ELC 1252 — Electronics

Lecture (4)
Introduction to BJT Transistors

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Spring 2024

Lecture Outline

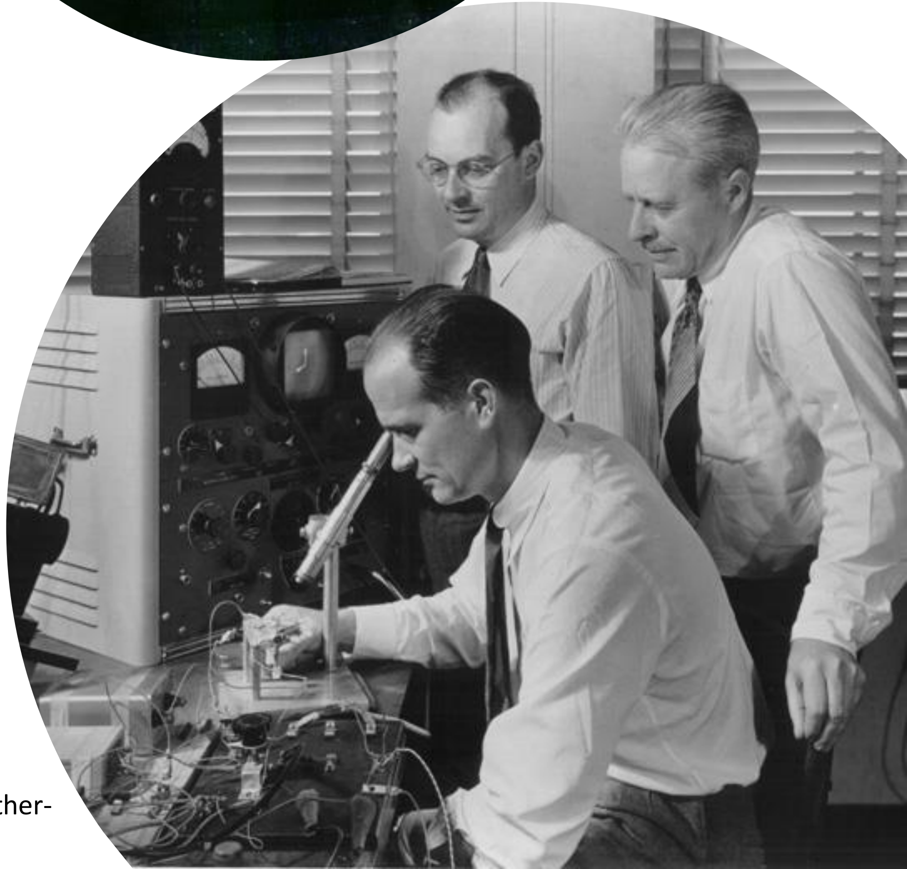
- Device Structure
- Modes of Operation
- Operation in the Active Mode
- Operation in the Saturation Mode
- DC Analysis Examples

Introduction to Bipolar Junction Transistor (BJT)

- Transistor is a nonlinear three terminal device.
- Transistor stands for transfer resistor.
- Two important transistor types.
  - Bipolar junction transistor (BJT)
  - Metal oxide semiconductor field effect transistor (MOSFET)
- BJT was invented in 1948 in Bell labs.
- MOSFET is dominant in digital applications and BJT is dominant in high performance applications.

History of Transistors

- The transistor was invented by Walter Brattain, John Bardeen and William Shockley on December 23, 1947, in Bell Labs, USA.
- Marvin Kelley, head of Bell Labs, had brought the trio together to combine different specialties: the brilliant theorist Brattain, the skilled materials expert Bardeen, and the very accomplished experimentalist Shockley.
- The first form of transistors was electronic tubes which were relatively bulky and consumed considerable energy.
- In 1958, the first major application of the transistor had emerged from Texas Instruments. This was a small portable radio that was even called a transistor after the component that made it possible.

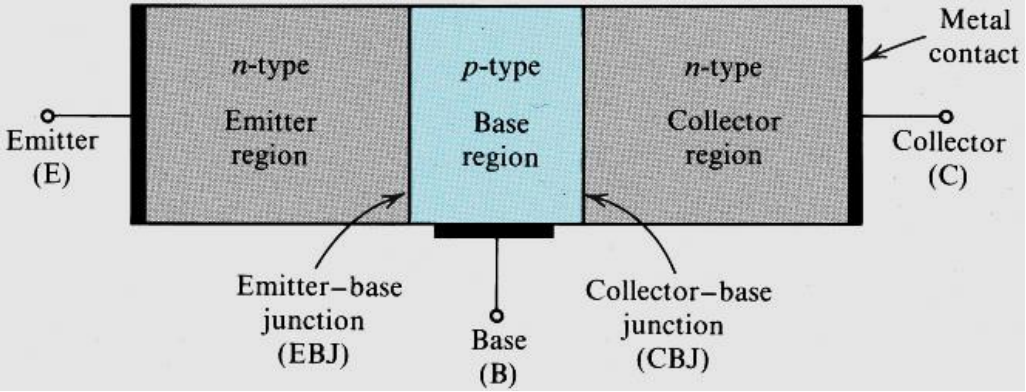


Source: https://www.ericsson.com/en/about-us/history/products/other-products/the-transistor--an-invention-ahead-of-its-time

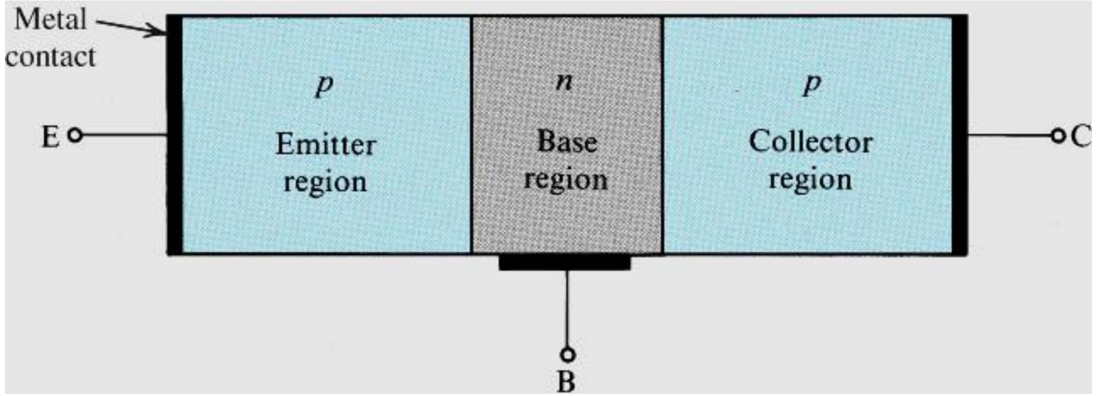
BJT Structure

- The BJT consists of two ***pn*** junctions as shown:
  - The emitter-base junction (EBJ)
  - The collector-base junction (CBJ)
- There is two types of BJT devices: (***npn***, ***pnp***)
- The three transistor's terminals are called emitter, base, and collector

