Bipolar Junction Transistor (BJT)

Lecture notes: Sec. 3

Sedra & Smith (6th Ed): Sec. 6.1-6.4*

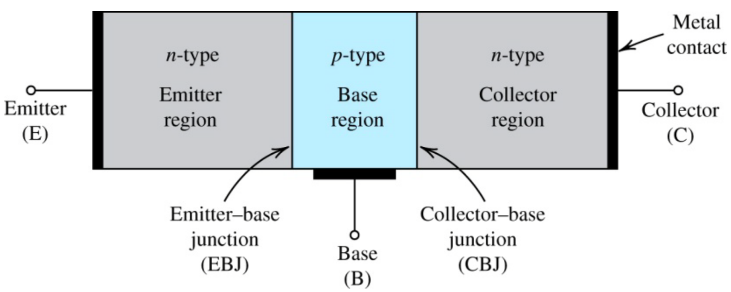
Sedra & Smith (5th Ed): Sec. 5.1-5.4*

* Includes details of BJT device operation which is not covered in this course

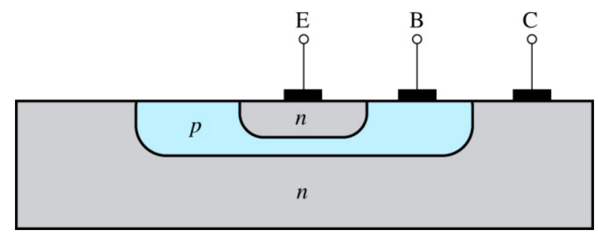
A BJT consists of three regions

NPN transistor

Simplified physical structure



An implementation on an IC

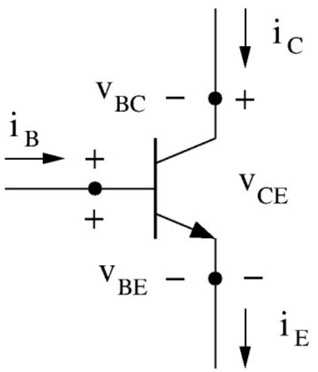


- Device is constructed such that BJT does NOT act as two diodes back to back (when voltages are applied to all three terminals).

- Device construction is NOT symmetric
  - "Thin" base region (between E & C)
  - Heavily doped emitter
  - Large area collector

BJT iv characteristics includes <u>four</u> parameters

NPN transistor



Circuit symbol and
Convention for current directions
(Note: $v_{CE} = v_C - v_E$)

- Six circuit variables: (3 i and 3 v)
- Two can be written in terms of the other four:

$$\text{KCL}: \quad i_E = i_C + i_B$$
$$\text{KVL}: \quad v_{BC} = v_{BE} - v_{CE}$$

- BJT iv characteristics is the relationship among (i_B , i_C , v_{BE} , and v_{CE})
- It is typically derived as

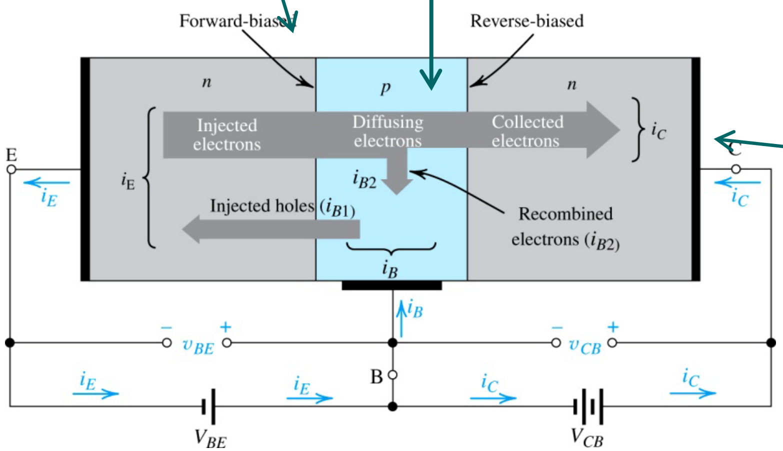
$$i_B = f\,(v_{BE})$$
$$i_C = g\,(i_B, v_{CE})$$

BJT operation in the "active" mode

BE junction is forward biased
($v_{BE} = V_{D0}$)

As Emitter is heavily doped, a large number of electrons diffuse into the base (only a small fraction combine with holes)

The number of these electrons scales as e^{v_{BE}/V_T}



- If the base is "thin" these electrons get near the depletion region of BC junction and are swept into the collector if $v_{CB} \geq 0$ ($v_{BC} \leq 0$: **BC junction is reverse biased**!)

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

- In this picture, i_c is independent of v_{BC} (and v_{CE}) as long as

$$v_{BC} = v_{BE} - v_{CE} = V_{D0} - v_{CE} \leq 0$$

$$v_{CE} \geq V_{D0}$$

Active mode:

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

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

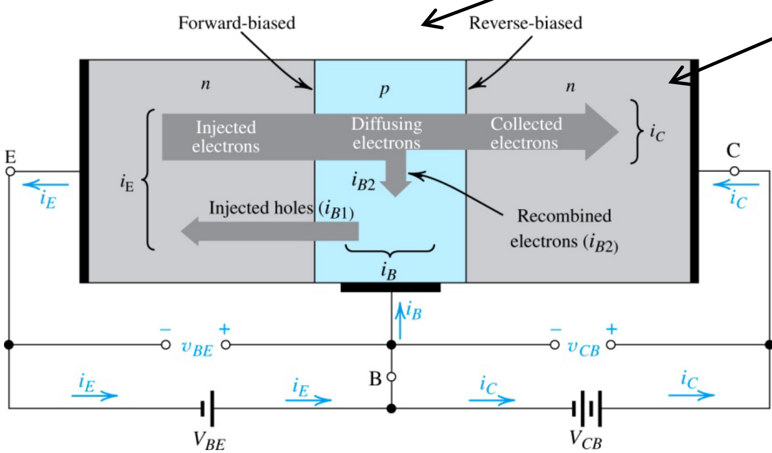
$$v_{CE} \geq V_{D0}$$

- Base current is also proportional to e^{v_{BE}/V_T} and therefore, $i_C : i_B = i_C/\beta$

BJT operation in saturation mode

BE junction is forward biased ($v_{BE} = V_{D0}$)

Similar to the active mode, a large number of electrons diffuse into the base.



