Lecture 8

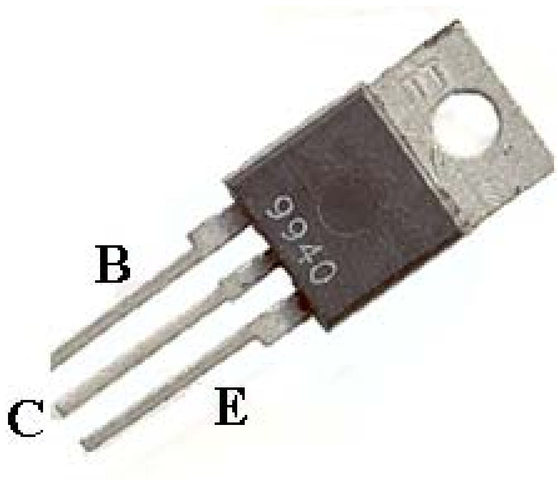
The Bipolar Junction Transistor

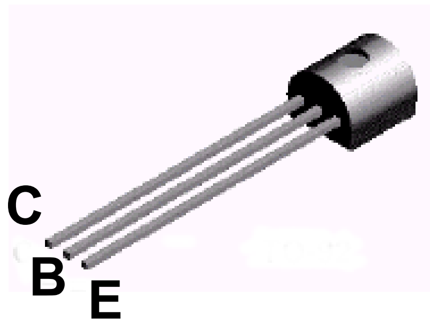
A bit of History

- BJT was invented in 1948 at Bell Telephone Laboratories.

  Ushered in a new era of solid-state circuits.

  It was replaced by MOSFET as predominant transistor used in modern electronics.

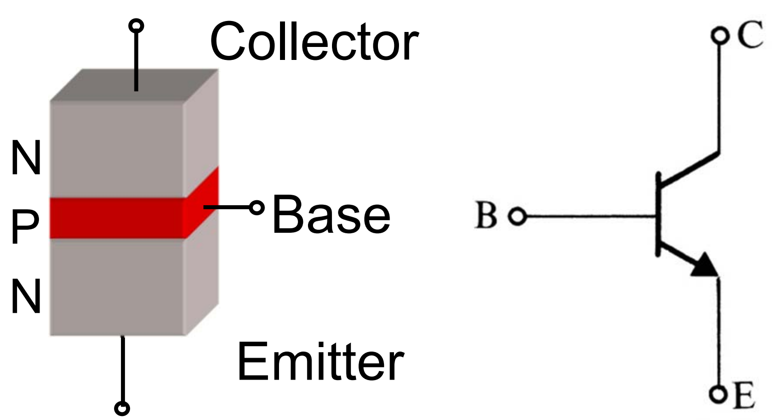




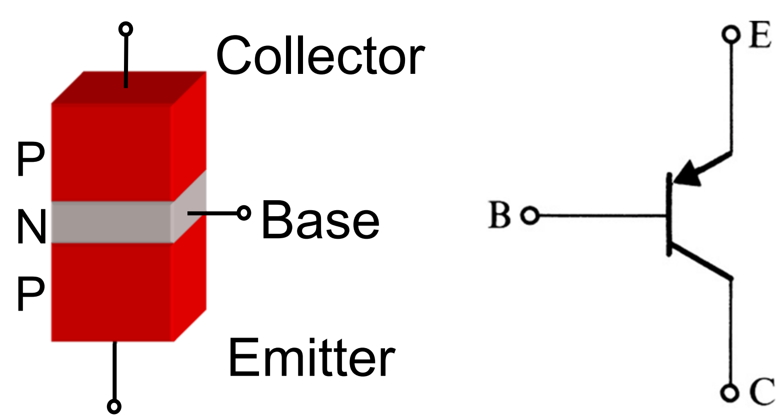
The BJT structure and symbols

- Two types of BJT:
  - npn. (most common, focus on it)
  - pnp.
- Three adjacent regions of doped Si (each connected to a lead):
  - Base. (thin layer, less doped).
  - Collector.
  - Emitter.

npn BJT



pnp BJT



npn BJT transistor

- N-type of emitter: <u>more heavily doped</u> than collector.

