ECEN 325
Electronics

Bipolar Junction Transistors

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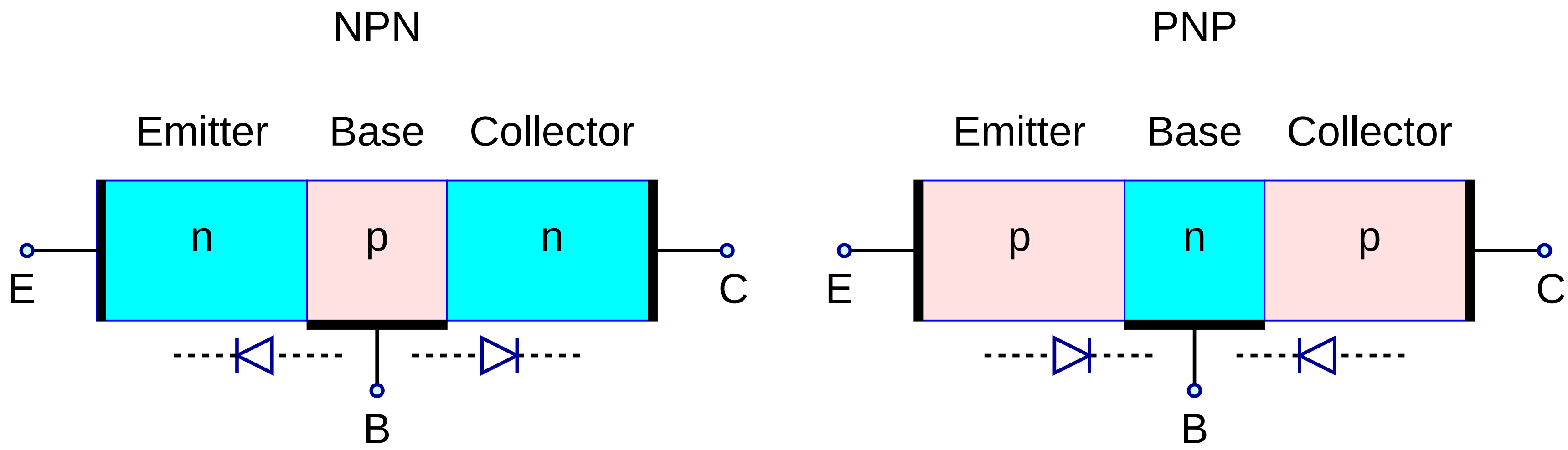
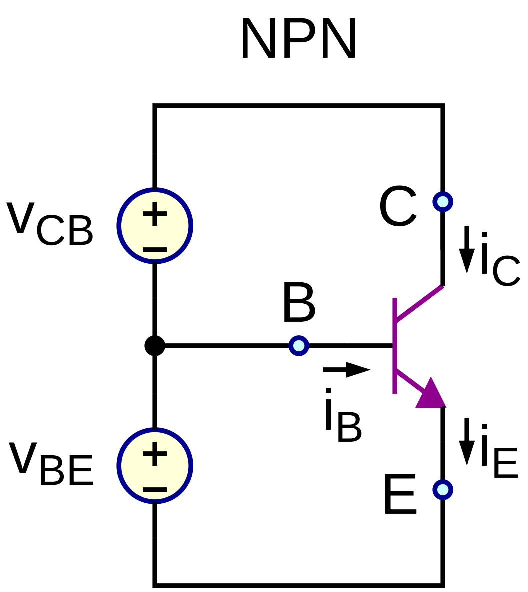
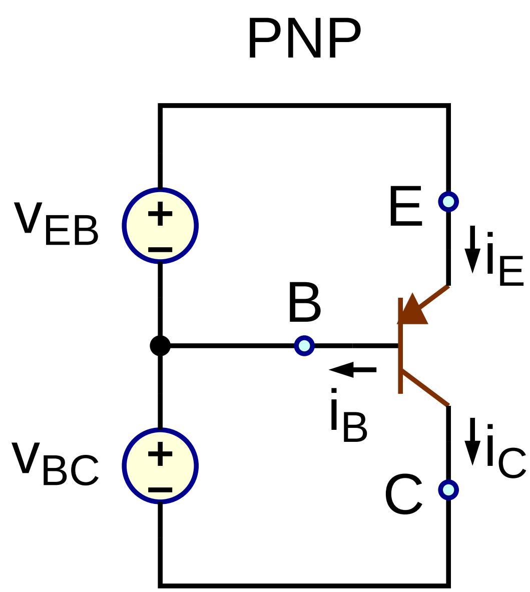
Bipolar Junction Transistor



Mode	Base-Emitter	Base-Collector
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Reverse Active	Reverse	Forward
Saturation	Forward	Forward