- For $v_{BC} \geq 0$ **BC junction is forward biased** and a diffusion current will set up, reducing i_C .

1. <u>Soft saturation:</u> $v_{CE} \geq 0.3$ V (Si)*
   $v_{BC} \leq 0.4$ V (Si), diffusion current is small and i_C is very close to its active-mode level.

2. <u>Deep saturation region:</u> $0.1 < v_{CE} < 0.3$ V (Si) or $v_{CE} \approx 0.2$ V = V_{sat} (Si), i_C is smaller than its active-mode level ($i_C < \beta\, i_B$).
   - Called saturation as i_C is set by outside circuit & does not respond to changes in i_B.

3. <u>Near cut-off:</u> $v_{CE} \leq 0.1$ V (Si)
   Both i_C & i_B are close to zero.

"Deep" Saturation mode:

$$i_B = \frac{I_S}{\beta} e^{v_{BE}/V_T}$$

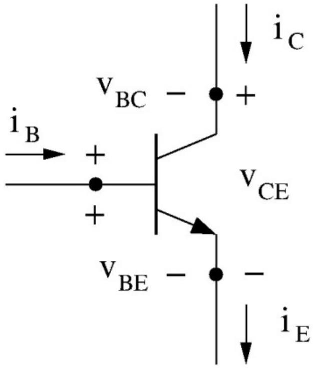
$$i_C < \beta\, i_B$$

$$v_{CE} \approx V_{sat}$$

* Sedra & Smith includes this in the active region, i.e., BJT is in active mode as long as $v_{CE} \geq 0.3$ V.

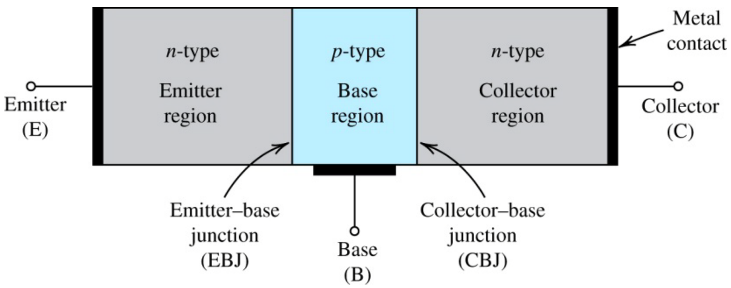
BJT iv characteristics includes <u>four</u> parameters

NPN transistor



Circuit symbol and
Convention for current directions
(Note: $v_{CE} = v_C - v_E$)

Simplified physical structure



- BJT iv characteristics is the relationship among (i_B , i_C , v_{BE} , and v_{CE})
- It is typically derived as

$$i_B = f\ (v_{BE})$$

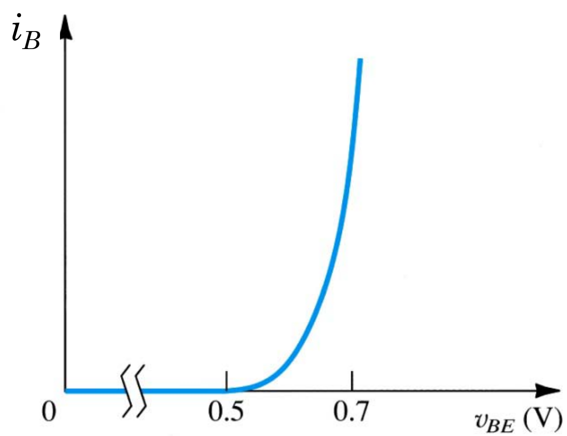
$$i_C = g\ (i_B, v_{CE})$$

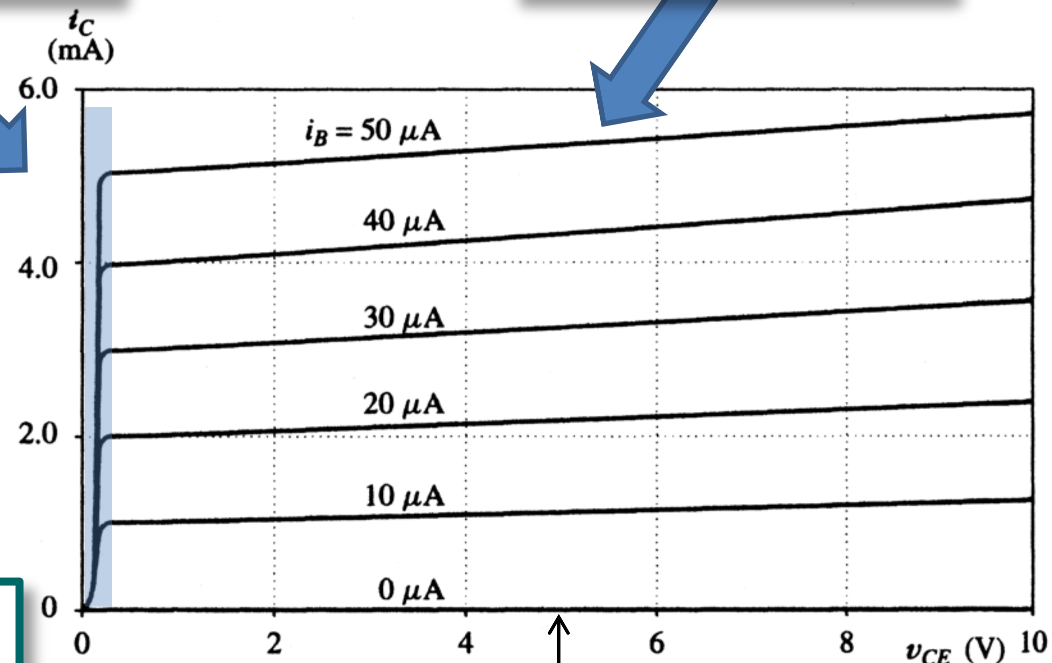
BJT iv characteristics: $i_B = f(v_{BE})$ & $i_C = g(i_B, v_{CE})$

