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Sesión 15
Configuraciones del transistor como dispositivo amplificador.

Componentes y Circuitos Electrónicos

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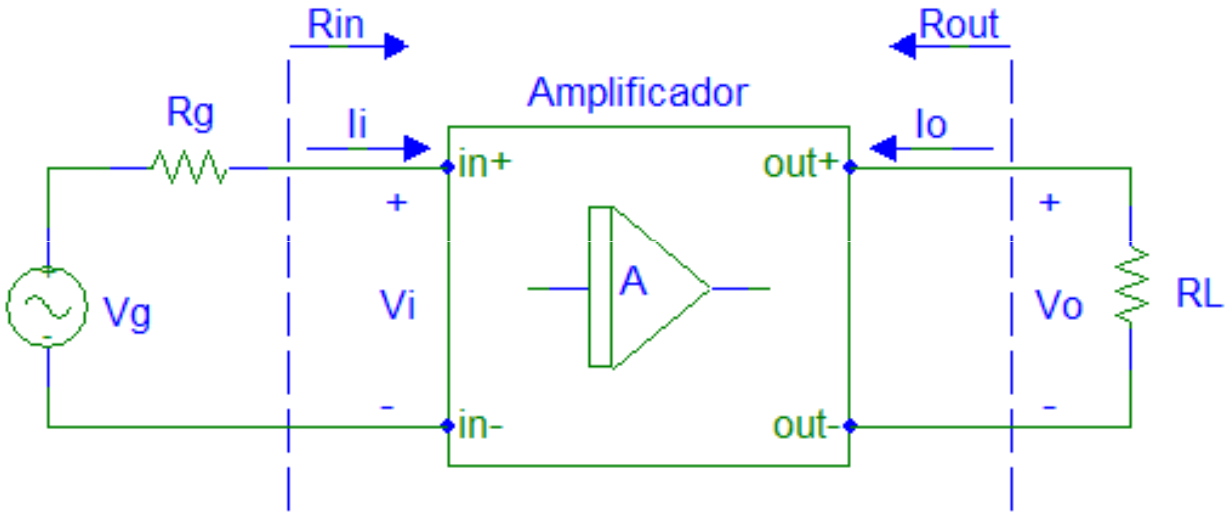
Configuraciones del Transistor como Dispositivo Amplificador

OBJETIVOS

- Entender el procedimiento de análisis de los parámetros característicos de amplificadores.
- Analizar los circuitos de pequeña señal correspondientes a amplificadores BJT de una etapa:
  - Emisor común.
  - Emisor común con resistencia de emisor.
  - Colector común.
  - Base común.
- Comparar las características de estas configuraciones.

Parámetros característicos de amplificadores



- Ganancia de Tensión, Av y Gv

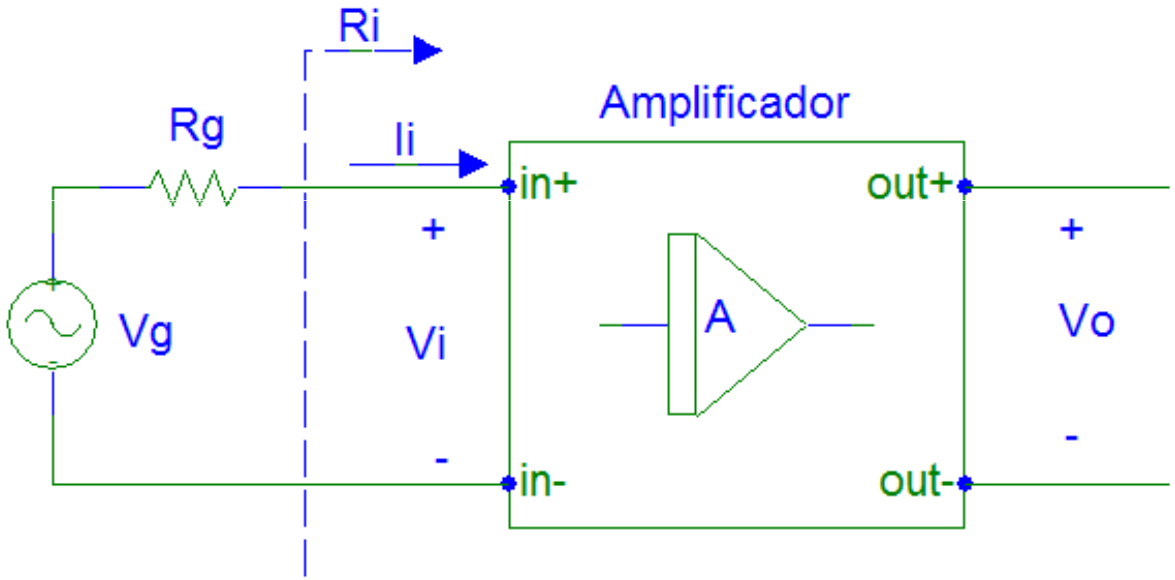
$$A_v = \frac{V_o}{V_i} \qquad G_v = \frac{V_o}{V_g} \qquad A_i = \frac{i_o}{i_i}$$

- Ganancia de corriente, Ai
- Resistencia de entrada, Rin

$$R_{in} = \frac{V_i}{i_i} \qquad R_{out} = \frac{V_o}{i_o}$$

- Resistencia de salida, Rout

Parámetros característicos en circuito abierto



$R_L \to \infty$

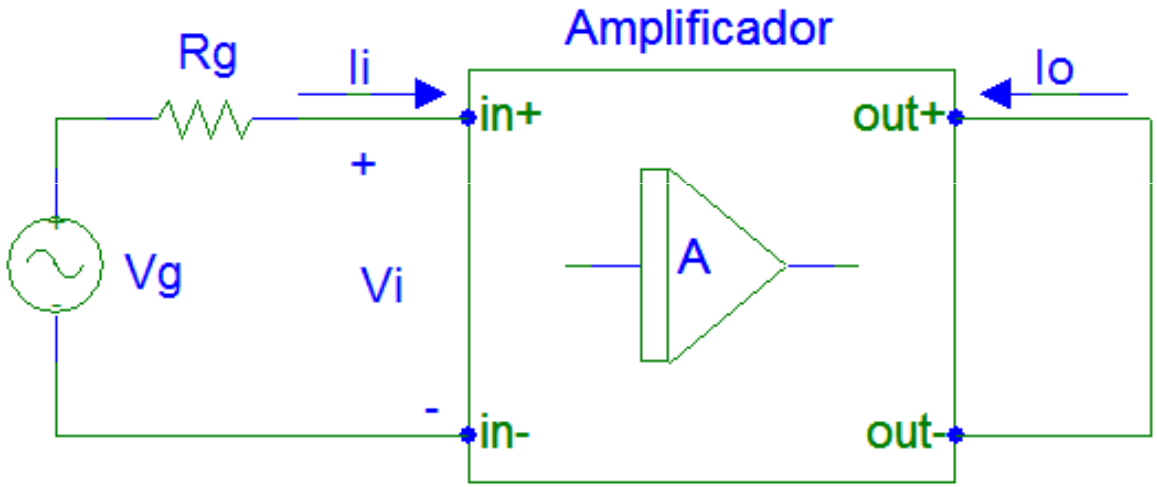
- Ganancia de Tensión sin carga, Avo

$$A_{vo} = \left.\frac{V_o}{V_i}\right|_{R_L \to \infty}$$

- Resistencia de entrada sin carga, Ri

$$R_i = \left.\frac{V_i}{i_i}\right|_{R_L \to \infty}$$

Parámetros característicos en cortocircuito



$$R_L = 0$$

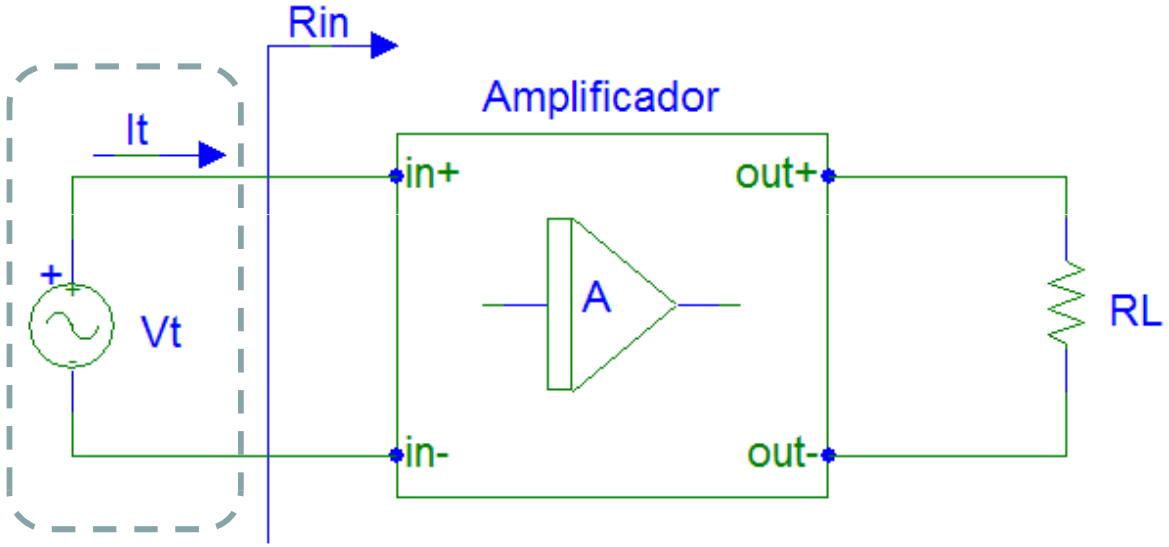
- Ganancia de Corriente de cortocircuito, $A_{i(sc)}$

$$A_{i(sc)} = \left.\frac{i_o}{i_i}\right|_{R_L=0}$$

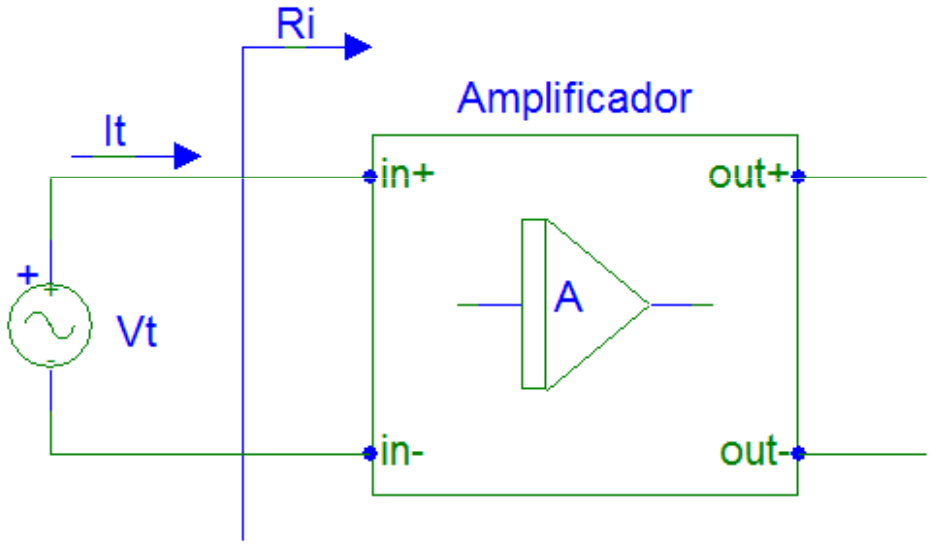
- Transconductancia de cortocircuito, Gm