BJT Large-Signal Model





$$v_{CE} \geq V_{CE,sat}$$

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

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

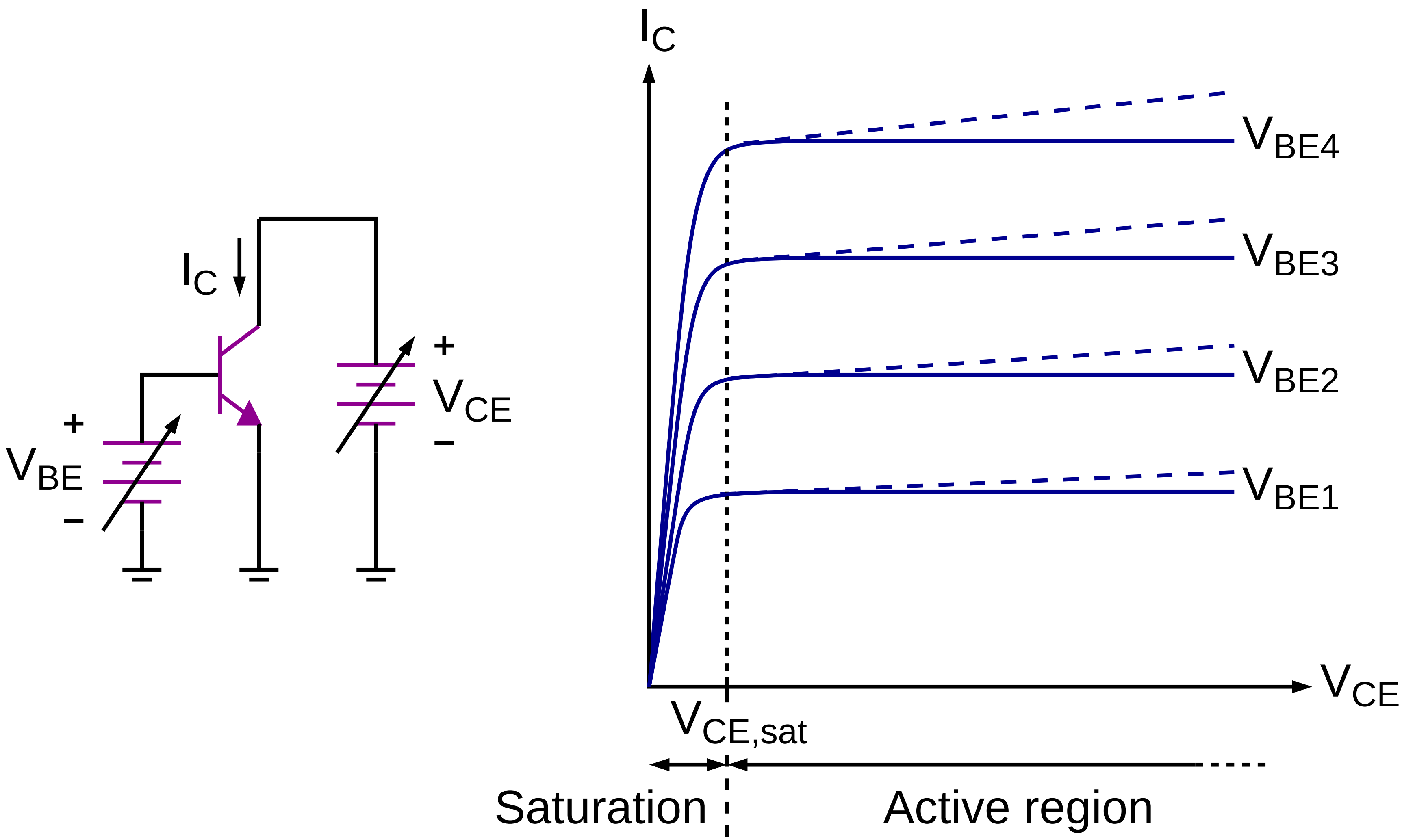
$$v_{EC} \geq V_{EC,sat}$$

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

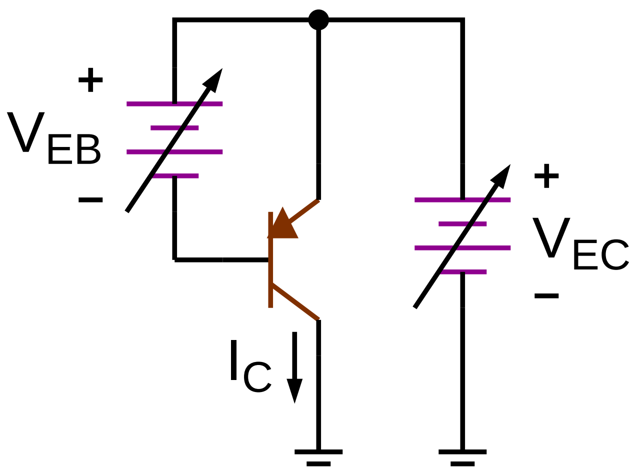
$$i_C = I_S e^{v_{EB}/V_T}$$

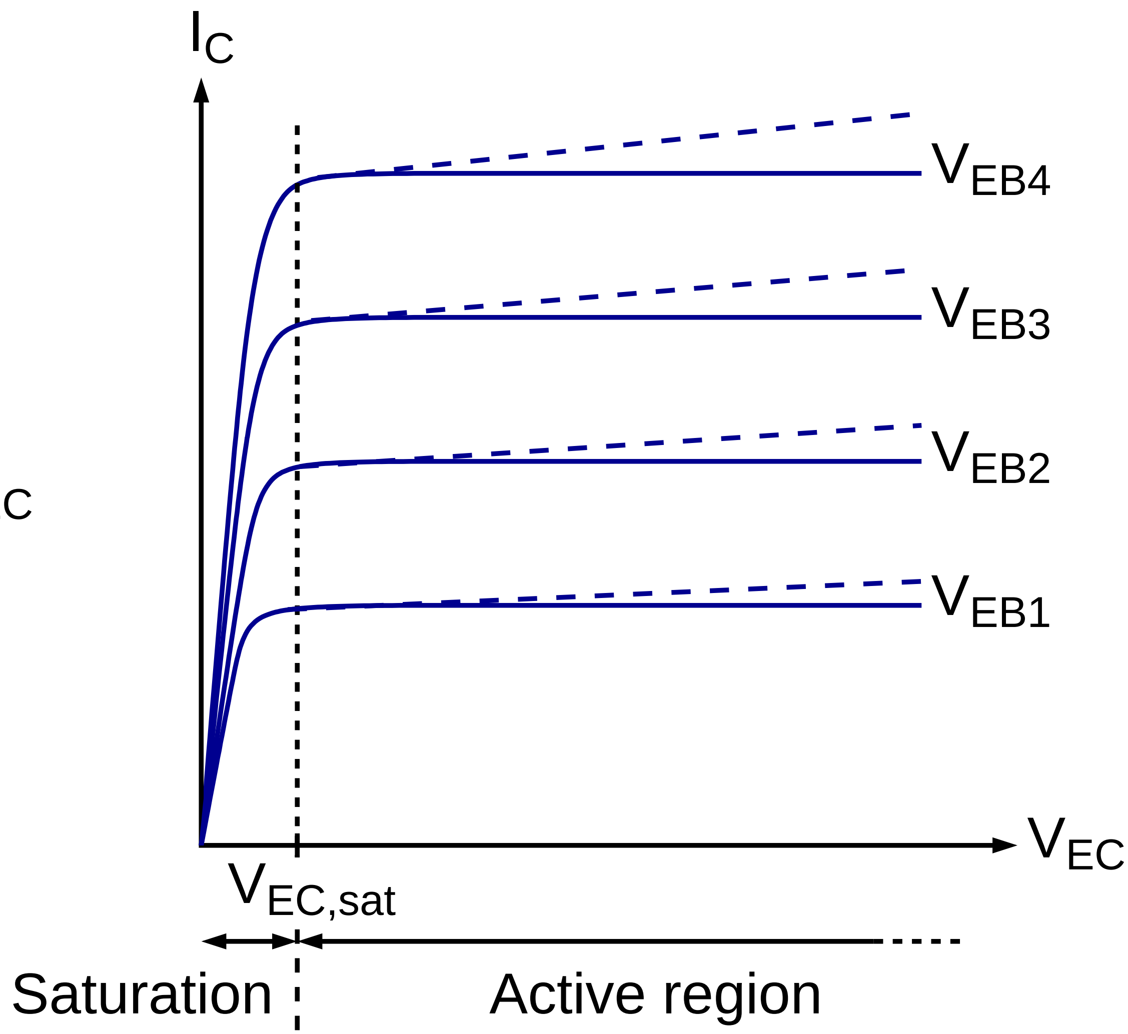
I_C-V_{CE} Characteristics

NPN

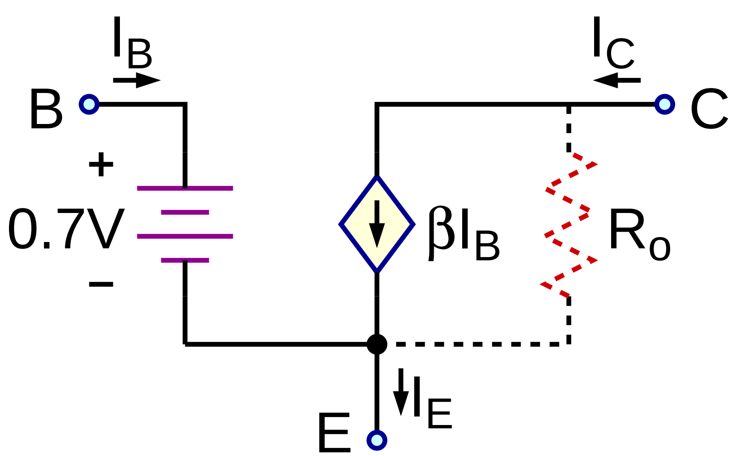


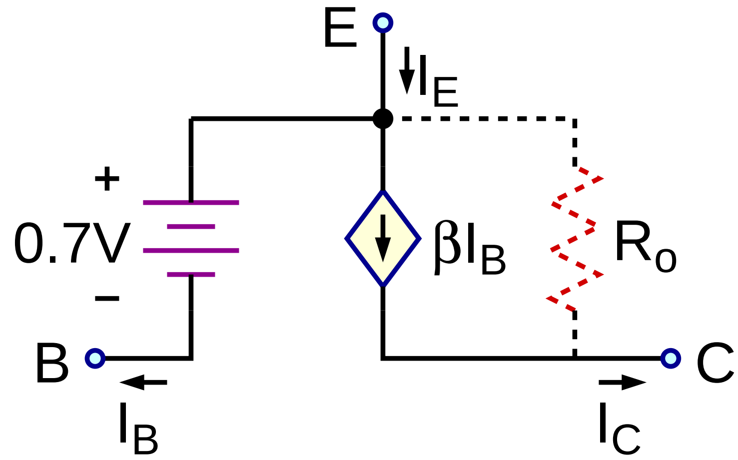
I_C-V_{EC} Characteristics





BJT DC Model





$$V_{CE} \geq V_{CE,sat}$$
$$V_{BE} = 0.7\ V$$

$$V_{EC} \geq V_{EC,sat}$$
$$V_{EB} = 0.7\ V$$

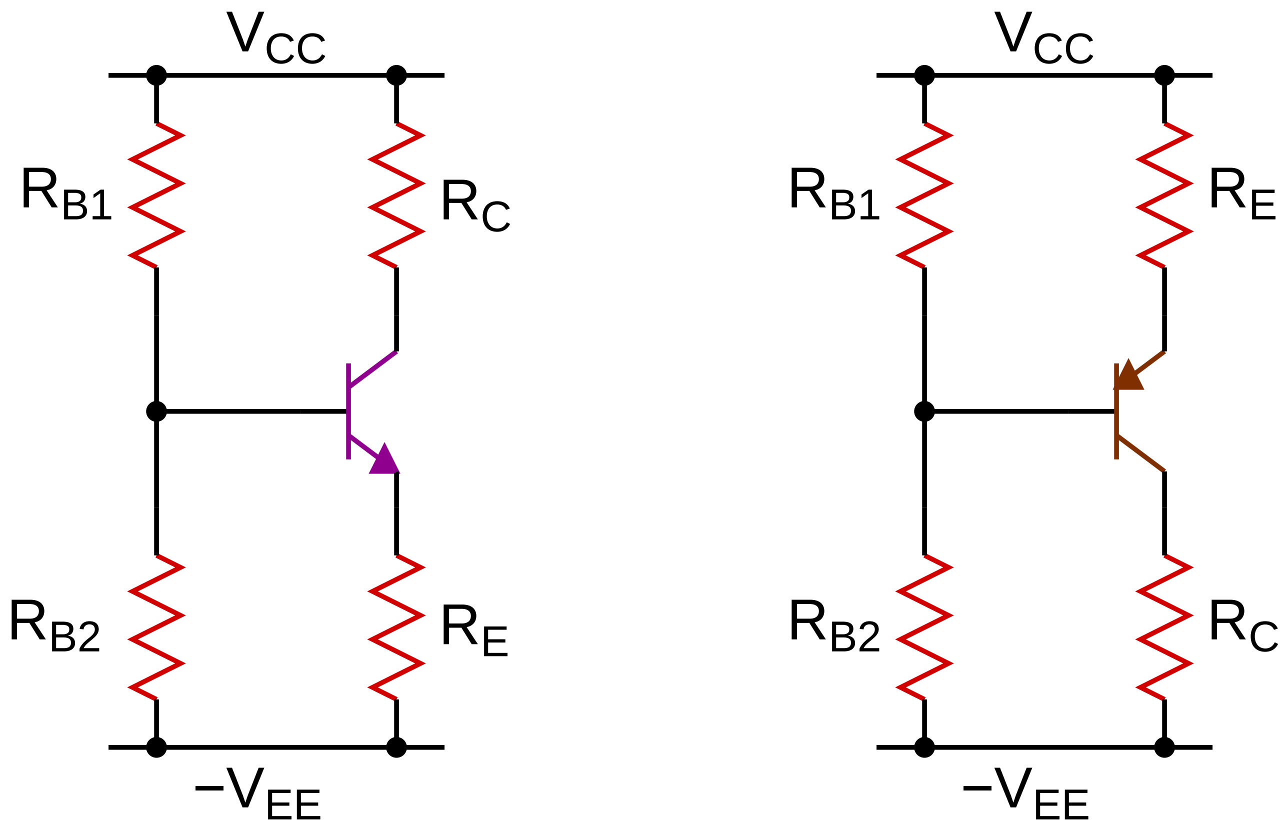
$$\alpha = \beta/(\beta + 1)$$

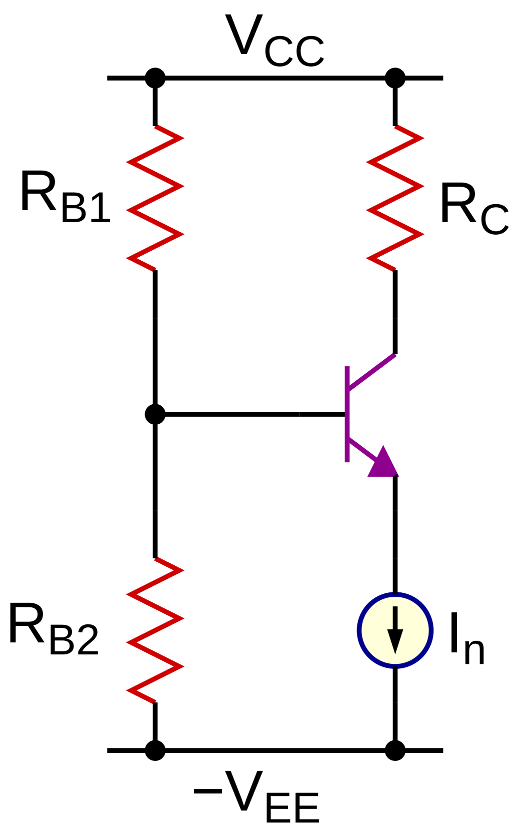
$$I_C = \beta I_B = \alpha I_E$$

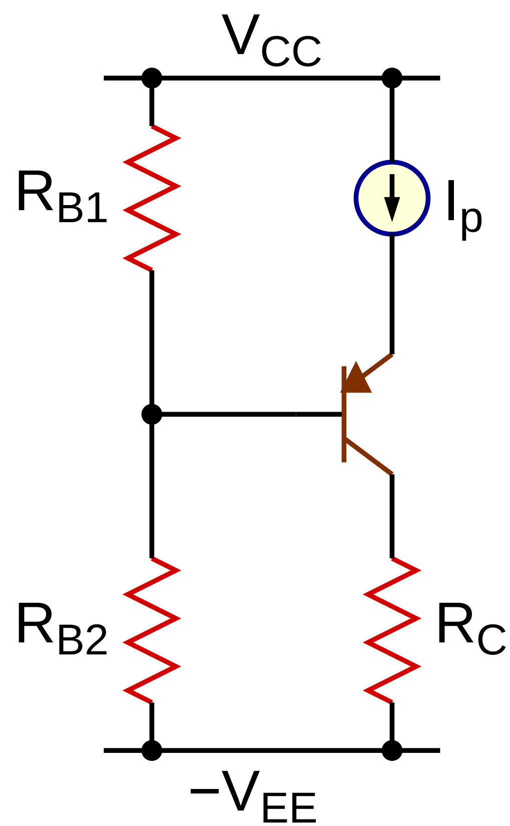
$$I_E = (\beta + 1) I_B = I_C/\alpha$$

$$I_B = I_C/\beta = I_E/(\beta + 1)$$

BJT DC Biasing

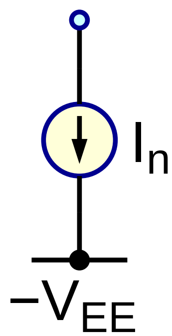


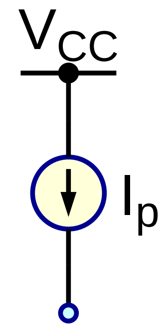

V_{CC}
R_{B1}
R_C
R_{B2}
I_n
$-V_{EE}$

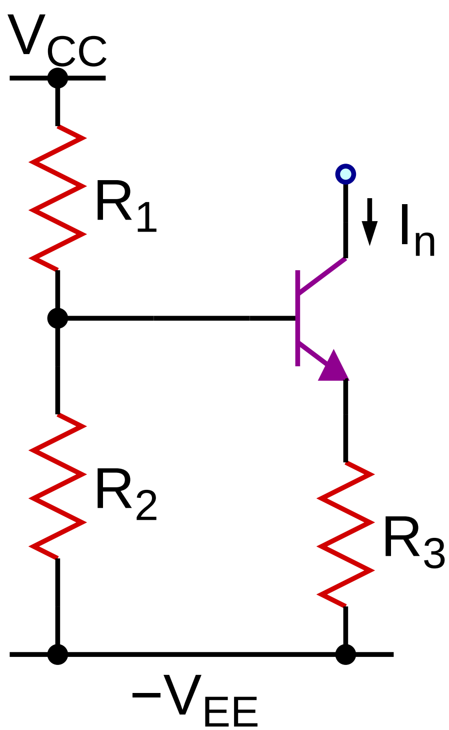

V_{CC}
R_{B1}
I_p
R_{B2}
R_C
$-V_{EE}$

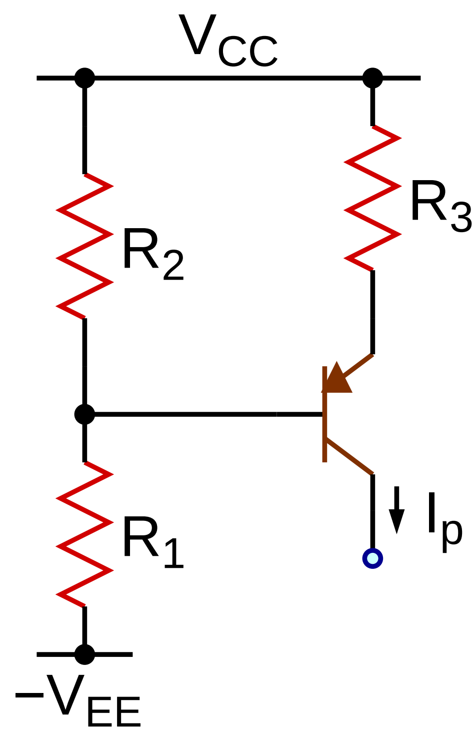
BJT DC Biasing

