

OPERATION OF BIPOLAR TRANSISTOR IN ACTIVE MODE

- In this section, we analyze the operation of the transistor, aiming to prove that, under certain conditions, it indeed acts as a voltage-controlled current source.
- More specifically, we intend to show that (a) the current flow from the emitter to the collector can be viewed as a current source tied between these two terminals, and (b) this current is controlled by the voltage difference between the base and the emitter, V_{BE}.
- The base-emitter junction is forward biased ($V_{BE} > 0$) and the base-collector junction is reverse-biased ($V_{BC} < 0$). Under these conditions, we say the device is biased in the "forward active region" or simply in the "active mode."



- $$V_{BC} = 0.8 - 1 = -0.2V < 0$$

Collector current

$$I_C = \frac{A_E q D_n n_i^2}{N_E W_B}\left(\exp\frac{V_{BE}}{V_T} - 1\right)$$

$$I_C = I_S \exp\frac{V_{BE}}{V_T}$$

$$I_S = \frac{A_E q D_n n_i^2}{N_E W_B}$$

W_B: Width of the base region

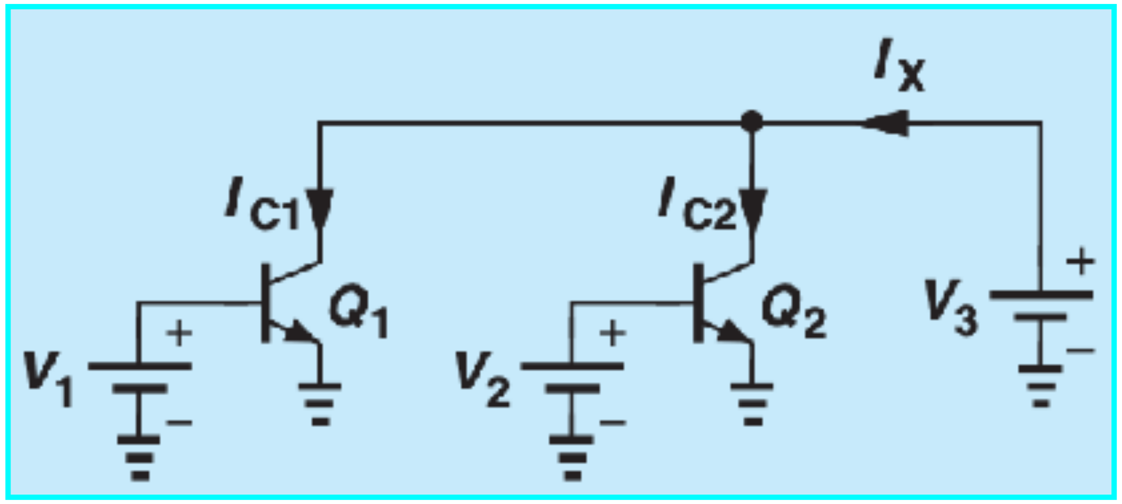
A_E: Emitter cross section

N_E: Emitter doping concentration

- Applying the law of diffusion, we can determine the charge flow across the base region into the collector.
- The equation above shows that the transistor is indeed a voltage-controlled element, thus a good candidate as an amplifier.

Collector current

- Example 2: In the circuit of Fig. below, Q_1 and Q_2 are identical and operate in the active mode. Determine $V_1 - V_2$ such that $I_{C1} = 10I_{C2}$.



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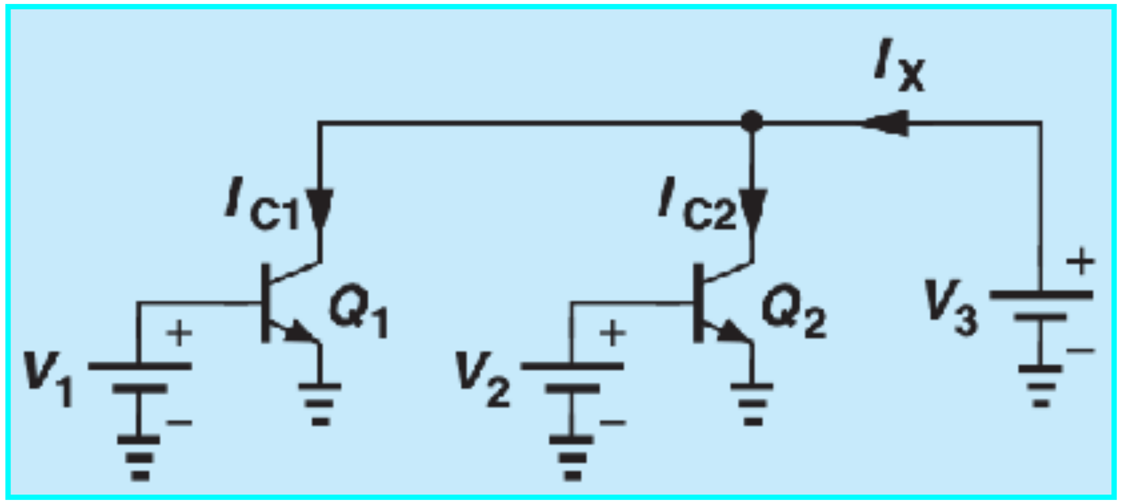
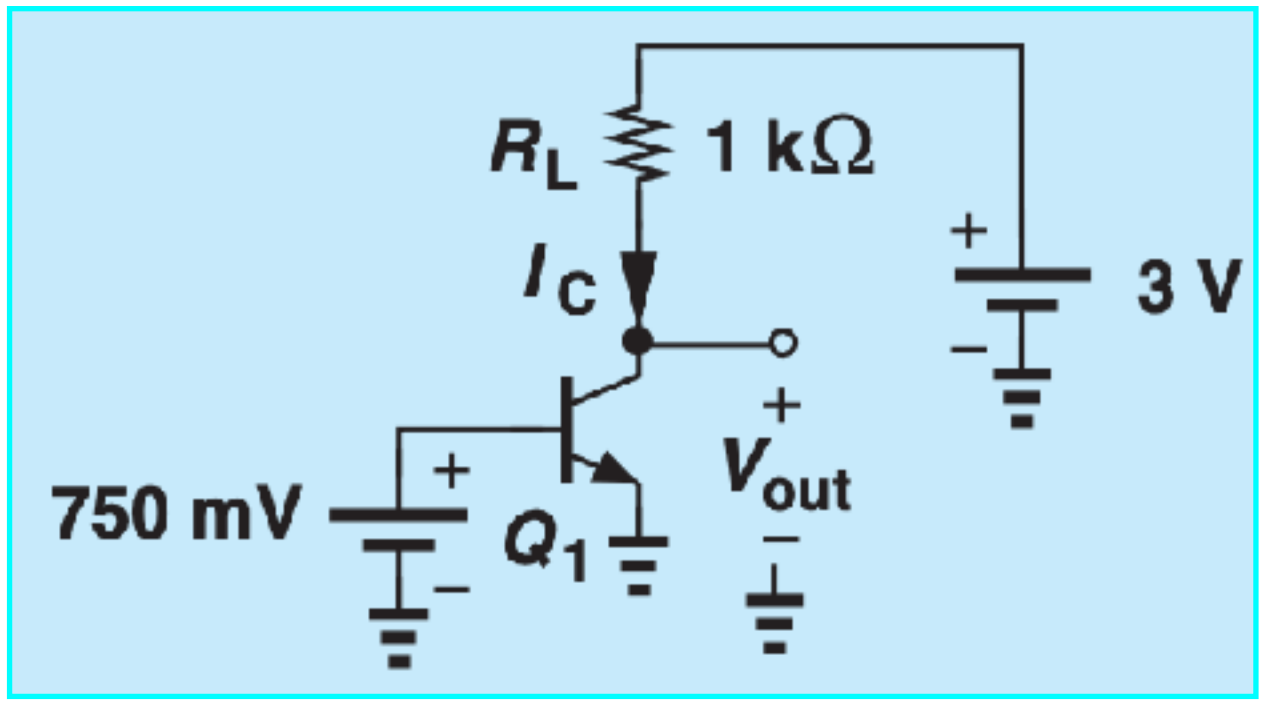
$$I_C = I_S \exp\frac{V_{BE}}{V_T}$$



- Solution:
- $$\frac{I_{C1}}{I_{C2}} = \frac{I_s \times exp(\frac{V_1}{V_T})}{I_s \times exp(\frac{V_2}{V_T})} = exp(\frac{V_1 - V_2}{V_T}) = 10$$
- $$\Longrightarrow V_1 - V_2 = V_T ln(10)$$
-

Collector current

- Example 3: Determine the output voltage in Fig. below if $I_S = 5 \times 10^{-16}$ A.