Saturation:
BE is forward biased, BC is forward biased

1. Soft saturation: $0.3 \le v_{CE} \le 0.7\ \mathrm{V}, \quad i_C \approx \beta\, i_B$
2. Deep saturation: $0.1 \le v_{CE} \le 0.3\ \mathrm{V}, \quad i_C < \beta\, i_B$
3. Near cut-off: $v_{CE} \le 0.1\ \mathrm{V}, \quad i_C \approx 0$

Active:
BE is forward biased
BC is reverse biased
$i_C = \beta\, i_B$



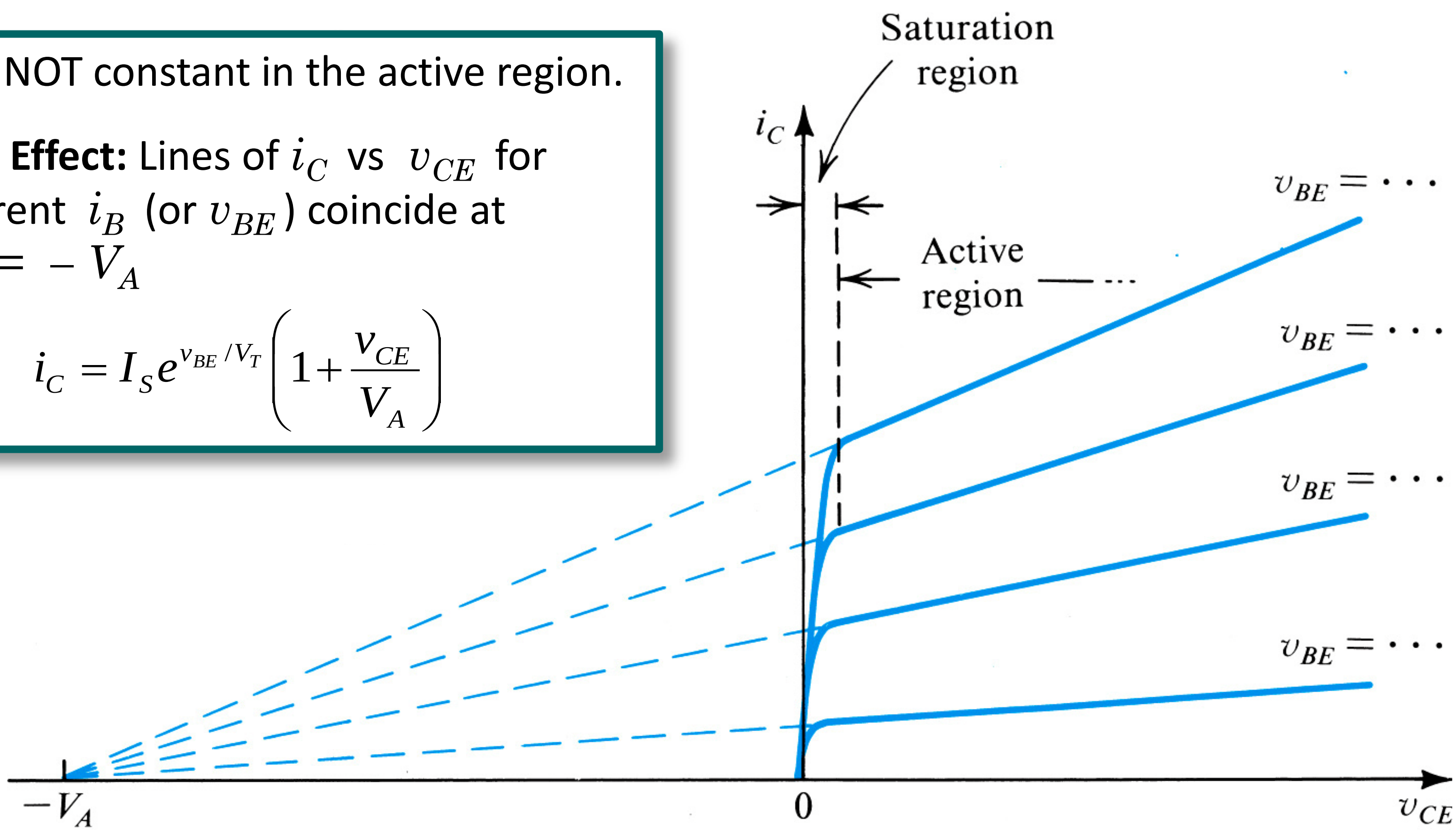


Cut-off :
BE is reverse biased
$i_B = 0, \quad i_C = 0$

Early Effect modifies iv characteristics in the active mode

- i_C is NOT constant in the active region.
- **Early Effect:** Lines of i_C vs v_{CE} for different i_B (or v_{BE}) coincide at $v_{CE} = -V_A$

