Lecture 10b

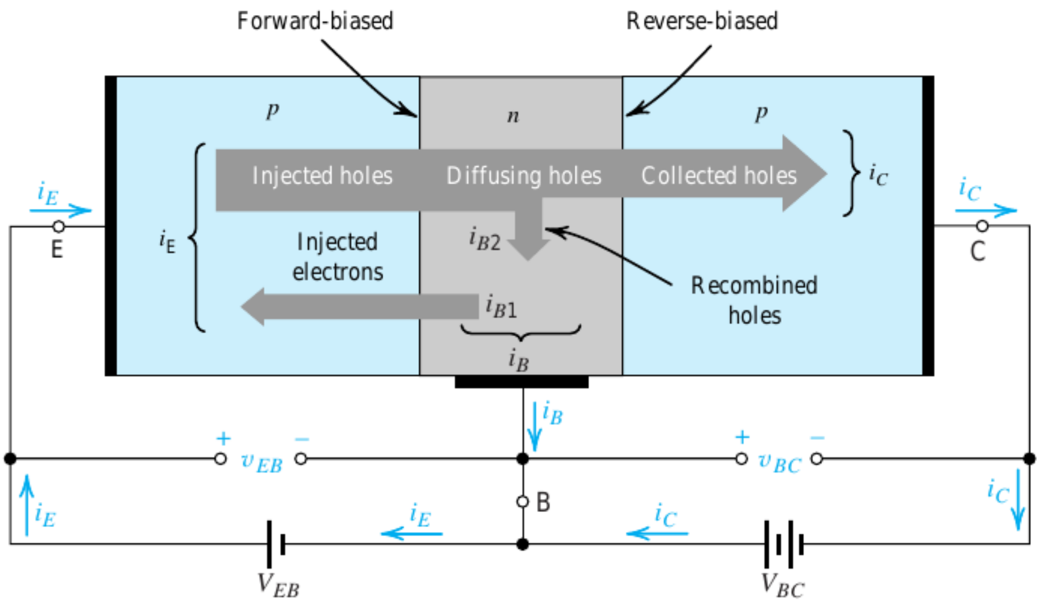
EE-215 Electronic Devices and Circuits

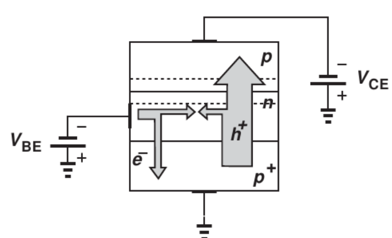
Asst Prof Muhammad Anis Chaudhary

BJT: Device Structure and Physical Operation

The pnp Transistor

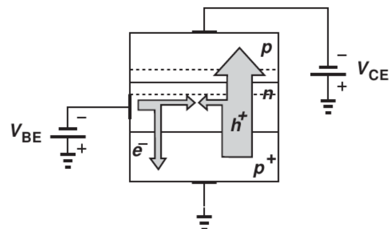
- figure shows a pnp transistor biased to operate in the active mode



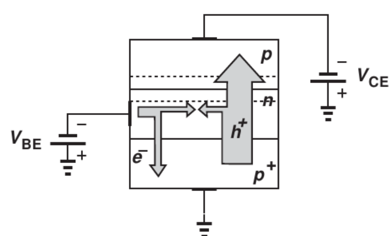
  - **Figure 6.10** Current flow in a *pnp* transistor biased to operate in the active mode.
- to achieve active mode of operation, EBJ is forward-biased while CBJ is reverse-biased
  - Unlike the npn transistor, current in the pnp transistor
    - is mainly conducted by holes, injected from the emitter
      - into the base as a result of the forward-bias voltage v_{EB}
    - 

      pnp (Active Mode: EBJ=Forward-biased CBJ=Reverse-biased)
  - These holes injected into the base diffuse through the
    - base region into the depletion region of CBJ and are

        - then swept away into the collector region under the
        - influence of the electric field, resulting in i_C
- A small number of base majority carriers (electrons) are
    - injected into the emitter (forming i_{B1}) or recombined with the
        - holes in the base region (forming i_{B2}), thus creating the base current ($i_B = i_{B1} + i_{B2}$)
    - thus the pnp transistor operates in a manner similar to that of the npn transistor
        - $= \Rightarrow$ the current-voltage relations for the pnp transistor are
            - identical to that of the npn transistor except that v_{BE} has to be replaced by v_{EB}



        - pnp (Active Mode: EBJ=Forward-biased CBJ=Reverse-biased)
- $= \Rightarrow$for a pnp transistor
    - $i_C = I_S e^{v_{EB}/V_T}$
        - $i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{EB}/V_T}$
            - $i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{EB}/V_T}$
            - $i_E = i_C + i_B$
            - where $\alpha = \frac{\beta}{\beta+1}$, $\beta = \frac{\alpha}{1-\alpha}$



        - pnp (Active Mode: EBJ=Forward-biased CBJ=Reverse-biased)
- Also the large signal operation of a pnp device in active mode can be modeled as