npn

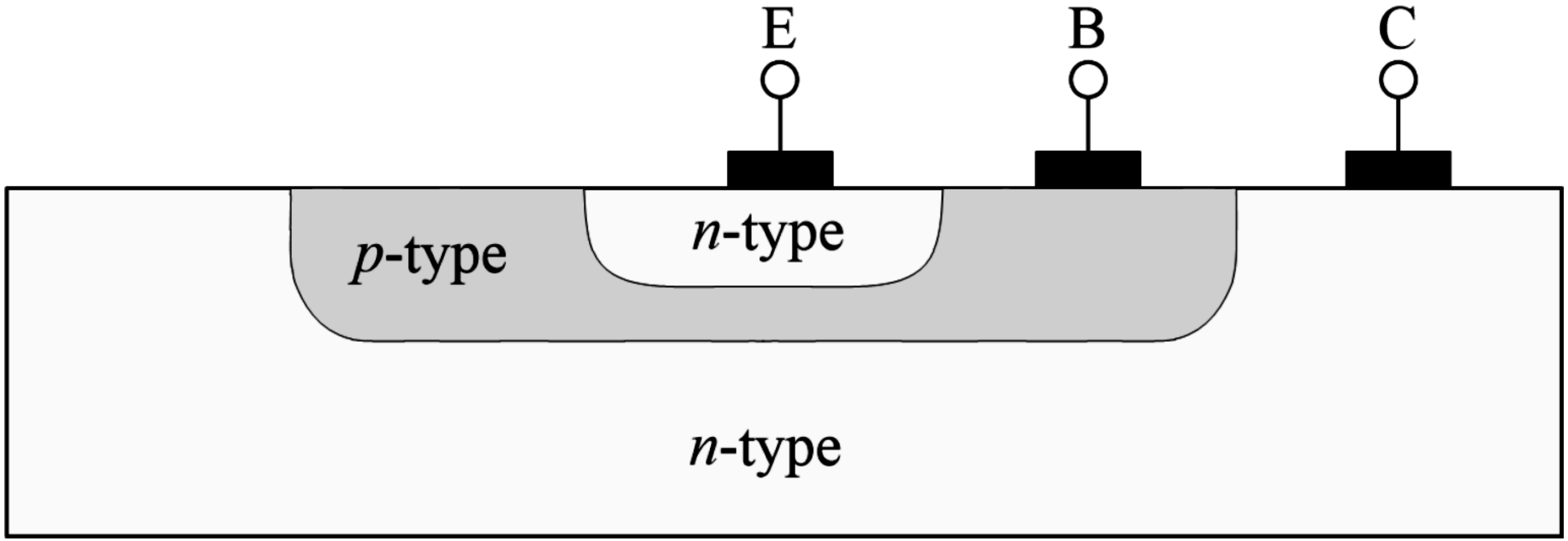


pnp



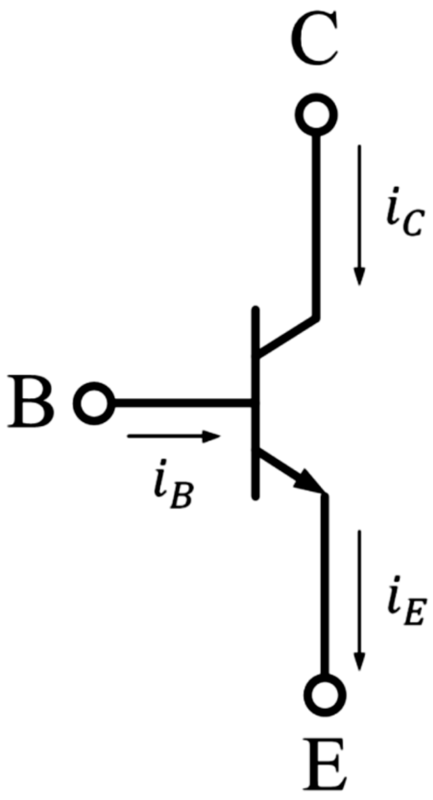
Structure of Actual Transistor

- The actual BJT transistor is not symmetrical
- The emitter and collector cannot be interchanged
- The collector virtually surrounds the emitter region

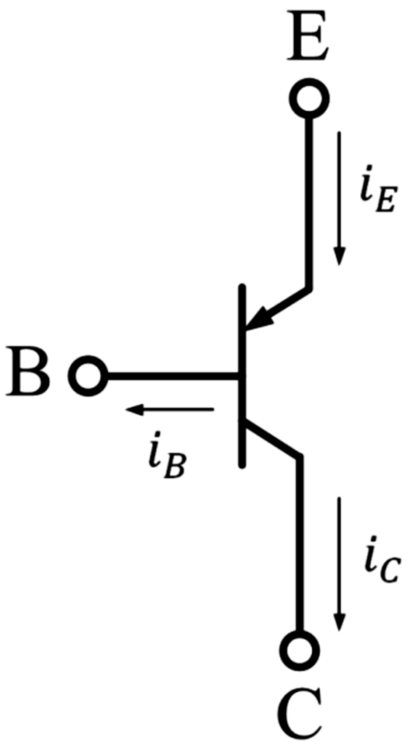


Circuit Symbol

- In both symbols the emitter is distinguished by an arrowhead.
- "*npn*" and "*pnp*" BJT devices are equivalent and have the same analysis.