- <u>With $V_C>V_B>V_E$:</u>

  <u>Base-Emitter</u> junction <u>forward biased</u>, <u>Base-Collector</u> <u>reverse biased</u>.

  Electrons diffuse from Emitter to Base (from n to p).

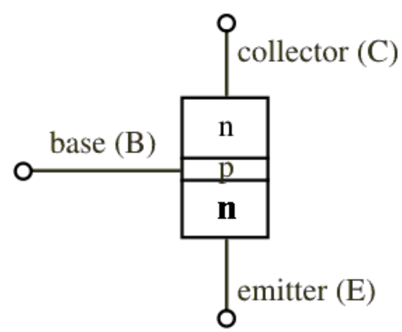
  There's a <u>depletion layer</u> on the Base-Collector junction → no flow of e^- allowed.

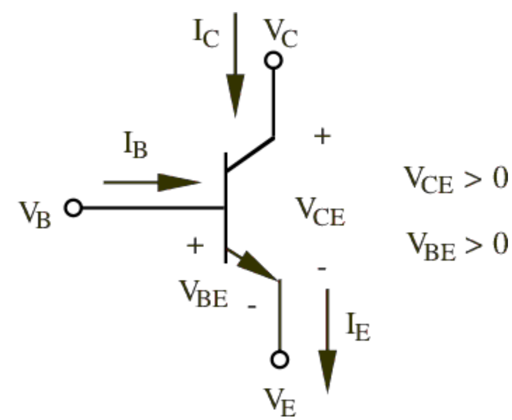
  BUT the <u>Base is thin and Emitter region is n^+ (heavily doped)</u> → electrons have enough momentum to cross the Base into the Collector.

  The small base current I_B controls a large current I_C

$$V_C > V_B > V_E$$

$$\begin{aligned} I_E &= I_C + I_B \\ V_{BE} &= V_B - V_E \\ V_{CE} &= V_C - V_E \\ I_C &= \beta I_B \end{aligned}$$





BJT characteristics

- All current which enters transistor must leave: $i_E = i_C + i_B$

- Current Gain:

  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 current Gain is expressed in terms of the **β** (beta) of the transistor (often called h_{fe} by manufacturers).

- β (beta) is Temperature and Voltage dependent.

- It can vary a lot among transistors (common values for signal BJT: 20 - 200).

$$I_C = \alpha I_E \qquad I_B = (1-\alpha) I_E \qquad \beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$$

BJT characteristics (cont'd)

- **common-emitter current gain** (β) – is influenced by two factors:
  - width of base region (W)
  - relative doping of base emitter regions (N_A/N_D)
- High Value of β
  - thin base (small W in nano-meters)
  - lightly doped base / heavily doped emitter (small N_A/N_D)

$$i_C = I_s e^{V_{BE}/V_T}$$

$$i_E = \frac{\beta+1}{\beta} i_C = \frac{\beta+1}{\beta}\left(I_s e^{V_{BE}/V_T}\right)$$

- **common-base current gain** (α)

$$i_C = \alpha I_E \quad \Rightarrow \quad \alpha = \frac{\beta}{\beta+1} \qquad \beta = \frac{\alpha}{1-\alpha}$$

Modes of Operation

- Transistor consists of two *pn*-junctions:
  - **emitter-base** junction (EBJ)
  - **collector-base** junction (CBJ)
- Operating mode depends on biasing.
  - **active** mode – used for amplification
  - **cutoff** and **saturation** modes – used for switching.

