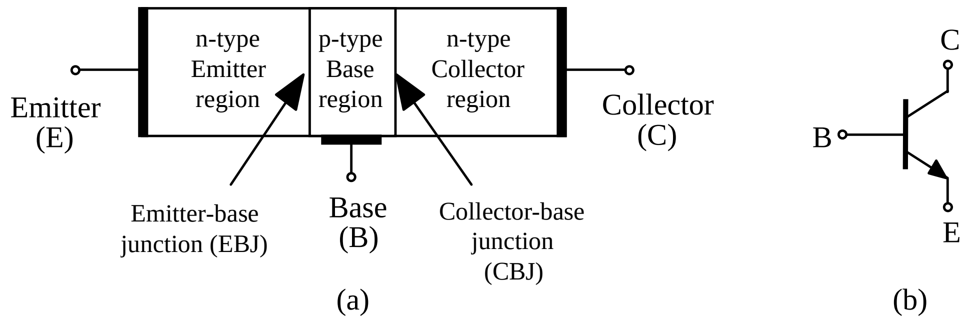
Bipolar Junction Transistors

• Physical Structure & Symbols

• NPN



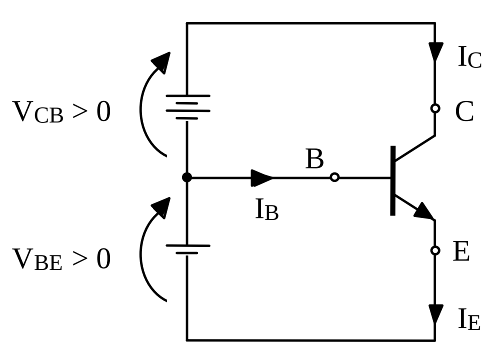
• PNP - similar, but:

- **N- and P-type regions interchanged**
- **Arrow on symbol reversed**

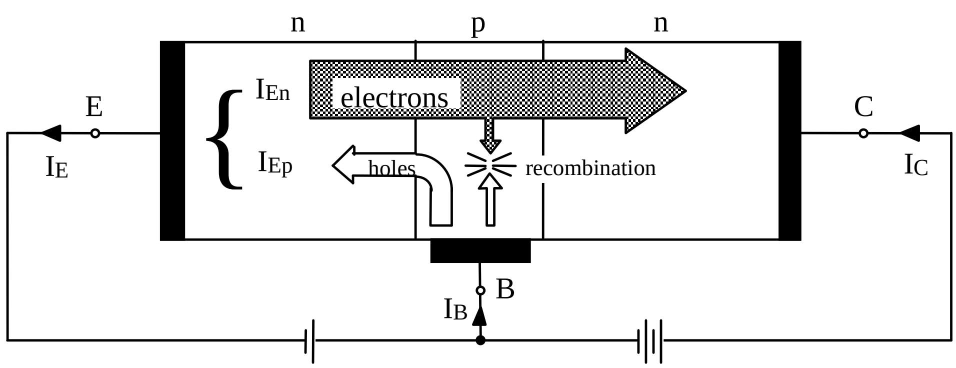
• Operating Modes

Operating mode	EBJ	CBJ
Cut-off	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward
Reverse-active	Reverse	Forward

• Active Mode - voltage polarities for NPN



BJT - Operation in Active Mode



• **I_{En} , I_{Ep} both proportional to exp(V_{BE}/V_T)**

• **$I_C \approx I_{En}$**

$$\Rightarrow I_C \approx I_S \exp(V_{BE}/V_T) \qquad (1.1)$$

• **$I_B \approx I_{Ep} \ll I_{En}$**

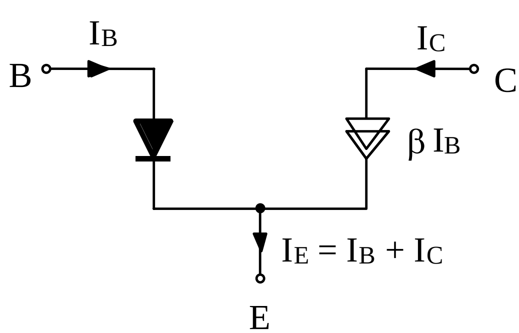
$\Rightarrow$ can write $\quad$ **$I_C = \beta\, I_B$ where β large** $\qquad$ **(1.2)**