$$i_C = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$$



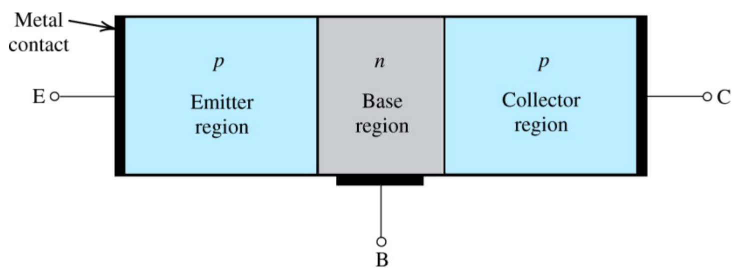
NPN BJT iv equations

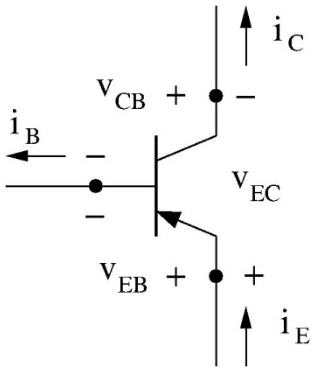
		"Linear" model
Cut-off : BE is reverse biased	$i_B = 0, \quad i_C = 0$	$i_B = 0, \quad i_C = 0$ $v_{BE} < V_{D0}$
Active: BE is forward biased BC is reverse biased	$i_B = \dfrac{i_C}{\beta} = \dfrac{I_S}{\beta} e^{v_{BE}/V_T}$ $i_C = I_S e^{v_{BE}/V_T} \left(1 + \dfrac{v_{CE}}{V_A}\right)$	$v_{BE} = V_{D0}, \quad i_B \geq 0$ $i_C = \beta\, i_B, \quad v_{CE} \geq V_{D0}$
(Deep) Saturation: BE is forward biased BC is reverse biased	$i_B = \dfrac{I_S}{\beta} e^{v_{BE}/V_T}$ $v_{CE} \approx V_{sat}, \quad i_C < \beta\, i_B$	$v_{BE} = V_{D0}, \quad i_B \geq 0$ $v_{CE} = V_{sat}, \quad i_C < \beta\, i_B$

$$\boxed{\text{For Si, } V_{D0} = 0.7 \text{ V}, \quad V_{sat} = 0.2 \text{ V}}$$

PNP transistor is the analog to NPN BJT

PNP transistor





Compared to a NPN:

1) **Current directions are reversed**
2) **Voltage subscripts "switched"**

"Linear" model

Cut-off :
EB is reverse biased

$$i_B = 0, \quad i_C = 0$$
$$v_{EB} < V_{D0}$$

Active:
EB is forward biased
CB is reverse biased

$$v_{EB} = V_{D0}, \quad i_B \geq 0$$
$$i_C = \beta\, i_B, \quad v_{EC} \geq V_{D0}$$

(Deep) Saturation:
EB is forward biased
CB is reverse biased

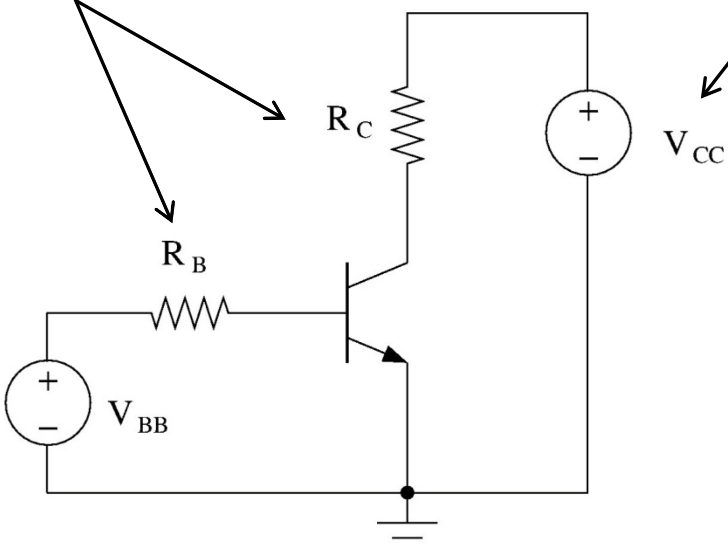
$$v_{EB} = V_{D0}, \quad i_B \geq 0$$
$$v_{EC} = V_{sat}, \quad i_C < \beta\, i_B$$

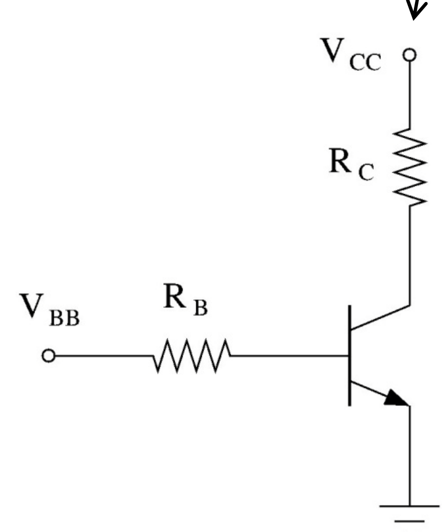
Notations

Resistors:
Use "subscript" of BJT terminal: R_C, R_B, R_E.

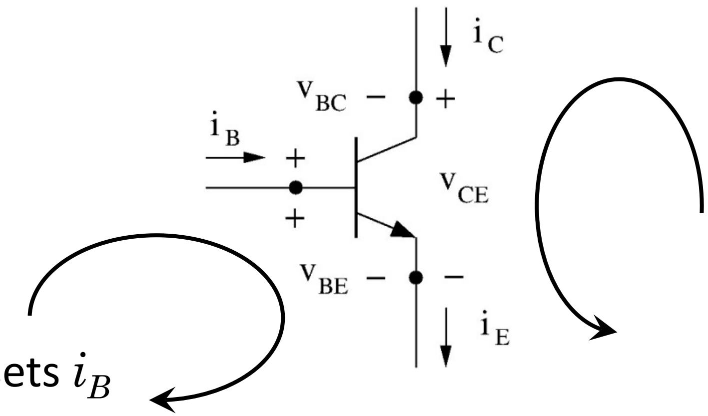
DC voltages:
Use "Double subscript" of BJT terminal: V_{CC}, V_{BB}, V_{EE}.

Voltage sources are identified by node voltage!