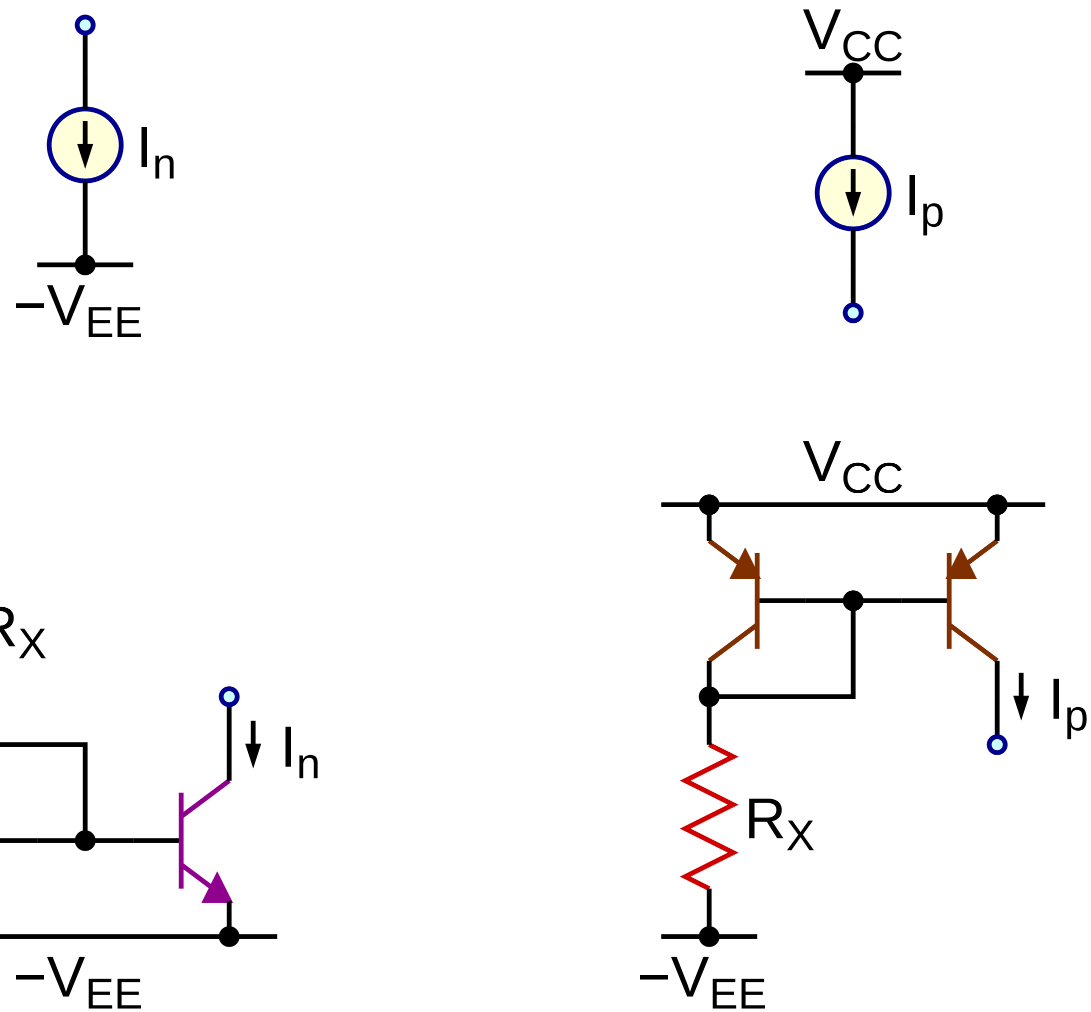
Current Source

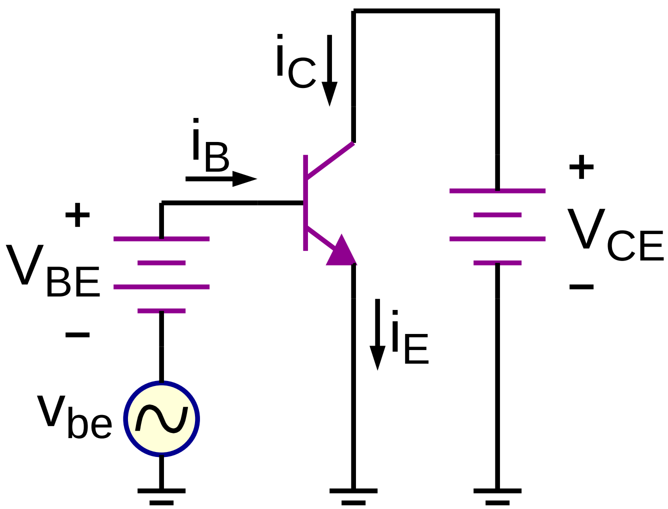









I_n
$-V_{EE}$
V_{CC}
I_p
V_{CC}
R_X
I_n
$-V_{EE}$
V_{CC}
I_p
R_X
$-V_{EE}$



$$v_{BE} = V_{BE} + v_{be}$$

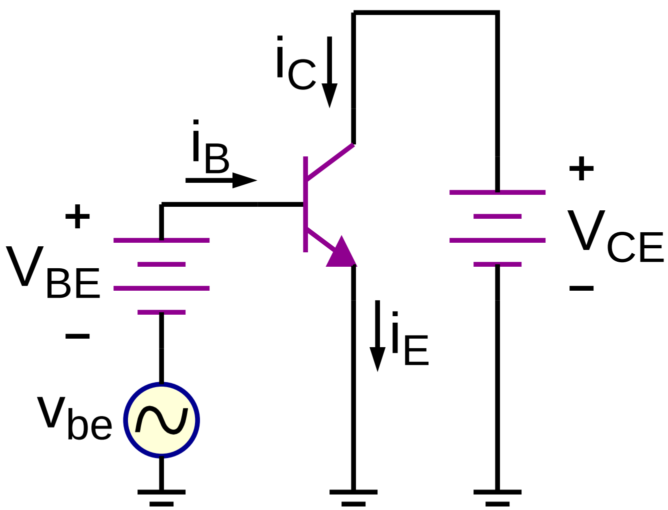
$$\begin{aligned} i_C &= I_S e^{v_{BE}/V_T} \\ &= I_S e^{V_{BE}/V_T} e^{v_{be}/V_T} \\ &= I_C e^{v_{be}/V_T} \end{aligned}$$

Assume $v_{be} \ll V_T$, then

$$\begin{aligned} i_C &\approx I_C \left(1 + \frac{v_{be}}{V_T}\right) \\ &= I_C + \frac{I_C}{V_T} v_{be} \\ &= I_C + g_m v_{be} \\ &= I_C + i_c \end{aligned}$$

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

BJT Small-Signal Operation

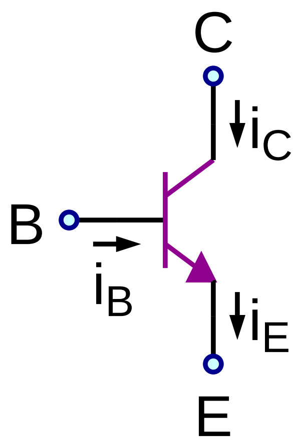


$$v_{be} \ll V_T$$
$$i_C = I_C + i_c$$
$$i_B = I_B + i_b$$
$$i_E = I_E + i_e$$

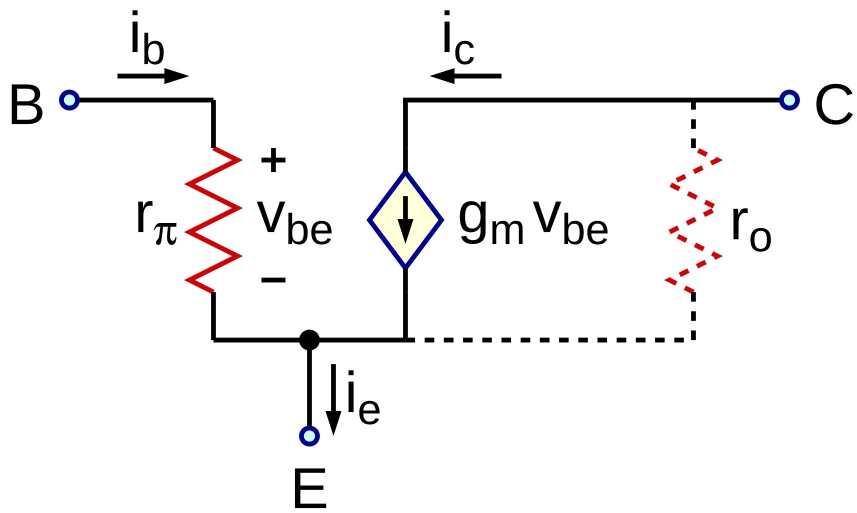
$$i_B = \frac{i_C}{\beta} = \frac{I_C}{\beta} + \frac{i_c}{\beta}$$
$$i_b = \frac{i_c}{\beta} = \frac{g_m v_{be}}{\beta}$$
$$\boxed{\frac{v_{be}}{i_b} = r_\pi = \frac{\beta}{g_m}}$$

$$i_E = \frac{i_E}{\alpha} = \frac{I_C}{\alpha} + \frac{i_c}{\alpha}$$
$$i_e = \frac{i_c}{\alpha} = \frac{g_m v_{be}}{\alpha}$$
$$\boxed{\frac{v_{be}}{i_e} = r_e = \frac{\alpha}{g_m} \approx \frac{1}{g_m}}$$