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

Summary of BJT C-V relationship in active mode

Summary of the BJT Current–Voltage Relationships in the Active Mode

$$i_C = I_S e^{v_{BE}/V_T}$$

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

$$i_E = \frac{i_C}{\alpha} = \left(\frac{I_S}{\alpha}\right) e^{v_{BE}/V_T}$$

Note: For the *pnp* transistor, replace v_{BE} with v_{EB}.

$$i_C = \alpha i_E \qquad i_B = (1-\alpha) i_E = \frac{i_E}{\beta+1}$$

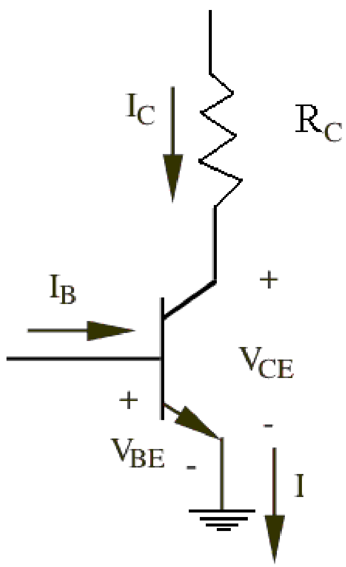
$$i_C = \beta i_B \qquad i_E = (\beta+1) i_B$$

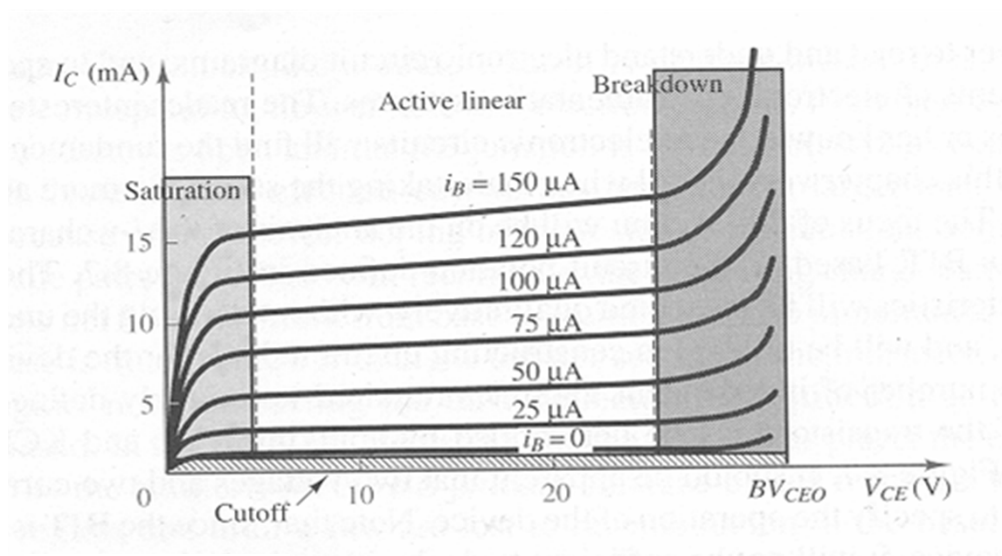
$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \frac{\beta}{\beta+1}$$

$$V_T = \text{thermal voltage} = \frac{kT}{q} \simeq 25 \text{ mV at room temperature}$$