• **I_S = SATURATION CURRENT (typ 10^{-15} to 10^{-12} A)**

• **V_T = THERMAL VOLTAGE = kT/e ≈ 25 mV at 25 °C**

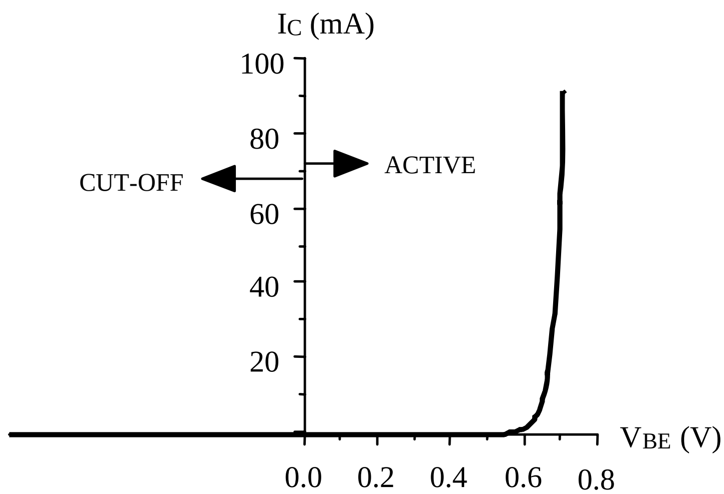
• **β = COMMON-EMITTER CURRENT GAIN (typ 50 to 250)**

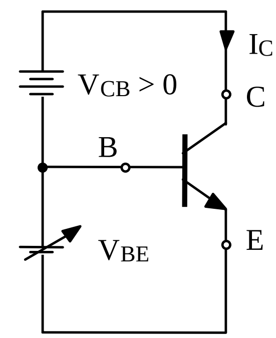
• **Active Mode Circuit Model**



BJT Operating Curves - 1

- **INPUT-OUTPUT** **I_C vs V_{BE}** **(for $I_S = 10^{-13}$ A)**





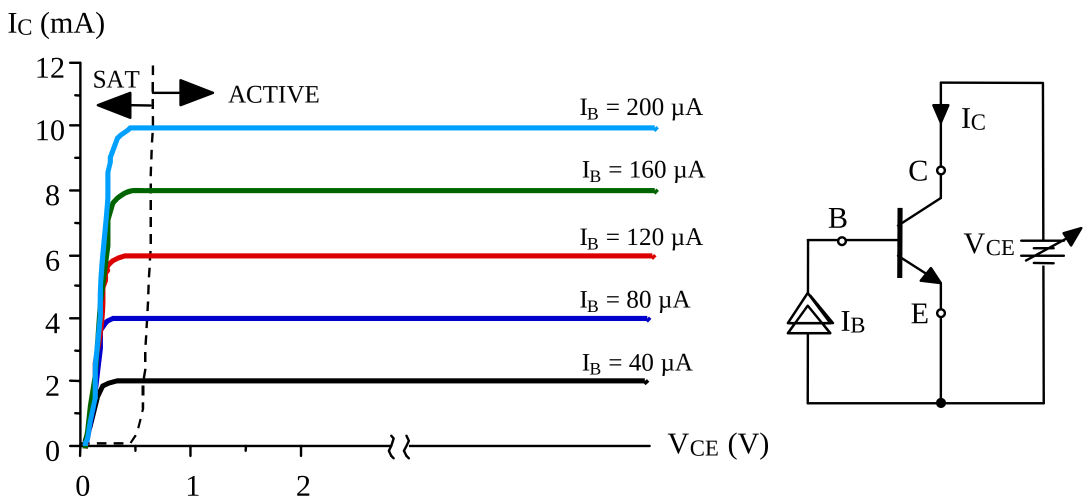
- **ACTIVE REGION:**
  - **$I_C \approx 0$ for $V_{BE} < \approx 0.5$ V**
  - **I_C rises very steeply for $V_{BE} > \approx 0.5$ V**
  - **$V_{BE} \approx 0.7$ V over most of useful I_C range**