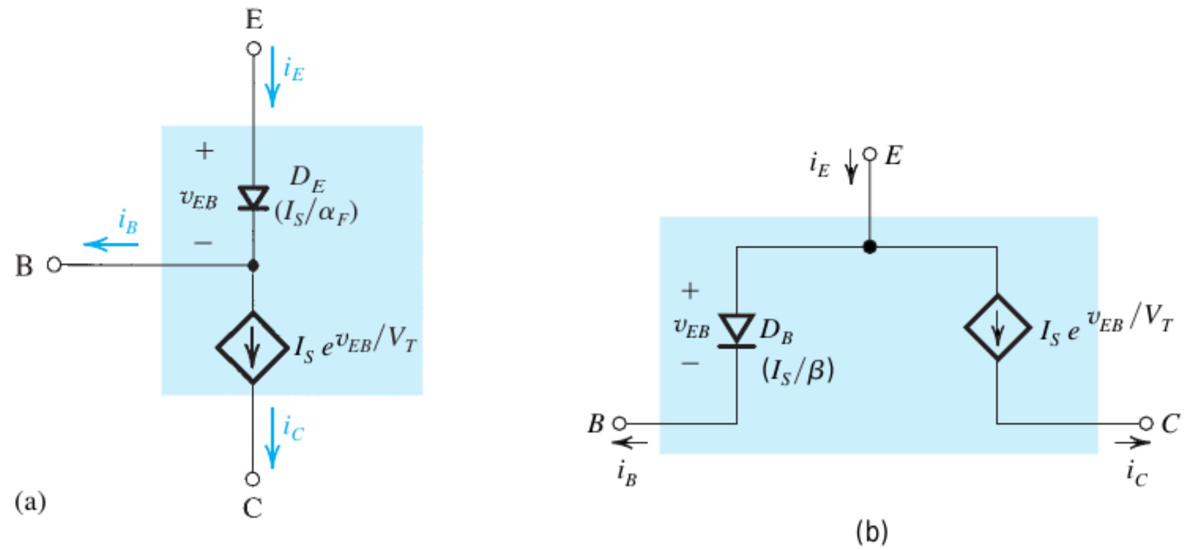
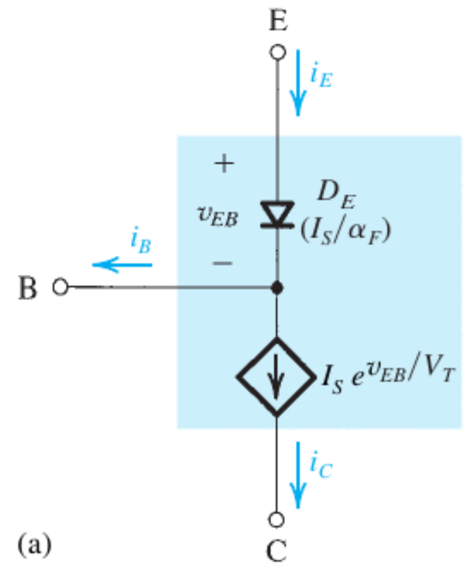
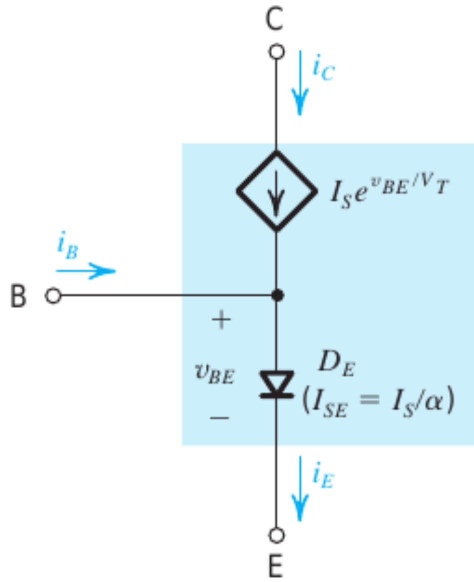


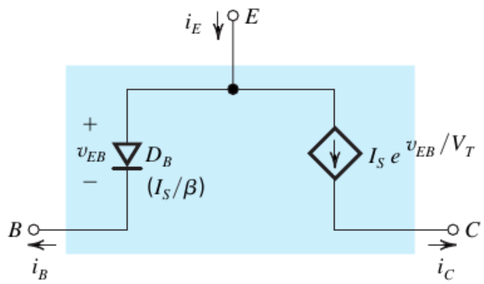
Figure 6.11 Two large-signal models for the *pnp* transistor operating in the active mode.

- 



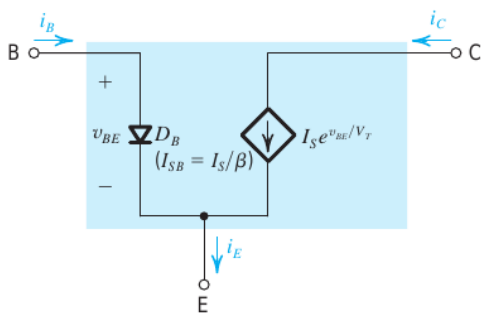
- The npn Transistor

(a)



- The pnp Transistor

(b)



- The npn Transistor

(c)

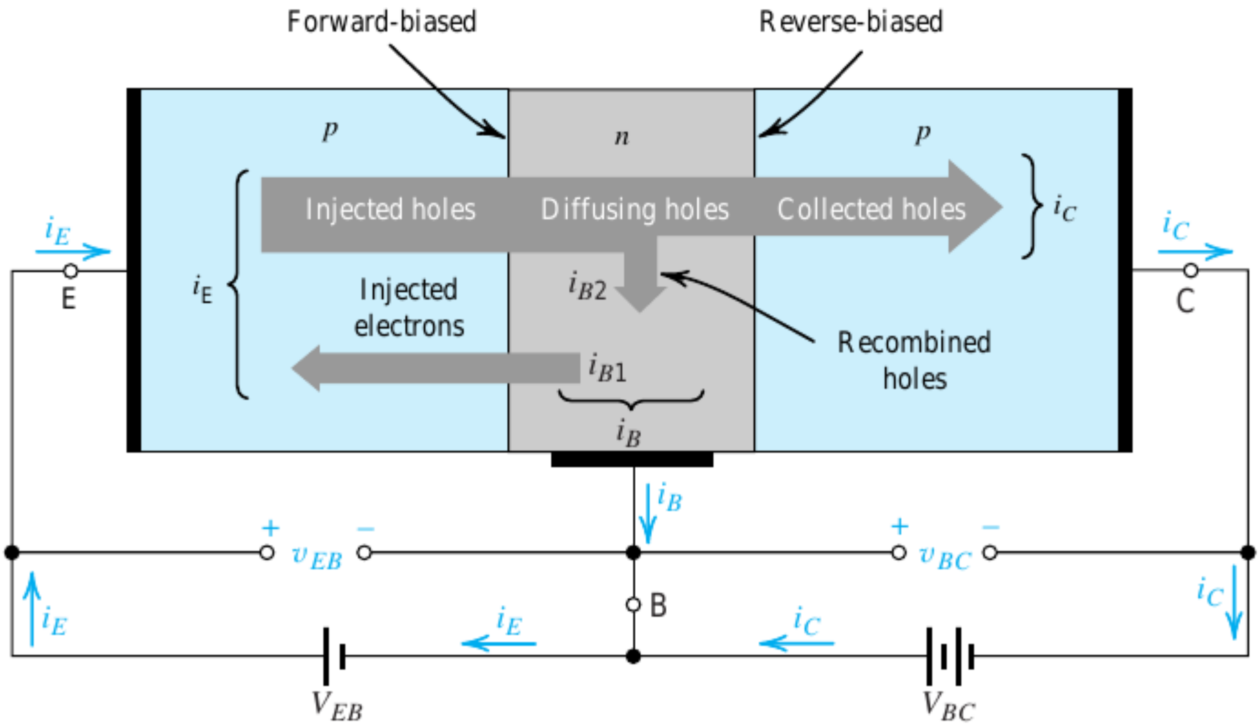


Figure 6.10 Current flow in a *pnp* transistor biased to operate in the active mode.