npn common emitter BJT circuits

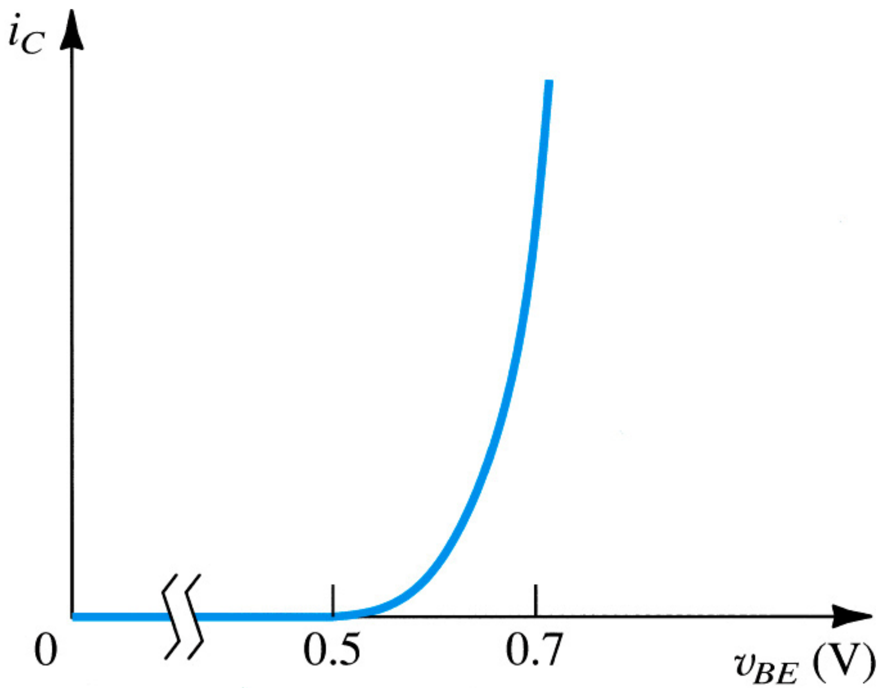
- Emitter is grounded.
- Base-Emitter starts to conduct with V_{BE}=0.6V (for example),I_C flows and it's I_C=b*I_B.
- Increasing I_B, V_{BE} slowly increases to 0.7V (for example) but I_C rises exponentially.
- As I_C rises ,voltage drop across R_C increases and V_{CE} drops toward ground. (transistor in saturation, no more linear relation between I_C and I_B)



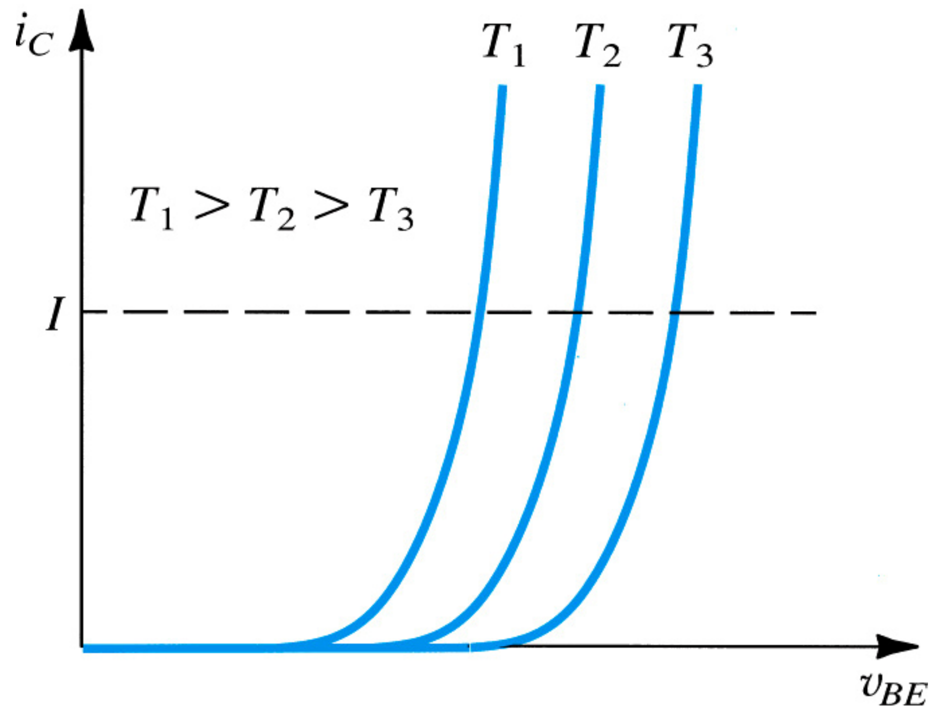


The collector-emitter output characteristics of a BJT

Common Emitter characteristics (input)



The i_C-v_{BE} characteristic for an npn transistor.