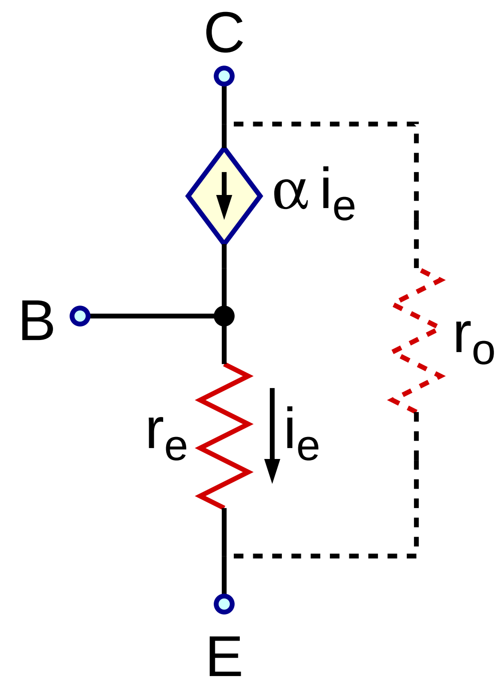
BJT Small Signal Model



NPN



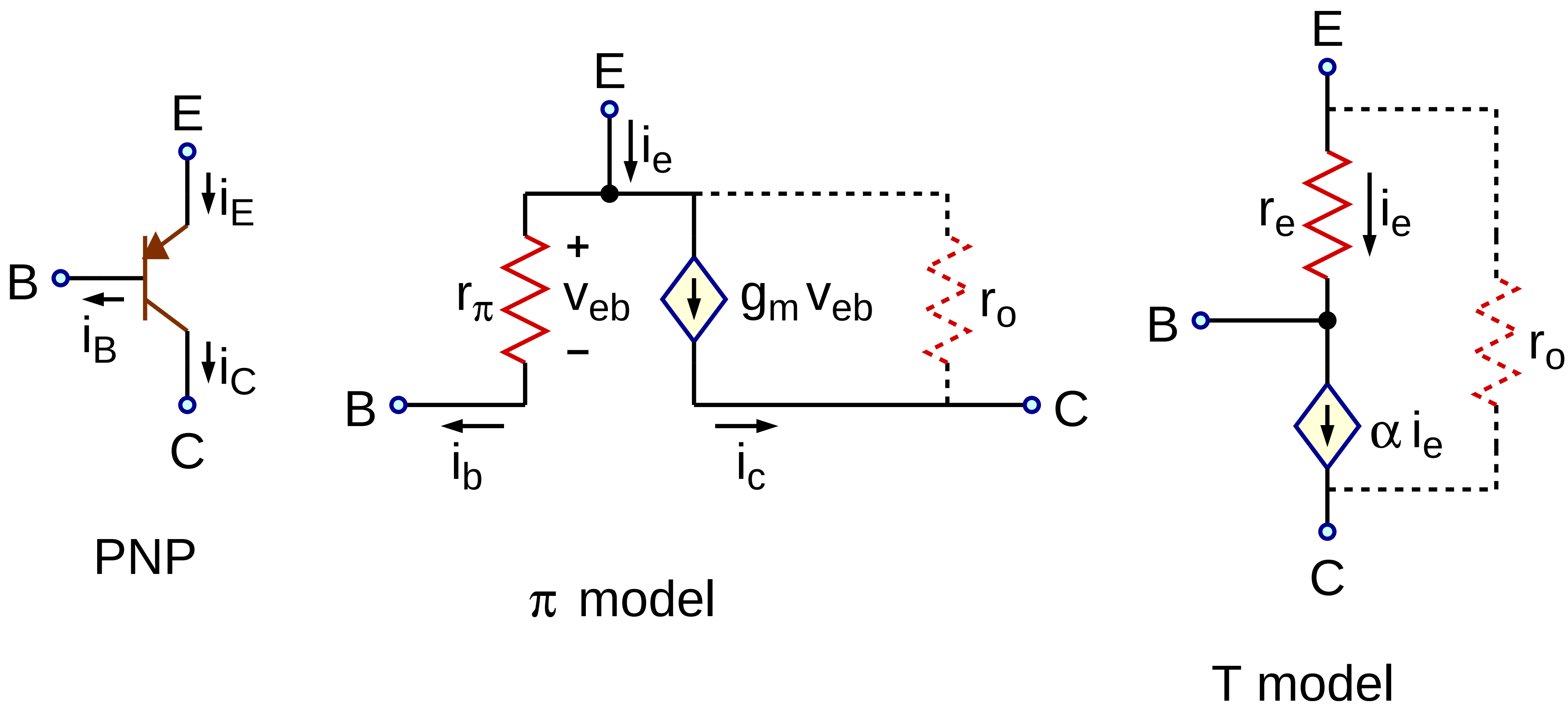
π model



T model

$$g_m = \frac{I_C}{V_T} \qquad r_\pi = \frac{\beta}{g_m} \qquad r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m} \approx \frac{1}{g_m} \qquad r_o = \frac{V_A}{I_C}$$

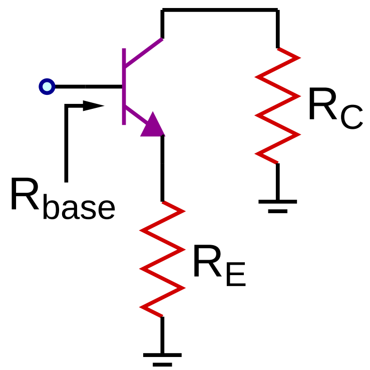
BJT Small Signal Model



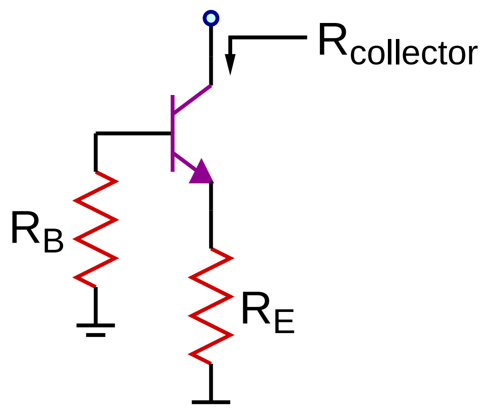
$$g_m = \frac{I_C}{V_T} \qquad r_\pi = \frac{\beta}{g_m} \qquad r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m} \approx \frac{1}{g_m} \qquad r_o = \frac{V_A}{I_C}$$