Transistor operates like a "valve:" i_C & v_{CE} are controlled by i_B



Controlled part:
i_C & v_{CE} are set by transistor state (& outside circuit)

Controller part:
Circuit connected to BE sets i_B

- **Cut-off** $(i_B = 0)$: **Valve Closed** $i_C = 0$
- **Active** $(i_B > 0)$: **Valve partially open** $i_C = \beta\, i_B$
- **Saturation** $(i_B > 0)$: **Valve open** $i_C < \beta\, i_B$
  i_C limited by circuit connected to CE terminals, increasing i_B does not increase i_C

Recipe for solving BJT circuits

(State of BJT is unknown before solving the circuit)

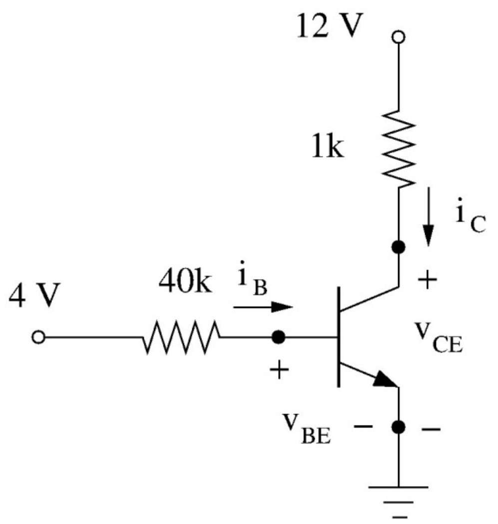
1. Write down BE-KVL and CE-KVL:
2. Assume BJT is OFF, Use BE-KVL to check:
   a. BJT OFF: Set $i_C = 0$, use CE-KVL to find v_{CE} (Done!)
   b. BJT ON: Compute i_B
3. Assume BJT in active. Set $i_C = \beta\, i_B$. Use CE-KVL to find v_{CE} . If $v_{CE} \geq V_{D0}$, Assumption Correct, otherwise in saturation:
4. BJT in Saturation. Set $v_{CE} = V_{sat}$. Use CE-KVL to find i_C . (Double-check $i_C < \beta\, i_B$)

NOTE:

- For circuits with R_E, both BE-KVL & CE-KVL have to be solved simultaneously.

Example 1: Compute transistor parameters (Si BJT with $\beta = 100$).

$$\text{BE-KVL}: \quad 4 = 40\times 10^3\, i_B + v_{BE}$$
$$\text{CE-KVL}: \quad 12 = 10^3\, i_C + v_{CE}$$



$$\text{Assume Cut-off}: \quad i_B = 0 \quad \text{and} \quad v_{BE} < V_{D0} = 0.7 \text{ V}$$
$$\text{BE-KVL}: \quad 4 = 40\times 10^3 \times 0 + v_{BE} \;\rightarrow\; v_{BE} = 4 \text{ V}$$
$$v_{BE} = 4 \text{ V} > V_{D0} = 0.7 \text{ V} \rightarrow \text{Assumption incorrect}$$

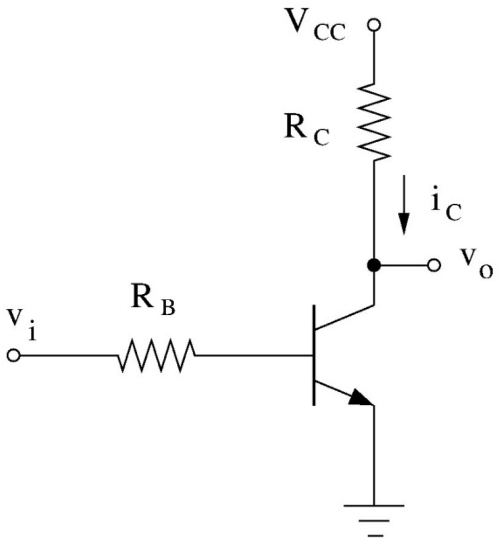
$$\text{BE ON}: \; \underline{v_{BE} = V_{D0} = 0.7 \text{ V}} \;\text{and}\; i_B \ge 0$$
$$\text{BE-KVL}: \quad 4 = 40\times 10^3 \times i_B + 0.7 \;\rightarrow\; \underline{i_B = 8.25\,\mu\text{A} > 0}$$

$$\text{Assume Active}: \quad i_C = \beta\, i_B \quad \text{and} \quad v_{CE} \ge V_{D0} = 0.7 \text{ V}$$
$$i_C = \beta\, i_B = \underline{100\times 8.25\times 10^{-6} = 8.25 \text{ mA}}$$
$$\text{CE-KVL}: \quad 12 = 10^3 \times 8.25\times 10^{-3} + v_{CE} \;\rightarrow\; \underline{v_{CE} = 3.75 \text{ V}}$$
$$v_{CE} = 3.75 \text{ V} > V_{D0} = 0.7 \text{ V} \rightarrow \text{Assumption correct}$$

BJT Transfer Function (1)

$$\text{BE-KVL:}\quad v_i = R_B\, i_B + v_{BE}$$

$$\text{CE-KVL:}\quad V_{CC} = R_C\ \ i_C + v_{CE}$$



$$\text{Cut-off:}\quad i_B = 0 \quad \text{and} \quad v_{BE} < V_{D0}$$

$$\text{BE-KVL:}\quad v_i = R_B \times 0 + v_{BE} \;\rightarrow\; v_{BE} = v_i$$

$$i_C = 0$$

$$\text{CE-KVL:}\quad V_{CC} = R_C \times 0 + v_{CE} \;\rightarrow\; v_{CE} = V_{CC}$$

$$\boxed{\begin{array}{l}\text{For } v_i < V_{D0} \quad \rightarrow \text{BJT in Cutoff} \\ i_B = 0,\ \ i_C = 0,\ v_{CE} = V_{CC}\end{array}}$$

$$\text{BE ON:}\ v_{BE} = V_{D0} \ \text{ and } \ i_B \geq 0$$

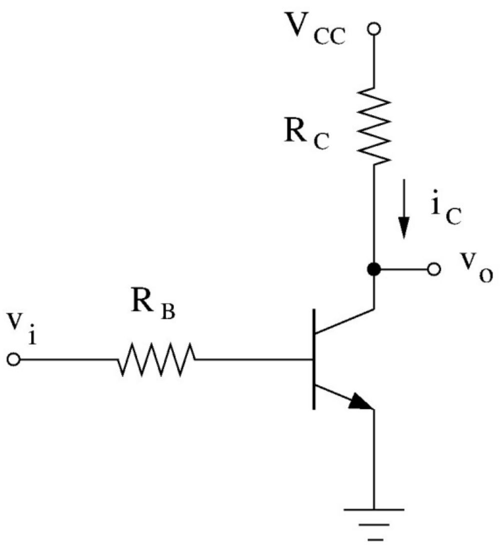
$$\text{BE-KVL:}\quad v_i = R_B \ \times i_B + V_{D0} \rightarrow\ i_B = \frac{v_i - V_{D0}}{R_B}$$

