## 固定偏壓 CE 放大電路



## 小訊號模型（不含 $r_o$）：



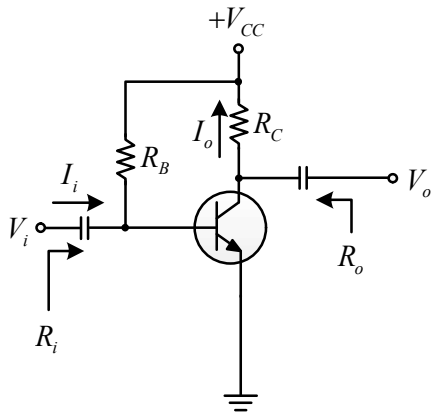**輸入阻抗：**

$$R_i = R_B // R_{ib}$$

$$R_{ib} = \frac{V_i}{i_b} = \frac{i_b \times r_\pi}{i_b} = r_\pi$$

$$R_i = R_B // r_\pi$$

**輸出阻抗（$V_i$接地）：** $R_{oc}$ 為理想電流源內阻 ∞

$$R_o = R_C // R_{oc} = R_C // \infty = R_C$$

**電壓增益：**

$$A_v = \frac{V_o}{V_i} = \frac{-i_c \times R_C}{i_b \times r_\pi} = \frac{-\beta i_b \times R_C}{i_b \times r_\pi} = \frac{-\beta R_C}{r_\pi}$$
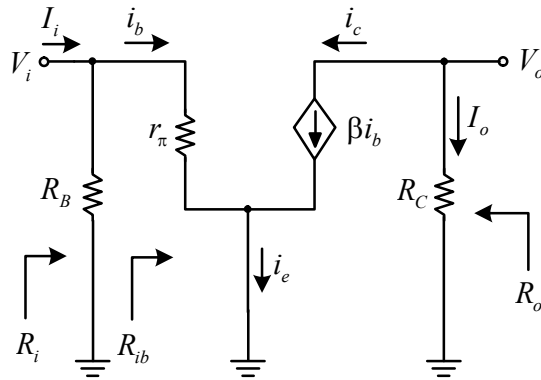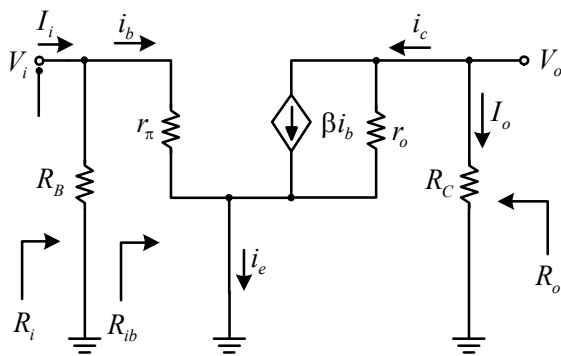
**電流增益：**

$$A_i = \frac{I_o}{I_i} = \frac{i_b}{I_i} \times \frac{I_o}{i_b} = \frac{R_B}{R_B + R_{ib}} \times (-\beta) = \frac{-\beta R_B}{R_B + r_\pi}$$

$$A_i = \frac{I_o}{I_i} = A_V \times \frac{R_i}{R_o} = \frac{-\beta R_C}{r_\pi} \times \frac{R_B // r_\pi}{R_C} = \frac{-\beta R_C}{r_\pi} \times \frac{\frac{R_B \times r_\pi}{R_B + r_\pi}}{R_C} = \frac{-\beta R_B}{R_B + r_\pi}$$

