Chapter 6

Bipolar Junction Transistors (BJT)

Outline

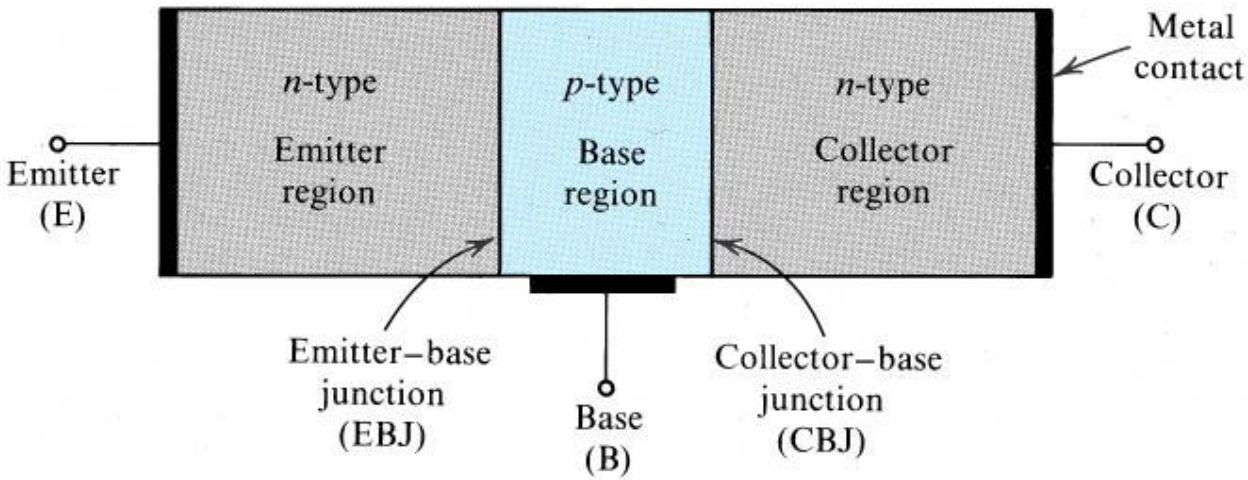
- Bipolar Junction transistors
  - Structure and modes of operation
  - Current-voltage characteristics
  - Biasing a BJT
  - Small-signal models
  - Single-stage amplifiers

- Conclusions

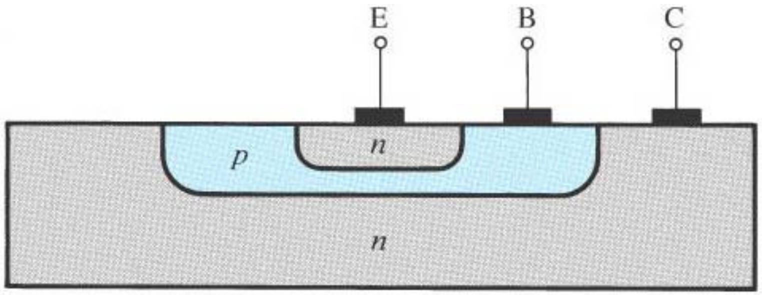
BJT structure

Remember P and N semiconductors ?

- BJT is a three-port structure
- Two types: NPN or PNP transistors



- Actual on-chip implementation:



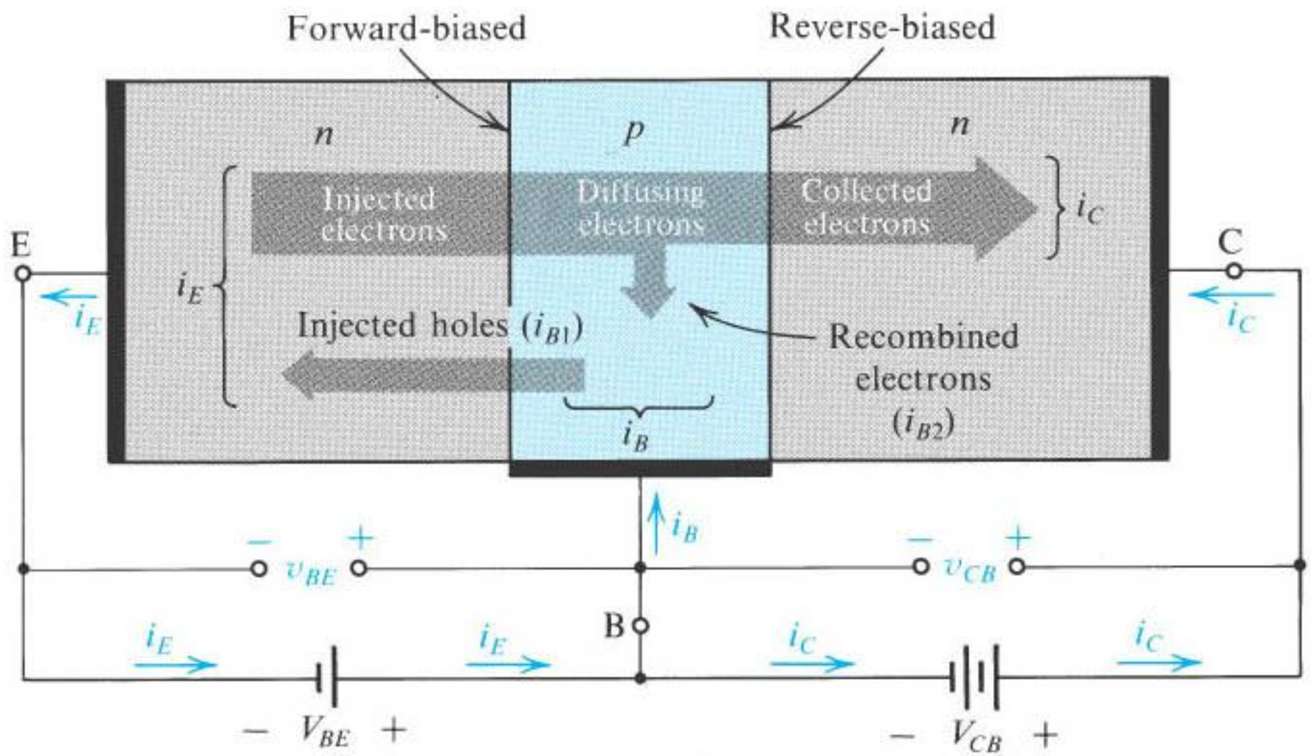
BJT operation: Active mode

EB forward biased, BC reverse biased

- EB depletion region narrows

  $\Rightarrow$ Electrons are able to cross depletion region from E to B

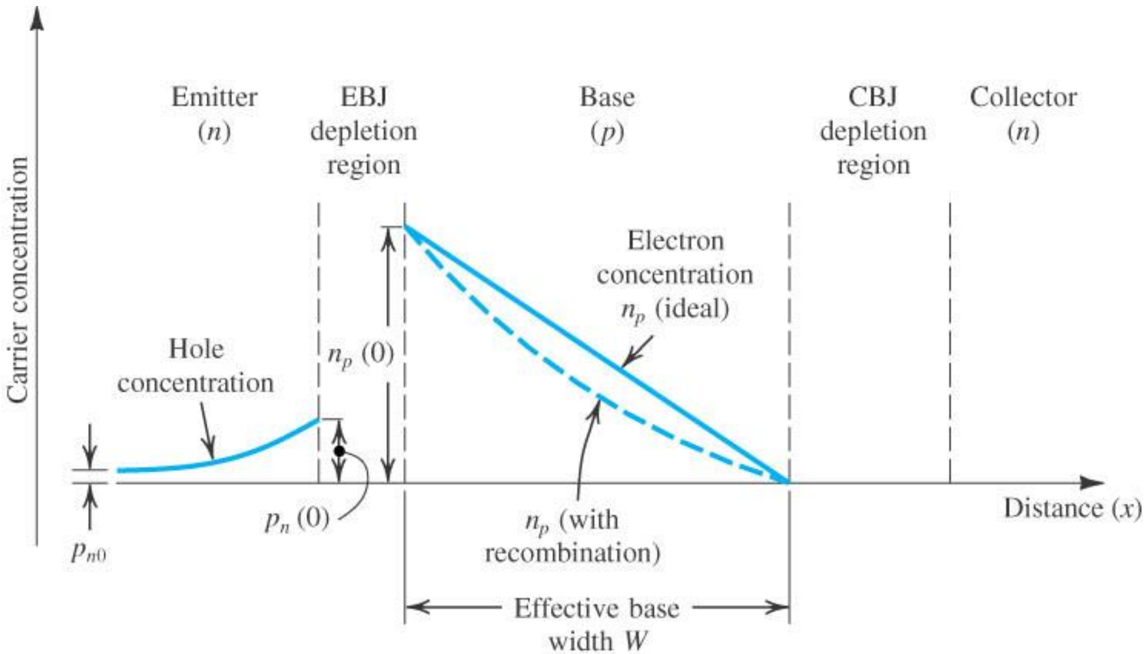
  $\Rightarrow$ Holes are able to cross depletion region from B to E



BJT operation: Active mode

Electron profile in the E-B regions

- Electron concentration highest at the edge of depletion region of base
  - Similar to PN junction (see chapter 2): $n_p(0) = n_{p0}e^{v_{BE}/V_T}$
  - Electron concentration profile creates E-B current



E-B current:

$$I_n = A_E q D_n \frac{dn_p(x)}{dx}$$

$$\Rightarrow I_n = A_E q D_n \left(-\frac{n_p(0)}{W}\right)$$

  - At collector side, electrons are swept through depletion region

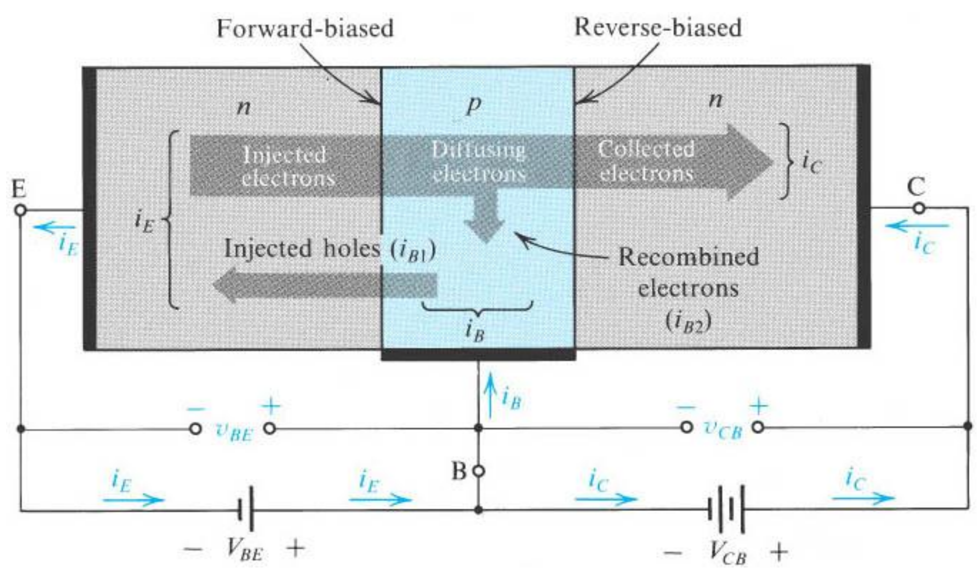
BJT operation: Active mode

At the collector …

- Diffusing electrons are swept through the depletion region
- The collector current $i_C = I_n$
- Using previous results:

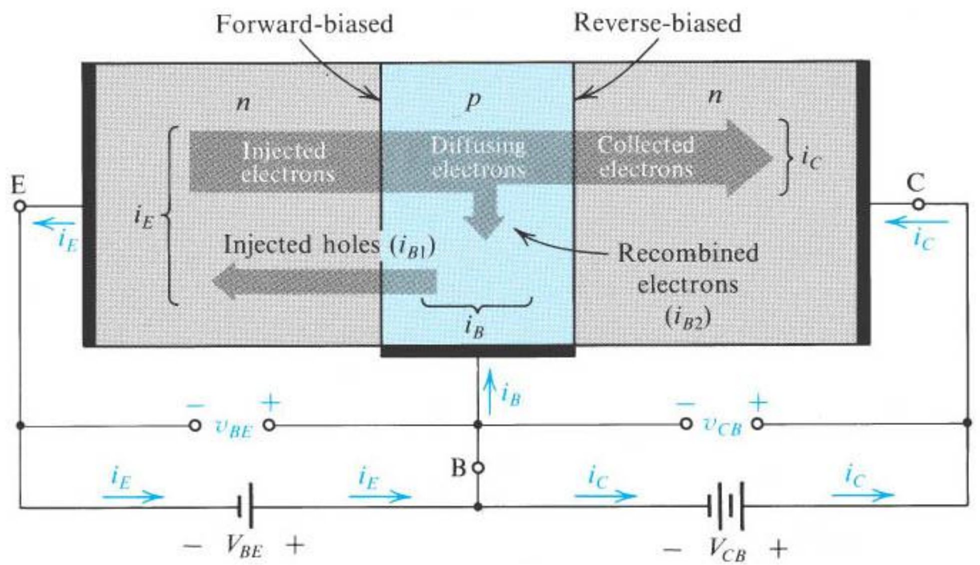
$$i_C = I_S e^{v_{BE}/V_T}$$

with $I_S = A_E q D_n n_{p0}/W$



BJT operation: Active mode

The base current



- Composed of holes injected from base to emitter

  $\Rightarrow$ Proportional to e^{v_{BE}/V_T} : $i_{B1} = \dfrac{A_E q D_p n_i^2}{N_D L_p} e^{v_{BE}/V_T}$