$$i_B \geq 0 \ \rightarrow\ \ v_i \geq V_{D0}$$

BJT Transfer Function (2)

$$\text{BE ON}: \ v_{BE} = V_{D0} \ \text{ and } \ i_B = \frac{v_i - V_{D0}}{R_B}$$

$$\text{CE-KVL}: \ V_{CC} = R_C \ i_C + v_{CE}$$



$$\text{Active}: \ i_c = \beta \, i_B \ \text{ and } \ v_{CE} \geq V_{D0}$$

$$i_C = \beta \times \frac{v_i - V_{D0}}{R_B}$$

$$\text{CE-KVL}: \ V_{CC} = R_C \ i_C + v_{CE} \ \rightarrow \ v_{CE} = V_{CC} - R_C \ i_C$$

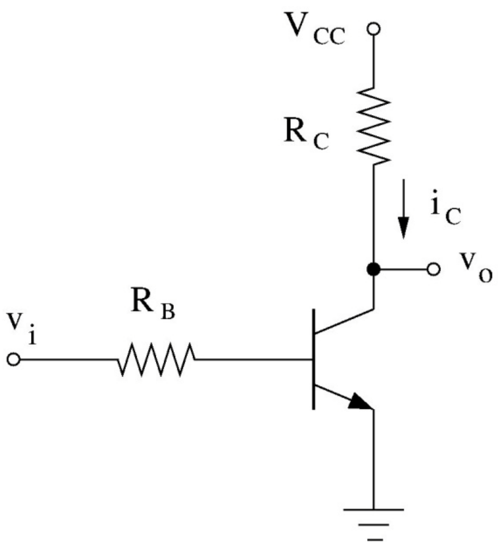
$$v_{CE} \geq V_{D0} \ \rightarrow \ v_i \leq V_{D0} + \frac{V_{CC} - V_{D0}}{\beta R_C / R_B}$$

$$\boxed{\text{For } \ V_{D0} \leq v_i \leq V_{D0} + \frac{V_{CC} - V_{D0}}{\beta R_C / R_B} \ \rightarrow \text{BJT in active}}$$

BJT Transfer Function (3)

$$\text{BE ON}: \ v_{BE} = V_{D0} \ \text{ and } \ i_B = \frac{v_i - V_{D0}}{R_B}$$

$$\text{CE - KVL}: \ V_{CC} = R_C \ i_C + v_{CE}$$



$$\text{Saturaation}: \ v_{CE} = V_{sat} \ \text{ and } \ i_c < \beta \, i_B$$

$$\text{CE - KVL}: \ V_{CC} = R_C \ i_C + V_{sat} \ \rightarrow \ i_C = \frac{V_{CC} \text{-} V_{sat}}{R_C}$$

$$i_c < \beta \, i_B \rightarrow \ v_i > V_{IH} = V_{D0} + \frac{V_{CC} - V_{sat}}{\beta R_C / R_B}$$

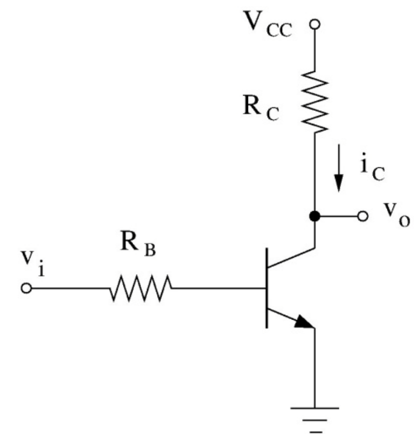
$$\boxed{\text{For } V_{D0} + \frac{V_{CC} - V_{D0}}{\beta R_C / R_B} < v_i \ \rightarrow \text{BJT in saturation}}$$

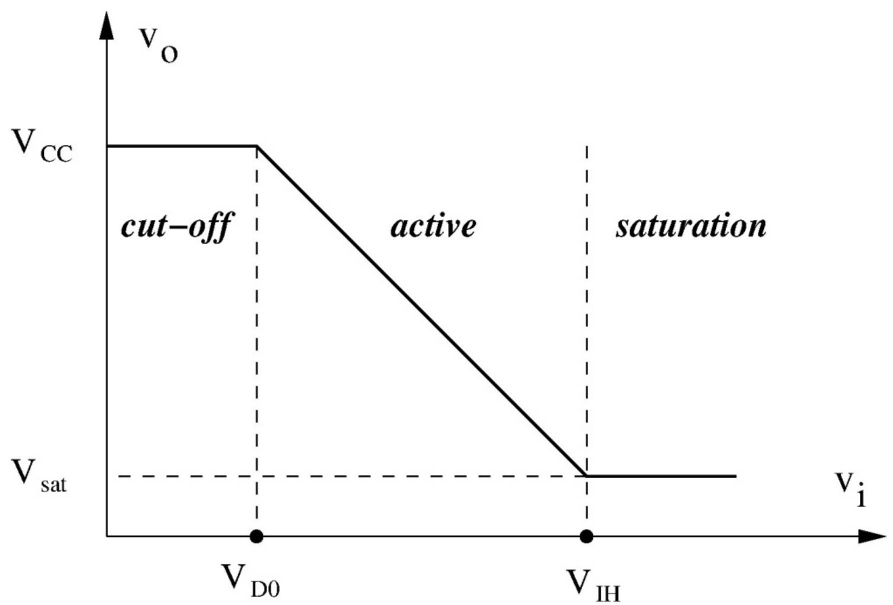
BJT Transfer Function (4)

