ELCT 508: Communication Microelectronics

Lecture 07:

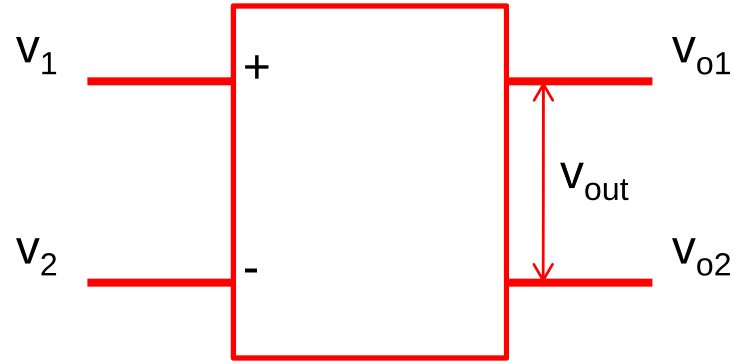
Differential Amplifiers

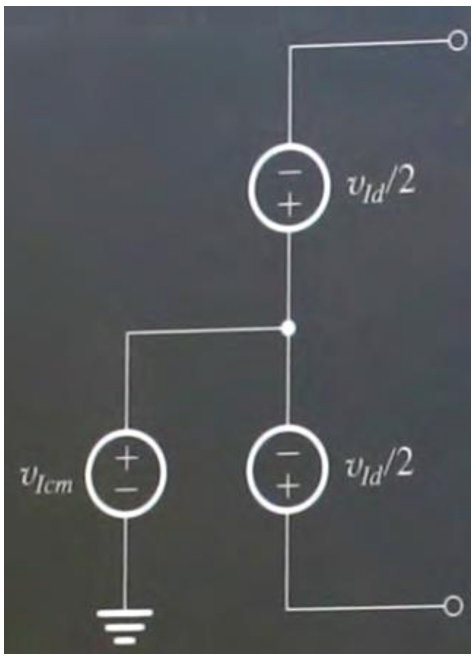
Dr. Hany Ayad Bastawrous

Department of Electronics and Electrical Engineering

hany.bastawrous@guc.edu.eg

A differential amplifier is one that responds to the difference between the two signals applied at its input and <u>ideally</u> rejects signals that are common to the two inputs





$$v_1 = v_{Icm} - \frac{v_{Id}}{2}$$

$$v_2 = v_{Icm} + \frac{v_{Id}}{2}$$

Possible configurations

1. **Dual-input balanced-output**
2. **Dual-input unbalanced-output**
3. **Single-input balanced-output**
4. **Single-input unbalanced-output**

$$v_{out} = A_d v_{Id} + A_{cm} v_{Icm}$$

Differential-mode gain **Common-mode gain**

Common-mode rejection ratio (CMRR)

A quantity that measures the degree of rejection of common-mode signals in preference to differential signals

$$\mathrm{CMRR} = 20\log\frac{|A_d|}{|A_{cm}|}$$

Output offset voltage

The voltage that appears at the output of the differential amplifier when the input terminals are connected together (V_{id}=0).