## 固定偏壓 CE 放大電路 小訊號模型（含 $r_o$）：



**輸入阻抗：**

$$R_i = R_B // r_\pi$$

**輸出阻抗（$V_i$接地）：** $R_{oc}$ 為理想電流源內阻 ∞

$$R_o = R_C // r_o // R_{oc} = R_C // r_o // \infty = R_C // r_o$$

**電壓增益：**

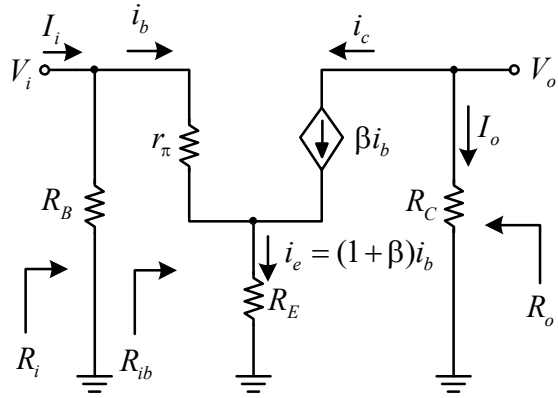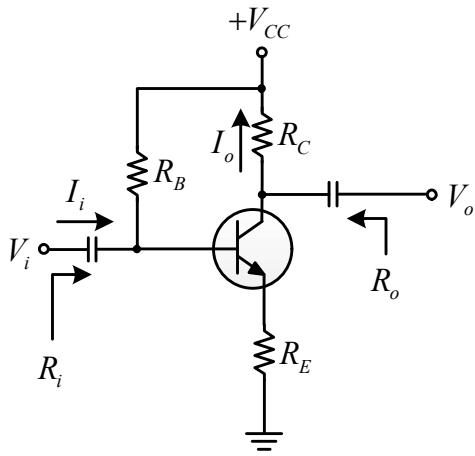$$A_v = \frac{V_o}{V_i} = \frac{-i_c \times R_C}{i_b \times r_\pi} = \frac{-\beta i_b \times \frac{r_o}{r_o + R_C} \times R_C}{i_b \times r_\pi}$$

$$= \frac{-\beta(R_C // r_o)}{r_\pi}$$

**電流增益：** 考慮 $r_o$ 時，$i_c \neq \beta i_b$，$i_c = \beta i_b \times \frac{r_o}{r_o + R_C}$ 。

$$A_i = \frac{I_o}{I_i} = \frac{i_b}{I_i} \times \frac{I_o}{i_b} = \frac{R_B}{R_B + r_\pi} \times \frac{-i_c}{i_b} = \frac{R_B}{R_B + r_\pi} \times \frac{-\beta i_b \times \frac{r_o}{r_o + R_C}}{i_b}$$

$$= \frac{R_B}{R_B + r_\pi} \times \frac{-\beta r_o}{r_o + R_C} = \frac{-\beta r_o R_B}{(R_B + r_\pi)(r_o + R_C)}$$

## 射極回授偏壓 CE 放大電路　　　　　小訊號模型（不含 $r_o$）：



**輸入阻抗：**

$$R_i = R_B // R_{ib}$$

$$R_{ib} = \frac{V_i}{i_b} = \frac{i_b \times r_\pi + i_e \times R_E}{i_b} = \frac{i_b \times r_\pi + (1+\beta)i_b \times R_E}{i_b} = r_\pi + (1+\beta)R_E$$

$$R_i = R_B // [r_\pi + (1+\beta)R_E]$$

**輸出阻抗（$V_i$ 接地）：**

$$R_o = R_C // R_{oc} = R_C // \infty = R_C$$
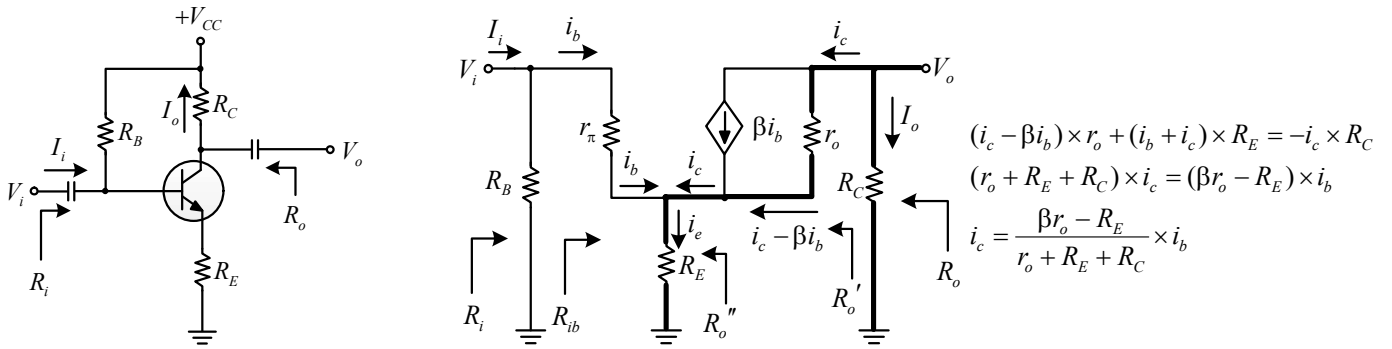
$R_{oc}$ 為理想電流源內阻 $\infty$

**電壓增益：**

$$A_v = \frac{V_o}{V_i} = \frac{-i_c \times R_C}{i_b \times r_\pi + i_e \times R_E} = \frac{-\beta i_b \times R_C}{i_b \times r_\pi + (1+\beta)i_b \times R_E} = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E}$$