- Also composed of electrons that recombine with holes in P-region

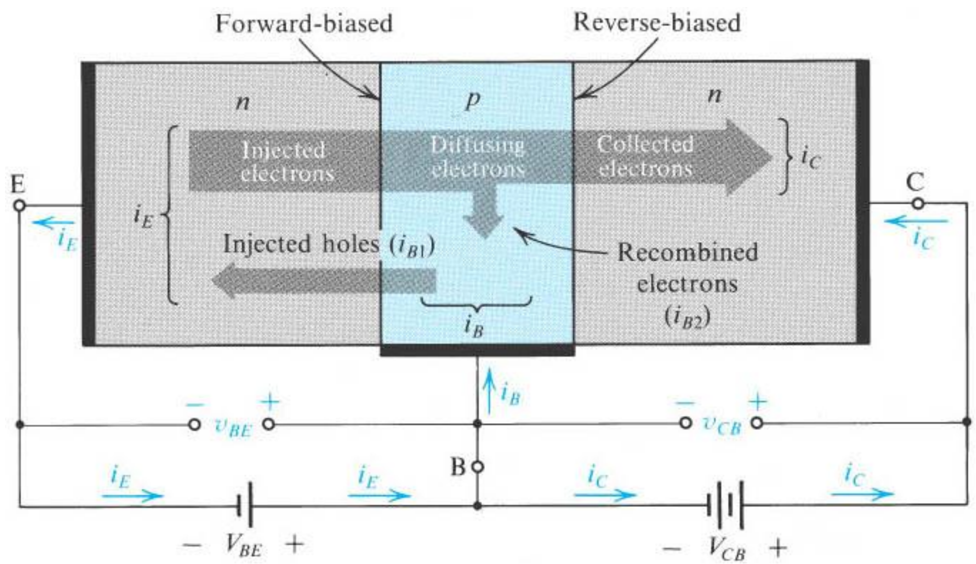
  $\Rightarrow$ Holes are resuplied by external circuit, also Proportional to e^{v_{BE}/V_T} :

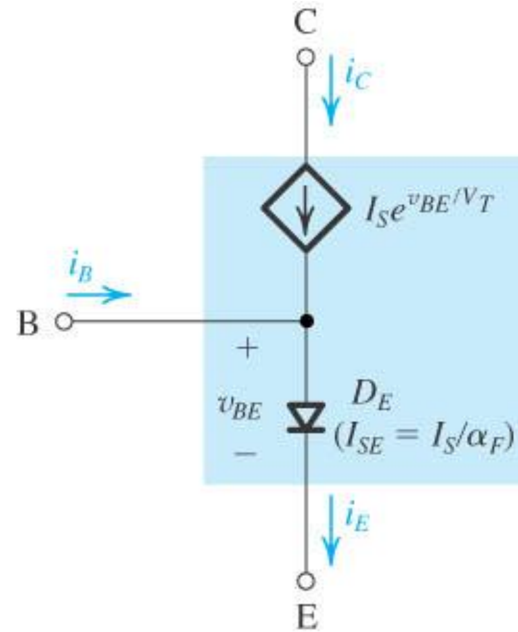
  $i_{B2} = \dfrac{1}{2}\dfrac{A_E q W n_i^2}{\tau_B n_A} e^{v_{BE}/V_T}$

BJT: Active mode

Summary of all currents

- $i_C = I_S e^{v_{BE}/V_T}$
- $i_B = \left(\frac{A_E q D_p n_i^2}{N_D L_p} + \frac{1}{2}\frac{A_E q W n_i^2}{\tau_B n_A}\right) e^{v_{BE}/V_T} = \frac{i_C}{\beta}$
- $i_E = i_C + i_B = \frac{\beta+1}{\beta} i_C = \frac{1}{\alpha_F} i_C$

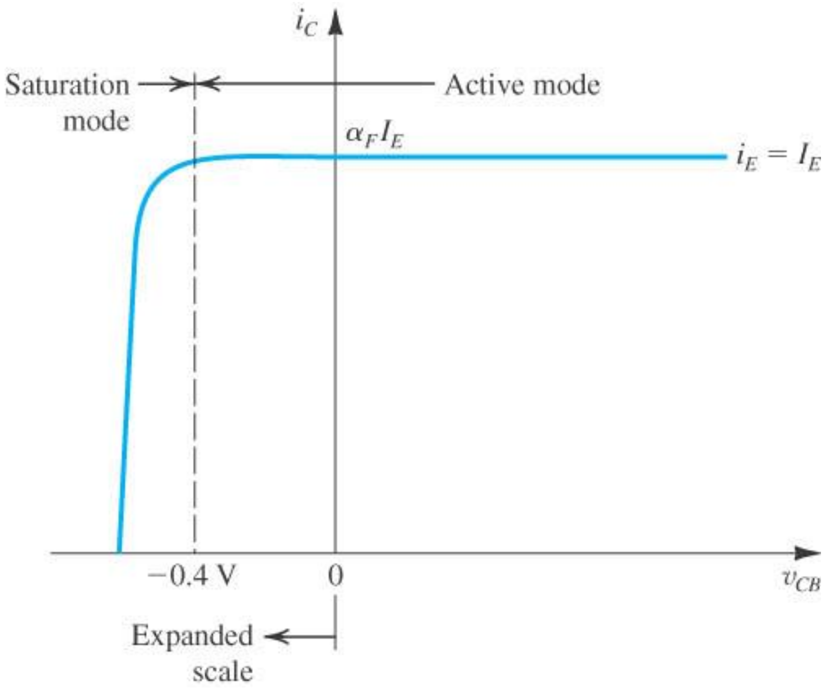




BJT: saturation mode

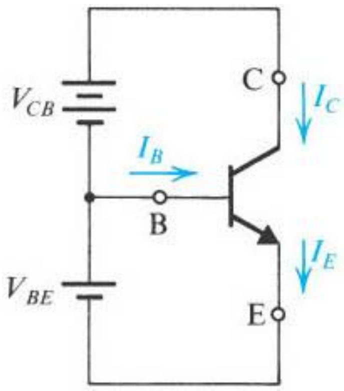
If v_{CB} is low, no current i_C

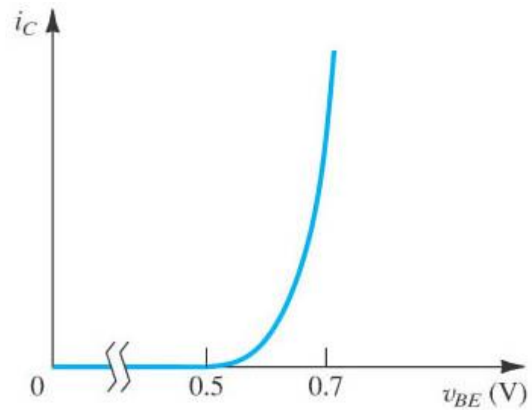
- Active mode if BC junction is reverse biased
- To have a BC junction forward biased, negative v_{CB} is required