BJT Node Resistances

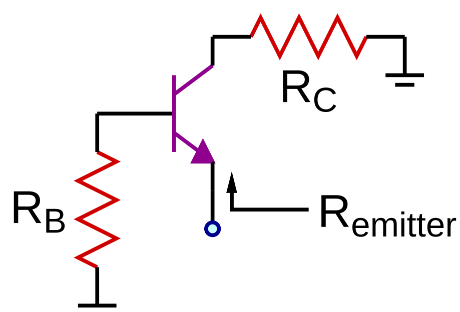
AC, $r_o = \infty$



$$R_{base} = (\beta + 1)(r_e + R_E)$$



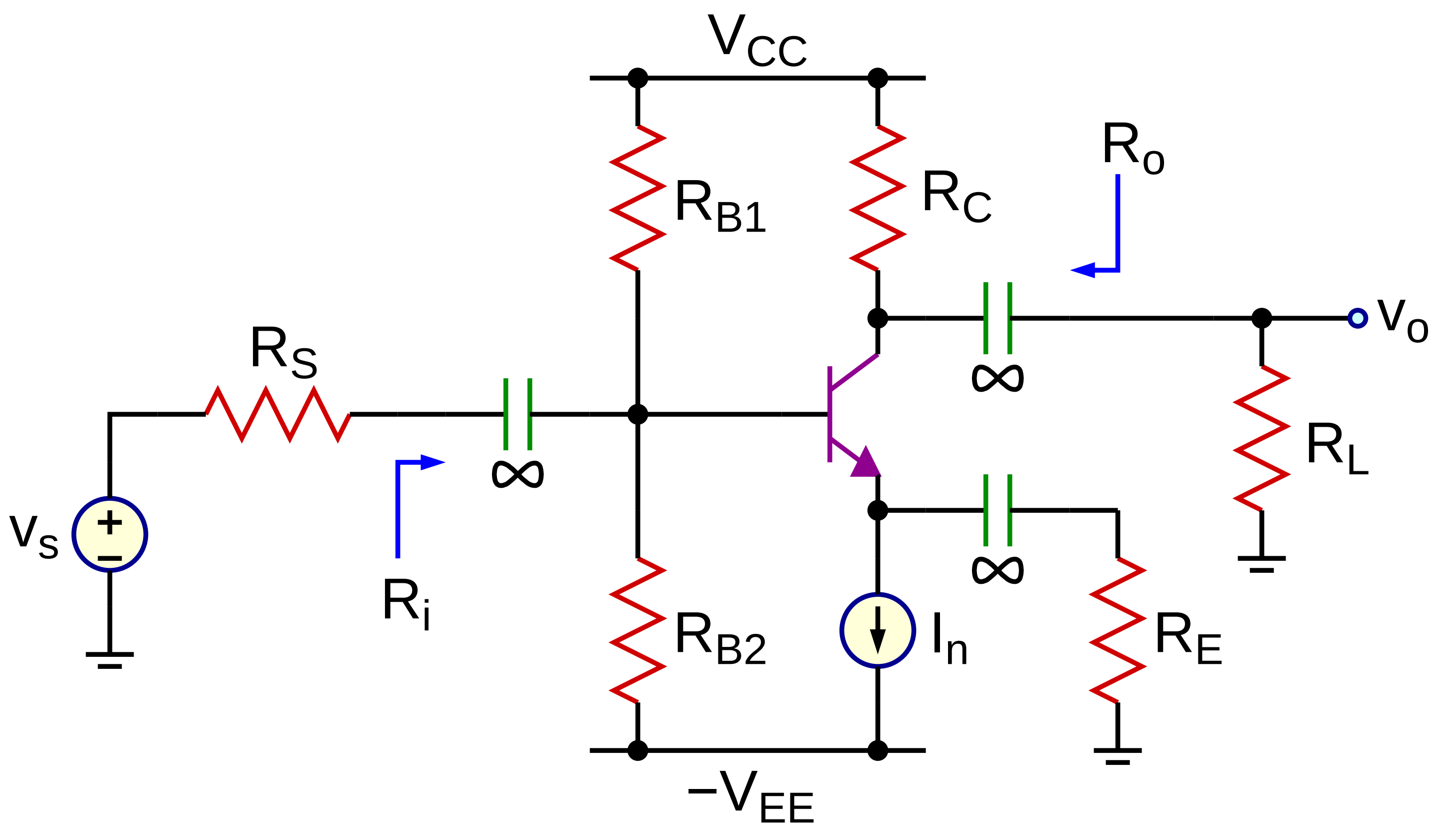
$$R_{collector} = \infty$$

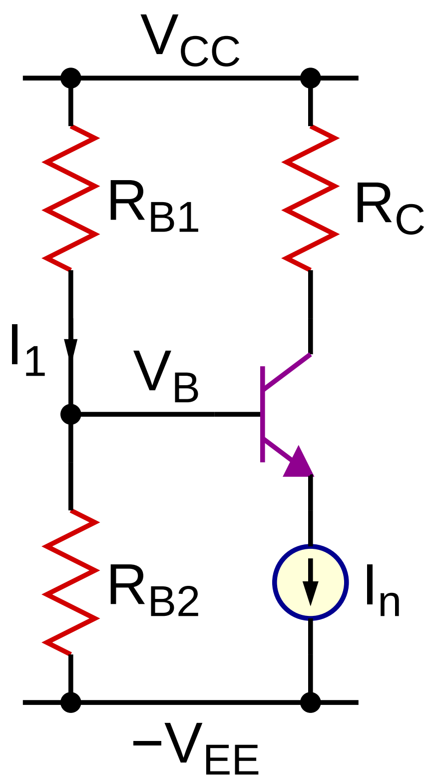


$$R_{emitter} = r_e + \frac{R_B}{\beta + 1}$$

Common Emitter Amplifier

$B \rightarrow C \quad (-)$





$$\mathbf{I_E = I_n \approx I_C}$$

$$\mathbf{V_C = V_{CC} - I_C R_C}$$

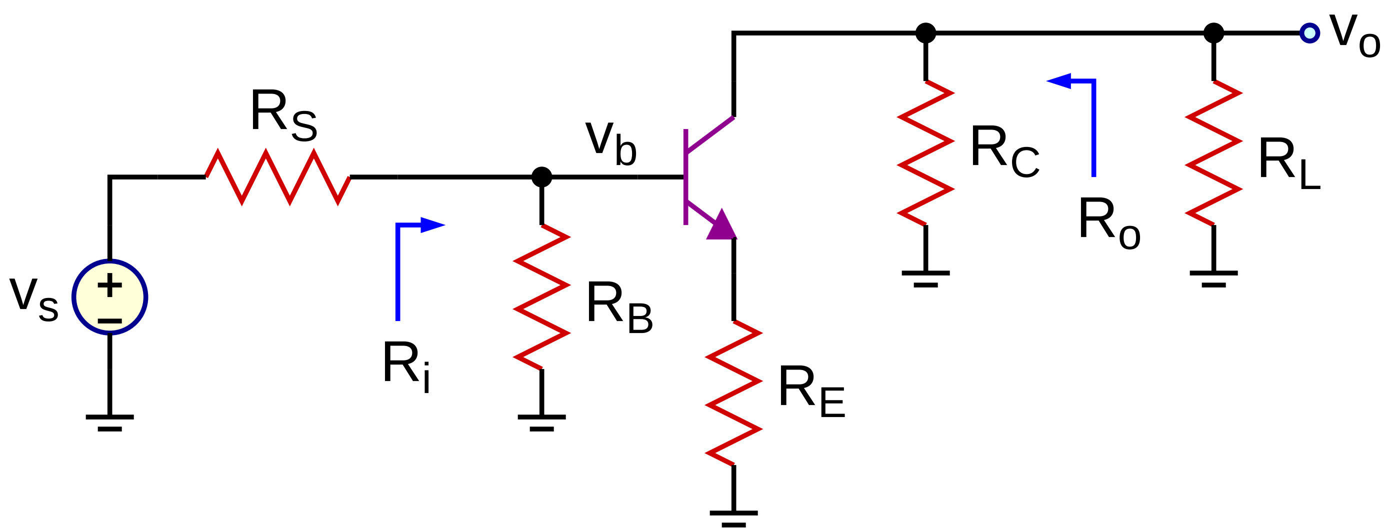
$$\mathbf{I_1 \gg I_B} \;\Rightarrow$$

$$\mathbf{V_B \approx V_{CC} - \frac{R_{B1}}{R_{B1}+R_{B2}}(V_{CC}+V_{EE})}$$

$$\mathbf{V_E = V_B - 0.7}$$

$$\mathbf{V_{CE} \geq V_{CE,sat}} \;\Rightarrow\; \text{ACTIVE}$$

Common Emitter Amplifier



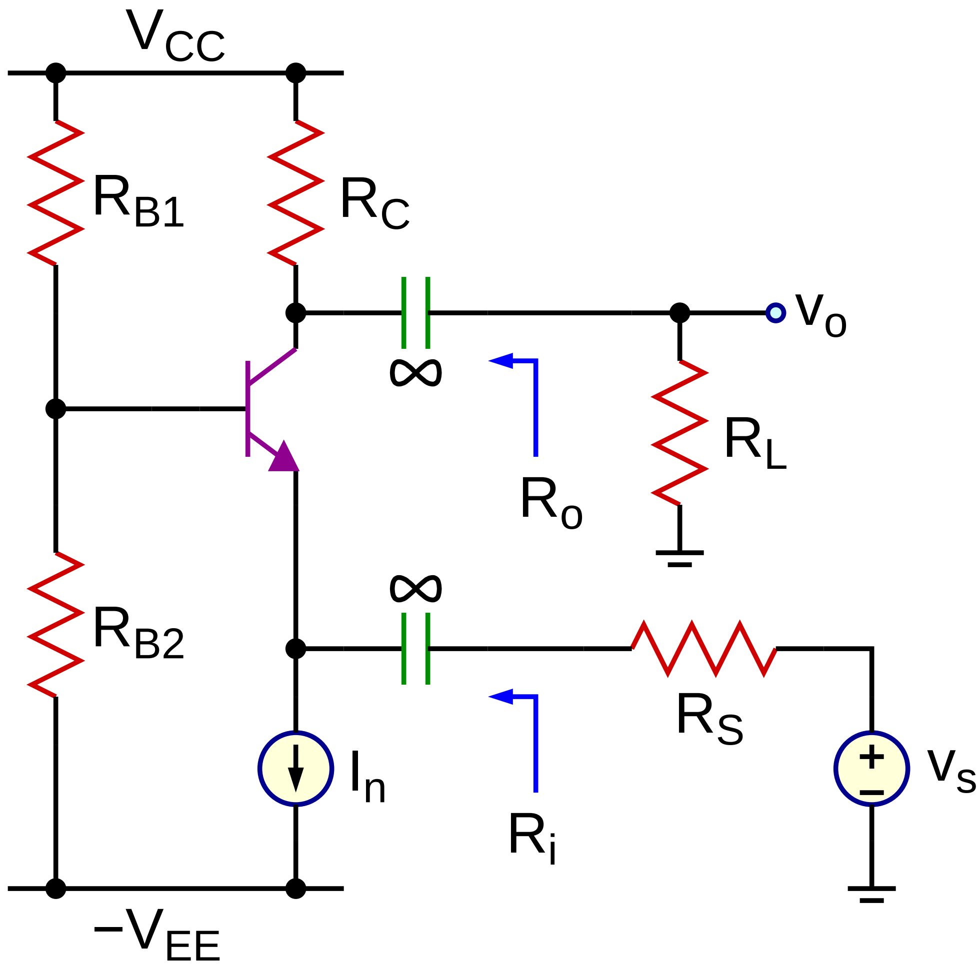
$$R_i = R_B \parallel R_{base} \quad , \quad R_B = R_{B1} \parallel R_{B2}$$

$$R_o = R_C \parallel R_{collector}$$

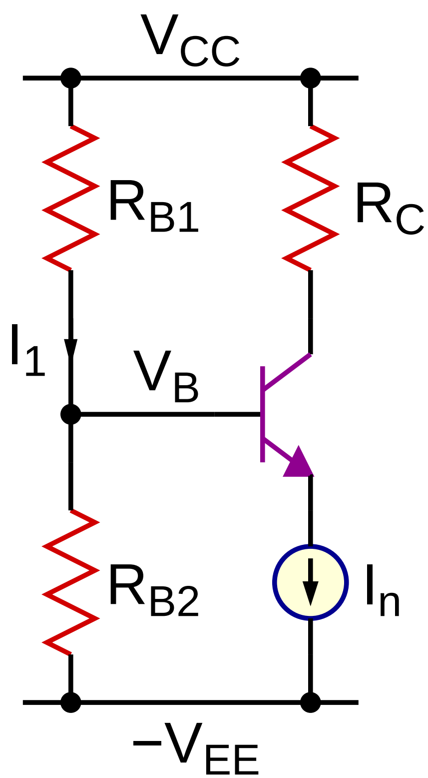
$$\frac{v_b}{v_s} = \frac{R_i}{R_i + R_S} \quad , \quad \frac{v_o}{v_b} = -\alpha \frac{R_C \parallel R_L}{r_e + R_E} \approx -\frac{R_C \parallel R_L}{r_e + R_E}$$