**電流增益：**

$$A_i = \frac{I_o}{I_i} = \frac{i_b}{I_i} \times \frac{I_o}{i_b} = \frac{R_B}{R_B + R_{ib}} \times (-\beta) = \frac{-\beta R_B}{R_B + [r_\pi + (1+\beta)R_E]}$$

$$A_i = \frac{I_o}{I_i} = A_V \times \frac{R_i}{R_o} = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E} \times \frac{R_B // [r_\pi + (1+\beta)R_E]}{R_C}$$

$$= \frac{-\beta R_C}{r_\pi + (1+\beta)R_E} \times \frac{\dfrac{R_B \times [r_\pi + (1+\beta)R_E]}{R_B + [r_\pi + (1+\beta)R_E]}}{R_C} = \frac{-\beta R_B}{R_B + [r_\pi + (1+\beta)R_E]}$$

## 射極回授偏壓 CE 放大電路　　　　　　小訊號模型（含 $r_o$）：



$$(i_c - \beta i_b) \times r_o + (i_b + i_c) \times R_E = -i_c \times R_C$$
$$(r_o + R_E + R_C) \times i_c = (\beta r_o - R_E) \times i_b$$
$$i_c = \frac{\beta r_o - R_E}{r_o + R_E + R_C} \times i_b$$

考慮 $r_o$ 時，$i_c \neq \beta i_b$，$i_e \neq (1+\beta)i_b$，但 $i_e = i_b + i_c$，須先找出 $i_b$ 與 $i_c$ 電流關係。

**輸入阻抗：**

$$R_i = R_B // R_{ib} = R_B //(r_\pi + R_E + \frac{(\beta r_o - R_E)R_E}{r_o + R_E + R_C})$$

$$R_{ib} = \frac{V_i}{i_b} = \frac{i_b \times r_\pi + i_e \times R_E}{i_b} = \frac{i_b \times r_\pi + (i_b + i_c) \times R_E}{i_b} = \frac{i_b \times r_\pi + i_b \times R_E + i_c \times R_E}{i_b} = \frac{i_b \times r_\pi + i_b \times R_E + i_b \times \frac{(\beta r_o - R_E)R_E}{r_o + R_E + R_C}}{i_b}$$

$$= r_\pi + R_E + \frac{(\beta r_o - R_E)R_E}{r_o + R_E + R_C}$$

**輸出阻抗（$V_i$ 接地）：**

$$R_o = R_C // R_o'$$

$$R_o' = \frac{V_o}{i_c} = \frac{i_c \times R_o'' + (i_c - \beta i_b)r_o}{i_c} = \frac{i_c R_o'' + i_c r_o - \beta i_b r_o}{i_c} = \frac{i_c R_o'' + i_c r_o - i_c(\frac{r_o + R_E + R_C}{\beta r_o - R_E})\beta r_o}{i_c}$$

$$= R_o'' + r_o + \frac{\beta r_o(r_o + R_E + R_C)}{\beta r_o - R_E} \qquad R_o'' = \frac{-i_b r_\pi}{i_c} or \frac{i_e R_E}{i_c} = \frac{-(r_o + R_E + R_C)r_\pi}{\beta r_o - R_E} or R_E + \frac{(r_o + R_E + R_C)R_E}{\beta r_o - R_E}$$
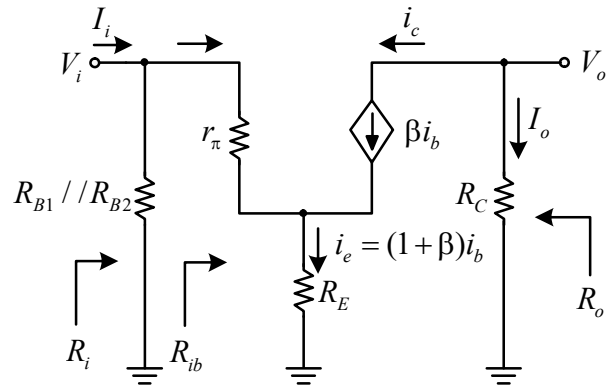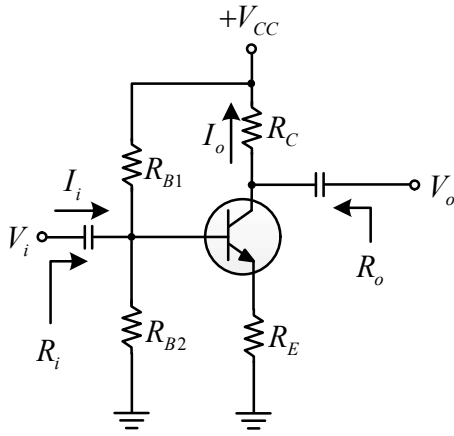
**電壓增益：**

$$A_v = \frac{V_o}{V_i} = \frac{-i_c \times R_C}{i_b \times r_\pi + i_e \times R_E} = \frac{-i_c \times R_C}{i_b \times r_\pi + i_b \times R_E + i_c \times R_E} = \frac{-i_b \times \frac{\beta r_o - R_E}{r_o + R_E + R_C} \times R_C}{i_b \times r_\pi + i_b \times R_E + i_b \times \frac{\beta r_o - R_E}{r_o + R_E + R_C} \times R_E}$$

$$= \frac{-\frac{(\beta r_o - R_E)R_C}{r_o + R_E + R_C}}{r_\pi + R_E + \frac{(\beta r_o - R_E)R_E}{r_o + R_E + R_C}} = \frac{-(\beta r_o - R_E)R_E}{(r_\pi + R_E)(r_o + R_E + R_C) + (\beta r_o - R_E)R_E}$$