BJT: current-voltage characteristics

… for npn transistor

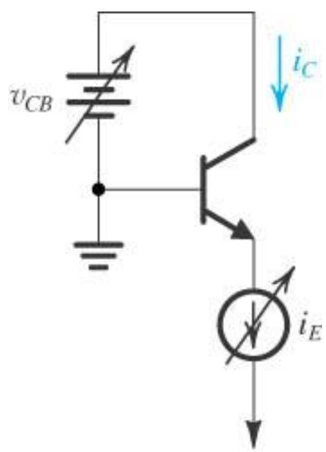


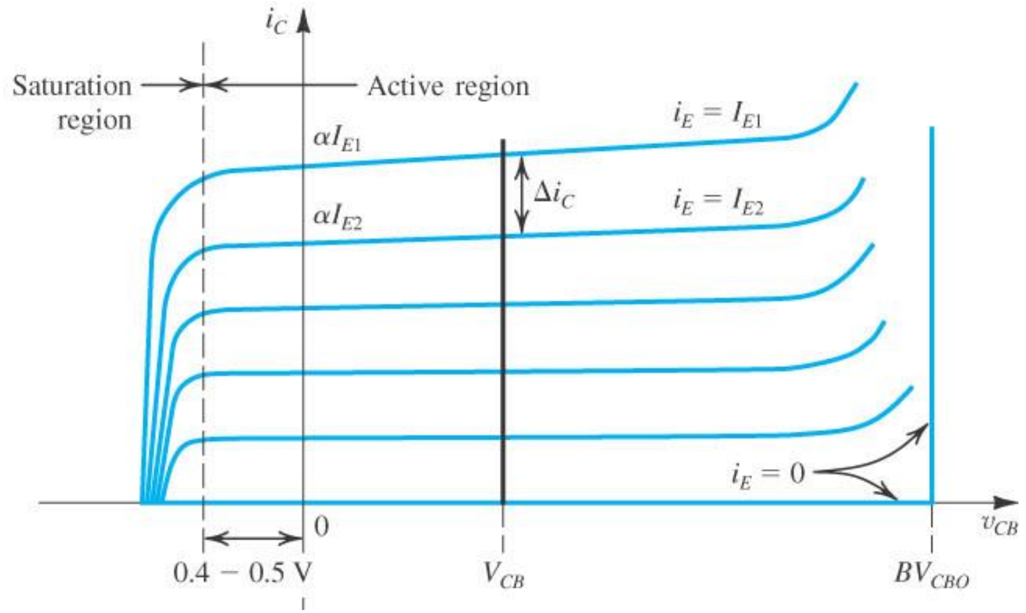


$$i_C = I_S e^{v_{BE}/V_T}$$

$$i_C = \alpha_F i_E$$

$$v_{BE} \approx 0.7\ V$$





BJT: current-voltage characteristics

Early effect

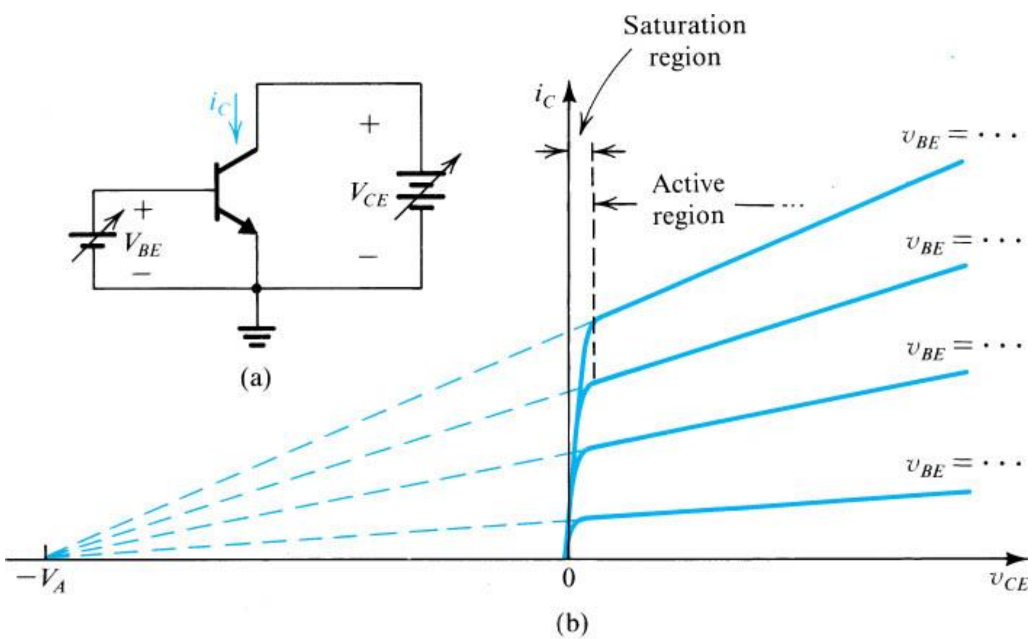
- For a given v_{BE}, increasing v_{CE} increases the reverse-bias voltage on collector-base junction

  $\Rightarrow$ increases width of depletion region

  $\Rightarrow$ Decreases the effective base width

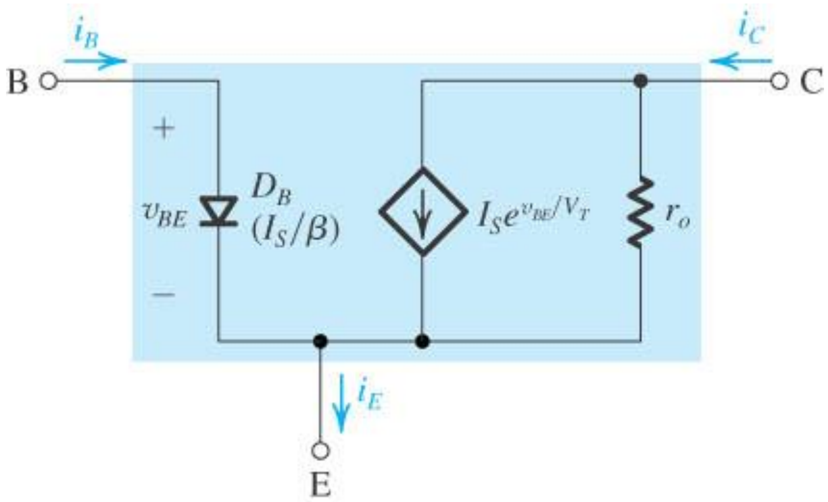
  $\Rightarrow$ Increases $I_S = A_E \, qD_n n_{p0}/W$

  $\Rightarrow$ increases i_C



BJT: current-voltage characteristic

Large-signal equivalent circuit



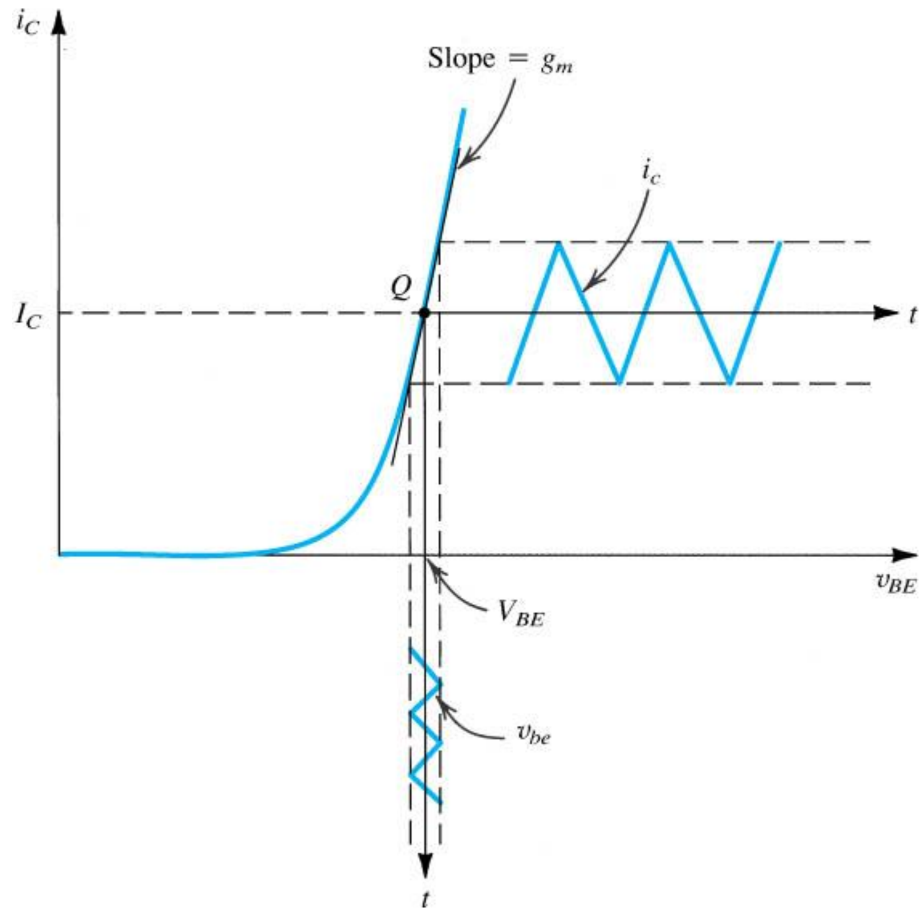
$$i_C = I_S e^{v_{BE}/V_T}$$
$$i_B = \frac{i_C}{\beta}$$
$$i_E = i_C + i_B = (\beta + 1) i_B$$
$$v_{BE} \approx 0.7\ V$$