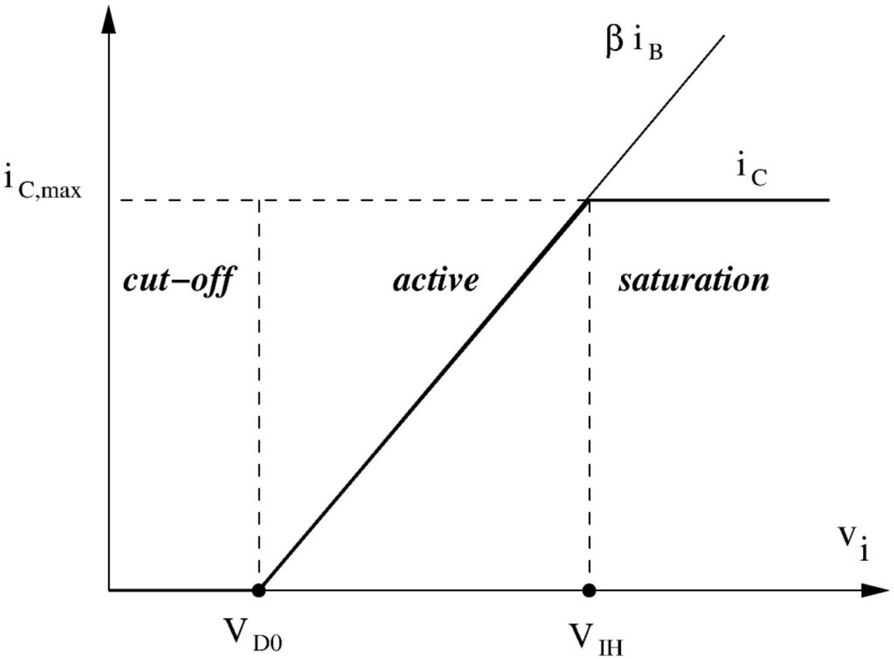
$$v_i < V_{D0} \qquad \rightarrow \text{BJT in Cutoff}$$

$$V_{D0} \le v_i \le V_{D0} + \frac{V_{CC} - V_{D0}}{\beta R_C / R_B} \qquad \rightarrow \text{BJT in active}$$

$$V_{D0} + \frac{V_{CC} - V_{sat}}{\beta R_C / R_B} < v_i \qquad \rightarrow \text{BJT in deep saturation}$$







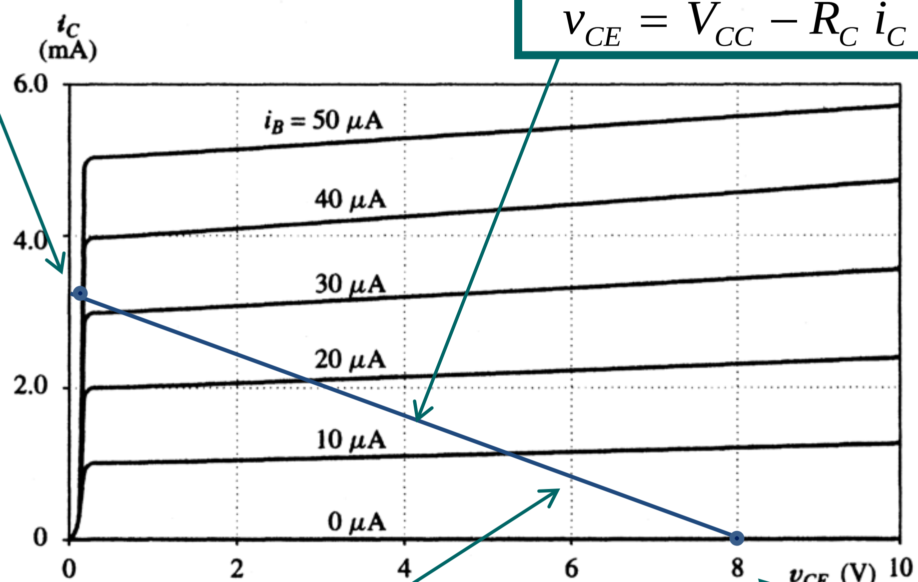
BJT transfer function on the load line

Saturation : $V_{IH} < v_i$

i_B increases but i_C unchanged

Load Line (CE - KVL)