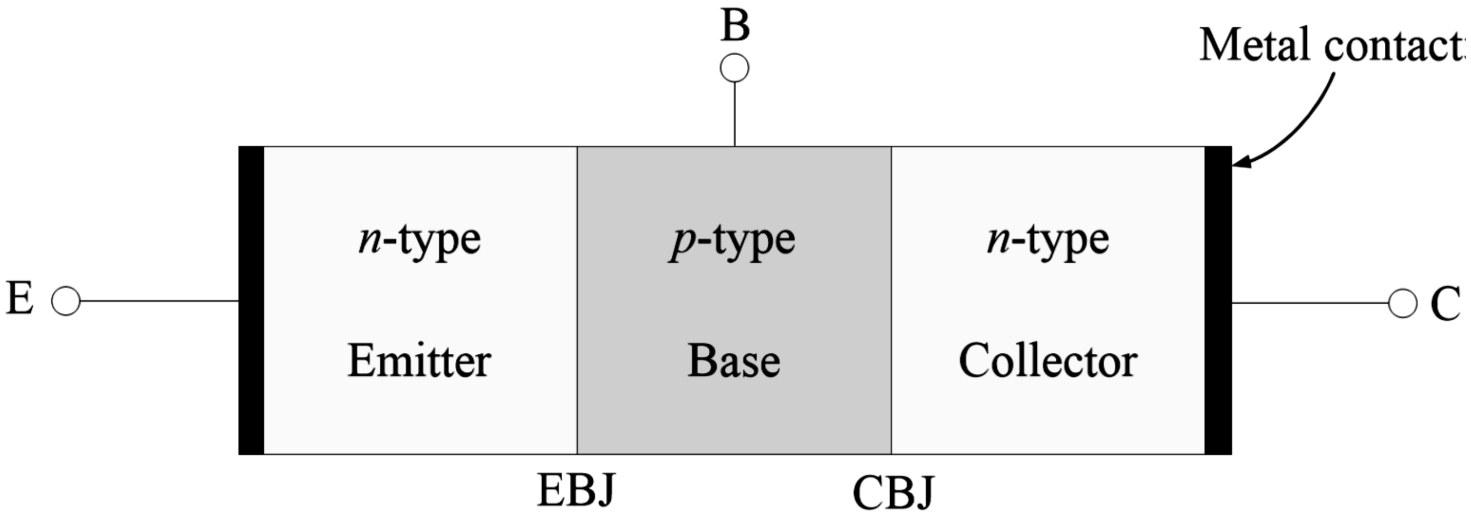
npn



pnp

Modes of Operations

Mode	EBJ	CBJ	Application
cutoff	Reverse	Reverse	Logic Circuits
Saturation	Forward	Forward	
Active	Forward	Reverse	Amplifier



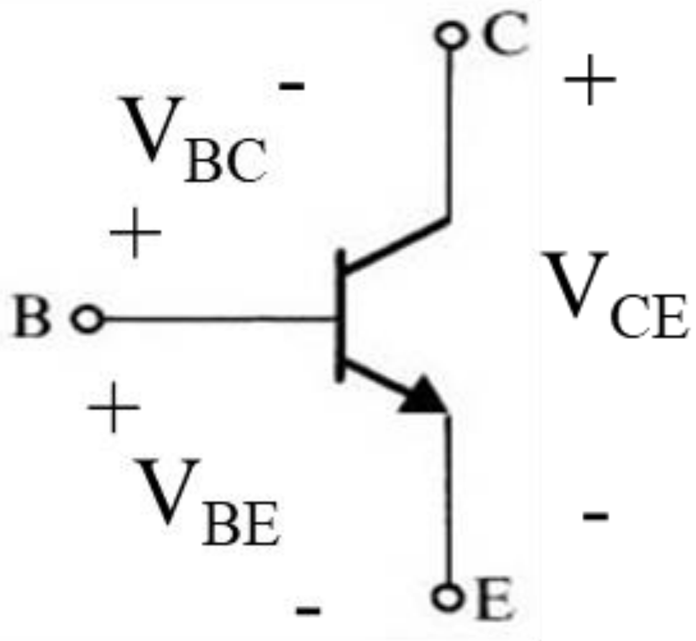
Operation in the Cutoff Mode [NPN]

- EBJ is reverse and CBJ is reverse.

- $V_{BE} < V_{BE,ON}$
- For base-emitter junction $V_{BE,ON} \approx 0.7V$

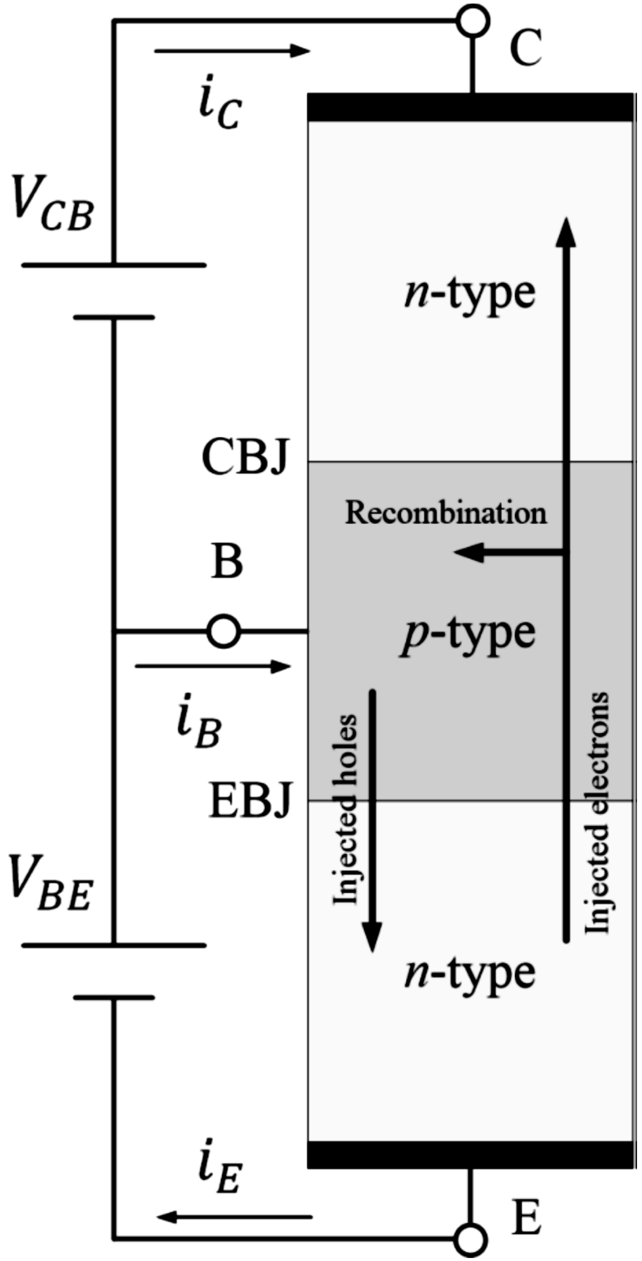
- $V_{BC} < V_{BC,ON}$
- For base-collector junction $V_{BC,ON} \approx 0.5V$