**電流增益：**

$$A_i = \frac{I_o}{I_i} = \frac{i_b}{I_i} \times \frac{I_o}{i_b} = \frac{R_B}{R_B + R_{ib}} \times \frac{-i_c}{i_b} = \frac{R_B}{R_B + r_\pi + R_E + \frac{\beta r_o - R_E}{r_o + R_E + R_C}} \times \frac{-i_b \times \frac{\beta r_o - R_E}{r_o + R_E + R_C}}{i_b}$$

$$= \frac{R_B}{R_B + r_\pi + R_E + \frac{\beta r_o - R_E}{r_o + R_E + R_C}} \times \frac{\beta r_o - R_E}{r_o + R_E + R_C} = \frac{(\beta r_o - R_E)R_B}{(R_B + r_\pi + R_E)(r_o + R_E + R_C) + (\beta r_o - R_E)}$$

分壓式偏壓 CE 放大電路　　　　　　　　小訊號模型（不含 $r_o$）：

**輸入阻抗：**

$$R_i = R_{B1} // R_{B2} // R_{ib}$$

$$R_{ib} = \frac{V_i}{i_b} = \frac{i_b \times r_\pi + i_e \times R_E}{i_b} = \frac{i_b \times r_\pi + (1+\beta)i_b \times R_E}{i_b} = r_\pi + (1+\beta)R_E$$

$$R_i = R_{B1} // R_{B2} // [r_\pi + (1+\beta)R_E]$$

**輸出阻抗（$V_i$ 接地）：**

$$R_o = R_C // R_{oc} = R_C // \infty = R_C$$

$R_{oc}$ 為理想電流源內阻 $\infty$

**電壓增益：**

$$A_v = \frac{V_o}{V_i} = \frac{-i_c \times R_C}{i_b \times r_\pi + i_e \times R_E} = \frac{-\beta i_b \times R_C}{i_b \times r_\pi + (1+\beta)i_b \times R_E} = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E}$$
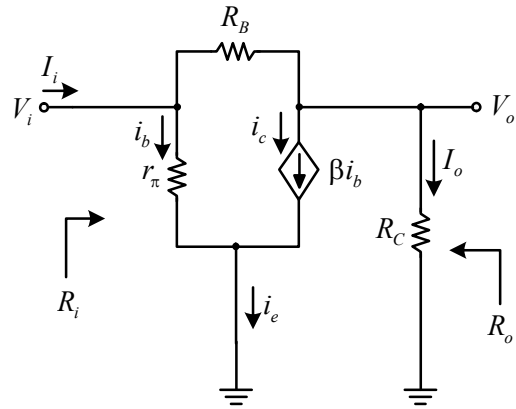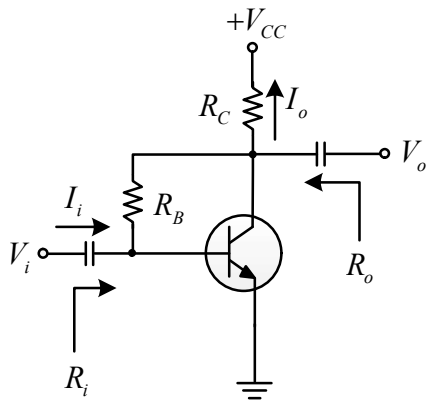
**電流增益：**