$$G_m = \left.\frac{i_o}{V_i}\right|_{R_L=0}$$

Cálculo de Impedancias de entrada

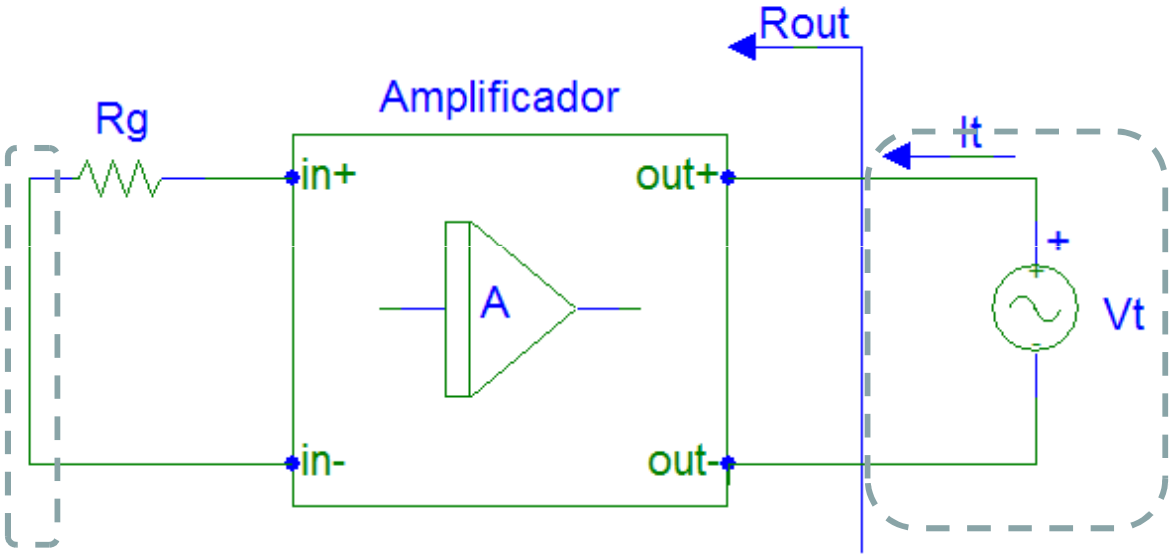


$$R_{in} = \frac{V_t}{i_t}$$

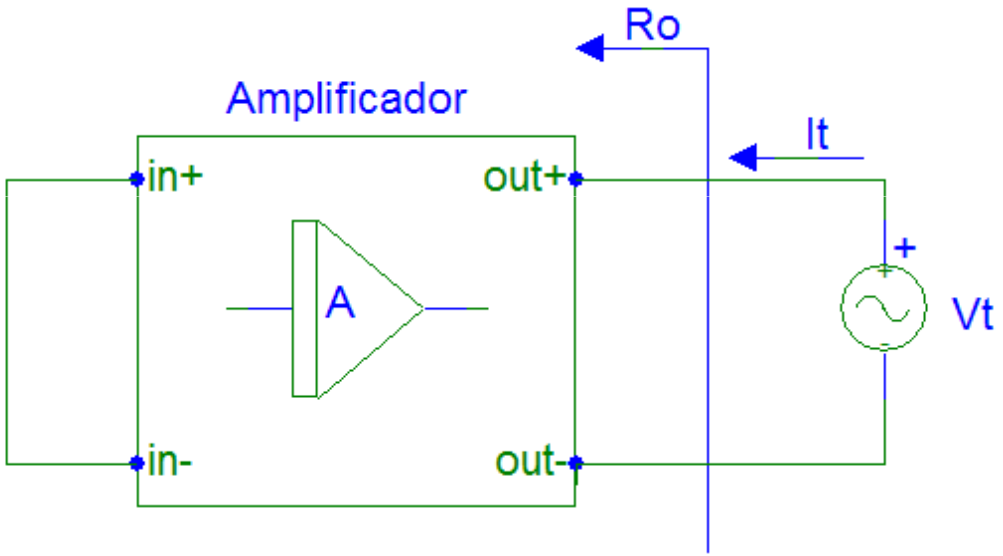


$$R_i = \left.\frac{V_t}{i_t}\right|_{R_L \to \infty}$$

Cálculo de Impedancias de salida

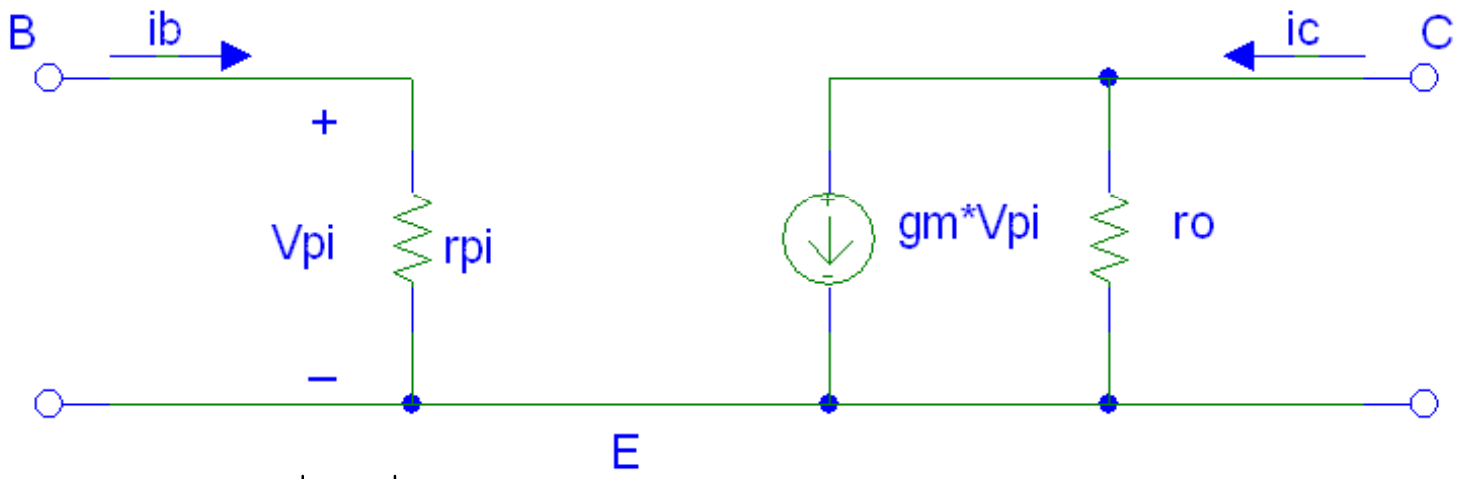


$$R_{out} = \left.\frac{V_t}{i_t}\right|_{V_g=0}$$



$$R_o = \left.\frac{V_t}{i_t}\right|_{V_i=0}$$

Equivalente de pequeña señal



$$g_m = \frac{|I_{CQ}|}{V_T}(\Omega^{-1})$$

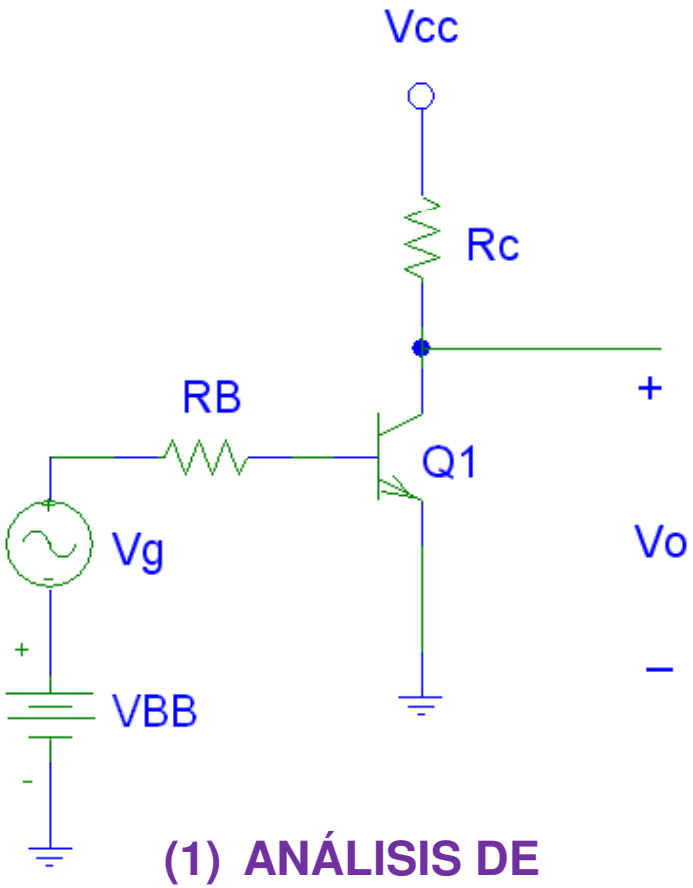
$$V_T\big|_{T_{amb}=300^\circ K} \approx 25mV$$

$$r_\pi = \frac{\beta_o}{g_m} = \frac{\beta_o \cdot V_T}{|I_{CQ}|}(\Omega)$$

$$\beta_o = g_m \cdot r_\pi$$

$$r_0 = \frac{V_A}{|I_{CQ}|}(\Omega)$$

Ejemplo de pequeña señal



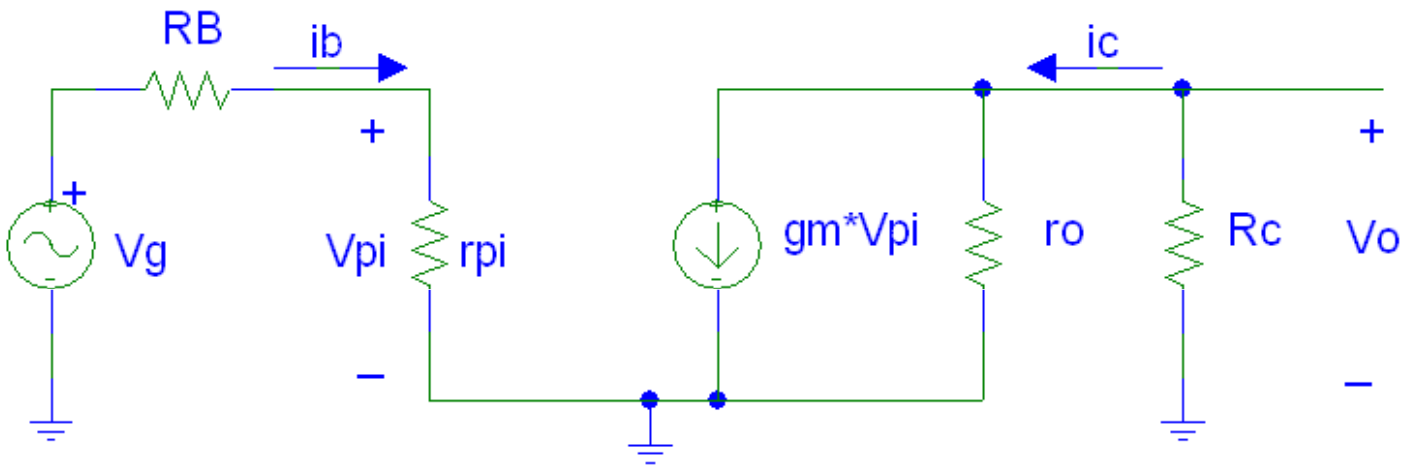
- RC = 3 kΩ
- RB = 15 kΩ
- VCC = 18 V
- VBB = 1,2 V
- Vg = 0,2 V (pico)
- $V_{BE\text{-}on}$ = 0,6 V
- β_F = 100

(1) ANÁLISIS DE POLARIZACIÓN

$$V_g = 0V$$

$$V_{BE_Q} \approx 0{,}6V$$
$$I_{B_Q} \approx 40\mu A$$
$$I_{C_Q} \approx 4mA$$
$$V_{CE_Q} \approx 6V$$

Ejemplo de pequeña señal



- βo = 100
- VA = 100 V

(2) PARÁMETROS DE PEQUEÑA SEÑAL

$$g_m = \frac{4mA}{25mV} = 160mA/V$$

$$r_\pi = \frac{100 \cdot 25mV}{4mA} = 625\Omega$$

$$r_0 = \frac{100V}{4mA} = 25k\Omega$$

(3) ANÁLISIS DE PEQUEÑA SEÑAL

$$\begin{cases} V_{BB} = 0V \\ V_{CC} = 0V \end{cases}$$

$$\begin{cases} V_0 = -g_m V_\pi (r_0 \,//\, R_C) \\ V_\pi = V_g \dfrac{r_\pi}{R_B + r_\pi} \end{cases}$$

