TÉCNICO LISBOA

Circuit Theory and Electronics Fundamentals

Lecture 15: The Bipolar Junction Transistor

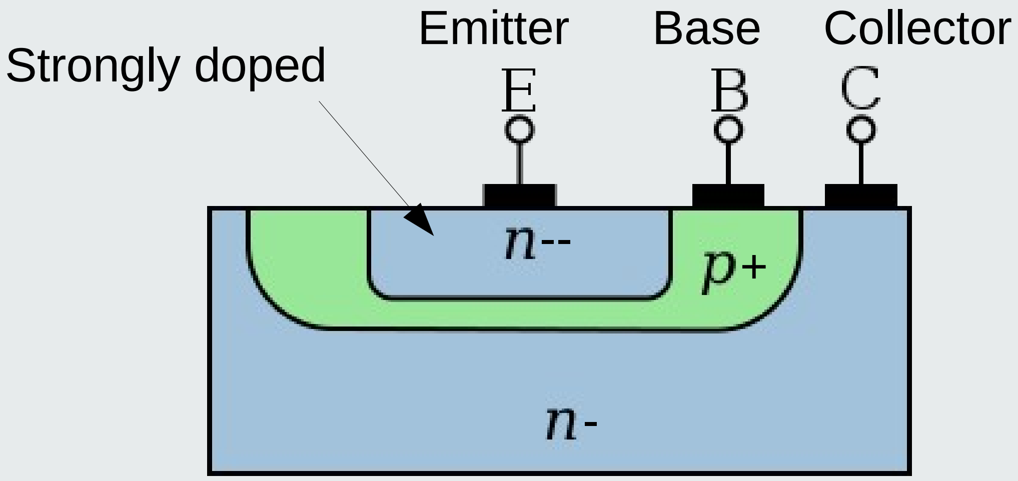
- The transistor
- The Bipolar Junction Transistor (BJT):
  - Operation regions
  - Large signal model (DC)
  - Small signal model (AC)
  - Spice model

The transistor

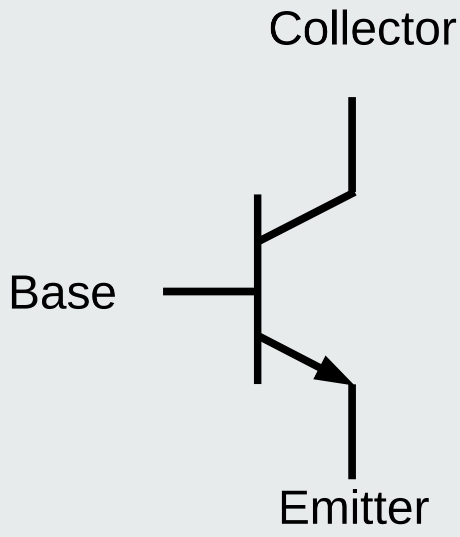
- The transistor is the most widespread semiconductor device
- The transistor is used in both analogue and digital electronic circuits
  - In analogue circuits it is mostly used as a controlled voltage or current amplifier
  - In digital circuits it is used as controlled switch useful for logic operations
- The main transistor types are
  - Bipolar Junction Transistors (BJT)
  - Field effect transistors
- In this lecture we focus on BJTs

The BJT: npn and pnp junctions

- The diode is a ***pn junction***
- The transistor is a ***npn*** or ***pnp junction***
- Let's focus on ***npn*** first