$$A_i = \frac{I_o}{I_i} = \frac{i_b}{I_i} \times \frac{I_o}{i_b} = \frac{R_{B1} // R_{B2}}{R_{B1} // R_{B2} + R_{ib}} \times (-\beta) = \frac{-\beta(R_{B1} // R_{B2})}{(R_{B1} // R_{B2}) + [r_\pi + (1+\beta)R_E]}$$
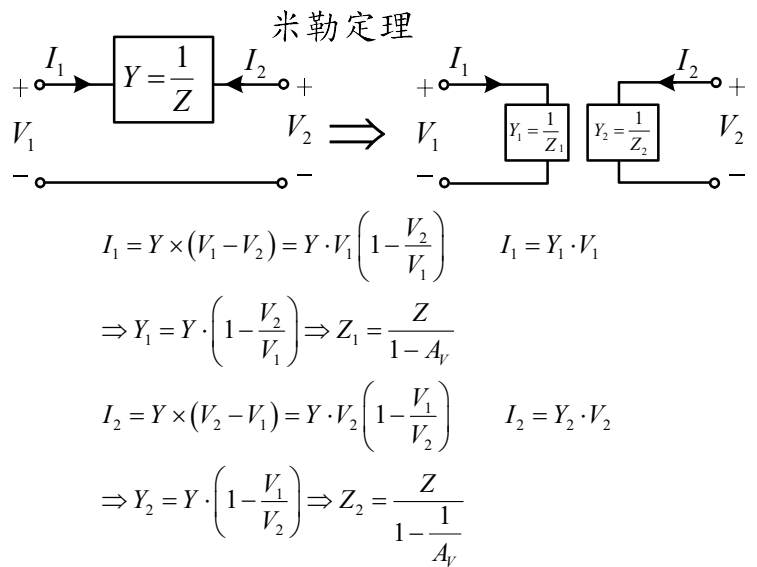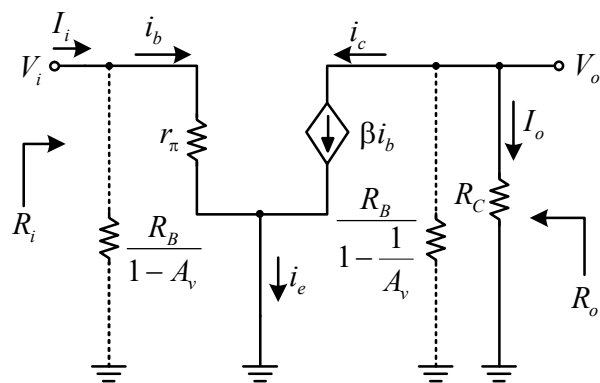
$$A_i = \frac{I_o}{I_i} = A_V \times \frac{R_i}{R_o} = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E} \times \frac{R_{B1} // R_{B2} // [r_\pi + (1+\beta)R_E]}{R_C}$$

$$= \frac{-\beta R_C}{r_\pi + (1+\beta)R_E} \times \frac{\dfrac{(R_{B1} // R_{B2}) \times [r_\pi + (1+\beta)R_E]}{(R_{B1} // R_{B2}) + [r_\pi + (1+\beta)R_E]}}{R_C} = \frac{-\beta(R_{B1} // R_{B2})}{(R_{B1} // R_{B2}) + [r_\pi + (1+\beta)R_E]}$$

■分壓式偏壓 CE 放大電路小訊號（含 $r_o$）模型與上述射極回授偏壓 CE 放大電路小訊號（含 $r_o$）模型相同，唯 $R_B$ 改為 $R_{B1} // R_{B2}$。

## 集極回授偏壓 CE 放大電路　　　　　小訊號模型（不含 $r_o$）：



依據米勒定理將電路等效如下：



米勒定理

$$I_1 = Y \times (V_1 - V_2) = Y \cdot V_1 \left(1 - \frac{V_2}{V_1}\right) \qquad I_1 = Y_1 \cdot V_1$$

$$\Rightarrow Y_1 = Y \cdot \left(1 - \frac{V_2}{V_1}\right) \Rightarrow Z_1 = \frac{Z}{1 - A_V}$$

$$I_2 = Y \times (V_2 - V_1) = Y \cdot V_2 \left(1 - \frac{V_1}{V_2}\right) \qquad I_2 = Y_2 \cdot V_2$$

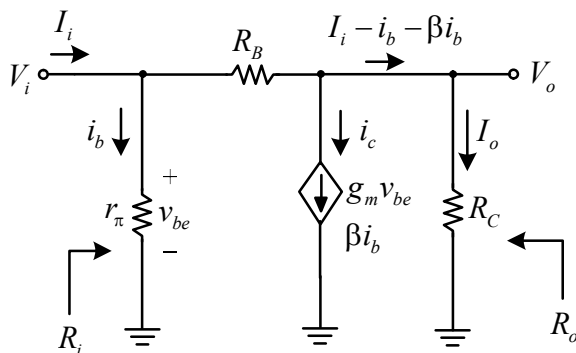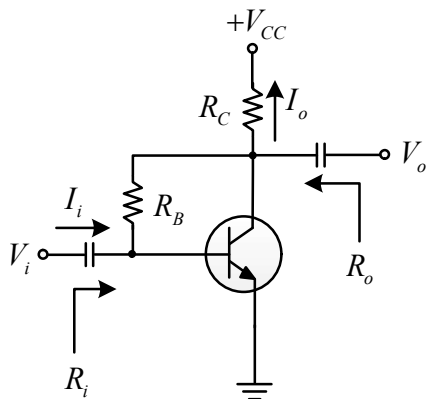$$\Rightarrow Y_2 = Y \cdot \left(1 - \frac{V_1}{V_2}\right) \Rightarrow Z_2 = \frac{Z}{1 - \frac{1}{A_V}}$$

