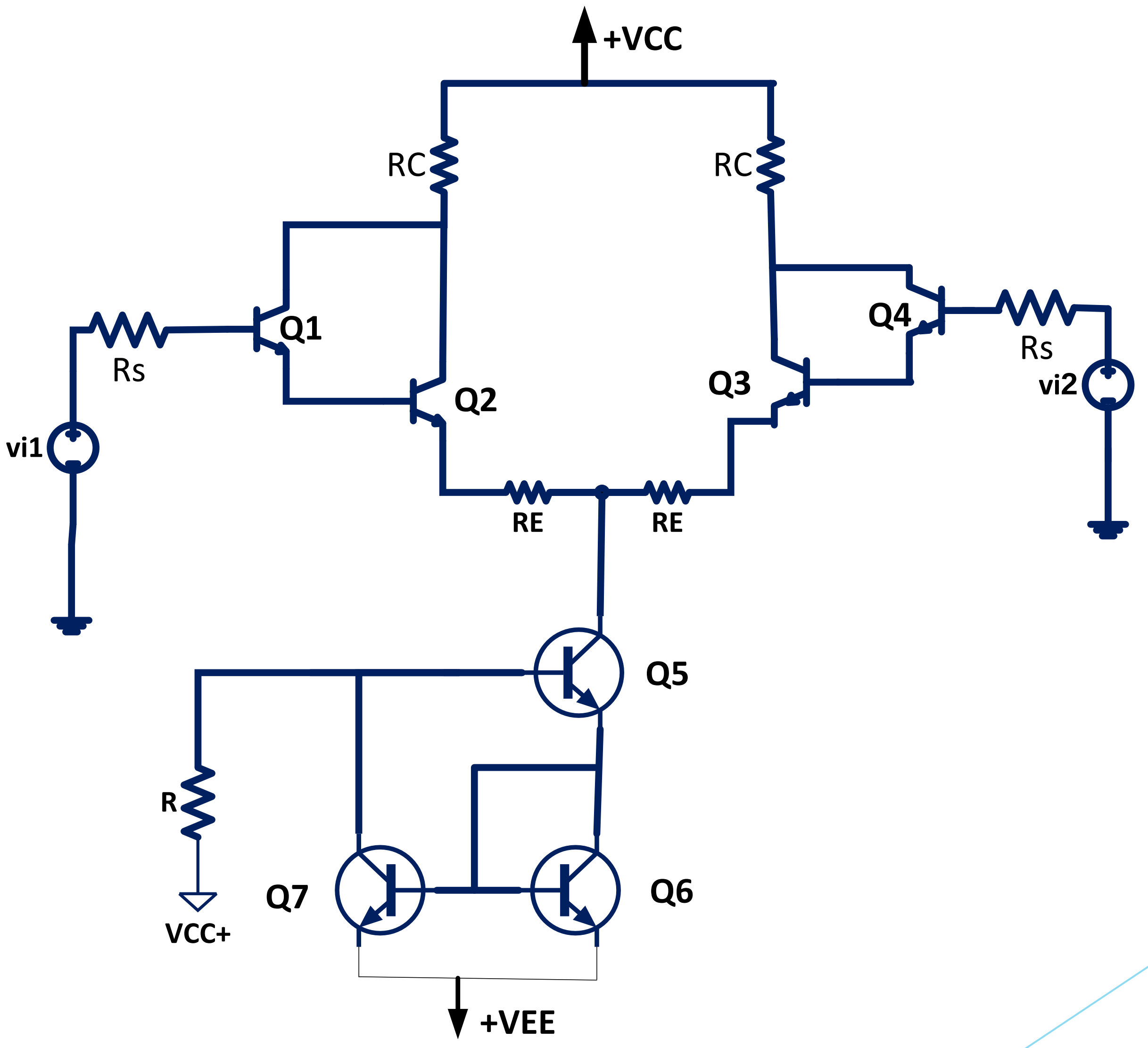
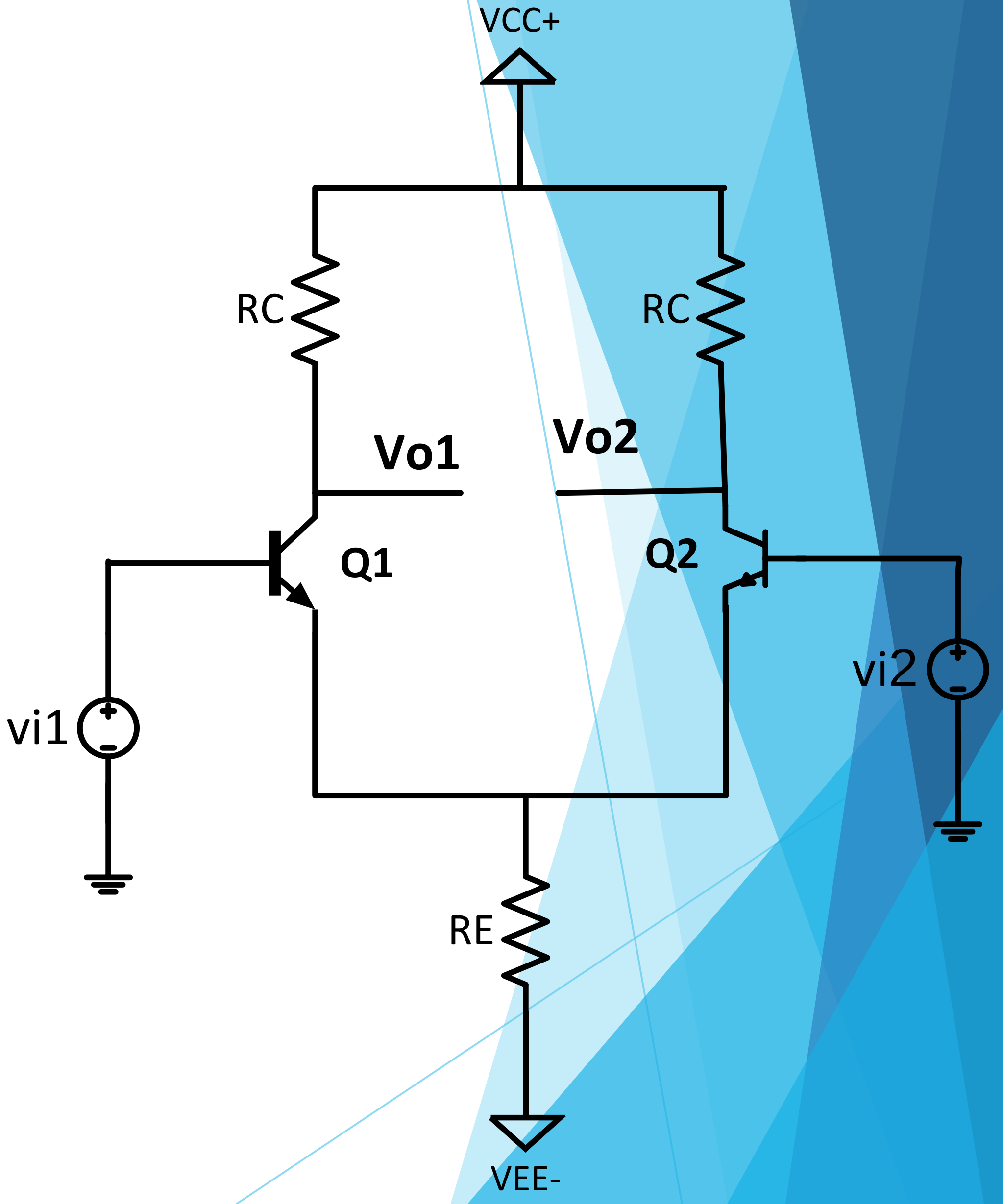
Differential Amplifiers



Differential Amplifiers

- Designed to amplify the difference between two input signal voltages.
- Found in many electronic circuits, including low and high frequency amplifiers.
- Almost always used as the input stage inside an IC operational amplifier to provide :
- Large input impedance .
- Rejection of the noise .



Differential Amplifiers

Simple Differential Amplifier

DC Analysis:

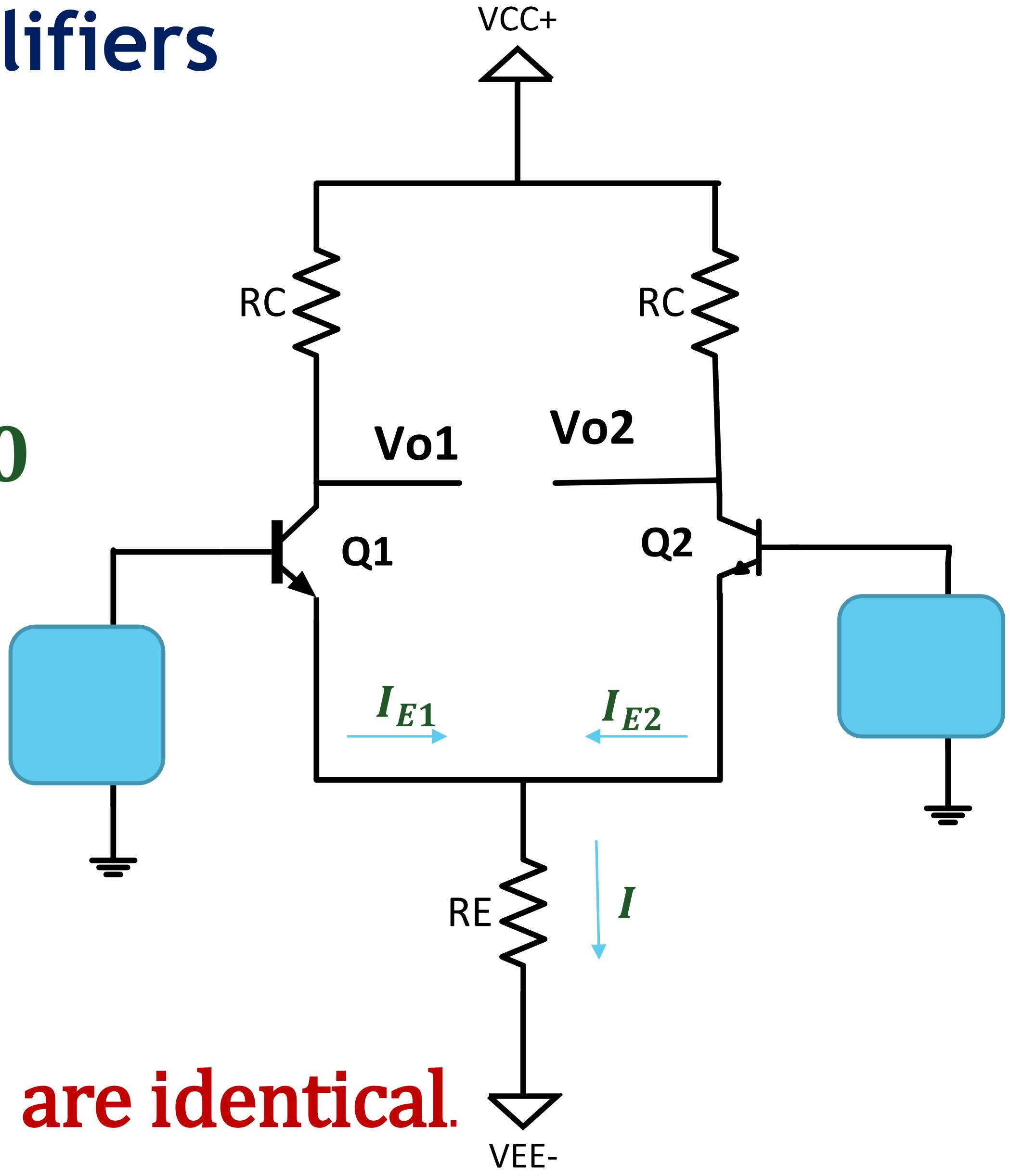
$$V_{B1} = V_{B2} = 0 \qquad since \quad v_{i1} = v_{i2} = 0$$

$$V_{E1} = V_{E2} = -0.7 \text{ v}$$

$$I = \frac{-0.7 + V_{EE}}{R_E}$$

$$I_{E1} = I_{E2} = \frac{1}{2} I$$

symmetry



Q1 & Q2 are identical.

$$\therefore \quad \beta_1 = \beta_2$$

Differential Amplifiers

Simple Differential Amplifier

Ac small Signal Analysis:

Calculate and sketch Vo1(t) and Vo2(t) if Vi1(t) = Vi2(t) = 100mV Peak sinusoidal