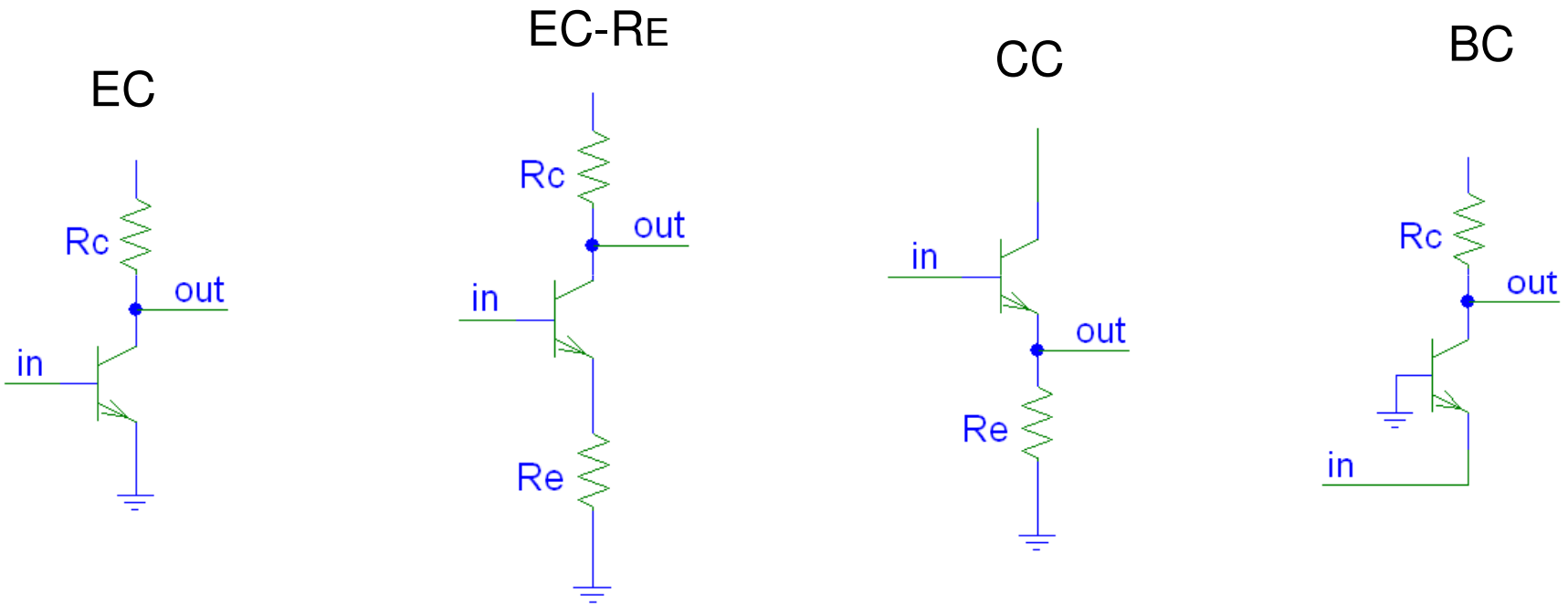
$$\frac{V_0}{V_g} = -g_m (r_0 \,//\, R_C) \frac{r_\pi}{R_B + r_\pi} \approx -17 \, {}^{V}\!/_{V}$$

$$\frac{V_0}{V_\pi} = -g_m (r_0 \,//\, R_C) \approx -428 \, {}^{V}\!/_{V}$$

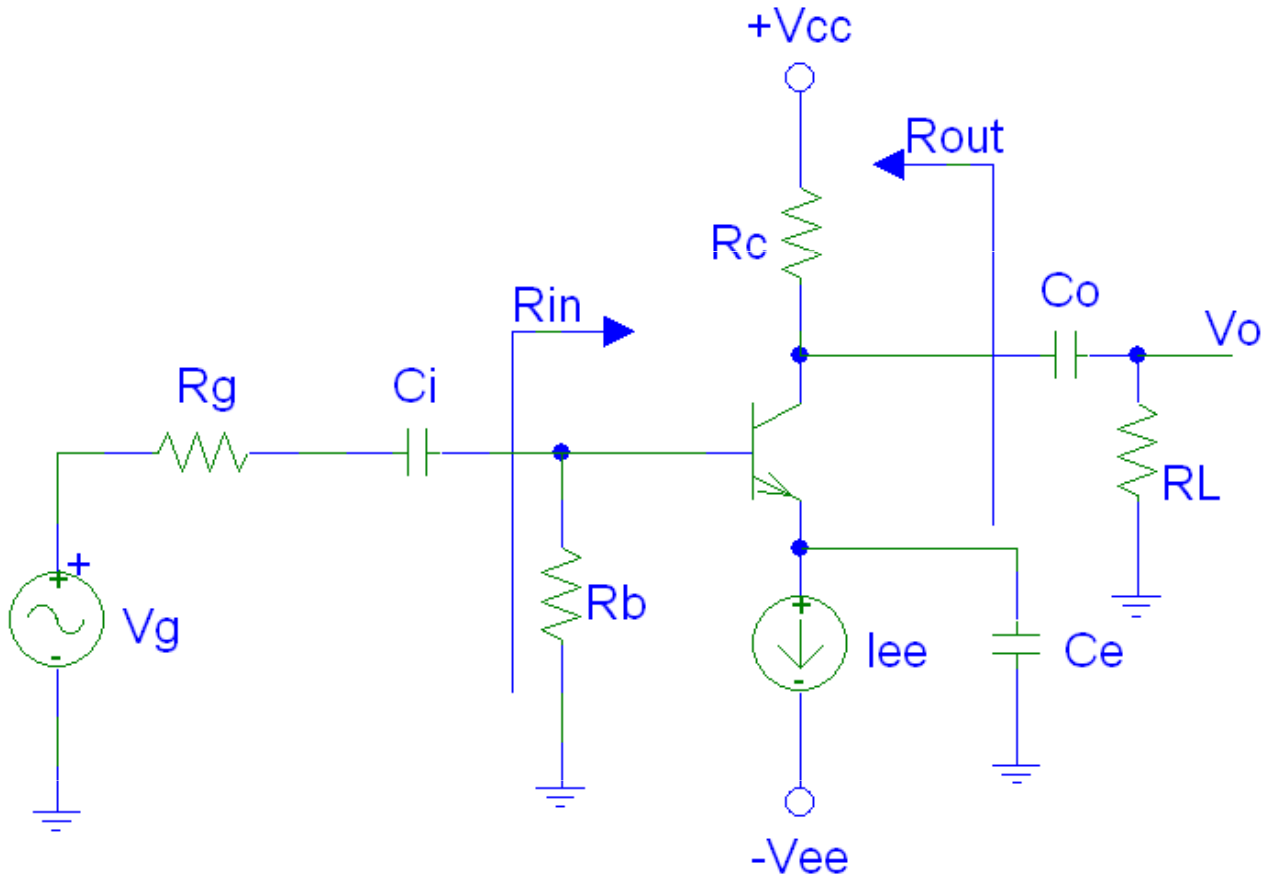
$$\frac{i_c}{i_b} = \beta_o = 100 \, {}^{A}\!/_{A}$$

Amplificadores de una etapa

- Amplificador en emisor común (EC)
- Amplificador en emisor común con R_E y degeneración de emisor
- Amplificador en colector común (CC) o seguidor de emisor
- Amplificador en base común (BC)



Amplificador en emisor común (EC)



(1) ANÁLISIS DE POLARIZACIÓN

$C_i, C_o, C_e \rightarrow \infty$ (Circuito Abierto)

$I_E = I_{ee}$

$I_{CQ} \approx I_{ee}$

EJEMPLO

- βo = 100
- V_A = 100 V
- Rb = 100 kΩ
- Rc = 8 kΩ
- R_L = 100 kΩ
- Vcc = Vee = 10V
- Iee = 1mA

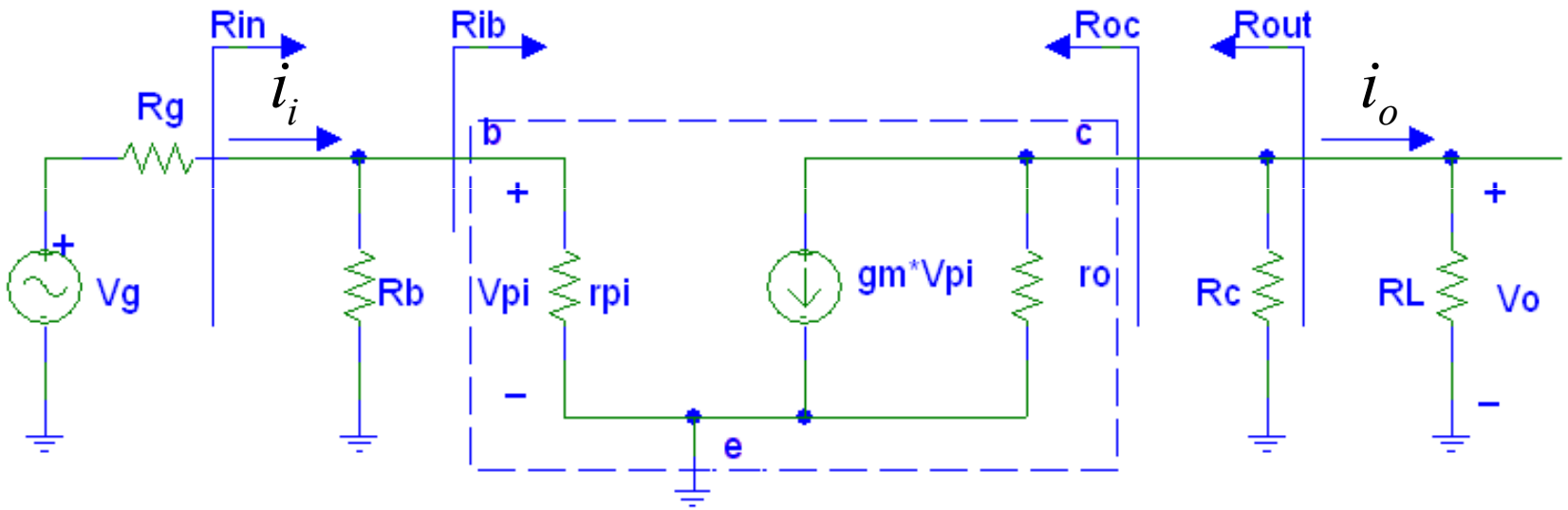
$$I_{CQ} \approx 1mA$$

$$g_m = 40mA/V$$

$$r_\pi = 2{,}5k\Omega$$

$$r_0 = 100k\Omega$$

Emisor Común (Impedancias)

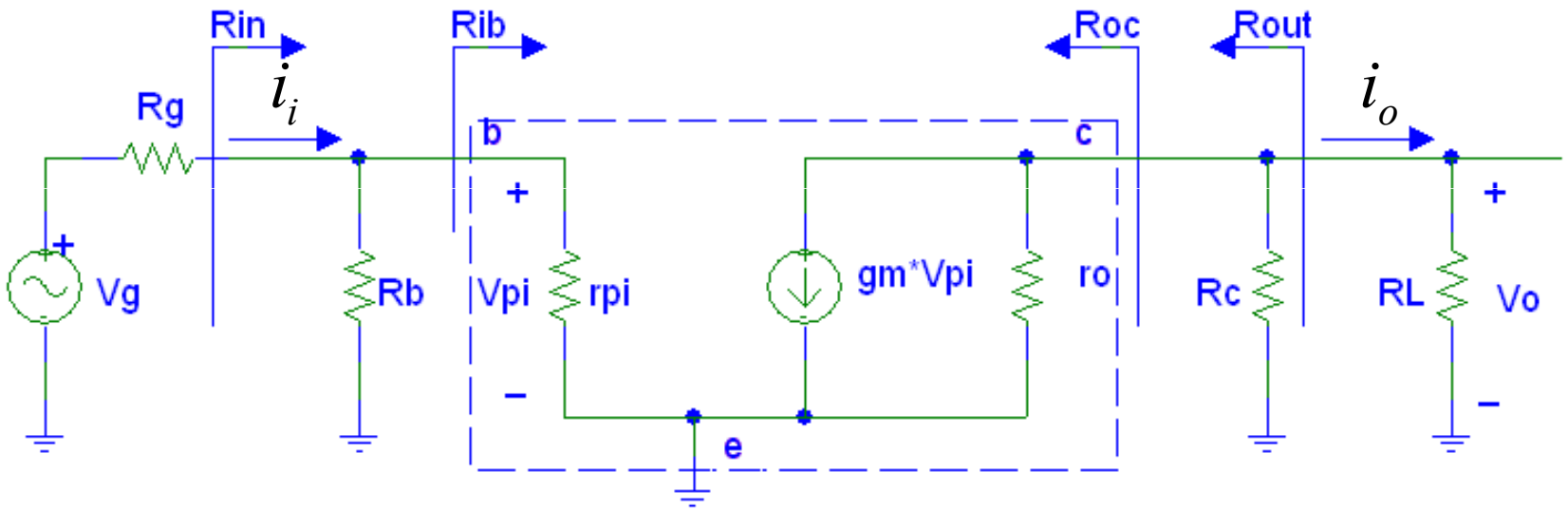


(2) ANÁLISIS DE PEQUEÑA SEÑAL

$$R_{ib} = r_\pi \qquad R_{in} = R_b \,//\, r_\pi \qquad R_{in}\big|_{R_b >> r_\pi} \approx r_\pi$$

$$R_{oc} = r_o \qquad R_{out} = R_c \,//\, r_o \qquad R_{out}\big|_{r_o >> R_c} \approx R_c$$

Emisor Común (Pequeña señal)