$$r_o = \frac{V_A}{I'_C}$$
$$I'_C = I_S e^{V_{BE}/V_T}$$

Biasing BJTs

Why biasing?

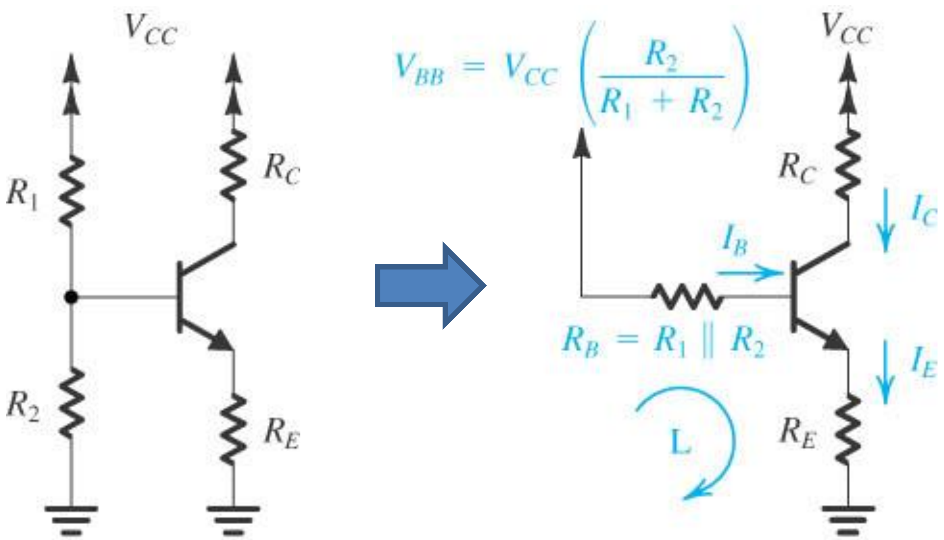
- Fix V_{BE} so that small variations of v_{be} result in linear change in i_c
- Also ok to fix I_C or I_E



Biasing BJTs

with discrete-circuit bias arrangement

- Single power supply
- Poor performances against BJT dispersion



$$V_{BB} = \frac{R_2}{R_1 + R_2} V_{CC}$$

$$R_B = R_1 || R_2$$

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

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

$$V_{BE} \approx 0.7\ V$$

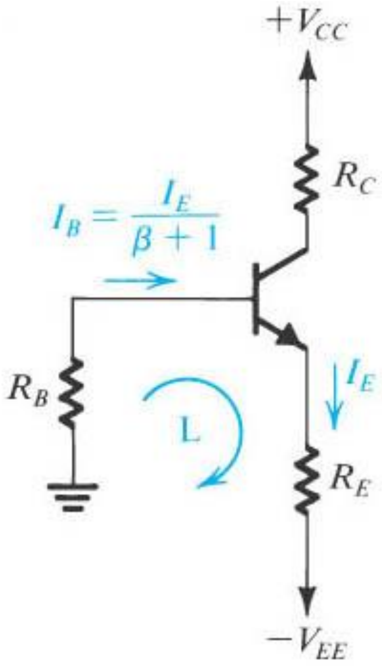
$$\Rightarrow I_E = \frac{V_{BB} - V_{BE}}{R_E + \frac{R_B}{\beta + 1}}$$

Try to make robust against transistor dispersion with $V_{BB} \gg V_{BE}$ and $R_E \gg \frac{R_B}{\beta+1}$

Biasing BJTs

with two-power supply arrangement

- Also poor performances against BJT dispersion



$$R_B I_B + V_{BE} + R_E I_E = V_{EE}$$

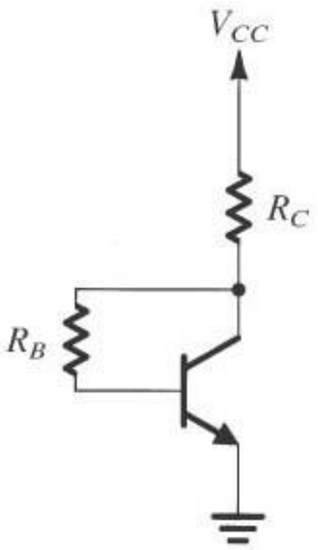
$$\Rightarrow I_E = \frac{V_{EE} - V_{BE}}{R_E + \frac{R_B}{\beta + 1}}$$

- Try to make robust against transistor dispersion with $V_{EE} \gg V_{BE}$ and $R_E \gg \frac{R_B}{\beta+1}$
- If base connected to ground, biasing almost totally independent from β

Biasing BJTs

with collector-to-base feedback resistor

- Resistor R_B provides negative feedback, which helps stabilizing bias point



$$V_{CC} = R_C I_C + R_B I_B + V_{BE}$$

$$V_{CC} = R_C I_C + R_B \frac{I_E}{\beta + 1} + V_{BE}$$

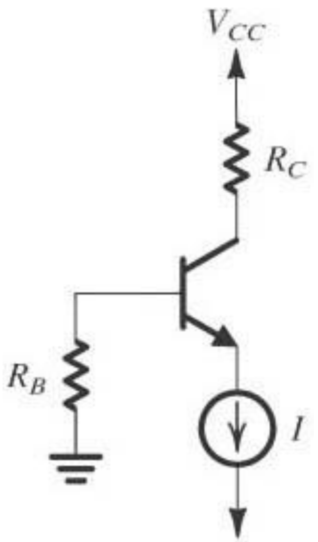
$$\Rightarrow I_E = \frac{V_{CC} - V_{BE}}{R_C + \frac{R_B}{\beta + 1}}$$