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Collector current

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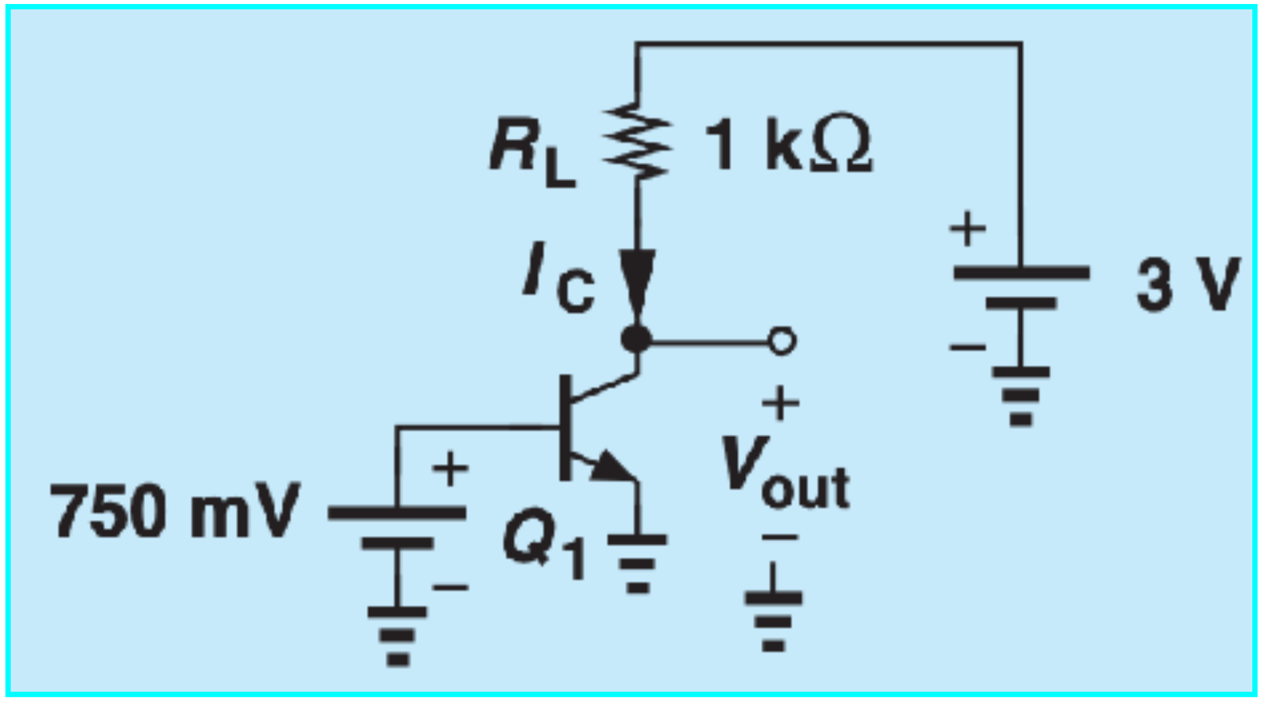

- Solution:
- $I_C = I_s \times exp(\frac{V_{BE}}{V_T}) = 5\times 10^{-16} exp(\frac{750}{26}) = 1.685\times 10^{-3} A \rightarrow 1.685 mA$
- $V_{out} = V_{CE} = 3 - R_L I_C = 1.315V$
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Base and emitter currents

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

$$I_C = I_S \exp\frac{V_{BE}}{V_T}$$

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

$$I_B = \frac{1}{\beta} I_S \exp\frac{V_{BE}}{V_T}$$

$$I_E = I_C + I_B$$

$$I_E = \frac{\beta + 1}{\beta} I_S \exp\frac{V_{BE}}{V_T}$$

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

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

- Applying Kirchoff's current law to the transistor, we can easily find the emitter current.
- β is called the "current gain" of the transistor
- For $\beta = 100$, $\alpha = I_C/I_E = 0.99 \approx 1$ and $I_C \approx I_E$… reasonable approximations

Base and emitter currents

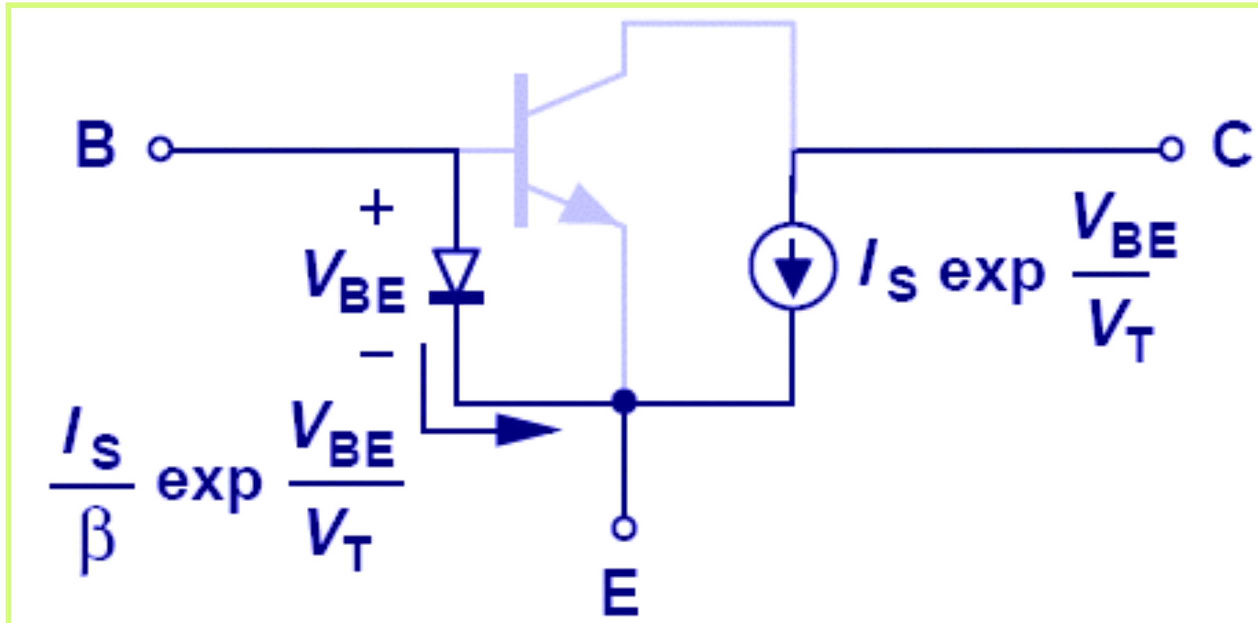
- Example 3: A bipolar transistor having $I_S = 5 \times 10^{-16}$ A is biased in the forward active region with V_{BE}=750mV. If the current gain varies from 50 to 200 due to manufacturing variations, calculate the minimum and maximum terminal currents of the device.

Base and emitter currents

- Example 3: A bipolar transistor having $I_S = 5 \times 10^{-16}$ A is biased in the forward active region with V_{BE}=750mV. If the current gain varies from 50 to 200 due to manufacturing variations, calculate the minimum and maximum terminal currents of the device.