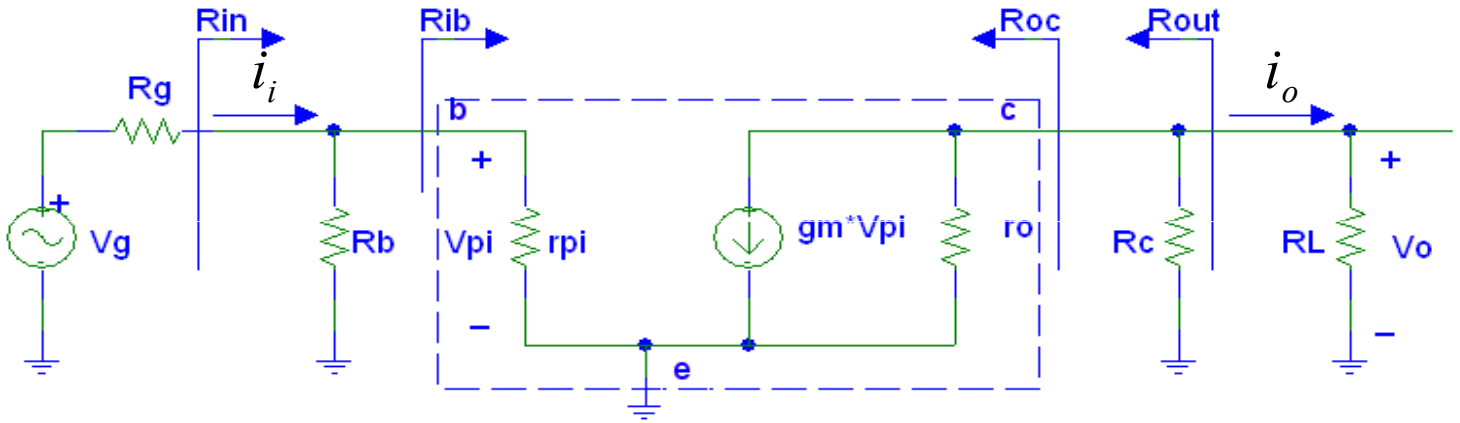


(2) ANÁLISIS DE PEQUEÑA SEÑAL

$$i_i = \frac{V_g}{R_g + R_{in}} \qquad V_\pi = V_g \frac{R_{in}}{R_g + R_{in}}$$

$$i_o = -g_m V_\pi \frac{R_{out}}{R_L + R_{out}} \qquad V_o = -g_m V_\pi (r_o \,//\, R_c \,//\, R_L)$$

Emisor Común (Ganancia)



$$A_v = \frac{V_o}{V_\pi} = -g_m (r_o \,//\, R_c \,//\, R_L)$$

$$G_v = \frac{V_o}{V_g} = -g_m (r_o \,//\, R_c \,//\, R_L) \frac{R_{in}}{R_g + R_{in}}$$

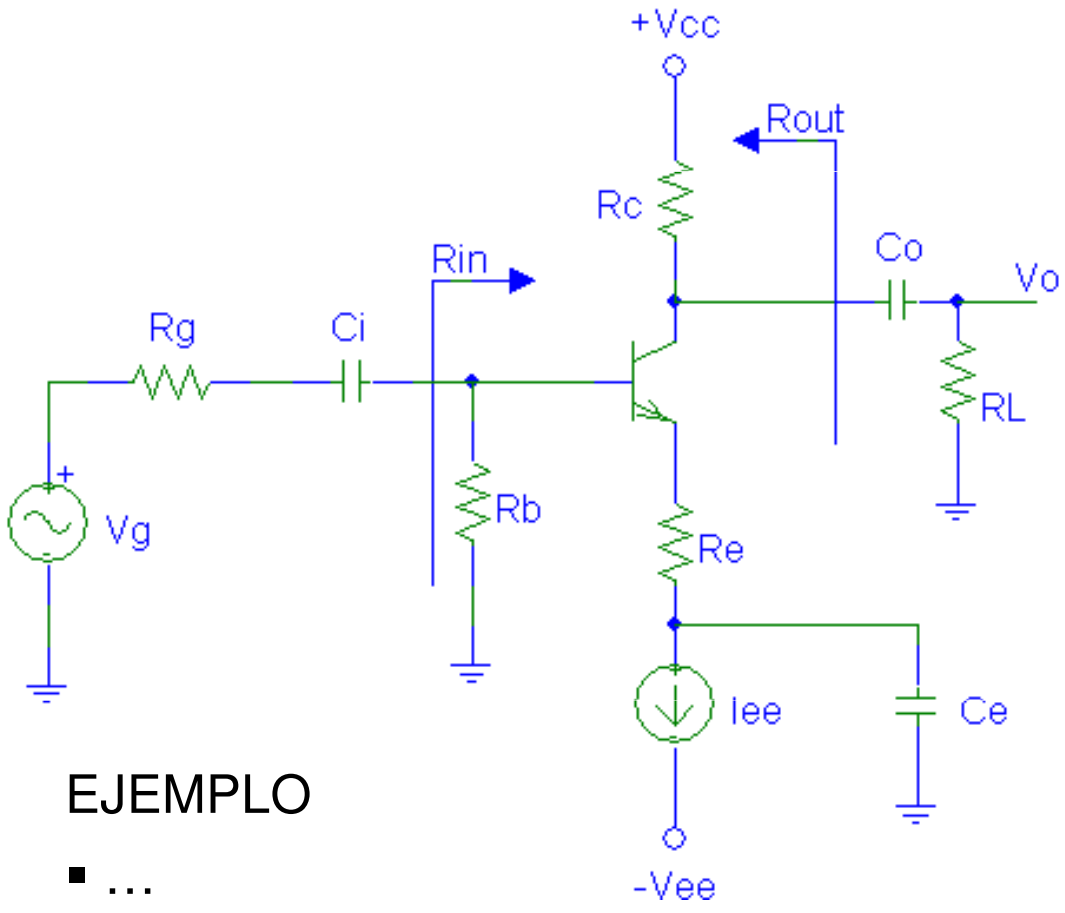
$$A_i = \frac{i_o}{i_i} = -g_m \frac{R_{out}}{R_L + R_{out}} R_{in}$$

$$A_{vo}\Big|_{r_o >> R_c} \approx -g_m R_c$$

$$G_v\Big|_{R_b >> r_\pi} \approx -\frac{\beta_o}{R_g + r_\pi} (r_o \,//\, R_c \,//\, R_L)$$

$$A_{i(sc)}\Big|_{R_b >> r_\pi} = -\beta_o$$

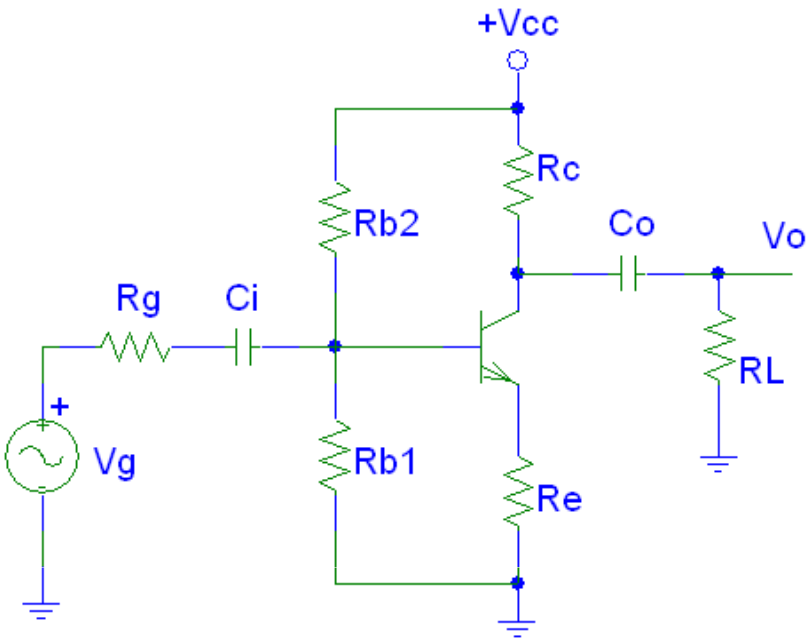
Amplificador en emisor común con RE



EJEMPLO

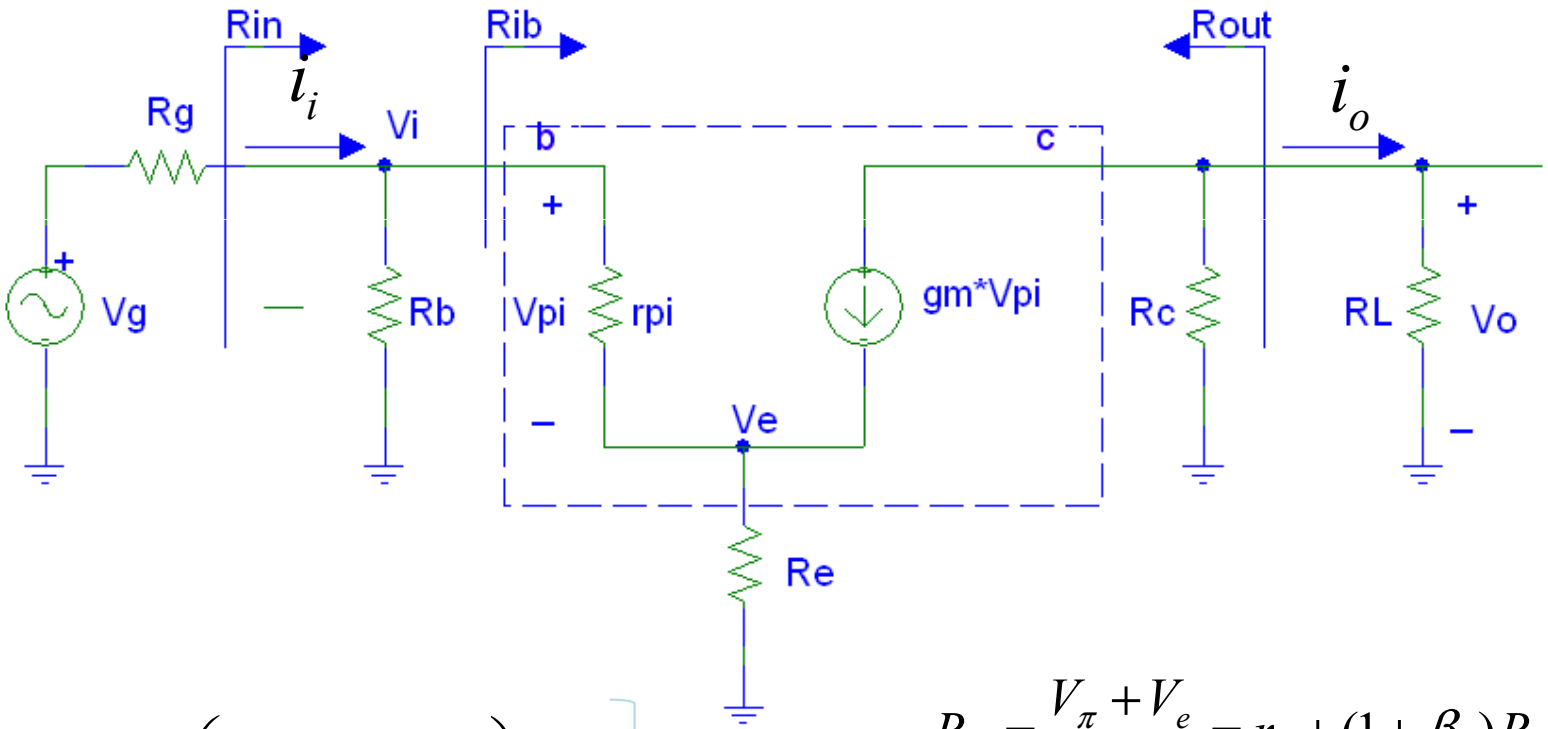
- …
- Re = 1 kΩ

$$I_{CQ} \approx 1mA$$



$$R_b = R_{b1} // R_{b2}$$

Emisor Común con RE (Impedancia)