  - **I_B vs V_{BE} similar, but current reduced by factor β**

- **CUT-OFF REGION:**
  - **$I_C \approx 0$**
  - **Also I_B, $I_E \approx 0$**

BJT Operating Curves - 2

- **OUTPUT** **I_C vs V_{CE}** **(for $\beta = 50$)**



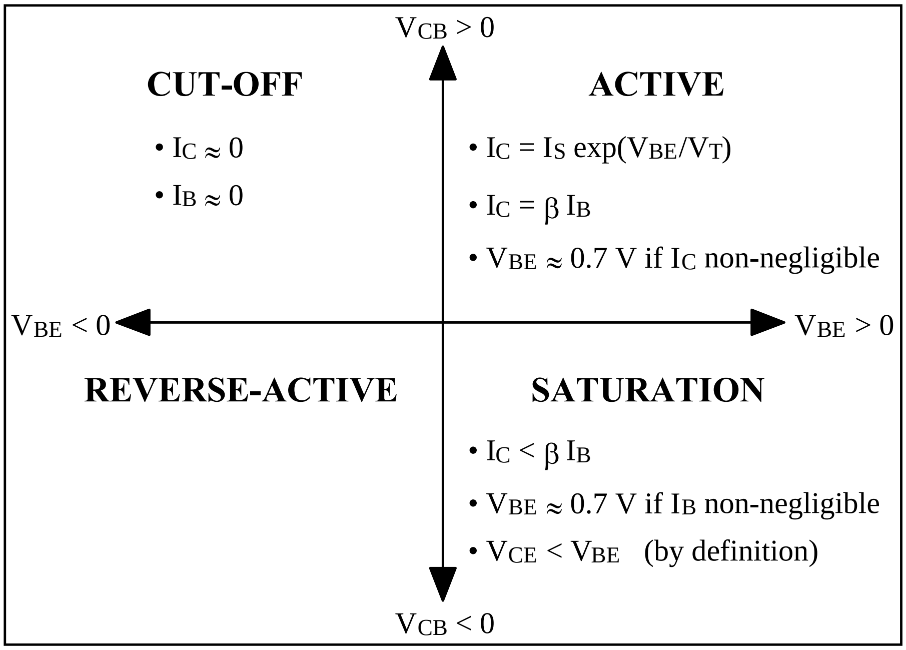
- **ACTIVE REGION ($V_{CE} > V_{BE}$):**
  - **$I_C = \beta\, I_B$, regardless of V_{CE}**

  i.e. CONTROLLED CURRENT SOURCE

- **SATURATION REGION ($V_{CE} < V_{BE}$):**
  - **I_C falls off as $V_{CE} \rightarrow 0$**
  - **$V_{CEsat} \approx 0.2$ V on steep part of each curve**

- **In both cases:**
  - **$V_{BE} \approx 0.7$ V if I_B non-negligible**

Summary of BJT Characteristics



- **Also** $\quad \mathbf{I_E = I_B + I_C}$ **(always)**

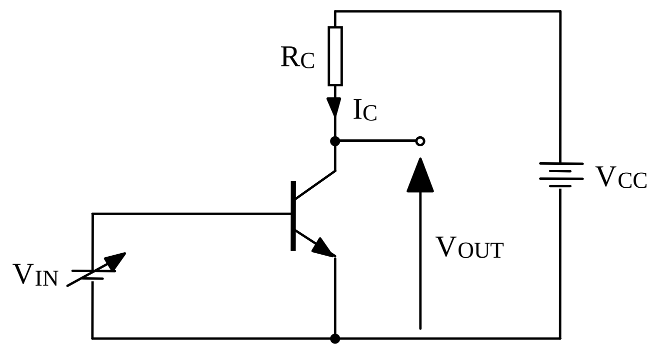
- **THIS TABLE IS IMPORTANT - GET TO KNOW IT !**

- **For PNP table:**
  - **Reverse order of suffices on all voltages in table**

    i.e. $\mathbf{V_{CB} \rightarrow V_{BC}}$ etc
  - **Reverse arrows on currents in circuit**

    i.e. arrows on $\mathbf{I_B}$, $\mathbf{I_C}$ point out of PNP device, while arrow on $\mathbf{I_E}$ points in.