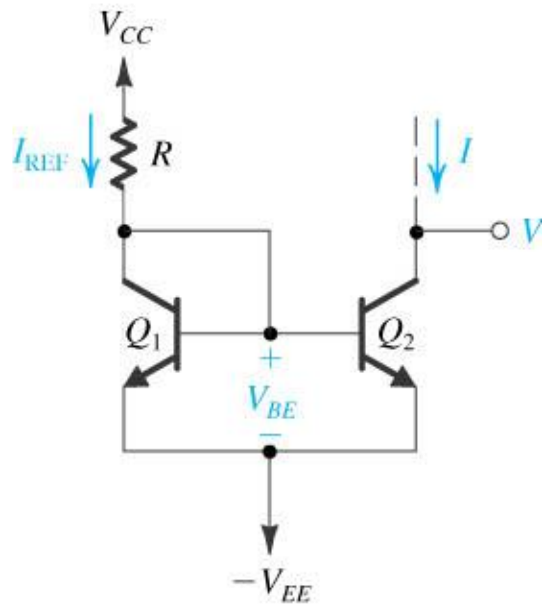
Try to make robust against transistor dispersion with $V_{CC} \gg V_{BE}$ and $R_C \gg \frac{R_B}{\beta+1}$

Biasing BJTs

with a constant-current source

- Emitter current independent of transistor parameters ⇒ $I_E = I$
- Source current implemented with BJT current mirror





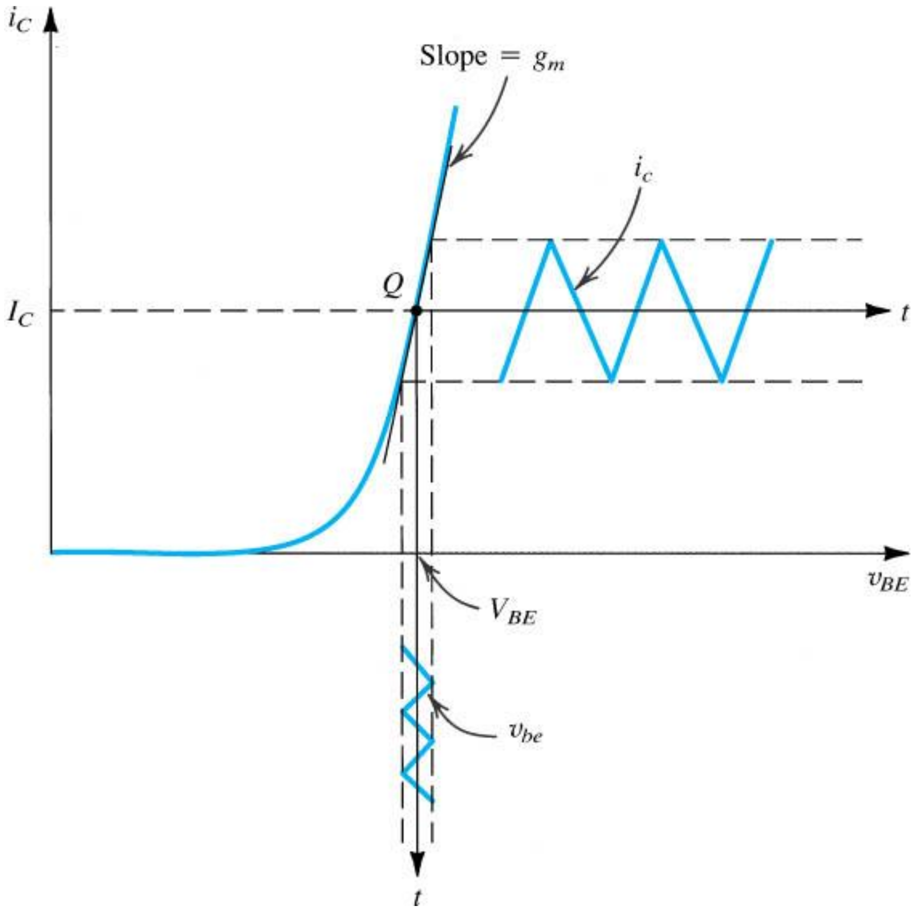
(b)

$$I_{REF} = \frac{V_{CC} - V_{BE} + V_{EE}}{R}$$

$$I = I_{REF}$$

BJT small signal model

Small-signal operation: collector current



$$i_C = I_C e^{v_{be}/V_T}$$

$$\Rightarrow i_C \approx I_C \left(1 + \frac{v_{be}}{V_T}\right)$$

$$\Rightarrow i_C \approx I_C + \frac{I_C}{V_T} v_{be}$$

$$\Rightarrow i_c = \frac{I_C}{V_T} v_{be}$$

$$\Rightarrow i_c = g_m v_{be}$$ with $$g_m = I_C / V_T$$

BJT small signal model

base current and input resistance

$$i_B = \frac{i_C}{\beta} = \frac{I_C}{\beta} + \frac{1}{\beta}\frac{I_C}{V_T} v_{be}$$

$$i_B = I_B + i_b$$

$$\Rightarrow i_b = \frac{1}{\beta}\frac{I_C}{V_T} v_{be}$$

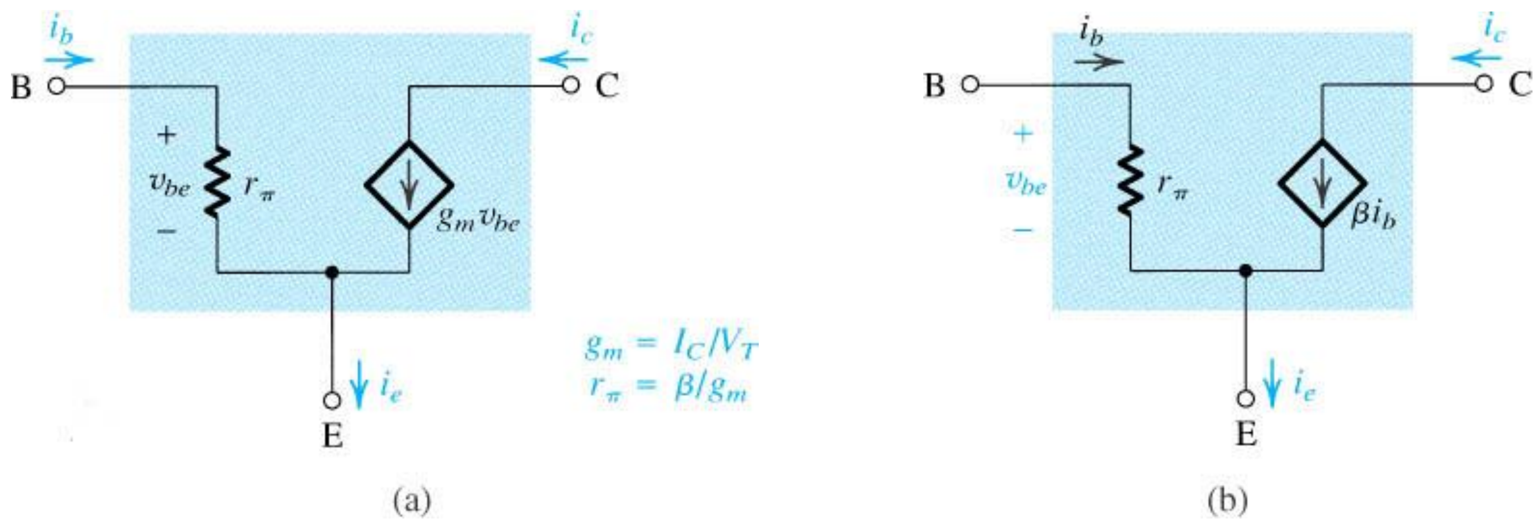
$$\Rightarrow i_b = \frac{1}{r_\pi} v_{be}$$