$$V_e = \left(\frac{V_\pi}{r_\pi} + g_m V_\pi \right) \cdot R_e$$

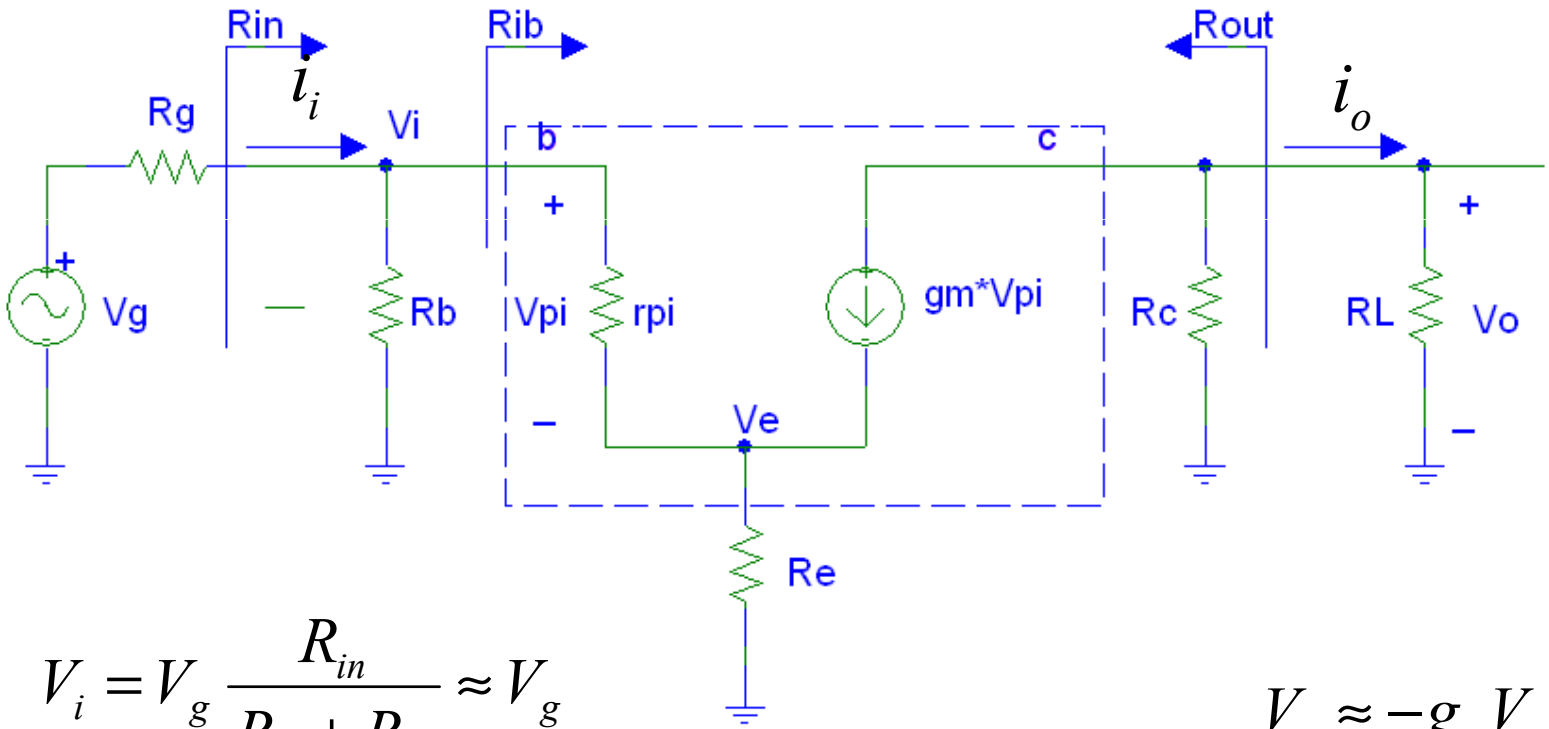
$$V_i = V_\pi + V_e$$

$$R_{ib} = \frac{V_\pi + V_e}{V_\pi / r_\pi} = r_\pi + (1+\beta_o) R_e$$

$$R_{in} = R_b \,//\, [r_\pi + (1+\beta_o) R_e]$$

$$R_{out}\big|_{r_o >> R_c} \approx R_c$$

Emisor Común con RE (Peq. señal)



$$V_i = V_g \frac{R_{in}}{R_g + R_{in}} \approx V_g$$

$$V_e = \left(\frac{V_\pi}{r_\pi} + g_m V_\pi \right) \cdot R_e$$

$$V_i = V_\pi + V_e$$

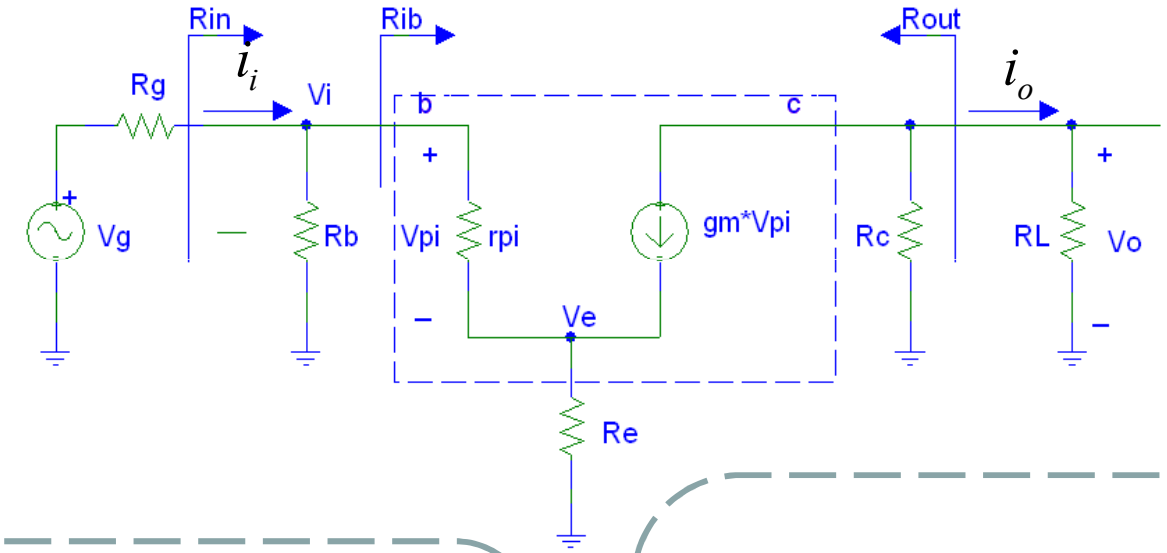
$$\frac{V_\pi}{V_i} \approx \frac{1}{1 + g_m R_e}$$

$$V_o \approx -g_m V_\pi (R_c \,//\, R_L)$$

$$i_i = \frac{V_g}{R_g + R_{in}}$$

$$i_o = -g_m V_\pi \frac{R_{out}}{R_L + R_{out}}$$

Emisor Común con RE (Ganancia)



$$A_v = \frac{V_o}{V_i} = -\frac{\beta_o (R_c \,//\, R_L)}{r_\pi + (1+\beta_o)\cdot R_e}$$

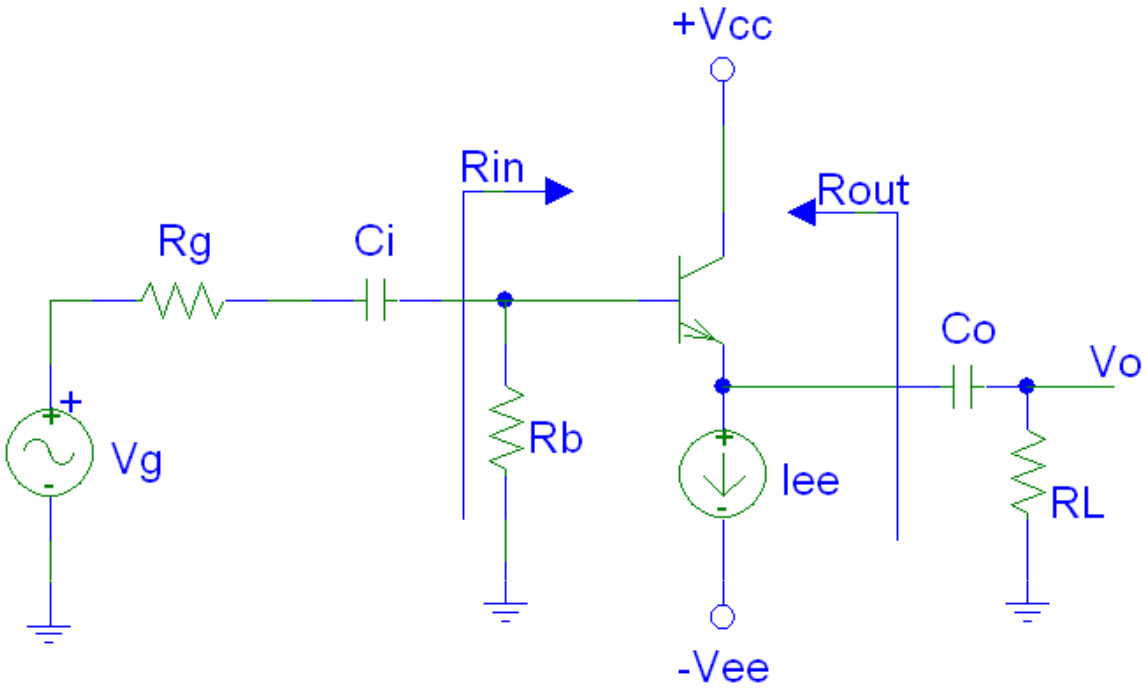
$$A_i = \frac{i_o}{i_i} = -\beta_o \frac{R_c}{R_L + R_c} \frac{R_b + R_{ib}}{R_b}$$

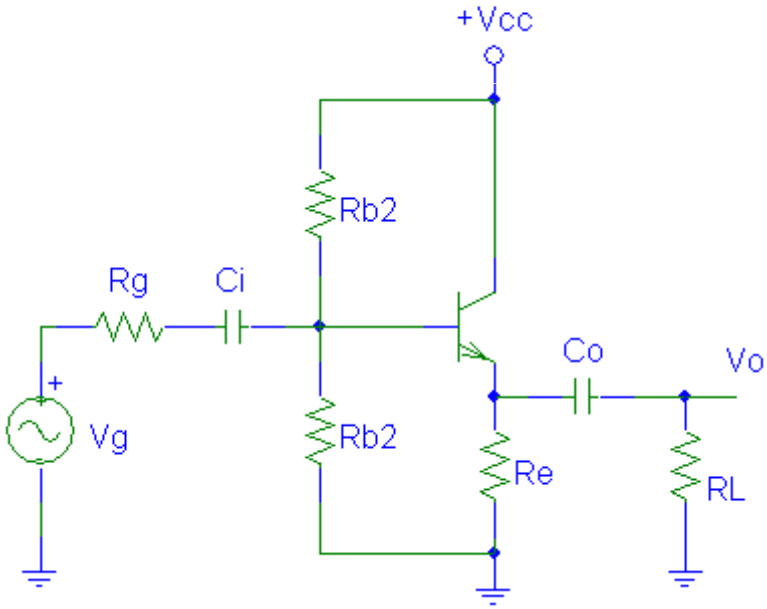
$$G_v\Big|_{r_\pi << \beta_o R_e}^{R_g << R_{in}} \approx -\frac{(R_c \,//\, R_L)}{R_e} \approx -\frac{R_c}{R_e} \cdot \frac{R_L}{R_c + R_L}$$

$$A_{vo} = -\frac{\beta_o R_c}{r_\pi + (1+\beta_o) R_e} \approx -\frac{g_m R_c}{1 + g_m R_e}$$

$$A_{i(sc)}\Big|_{R_b >> R_{ib}}^{Rg << R_{in}} \approx -\beta_o$$

Amplificador en colector común (CC)





EJEMPLO

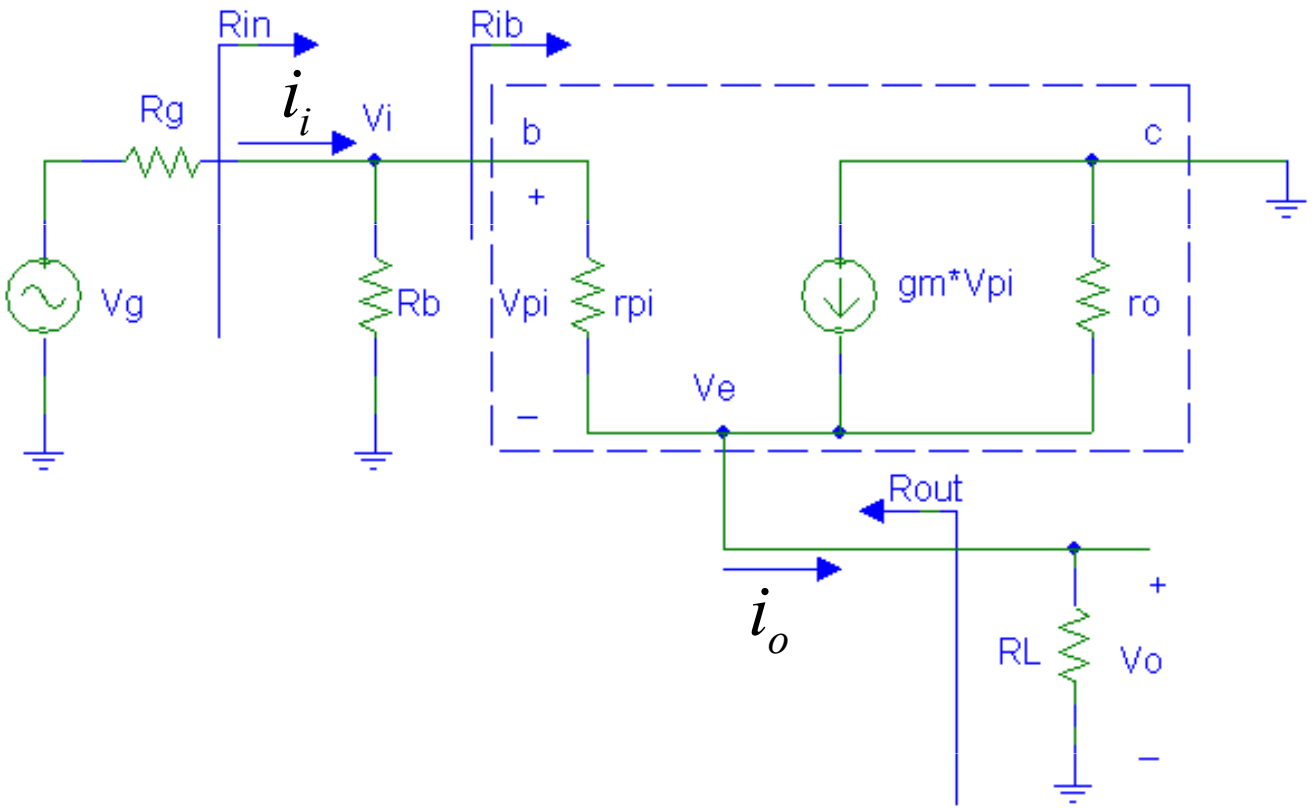
- …

$$I_{CQ} \approx 1mA$$

$$R_b = R_{b1} // R_{b2}$$

$$R_{EMISOR} = R_e // R_L$$

Colector Común (Impedancias)