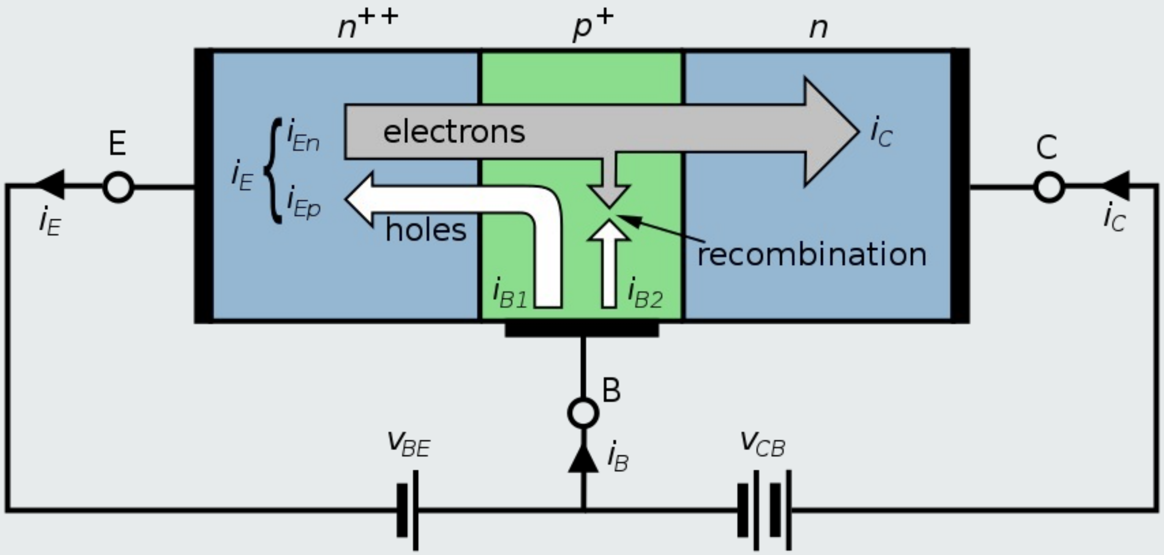
npn junction cross section

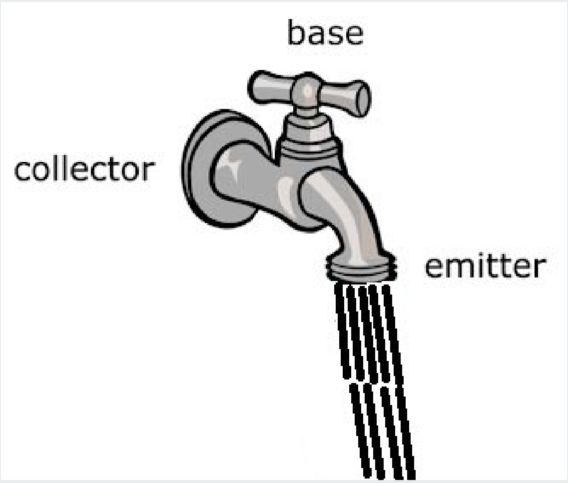


npn transistor circuit symbol

How the BJT works

- The npn BJT is not two back to back diodes!
- The the two pn junctions interact with each other!





Base-emitter junction forwardly biased
Bias voltage is V_{BE}

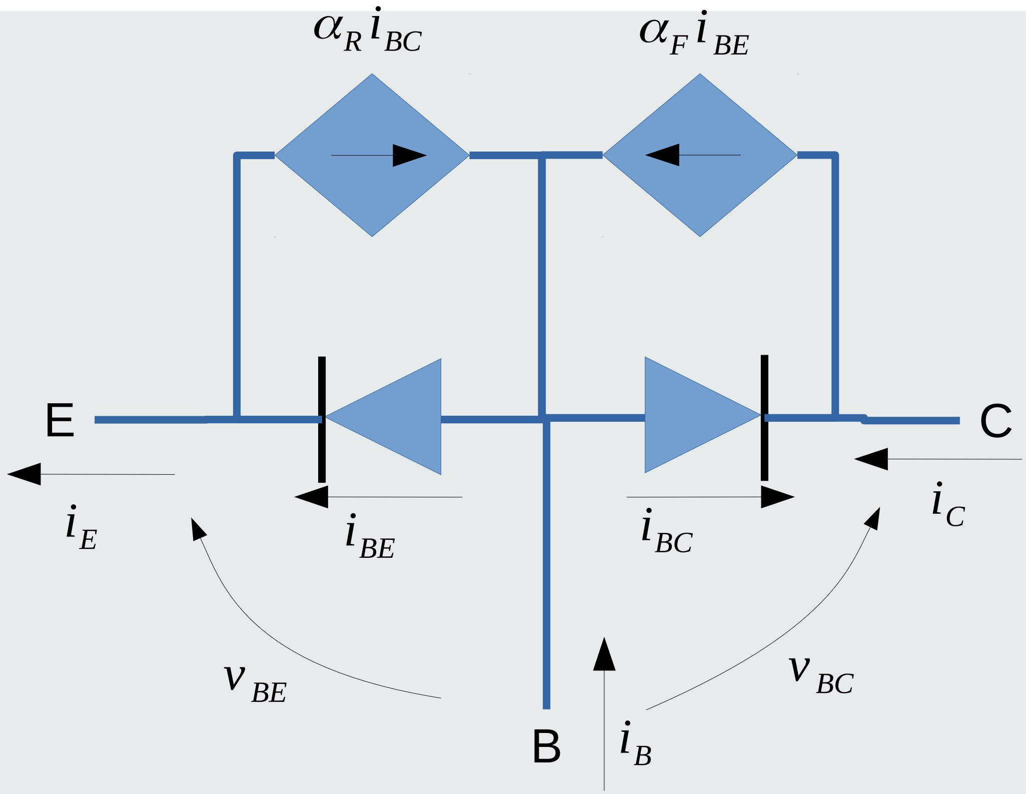
Base-collector junction reversely biased
Bias voltage is V_{CB}

$$I_E = I_B + I_C (KCL)$$

The BJT operation regions

- The bipolar is a highly non-linear device with four different operation regions:
  1) Forward active region: base-emitter junction forwardly biased and base-collector junction reversely biased. In this region $I_C = \beta_F I_B$
  2) Reverse active region: base-emitter junction reversely biased and base-collector junction forwardly biased. In this region $-I_E = \beta_R I_B$
  3) Saturation region: both base-emitter and base-collector junctions forwardly biased
  4) Cut-off region: both base-emitter and base-collector junctions reversely biased