Effect of temperature on the i_C-v_{BE} characteristic.

Common Emitter characteristics (output)

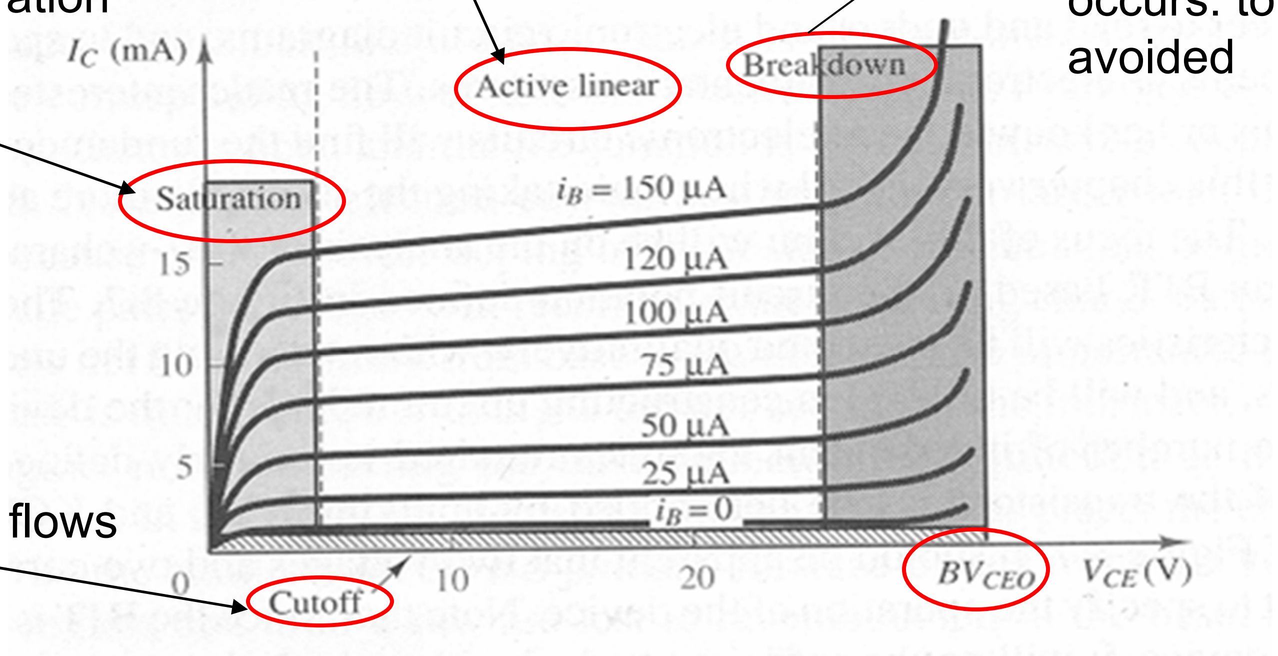
Collector current controlled by the collector circuit. (Switch behavior)

In full saturation V_{CE}=0.2V.