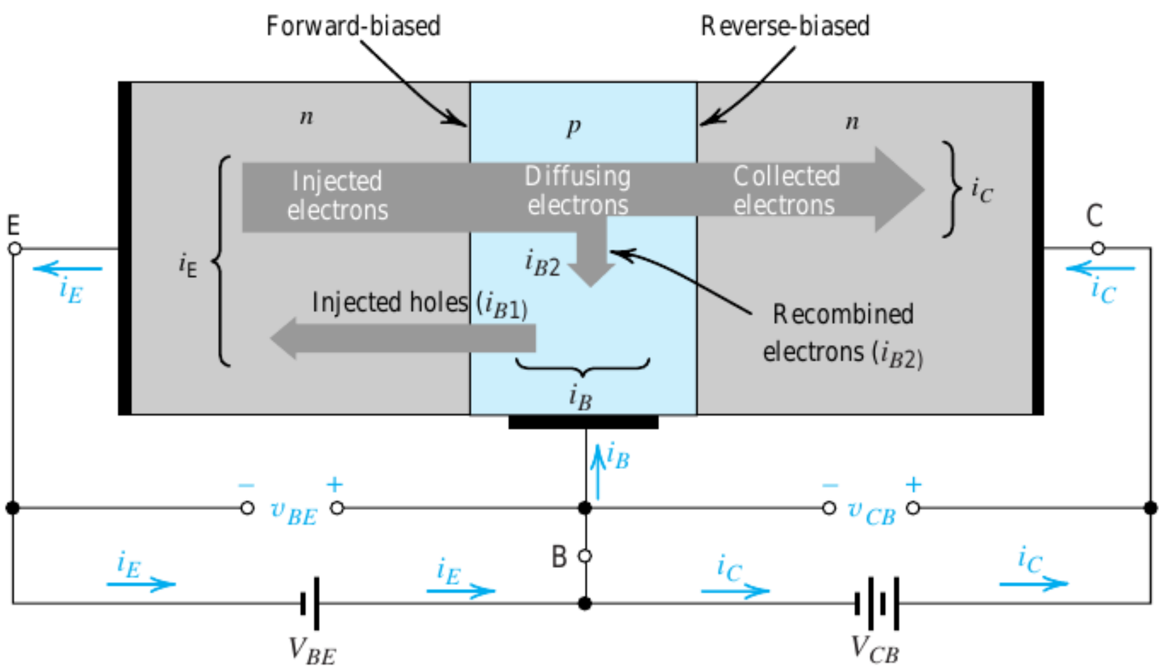
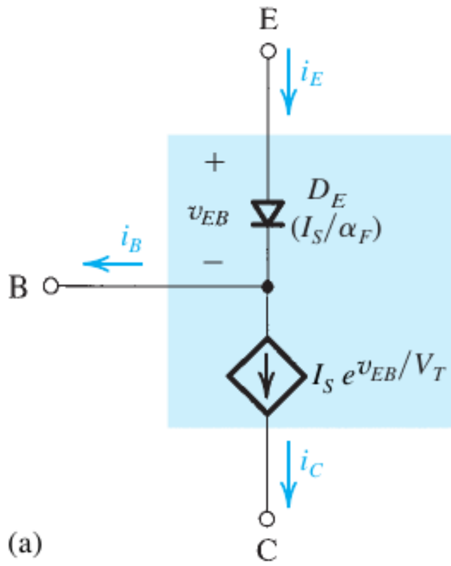


Figure 6.3 Current flow in an *npn* transistor biased to operate in the active mode. (Reverse current components due to drift of thermally generated minority carriers are not shown.)

Exercise 6.10

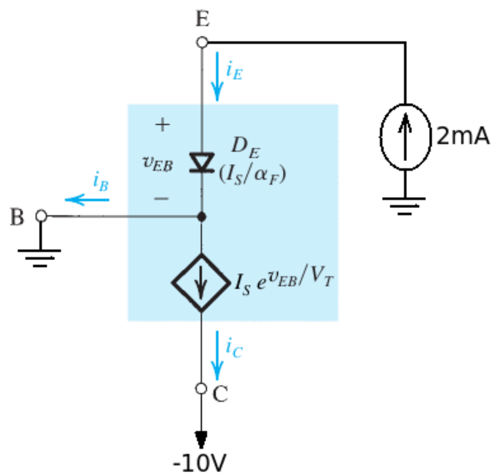
- Consider the model in Fig. 6.11(a) applied in the case of a pnp transistor whose base is grounded, the emitter is fed by a constant-current source that supplies a $2mA$ current into the emitter terminal, and the collector is connected to a $-10V$ dc supply. Find the emitter voltage, the base current, and the collector current if for this transistor $\beta = 50$ and $I_S = 10^{-14}A$.



(a)

Solution: Exercise 6.10

- here $\beta = 50$, $I_S = 10^{-14}A$, $i_E = 2mA$
  - $v_E = ?$, $i_B = ?$, $i_C = ?$
    - $\alpha = \frac{\beta}{\beta+1} = \frac{50}{51} = 0.9804$
    - $= \Rightarrow i_E = 2mA = \frac{i_C}{\alpha} = \frac{i_C}{0.9804}$
    - or $i_C = 0.9804 i_E = 0.9804 \times 2m = 1.9608mA$
    - $i_B = \frac{i_C}{\beta} = \frac{1.9608m}{50} = 39.216\mu A$
    - $I_S e^{v_{EB}/V_T} = i_C = 1.9608mA$
    - $= \Rightarrow v_{EB} = V_T \ln \frac{1.9608m}{I_S} = 0.65004V$
    - $= \Rightarrow v_E - v_B = v_E - 0 = 0.65004V$ or $v_E = 0.65004V$



Exercise 6.11

- For a pnp transistor having $I_S = 10^{-11}A$ and $\beta = 100$, calculate v_{EB} for $i_C = 1.5A$.