- Solution:
- $50 < \beta < 200$
- $I_C = I_S exp(\frac{V_{BE}}{V_T}) = 1.685 \times 10^{-3} A$
- $\beta = I_c / I_B \Longrightarrow I_B = I_C / \beta$
- $8.43 \mu A < I_B < 33.7 \mu A$
- $\alpha = \frac{\beta}{\beta + 1} = \frac{I_C}{I_E}$
- $1.693 mA < I_E < 1.719 mA$

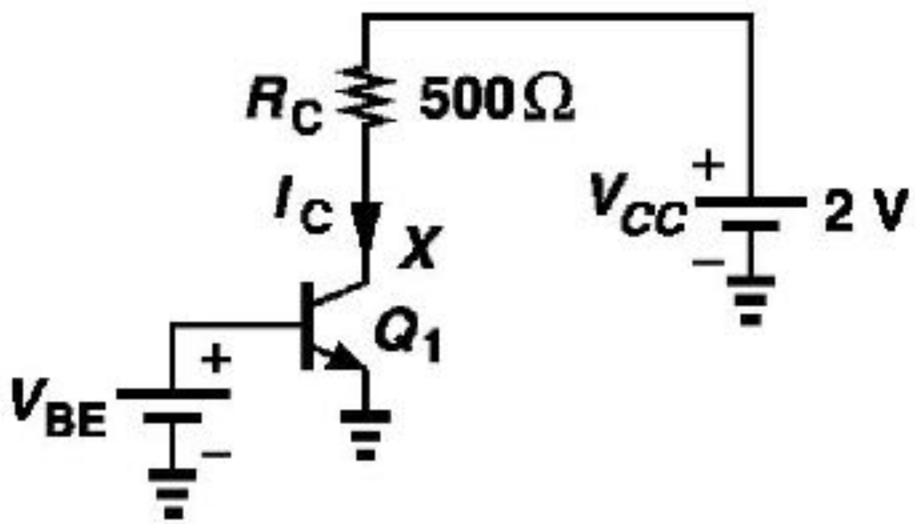
Bipolar Transistor Large Signal Model



- Since the base-emitter junction is forward-biased in the active mode, we can place a diode between the base and emitter terminals.
- Moreover, since the current drawn from the collector and flowing into the emitter depends on only the base-emitter voltage, we add a voltage-controlled current source between the collector and the emitter.
- A diode is placed between base and emitter and a voltage controlled current source is placed between the collector and emitter.

Bipolar Transistor Large Signal Model

- Example 4: Consider the circuit shown in Fig. below, where $I_{S,Q1} = 5 \times 10^{-17}$ A and $V_{BE} = 800$ mV. Assume $\beta = 100$.
- (a) Determine the transistor terminal currents and voltages and verify that the device indeed operates in the active mode.
- (b) Determine the maximum value of R_C that permits operation in the active mode.



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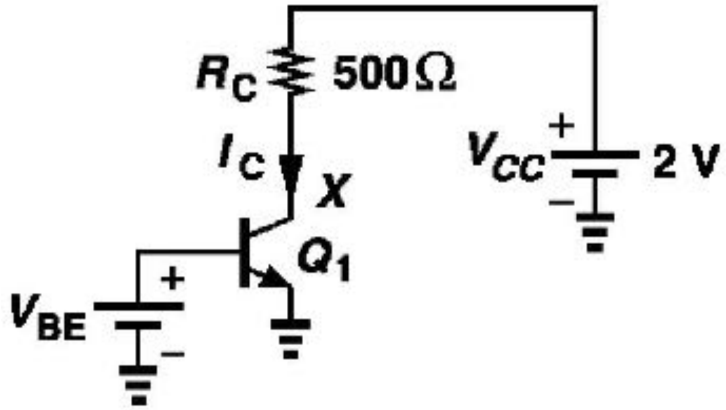
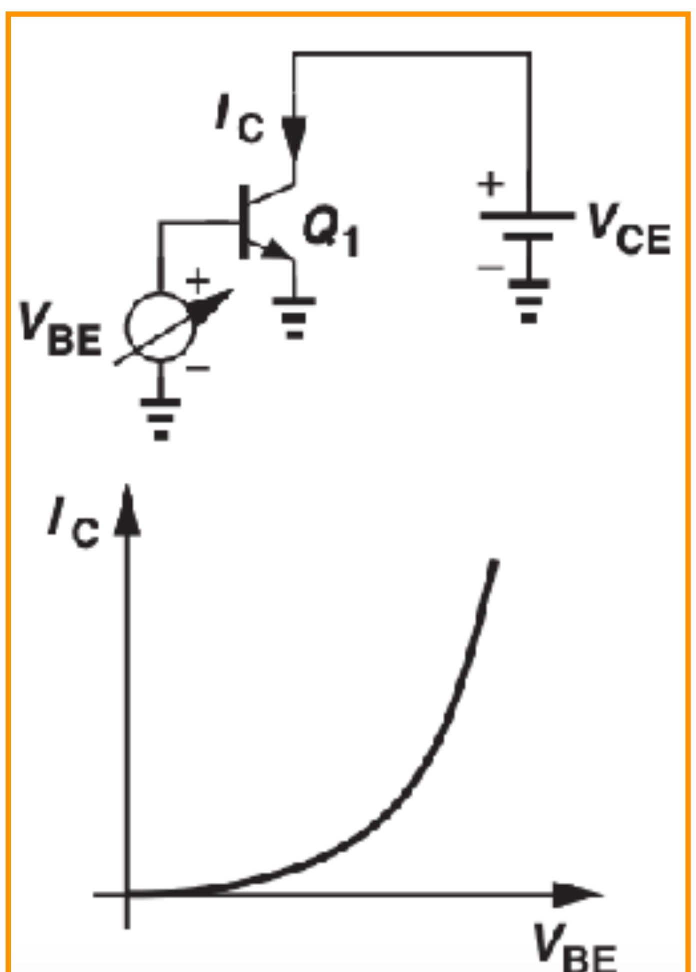
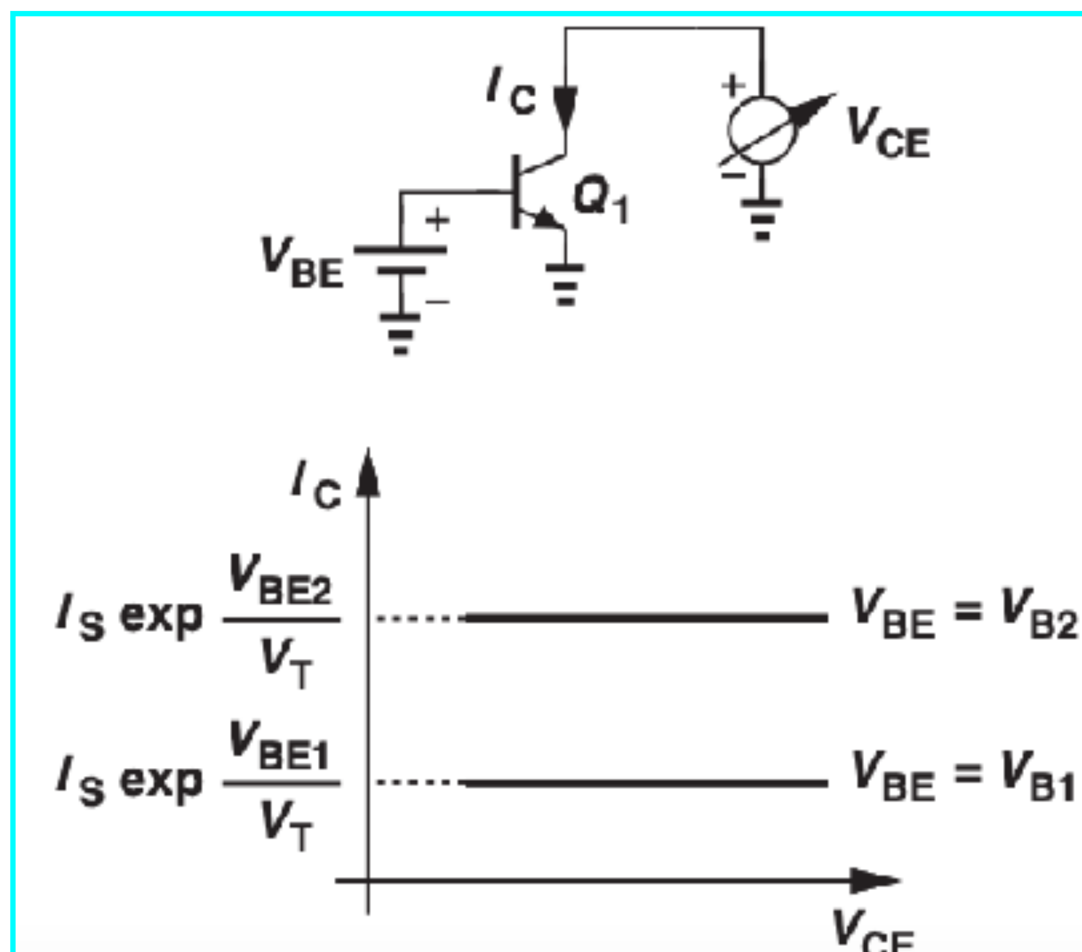