Common-Emitter Amplifier
Conceptual Circuit



• Assume active mode:

$$I_C = I_S \exp(V_{IN}/V_T)$$

• Apply Ohm's Law and KVL to output side:

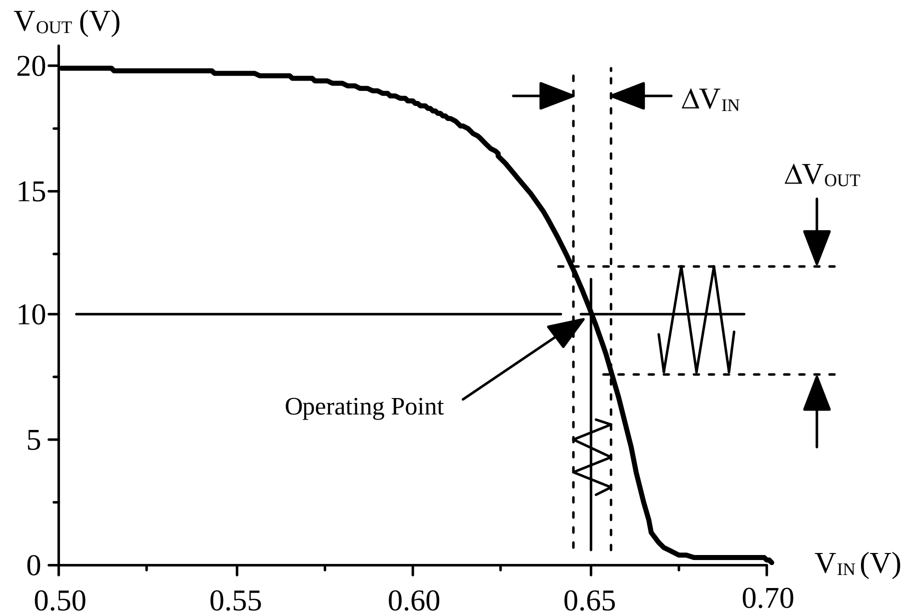
$$V_{OUT} = V_{CC} - R_C I_C \tag{1.3}$$

$$= V_{CC} - R_C I_S \exp(V_{IN}/V_T)$$

NOTE: Called 'common-emitter' because emitter is connected to reference point for both input and output circuits. Common-Base and Common-Collector also important.

C-E Amplifier
Input-Output Relationship

- **e.g. V_{CC} = 20 V, R_C = 10 kΩ, $I_S = 10^{-14}$ A, V_T = 25 mV.**



- **Plenty of voltage gain i.e. $\Delta V_{OUT} >> \Delta V_{IN}$**

BUT:

- **Highly non-linear**

  ⇒ **Output distorted unless input signal very small**

  ⇒ **Need to BIAS transistor to operate in correct region of graph to get high gain without distortion**

C-E Amplifier
Small-Signal Response - 1

Aim: to get quantitative information about the small-signal voltage gain and the linearity of a C-E amplifier

- **Start with the large signal equations:**

$$\begin{aligned} V_{OUT} &= V_{CC} - R_C I_C \\ &= V_{CC} - R_C I_S \exp(V_{IN}/V_T) \end{aligned}$$

- **Suppose we add to V_{IN} a small input signal voltage v_{in}, resulting in a corresponding signal v_{out} at the output. We can relate v_{out} to v_{in} by expanding the above as a Taylor series:**

$$V_{OUT} + v_{out} = V_{CC} - R_C I_C [1 + v_{in}/V_T + (v_{in}/V_T)^2/2 + ..] \qquad (1.5)$$

- **Assuming $v_{in} << V_T$, we can neglect quadratic and higher terms, giving:**

$$V_{OUT} + v_{out} \approx V_{CC} - R_C I_C - R_C(I_C/V_T)v_{in} \qquad v_{in} << V_T$$

This is a LINEAR APPROXIMATION, valid only when v_{in} is small

Cont'd . .

C-E Amplifier
Small-Signal Response - 2

- **Using (1.3), we can separate the output voltage into BIAS and SIGNAL components:**

$$V_{OUT} = V_{CC} - R_C I_C \qquad \text{Quiescent O/P Voltage}$$

$$v_{out} \approx - R_C (I_C / V_T) v_{in} \qquad \text{Output Signal}$$

- **SMALL-SIGNAL VOLTAGE GAIN:**

$$A_v = v_{out}/v_{in} = - R_C I_C / V_T = - R_C g_m \qquad (1.10)$$

e.g. If quiescent O/P voltage lies roughly mid-way between the supply rails then $R_C I_C \approx V_{CC}/2$. In this case $A_v = -V_{CC}/(2V_T)$, so for $V_{CC} = 20$ V we get $A_V = -400$.