電壓增益：求解 $A_v$ 一元二次方程式（複雜）

$$A_v = \frac{V_o}{V_i} = \frac{-i_c \times (\frac{R_B}{1 - \frac{1}{A_v}} // R_C)}{i_b \times r_\pi} = \frac{-\beta i_b \times (\frac{R_B}{1 - \frac{1}{A_v}} // R_C)}{i_b \times r_\pi} = \frac{-\beta(\frac{R_B A_v}{A_v - 1} // R_C)}{r_\pi}$$

$$= \frac{-\beta\left(\frac{\frac{A_v R_B}{A_v - 1} + R_C}{\frac{A_v R_B}{A_v - 1} \times R_C}\right)}{r_\pi} = -\beta\left(\frac{\frac{A_v R_B}{A_v - 1} + R_C}{\frac{r_\pi A_v R_B R_C}{A_v - 1}}\right) = -\beta\left(\frac{A_v R_B + A_v R_C - R_C}{r_\pi A_v R_B R_C}\right)$$

$$A_v{}^2 = \frac{-\beta(R_B + R_C)}{r_\pi R_B R_C} A_v + \frac{\beta R_C}{r_\pi R_B R_C} \Rightarrow A_v{}^2 + \frac{\beta(R_B + R_C)}{r_\pi R_B R_C} A_v - \frac{\beta R_C}{r_\pi R_B R_C} = 0$$
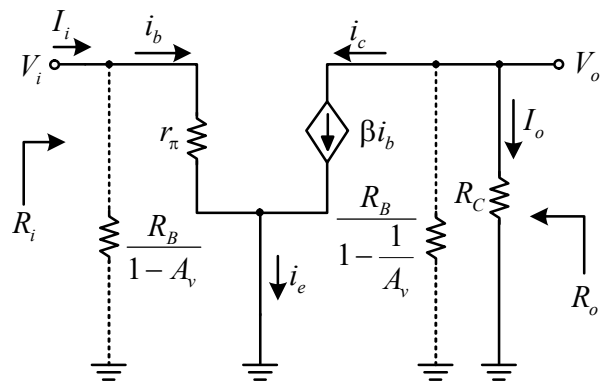
## 集極回授偏壓 CE 放大電路

**電壓增益**：利用節點電壓方法解出，再將小訊號模型轉換為米勒等效電路。

$$V_i = v_{be}$$

$$\frac{V_o - V_i}{R_B} + g_m v_{be} + \frac{V_o}{R_C} = 0 \Rightarrow \frac{V_o - V_i}{R_B} + g_m V_i + \frac{V_o}{R_C} = 0$$

$$(\frac{1}{R_B} + \frac{1}{R_C})V_o = (\frac{1}{R_B} - g_m)V_i$$

$$A_v = \frac{V_o}{V_i} = \frac{(\frac{1}{R_B} - g_m)}{(\frac{1}{R_B} + \frac{1}{R_C})}$$



**輸入阻抗**：

$$R_i = r_\pi \, // \, \frac{R_B}{1 - A_v} \,（並聯米勒電阻）$$

**輸出阻抗**（$V_i$接地）：

$$R_o = R_C \, // \, \frac{R_B}{1 - \frac{1}{A_v}} \, // \, R_{oc} = R_C \, // \, \frac{R_B}{1 - \frac{1}{A_v}} \, // \, \infty = R_C \, // \, \frac{R_B}{1 - \frac{1}{A_v}}$$
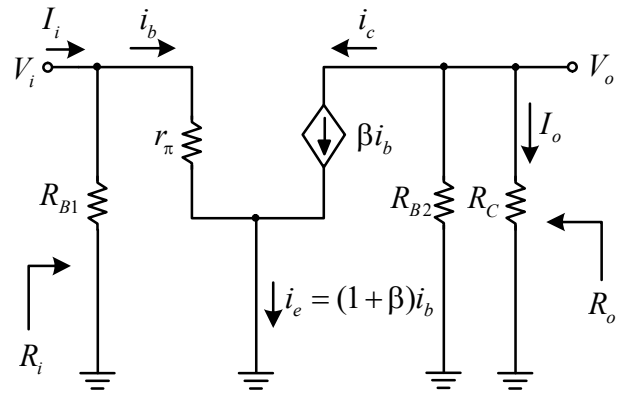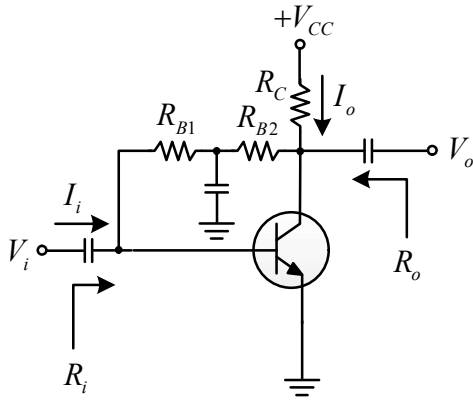
$R_{oc}$ 為理想電流源內阻 $\infty$