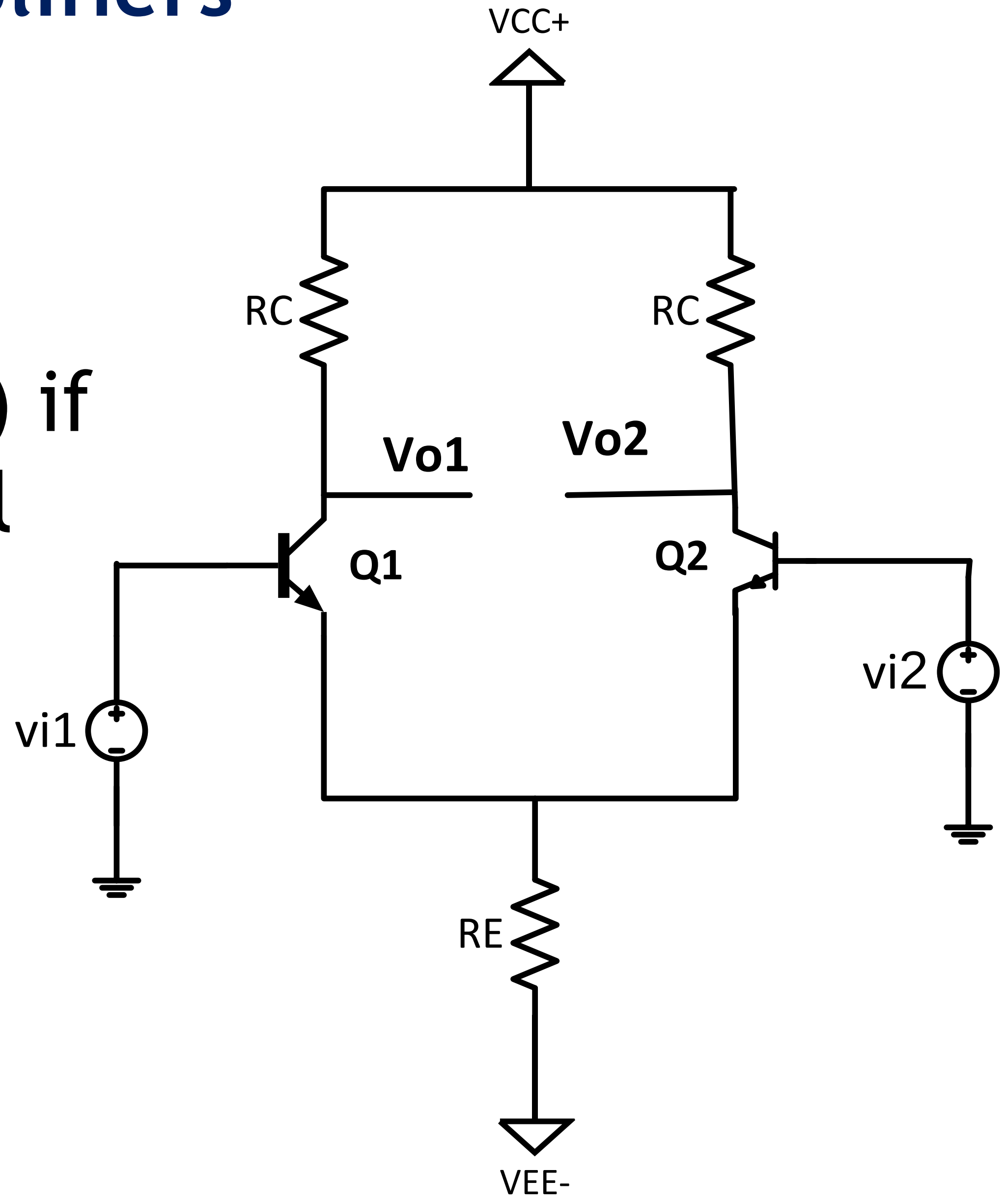
assuming

$$\beta_1 = \beta_2$$

and

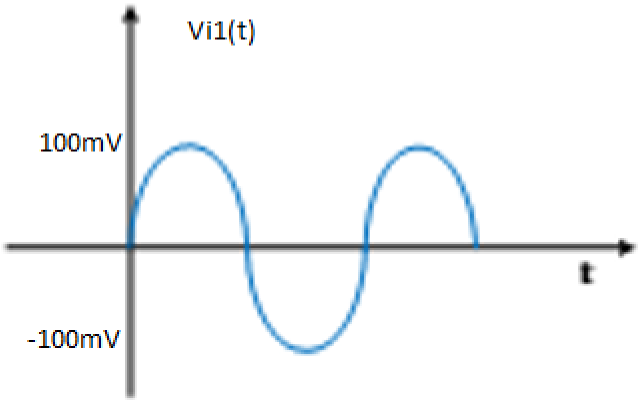
$$\frac{v_{c1}}{v_{be1}} = \frac{v_{c2}}{v_{be2}} = -100$$

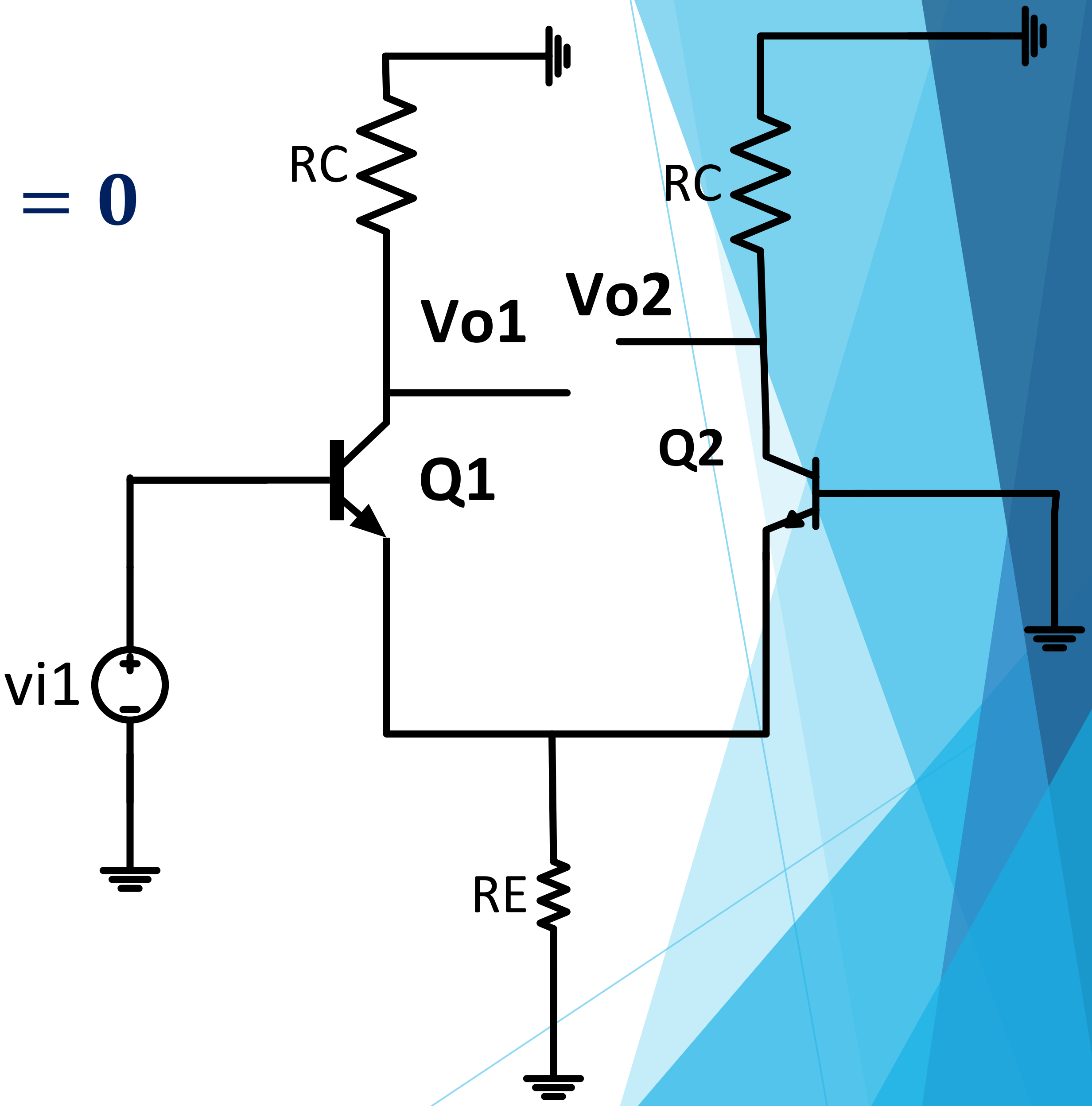
$$\frac{v_{o1}}{v_{be1}} = \frac{v_{o2}}{v_{be2}} = -100$$



Using superposition

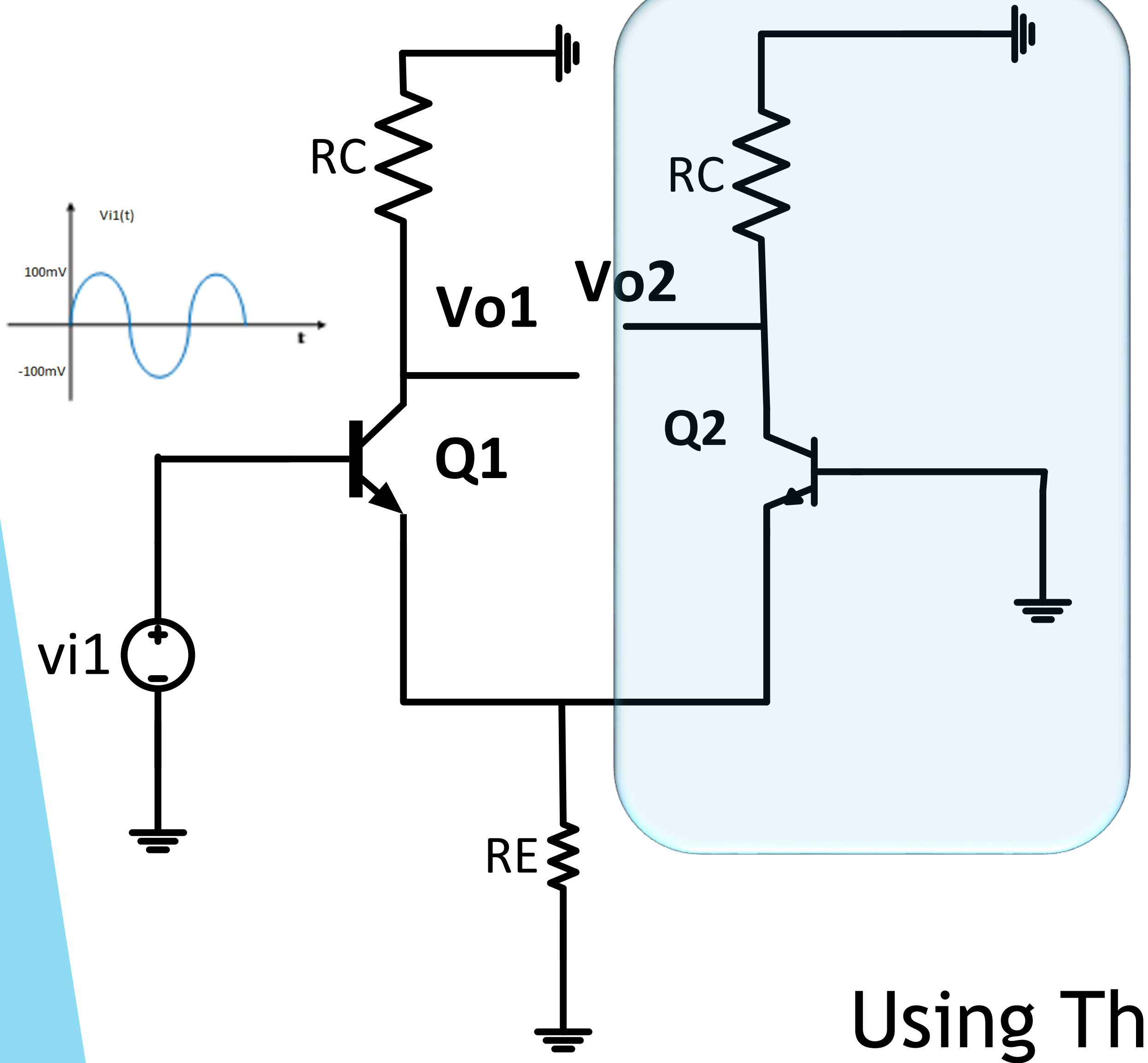
$$1)\ \ let\ \ v_{i1} = 100\, mV\ \ \ peak\, , v_{i2} = 0$$