The quantity $g_m = I_C/V_T$ is known as the TRANSCONDUCTANCE of the transistor.

- **LINEARITY**

Include higher order terms from Equation 1.5:

$$v_{out} \approx - R_c\, g_m [\, v_{in} + v_{in}^2/2\, V_T + \; .\;.\;.\;. \,]$$

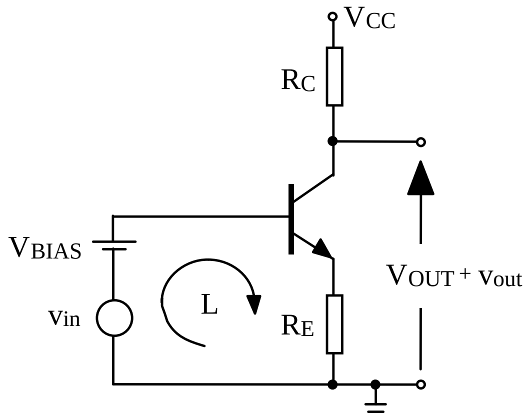
Ratio of unwanted quadratic term to linear term is $v_{in}/2V_T$, so expect 10 % distortion when $v_{in}/2V_T \approx 0.1$, or $v_{in} \approx 5$ mV.

⇒ Amplifier is linear only for very small signals

Bias Stabilisation - 1

- **Biasing at constant V_{BE} is a bad idea, because I_S and V_T both vary with temperature, and we require constant I_C (or I_E) for stable operation. Also, I_S is not a well-defined transistor parameter.**

- **We can obtain approximately constant I_E as follows:**



- **KVL in loop L (with no signal) gives:**

$$I_E = (V_{BIAS} - V_{BE})/R_E \qquad (1.11)$$

$$\approx (V_{BIAS} - 0.7\text{ V})/R_E \qquad \text{if } V_{BIAS} >> V_{BE}$$

$\Rightarrow$ I_E relatively insensitive to exact value of V_{BE}

- **Get I_C from $\quad I_C = \alpha I_E \quad$ where $\alpha = \beta/(1 + \beta) \approx 1$**

- **α is the COMMON-BASE CURRENT GAIN**

Bias Stabilisation - 2

• R_E provides NEGATIVE FEEDBACK

> **i.e. if the emitter current starts to rise as a result of some change in the transistor's characteristics, then the voltage across R_E rises accordingly. This in turn lowers the base-emitter voltage of the transistor, tending to bring the emitter current back down towards its original value.**

⇒ STABILISATION

BUT R_E also:

• Reduces small-signal voltage gain:

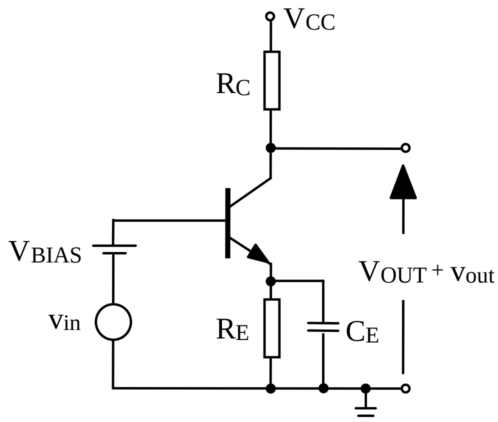
$$A_v = -R_C g_m /(1 + I_E R_E/V_T) \qquad (1.12)$$

$$\approx -\alpha R_C/R_E$$

• Reduces output swing

Bias Stabilisation - 3
Recovery of Small-Signal Voltage Gain

- **We can recover the original value of A_v for AC signals by using a BYPASS CAPACITOR:**



- **Now we have:**

$$A_v = -R_C\, g_m /(1 + I_E Z_E/V_T) \qquad (1.12b)$$

where Z_E is the combined impedance of R_E and C_E:

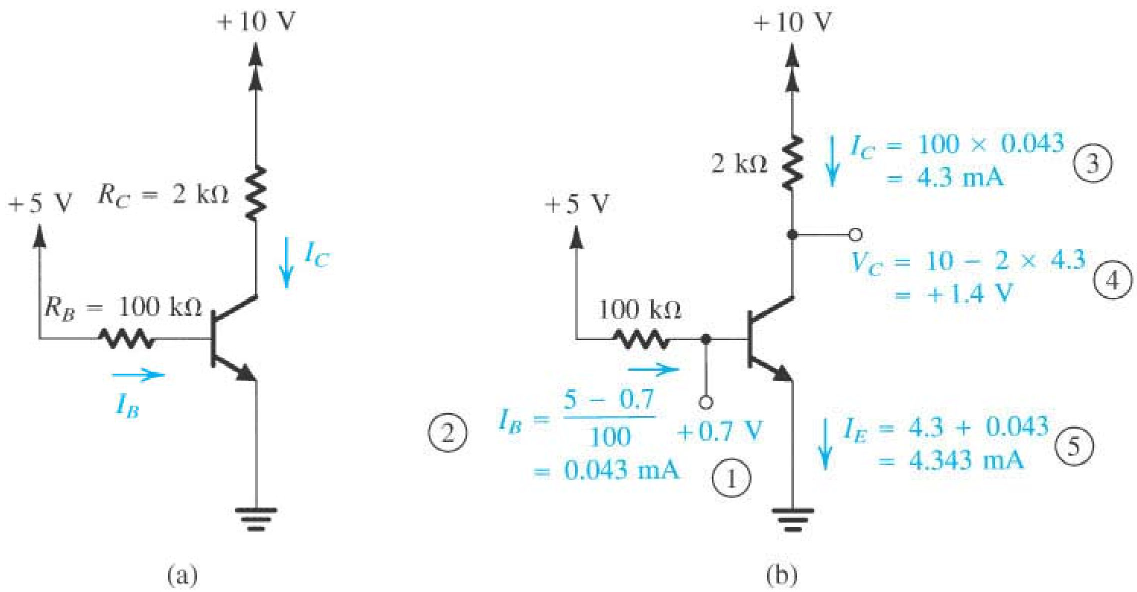
$$Z_E = R_E /(1 + j\omega R_E C_E)$$

By making C_E large enough, we can make the parallel combination appear like a short circuit (i.e. $|Z_E| \approx 0$) at all AC frequencies of interest, so that Equation 1.12b reduces to $A_v \approx -R_C g_m$ as for our original common-emitter amplifier. On the other hand, the capacitor has no effect on biasing, because it passes no DC current.

NB **Technique only really relevant to discrete circuits (no big capacitors inside IC's!)**

Example 1

Analyze the circuit below to determine the voltages at all nodes and the currents in all branches. Assume β = 100.



1. **V_{BE} is around 0.7V**

2. $$I_B = \frac{+5 - V_{BE}}{R_B} \simeq \frac{5 - 0.7}{100} = 0.043 \text{ mA}$$