Collector current proportional to Base current

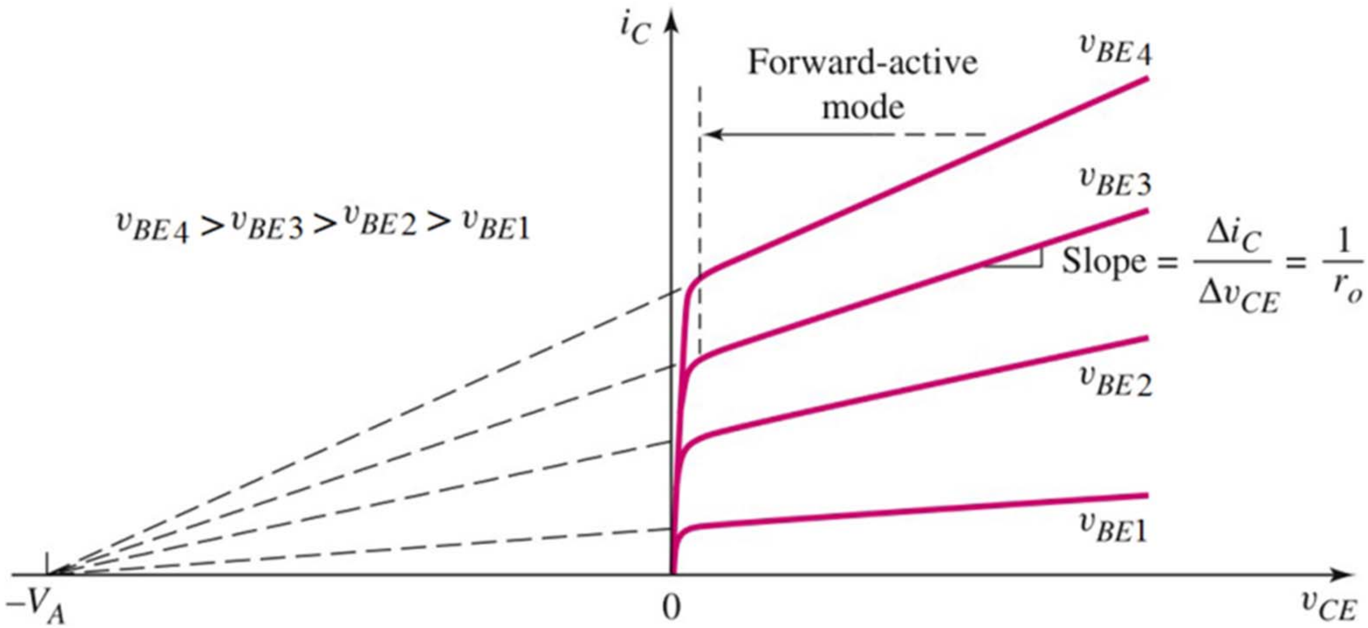
The avalanche multiplication of current through collector junction occurs: to be avoided