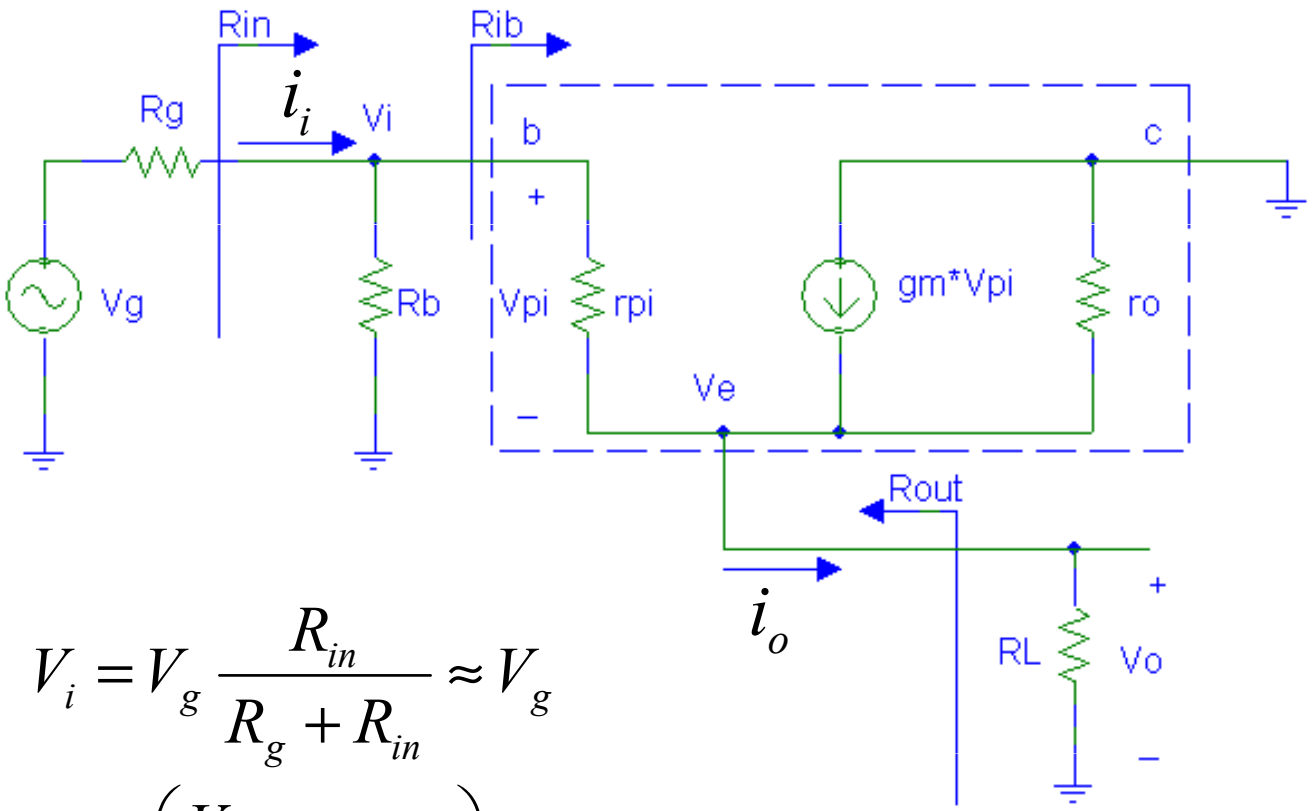


$$R_{EM} = r_o \,//\, R_L$$

$$R_{out} = r_o \,//\, \frac{r_\pi + (R_b \,//\, R_g)}{1+\beta_o} \approx \frac{r_\pi + (R_b \,//\, R_g)}{1+\beta_o}$$

$$R_{ib} = \frac{V_\pi + V_e}{V_\pi / r_\pi} = r_\pi + (1+\beta_o)\cdot R_{EM}$$

Colector Común (Pequeña señal)



$$R_{EM} = r_o \,//\, R_L$$

$$V_i = V_g \frac{R_{in}}{R_g + R_{in}} \approx V_g$$

$$V_e = \left(\frac{V_\pi}{r_\pi} + g_m V_\pi \right) \cdot R_{EM}$$

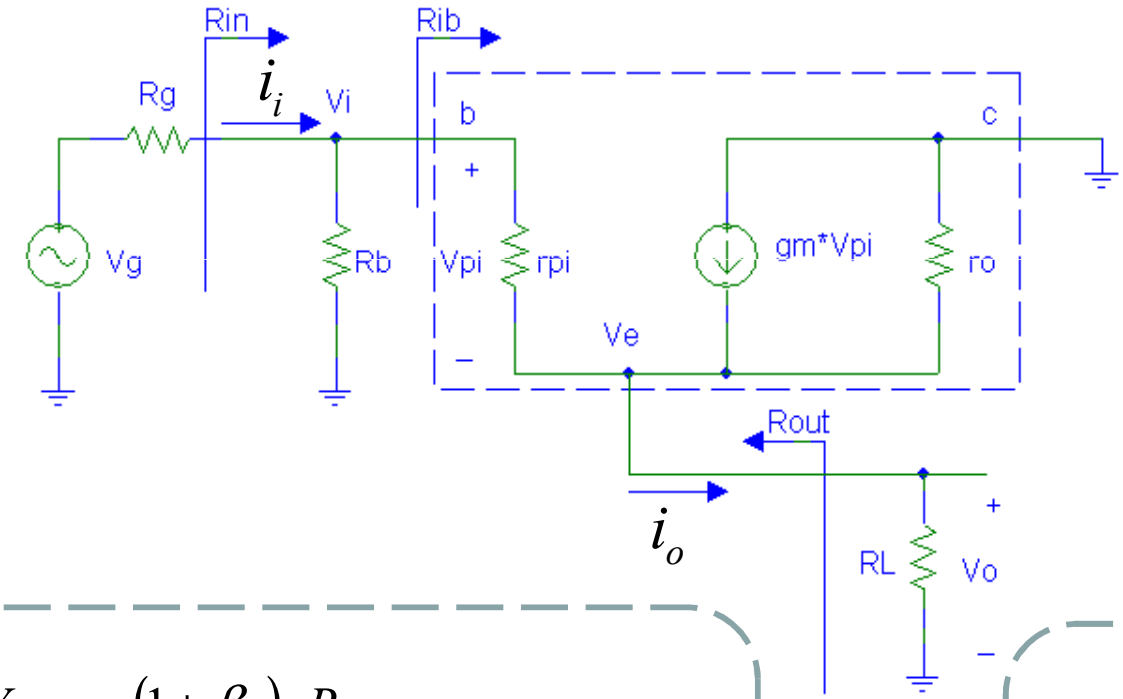
$$V_i = V_\pi + V_e$$

$$V_o = V_e$$

$$i_i = \frac{V_g}{R_g + R_{in}}$$

$$i_o = \left(\frac{V_\pi}{r_\pi} + g_m V_\pi \right) \left(\frac{r_o}{r_o + R_L} \right)$$

Colector Común (Ganancia)



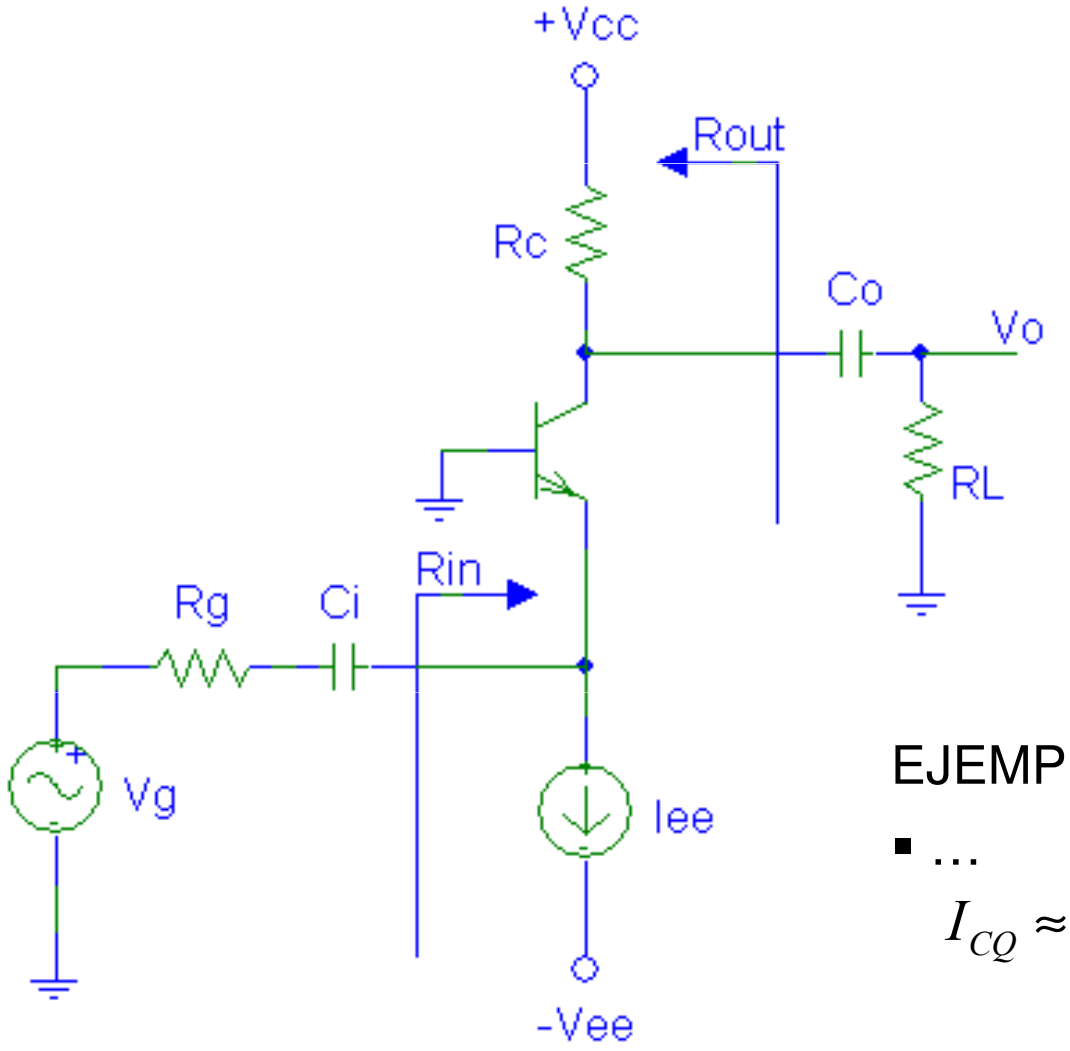
$$A_v = \frac{V_o}{V_i} = \frac{(1+\beta_o)\cdot R_{EM}}{r_\pi + (1+\beta_o)\cdot R_{EM}}$$

$$A_i = \frac{i_o}{i_i} = (1+\beta_o)\frac{r_o}{r_o + R_L}\frac{R_b + R_{ib}}{R_b}$$

$$G_v = \frac{V_o}{V_g} \approx 1$$

$$A_{i(sc)}\Big|_{R_b >> R_{ib}}^{Rg << R_{in}} \approx 1 + \beta_o$$

Amplificador en base común (BC)