The Ebers-Moll bipolar npn transistor model



$$i_B=\left[\frac{I_S}{\beta_F}\left(e^{\frac{v_{BE}}{V_T}}-1\right)+\frac{I_S}{\beta_R}\left(e^{\frac{v_{BC}}{V_T}}-1\right)\right]$$

$$i_C=\left[I_S\left(e^{\frac{v_{BE}}{V_T}}-e^{\frac{v_{BC}}{V_T}}\right)-\frac{I_S}{\beta_R}\left(e^{\frac{v_{BC}}{V_T}}-1\right)\right]$$

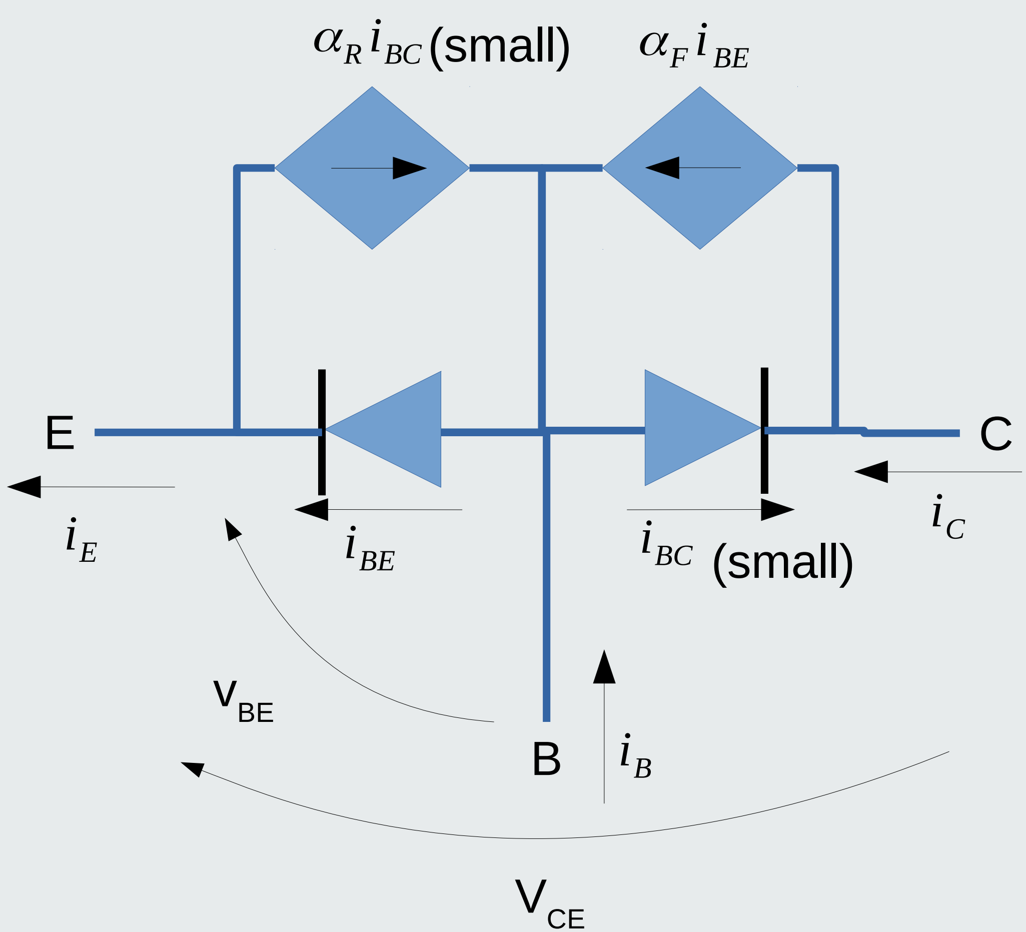
$$i_E=\left[I_S\left(e^{\frac{v_{BE}}{V_T}}-e^{\frac{v_{BC}}{V_T}}\right)+\frac{I_S}{\beta_F}\left(e^{\frac{v_{BE}}{V_T}}-1\right)\right]$$

$$\beta_F=\frac{\alpha_F}{1-\alpha_F}$$

α_F is the forward common base current gain (0.98 to 0.998)
α_R is the reverse common base current gain (0 to 0.952)
β_F is the forward common emitter current gain (20 to 500)
β_R is the reverse common emitter current gain (0 to 20)

$$\beta_R=\frac{\alpha_R}{1-\alpha_R}$$

Forward active region (Ebbers-Moll model)