**電流增益**：

$$A_i = \frac{I_o}{I_i} = \frac{i_b}{I_i} \times \frac{I_o}{i_b} = \frac{R_B}{r_\pi(1 - A_v) + R_B} \times \frac{-\beta R_B}{(1 - \frac{1}{A_v})R_C + R_B}$$

$$i_b = I_i \times \frac{\frac{R_B}{1 - A_v}}{r_\pi + \frac{R_B}{1 - A_v}} \Rightarrow \frac{i_b}{I_i} = \frac{\frac{R_B}{1 - A_v}}{r_\pi + \frac{R_B}{1 - A_v}} = \frac{R_B}{r_\pi(1 - A_v) + R_B} \qquad I_o = -\beta i_b \times \frac{\frac{R_B}{1 - \frac{1}{A_v}}}{R_C + \frac{R_B}{1 - \frac{1}{A_v}}} \Rightarrow \frac{I_o}{i_b} = \frac{-\beta R_B}{(1 - \frac{1}{A_v})R_C + R_B}$$

## 集極回授偏壓 CE 放大電路 (反交連電容)



## 小訊號模型（不含 $r_o$）：



**輸入阻抗：**

$$R_i = R_{B1} // R_{ib}$$

$$R_{ib} = \frac{V_i}{i_b} = \frac{i_b \times r_\pi}{i_b} = r_\pi$$

$$R_i = R_{B1} // r_\pi$$

**輸出阻抗（$V_i$ 接地）：** $R_{oc}$ 為理想電流源內阻 $\infty$

$$R_o = R_C // R_{B2} // R_{oc} = R_C // R_{B2} // \infty = R_C // R_{B2}$$
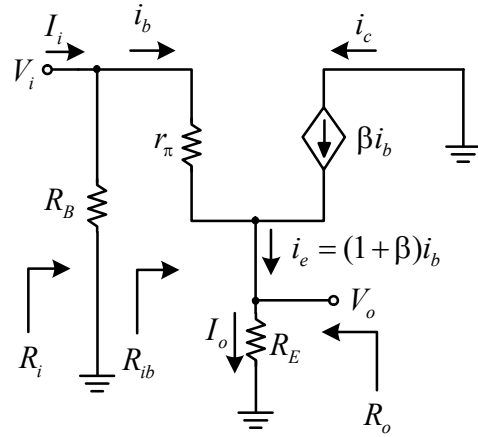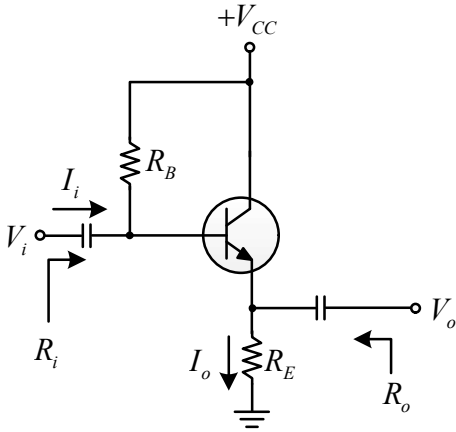
**電壓增益：**

$$A_v = \frac{V_o}{V_i} = \frac{-i_c \times (R_C // R_{B2})}{i_b \times r_\pi} = \frac{-\beta i_b \times (R_C // R_{B2})}{i_b \times r_\pi} = \frac{-\beta(R_C // R_{B2})}{r_\pi}$$