Common Base Amplifier

$E \rightarrow C \ (+)$



Common Base Amplifier



$$I_E = I_n \approx I_C$$

$$V_C = V_{CC} - I_C R_C$$

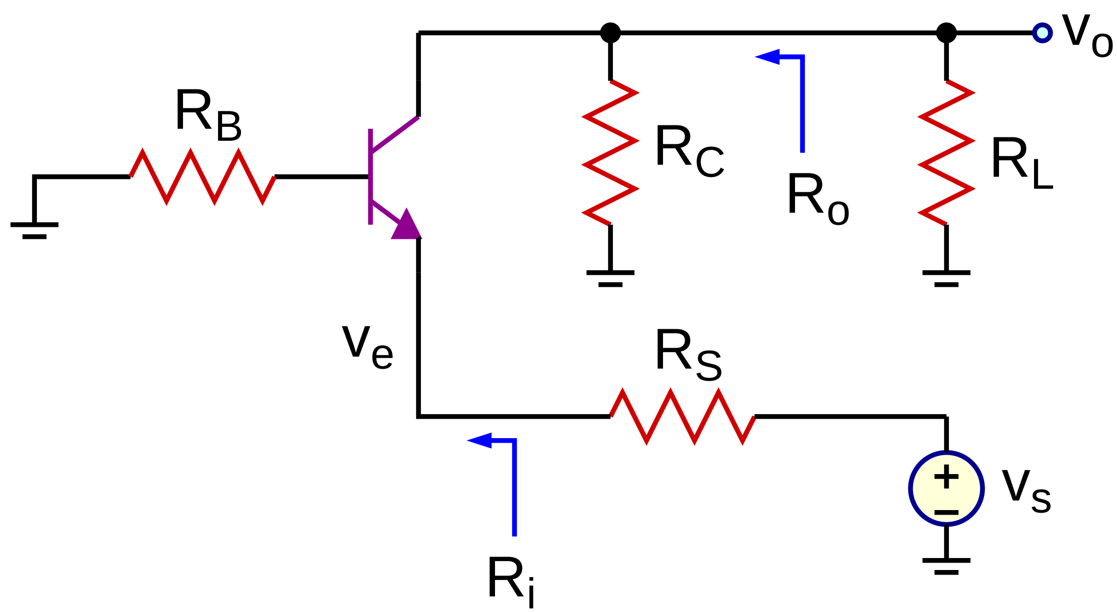
$$I_1 \gg I_B \;\Rightarrow$$

$$V_B \approx V_{CC} - \frac{R_{B1}}{R_{B1}+R_{B2}}(V_{CC}+V_{EE})$$

$$V_E = V_B - 0.7$$

$$V_{CE} \geq V_{CE,sat} \;\Rightarrow\; \text{ACTIVE}$$

Common Base Amplifier



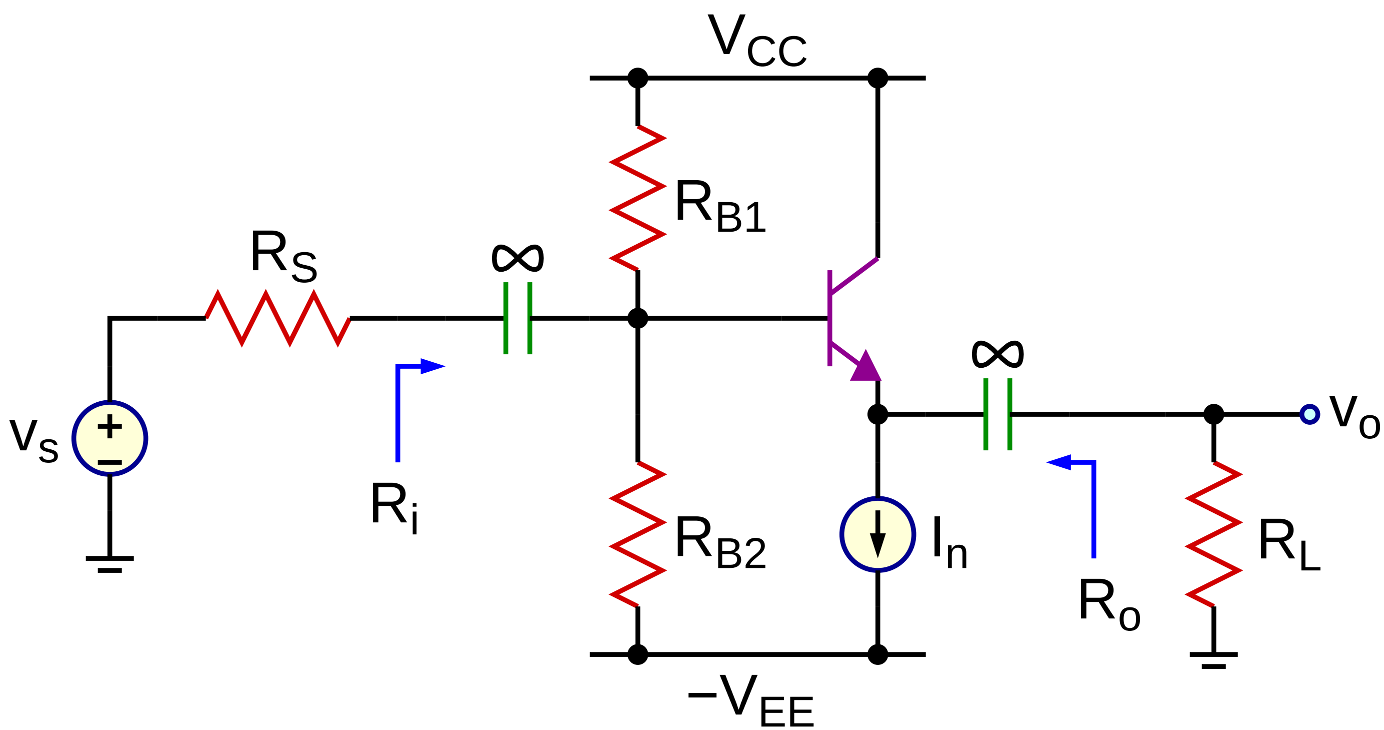
$$R_i = R_{emitter} \quad , \quad R_B = R_{B1} \parallel R_{B2}$$

$$R_o = R_C \parallel R_{collector}$$

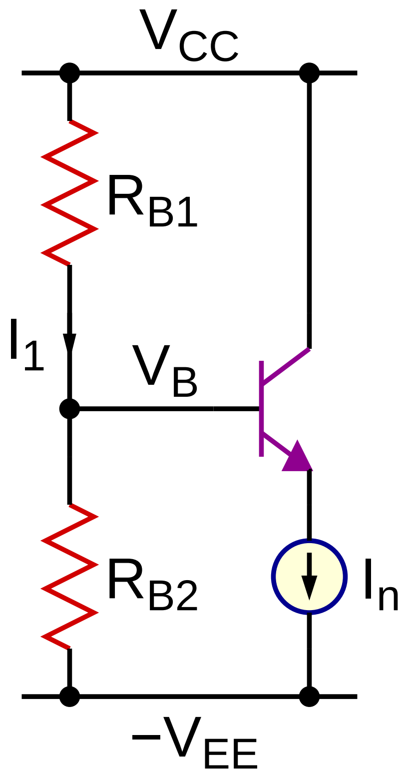
$$\frac{v_e}{v_s} = \frac{R_i}{R_i + R_S} \quad , \quad \frac{v_o}{v_e} = \alpha \frac{R_C \parallel R_L}{R_{emitter}} \approx \frac{R_C \parallel R_L}{R_{emitter}}$$

Common Collector Amplifier

$B \rightarrow E \quad (+)$



Common Collector Amplifier



$$\mathbf{I_E = I_n \approx I_C}$$

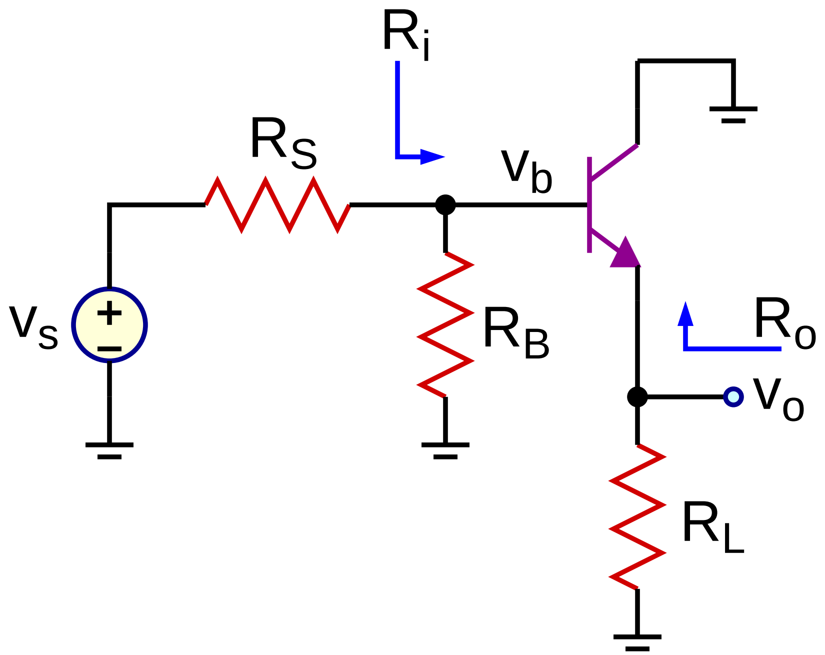
$$\mathbf{V_C = V_{CC}}$$

$$\mathbf{I_1 \gg I_B \;\Rightarrow}$$

$$\mathbf{V_B \approx V_{CC} - \frac{R_{B1}}{R_{B1}+R_{B2}}(V_{CC}+V_{EE})}$$

$$\mathbf{V_E = V_B - 0.7}$$

$$\mathbf{V_{CE} \geq V_{CE,sat}} \;\Rightarrow\; \text{ACTIVE}$$



$$R_B = R_{B1} \parallel R_{B2}$$

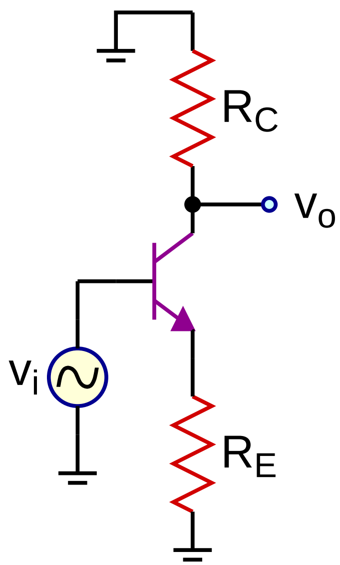
$$R_i = R_B \parallel R_{base}$$

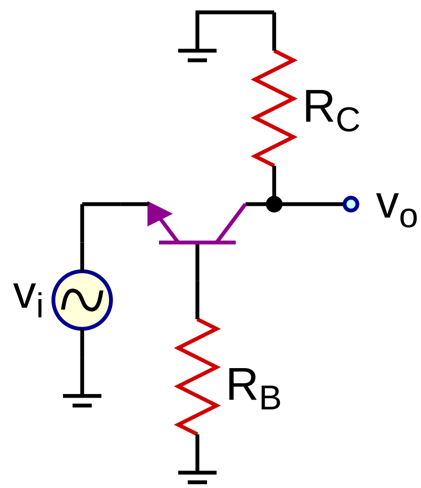
$$R_o = R_{emitter}$$

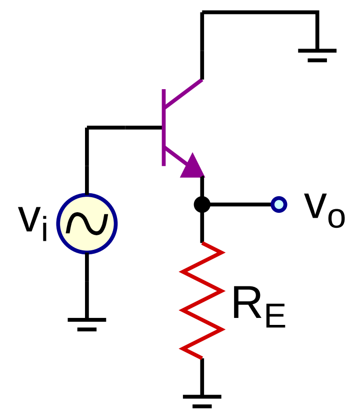
$$\frac{v_b}{v_s} = \frac{R_i}{R_i + R_S}$$