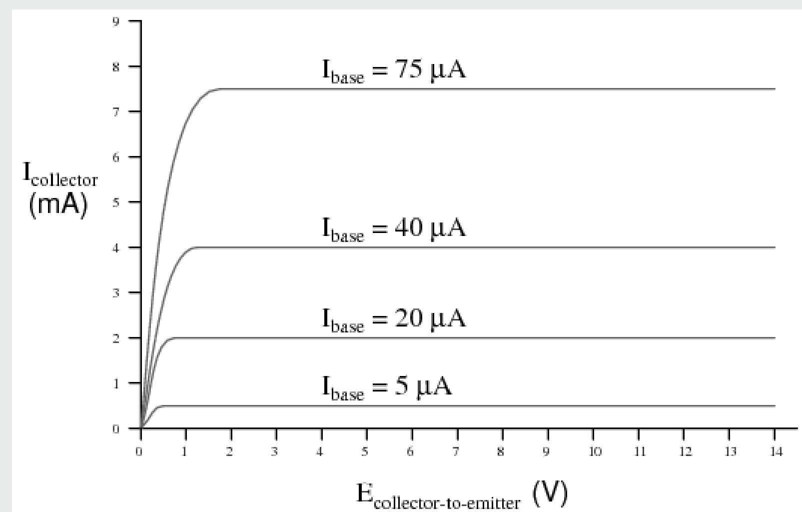
Collector-emitter voltage

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

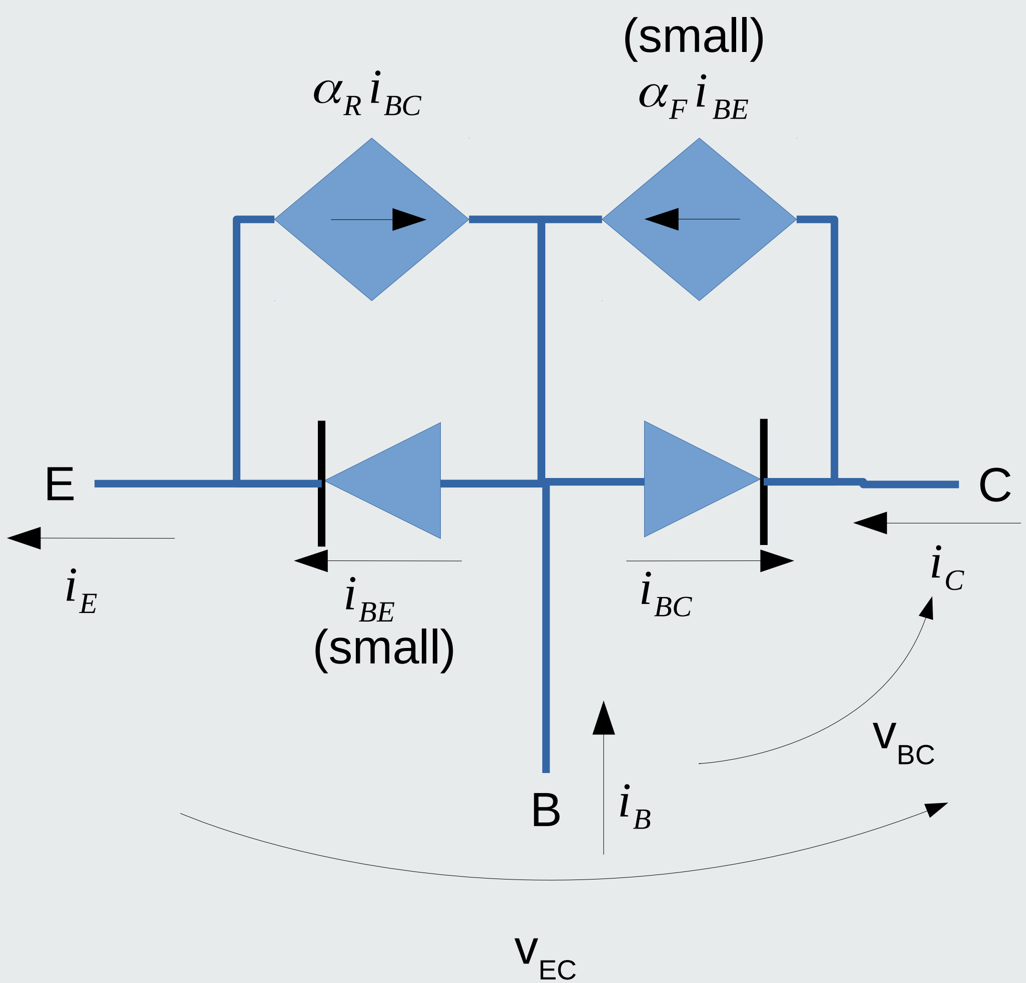
$$i_C = I_S e^{\frac{v_{BE}}{V_T}}$$

$$i_C = \beta_F i_B$$

Use Ebbers-Moll equations and neglect the reverse biased terms



Reverse active region (Ebbers-Moll model)