**電流增益：**

$$A_i = \frac{I_o}{I_i} = \frac{i_b}{I_i} \times \frac{I_o}{i_b} = \frac{(\frac{R_{B1}}{R_{B1} + R_{ib}})I_i}{I_i} \times \frac{-\beta i_b(\frac{R_{B2}}{R_{B2} + R_C})}{i_b} = \frac{-\beta R_{B1} R_{B2}}{(R_{B1} + r_\pi)(R_{B2} + R_C)}$$
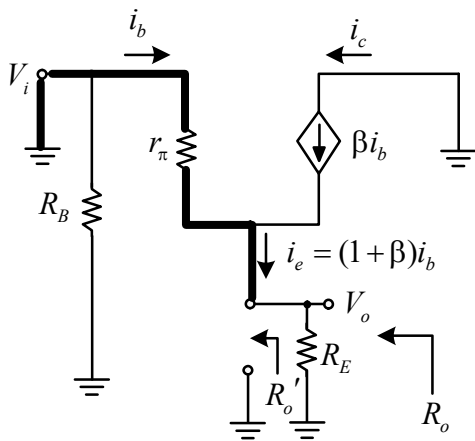
## CC 放大電路(射極隨耦器、電壓緩衝器)　　小訊號模型（不含 $r_o$）：



**輸入阻抗：**

$$R_i = R_B // R_{ib}$$

$$R_{ib} = \frac{V_i}{i_b} = \frac{i_b \times r_\pi + i_e \times R_E}{i_b} = \frac{i_b \times r_\pi + (1+\beta)i_b \times R_E}{i_b} = r_\pi + (1+\beta)R_E$$

$$R_i = R_B // [r_\pi + (1+\beta)R_E]$$

**輸出阻抗（$V_i$ 接地）：**



$$R_o' = \frac{V_o}{-i_e} = \frac{-i_b r_\pi}{-i_e} = \frac{-i_b r_\pi}{-(1+\beta)i_b} = \frac{r_\pi}{1+\beta}$$

$$R_o = R_E // R_o' = R_E // (\frac{r_\pi}{1+\beta}) = R_E // r_e$$

**電壓增益：**
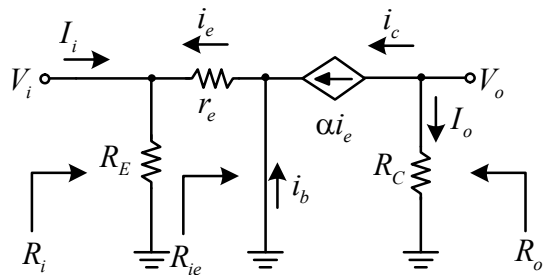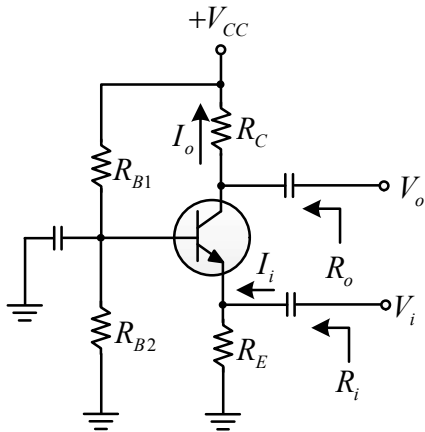
$$A_v = \frac{V_o}{V_i} = \frac{i_e \times R_E}{i_b \times r_\pi + i_e \times R_E} = \frac{(1+\beta)i_b \times R_E}{i_b \times r_\pi + (1+\beta)i_b \times R_E} = \frac{(1+\beta)R_E}{r_\pi + (1+\beta)R_E} \approx 1$$

**電流增益：**

$$A_i = \frac{I_o}{I_i} = \frac{i_b}{I_i} \times \frac{I_o}{i_b} = \frac{R_B}{R_B + R_{ib}} \times (1+\beta) = \frac{(1+\beta)R_B}{R_B + [r_\pi + (1+\beta)R_E]}$$

## CB 放大電路(電流緩衝器)



## 小訊號模型（不含 $r_o$）：



**輸入阻抗：**

$$R_i = R_E / / R_{ie} = R_E / / r_e$$

**輸出阻抗（$V_i$ 接地）：** $R_{oc}$ 為理想電流源內阻 $\infty$

$$R_o = R_C / / R_{oc} = R_C / / \infty = R_C$$

**電壓增益：**

$$A_v = \frac{V_o}{V_i} = \frac{-\alpha i_e \times R_C}{-i_e \times r_e} = \frac{\alpha R_C}{r_e} \approx \frac{R_C}{r_e}$$

**電流增益：**

$$A_i = \frac{I_o}{I_i} = \frac{i_e}{I_i} \times \frac{I_o}{i_e} = \frac{-(\frac{R_E}{R_E + r_e})I_i}{I_i} \times \frac{-\alpha i_e}{i_e} = \frac{\alpha R_E}{R_E + r_e} \approx 1$$

$$A_i = A_v \times \frac{R_i}{R_o} = \frac{\alpha R_C}{r_e} \times \frac{R_E / / r_e}{R_C} = \frac{\alpha R_C}{r_e} \times \frac{\frac{R_E r_e}{R_E + r_e}}{R_C} = \frac{\alpha R_E}{R_E + r_e}$$