- Solution:
- a) $I_C = I_s \times exp(\frac{V_{BE}}{V_T}) = 1.153 \times 10^{-3} A$
- $\Longrightarrow I_B = I_C/\beta = 1.153 \times 10^{-5} A$, and $I_E = I_C/\alpha = 1.165 \times 10^{-3} A$
- Where $\alpha = \dfrac{\beta}{\beta + 1}$
- active mode $\Longrightarrow V_{BE} > 0$ and $V_{BC} < 0??$
- $V_{BC} = V_B - V_C = V_{BE} - V_X$, applying KVL: $V_X = V_{CC} - R_C I_C = 1.4235V$
- $V_{BC} = V_{BE} - V_X = -0.6235V$
- b) $V_{BC} < 0 \Longrightarrow V_X > V_{BE} \Longrightarrow V_{CC} - R_C I_C > 0.8 \Longrightarrow R_C < 1041\Omega$

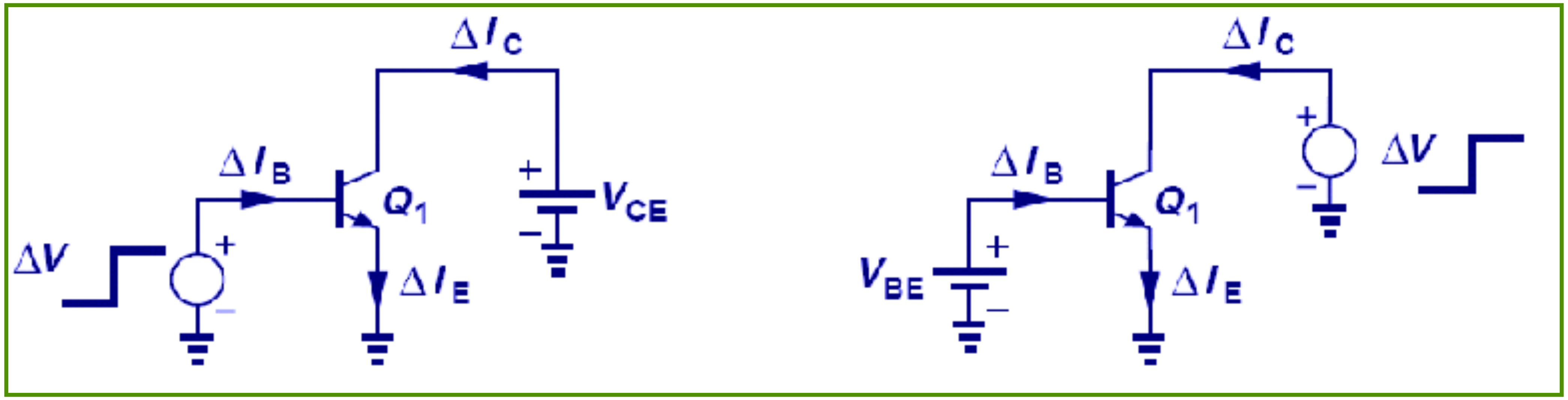
I/V Characteristics of Bipolar Transistor

- The large-signal model naturally leads to the I/V characteristics of the transistor. With three terminal currents and voltages, we may envision plotting different currents as a function of the potential difference between every two terminals.
- The first characteristic to study is, of course, the exponential relationship inherent in the device
- I_C for a given V_{BE} but with V_{CE} varying. The characteristic is a horizontal line because I_C is constant if the device remains in the active mode ($V_{CE} > V_{BE}$).



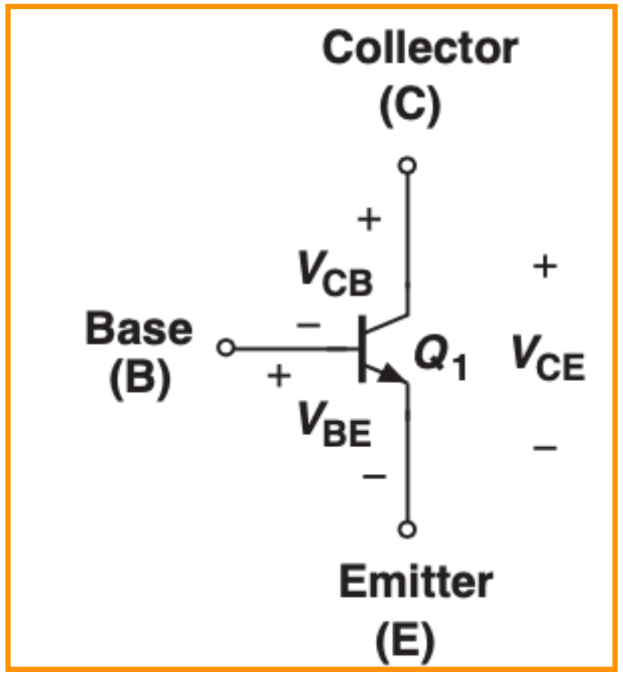


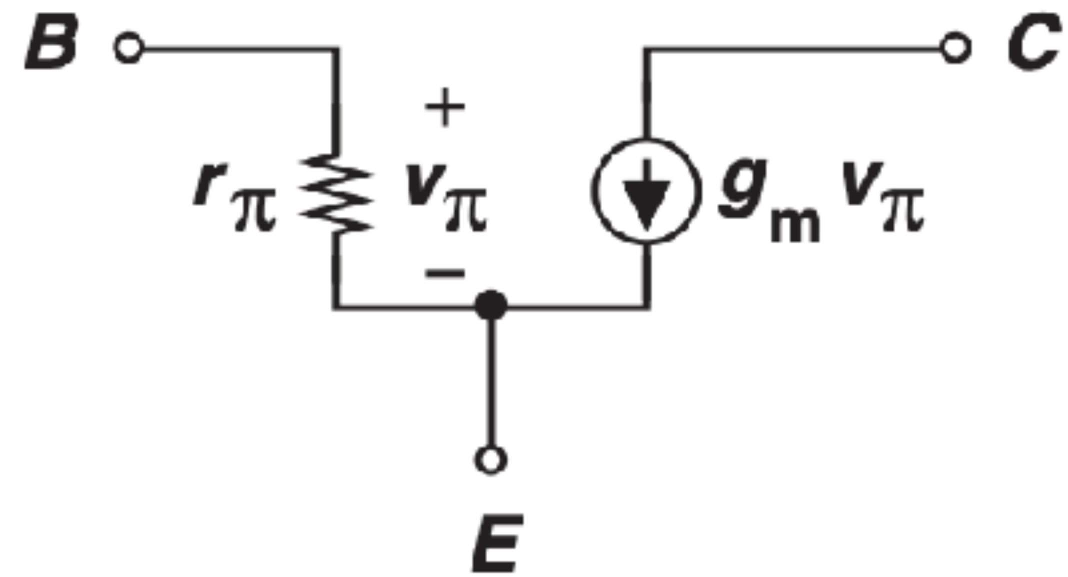
Bipolar Transistor Small Signal Model



- Electronic circuits, e.g., amplifiers, may incorporate a large number of transistors, thus posing great difficulties in the analysis and design.
- The transistor can be reduced to linear devices through the use of the small-signal model.
- Small signal model is derived by perturbing voltage difference every two terminals while fixing the third terminal and analyzing the change in current of all three terminals. We then represent these changes with controlled sources or resistors.