- $i_C = 0, \;\; i_B = 0, \;\; i_E = 0$



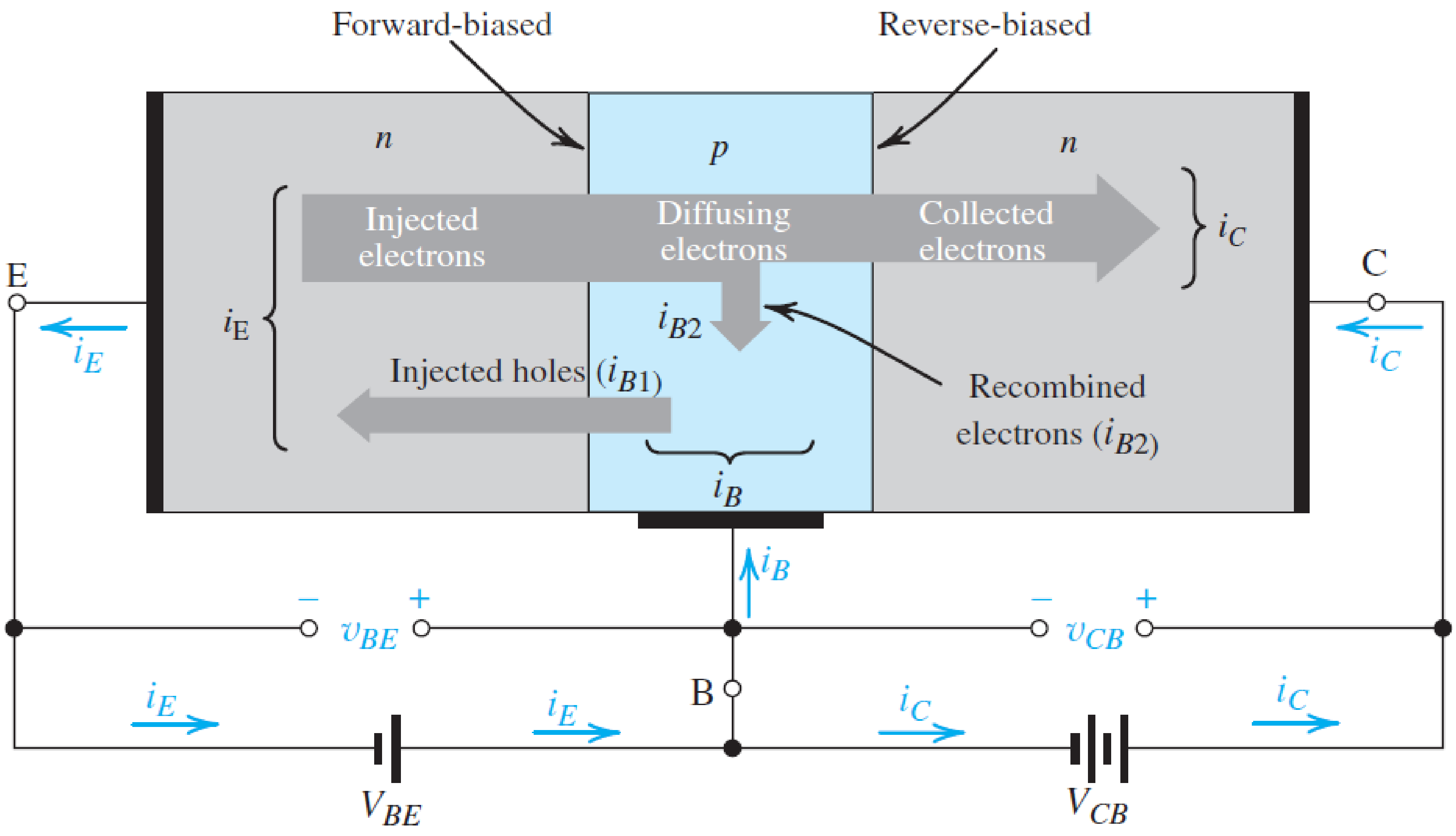
Operation in the Active Mode [NPN]

- EBJ is forward and CBJ is reverse.
  - $V_{BE} = 0.7V,\ V_{BC} < 0.5$
  - $V_{CE} = V_{BE} - V_{BC} > 0.2V$
- The emitter is heavily dopped.
- The base is usually very thin and lightly doped.
- The emitter current i_E is dominated by the electron current.
- The proportion of electrons lost through the recombination process in the base is quite small.



Operation in the Active Mode [NPN]

- Base is very thin region
  - Injected electrons from emitter cross base and continue to collector
  - Collector current has an exponential relation with BE voltage



Operation in the Active Mode [NPN]

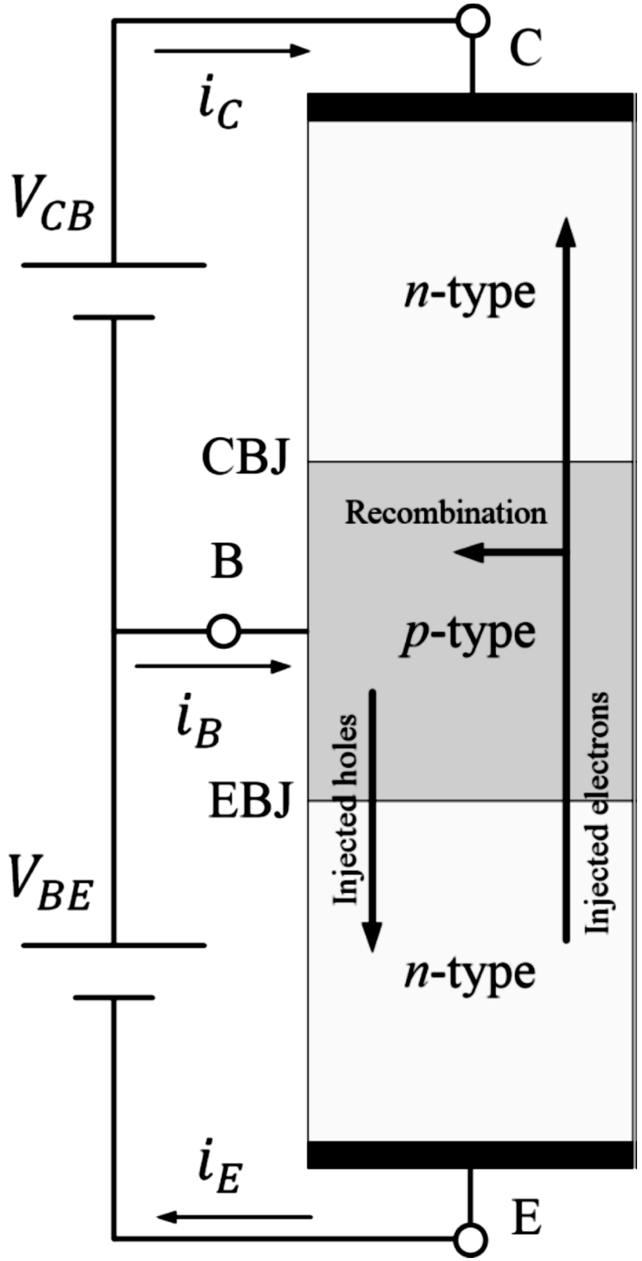
- The electrons will be swept across the CBJ depletion region into the collector. This results in the collector current (i_C):

$$i_C = I_S e^{\frac{V_{BE}}{V_T}}$$

$I_s = 10^{-18} \sim 10^{-12} A$ (I_S is proportional to transistor area)

- The base current $i_B = i_{B1} + i_{B2}$
  - i_{B1} is due to the holes injected from the base into the emitter.
  - i_{B2} is due to holes that must be supplied to replace the holes lost from the base through the recombination process.