Input offset voltage

Equals to the output offset voltage divided by the differential voltage gain

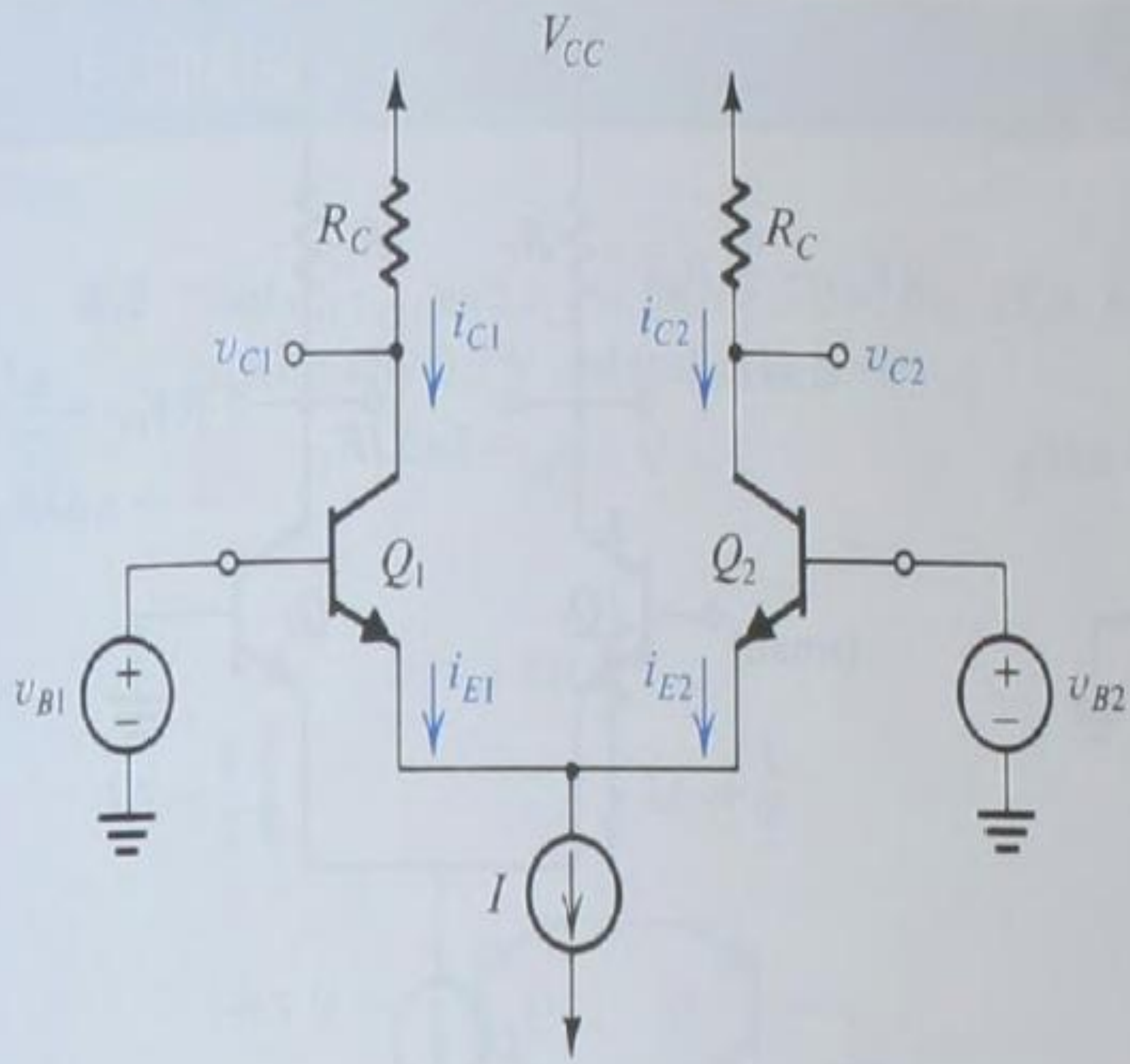
Control parameters:
v_{B1} and v_{B2}

Outputs:
v_{C1} and v_{C2}

1) Large-signal analysis

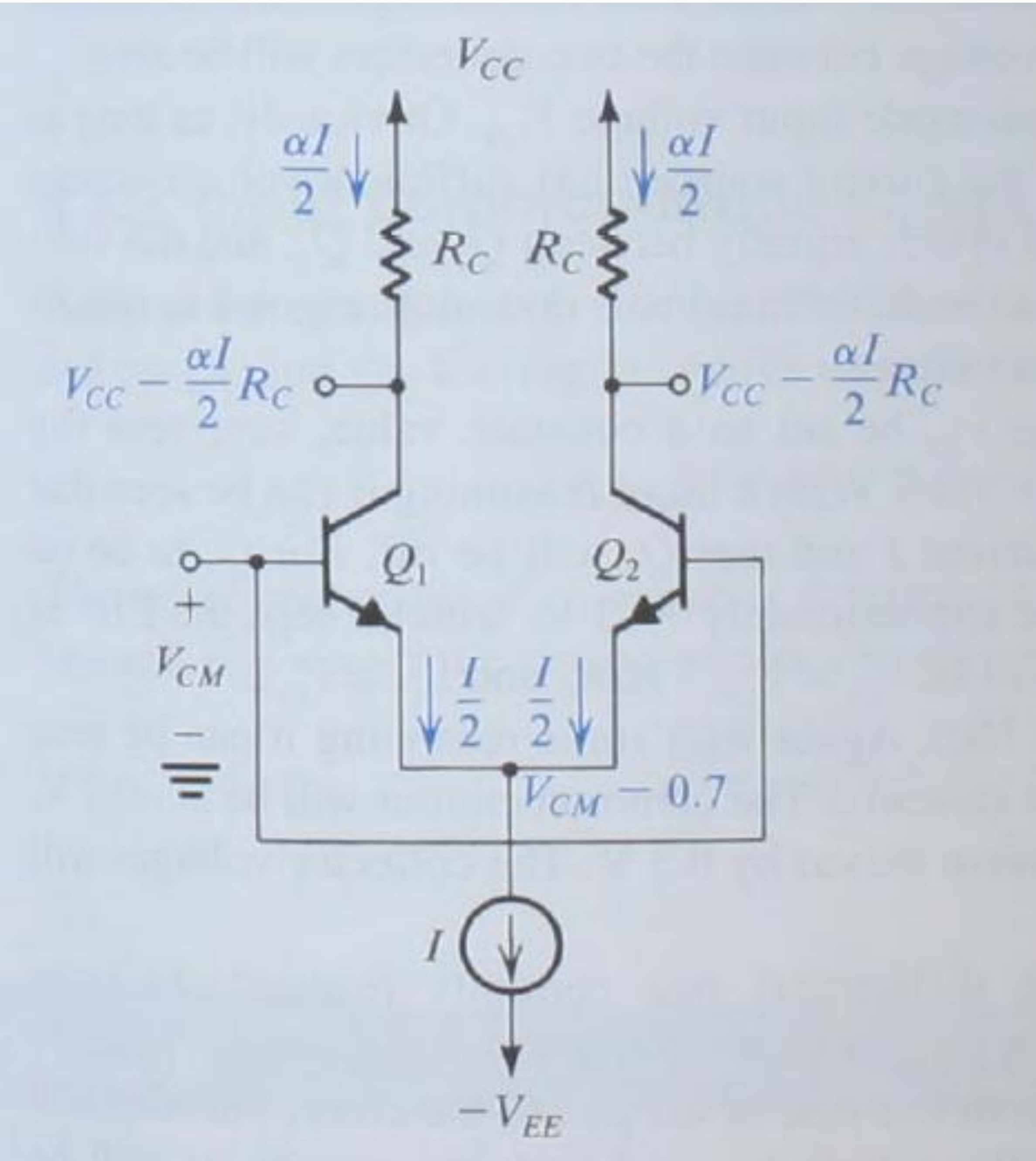
2) Small-signal analysis

BJT differential pair



Large-signal analysis

Case 1: $v_{B1}=v_{B2}=v_{CM}$

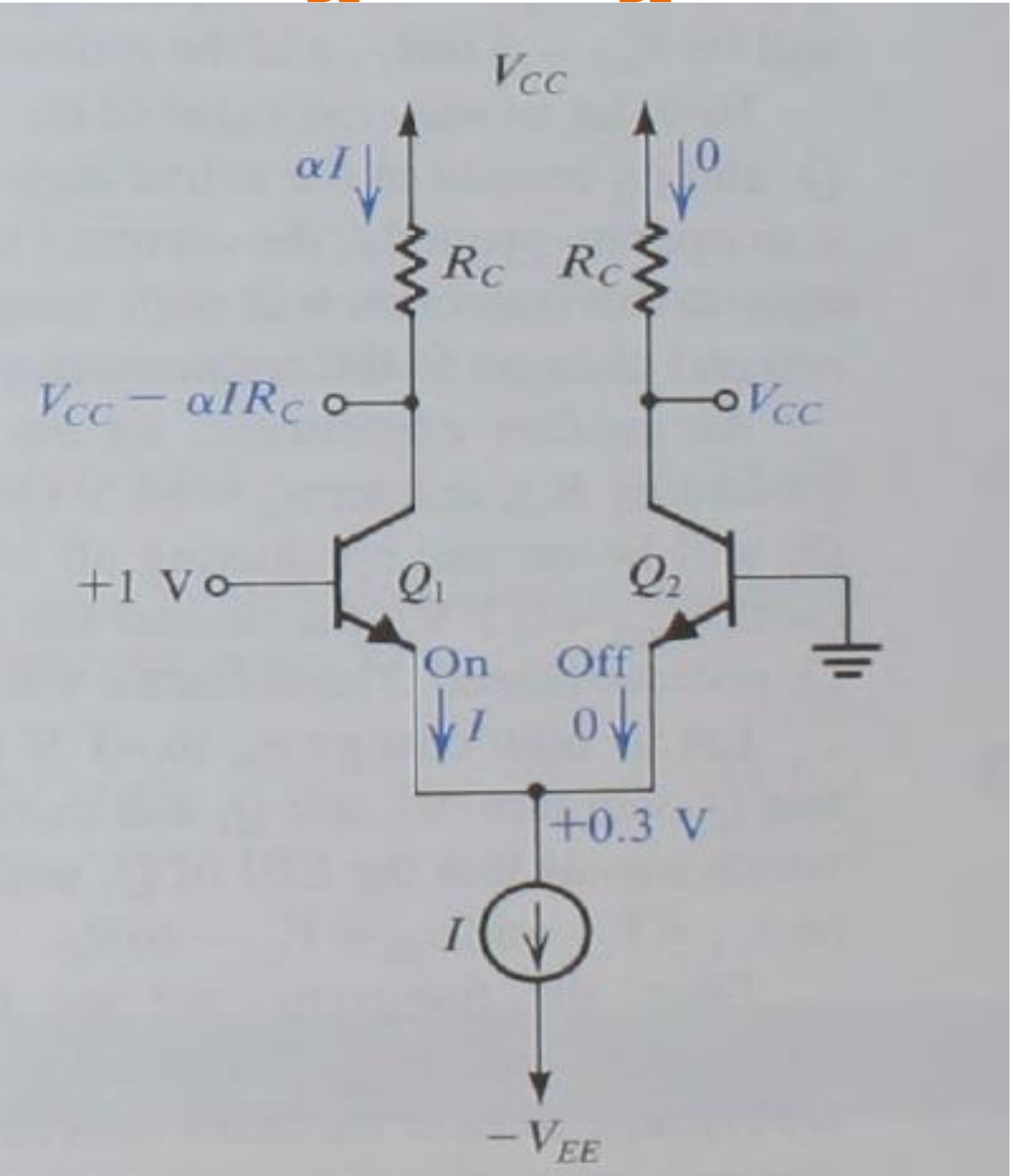


Q_1 and Q_2 are matched transistors and operating in the active mode

Only common-mode output is available and differential-mode output is zero

$$v_{O1} = v_{O2} = V_{CC} - \frac{\alpha I}{2} R_C$$

Case 2: v_{B1}= 1V & v_{B2}=0V



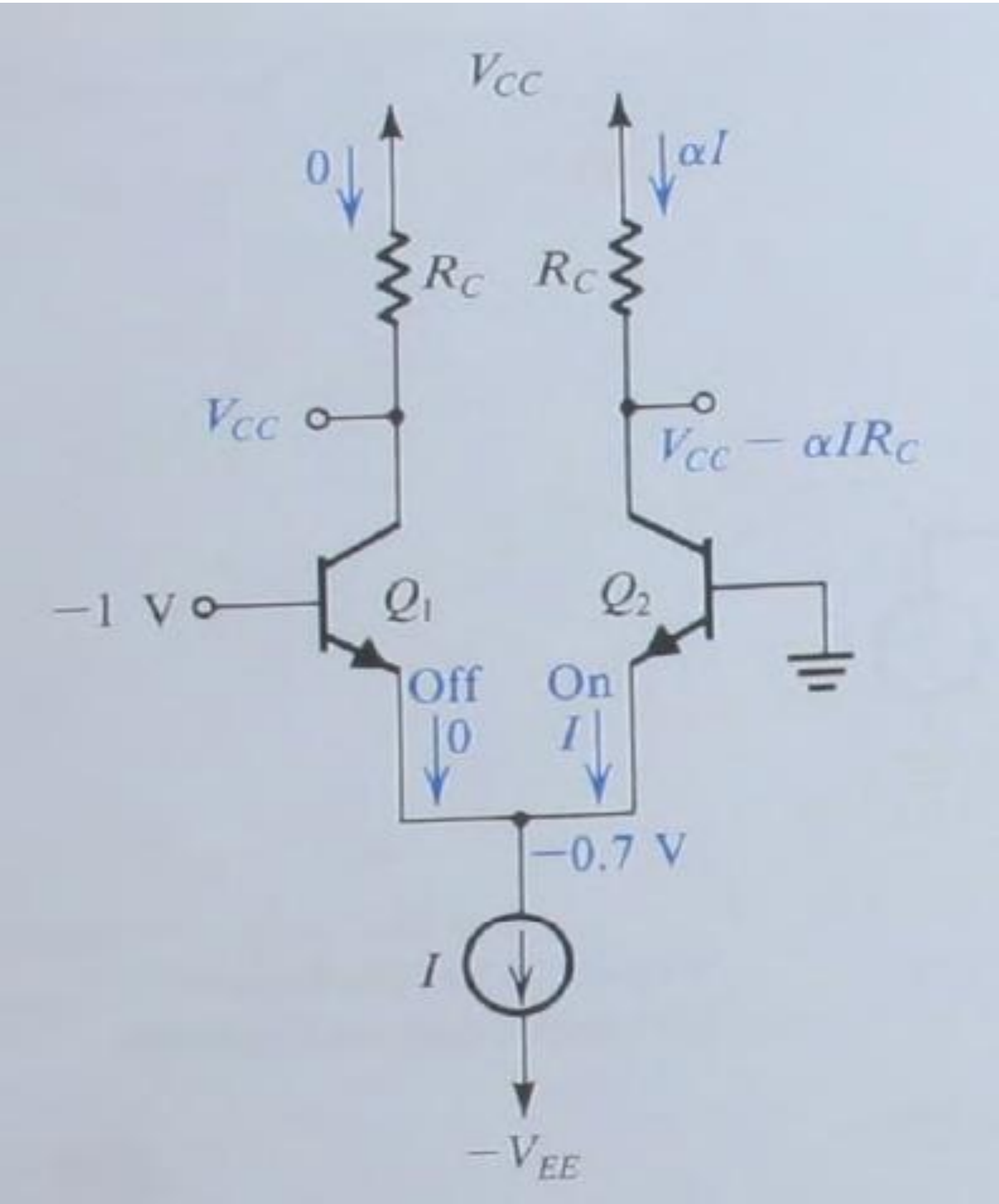
Q_1 is ON and operating in the active region while Q_2 is OFF

Differential-mode output is not zero