with $r_\pi = \frac{\beta V_T}{I_C} = \frac{\beta}{g_m} = \frac{V_T}{I_B}$

BJT small signal model

Hybrid π-model

- Voltage-controlled current source
- current-controlled current source

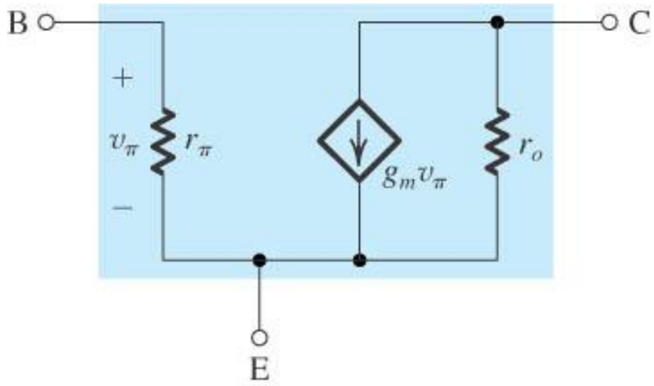


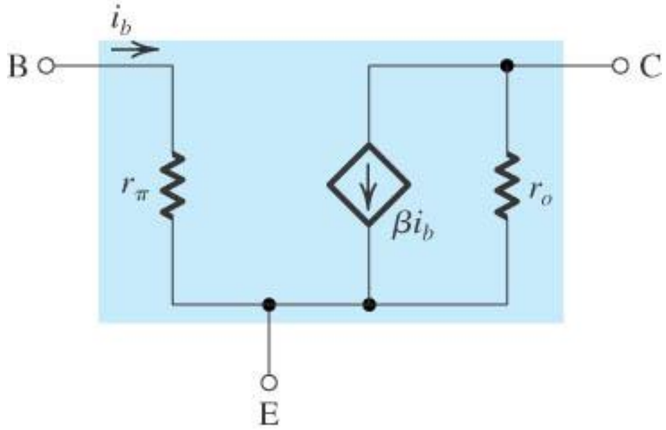
$$i_e = \frac{v_{be}}{r_\pi} + g_m v_{be} = \frac{v_{be}}{r_\pi} + g_m(r_\pi i_b) = \frac{v_{be}}{r_\pi} + \beta i_b$$

$$g_m = I_C/V_T \quad \text{and} \quad r_\pi = \frac{\beta}{g_m} = \frac{V_T}{I_B}$$

BJT small signal model

… with output resistance r_o





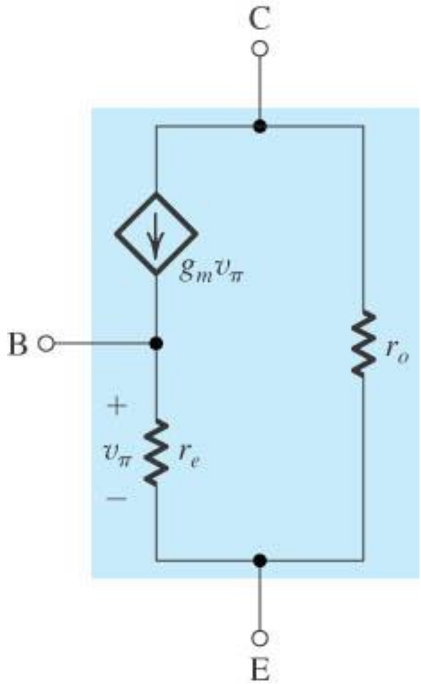
$$g_m = \frac{I_C}{V_T}$$

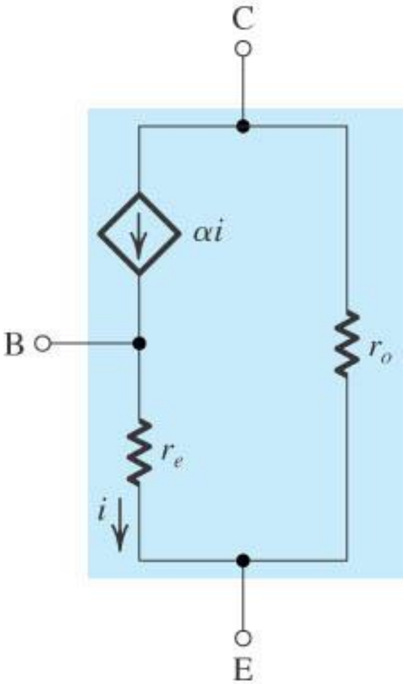
$$r_\pi = \frac{V_T}{I_B} = \beta\left(\frac{V_T}{I_C}\right)$$

$$r_o = \frac{V_A}{I_C}$$

BJT small signal model

T-model also exists



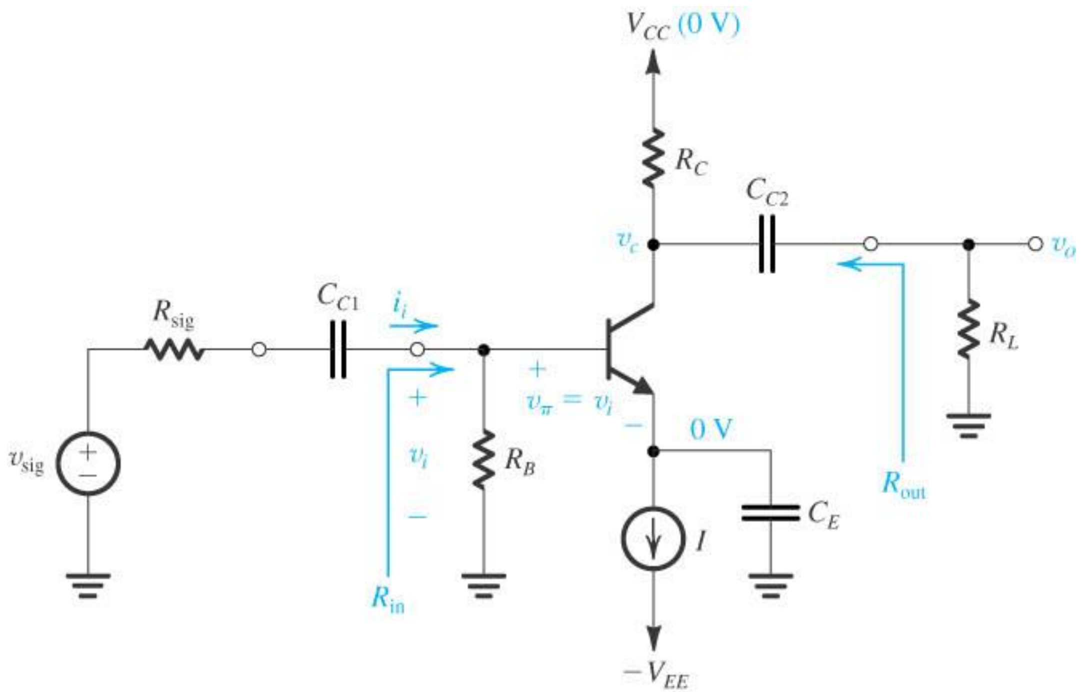


$$g_m = \frac{I_C}{V_T} \qquad r_e = \frac{V_T}{I_E} = \alpha\left(\frac{V_T}{I_C}\right) \qquad r_o = \frac{V_A}{I_C}$$