$$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{\frac{V_{BE}}{V_T}} \rightarrow \beta = \frac{i_C}{i_B} = 50 \sim 200$$



Operation in the Active Mode [NPN]

- Applying KCL,

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

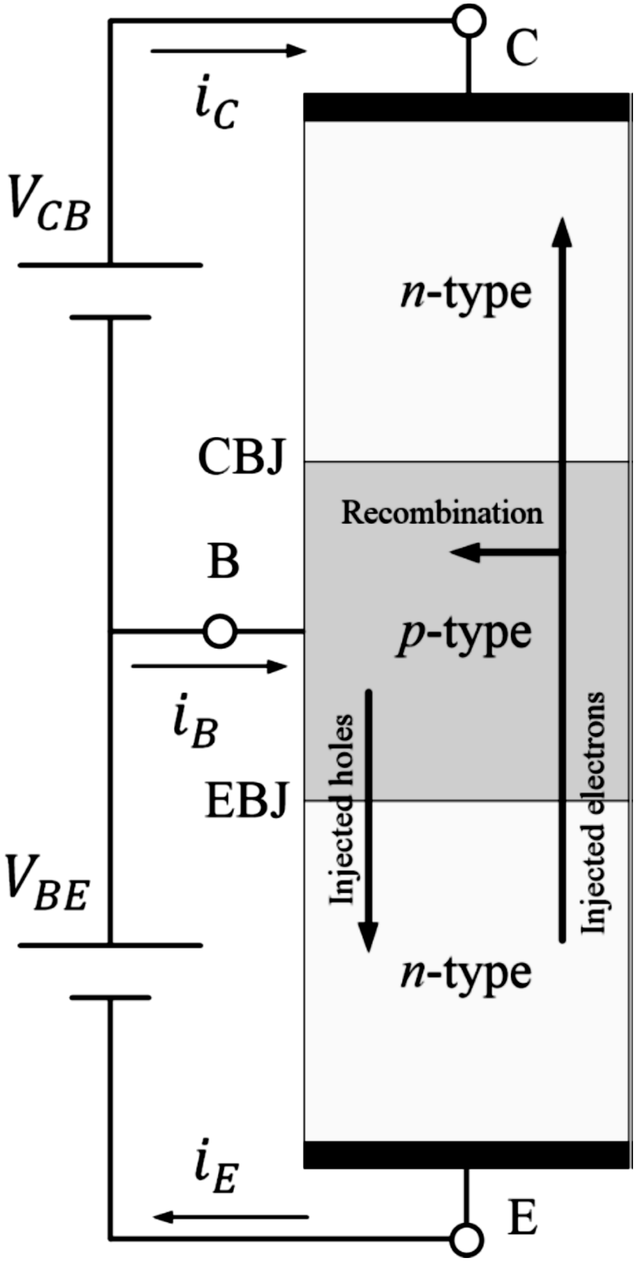
Alternatively,

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

$$\alpha = \frac{\beta}{\beta+1} \qquad and \qquad \beta = \frac{\alpha}{1-\alpha}$$

  - β is called the common-emitter current gain.
  - α is called the common-base current gain.

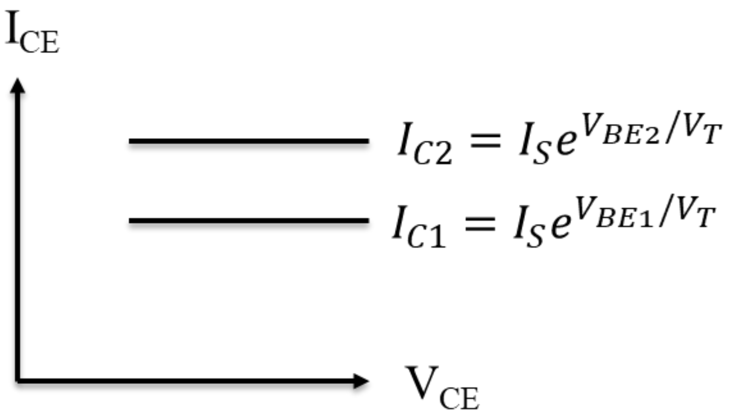
- $\therefore i_E = i_C + i_B = (\beta + 1) i_B = \left(\frac{\beta+1}{\beta}\right) i_C \approx i_C$



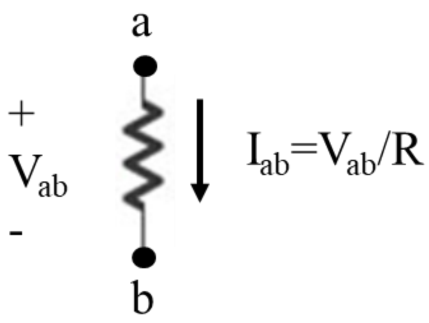
What does transistor mean?

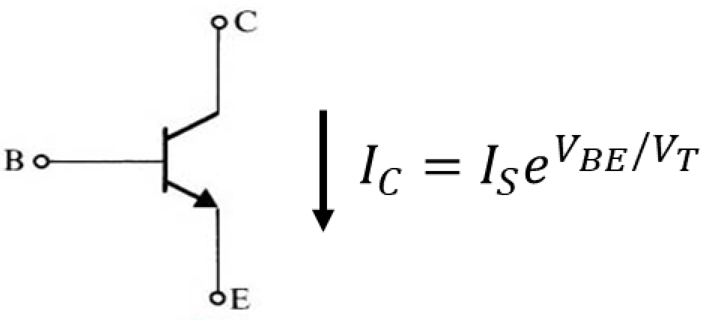
- In Active region, collector current is mainly controlled by base-emitter voltage (V_{BE})

$$i_C = I_S e^{\frac{V_{BE}}{V_T}}$$



- Transistor stands for transfer resistor





Operation in the Saturation Mode [NPN]

- The npn BJT operates in active mode for V_{BC} <0.5V.