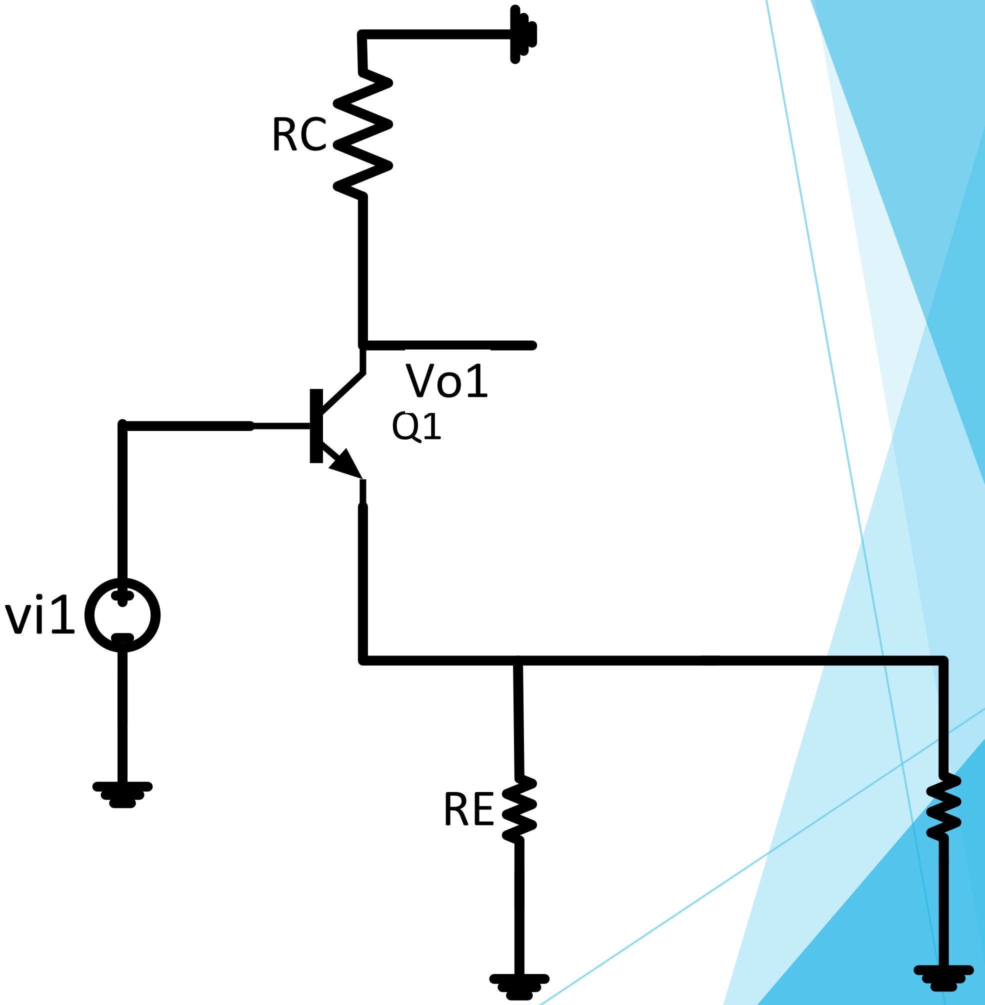




Simple Differential Amplifier

$$1)\ let\ v_{i1} = 100\, mV\ \ peak\ , v_{i2} = 0$$

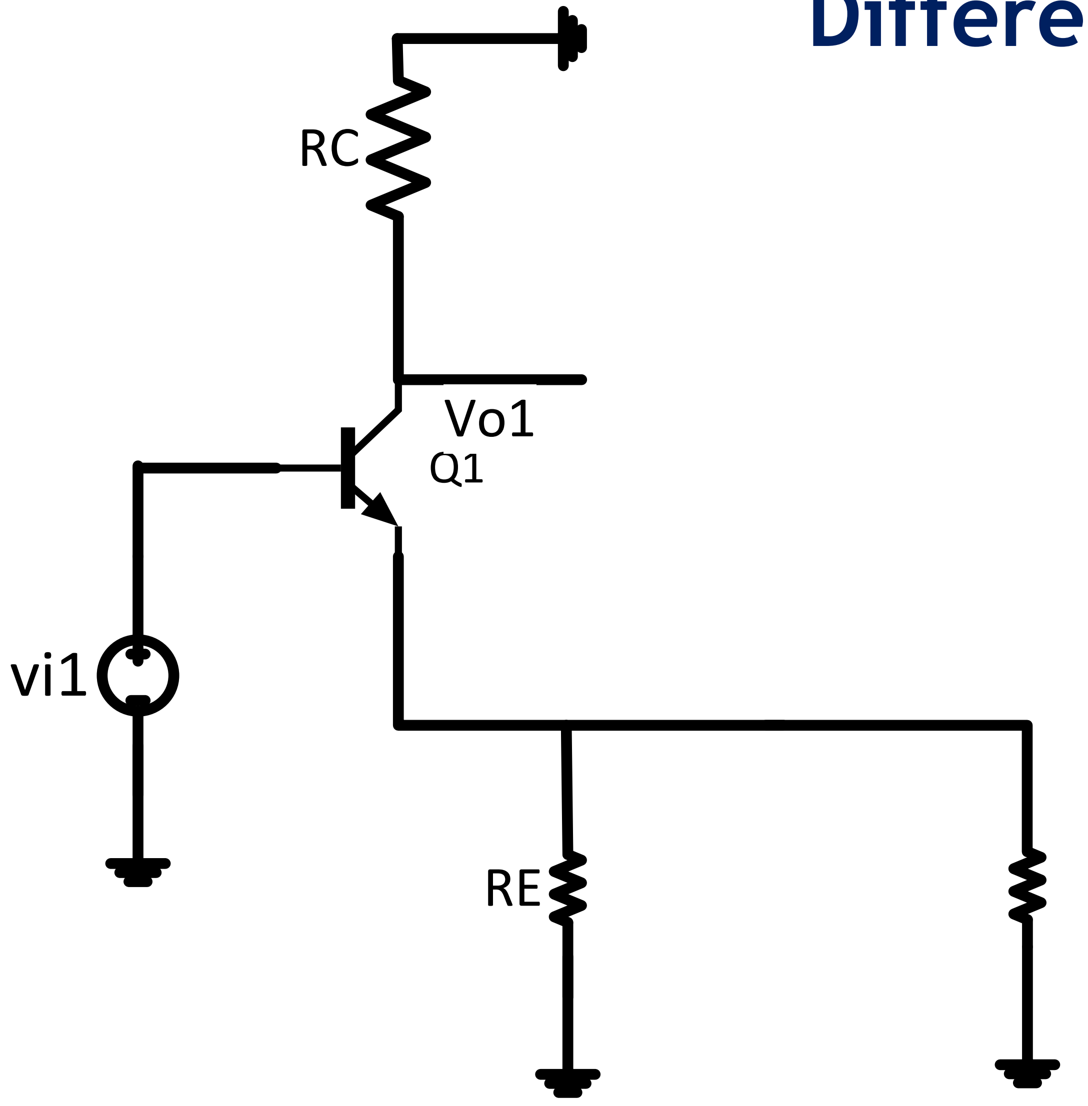




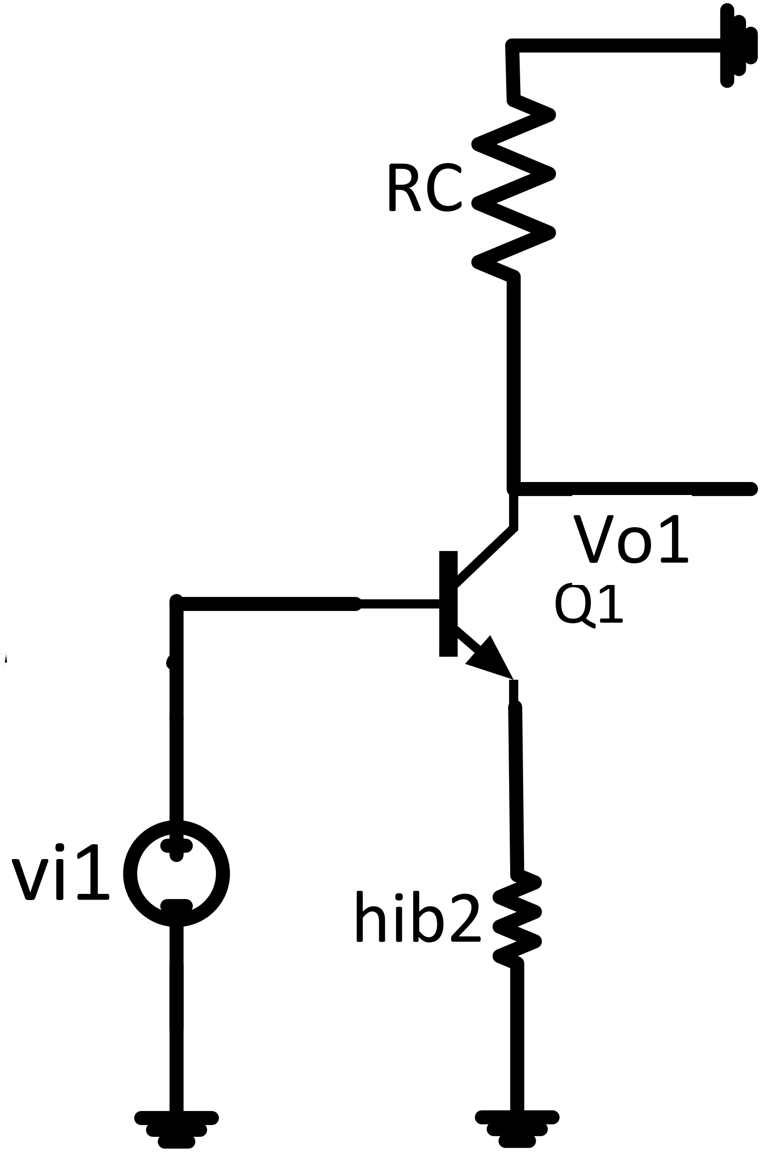
$$\frac{h_{ie2}}{h_{fe+1}} = h_{ib2}$$

Using Thevenin theorem

Differential Amplifiers



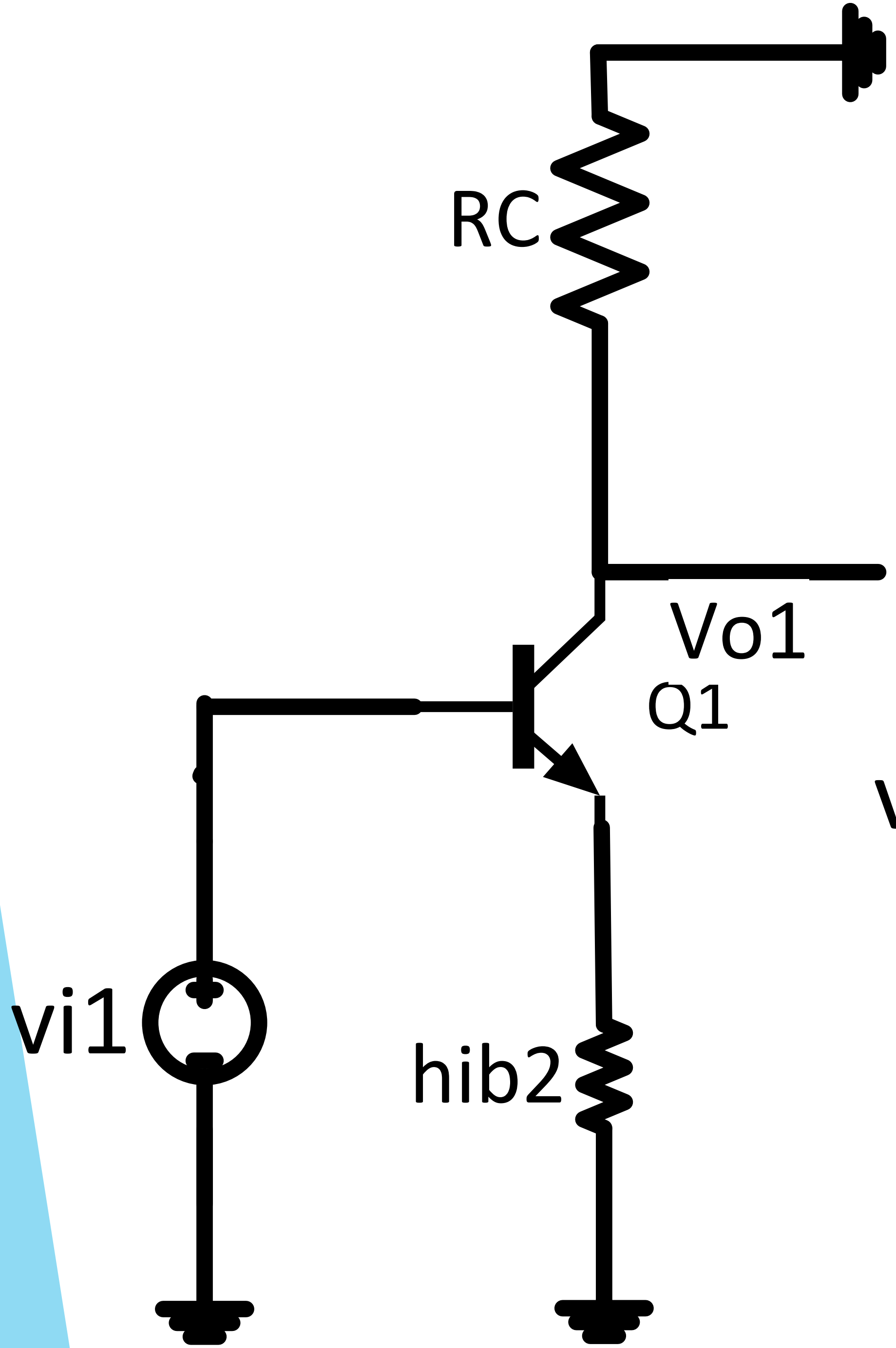
$$\frac{h_{ie2}}{h_{fe+1}} = h_{ib2}$$



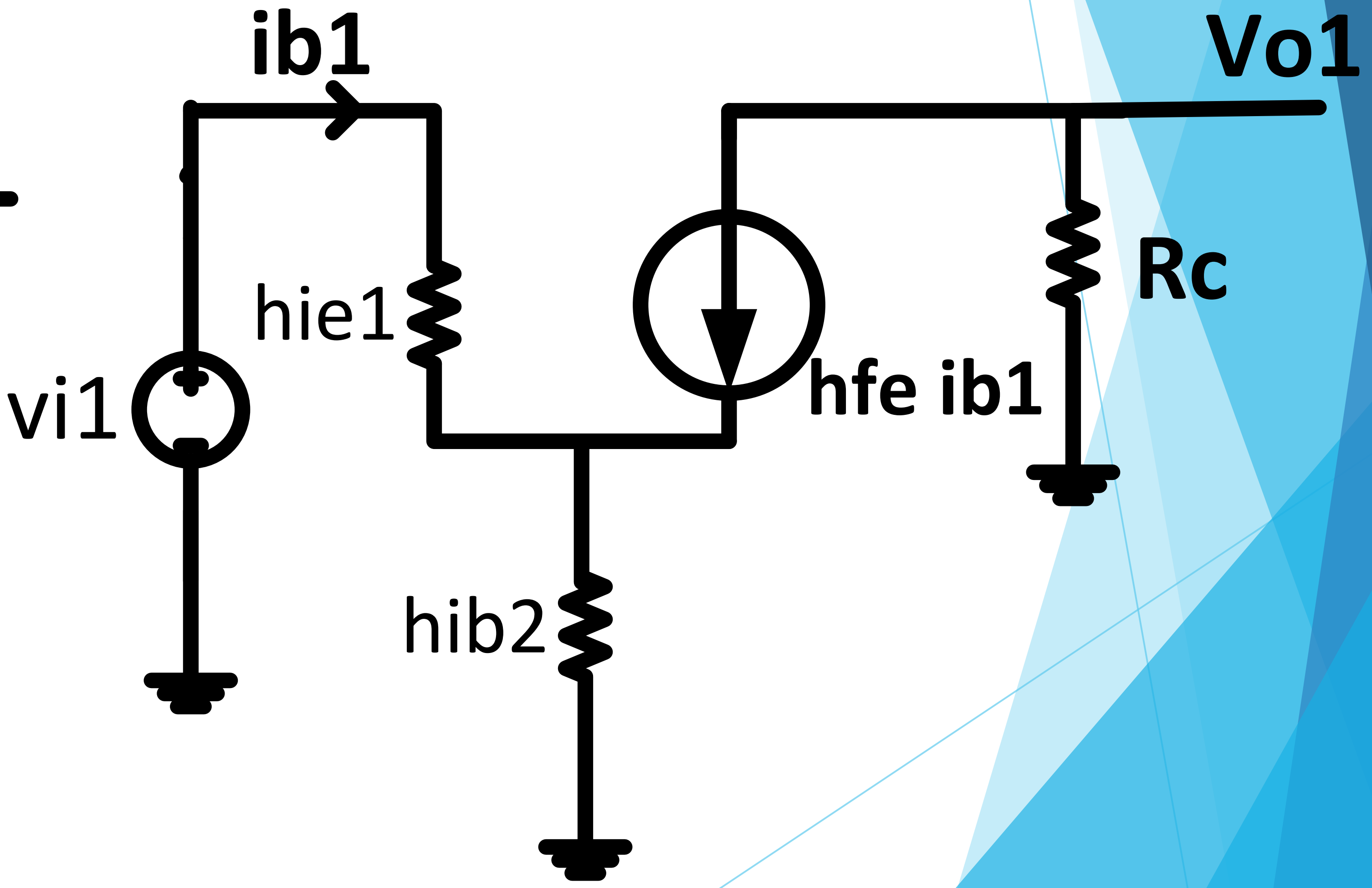
$$if \quad R_E \gg h_{ib2}$$

$$\therefore \quad R_E \,\|\, h_{ib2} \approx h_{ib2}$$

$$\frac{v_{o1}}{v_{be1}} = \frac{v_{o2}}{v_{be2}} = -100$$



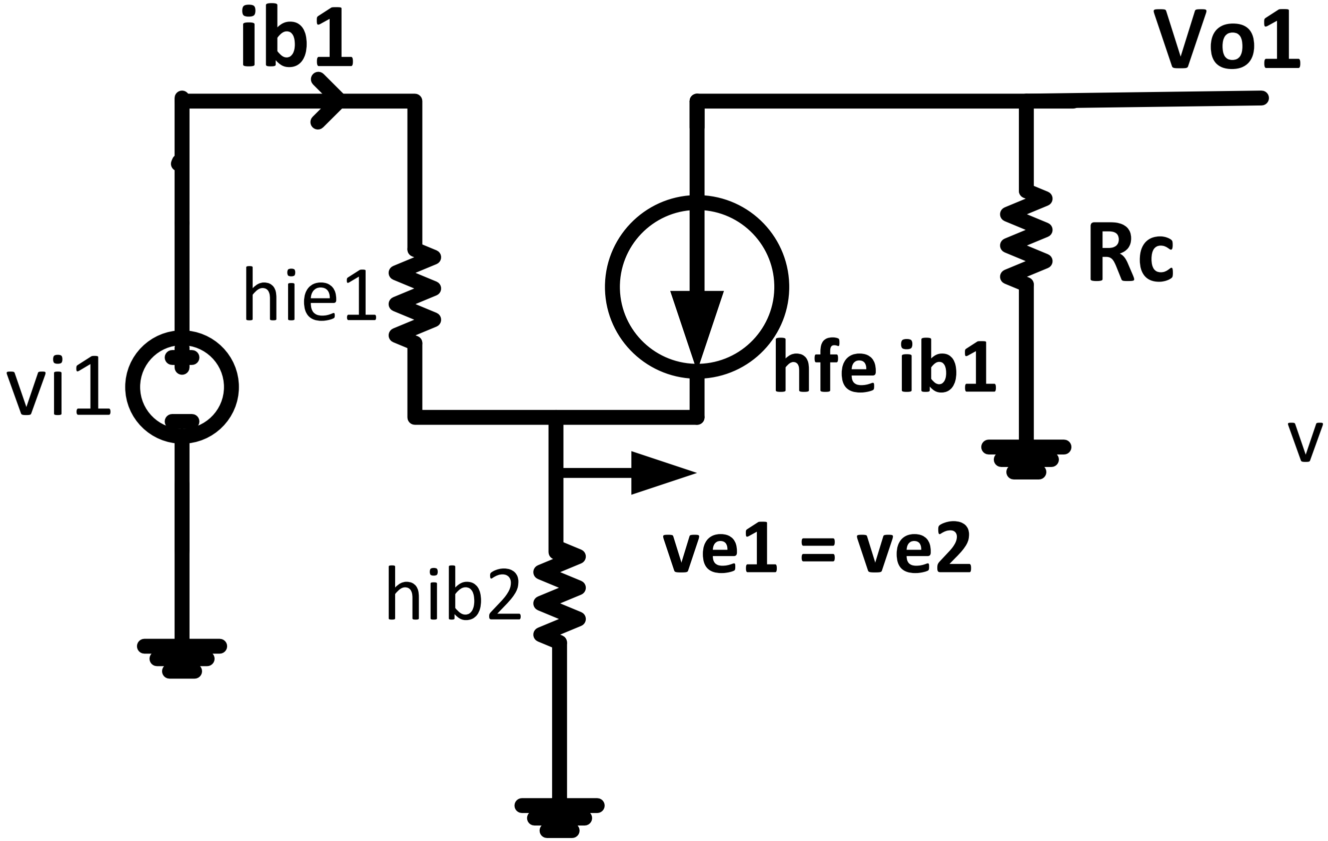
Ac small signal equivalent circuit



Differential Amplifiers

Simple Differential Amplifier

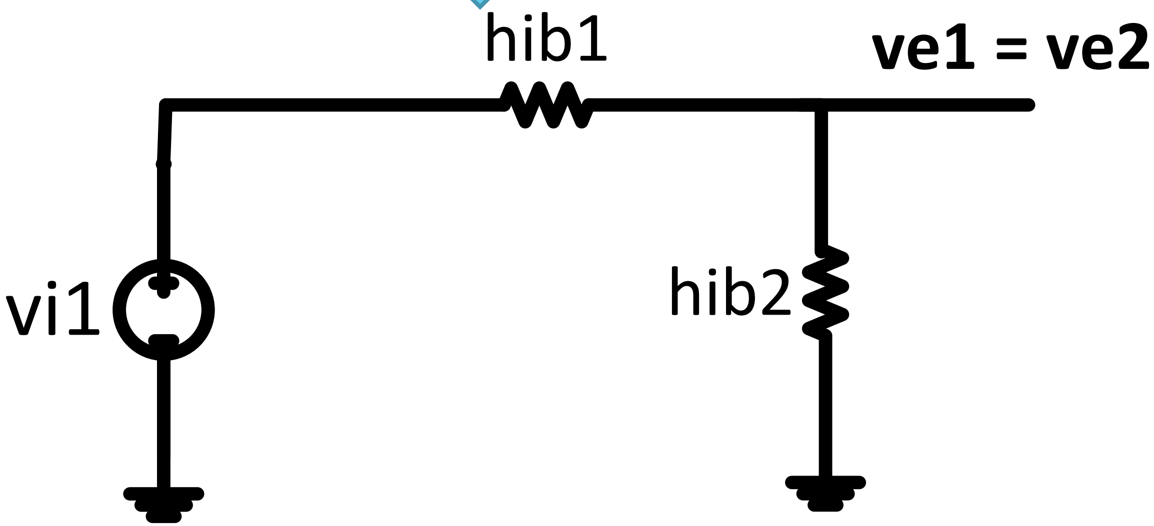
<u>AC Small Signal Analysis:</u>



hib1 = hib2

To find ve1 = ve2

Emitter equivalent circuit



$$v_{e1} = \frac{1}{2} v_{i1} = 50\ mV\ peak$$

Differential Amplifiers