Solution: Exercise 6.11

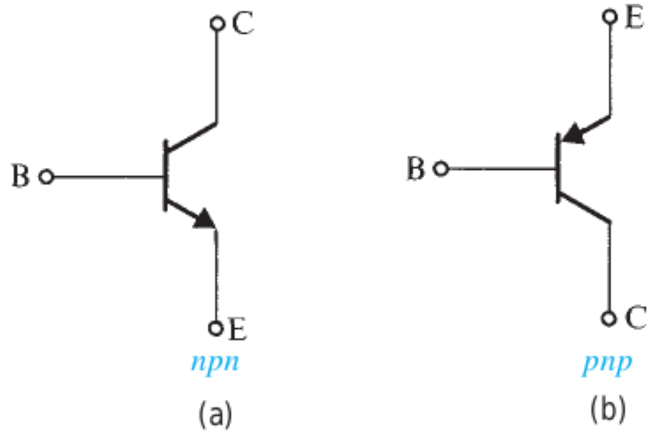
- here $I_S = 10^{-11}A$, $\beta = 100$, $i_C = 1.5A$
  - $v_{EB} = ?$
  - $i_C = I_S e^{v_{EB}/V_T}$
  - $= \Rightarrow 1.5 = 10^{-11} e^{v_{EB}/V_T}$
  - or $e^{v_{EB}/V_T} = \frac{1.5}{10^{-11}}$
  - take natural log on both sides
  - $\frac{v_{EB}}{V_T} = \ln\left(\frac{1.5}{10^{-11}}\right)$
  - $v_{EB} = V_T \ln\left(\frac{1.5}{10^{-11}}\right) = 25m \ln\left(\frac{1.5}{10^{-11}}\right) = 0.64335V$

BJT:

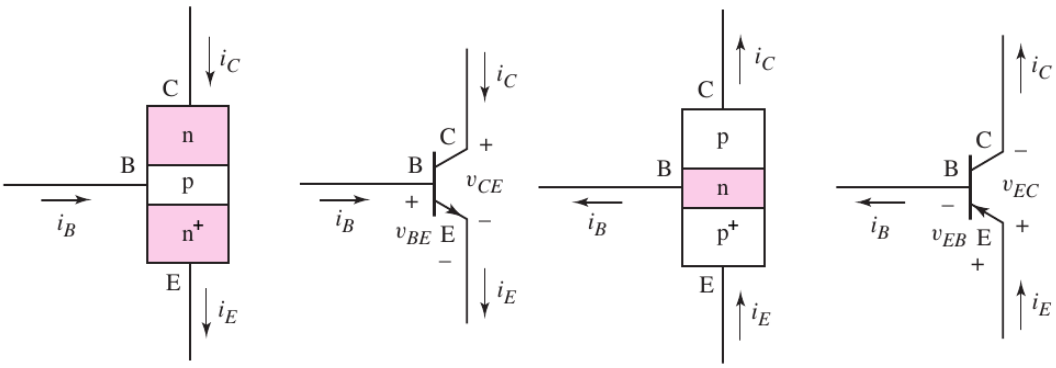
Current-Voltage Characteristics

Circuit Symbols and Conventions

- the circuit symbols for an npn and pnp transistor are indicated in fig



- **Figure 6.12** Circuit symbols for BJTs.
- In both symbols, the emitter is distinguished by an arrowhead.
- this distinction is important as practical BJT is not a symmetrical device



(a) (b)
npn bipolar transistor

(a) (b)
pnp bipolar transistor

- The polarity of the device i.e. npn or pnp
  - is indicated by the direction of the arrowhead on the emitter.
  - This arrowhead points in the direction of the conventional current flow.
- Recall that in npn BJT, current flows from the collector to emitter
  - (as the electrons are flowing from emitter to the collector)
  - in a pnp BJT, the current flows from emitter to the collector
    - (as the holes flow from emitter to the collector)
- A summary of the BJT current-voltage relationships in the active mode of operation can be given as

Table 6.2 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}.

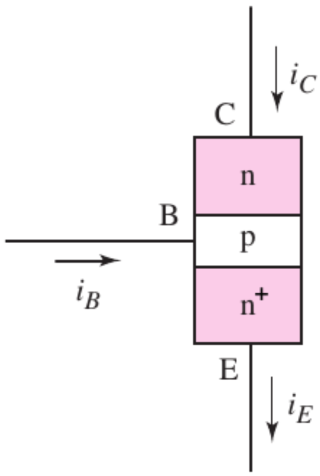
$$i_C = \alpha i_E \qquad i_B = (1-\alpha) i_E = \frac{i_E}{\beta + 1}$$

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

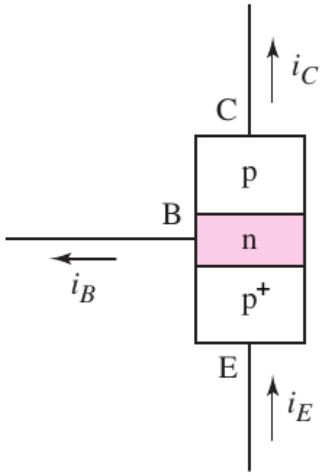
$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \frac{\beta}{\beta + 1}$$

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

- Note that an npn transistor, whose EBJ is forward-biased,
  - will operate in the active mode as long as
    - the collector voltage doesnot fall below that of the base by
      - more than approximately 0.4V
      - i.e. $v_{CB} > -0.4V$