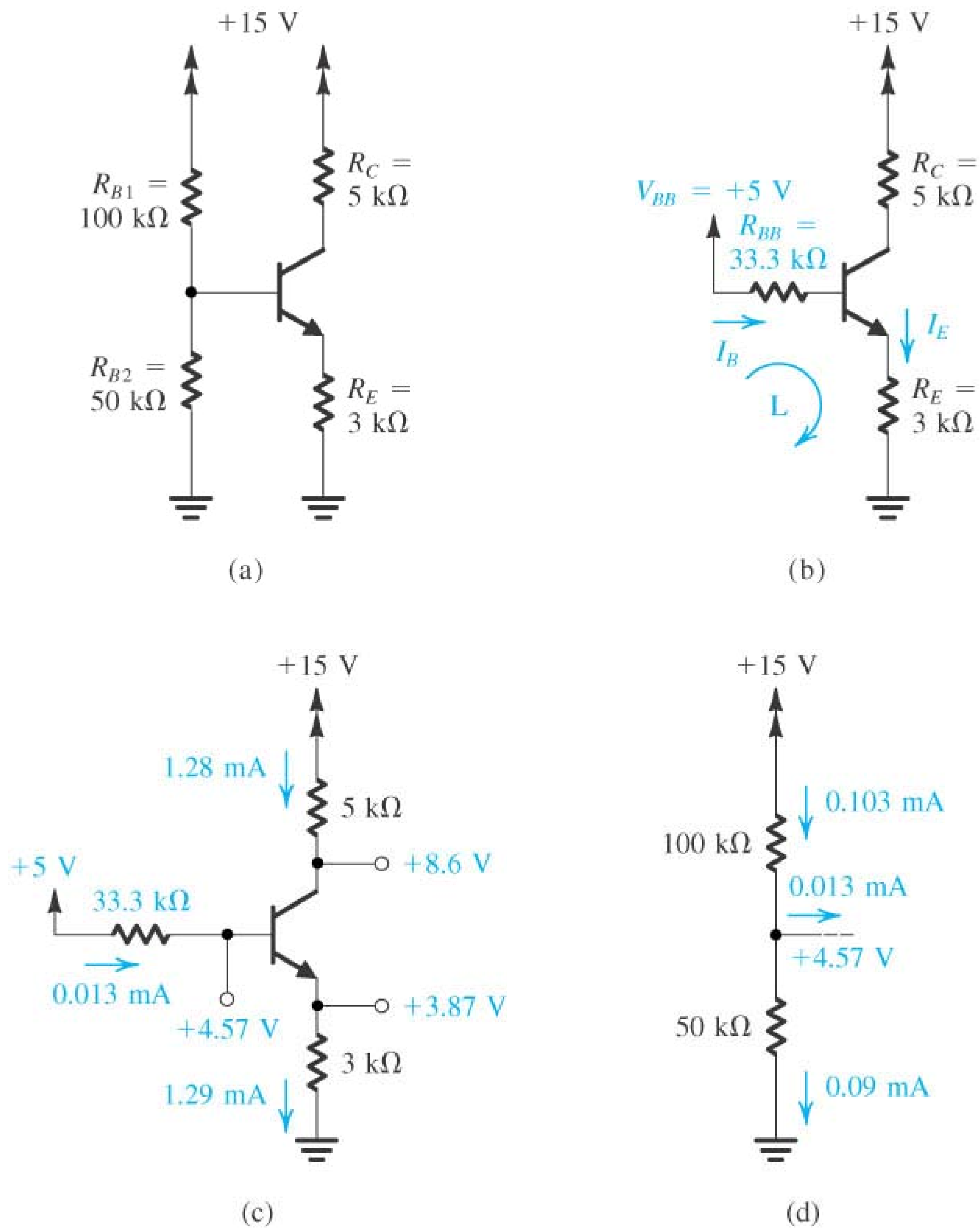
3. $$I_C = \beta I_B = 100 \times 0.043 = 4.3 \text{ mA}$$

4. $$V_C = +10 - I_C R_C = 10 - 4.3 \times 2 = +1.4 \text{ V}$$

5. $$I_E = (\beta + 1) I_B = 101 \times 0.043 = 4.3 \text{ mA}$$

Example 2

Analyze the circuit below to determine the voltages at all nodes and the currents in all branches. Assume β = 100.



Step 1: Simplify base circuit using Thévenin's theorem.

$$V_{BB} = +15\frac{R_{B2}}{R_{B1}+R_{B2}} = 15\frac{50}{100+50} = +5\text{ V}$$

$$R_{BB} = (R_{B1} // R_{B2}) = (100 // 50) = 33.3\text{ k}\Omega$$

Step 2: Evaluate the base or emitter current by writing a loop equation around the loop marked L.

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

Substituting for I_B by

$$I_B = \frac{I_E}{\beta+1}$$

and rearranging the equation gives

$$I_E = \frac{V_{BB}-V_{BE}}{R_E + [R_{BB}/(\beta+1)]}$$

For the numerical values given we have

$$I_E = \frac{5-0.7}{3+(33.3/101)} = 1.29\text{ mA}$$

The base current will be

$$I_B = \frac{1.29}{101} = 0.0128\text{ mA}$$

- **Step 3: Now evaluate all the voltages.**

$$V_B = V_{BE} + I_E R_E = 0.7 + 1.29\times 3 = 4.57V$$

$$I_C = (\frac{\beta}{1+\beta})I_E = 0.99\times 1.29 = 1.28mA$$

$$V_C = +15 - I_C R_C = 15 - 1.28\times 5 = 8.6V$$