$$\frac{v_{o1}}{v_{be1}} = \frac{v_{o2}}{v_{be2}} = -100$$

AC Small Signal Analysis:

$$v_{e1} = v_{e2} = \frac{1}{2} v_{i1} = 50\ mV\ peak$$

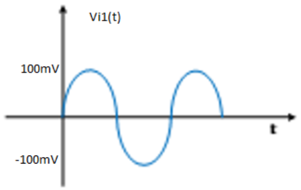
$$v_{be1} = v_{b1} - v_{e1}$$

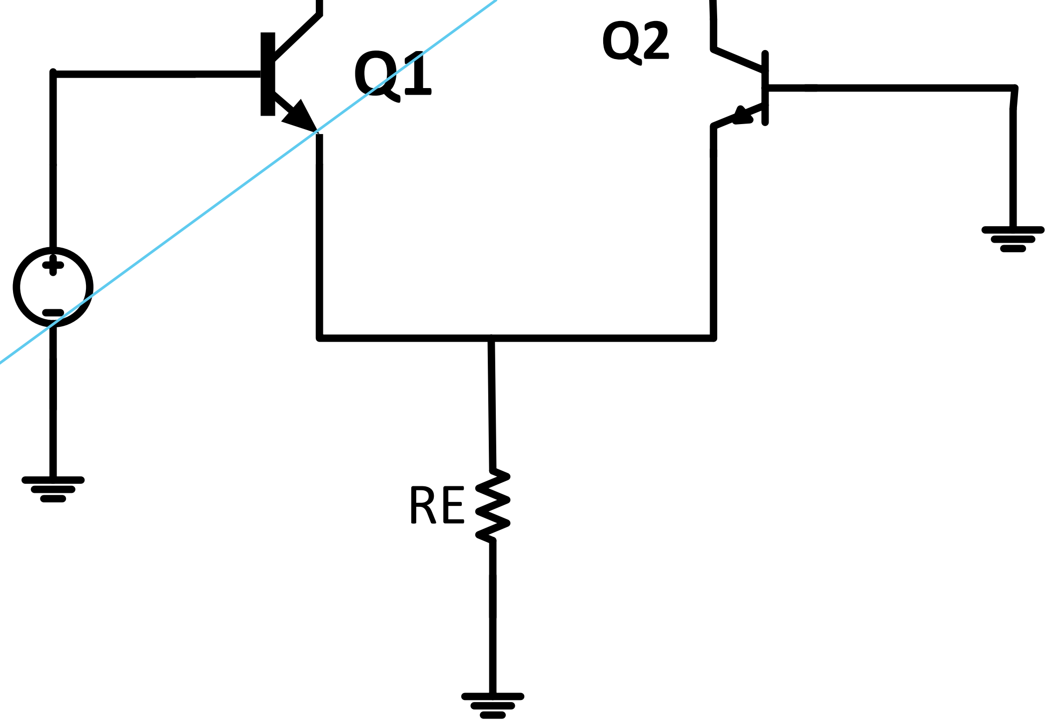
$$v_{be1} = 100\ mV\ peak - 50\ mV\ peak$$

$$v_{be1} = 50\ mV\ peak$$

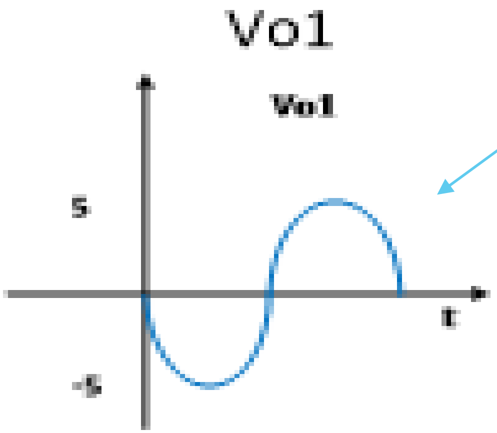
$$\therefore \quad v_{c1} = v_{o1} = (-100)(50\ mV\ peak)$$

$$\therefore \quad v_{c1} = -5\ V\ peak$$

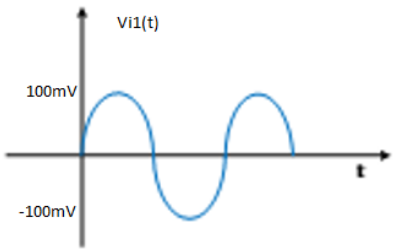


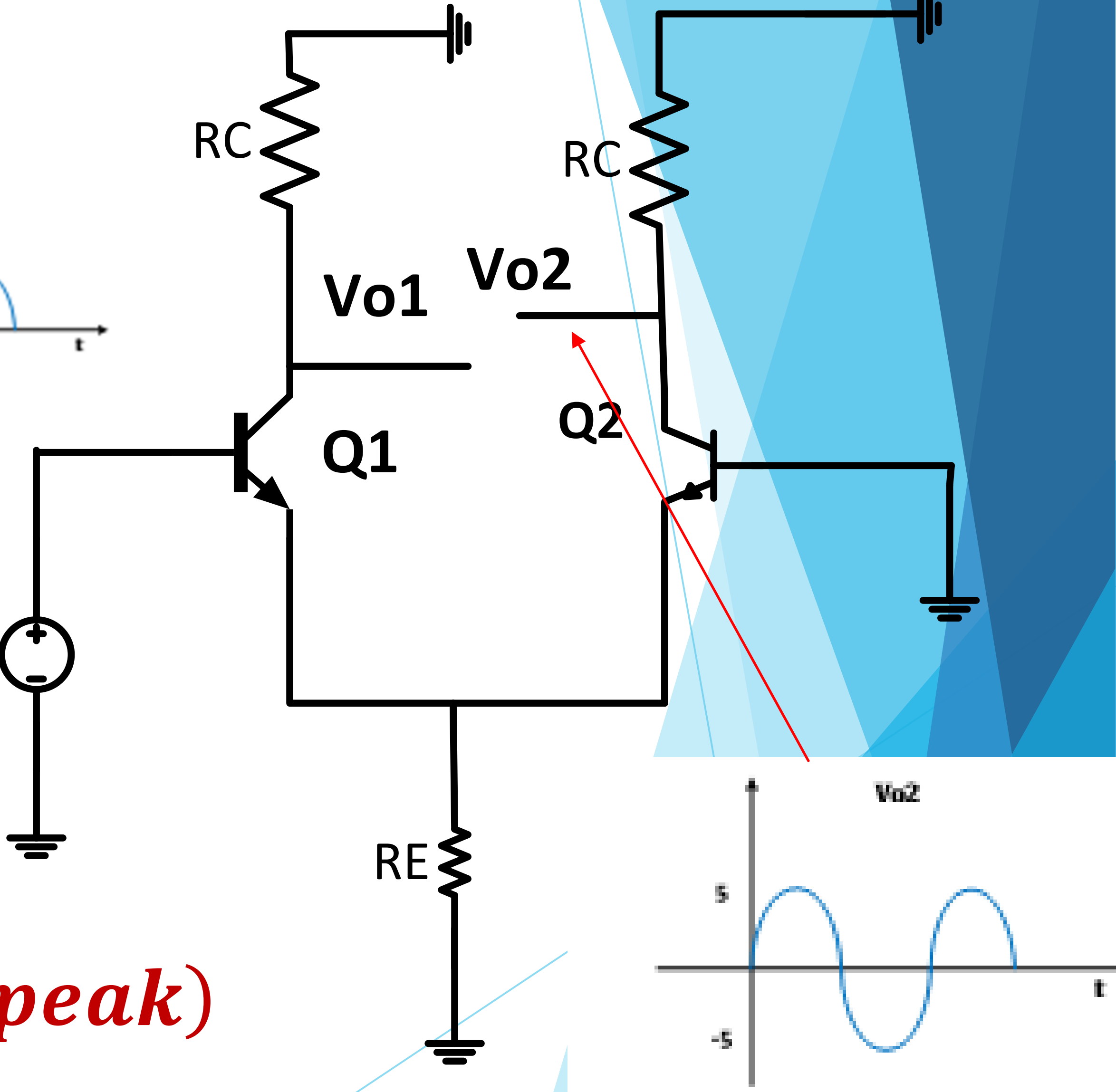


$$v_{o1} = -5\ V\ peak$$



$$\frac{v_{o2}}{v_{be2}} = -100$$





- $to\ find \quad v_{c2} = v_{o2} \quad ,$
- $we\ need\ to find \quad v_{be2}$
- $v_{be2} = v_{b2} - v_{e2}$
- $= v_{b2} - v_{e2}$
- $v_{be2} = 0 - 50\ mV\ peak$
- $v_{be2} = -50\ mV\ peak$
- $\therefore \quad v_{o2} = v_{c2} = (-100)(-50\ mV\ peak)$
- $v_{o2} = \ +5\ V\ peak$