$$v_{O1} = V_{CC} - \alpha I R_C$$

$$v_{O2} = V_{CC}$$

Case 3: v_{B1}= -1V & v_{B2}=0V



Q_1 is OFF while Q_2 is ON and operating in the active region

Differential-mode output is not zero

$$v_{O1} = V_{CC}$$

$$v_{O2} = V_{CC} - \alpha I R_C$$

Large-signal operation of BJT differential pair

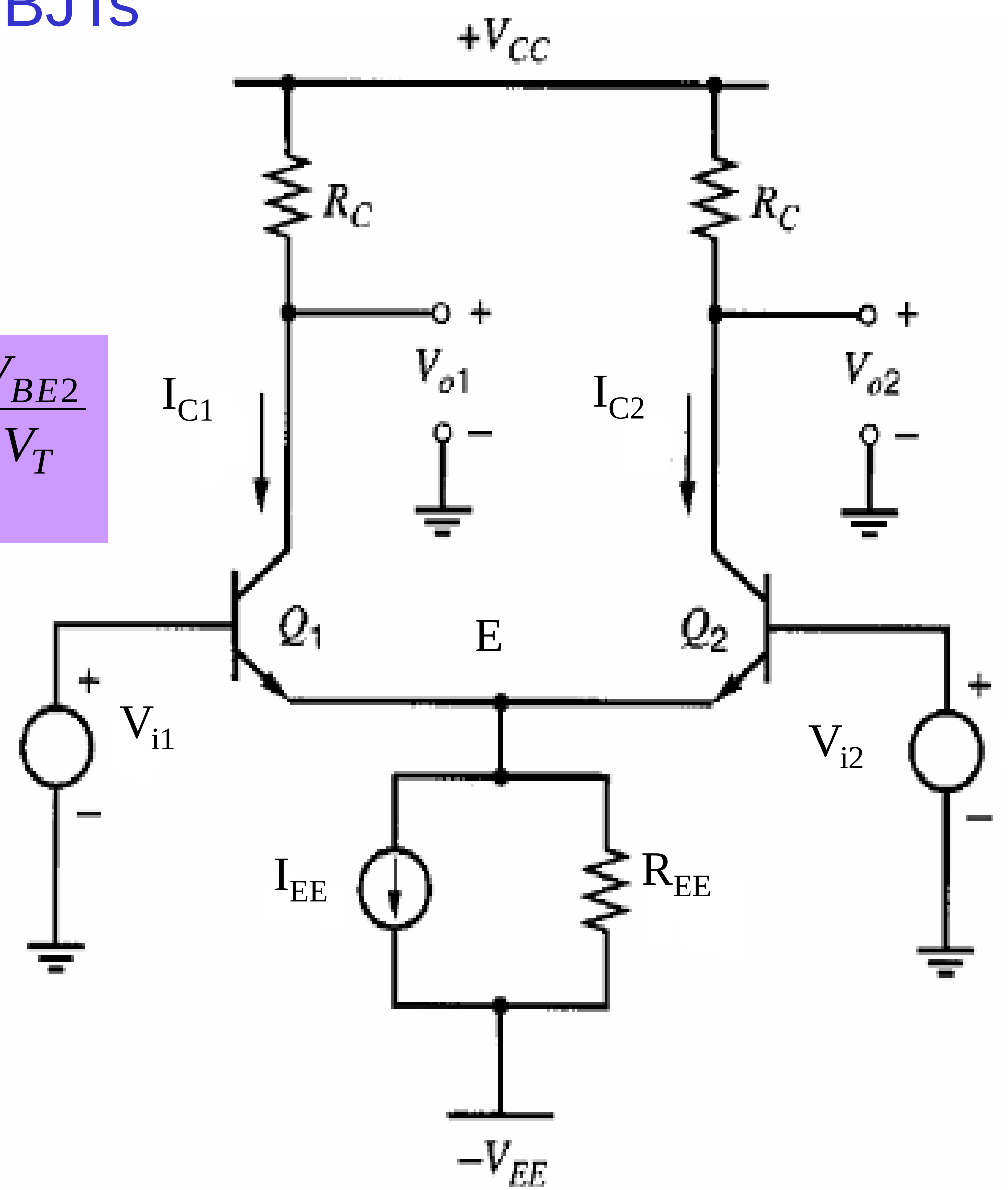
Q_1 and Q_2 are 2 matched BJTs

$$\therefore \beta_1 = \beta_2 = \beta$$

and $$I_{S1} = I_{S2} = I_S$$

$$I_{C1} = I_S e^{\frac{V_{BE1}}{V_T}}$$

$$I_{C2} = I_S e^{\frac{V_{BE2}}{V_T}}$$



$$V_{BE1} = V_T \ln\left(\frac{I_{C1}}{I_S}\right)$$

$$V_{BE2} = V_T \ln\left(\frac{I_{C2}}{I_S}\right)$$

$$V_E = V_{i1} - V_{BE1} = V_{i2} - V_{BE2}$$

$$V_{i1} - V_{i2} = V_{id} = V_T \ln(\frac{I_{C1}}{I_S}) - V_T \ln(\frac{I_{C2}}{I_S})$$