No current flows



The collector-emitter output characteristics of a BJT

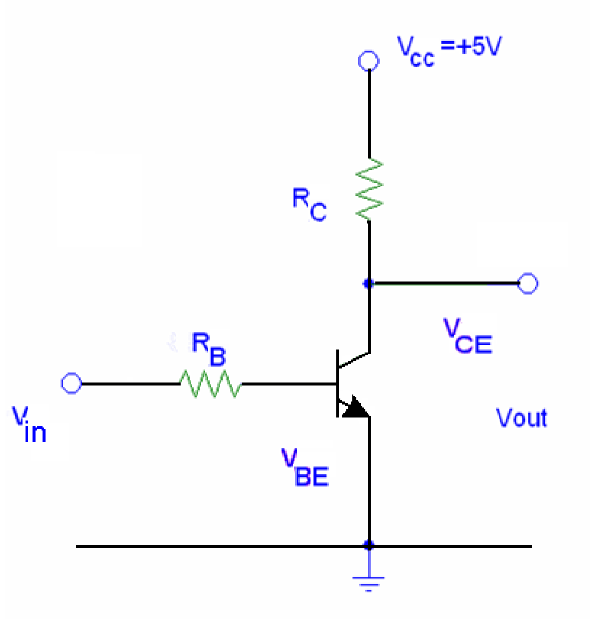
Common Emitter characteristics – cont’d



$$\rightarrow \quad r_0 \cong \frac{V_A}{I_C}$$

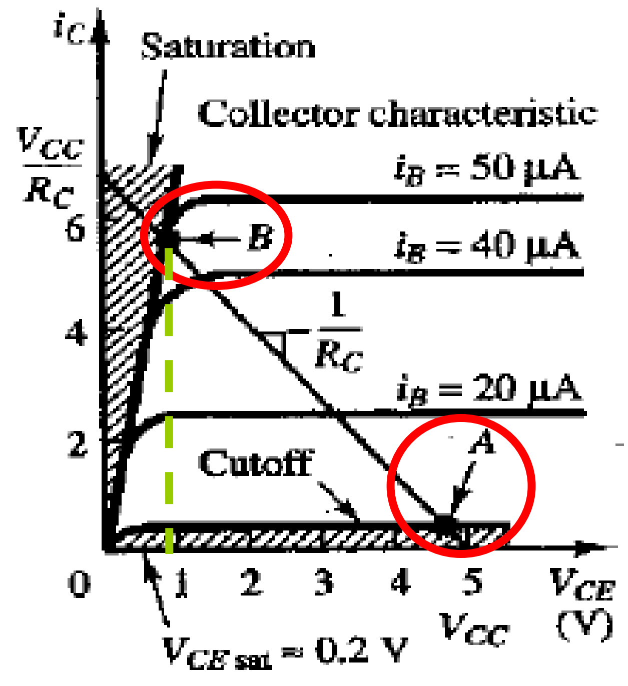
I-*V* characteristic of common-emitter BJT circuit, showing Early voltage and the finite output resistance, of the transistor

BJT as switch (digital circuit)- example

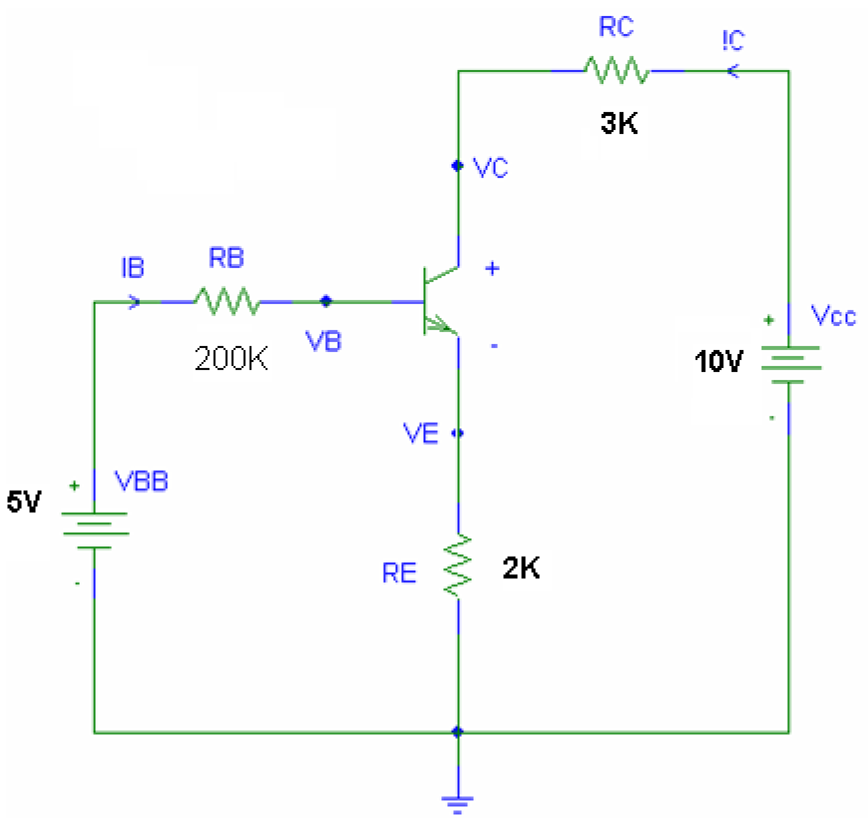


- **V_{in}(Low) < 0.7 V**
  - BE junction <u>not</u> forward biased
  - Cutoff region
  - No current flows
  - $V_{out} = V_{CE} = V_{cc}$
- **V_{out} = High**