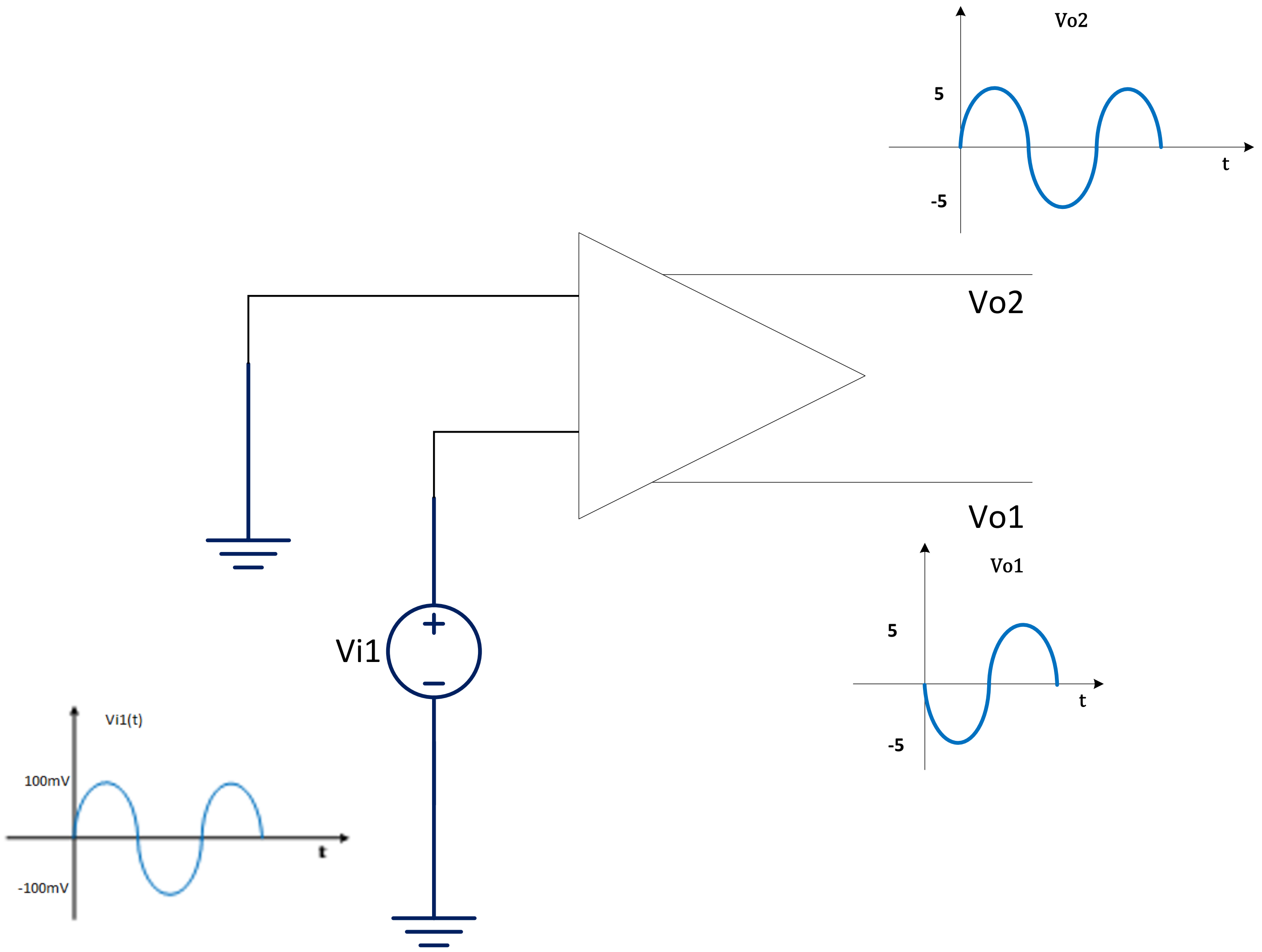
Differential Amplifiers

Simple Differential Amplifier

AC Small Signal Analysis:

$$v_{o1} = -5\,V\,peak$$

$$v_{o2} = +5\,V\,peak$$



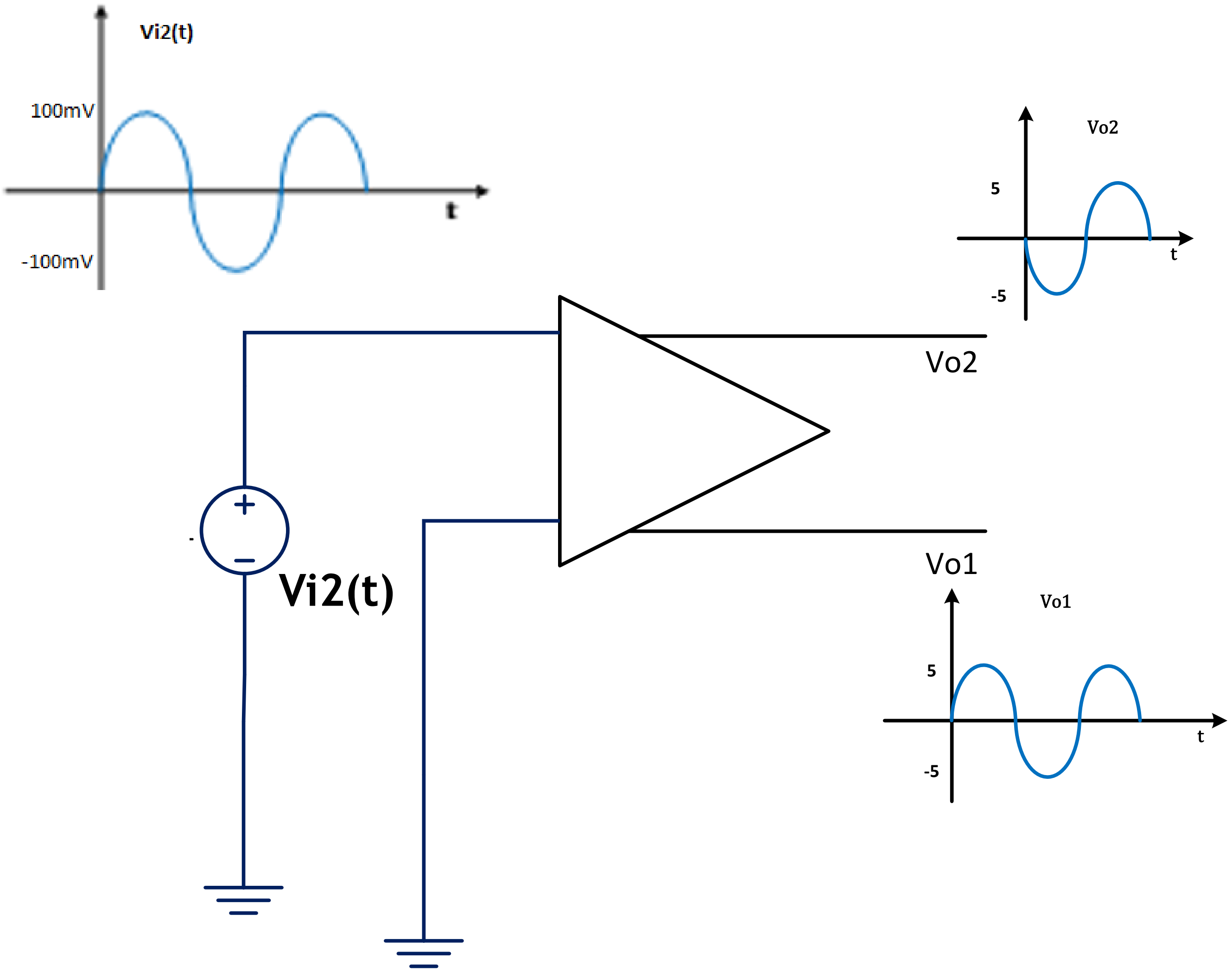
Differential Amplifiers

AC Small Signal Analysis:

Using same steps for

$$v_{i2} = 100\ mV\ peak$$
$$v_{i1} = 0$$

$$v_{o1} = +5\ V\ peak$$
$$v_{o2} = -5\ V\ peak$$



Differential Amplifiers

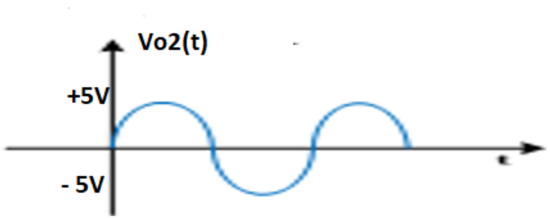
Simple Differential Amplifier

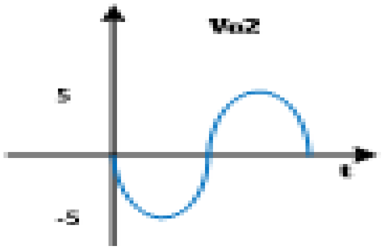
AC Small Signal Analysis:

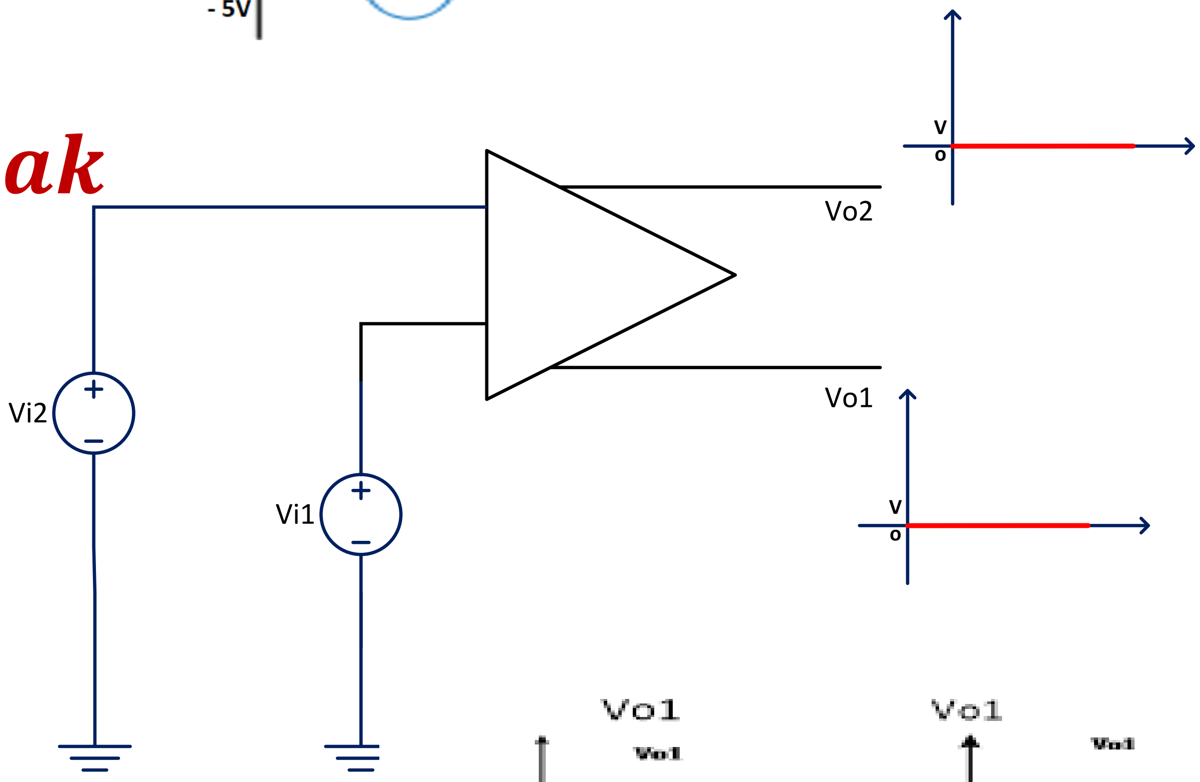
$$now\ if\ v_{i1} = v_{i2} = 100\ mV\ peak$$