Bipolar Transistor Small Signal Model





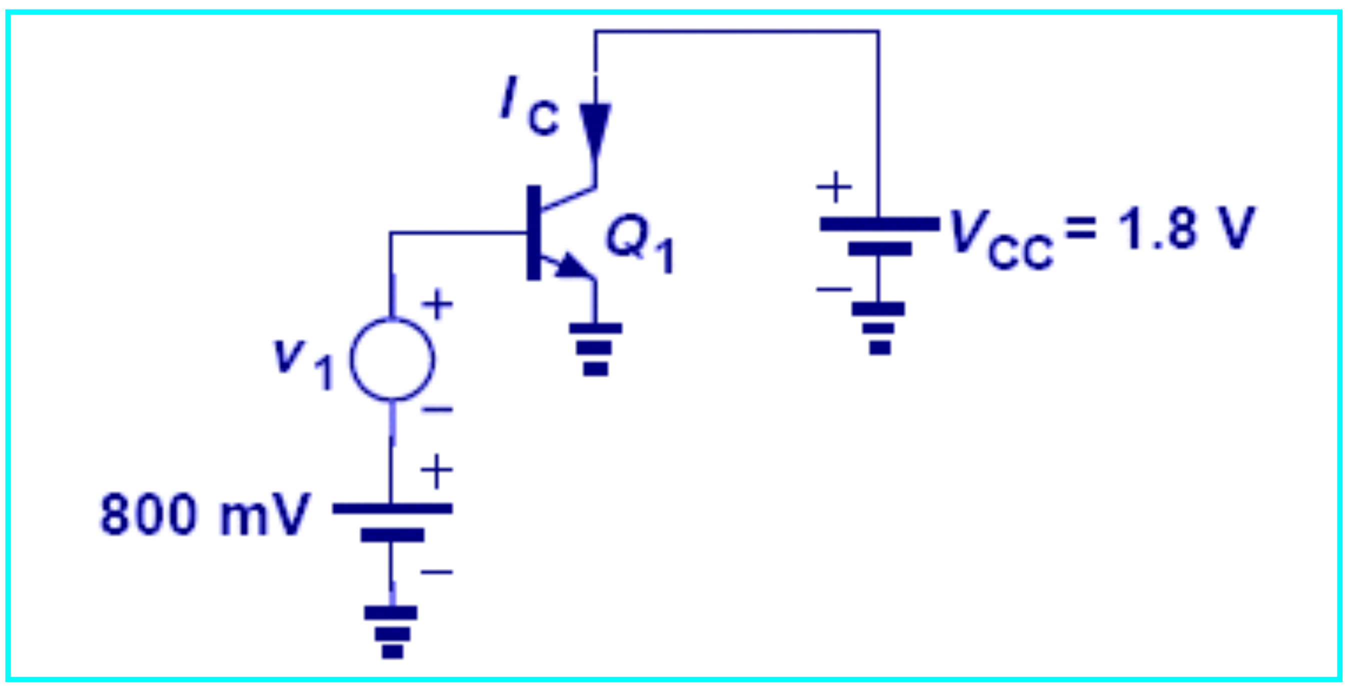
- g_m is the transconductance, $g_m = \dfrac{I_C}{V_T}$.
- g_m shows a measure of how well the transistor converts voltage to current.
- r_π resistor placed between the base and emitter having a value: $r_\pi = \dfrac{\beta}{g_m}$

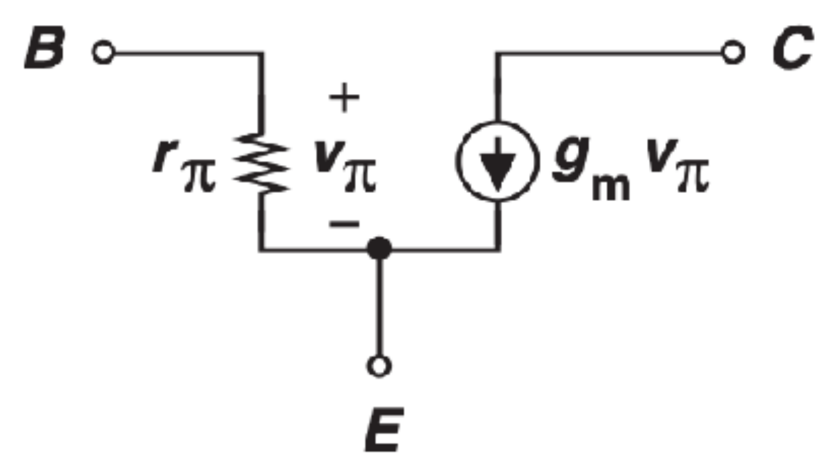
Bipolar Transistor Small Signal Model

- Analyze a circuit containing bipolar transistor using small signal model:
  - DC Analysis:
    - Deactivate AC sources and keep the DC sources
    - Find $g_m = \dfrac{I_C}{V_T}$ and $r_\pi = \dfrac{\beta}{g_m}$.
  - AC Analysis:
    - Deactivate DC sources and keep AC sources
    - Find $A_v = \dfrac{V_{out}}{V_{in}}$

Bipolar Transistor Small Signal Model

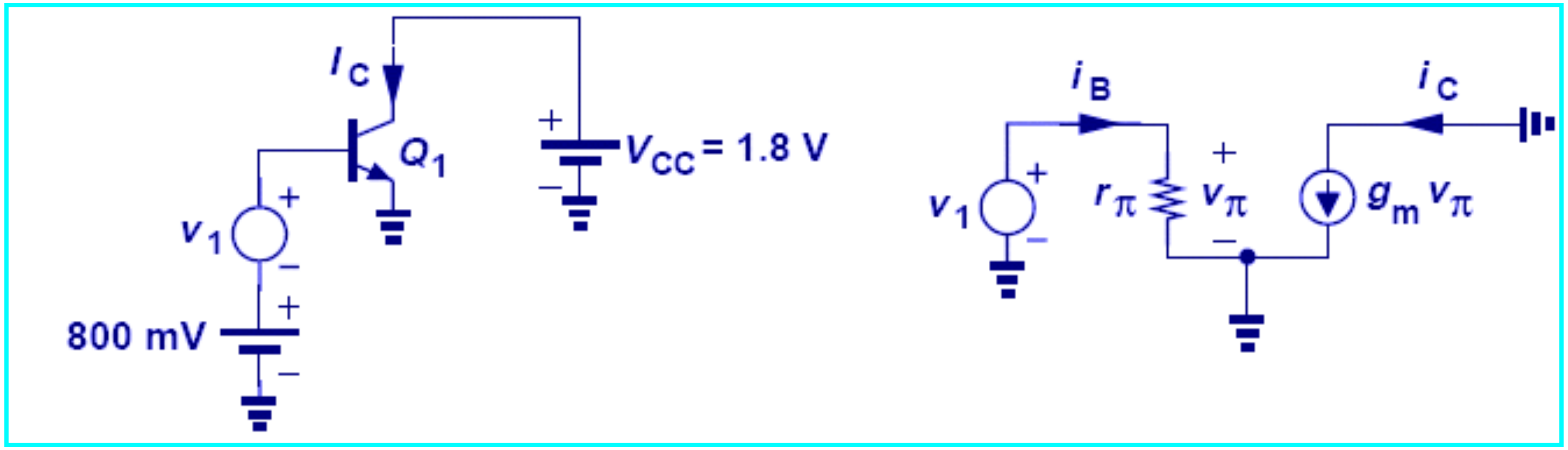
- Example 5: Consider the circuit shown in Fig. below, where v_1 represents the signal generated by a microphone, $I_S = 3 \times 10^{-16}$ A, $\beta = 100$, and Q_1 operates in the active mode.
- (a) If $v_1 = 0$, determine the small-signal parameters of Q_1.
- (b) If the microphone generates a 1-mV signal, how much change is observed in the collector and base currents?