$$\boxed{\therefore V_{id} = V_T \ln(\frac{I_{C1}}{I_{C2}})}$$

$$\boxed{\Rightarrow \frac{I_{C1}}{I_{C2}} = e^{\frac{V_{id}}{V_T}}}$$

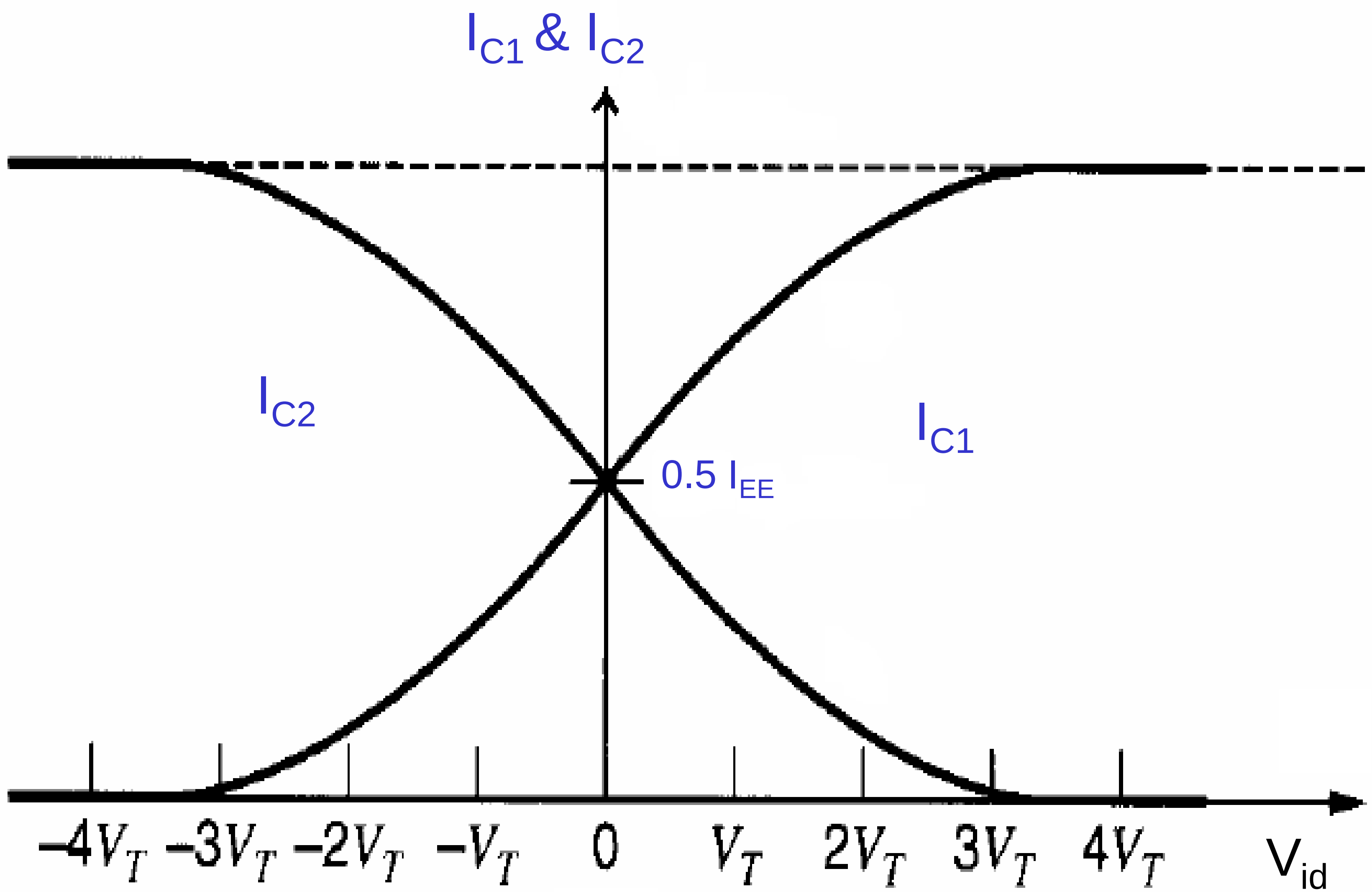
Assume that R_{EE} ~ ∞ and β≈∞

$$\Rightarrow I_{C1} + I_{C2} = I_{EE}$$

$$\boxed{\therefore I_{C1} = \frac{I_{EE}}{1 + e^{-\frac{V_{id}}{V_T}}}}$$

and

$$\boxed{I_{C2} = \frac{I_{EE}}{1 + e^{\frac{V_{id}}{V_T}}}}$$



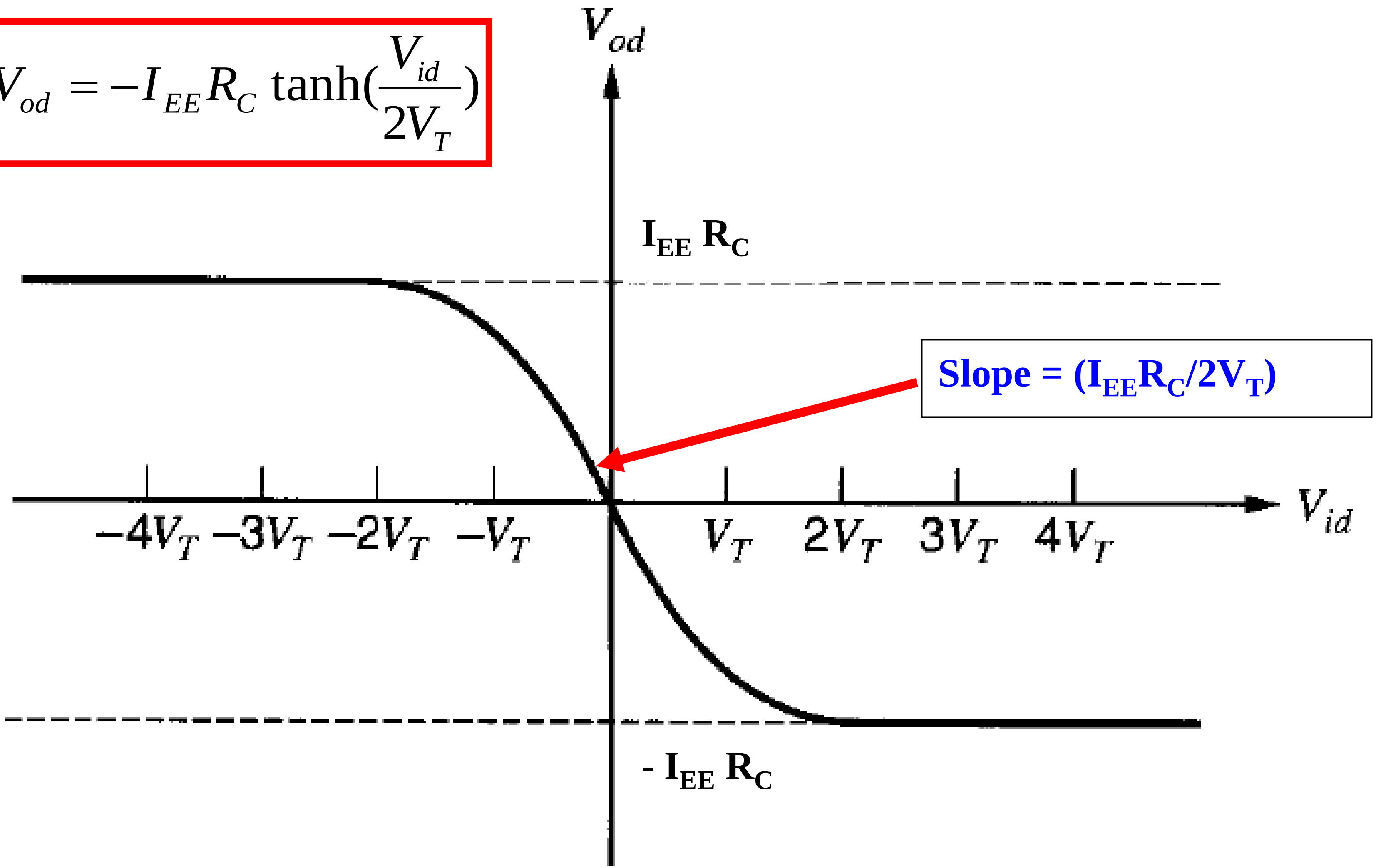
I_{C1} & I_{C2}
I_{C2}
I_{C1}
0.5 I_{EE}
$-4V_T$
$-3V_T$
$-2V_T$
$-V_T$
0
V_T
$2V_T$
$3V_T$
$4V_T$
V_{id}