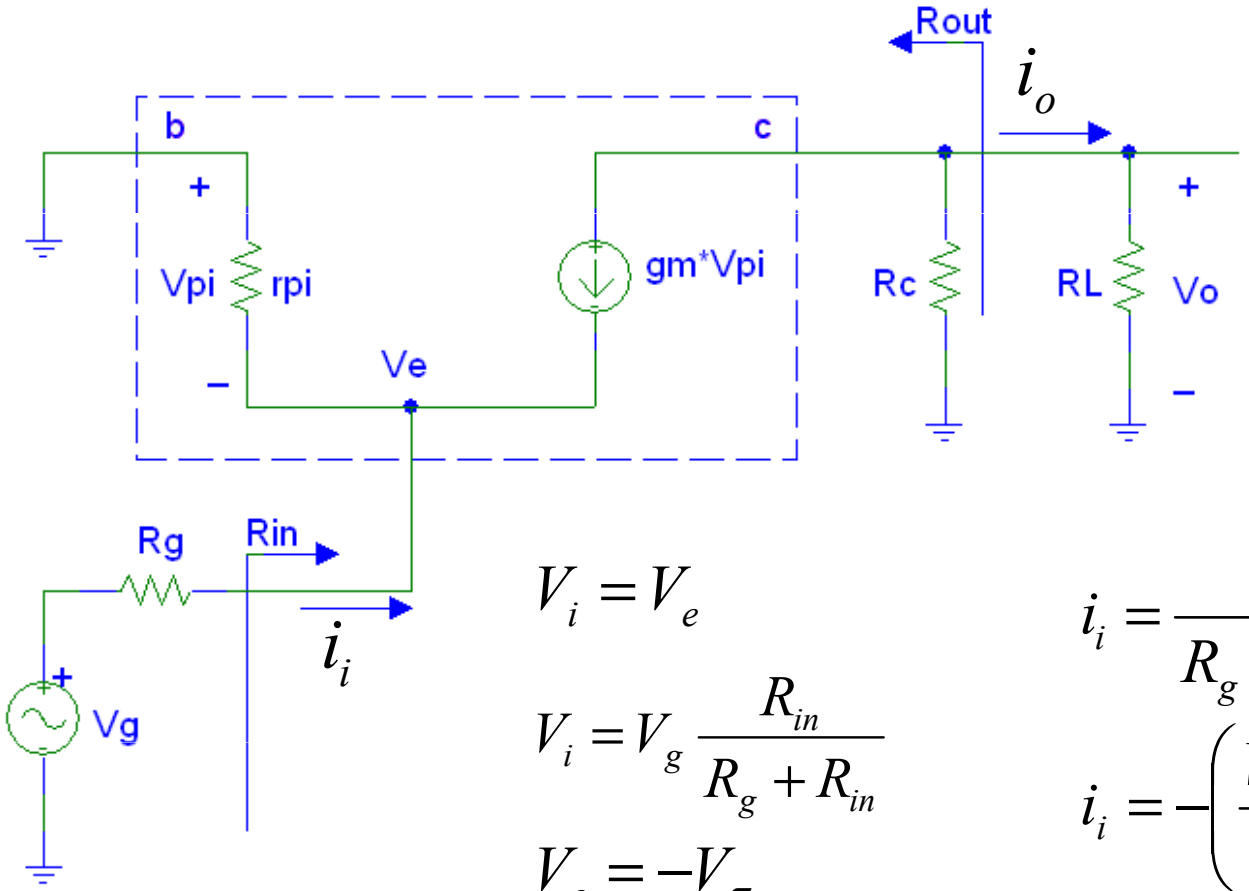


EJEMPLO

- …

$$I_{CQ} \approx 1mA$$

Base Común (Pequeña señal)



$$V_i = V_e$$

$$V_i = V_g \frac{R_{in}}{R_g + R_{in}}$$

$$V_e = -V_\pi$$

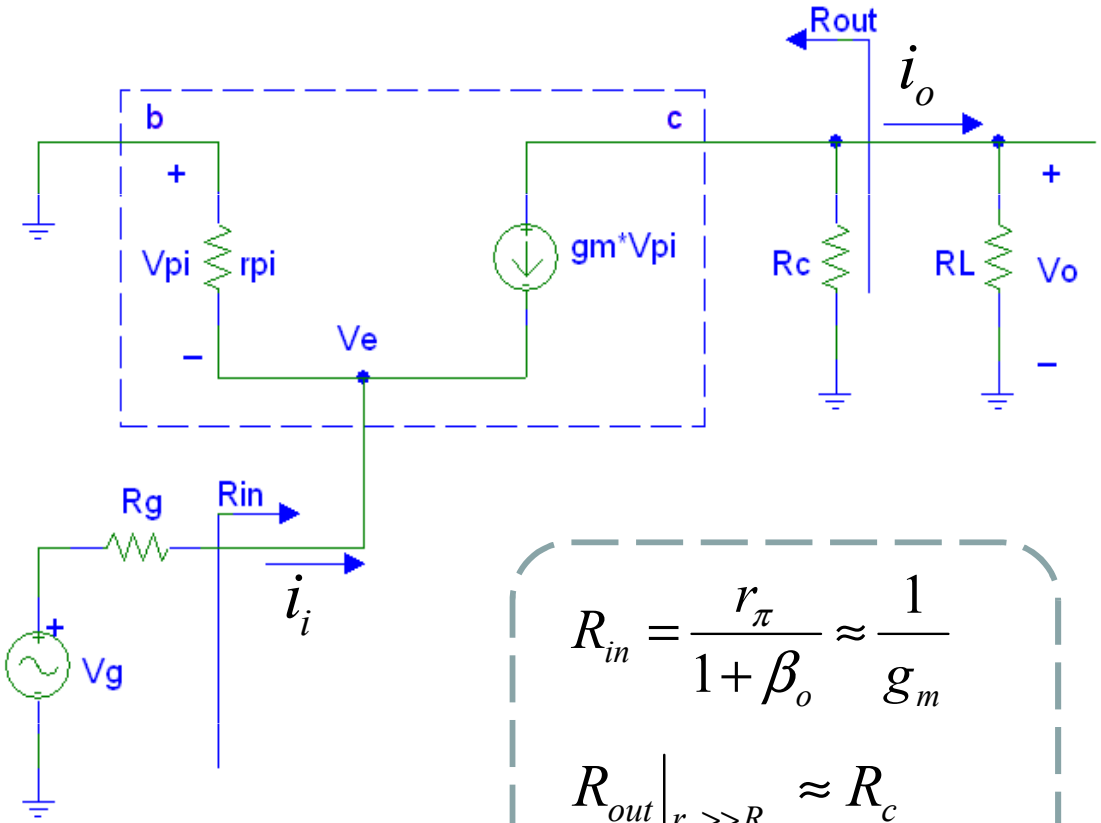
$$V_o \approx -g_m V_\pi (R_c // R_L)$$

$$i_i = \frac{V_g}{R_g + R_{in}}$$

$$i_i = -\left(\frac{V_\pi}{r_\pi} + g_m V_\pi \right)$$

$$i_o = -g_m V_\pi \frac{R_{out}}{R_L + R_{out}}$$

Base Común (Características)



$$A_v = \frac{V_o}{V_i} = +g_m (R_c \,//\, R_L)$$

$$R_{in} = \frac{r_\pi}{1+\beta_o} \approx \frac{1}{g_m}$$

$$R_{out}\big|_{r_o >> R_c} \approx R_c$$

$$A_{vo} = +g_m R_c$$

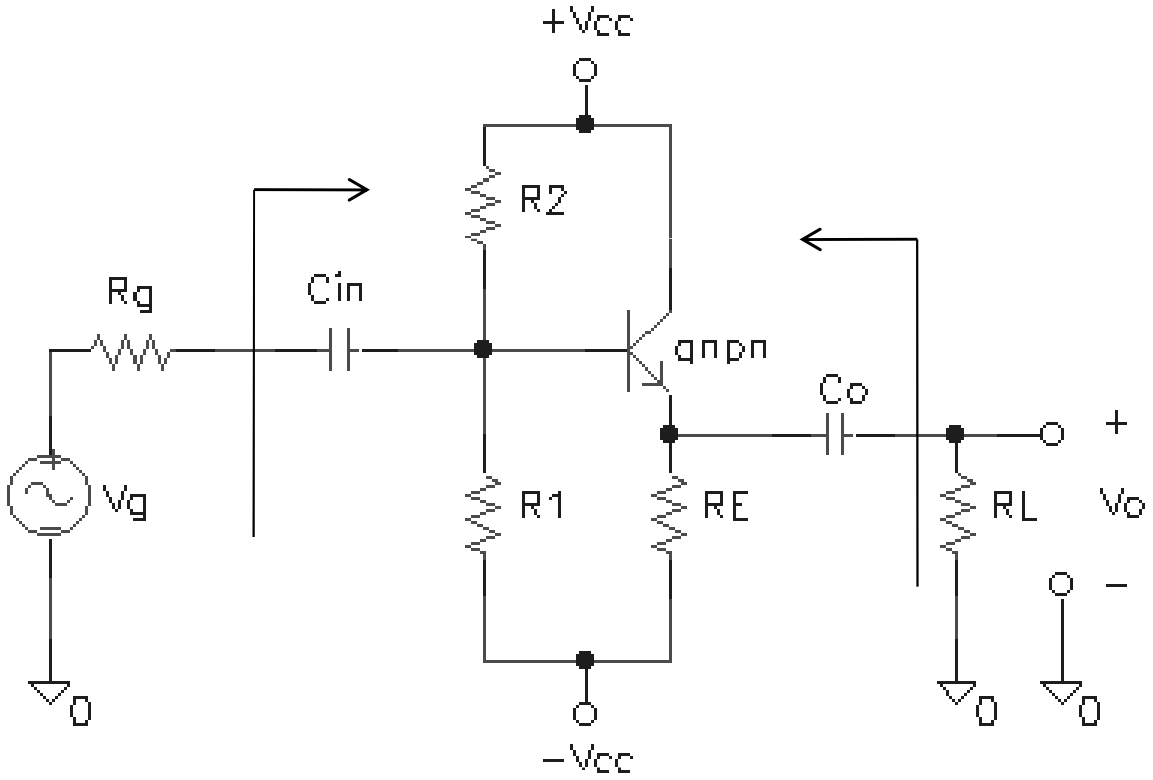
$$A_{i(sc)} = \alpha$$

Comparación

Etapa	Rin	Rout	Av	Ai(sc)
EC	$R_b // r_\pi \approx r_\pi$	$R_c // r_o$	✸ $-g_m(r_o // R_c // R_L)$	$-g_m R_{in} \approx -\beta_o$
EC-RE	✸ $R_b // [r_\pi + (1+\beta_o)R_e]$	R_c	✸ $-\dfrac{\beta_o(R_c // R_L)}{r_\pi + (1+\beta_o)\cdot R_e}$	$-\beta_o \dfrac{R_b + R_{ib}}{R_b} \approx -\beta_o$
CC	✸ $R_b // [r_\pi + (1+\beta_o)\cdot R_{EM}]$	✸ $\dfrac{r_\pi + (R_b // R_g)}{1+\beta_o}$	$\dfrac{(1+\beta_o)\cdot R_{EM}}{r_\pi + (1+\beta_o)\cdot R_{EM}} \approx 1$	$(1+\beta_o)\dfrac{R_b + R_{ib}}{R_b}$
BC	$\dfrac{r_\pi}{1+\beta_o} \approx \dfrac{1}{g_m}$ ✸	R_c	$+g_m(R_c // R_L)$	$\dfrac{\beta_o}{(1+\beta_o)} = \alpha$

$$G_v = A_v \frac{R_{in}}{R_g + R_{in}} \qquad G_v\Big|_{EC}^{máx} \approx -g_m r_o = -\frac{V_A}{V_T} \qquad G_v\Big|_{CC}^{máx} \approx 1$$