Emitter-collector voltage

$$i_B = \frac{I_S}{\beta_R} e^{\frac{v_{BC}}{V_T}}$$

$$-i_E = I_S e^{\frac{v_{BC}}{V_T}}$$

$$-i_E = \beta_R i_B$$

Bipolar transistor large signal Ebbers-Moll model (DC)

Forward active region

$$i_C = \alpha_F i_E$$
$$i_C = \beta_F i_B$$

KCL: $i_E = i_B + i_C = (1+\beta_F) i_B = (1+\frac{1}{\beta_F}) i_C$

$$\alpha_F = \frac{\beta_F}{1+\beta_F} \Leftrightarrow \beta_F = \frac{\alpha_F}{1-\alpha_F}$$

Reverse active region

$$i_E = \alpha_R i_C$$
$$-i_E = \beta_R i_B$$

KCL: $-i_C = i_B - i_E$

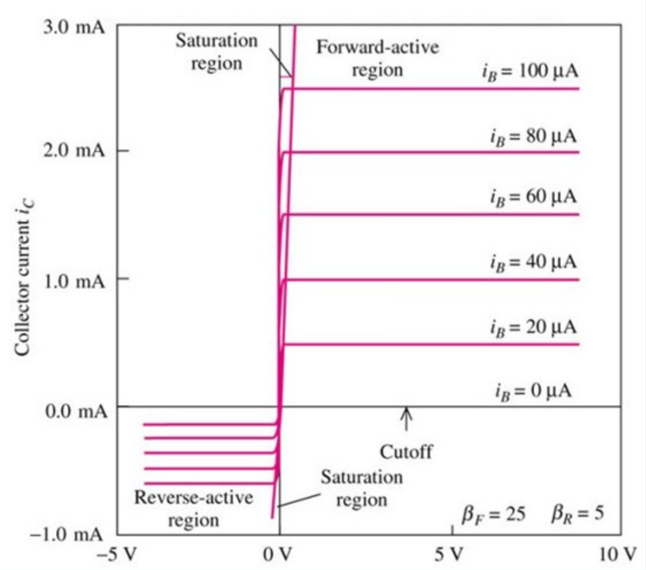
$$\alpha_R = \frac{\beta_R}{1+\beta_R} \Leftrightarrow \beta_R = \frac{\alpha_R}{1-\alpha_R}$$