$$\frac{v_o}{v_b} = \frac{R_L}{r_e + R_L}$$

BJT Amplifiers - Summary





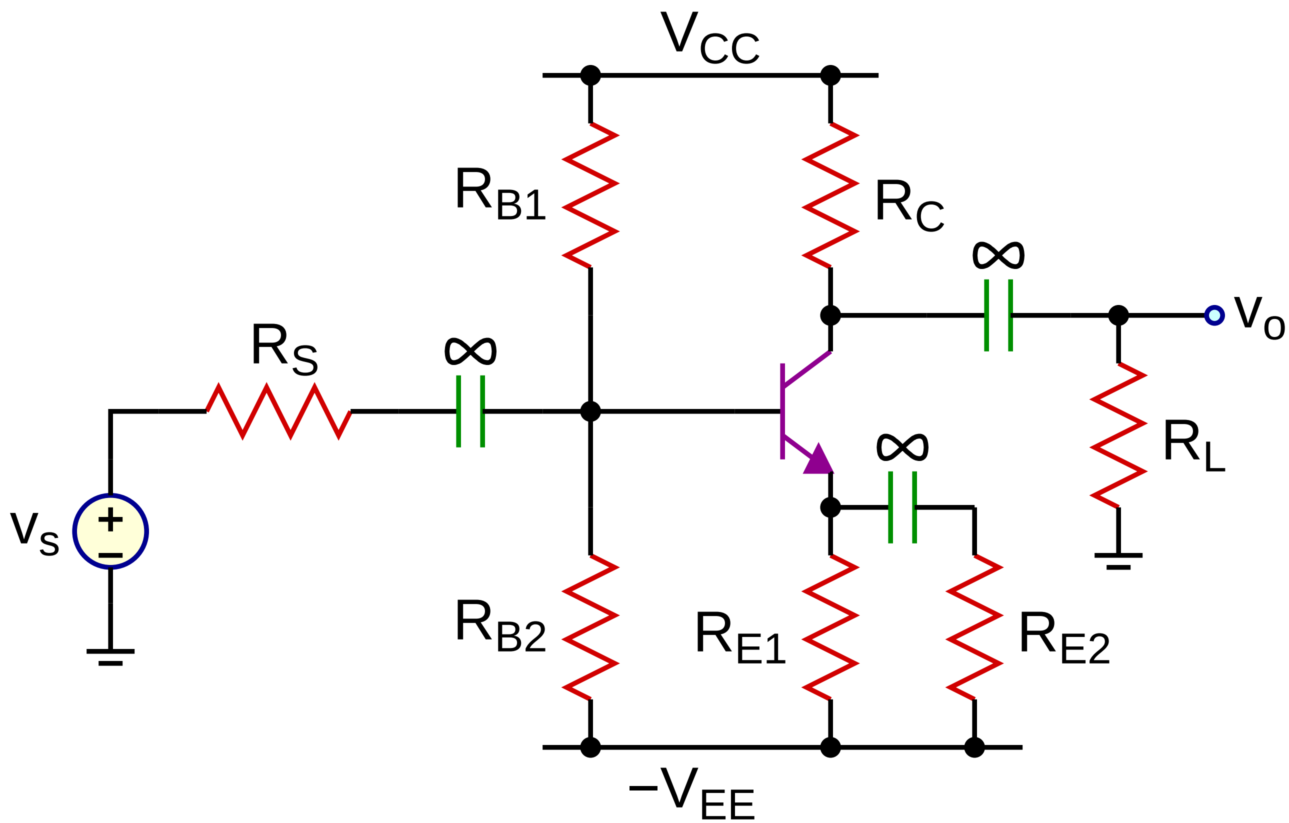


$$\frac{v_o}{v_i} = \frac{-\alpha R_C}{r_e + R_E}$$

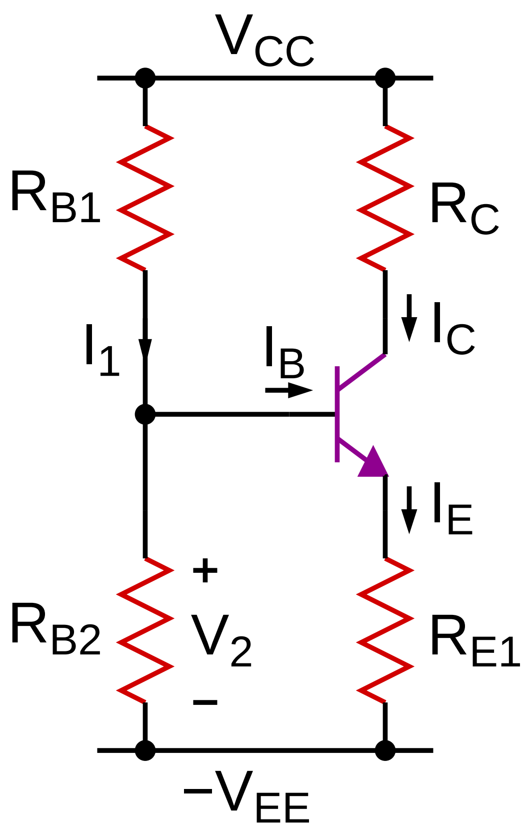
$$\frac{v_o}{v_i} = \frac{\alpha R_C}{R_{emitter}}$$

$$\frac{v_o}{v_i} = \frac{R_E}{r_e + R_E}$$

Example 1



Example 1



$$I_1 \gg I_B \;\Rightarrow$$

$$V_2 \approx \frac{R_{B2}}{R_{B1} + R_{B2}}(V_{CC} + V_{EE})$$

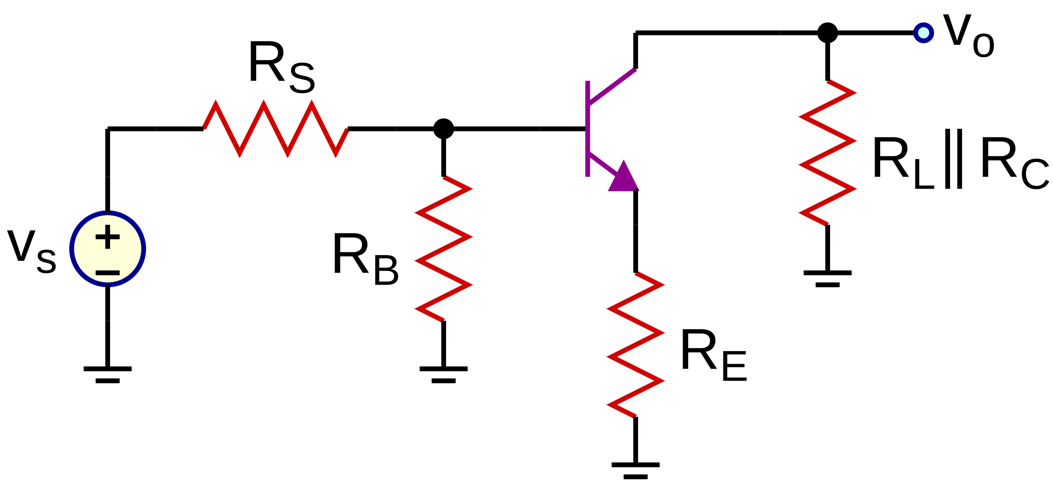
$$V_2 = 0.7 + I_E R_{E1}$$

$$I_E = \frac{V_2 - 0.7}{R_{E1}} \approx I_C$$

$$V_{CE} \approx V_{CC} + V_{EE} - (R_C + R_{E1})I_C$$

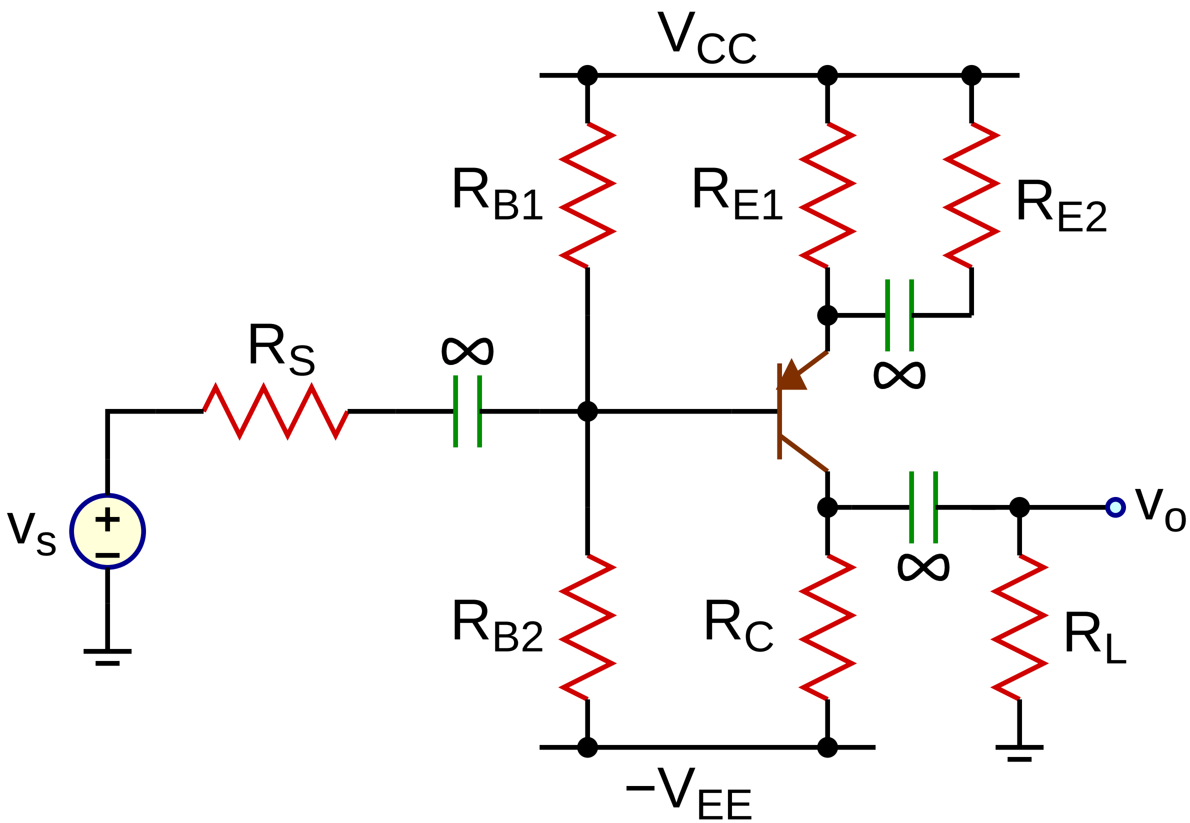
$$V_{CE} \geq V_{CE,sat} \;\Rightarrow\; \text{ACTIVE}$$