$v_{CE} = V_{CC} - R_C\, i_C$

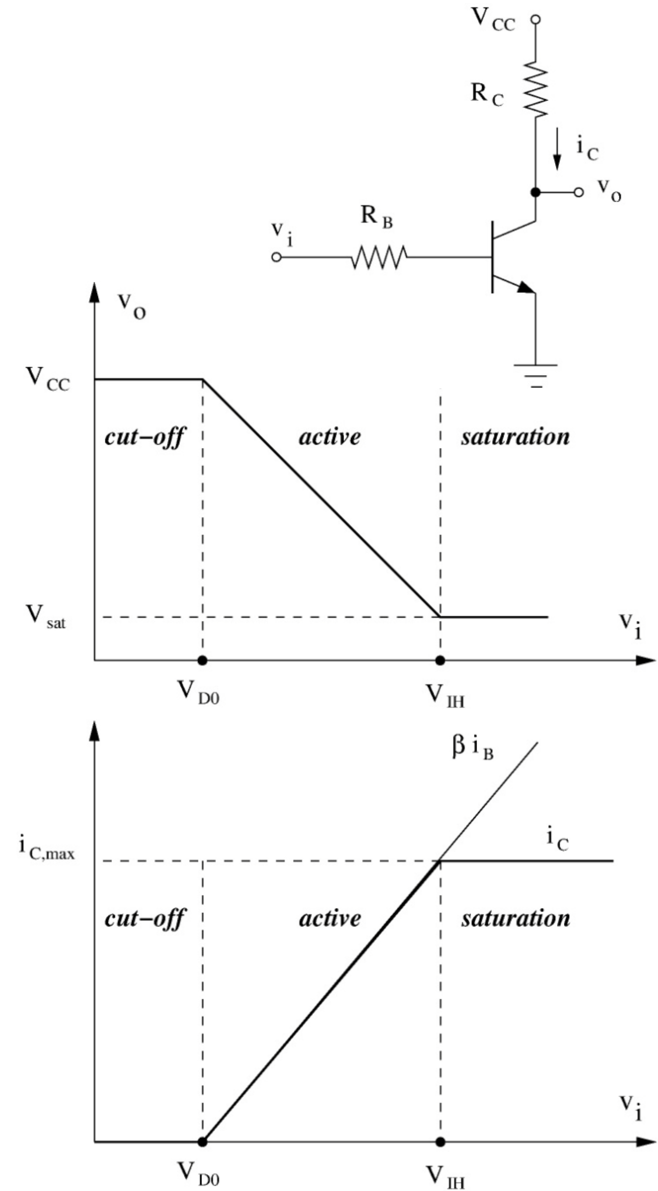


Active : $V_{D0} \le v_i \le V_{IH}$

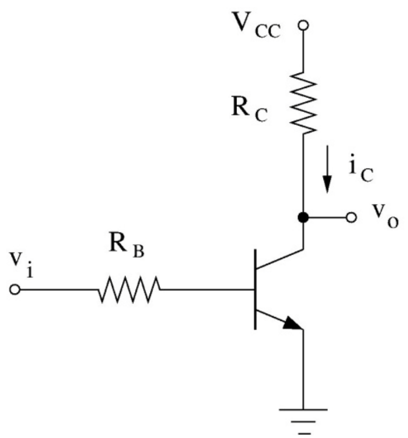
i_B & i_C increase together

Cut – off :

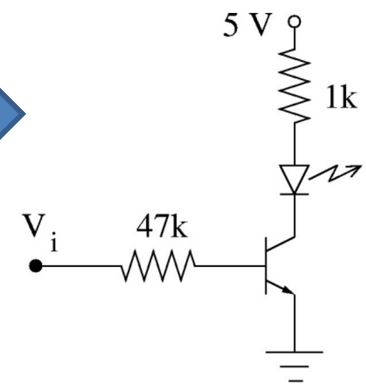
$v_i < V_{D0}$



BJT as a switch



Load is placed in collector circuit



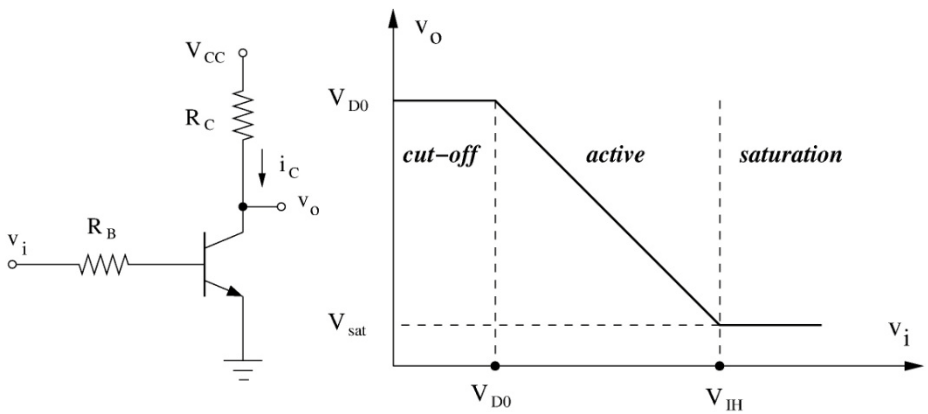
- Use: Logic gate can turn loads ON (BJT in saturation) or OFF (BJT in cut-off)
- i_c is uniquely set by CE circuit (as $v_{ce} = V_{sat}$)
- R_B is chosen such that BJT is in deep saturation with a wide margin (e.g., $i_B = 0.2\ i_c/\beta$)

*Lab 4 circuit
Solved in Lecture notes (problems 12 & 13)

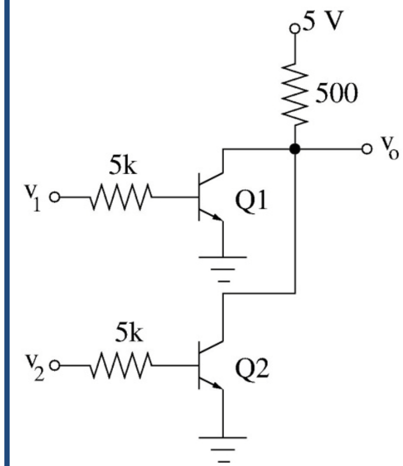
BJT as a Digital Gate

Resistor-Transistor logic (RTL)

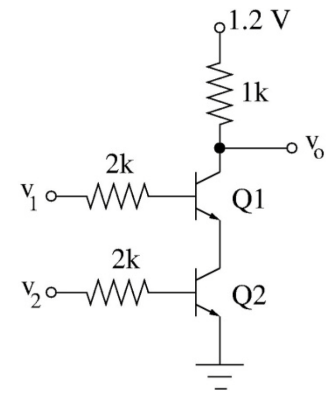
RTL NOT gate ($V_L = V_{sat}$, $V_H = V_{CC}$)



RTL NOR gate*



RTL NAND gate*



- Other variants: Diode-transistor logic (DTL) and transistor-transistor logic (TTL)
- BJT logic gates are not used anymore except for high-speed emitter-coupled logic circuits
  - Low speed (switching to saturation is quite slow).
  - Large space and power requirements on ICs

*Solved in Lecture notes (problems 14 & 15)

BJT β varies substantially

- Our BJT model includes three parameters: V_{D0} , V_{sat} and β
  - V_{D0} and V_{sat} depend on base semiconductor:
  - For Si, V_{D0} = 0.7 V, V_{sat} = 0.2 V
- Transistor β depends on many factors:
  - Strongly depends on temperature (9% increase per ^{o}C)
  - Depends on i_C (not constant as assumed in the model)
  - β of similarly manufactured BJT can vary (manufacturer spec sheet typically gives a range as well as an average value for β)
  - We will use the average β in calculations (PSpice also uses average β but includes temperature and i_C dependence).
  - β_{min} is an important parameter. For example, to ensure operation in deep saturation for all similar model BJTs, we need to set $i_C / i_B < \beta_{min}$