$$I_{C1} - I_{C2} = I_{EE}\tanh\left(\frac{V_{id}}{2V_T}\right)$$

$$V_{od} = V_{o1} - V_{o2} = -(I_{C1} - I_{C2})R_C = -I_{EE}R_C\tanh\left(\frac{V_{id}}{2V_T}\right)$$

$$\boxed{\therefore V_{od} = -I_{EE}R_C\tanh\left(\frac{V_{id}}{2V_T}\right)}$$

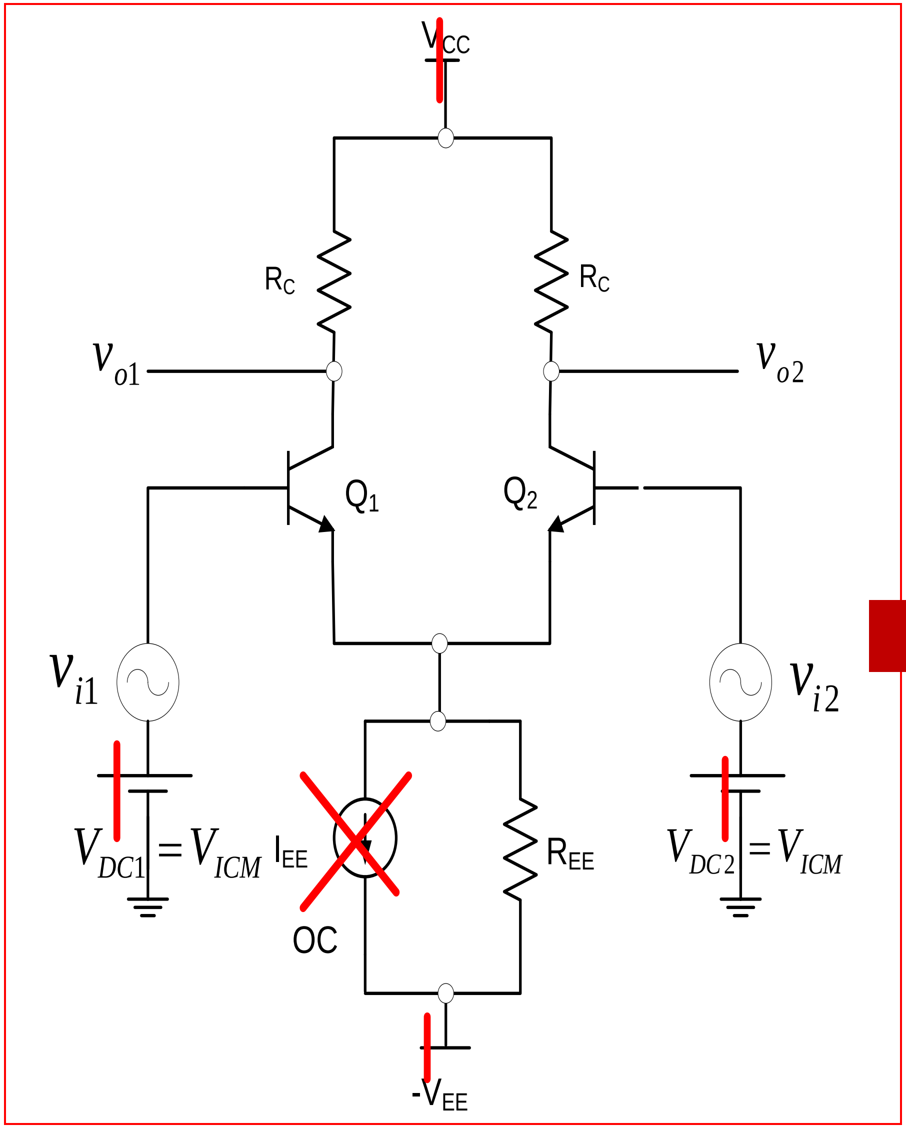
$$\boxed{V_{od} = -I_{EE}R_C \tanh\left(\frac{V_{id}}{2V_T}\right)}$$



Note: $\boxed{V_{od} \cong \left(\frac{I_{EE}R_C}{2V_T}\right)V_{id}}$ For $\boxed{\left|V_{id}\right| << V_T}$

Small-signal analysis

Small-signal operation of BJT differential pair
(a) Using small-signal model

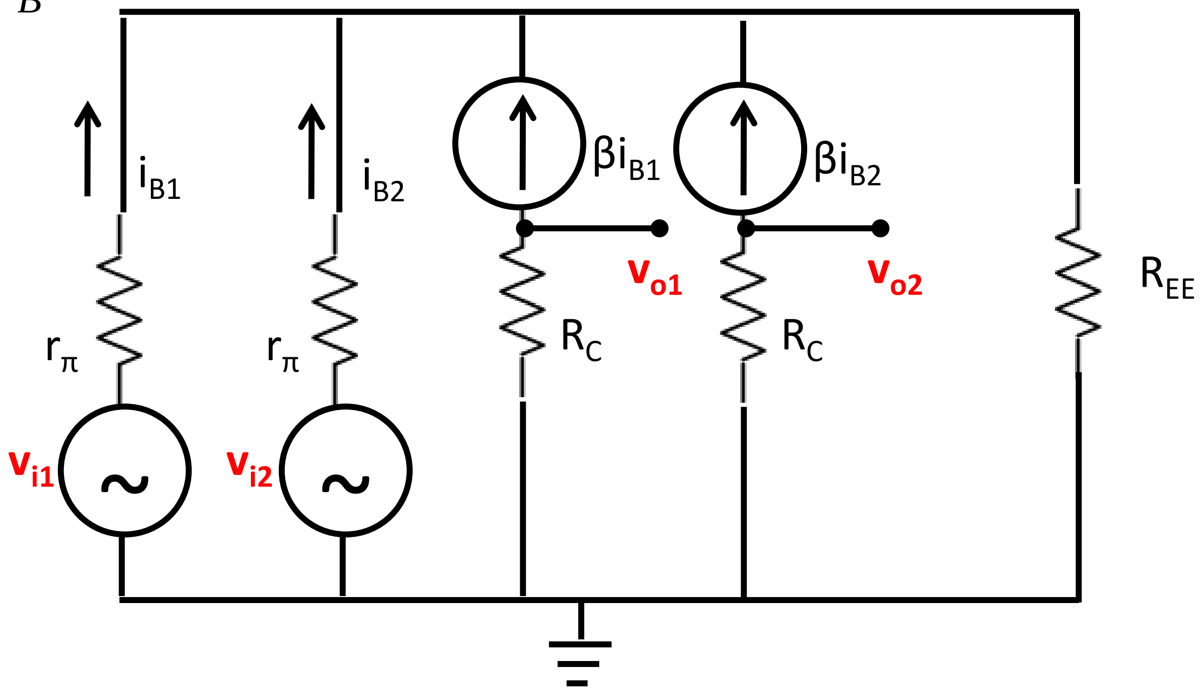


$$v_{i1} = v_{ic} - \frac{v_{id}}{2}$$

$$v_{i2} = v_{ic} + \frac{v_{id}}{2}$$

Case 1: $v_{id} = 0 \Rightarrow v_{i1} = v_{i2} = v_{ic}$ (Common-mode)

$$\because v_{i1} = v_{i2} \Rightarrow \therefore i_{B1} = i_{B2} = i_B$$



$$v_{R_{EE}} = 2R_{EE}(\beta + 1)i_B$$

$$i_B = \frac{v_{ic}}{2(\beta+1)R_{EE} + r_\pi}$$

$$\boxed{\therefore \frac{v_{o1}}{v_{ic}} = \frac{v_{o2}}{v_{ic}} = \frac{\beta R_C}{2(\beta+1)R_{EE} + r_\pi} \approx \frac{g_m R_C}{1 + 2g_m R_{EE}}}$$