Saturation region

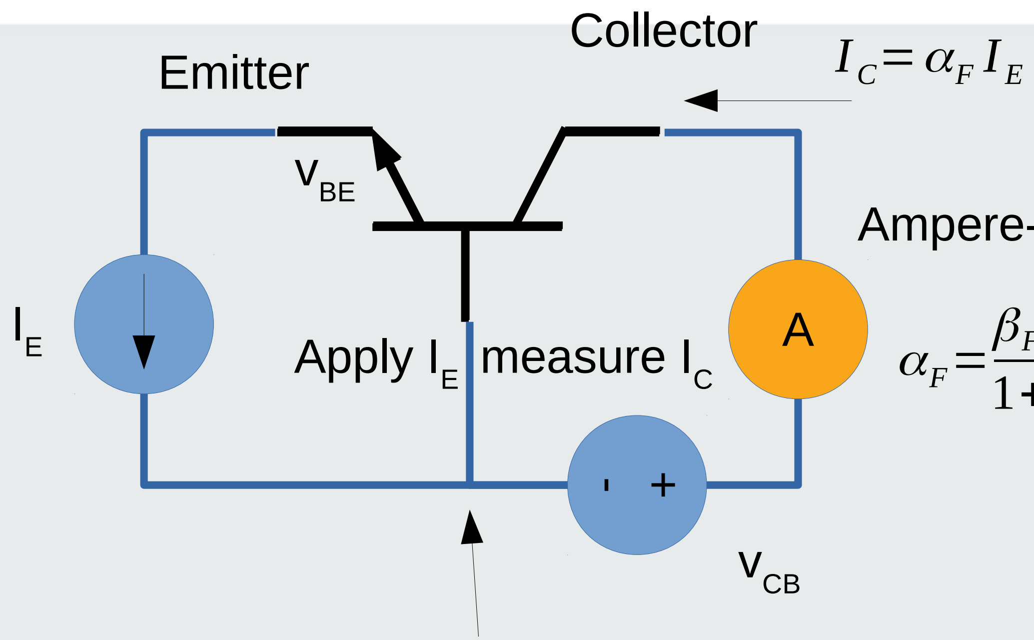
$$i_C < \beta_F i_B$$

Cut-off region

$$i_C = i_B = i_E = 0$$



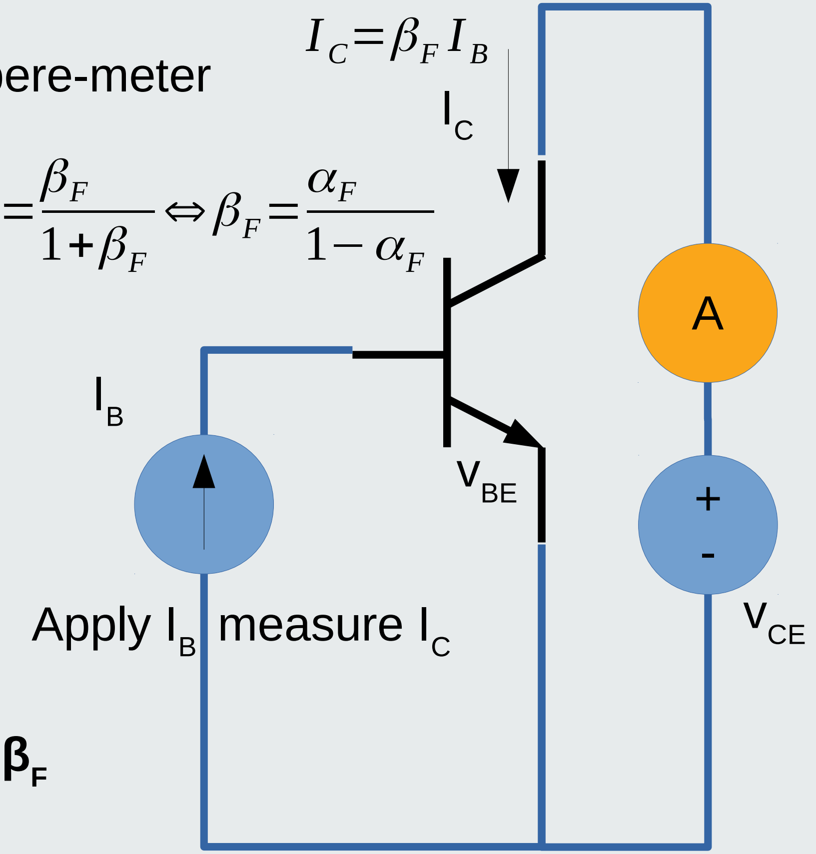
Experimental setup to measure α_F or β_F



Common-Base

Ampere-meter

$$\alpha_F = \frac{\beta_F}{1+\beta_F} \Leftrightarrow \beta_F = \frac{\alpha_F}{1-\alpha_F}$$



Common-Emitter

Experimentally, α_F varies with I_E and V_{CB} and β_F varies with I_B and V_{CE}!!

It's called the Early Effect!