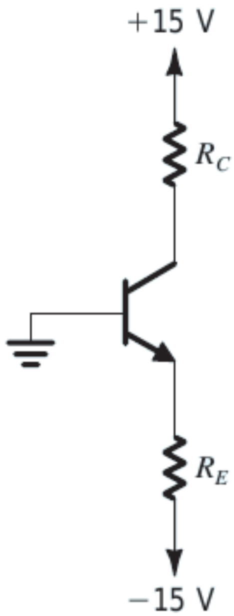


- for a pnp transistor whose EBJ is forward-biased
  - will operate in the active mode as long as
    - the collector voltage is not allowed to rise above that
    - of the base by more than 0.4V
    - i.e. $v_{CB} < 0.4V$
    - or $v_{BC} > -0.4V$



Example 6.2

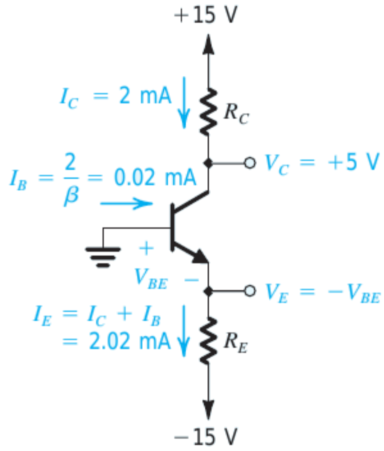
- The transistor in the circuit of Fig. 6.14(a) has $\beta = 100$ and exhibits a $v_{BE}\ of\ 0.7V$ at $i_C = 1mA$. Design the circuit so that a current of $2mA$ flows through the collector and a voltage of $+5V$ appears at the collector.
  2.8cm



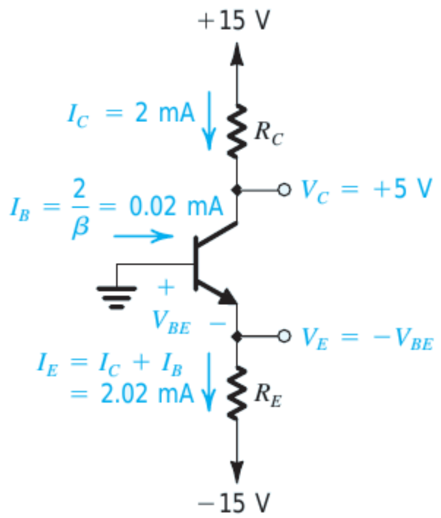
Solution: Example 6.2

- here npn, $\beta = 100$, $v_{BE1} = 0.7V$ at $i_{C1} = 1mA$
  - $i_C = 2mA$, $v_C = 5V$
    - $R_C = ?$, $R_E = ?$
    - As $i_C = I_S e^{v_{BE}/V_T}$
    - $= \Rightarrow i_{C1} = I_S e^{v_{BE1}/V_T}$, $i_{C2} = I_S e^{v_{BE2}/V_T}$
      - dividing
      - $\frac{i_{C2}}{i_{C1}} = \frac{I_S e^{v_{BE2}/V_T}}{I_S e^{v_{BE1}/V_T}} = e^{(v_{BE2} - v_{BE1})/V_T}$

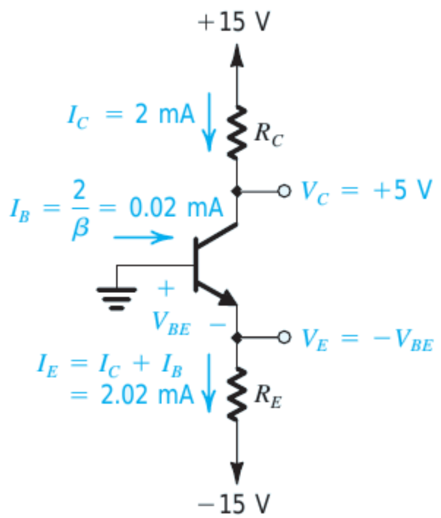
- take natural log on both sides
- $\ln \frac{i_{C2}}{i_{C1}} = \left(v_{BE2} - v_{BE1}\right)/V_T$
- $v_{BE2} - v_{BE1} = V_T \ln \frac{i_{C2}}{i_{C1}}$
- $v_{BE2} = v_{BE1} + V_T \ln \frac{i_{C2}}{i_{C1}}$



- $v_{BE2} = v_{BE1} + V_T \ln \frac{i_{C2}}{i_{C1}}$
  - here $v_{BE1} = 0.7V$ at $i_{C1} = 1mA$, $i_{C2} = i_C = 2mA$, $v_{BE2} = v_{BE} = ?$
    - $= \Rightarrow v_{BE} = v_{BE2} = 0.7 + \left(25m\right) \ln \frac{2m}{1m} = 0.717V$
    - As the base is grounded
      - $= \Rightarrow v_{BE} = 0.717 = v_B - v_E = 0 - v_E$
      - or $v_E = -0.717V$
    - $\alpha = \frac{\beta}{\beta+1} = \frac{100}{101} = 0.9901$
    - $i_E = \frac{i_C}{\alpha} = \frac{2m}{0.9901} = 2.02mA$
    - By ohm's law
      - $R_C = \frac{15 - v_C}{i_C} = \frac{15-5}{2m} = \frac{10}{2m} = 5k\Omega$

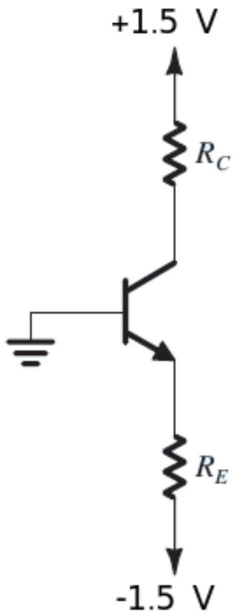


- also by ohm's law
  - $R_E = \frac{v_E - (-15)}{i_E} = \frac{-0.717-(-15)}{2.02m} = \frac{-0.717+15}{2.02m} = 7.0708k\Omega$



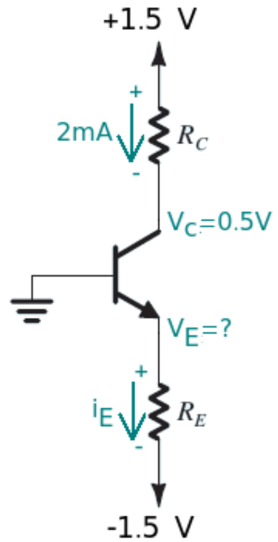
Exercise D6.12

- Repeat Example 6.2 for a transistor fabricated in a modern integrated-circuit process. Such a process yields devices that exhibit larger v_{BE} at the same i_C because they have much smaller junction areas. The dc power supplies utilized in modern IC technologies fall in the range of $1V$ to $3V$. Design a circuit similar to that shown in Fig. 6.14 except that now the power supplies are $\pm 1.5V$ and the BJT has $\beta = 100$ and exhibits v_{BE} of $0.8V$ at $i_C = 1mA$. Design the circuit so that a current of $2mA$ flows through the collector and a voltage of $+0.5V$ appears at the collector.