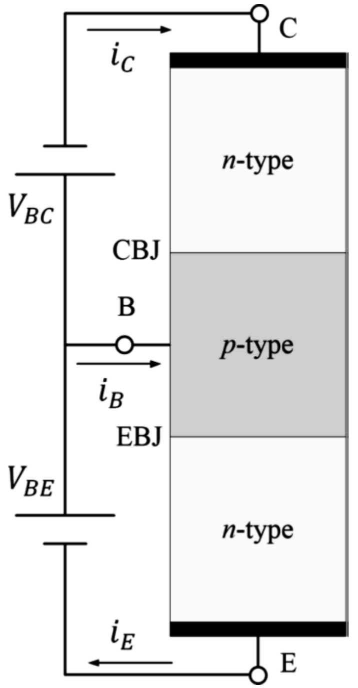
- EBJ is forward and CBJ is Forward.
  - $V_{BE} \approx 0.7\,V,\ V_{BC} \approx 0.5V$
  - $V_{CE} = V_{BE} - V_{BC} \approx 0.2V$

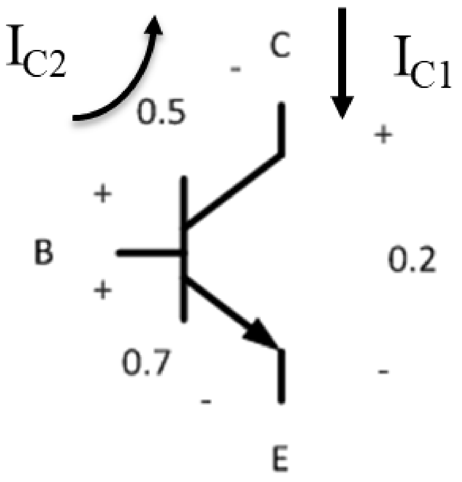
- The CBJ begins to conduct sufficiently and i_C decreases:

$$I_C = I_s e^{\frac{V_{BE}}{V_T}} - I_s e^{\frac{V_{BC}}{V_T}} \leq \beta i_B$$

- i_C/i_B is controlled by adjusting V_{BC}:

$$\beta_{forced} = \left.\frac{i_C}{i_B}\right|_{sat} \leq \beta$$



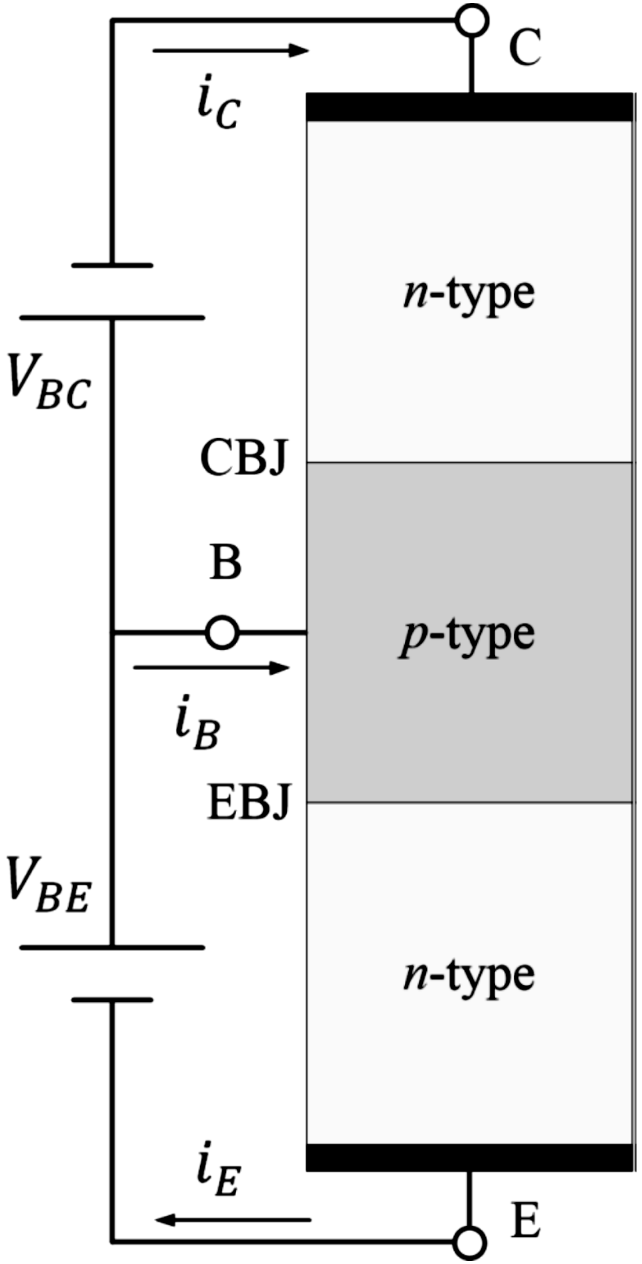


Operation in the Saturation Mode [NPN]

- Applying KCL,

$$i_E = i_C + i_B$$

- $V_{CE,sat} = V_{BE} - V_{BC} \approx 0.7 - 0.5 \approx 0.2V.$

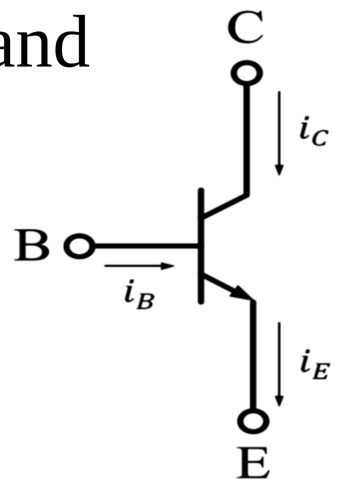


BJT Applications

Three main circuits can be done using transistors

- Current Sources
  - Transistor operates in active region $\left(i_C = I_S e^{\frac{V_{BE}}{V_T}}\right)$
- Amplifiers
  - Transistor operates in active region $(i_C = \beta i_B)$
- Switches
  - OFF: Transistor is in cutoff region $(i_C = i_E = 0)$
  - ON: Transistor is in saturation region $(V_{CE} \approx 0.2V)$

BJT Circuits at DC



- For transistor circuits, we use KCL and KVL to calculate voltages and currents of the three BJT terminals.
- In all modes of operations $i_E = i_C + i_B$
- First, you need to determine the mode of operation of the transistor
  - Cutoff, Active, or Saturation
- You may start by assuming the transistor is operating in the active region.
- Check your assumption by calculating $V_{CE} > V_{CE,sat} (\sim 200mV)$
- If the assumption was wrong, assume saturation-mode operation and check if $\frac{i_C}{i_B} < \beta$
- Unless it is specified in the question, assume $V_{BE} = 0.7V$
- Unless it is given in the question, assume $V_{CE,sat} = 0.2V$

NPN BJT Summary

- If transistor is off, both junctions are reverse biased and all currents = 0

- If transistor is Active (EBJ is forward, CBJ is reverse)
  - $i_C \approx i_E = I_S e^{V_{BE}/V_T}$
  - $i_C = \beta i_B$
  - Check that $V_{CE} > 0.2V$