Example 1

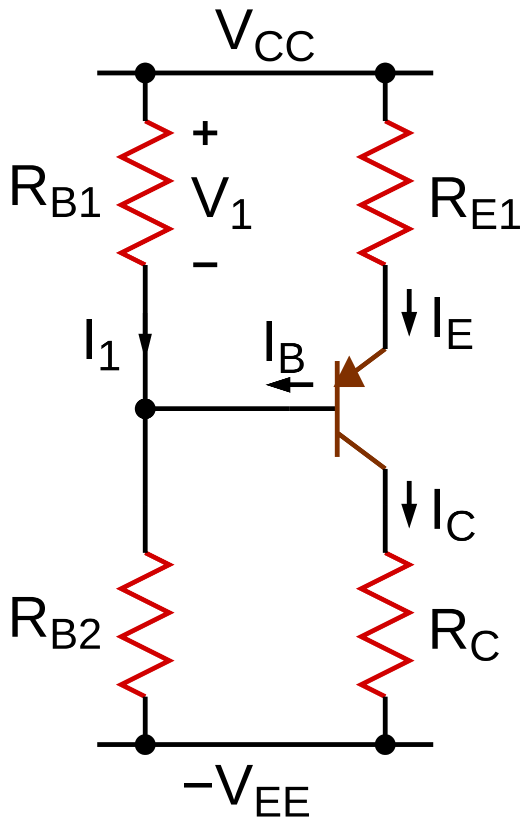


$$R_B = R_{B1} \| R_{B2}$$
$$R_E = R_{E1} \| R_{E2}$$

Example 2



Example 2



$I_1 \gg I_B \Rightarrow$

$$V_1 \approx \frac{R_{B1}}{R_{B1}+R_{B2}}(V_{CC}+V_{EE})$$

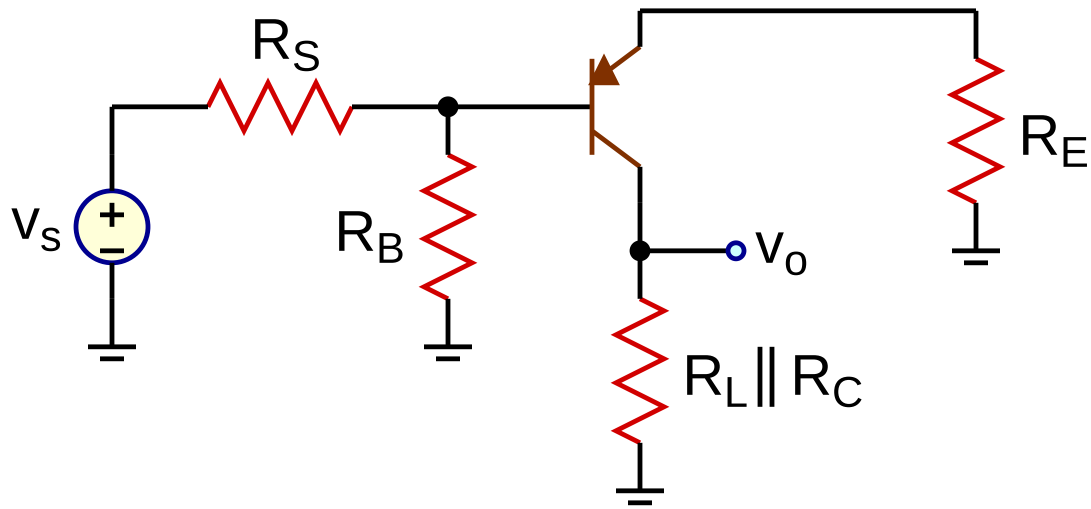
$$V_1 = I_E R_{E1} + 0.7$$

$$I_E = \frac{V_1 - 0.7}{R_{E1}} \approx I_C$$

$$V_{EC} \approx V_{CC} + V_{EE} - (R_C + R_{E1})I_C$$

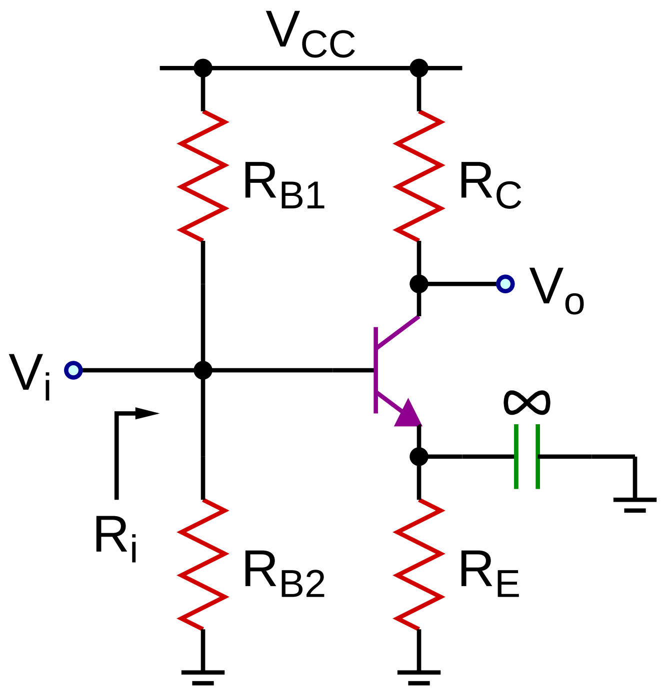
$$V_{EC} \geq V_{EC,sat} \Rightarrow \text{ ACTIVE}$$

Example 2

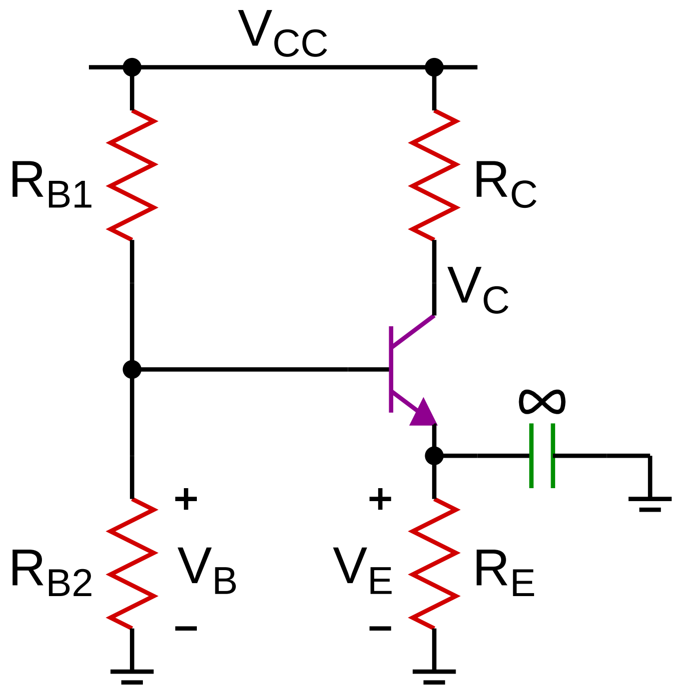


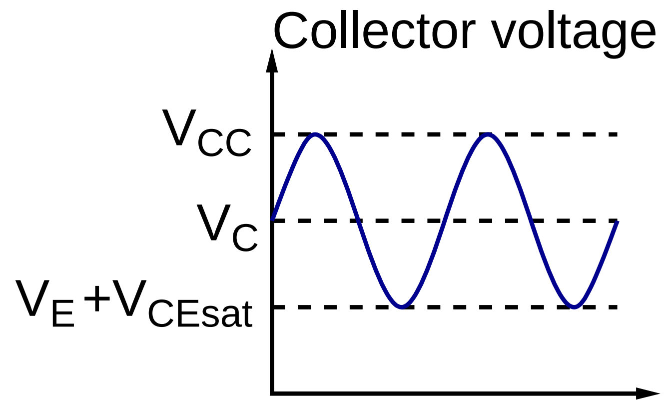
$$R_B = R_{B1} \parallel R_{B2}$$

$$R_E = R_{E1} \parallel R_{E2}$$

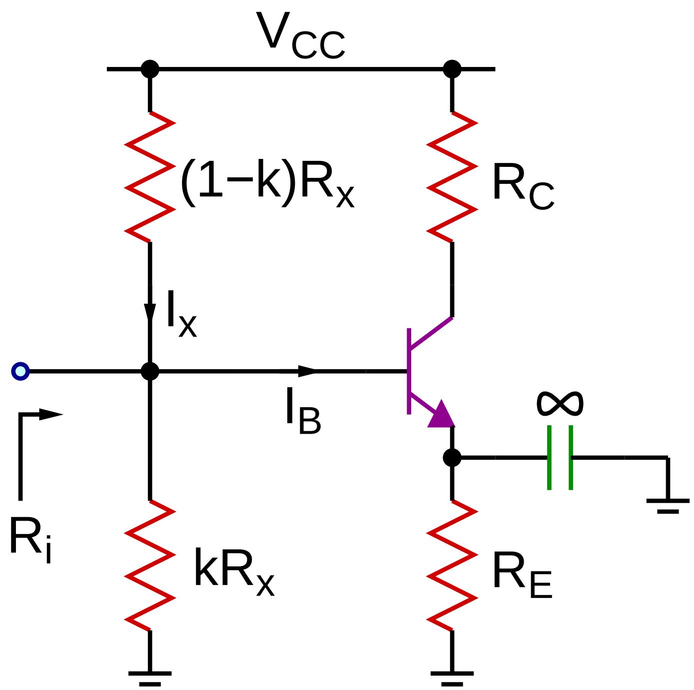


- Output voltage swing ($\mathbf{V_{0-p}}$)
- Input resistance ($\mathbf{R_i}$)
- Voltage gain ($|\mathbf{A_v}|$)
- Insensitive to:
  - $\mathbf{V_{BE}}$ variations
  - β variations





- For $\mathbf{V_{BE}}$-insensitivity, choose $\mathbf{V_E}$ as large as possible. *Example:* Assume $\mathbf{V_B}$ is set to **1.7V** to have $\mathbf{V_E = 1V}$. If $\mathbf{V_{BE}}$ varies $\pm\mathbf{0.1V}$, the resulting variation in $\mathbf{I_C}$ is $\mp\mathbf{10\%}$.
- For the $\mathbf{V_{0-p}}$ requirement, choose $\mathbf{V_E}$ and $\mathbf{V_C}$ to satisfy: $\mathbf{V_C - (V_E + V_{CEsat}) \geq V_{0-p}}$ and $\mathbf{V_{CC} - V_C \geq V_{0-p}}$



$$k = \frac{V_B}{V_{CC}}$$

$$R_{B1} = (1 - k)R_X$$

$$R_{B2} = kR_X$$

- For β-insensitivity, $I_B \ll I_X$.

$$I_B \ll I_X \Rightarrow \frac{I_C}{\beta} \ll \frac{V_{CC}}{R_X} \Rightarrow I_C \ll \frac{\beta V_{CC}}{R_X}$$

$$\Rightarrow I_C = \frac{\beta V_{CC}}{N R_X}, \quad R_X = \frac{\beta V_{CC}}{N I_C}, \quad N \geq 10$$

Amplifier Design

$$R_i = kR_X \parallel (1-k)R_X \parallel \beta r_e = [k(1-k)R_X] \parallel \left[\beta \frac{V_T}{I_C}\right]$$
$$= \left[k(1-k)\frac{\beta V_{CC}}{NI_C}\right] \parallel \left[\beta \frac{V_T}{I_C}\right]$$

$$R_i = \frac{\beta}{\dfrac{1}{V_T} + \dfrac{N}{k(1-k)V_{CC}}} \frac{1}{I_C} \quad \rightarrow \text{ Find } I_C$$

$$R_X = \frac{\beta V_{CC}}{NI_C}, \quad R_C = \frac{V_{CC} - V_C}{I_C}, \quad R_E = \frac{V_E}{I_C}$$

$$|A_v| = \frac{R_C}{r_e} = \frac{(V_{CC} - V_C)/I_C}{V_T/I_C} = \frac{V_{CC} - V_C}{V_T}$$