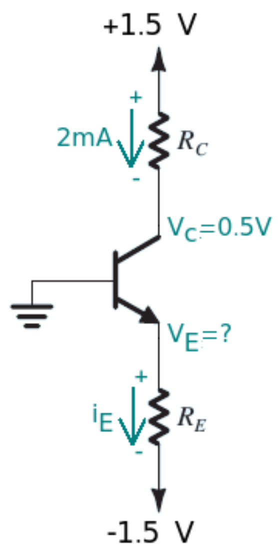


Solution: Exercise D6.12

- here $\beta = 100$, $v_{BE1} = 0.8V$ at $i_{C1} = 1mA$
  - $i_C = 2mA$, $v_C = 0.5V$
    - By ohm's law
      - $R_C = \frac{1.5 - v_C}{i_C} = \frac{1.5-0.5}{2m} = 500\Omega$
    - As $v_{BE} = v_{BE1} + V_T \ln \frac{i_C}{i_{C1}}$
      - $= \Rightarrow v_{BE} = 0.8 + (25m) \ln \left(\frac{2m}{1m}\right) = 0.81733V$
    - or $v_{BE} = 0.81733 = v_B - v_E = 0 - v_E = -v_E$
    - $= \Rightarrow v_E = -0.81733V$
    - By ohm's law
      - $R_E = \frac{v_E - (-1.5)}{i_E}$

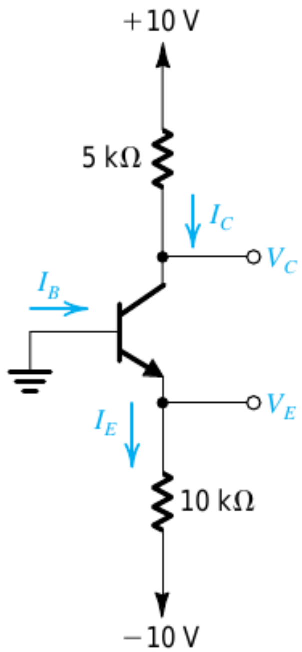


- As $i_E = \frac{i_C}{\alpha} = \frac{2m}{\alpha}$ and $\alpha = \frac{\beta}{\beta+1} = \frac{100}{101} = 0.9901$
  - $= \Rightarrow i_E = \frac{2m}{\alpha} = \frac{2m}{0.9901} = 2.02mA$
    - $= \Rightarrow R_E = \frac{v_E-(-1.5)}{i_E} = \frac{-0.81733-(-1.5)}{2.02m} = \frac{-0.81733+1.5}{2.02m} = 337.96\Omega$



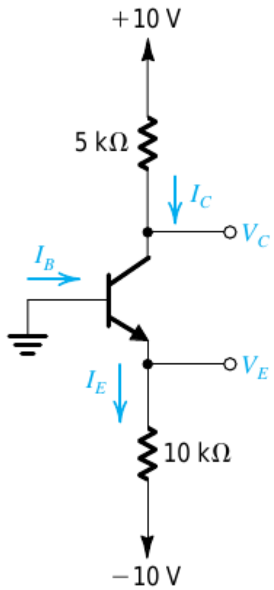
Exercise 6.13

- In the circuit shown in Fig. E6.13, the voltage at the emitter was measured and found to be $-0.7V$. If $\beta = 50$, find I_E, I_B, I_C, and V_C.

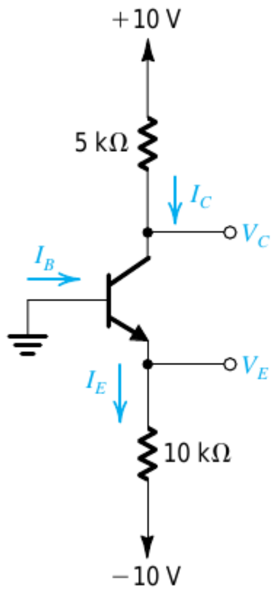


Solution: Exercise 6.13

- here v_E =$-0.7V$, $\beta = 50$
  - I_E =?, I_B =?, I_C =?, and V_C =?.
    - As $v_E = -0.7V$ and $v_B = 0V$
      - $= \Rightarrow v_{BE} = v_B - v_E = 0 - (-0.7) = 0.7V$
    - by ohm's law
      - $i_E = \frac{v_E-(-10)}{10k} = \frac{-0.7+10}{10k} = 0.93mA$
    - as $i_E = \frac{i_C}{\alpha}$
      - $= \Rightarrow i_C = \alpha i_E$ where $\alpha = \frac{\beta}{\beta+1} = \frac{50}{51} = 0.98039$
      - $i_C = \alpha i_E = 0.98039 \times 0.93m = 0.91176mA$
    - $i_B = \frac{i_C}{\beta} = \frac{0.91176m}{50} = 18.235\mu A$