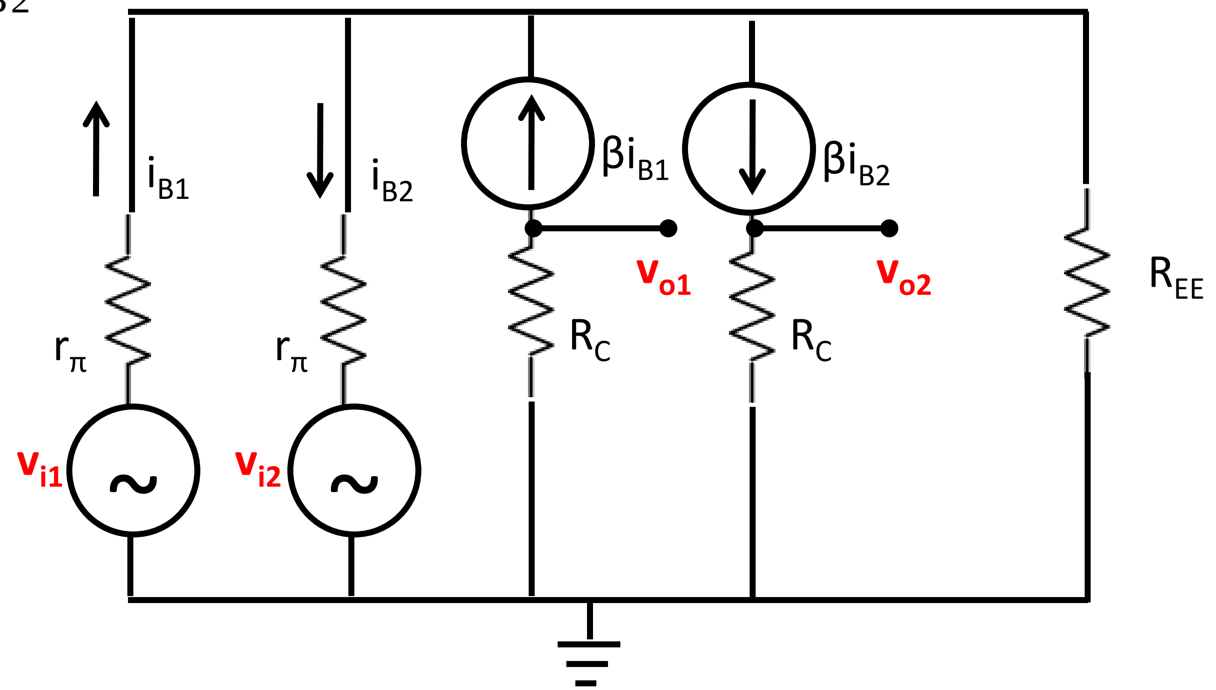
$$\boxed{A_{CM} \equiv \frac{v_{o1}}{v_{ic}} \approx \frac{g_m R_C}{1 + 2g_m R_{EE}}}$$

Case 2: $v_{ic} = 0 \Rightarrow v_{i1} = -v_{i2} = v_{id}/2$ (Differential-mode)

$$\because v_{i1} = -v_{i2} \Rightarrow \therefore i_{B1} = -i_{B2}$$

$$\therefore v_{R_{EE}} = 0$$

$$i_{B1} = \frac{v_{id}/2}{r_\pi}$$

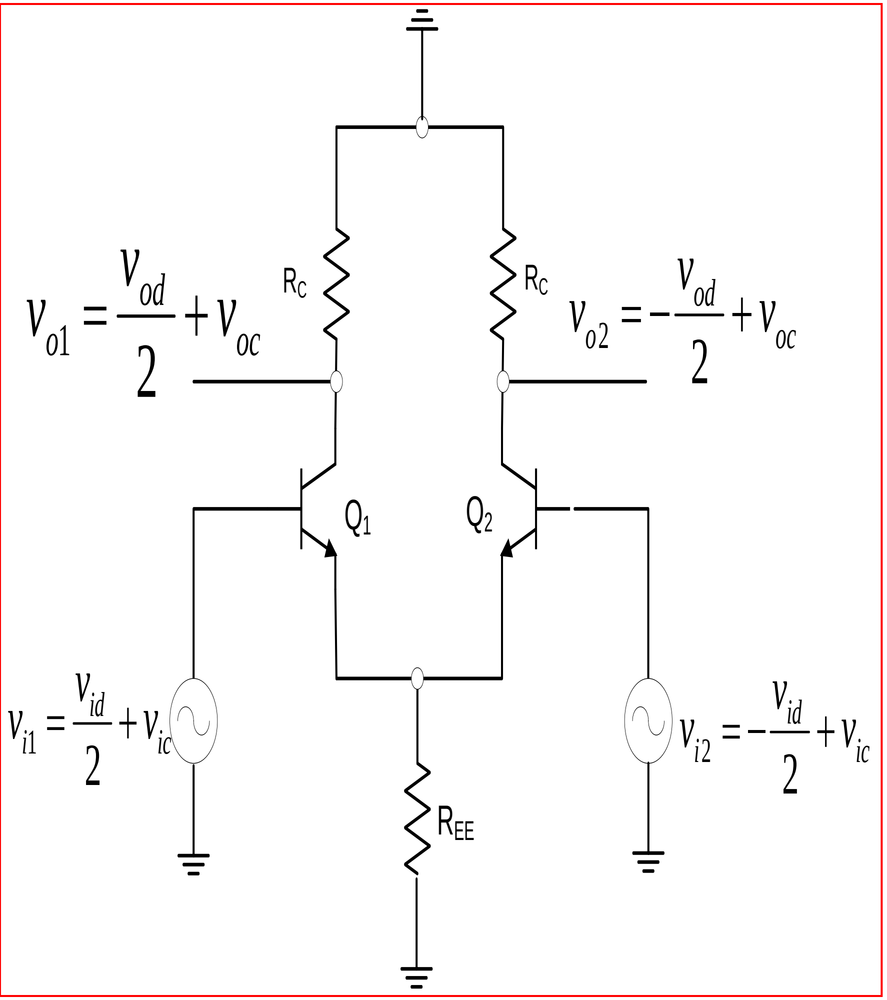


$$\boxed{\therefore \frac{v_{o1}}{v_{id}/2} = -\frac{v_{o2}}{v_{id}/2} = -g_m R_C}$$

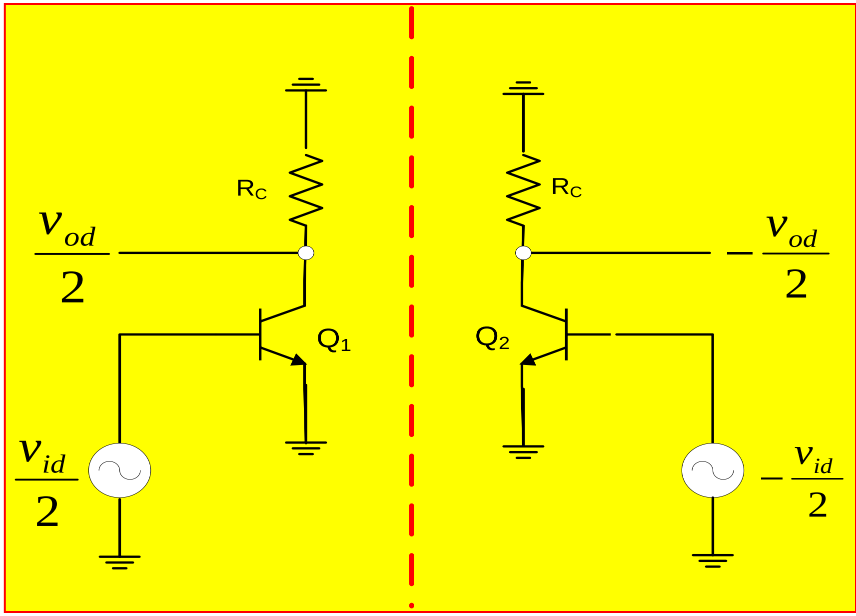
$$\boxed{A_{DM} \equiv \frac{v_{o2} - v_{o1}}{v_{id}} = g_m R_C}$$