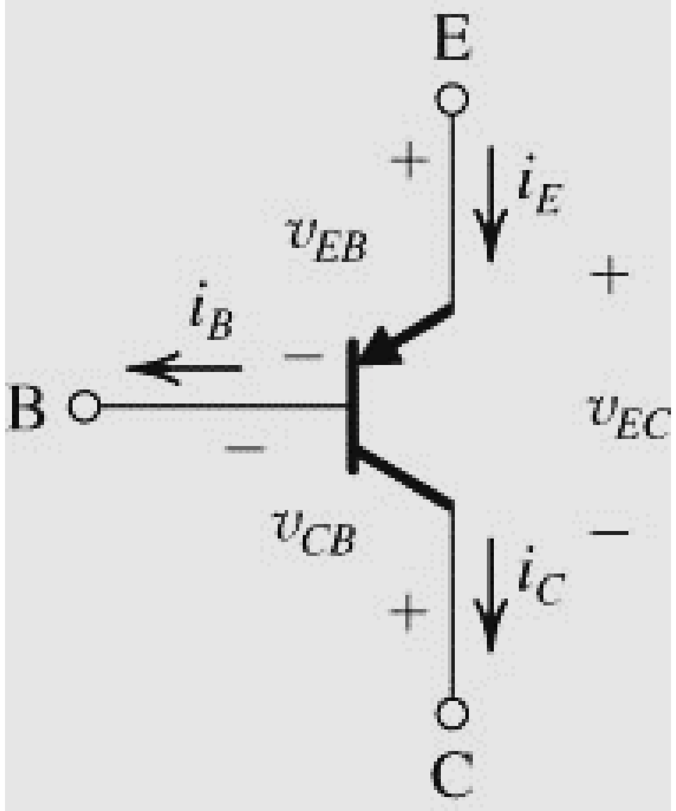
- If transistor is Sat (EBJ is forward, CBJ is forward)
  - $V_{CE} = 0.2V$
  - Check that $i_C < \beta i_B$

PNP BJT Summary

- If transistor is off, both junctions are reverse biased and all currents = 0

- If transistor is Active (EBJ is forward, CBJ is reverse)
  - $i_C \approx i_E = I_S e^{\boldsymbol{V_{EB}}/V_T}$
  - $i_C = \beta i_B$
  - Check that $\mathbf{V_{EC}} > 0.2V$

- If transistor is Sat (EBJ is forward, CBJ is forward)
  - $\boldsymbol{V_{EC}} = 0.2V$
  - Check that $i_C < \beta i_B$



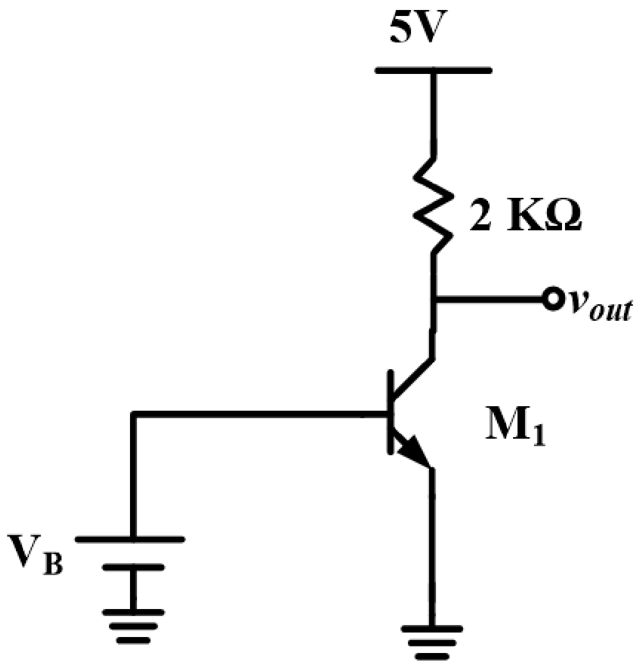
DC Analysis – Example 1

- Calculate V_{out} for $V_B = 0V, 0.7V\ and\ 0.75V$.

Assume $I_S = 10^{-15}A$.

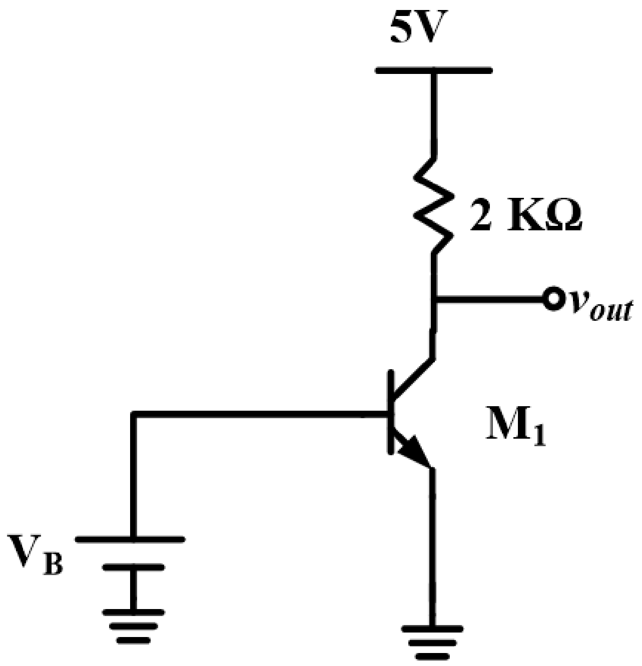
Solution:

- $V_B = 0V$
  - EB Junction is off
  - Assume transistor is off → $i_C = 0$
  - $5V = i_C R + \mathrm{V_{CE}} \rightarrow V_{CE} = 5V$
  - $V_{BC} = -5V \rightarrow CBJ\ is\ off\ as\ well$
  - Assumption is correct
  - $V_{out} = 5V$.



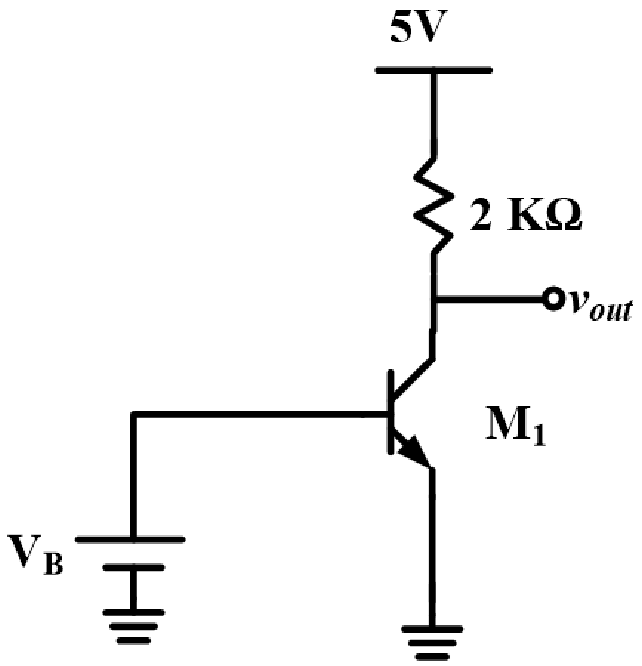
DC Analysis – Example 1

- $V_B = 0.7V$
  - EB Junction is ON
  - Transistor can be active or in saturation
- Assume Active
  - $i_C = I_S e^{V_{BE}/V_T}$
  - $V_T \approx 25mV$
  - $i_C = 1.4mA$
  - $5V = i_C R + \mathrm{V_{CE}} \rightarrow V_{CE} = 2.2V$
  - $V_{CE} > 0.2V$
  - *Correct Assumption*