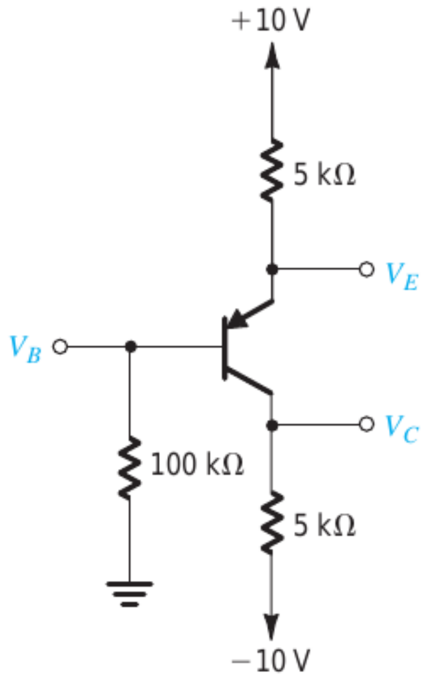


- thus $i_E = 0.93mA$, $i_C = 0.91176mA$, $i_B = 18.235\mu A$
  - by ohm's law
    - $10 - v_C = (5k)i_C = (5k)0.91176m$
      - $10 - v_C = 4.559$
      - or $10 - 4.559 = v_C$
      - $v_C = 5.441V$



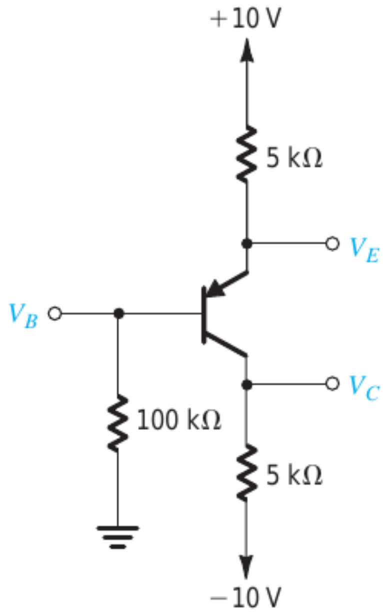
Exercise 6.14

- In the circuit shown in Fig. E6.14, measurement indicates V_B to be $+1.0V$ and V_E to be $+1.7V$. What are α and β for this transistor? What voltage V_C do you expect at the collector?

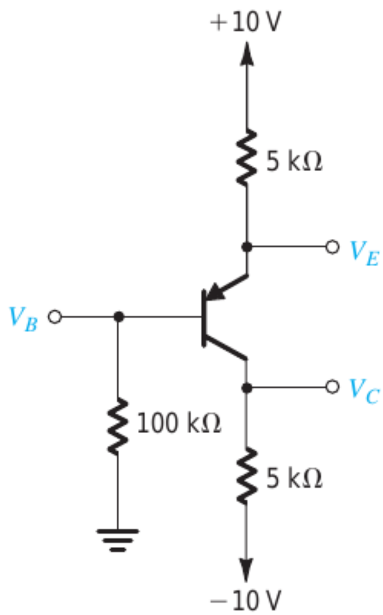


Solution: Exercise 6.14

- here $v_B = 1V$, $v_E = 1.7V$
  - $\alpha = ?$, $\beta = ?$, $v_C = ?$
    - by ohm's law,
      - $i_B = \frac{v_B}{100k} = \frac{1}{100k} = 10\mu A$
      - and $i_E = \frac{10-v_E}{5k} = \frac{10-1.7}{5k} = 1.66mA$
    - As $i_E = i_C + i_B$
      - $= \Rightarrow i_C = i_E - i_B = 1.66m - 10\mu = 1.65mA$
    - as $i_B = \frac{i_C}{\beta} = \Rightarrow \beta = \frac{i_C}{i_B}$
      - $= \Rightarrow \beta = \frac{i_C}{i_B} = \frac{1.65m}{10\mu} = 165$
    - as $i_E = \frac{i_C}{\alpha}$
      - $= \Rightarrow \alpha = \frac{i_C}{i_E} = \frac{1.65m}{1.66m} = 0.99398$



- by ohm's law
  - $v_C - (-10) = 5k(i_C) = 8.25V$
    - $v_C + 10 = 8.25$
      - or $v_C = 8.25 - 10 = -1.75V$



BJT: Current-Voltage Characteristics

Graphical Representation of Transistor Characteristics

- for an npn transistor, $i_C = I_S e^{v_{BE}/V_T}$
  - this relation can be represented graphically as
  - also $i_B = \frac{I_S}{\beta} e^{v_{BE}/V_T}$ and $i_E = \frac{I_S}{\alpha} e^{v_{BE}/V_T}$

- $= \Rightarrow i_B - v_{BE}$ and $i_E - v_{BE}$ characteristics are also exponential but with different scale currents
  - $\frac{I_S}{\beta}$ for i_B and $\frac{I_S}{\alpha}$ for i_E

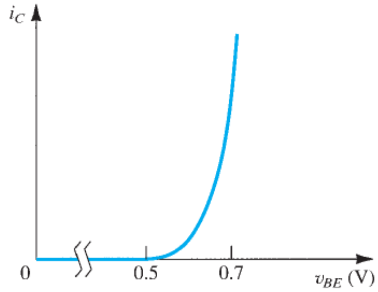


Figure 6.15 The i_C–v_{BE} characteristic for an *npn* transistor.

- As the constant of the exponential characteristic is $\frac{1}{V_T} = \frac{1}{25m} = 40$
  - $= \Rightarrow$the curve rises very sharply (you can verify this in matlab/octave)

- for v_{BE} smaller than about 0.5V (the cut-in voltage of EBJ), the current is negligibly small
  - Note that for most of the normal range,
    - v_{BE} lies in the range of 0.6V to 0.8V
    - $= \Rightarrow$In performing rapid first order dc calculations,
      - we can utilize the constant-voltage drop model
      - by assuming $v_{BE} \approx 0.7V$

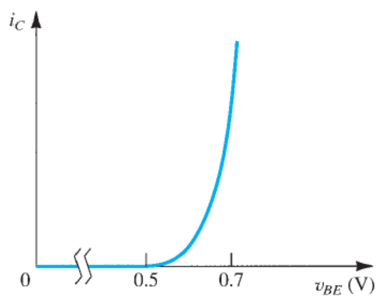
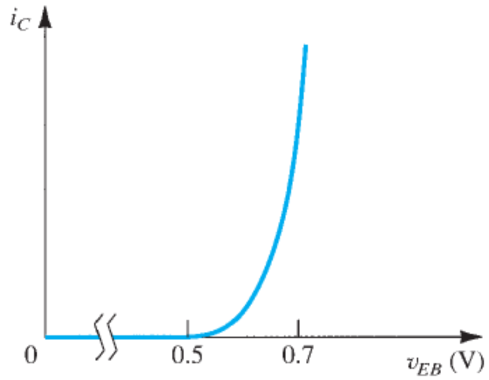


Figure 6.15 The i_C–v_{BE} characteristic for an *npn* transistor.