$$\boxed{CMRR \equiv \frac{A_{DM}}{A_{CM}} = 1 + 2 g_m R_{EE}}$$

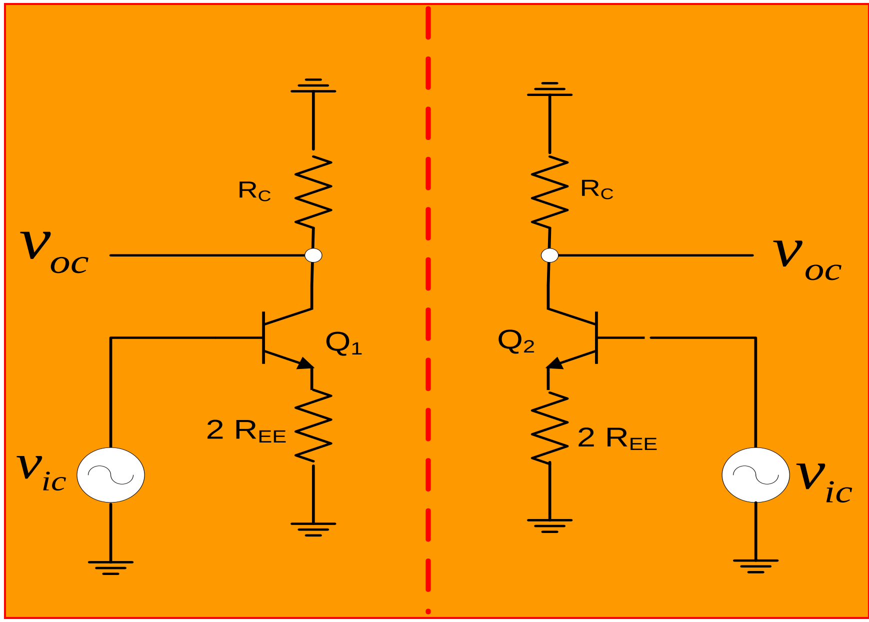
(b) Using half-circuit concept



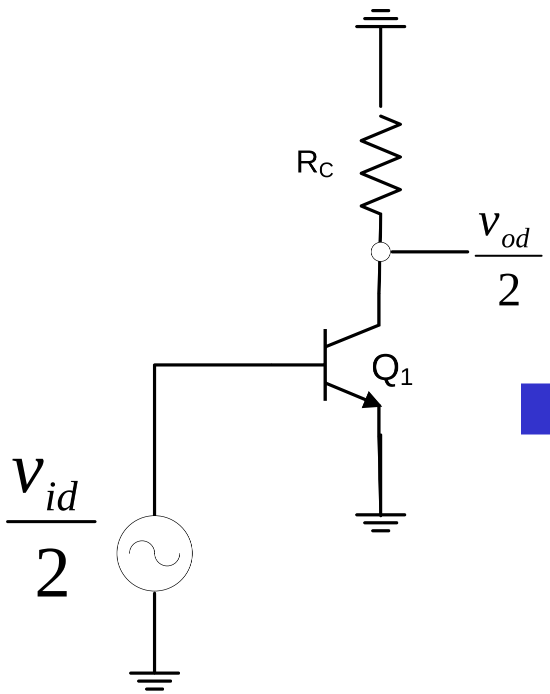
Differential-mode

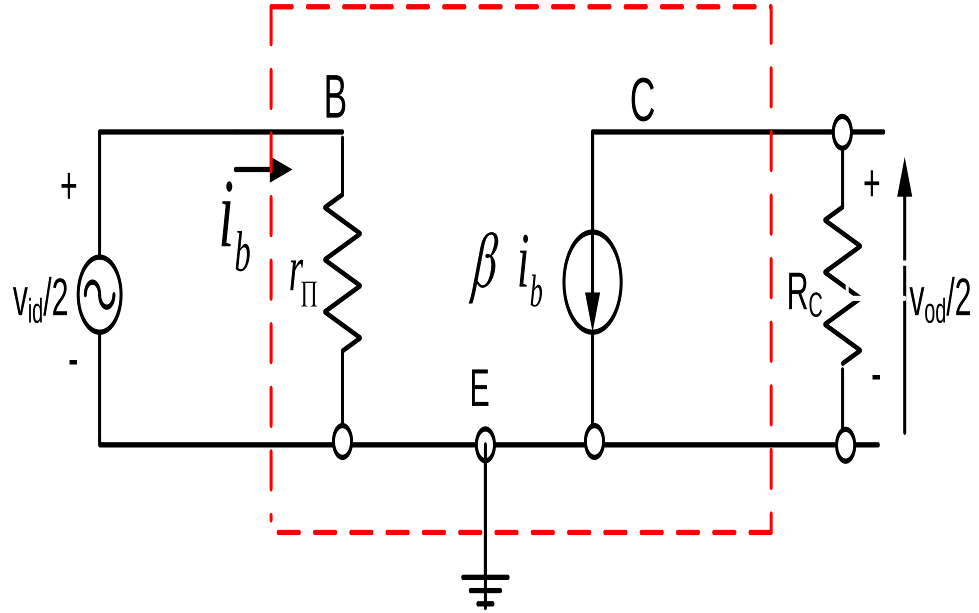


Common-mode



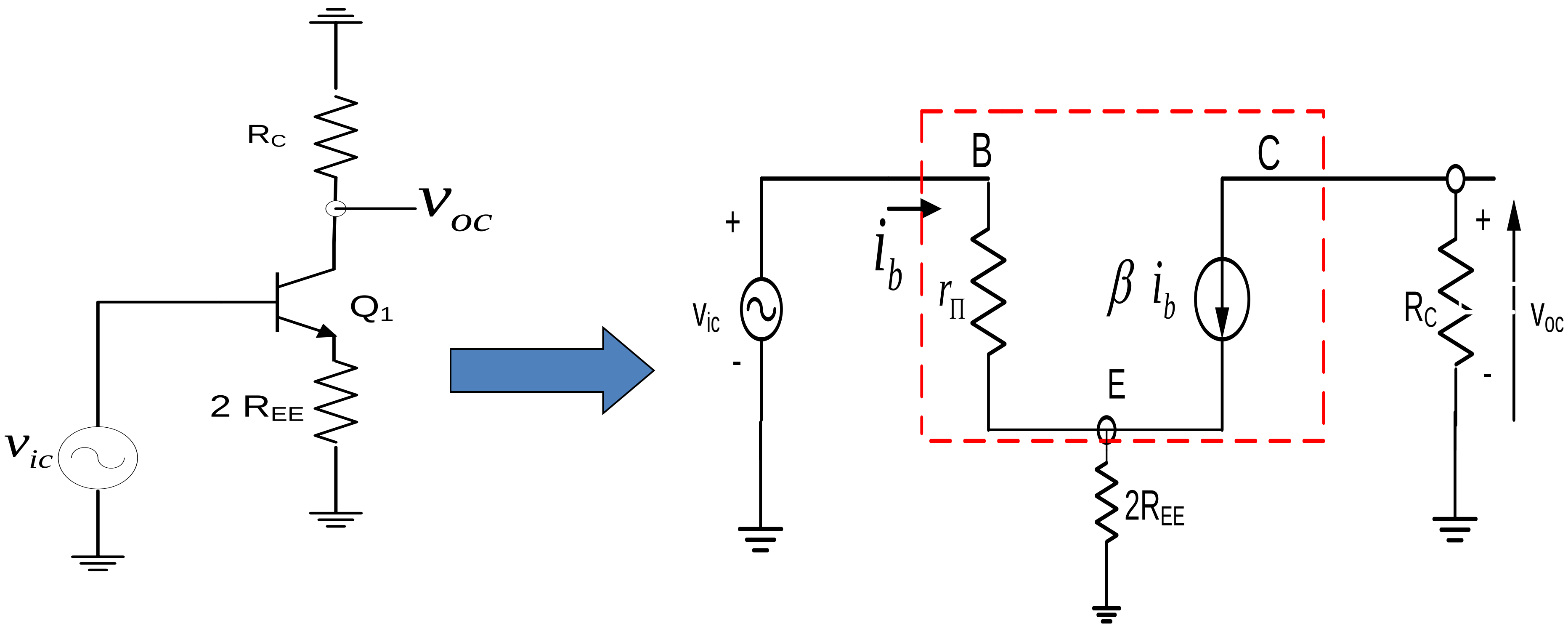
a- (Differential-mode)





$$A_{DM} = \frac{v_{od}}{v_{id}} = -\frac{\beta R_C}{r_\pi} = -g_m R_C$$

b- (Common-mode)



$$A_{CM}=\frac{v_{oc}}{v_{ic}}=-\frac{\beta R_C}{r_\pi+2(1+\beta)R_{EE}}\cong-\frac{g_m R_C}{1+2g_m R_{EE}}$$