Ejemplo: Circuito práctico

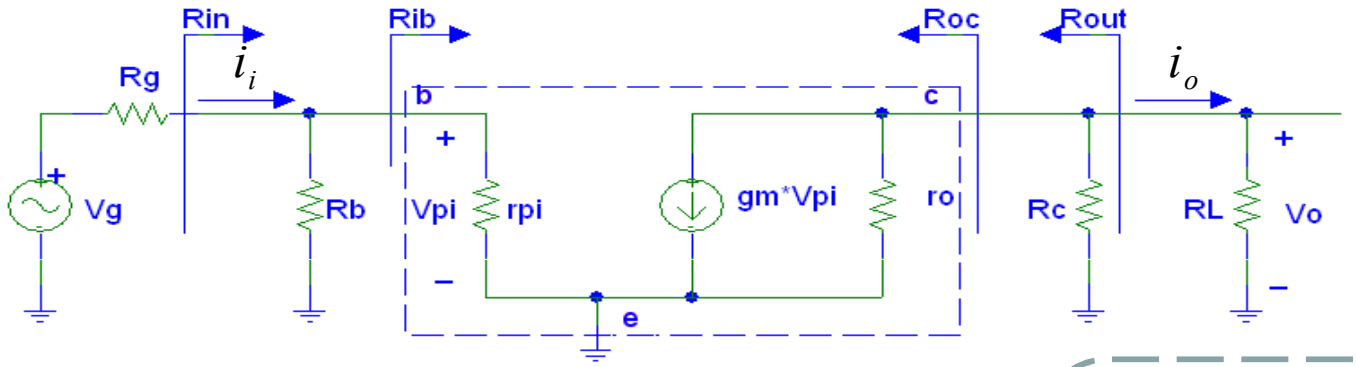


- Indicar qué tipo de amplificador es
- Calcular la ganancia Vo/Vg
- Calcular la impedancia de entrada
- Calcular la impedancia de salida

EJEMPLO

- Vcc = 12 V
- $I_C \cong 1$ mA
- $V_E \approx 0$ V (DC)
- $R_1=R_2=180K\Omega$
- R_E=?
- $R_L \cong 1K\Omega$
- $R_g = 50\Omega$
- $C_{in} = 10\mu F$
- $C_o = 100\mu F$
- Q_1 = BC547B
  ($\beta_F \approx \beta o \approx 300$)
  ($V_{BE\text{-}ON} = 0{,}7$ V)
  ($V_{CE\text{-}sat} = 0{,}2$ V)

ANEXO 1: Características EC



$$R_{ib} = r_\pi$$

$$R_{oc} = r_o$$

$$R_{in} = R_b // r_\pi \qquad R_{in}\big|_{R_b >> r_\pi} \approx r_\pi$$

$$R_{out} = R_c // r_o \qquad R_{out}\big|_{r_o >> R_c} \approx R_c$$

$$A_v = \frac{V_o}{V_\pi} = -g_m (r_o // R_c // R_L)$$

$$A_{vo} = -g_m (r_o // R_c)$$

$$A_{vo}\big|_{r_o >> R_c} \approx -g_m R_c$$

$$G_v = \frac{V_o}{V_g} = -g_m (r_o // R_c // R_L) \frac{R_{in}}{R_g + R_{in}}$$

$$G_v\big|_{R_b >> r_\pi} \approx -\frac{\beta_o}{R_g + r_\pi} (r_o // R_c // R_L)$$

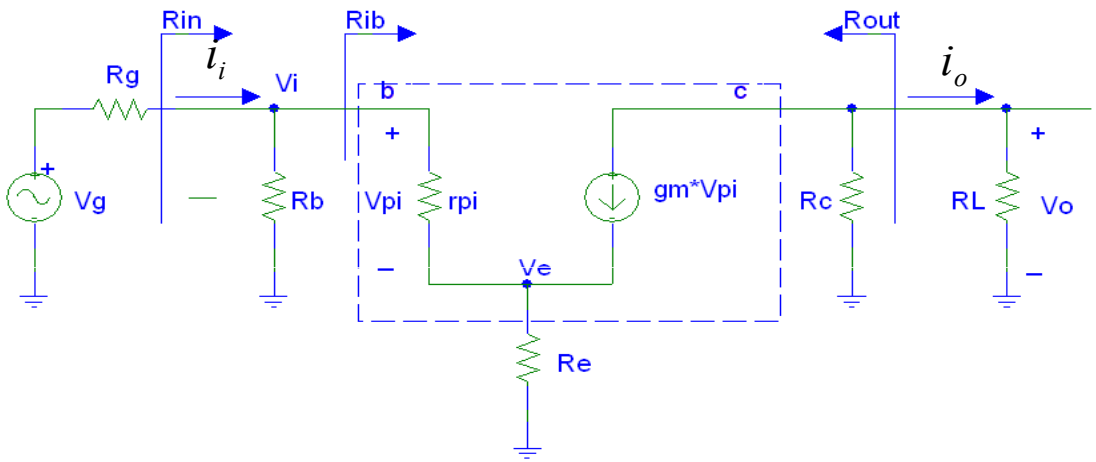
$$G_v\Big|_{R_b >> r_\pi}^{R_g << r_\pi} \approx -g_m (r_o // R_c // R_L)$$

$$A_i = \frac{i_o}{i_i} = -g_m \frac{R_{out}}{R_L + R_{out}} R_{in}$$

$$A_{i(sc)} = -g_m R_{in}$$

$$A_{i(sc)}\big|_{R_b >> r_\pi} = -\beta_o$$

ANEXO 2: Características EC con RE



$$R_{ib} = \frac{V_\pi + V_e}{V_\pi / r_\pi} = r_\pi + (1+\beta_o)R_e$$

$$R_{in} = R_b \,//\left[r_\pi + (1+\beta_o)R_e\right]$$

$$R_{out}\Big|_{r_o >> R_c} \approx R_c$$

$$A_v = \frac{V_o}{V_i} = -\frac{\beta_o (R_c \,//\, R_L)}{r_\pi + (1+\beta_o)\cdot R_e}$$

$$G_v = \frac{V_o}{V_g} = -\frac{\beta_o (R_c \,//\, R_L)}{r_\pi + (1+\beta_o)R_e} \cdot \frac{R_{in}}{R_g + R_{in}}$$

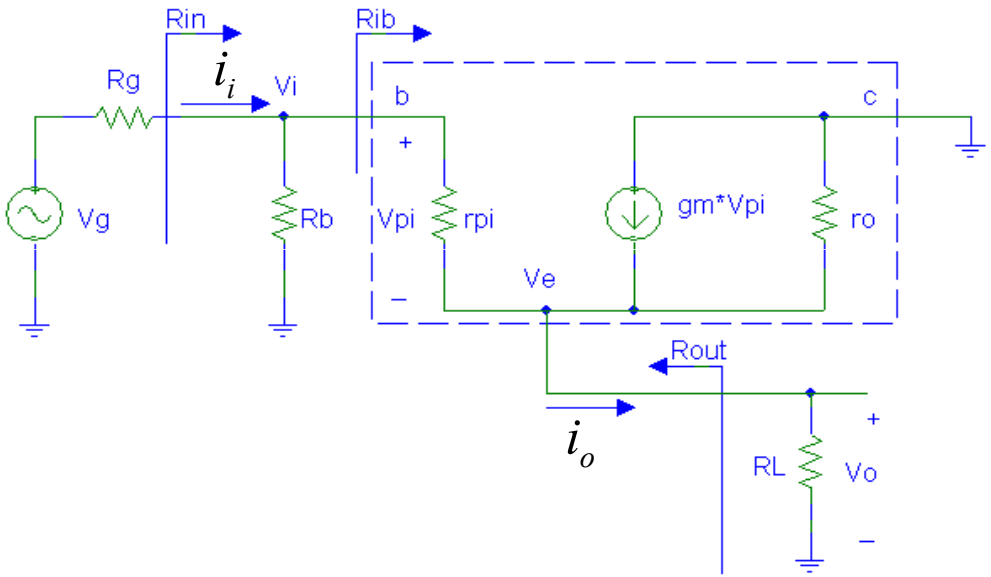
$$A_i = \frac{i_o}{i_i} = -\beta_o \frac{R_c}{R_L + R_c} \frac{R_b + R_{ib}}{R_b}$$

$$A_{vo} = -\frac{\beta_o R_c}{r_\pi + (1+\beta_o)R_e} \approx -\frac{g_m R_c}{1 + g_m R_e}$$

$$G_v\Big|_{r_\pi << \beta_o R_e}^{R_g << R_{in}} \approx -\frac{(R_c \,//\, R_L)}{R_e} \approx -\frac{R_c}{R_e} \cdot \frac{R_L}{R_c + R_L}$$

$$A_{i(sc)} = -\beta_o \frac{R_b + R_{ib}}{R_b} \qquad A_{i(sc)}\Big|_{R_b >> R_{ib}}^{Rg << R_{in}} \approx -\beta_o$$

ANEXO 3: Características CC



$$R_{ib} = \frac{V_\pi + V_e}{V_\pi / r_\pi} = r_\pi + (1+\beta_o)\cdot R_{EM}$$

$$R_{in} = R_b \,//\left[r_\pi + (1+\beta_o)\cdot R_{EM}\right]$$

$$R_{out} = r_o \,// \frac{r_\pi + \left(R_b \,// R_g\right)}{1+\beta_o} \approx \frac{r_\pi + \left(R_b \,// R_g\right)}{1+\beta_o}$$

$$G_v = \frac{V_o}{V_g} = \frac{(1+\beta_o)\cdot R_{EM}}{r_\pi + (1+\beta_o)\cdot R_{EM}} \cdot \frac{R_{in}}{R_g + R_{in}} \approx 1$$

$$A_v = \frac{V_o}{V_i} = \frac{(1+\beta_o)\cdot R_{EM}}{r_\pi + (1+\beta_o)\cdot R_{EM}}$$

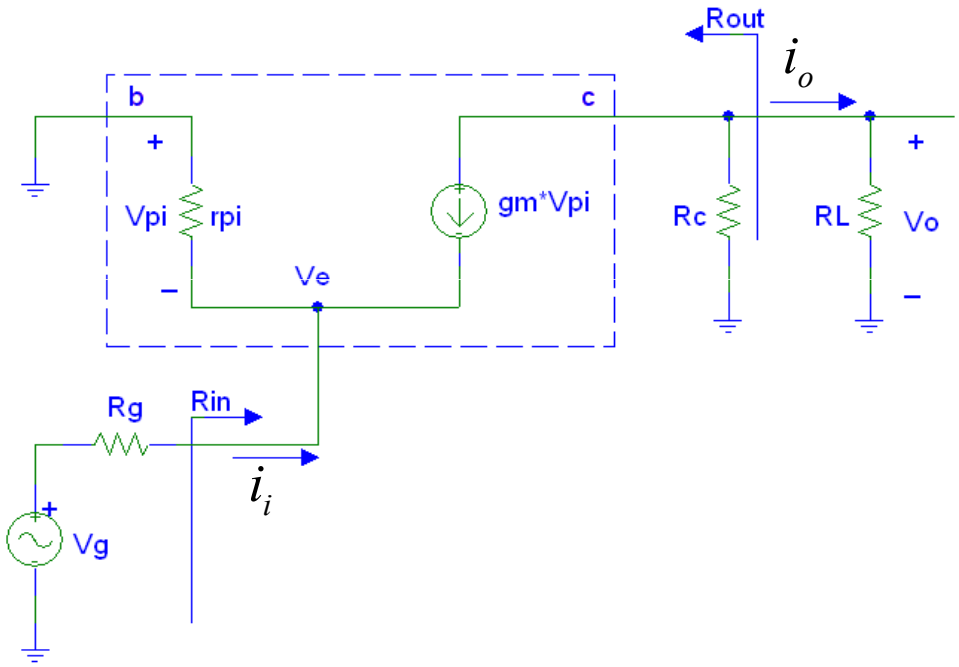
$$A_{vo} = \frac{(1+\beta_o)\cdot r_o}{r_\pi + (1+\beta_o)\cdot r_o} \approx 1$$

$$A_i = \frac{i_o}{i_i} = (1+\beta_o)\frac{r_o}{r_o + R_L}\frac{R_b + R_{ib}}{R_b}$$

$$A_{i(sc)} = (1+\beta_o)\frac{R_b + R_{ib}}{R_b}$$

$$A_{i(sc)}\Big|_{\substack{Rg<<R_{in} \\ R_b>>R_{ib}}} \approx 1+\beta_o$$

ANEXO 4: Características BC



$$R_{in} = \frac{r_\pi}{1+\beta_o} \approx \frac{1}{g_m}$$

$$R_{out}\Big|_{r_o >> R_c} \approx R_c$$

$$A_v = \frac{V_o}{V_i} = +g_m (R_c \,//\, R_L)$$

$$A_{vo} = +g_m R_c$$

$$G_v = \frac{V_o}{V_g} = +g_m (R_c \,//\, R_L)\frac{R_{in}}{R_g + R_{in}}$$

$$G_v = \frac{V_o}{V_g} = g_m (R_c \,//\, R_L)\frac{1}{1+g_m R_g}$$

$$A_i = \frac{i_o}{i_i} = \frac{\beta_o}{(1+\beta_o)}\frac{R_c}{R_c + R_L} = \alpha\frac{R_c}{R_c + R_L}$$

$$A_{i(sc)} = \alpha$$