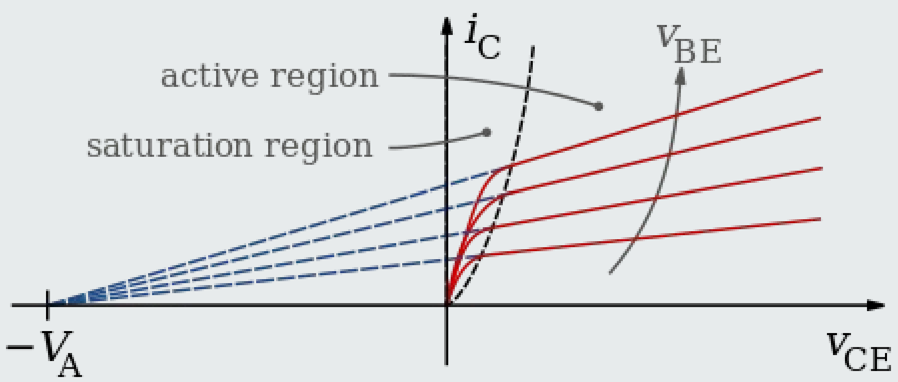
The Early Effect: base width modulation

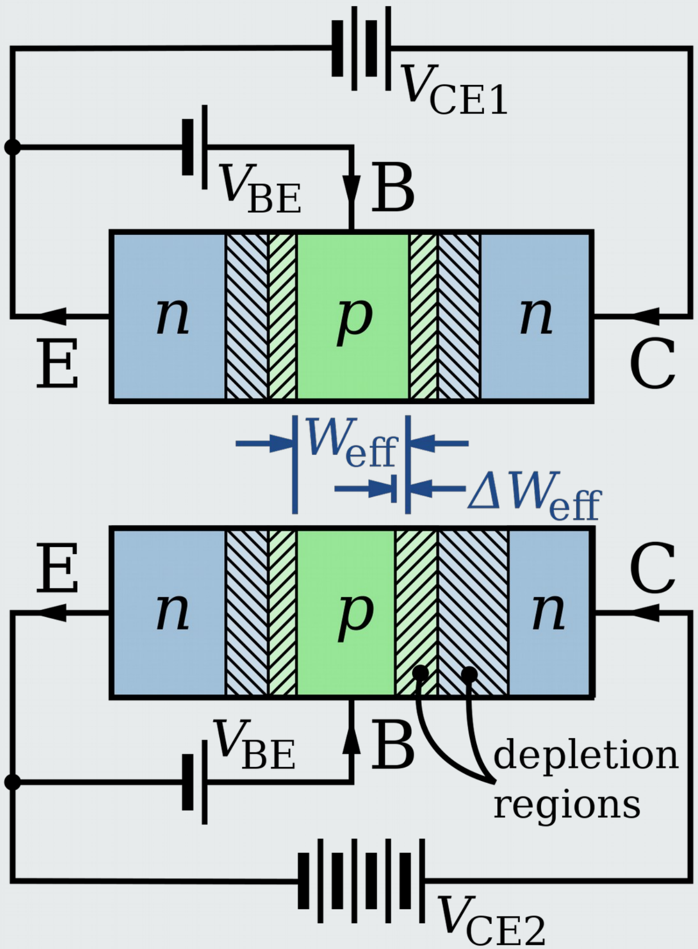
$$i_C = I_S e^{\frac{v_{BE}}{V_T}} \left(1 + \frac{V_{CE}}{V_A}\right)$$ Ebbers-Moll with Early correction

$$i_C' = I_S e^{\frac{v_{BE}}{V_T}}$$ Ebbers-Moll given

$$i_C = i_C' \left(1 + \frac{V_{CE}}{V_A}\right)$$ corrected

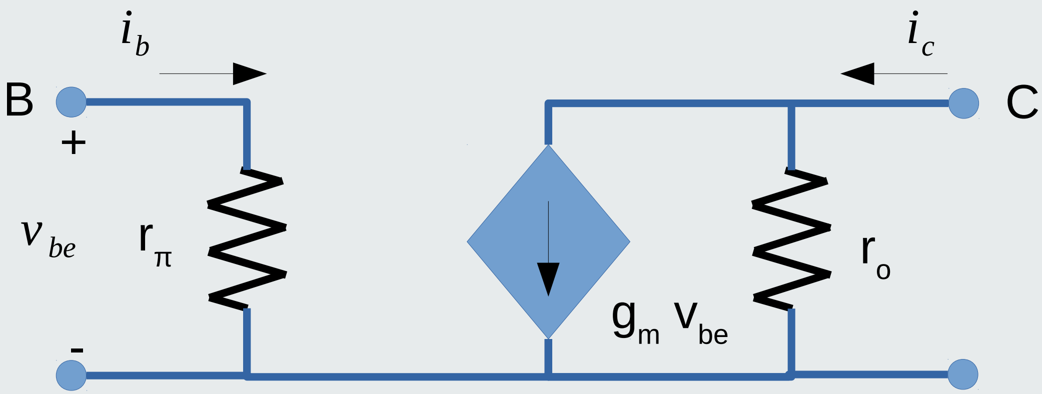
$$\beta_F = \beta_{F0} \left(1 + \frac{V_{CB}}{V_A}\right)$$ corrected





Bipolar transistor small signal model (AC)

Forward active region ONLY



$$g_m v_{BE} = \beta_F i_B$$

$$g_m = \frac{\partial i_C}{\partial v_{BE}} = \frac{i_C}{V_T} \approx \frac{i_C'}{V_T}$$

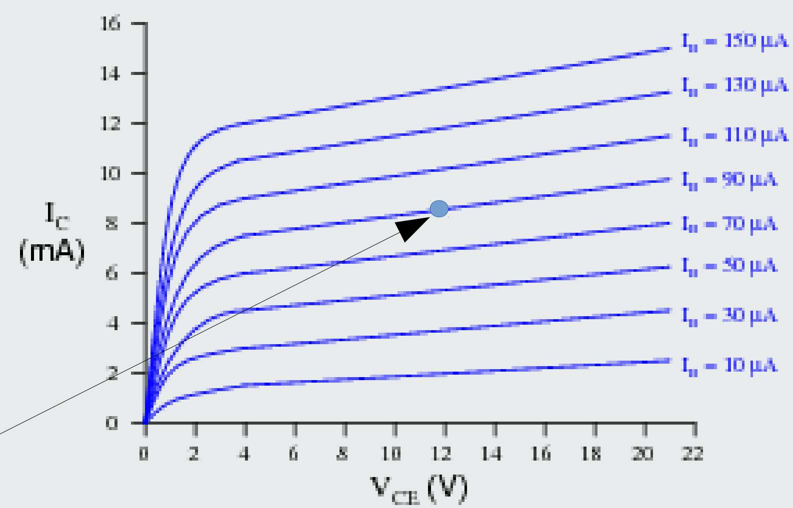
$$r_\pi = \frac{\partial v_{BE}}{\partial i_B} = \frac{\beta_F}{g_m}$$