Bipolar Transistor Small Signal Model

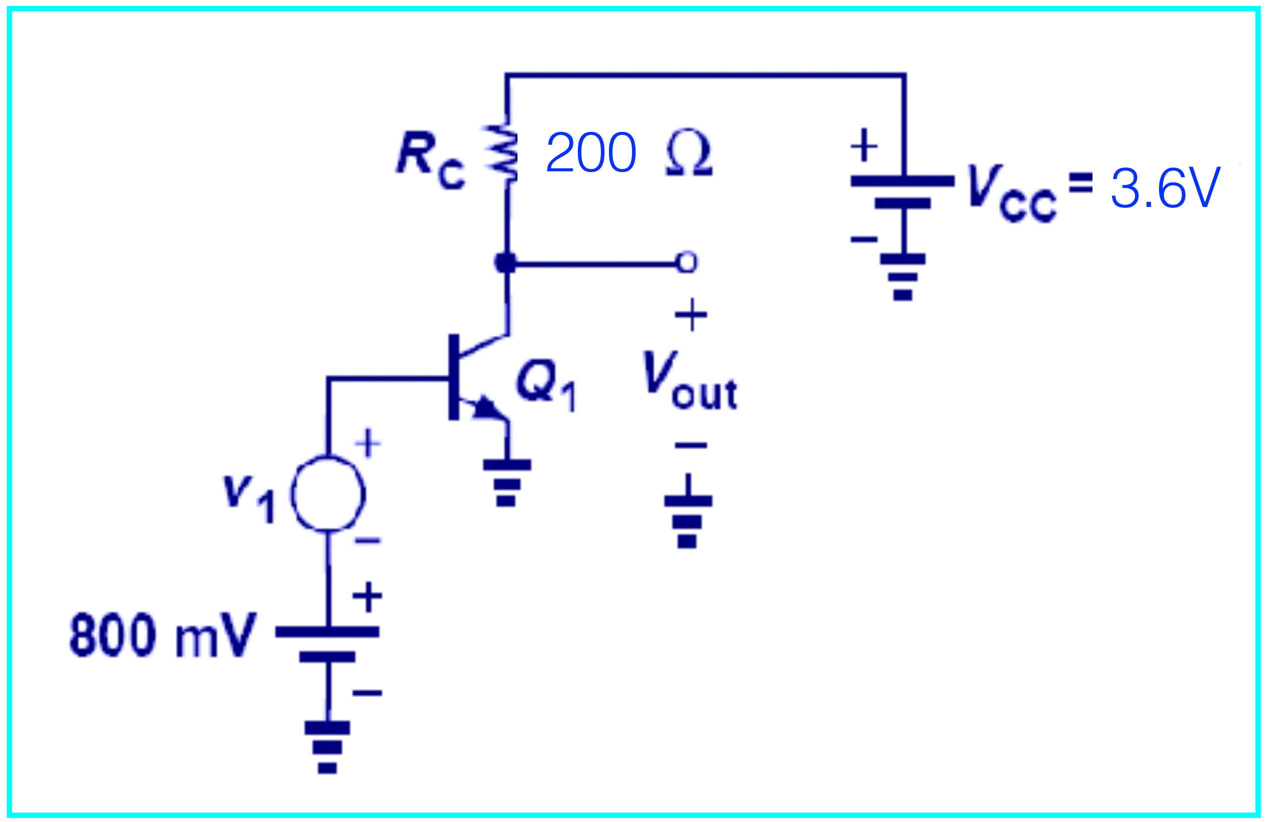
- Example 5: Consider the circuit shown in Fig. below, where v_1 represents the signal generated by a microphone, $I_S = 3 \times 10^{-16}$ A, β = 100, and Q_1 operates in the active mode. (a) If $v_1 = 0$, determine the small-signal parameters of Q_1. (b) If the microphone generates a 1-mV signal, how much change is observed in the collector and base currents?

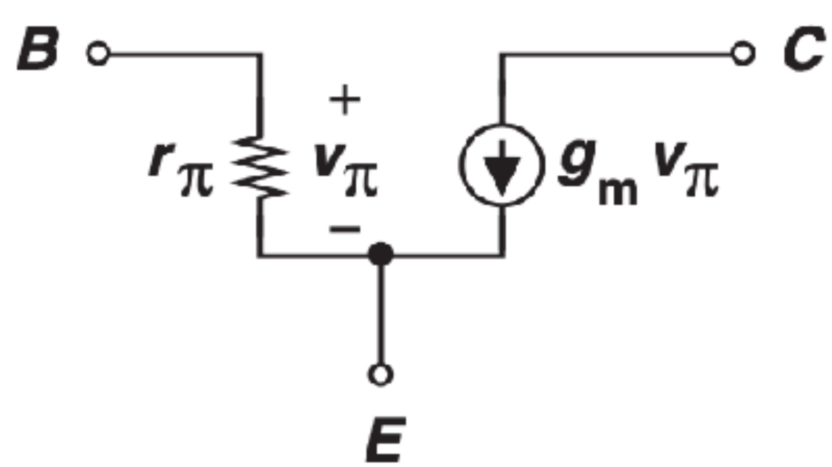


- Solution: a) DC analysis: $v_1 = 0 \Longrightarrow$ voltage source equivalent to short circuit.
- $I_C = I_s \times exp(\frac{V_{BE}}{V_T}) = 6.92 \times 10^{-3} A$, for $V_{BE} = 800mV$
- thus $g_m = \frac{I_C}{V_T} = 0.266\Omega^{-1}$ and $r_\pi = \frac{\beta}{g_m} = 375\Omega$
- b) AC analysis : if $v_1 = 1mV \Longrightarrow \Delta I_C = g_m v_\pi$, where $v_\pi = v_1$
- $\Delta I_C = g_m v_\pi = 0.266mA$, and $\Delta I_B = \Delta I_C/\beta = 2.66\mu A = v_\pi/r_\pi$

Bipolar Transistor Small Signal Model

- Example 6: Considering the circuit below, suppose we raise R_C to 200 and V_{CC} to 3.6 V. Verify that the device operates in the active mode and compute the voltage gain. $I_S = 3 \times 10^{-16}$ A, β = 100.