- **V_{in} (High)**
  - BE junction forward biased (V_{BE}=0.7V)
  - Saturation region
  - V_{CE} small (~0.2 V for saturated BJT)
  - V_{out} = small
  - $I_B = (V_{in}-V_B)/R_B$
- **V_{out} = Low**



BJT as amplifier (analogue circuit) - example

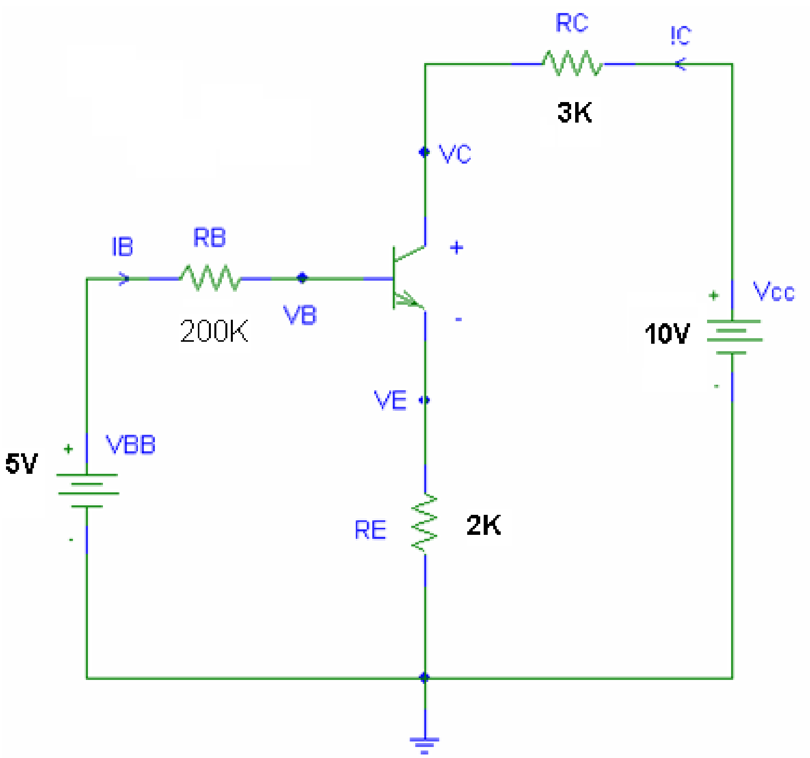


- Common emitter mode
- Linear Active Region
- Significant current Gain

Example:

- Let Gain, $\beta = 100$
- Assume to be in active region -> $V_{BE} = 0.7V$
- Find if it's in active region?

BJT as amplifier – example (cont'd)



$$V_{BE} = 0.7V$$

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

$$I_B = \frac{V_{BB} - V_{BE}}{R_B + R_E * 101} = \frac{5 - 0.7}{402} = 0.0107mA$$

$$I_C = \beta * I_B = 100 * 0.0107 = 1.07mA$$

$$V_{CB} = V_{CC} - I_C * R_C - I_E * R_E - V_{BE} =$$

$$= 10 - (3)(1.07) - (2)(101 * 0.0107) - 0.7 =$$

$$= 3.93V$$

$V_{CB}>0$ so the BJT is in active region

BJT as amplifier – example 2

Calculate the collector and emitter currents, given the base current and current gain. Assume a common-base current gain $\alpha = 0.97$ and a base current of $i_B = 25\ \mu\text{A}.$. Also assume that the transistor is biased forward in the forward active mode.

Solution: The common-emitter current gain is $\beta = \frac{\alpha}{1-\alpha} = \frac{0.97}{1-0.97} = 32.33$

The collector current is $i_C = \beta i_B = 32.33 \times 25 = 808.25\ \mu\text{A}$

And the emitter current is $i_E = i_B + i_C = 25 + 808.25 = 833.25\ \mu\text{A}$

Acknowledgments

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- Credit is acknowledged where credit is due. Please refer to the full list of references.