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

Common-emitter amplifier

Polarized with current source



BJT with parameters β, V_T and V_A

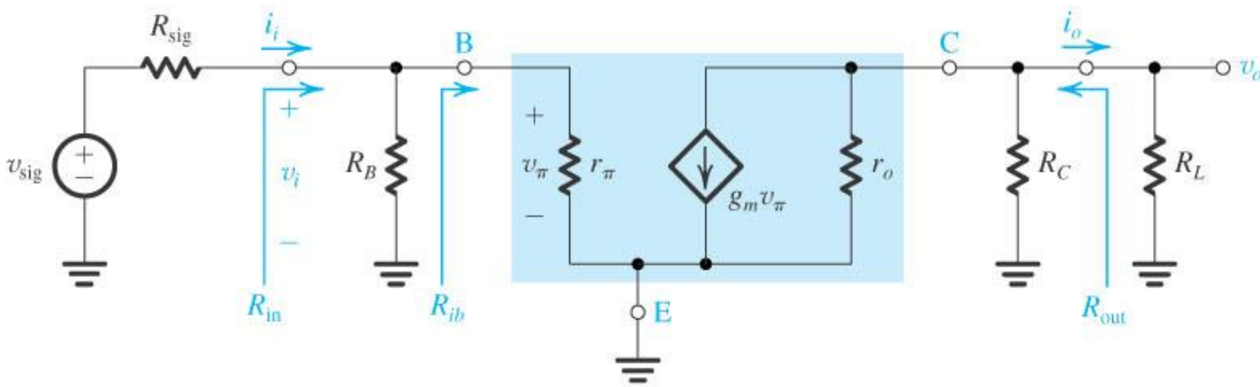
$$I_E = I$$

$$I_C = \frac{\beta}{\beta+1} I_E = \frac{\beta}{\beta+1} I$$

$$I_B = \frac{1}{\beta} I_C = \frac{1}{\beta+1} I$$

Common-emitter amplifier

Small-signal equivalent



Gain, input resistance, output resistance ?

$$v_\pi = v_i$$

$$v_o = -g_m v_\pi (r_o||R_C||R_L) = -g_m v_i (r_o||R_C||R_L)$$

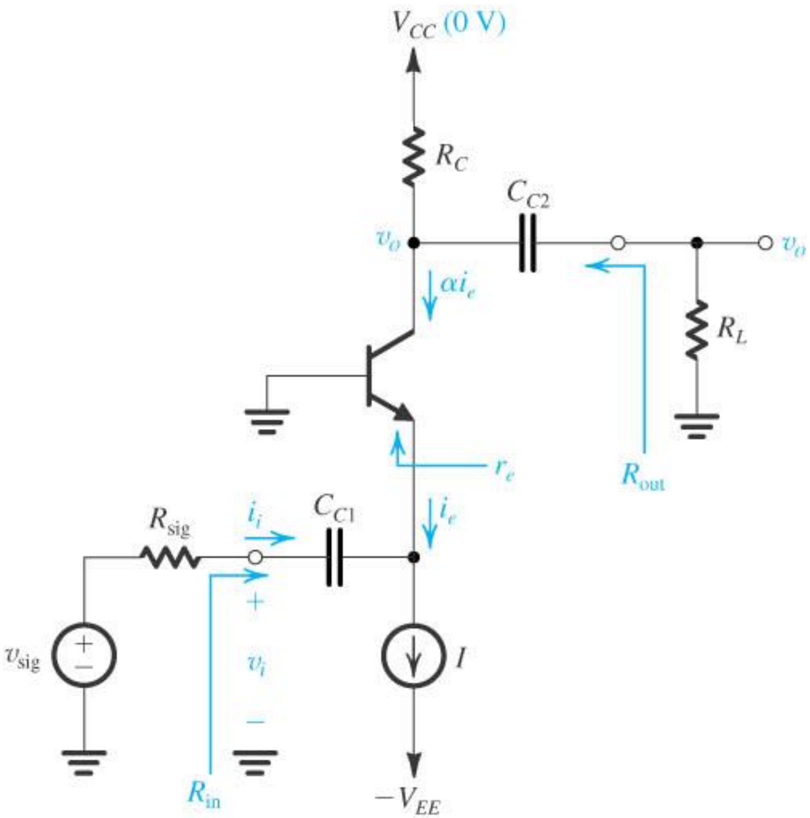
$$\Rightarrow A_v = \frac{v_o}{v_i} = -g_m (r_o||R_C||R_L)$$

$$R_{in} = R_B||r_\pi$$

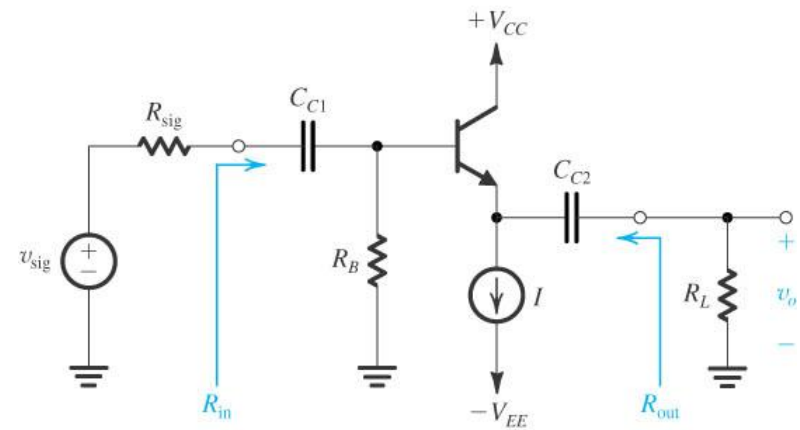
$$R_{out} = R_C||r_o$$

CB and CC amplifier

Find A_v, R_{in} and R_{out} as exercice



Same gain as CE, but non-inverting



Gain close to 1 => buffering stage

BJT vs MOSFET

BJT advantages

- Small input capacitance => very high speed (good for RF !)
- Higher transconductance => higher gain
- BJT amplifiers more linear than MOSFET amplifier stages
- BJT have lower output impedances and can handle higher output currents
- More choices for discrete components

BJT vs MOSFET

BJT drawbacks

- BJT are current-operated (rather than voltage operated)

  $\Rightarrow$Higher consumption
- Lower input resistance than MOSFET
- BJTs are harder to scale to large quantities
- BJTs have more fabrication dispersion

  $\Rightarrow$ More difficult to make good mirror currents, differential pairs, etc.
- Physical size about 10x as large as MOSFET

BJT vs MOSFET

MOSFET advantages

- MOSFET are easy to scale
  - Double the current? Double the width!
- High input impedance (almost infinite at low frequencies)
- Output are controlled by input voltage (not current)

  $\Rightarrow$Much lower power consumption

  $\Rightarrow$Main advantage MOSFET won for chip manufacturing
- Easy to make indentical MOSFETs
  - Good for CMOS transistors, mirror currents, differential pairs, etc.
- Mostly for integrated circuits, not discrete circuits
- Size about 10x smaller than BJT

BJT vs MOSFET

MOSFET drawbacks

- Input capacitance

  ⇒Not good for high frequencies
- Higher output resistance than BJT

  ⇒Not suited to drive low-impedance load
- Lower gain per stage

  ⇒Amplifier stages need to be cascaded

  ⇒Each stage adds noise

  ⇒SNR degrades