- for a pnp transistor, $i_C = I_S e^{v_{EB}/V_T}$
  - $= \Rightarrow i_C - v_{EB}$ characteristics will be identical to that of the npn transistor with v_{BE} replaced with v_{EB}



The i_C–v_{EB} characteristic for a *pnp* transistor.

- Note that for a BJT, the voltage across the emitter-base junction
  - decreases by about 2mV for each rise of 1^oC in temperature,
    - provided the junction is operating at a constant current

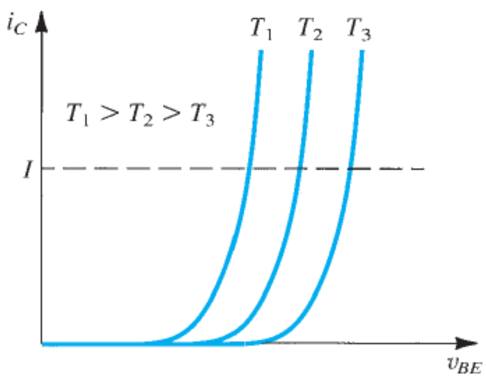


Figure 6.16 Effect of temperature on the i_C–v_{BE} characteristic. At a constant emitter current (broken line), v_{BE} changes by −2 mV/°C.

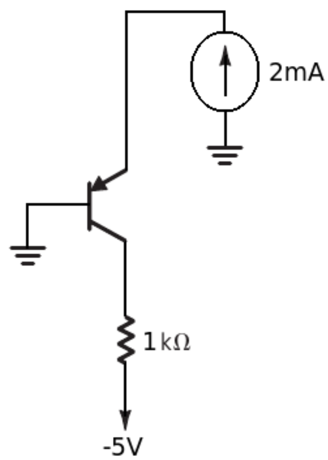
Exercise 6.15

- Consider a pnp transistor with $v_{EB} = 0.7V$ at $i_E = 1mA$. Let the base be grounded, the emitter be fed by a $2mA$ constant-current source, and the collector be connected to a $-5V$ supply through a $1k\Omega$ resistance. If the temperature increases by 30^oC, find the changes in emitter and collector voltages. Neglect the effect of I_{CBO}

Solution: Exercise 6.15

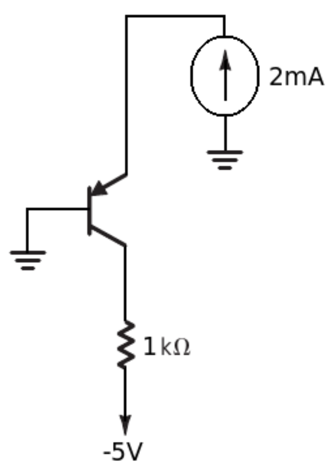
- here pnp, $v_{EB1} = 0.7V$ at $i_{E1} = 1mA$
  - change in v_E and v_C are ?
    - if i_{CBO} is neglected
      - $= \Rightarrow v_C$ will not change with temperature
      - $= \Rightarrow$change in v_C with temperature =0
    - as v_{EB} decreases by 2mV for every 1^oC rise in temperature
      - $= \Rightarrow v_{EB}$ decreases by 4mV for 2^oC rise in temperature
      - $= \Rightarrow v_{EB}$ decreases by 6mV for 3^oC rise in temperature
      -

$\vdots$



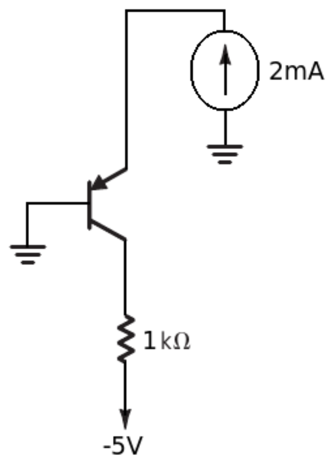
- $= \Rightarrow v_{EB}$ decreases by 60mV for $30^o C$ rise in temperature

- v_{EB} decreases by 60mV for $30^o C$ rise in temperature
  - as $v_B = 0 = \Rightarrow v_{EB} = v_E - v_B = v_E$
    - if v_{EB} decreases by 60mV $= \Rightarrow v_E$ will also decrease by 60mV



- exact value of v_{EB} can be determined as follows,
  - As $i_E = \frac{I_S}{\alpha} e^{v_{EB}/V_T}$
    - $= \Rightarrow i_{E1} = \frac{I_S}{\alpha} e^{v_{EB1}/V_T}$, $i_{E2} = \frac{I_S}{\alpha} e^{v_{EB2}/V_T}$
      - dividing
      - $\frac{i_{E2}}{i_{E1}} = \frac{e^{v_{EB2}/V_T}}{e^{v_{EB1}/V_T}} = e^{(v_{EB2} - v_{EB1})/V_T}$
    - for $v_{EB1} = 0.7V$, $i_{E1} = 1mA$, $i_{E2} = i_E = 2mA$, $v_{EB} = v_{EB2} = ?$
      - $\frac{i_{E2}}{i_{E1}} = \frac{2m}{1m} = e^{(v_{EB} - v_{EB1})/V_T} = e^{(v_{EB} - 0.7)/25m}$
      - $e^{(v_{EB} - 0.7)/25m} = 2$
      - $(v_{EB} - 0.7)/25m = \ln 2$

- $v_{EB} = 0.7 + (25m)\ln 2 = 0.71733V$



- $v_{EB} = 0.71733V$
  - when temperature increases by 30^oC
    - $= \Rightarrow v_{EB}$ decreases by 60mV
      - i.e. $v_{EB,\ (at\ T+30^oC)} = 0.71733 - 60m = 0.65733V$
    - $= \Rightarrow v_{EB\ (at\ T+30^oC)} - v_{EB} = 0.65733 - 0.71733 = -60mV$