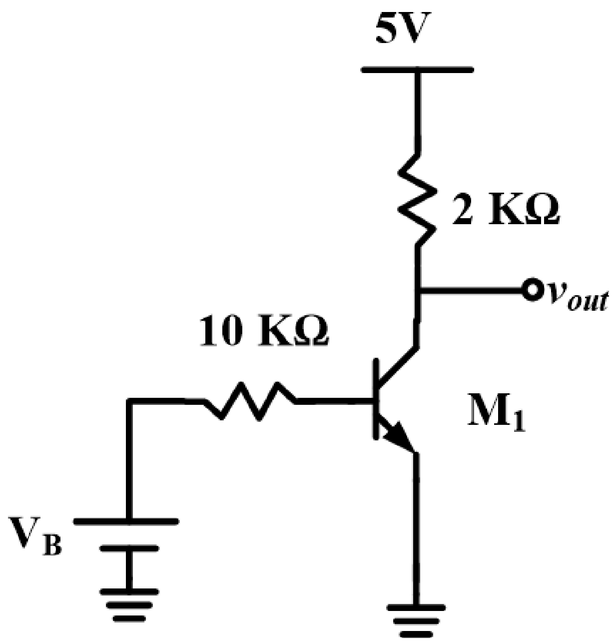
DC Analysis – Example 1

- $V_B = 0.75V$
  - EB Junction is ON
  - Transistor can be active or in saturation
- Assume Active
  - $i_C = I_S e^{V_{BE}/V_T}$
  - $V_T \approx 25mV$
  - $i_C = 10.7mA$
  - $5V = i_C R + \mathrm{V_{CE}} \rightarrow V_{CE} = -16.4V$
  - $V_{CE} < 0.2V$ → $Wrong\ Assumption$
- Assume SAT
  - $V_{out} = V_{CE} = 0.2V$
  - $i_C = \frac{5-0.2}{R} = 2.4mA$



DC Analysis – Example 2

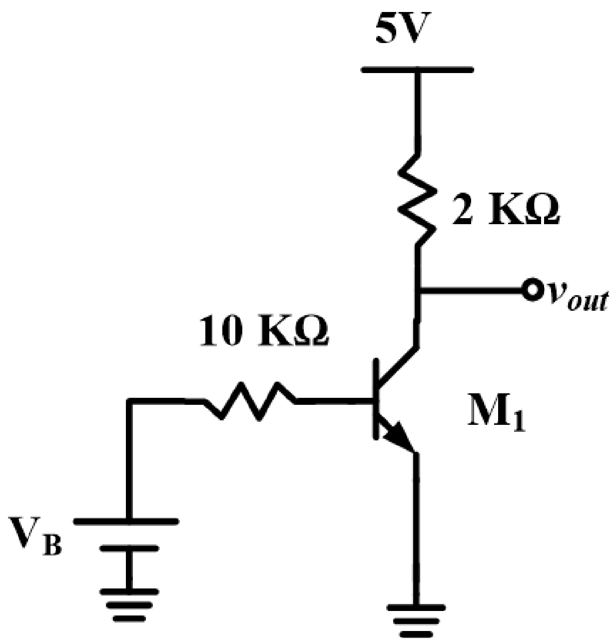
- Calculate V_{out} for $V_B = 0V \ and \ 5V$. Assume $\beta = 100$.



Solution:

- $V_B = 0V$
  - EB Junction is off
  - Assume transistor is off → $i_C = 0$
  - $5V = i_C R + V_{CE} \rightarrow V_{CE} = 5V$
  - $V_{BC} = -5V \rightarrow CBJ \ is \ off \ as \ well$
  - Assumption is correct
  - $V_{out} = 5V$.

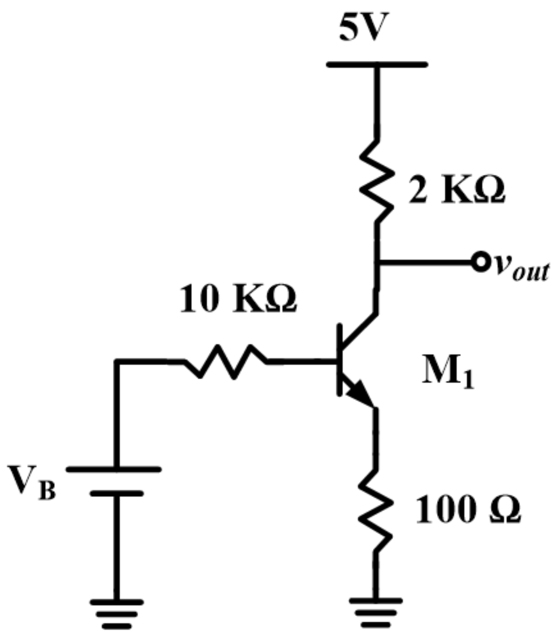
DC Analysis – Example 2



- $V_B = 5V$
  - EB Junction is ON
  - Transistor can be active or in saturation
- Assume Active
  - $i_B = \frac{5-0.7}{10K} = 0.43mA$
  - $i_C = \beta i_B = 43mA$
  - $5V = i_C R + V_{CE} \rightarrow V_{CE} = -81V < 0.2V$ (Wrong Assumption)
- Assume SAT
  - $i_B = \frac{5-0.7}{10K} = 0.43mA$
  - $V_{out} = V_{CE} = 0.2V$
  - $i_C = \frac{5-0.2}{2K} = 2.4mA$
  - $\frac{i_C}{i_B} = 5.6 < \beta$ (Correct Assumption)

DC Analysis – Example 3

- Calculate V_{out} for $V_B = 5V$. Assume $\beta = 100$.



Solution:

  - EB Junction is ON
  - Transistor can be active or in saturation

- Assume Active
  - $5V = i_B R_B + 0.7V + (\beta + 1) i_B R_E \rightarrow i_B = 0.21mA$
  - $i_C = \beta i_B = 21mA$
  - $5V = i_C R_C + V_{CE} + \frac{\beta+1}{\beta} i_C R_E \rightarrow V_{CE} = -39.1V < 0.2V$
  - Wrong Assumption!

DC Analysis – Example 3

- Assume SAT
  - $V_{CE} = 0.2V$
  - $5V = (10K)I_B + 0.7 + I_E(100)$
  - $5V = (2K)I_C + 0.2 + I_E(100)$
  - $I_E = I_C + I_B$
  - $I_C = 2.27mA, I_E = 2.67mA, I_B = 0.4mA$
  - $\frac{i_C}{i_B} < \beta$ (Correct Assumption)