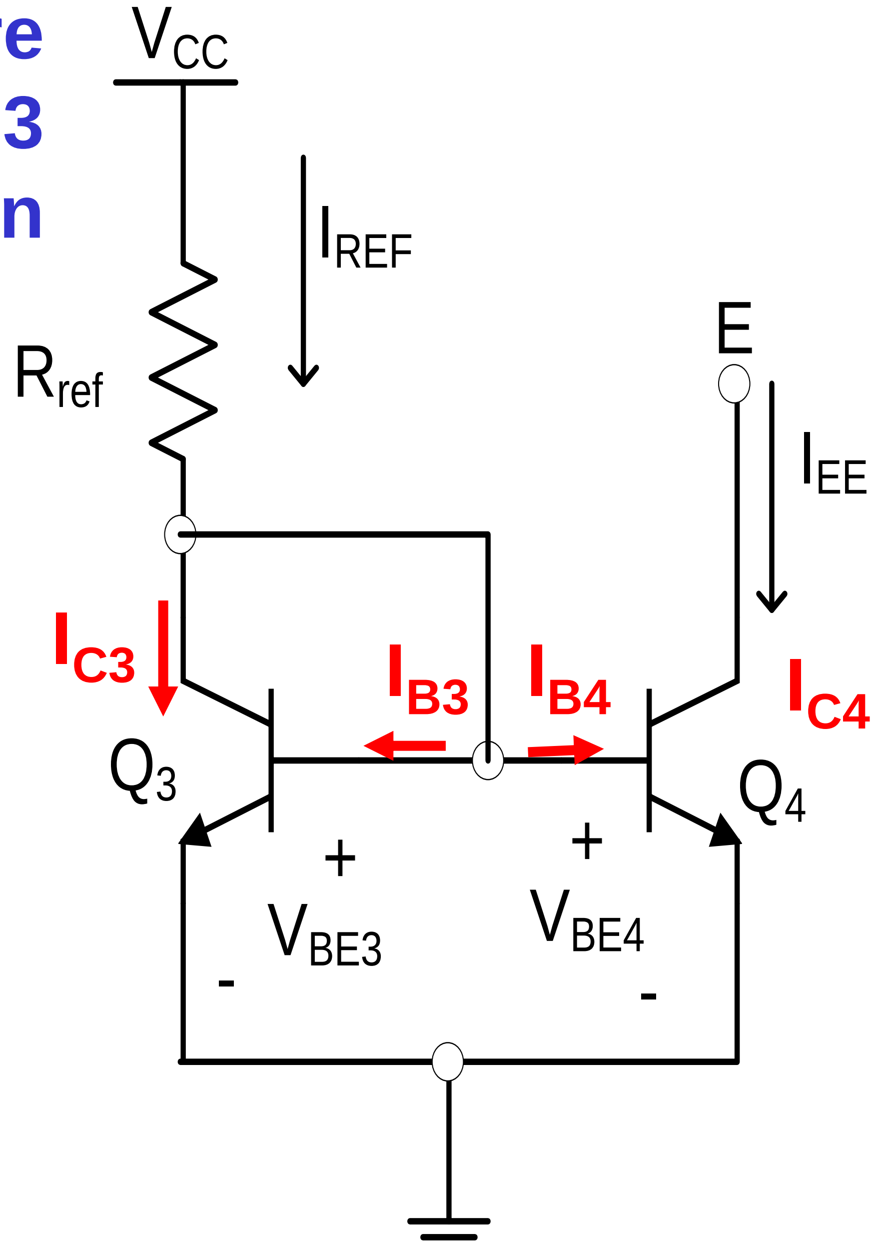
$$\therefore CMRR\equiv\frac{A_{DM}}{A_{CM}}=1+2g_m R_{EE}$$

Simple current source (Current mirror)

For Q3 and Q4 are matched transistors, Q3 is acting as a diode (in the active-mode)

$$V_{BE3} = V_{BE4} \Rightarrow I_{B3} = I_{B4}$$

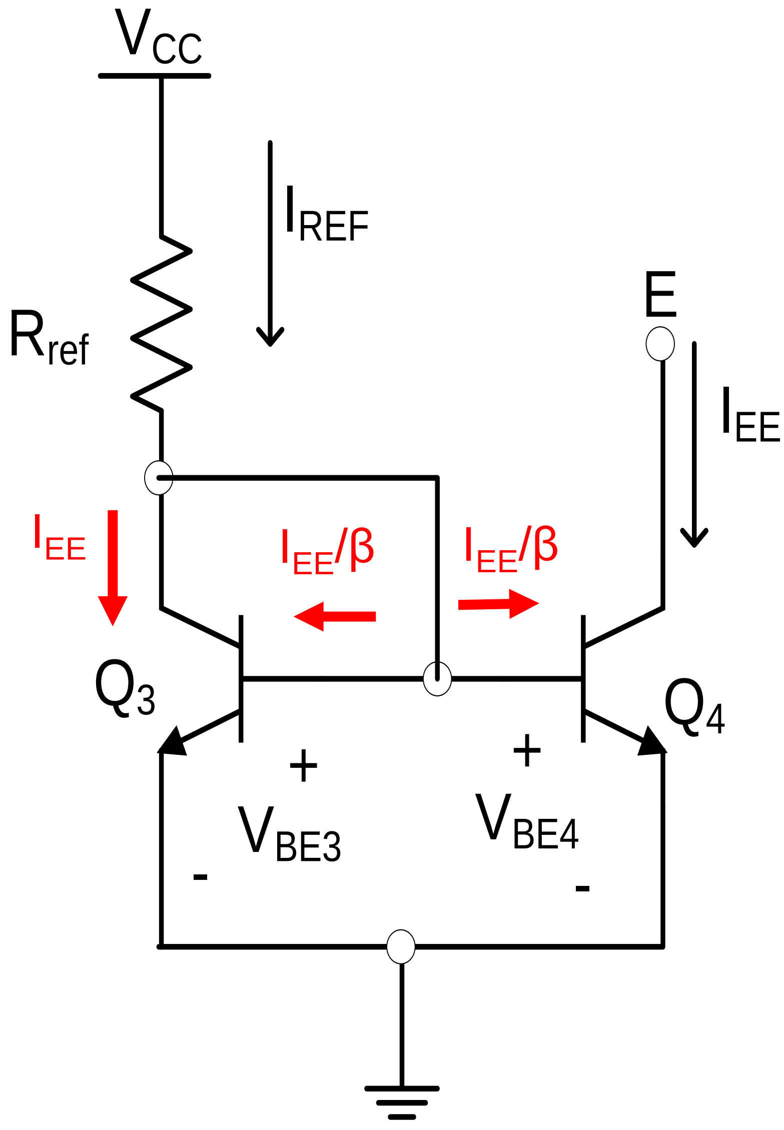
$$\boxed{\therefore I_{C3} = I_{C4} = I_{EE}}$$



$$I_{REF} = I_{EE} + \frac{2I_{EE}}{\beta}$$

$$I_{EE} = \frac{I_{REF}}{(1 + \frac{2}{\beta})}$$

$$\boxed{I_{REF} = \frac{(V_{CC} - V_{BE3})}{R_{ref}} = \frac{(V_{CC} - 0.7)}{R_{ref}}}$$



BJT differential amplifier biased by a current mirror