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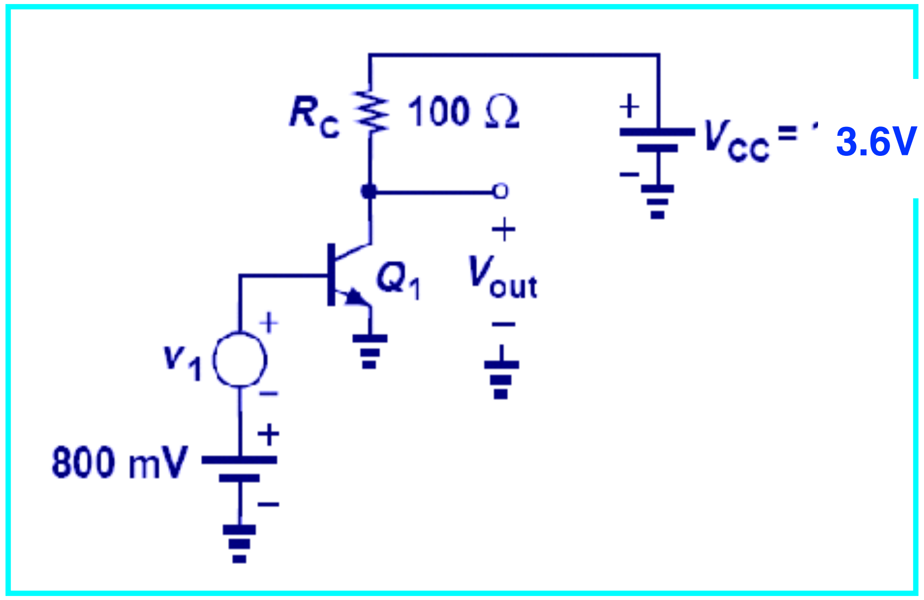
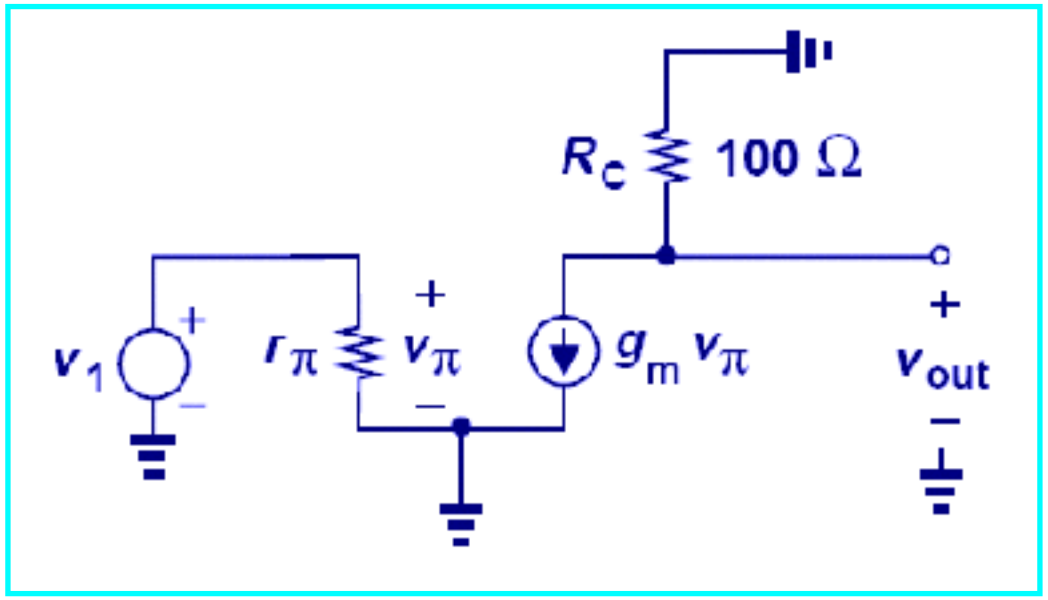
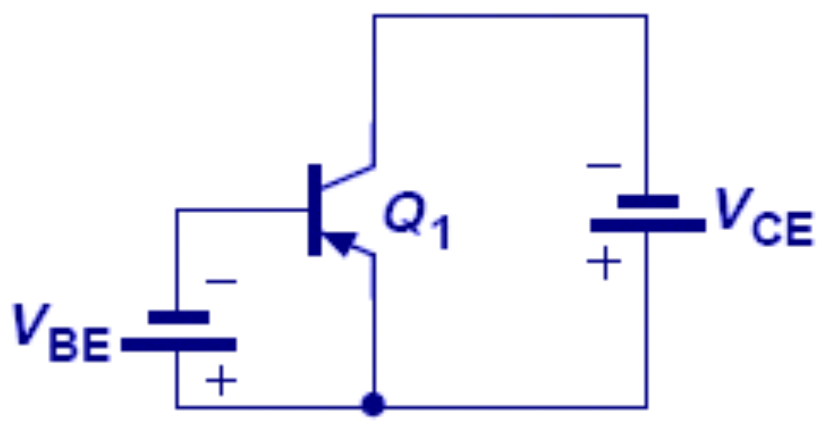
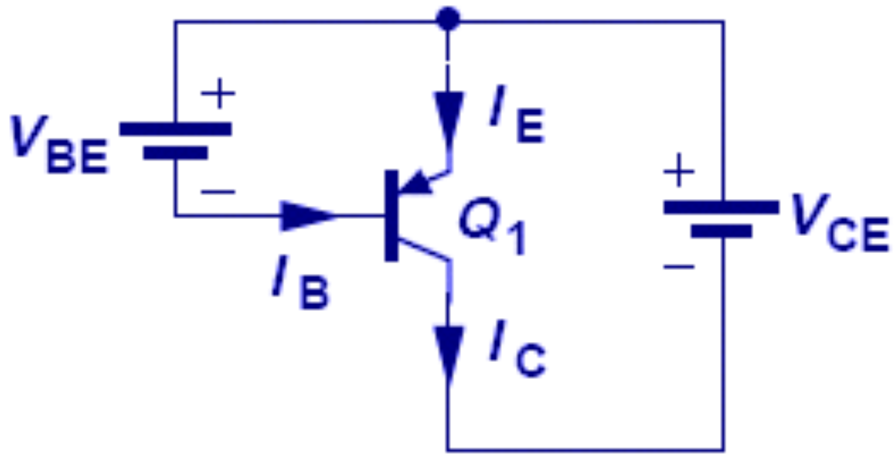


- Solution:
- $I_C = I_s \times exp(\frac{V_{BE}}{V_T}) = 6.92 \times 10^{-3} A$
- $V_C = V_{CC} - R_C I_C = 2.216V \Longrightarrow V_{BC} = 0.8 - 2.216 = -1.416V$
- $V_{BC} < 0 \Longrightarrow$ operates in active mode
- Voltage gain: small signal model:
- $V_{out} = -R_C g_m v_\pi$
- $v_\pi = v_1 \Longrightarrow A_v = \frac{V_{out}}{V_{in}} = -R_C g_m$
- $g_m = \frac{I_C}{V_T} = = 0.266\Omega^{-1} \Longrightarrow A_v = -53.23$



PNP transistor





- With the polarities of emitter, collector, and base reversed, a PNP transistor is formed.
- All the principles that applied to NPN's also apply to PNP’s, with the exception that emitter is at a higher potential than base and base at a higher potential than collector.
- Active mode: $V_{EB} > 0, V_{CB} < 0$

PNP transistor: equations

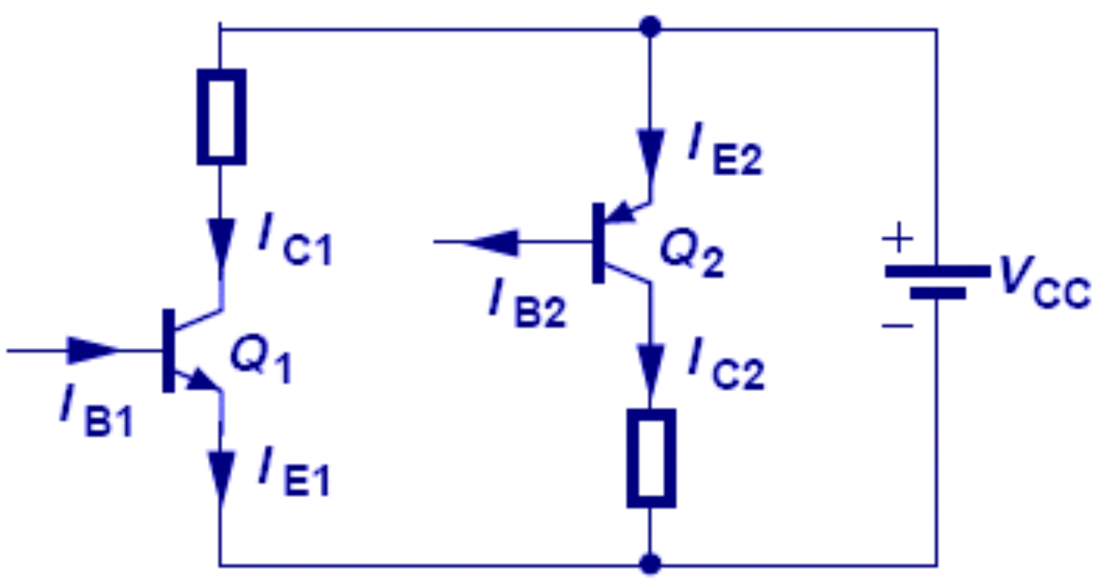
- The *npn* current equations must be modified as follows for the *pnp* device:

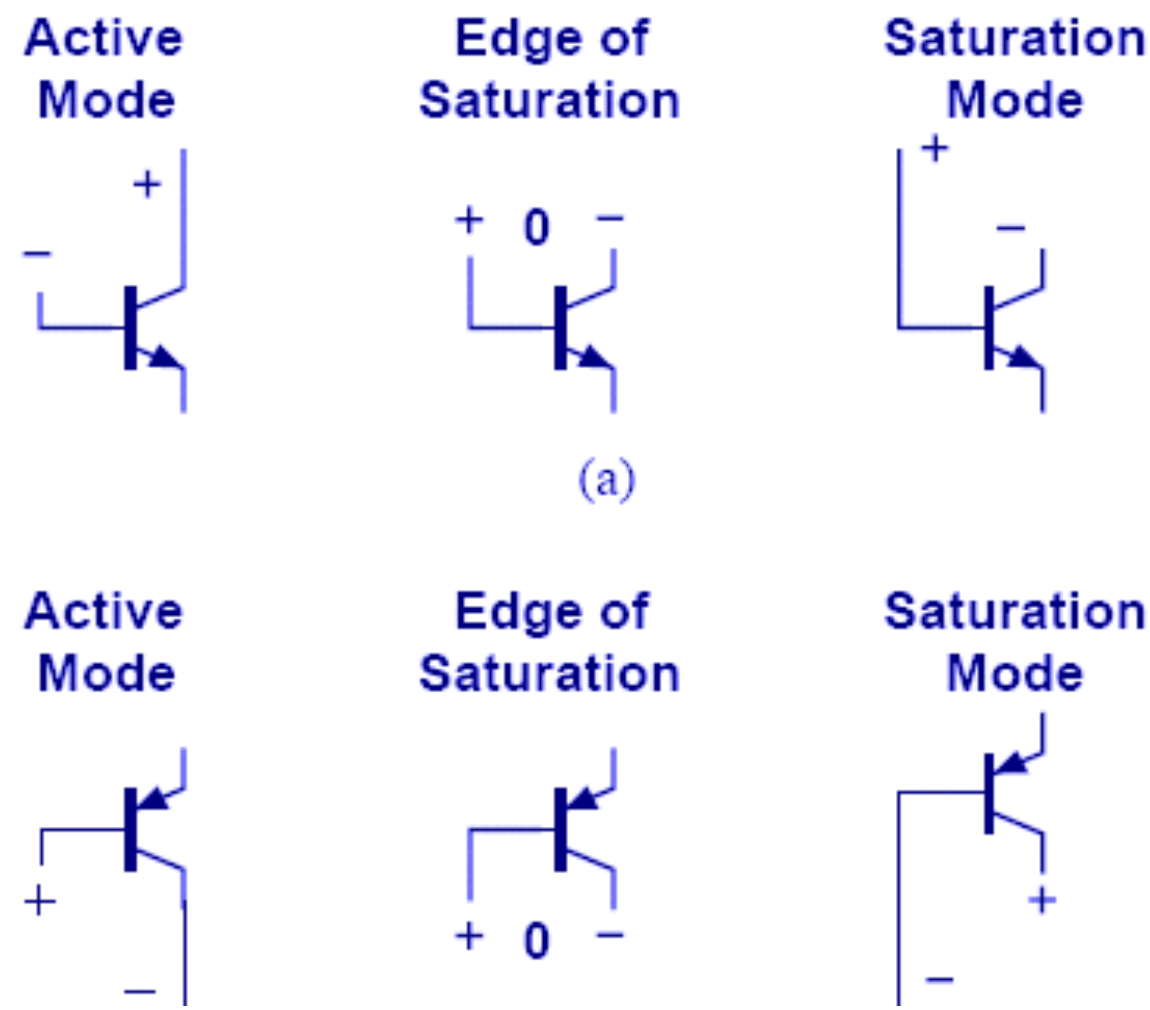
$$I_C = I_S \exp \frac{V_{EB}}{V_T}$$

$$I_B = \frac{I_S}{\beta} \exp \frac{V_{EB}}{V_T}$$

$$I_E = \frac{\beta + 1}{\beta} I_S \exp \frac{V_{EB}}{V_T}$$

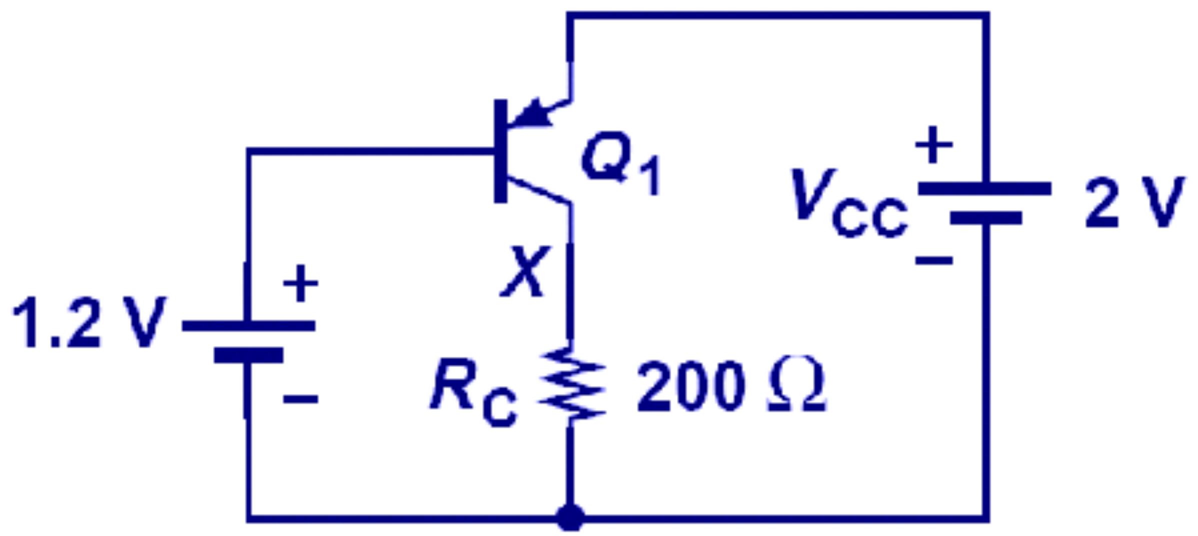
Comparison between NPN and PNP





PNP transistor

- Example 7: In the circuit shown in Fig. below, determine the terminal currents of Q_1 and verify operation in the forward active region. Assume $I_S = 2 \times 10^{-16}$ A and β = 50. $V_{CC} = 2V$



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PNP transistor

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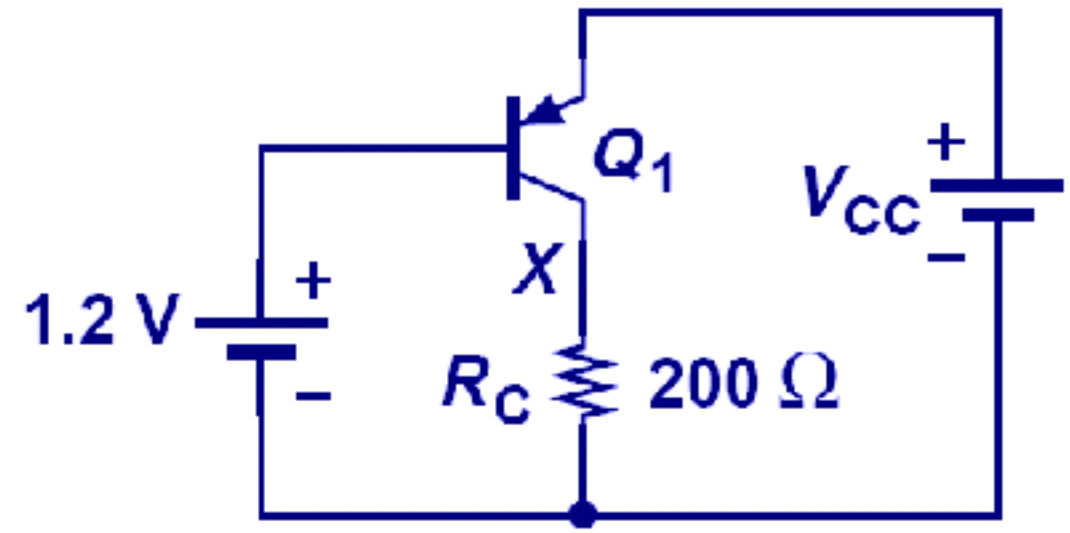

- Solution:
- $I_C = I_s \times exp(\frac{V_{EB}}{V_T}) = 4.61mA$
- $V_X = R_C I_C = 0.922V$
- $V_{EB} = 2 - 1.2 = 0.8V > 0$
- $V_{CB} = V_X - V_B = 0.922 - 1.2 = -0.278V < 0$
- $\Longrightarrow$ active mode
-

Summary

- The bipolar transistor consists of two *pn* junctions and three terminals: base, emitter, and collector. The carriers flow from the emitter to the collector and are controlled by the base.
- For proper operation, the base-emitter junction is forward-biased and the base-collector junction reverse-biased (forward active region).
- The ratio of collector current and base current is denoted by β.
- In the forward active region, the bipolar transistor exhibits an exponential relationship between its collector current and base-emitter voltage $$I_C = I_s \times exp(\frac{V_{BE}}{V_T})$$
- The transconductance of a bipolar transistor is given by $g_m = I_C / V_T$ and remains independent of the device dimensions.
- The small-signal model of bipolar transistors consists of a linear voltage-dependent current source, a resistance tied between the base and emitter, and an output high resistance.
- If the base-collector junction is forward-biased, the bipolar transistor enters saturation and its performance degrades.
- The small-signal models of *npn* and *pnp* transistors are identical.