$$r_o = \frac{\partial v_{CE}}{\partial i_C} = \frac{V_A + V_{CE}}{i_C} \approx \frac{V_A}{i_C'}$$

<u>Incremental parameters</u>

g_m	Transconductance
r_π	Input (incremental) impedance
r_o	Output (incremental) impedance

Computed using operating point



Bipolar pnp transistor DC model

Switch the direction of the currents and use the same equations!

Forward active region

$$i_C = \alpha_F i_E \qquad \beta_F = \beta_{F0}\left(1 + \frac{V_{CB}}{V_A}\right)$$
$$i_C = \beta_F i_B$$
$$i_E = i_B + i_C = (1+\beta_F) i_B = \left(1 + \frac{1}{\beta_F}\right) i_C$$
$$\alpha_F = \frac{\beta_F}{1+\beta_F} \Leftrightarrow \beta_F = \frac{\alpha_F}{1-\alpha_F}$$

Saturation region

$$i_C < \beta_F i_B$$

Cut-off region

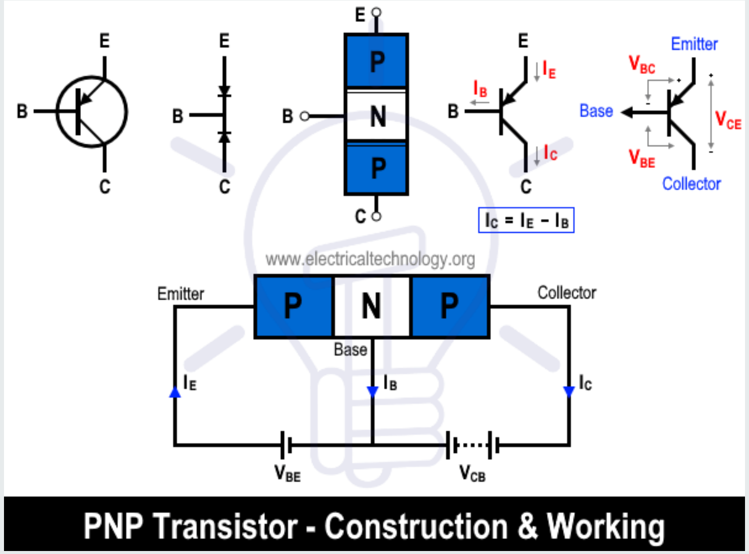
$$i_C = i_B = i_E = 0$$

AC model

$$g_m = \frac{\partial i_C}{\partial v_{BE}} = \frac{i_C}{V_T}$$
$$r_\pi = \frac{\partial v_{BE}}{\partial i_B} = \frac{\beta_F}{g_m}$$
$$r_o = \frac{\partial v_{CE}}{\partial i_C} \approx \frac{V_A}{I_C}$$

Reverse active region

$$i_E = \alpha_R i_C$$
$$-i_E = \beta_R i_B$$
$$-i_C = i_B - i_E$$
$$\alpha_R = \frac{\beta_R}{1+\beta_R} \Leftrightarrow \beta_R = \frac{\alpha_R}{1-\alpha_R}$$



Spice's BJT model

- Ngspice has very sophisticated BJT models
- Let's consider a reduced parameter set one
  - **BF**: Forward active current gain
  - VJE Base-emitter built-in potential
  - **BR**: Reverse active current gain
  - VJC Base-collector built-in potential
  - **IS**: Transport saturation current
  - **VAF** Forward mode Early voltage
  - CJE: Base-emitter zero-bias junction capacitance
  - **VAR** Reverse mode Early voltage
  - NF Forward mode ideality factor
  - NR Reverse mode ideality factor
  - CJC Base-collector zero-bias junction capacitance
- Check out l15.net: simulates $I_C(v_{CE})$ for constant v_{BE} using DC analysis (DC sweep) for a real commercial discret transistor: the BC547

Conclusion

- The transistor
- The Bipolar Junction Transistor:
- Operation regions
- Large signal model (DC)
- Small signal model (AC)
- Spice model