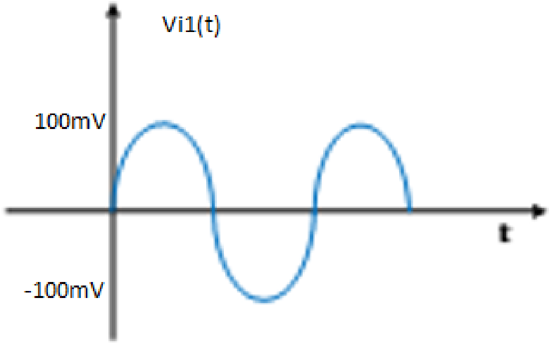
$$v_{o1} = 0$$

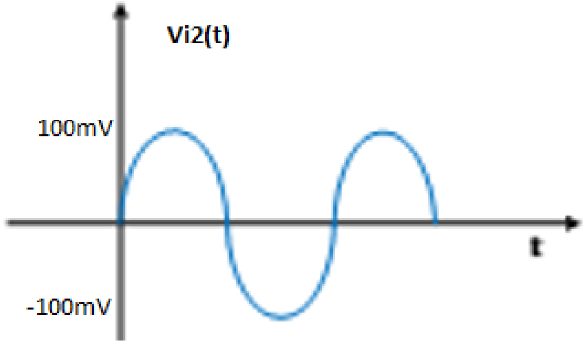
$$v_{o2} = 0$$

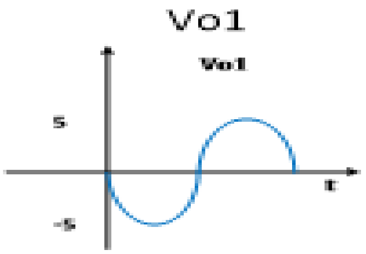


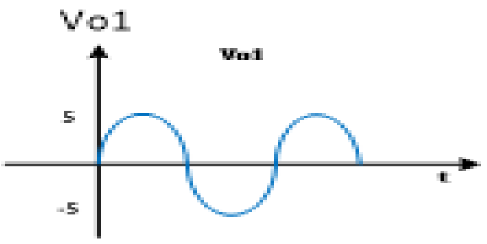












Differential Amplifiers

Simple Differential Amplifier

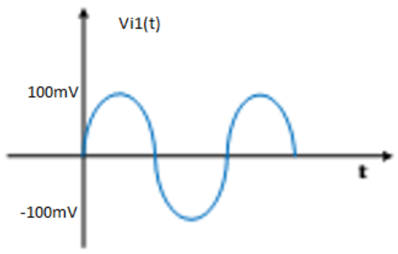
AC Small Signal Analysis:

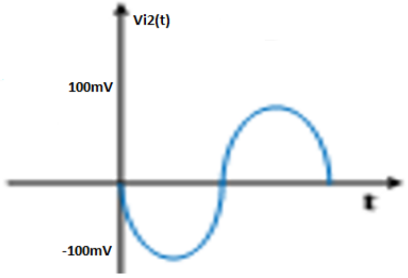
Using same steps for

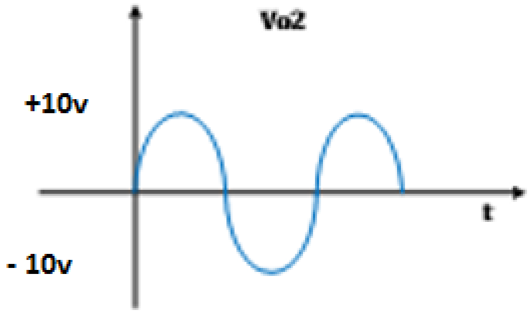
$$v_{i1} = 100\ \mathrm{m}V\ \mathbf{peak}$$
$$v_{i2} = -100\ \mathrm{m}V\ \mathbf{peak}$$

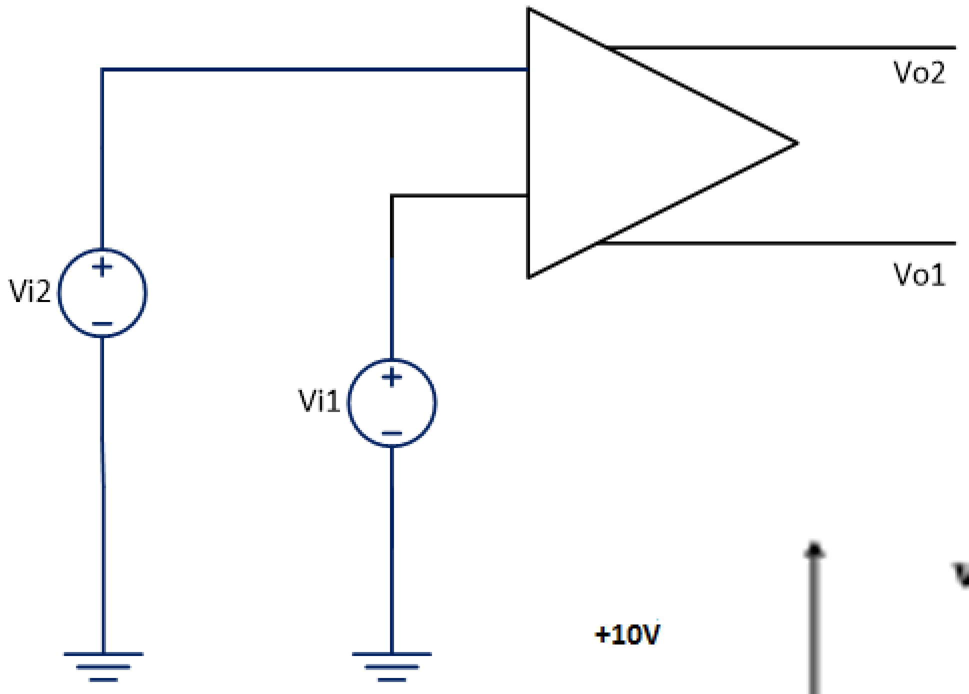
$$v_{o2} = +10\ \text{V}\ \ \text{peak}$$

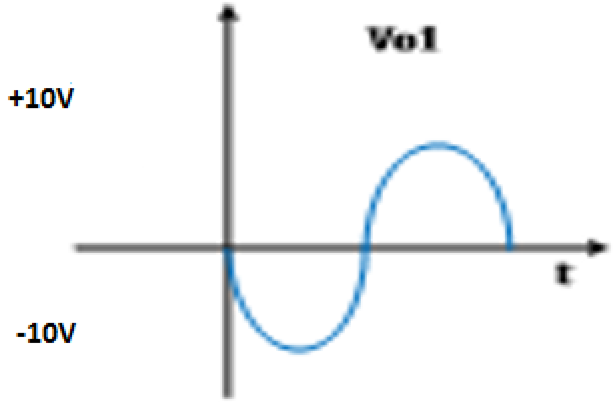
$$v_{o1} = -10\ \text{V peak}$$











Differential Amplifier Circuit:

Common Mode & Differential mode Signal

Since the differential amplifier is most often used to amplify the difference between two input signals.

$$let \quad v_d = v_{i2} - v_{i1}$$

$$v_d \equiv Differential\ mode\ input\ signal$$

$$let \quad v_c = \frac{v_{i2} + v_{i1}}{2}$$

$$v_c \equiv Common\ mode\ input\ signal$$

$$\therefore \quad v_{i2} = v_c + \frac{v_d}{2}$$

$$v_{i1} = v_c - \frac{v_d}{2}$$

Differential Amplifiers

Differential Amplifier Circuit:

Common Mode & Differential mode Signal

Input voltage can be represented in terms of a common mode and differential mode input signals.

In the usual application of the differential amplifier , the differential mode input is desired and to be amplified , while the common mode input is to be rejected.

Differential Amplifier Circuit:

DC Analysis: ⇨ $v_{i1} = v_{i2} = 0$

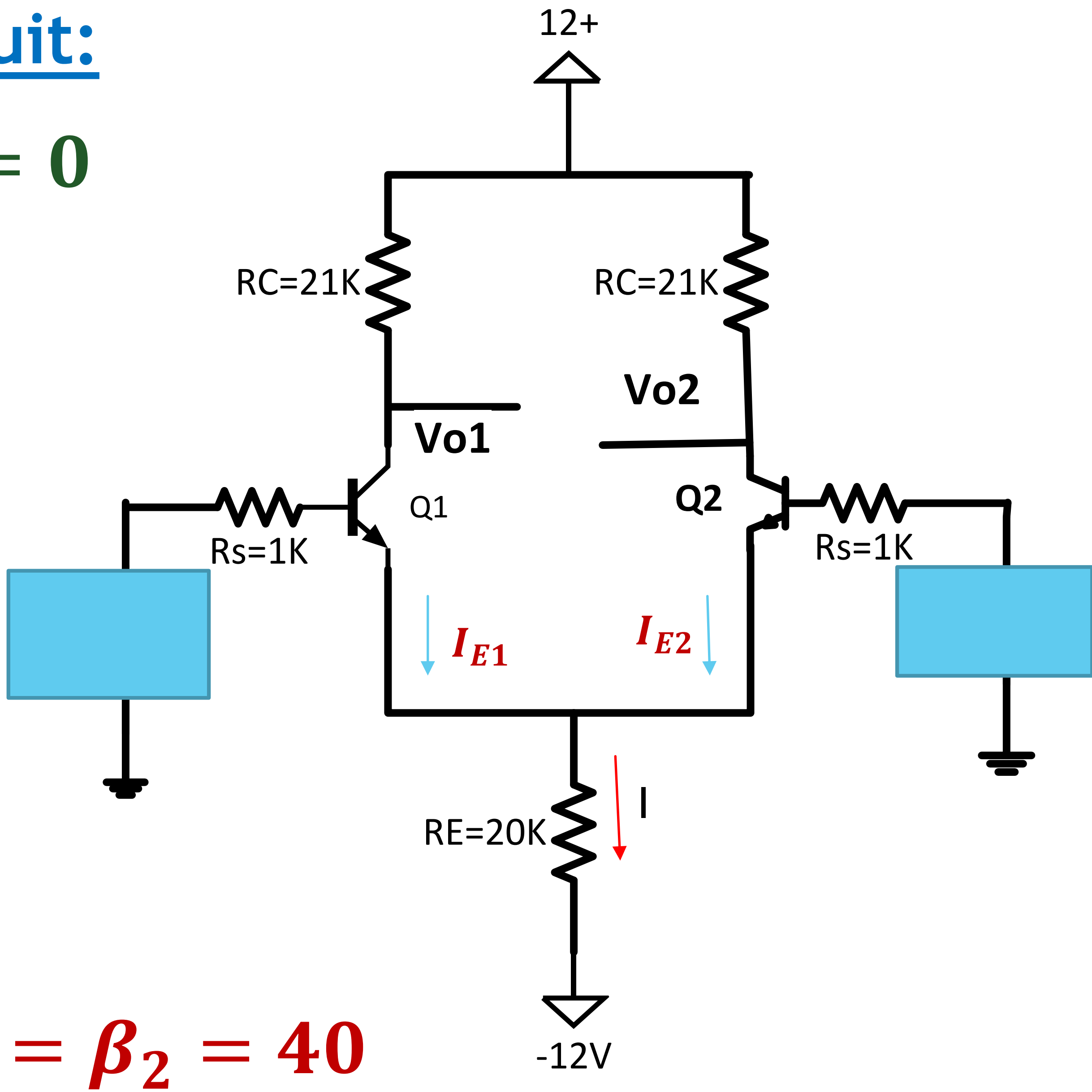
$$R_S I_{B1} + V_{BE1} + R_E I - 12 = 0$$

$$I = I_{E1} + I_{E2}$$

$$I_{E1} = I_{E2} \quad [symmetry]$$

$$I_{E1} = I_{E2} = \frac{12 - 0.7}{\frac{1k}{41} + (2)(20k)}$$

$$= 0.2825\, mA$$



$$\beta_1 = \beta_2 = 40$$

$$Q_1 \text{ and } Q_2 \text{ identical}$$

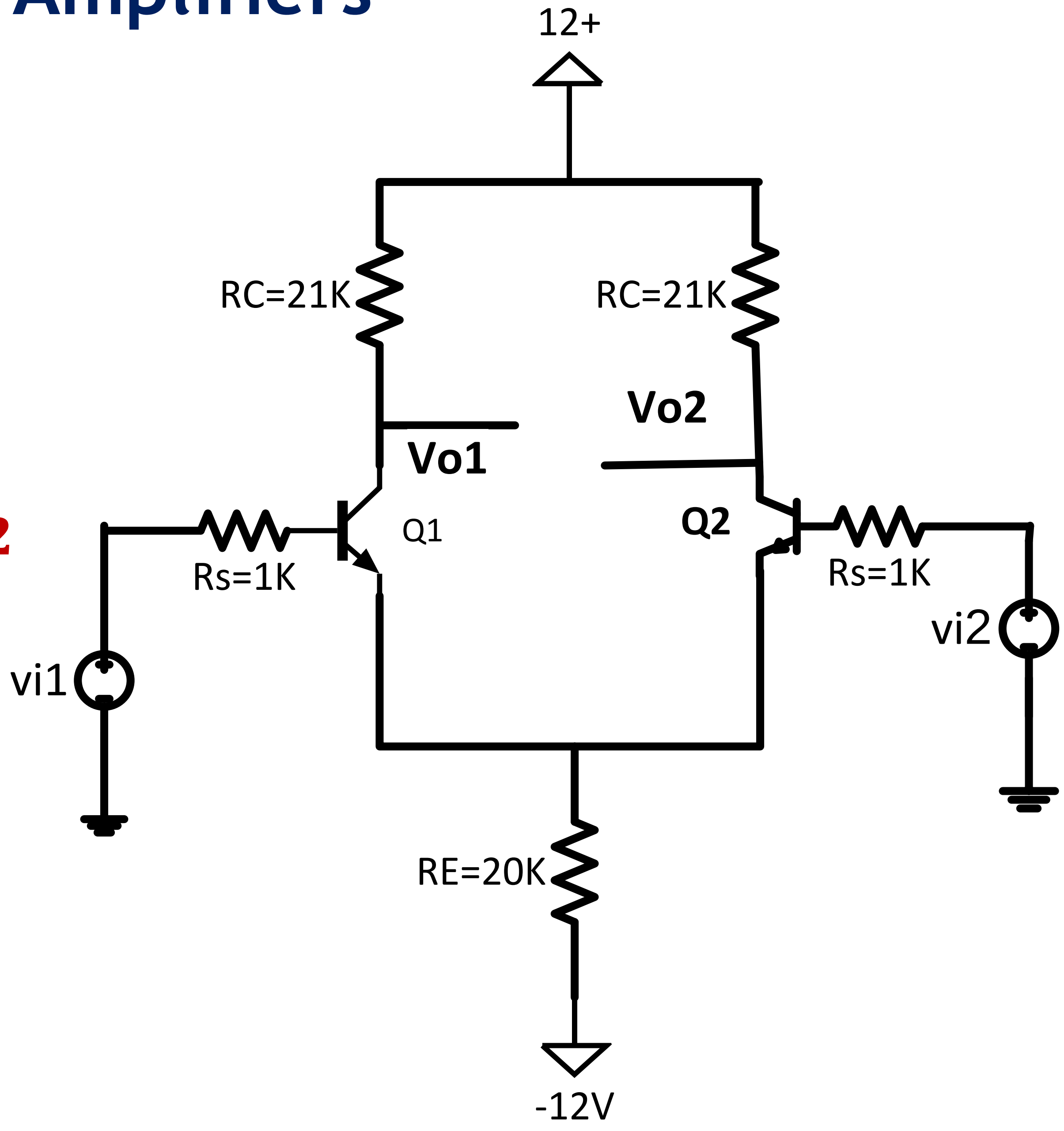
Differential Amplifiers

Differential Amplifier Circuit:

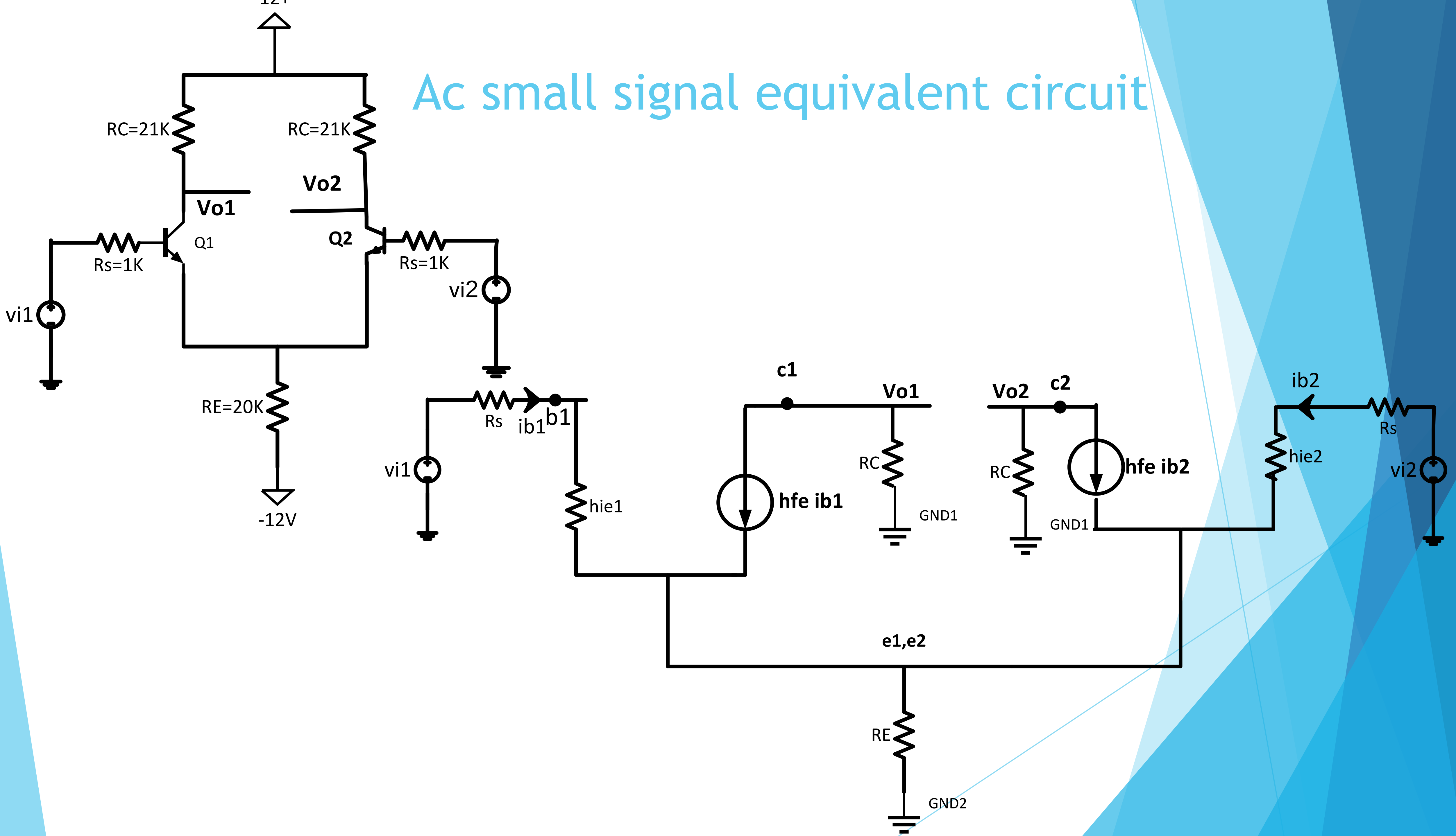
AC Analysis:

$$since \quad I_{E1} = I_{E2} \text{ and } \beta_1 = \beta_2$$

$$h_{ie1} = h_{ie2} = h_{ie}$$
$$h_{ib1} = h_{ib2} = h_{ib}$$



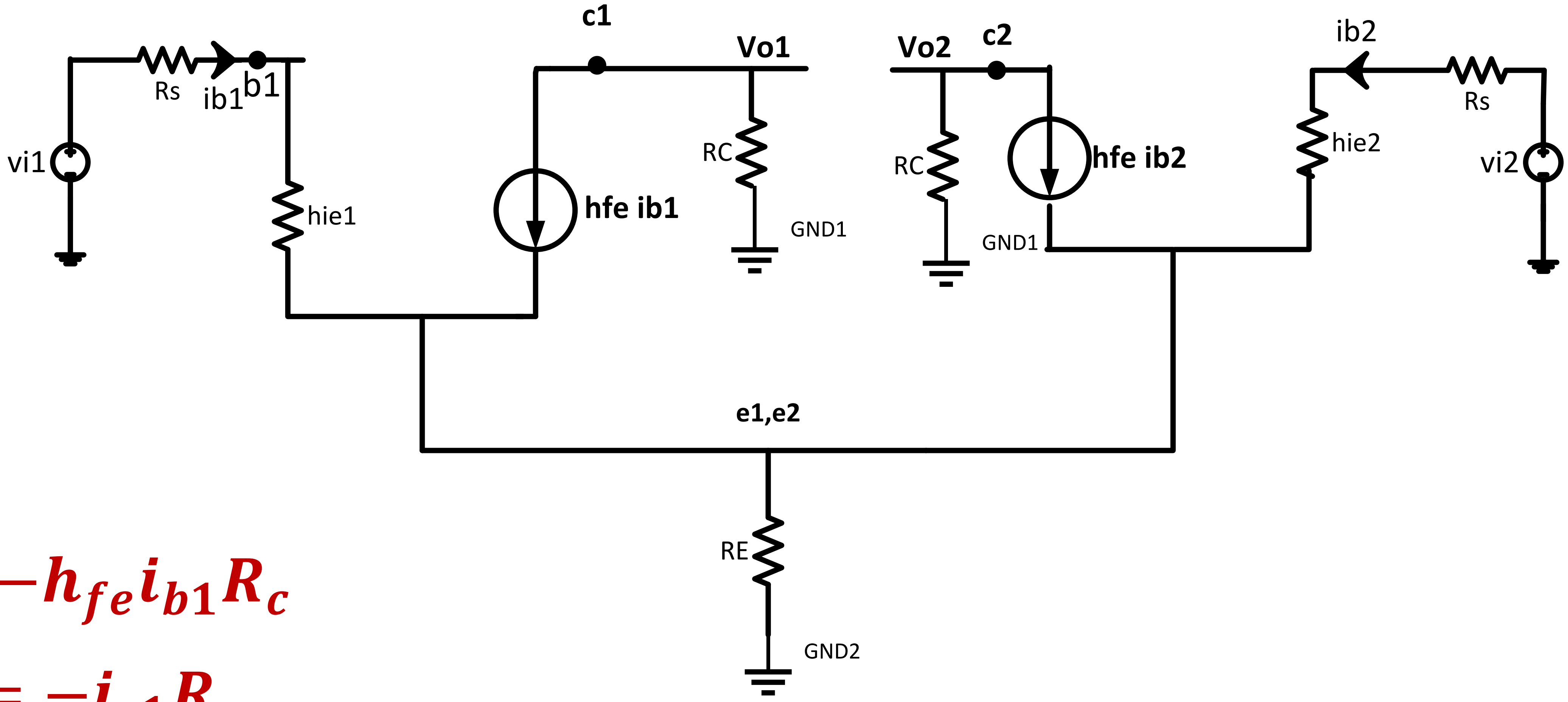
Ac small signal equivalent circuit



Differential Amplifiers

Differential Amplifier Circuit:

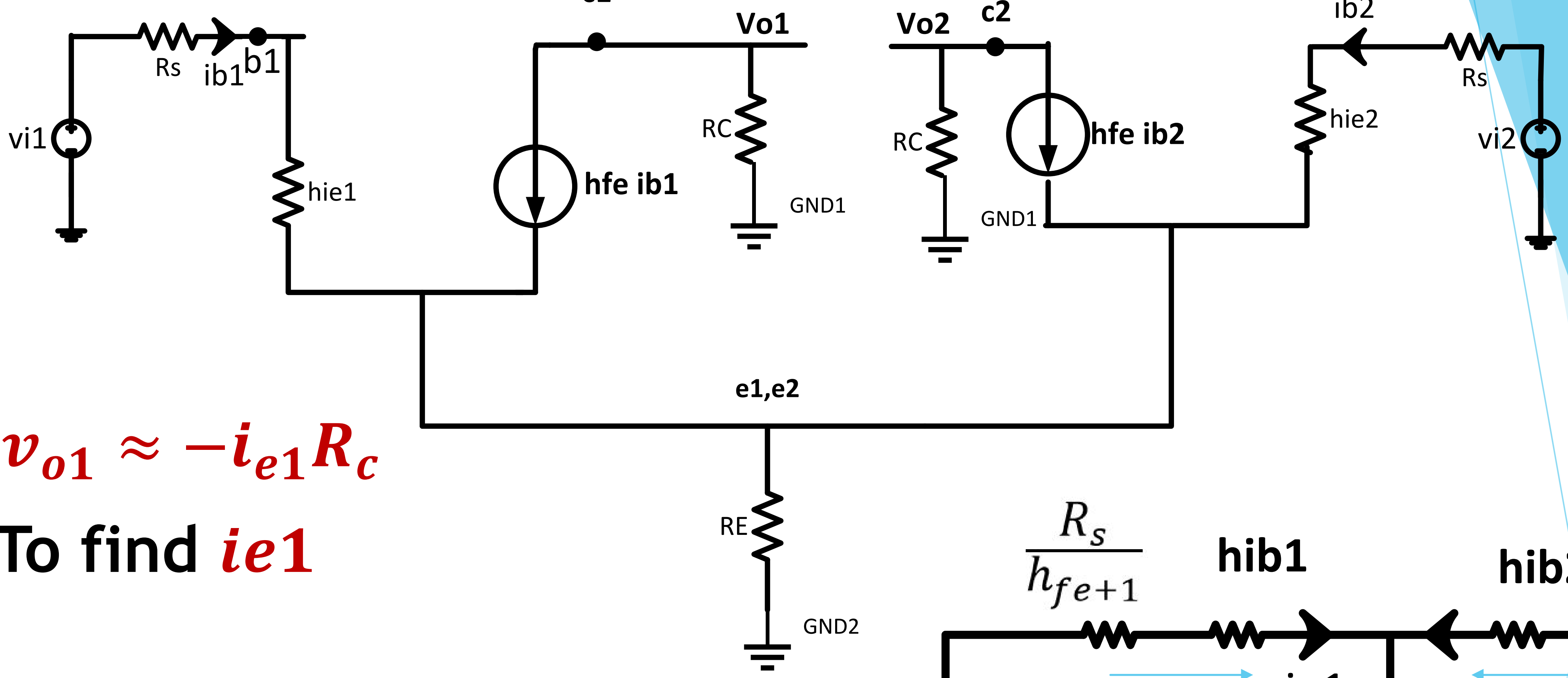
AC Analysis:



$$v_{o1} = -h_{fe} i_{b1} R_c$$

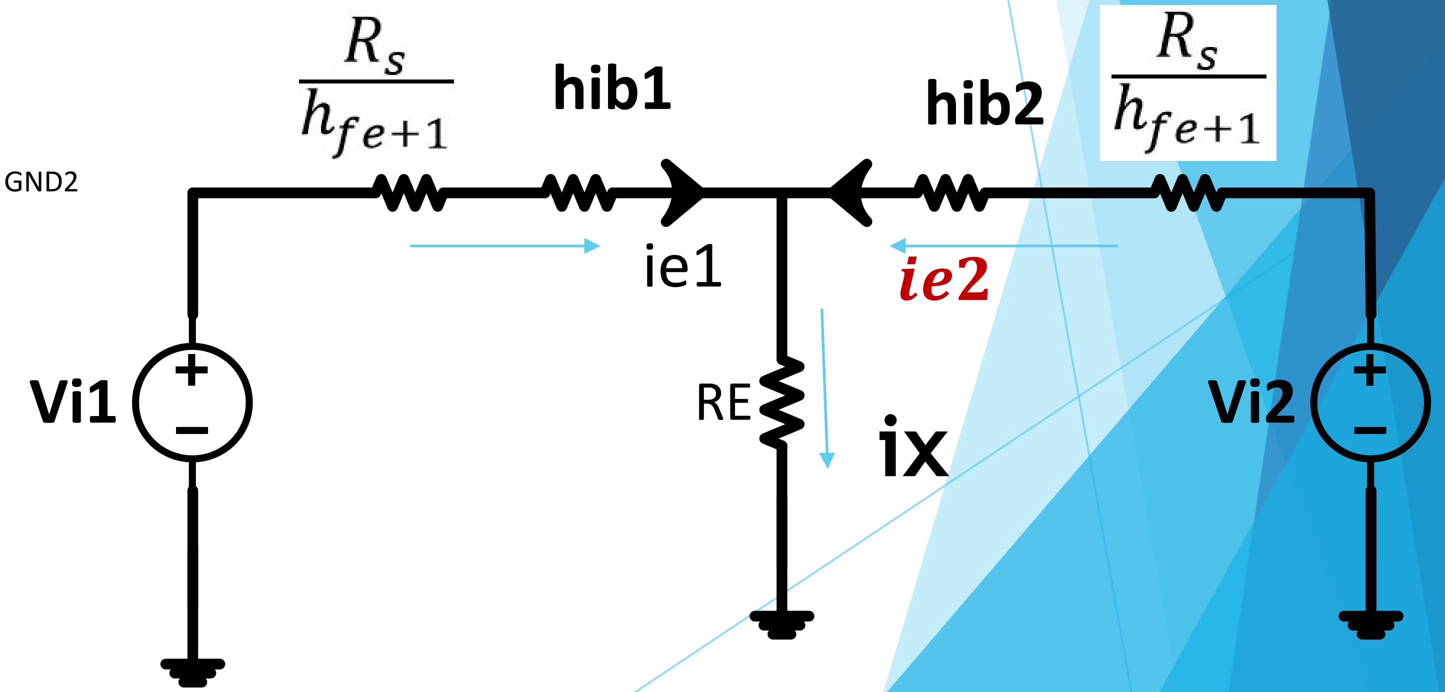
$$v_{o1} = -i_{c1} R_c$$

$$v_{o1} \approx -i_{e1} R_c$$



$$v_{o1} \approx -i_{e1} R_c$$

To find $ie1$



Emitter equivalent circuit

Differential Amplifiers

Differential Amplifier Circuit:

To find $ie1$ ➡

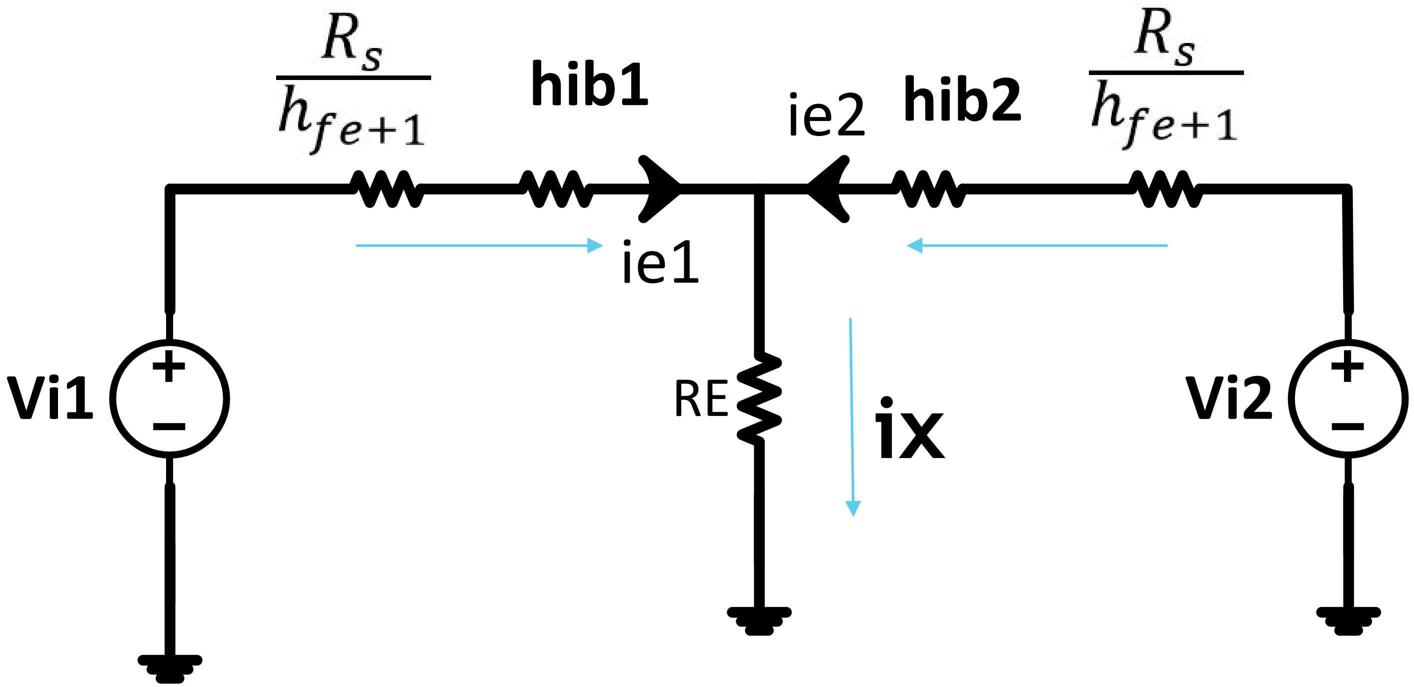
Small Signal Analysis

Using emitter equivalent ckt

$$v_{i1} = v_c - \frac{v_d}{2}$$

$$v_{i2} = v_c + \frac{v_d}{2}$$

$$v_{o1} \cong -ie1.Rc$$

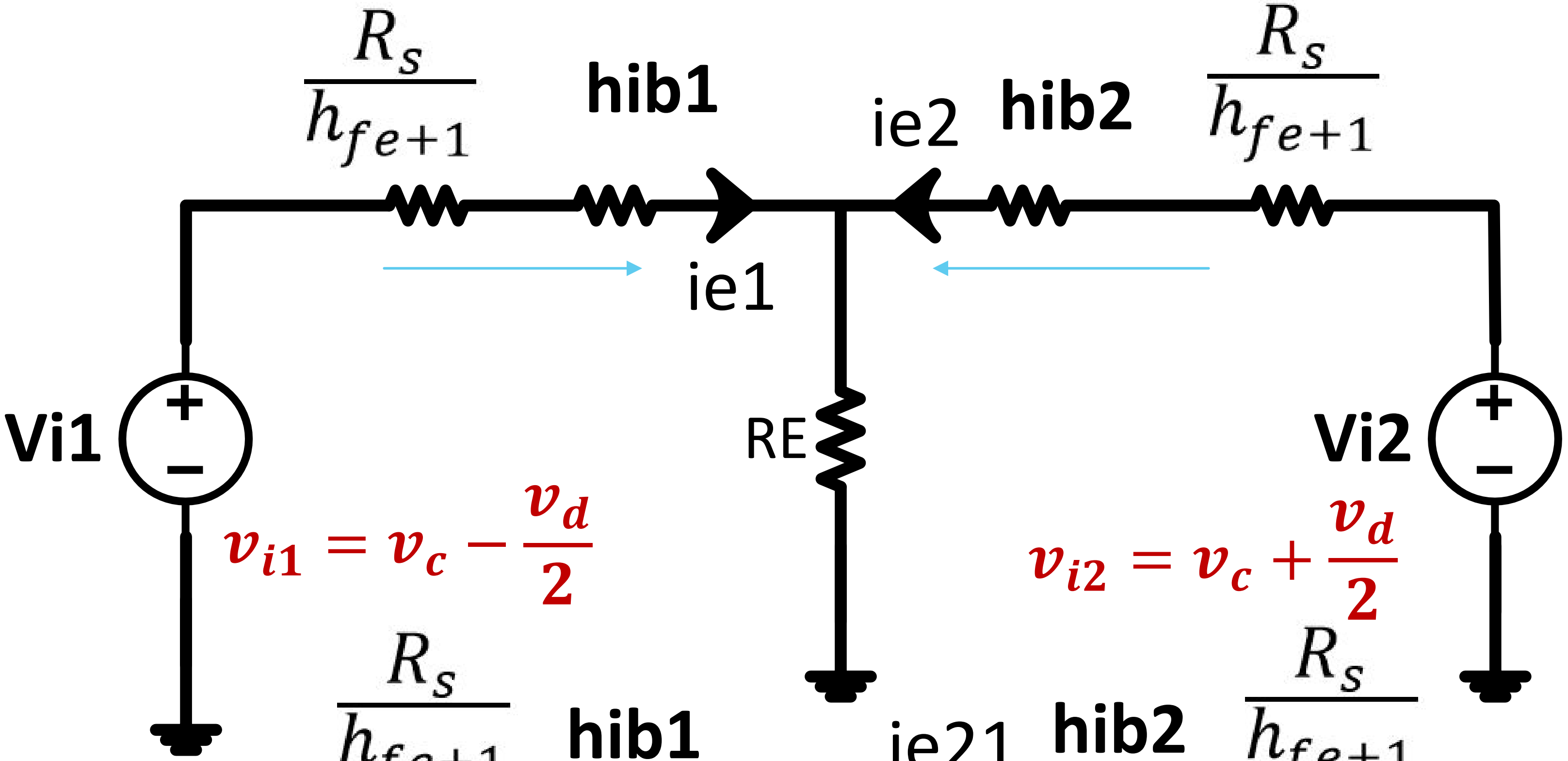


Differential Amplifiers

$$v_{o1} \cong -ie1.Rc$$

Using Superpostion

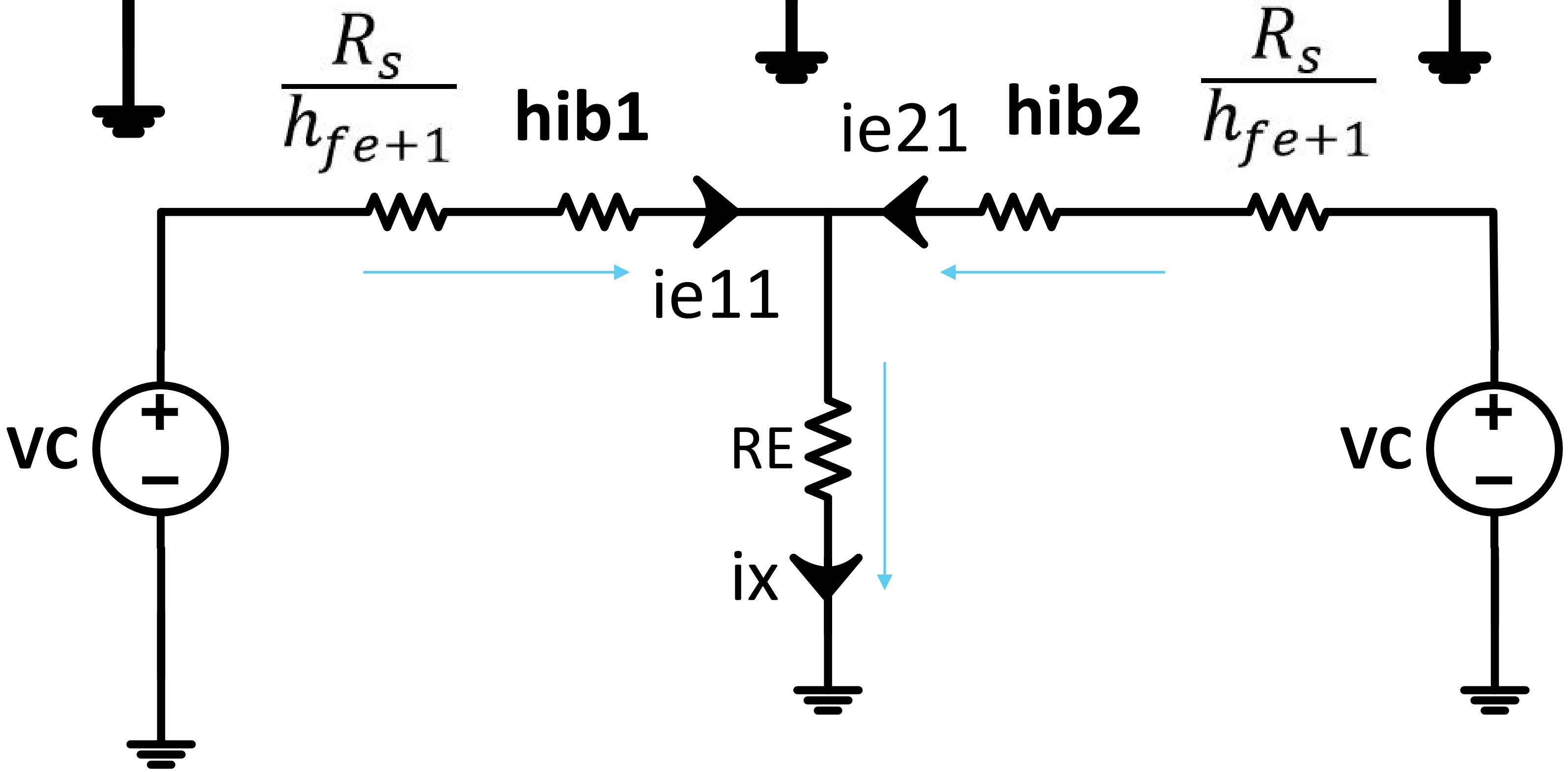
$$ie1 = ie11 + ie12$$



To find ie11

$let \quad v_d = 0$

$$v_{i1} = v_c \;\; ; \;\; v_{i2} = v_c$$



Differential Amplifiers

Small Signal Analysis

Using emitter equivalent ckt

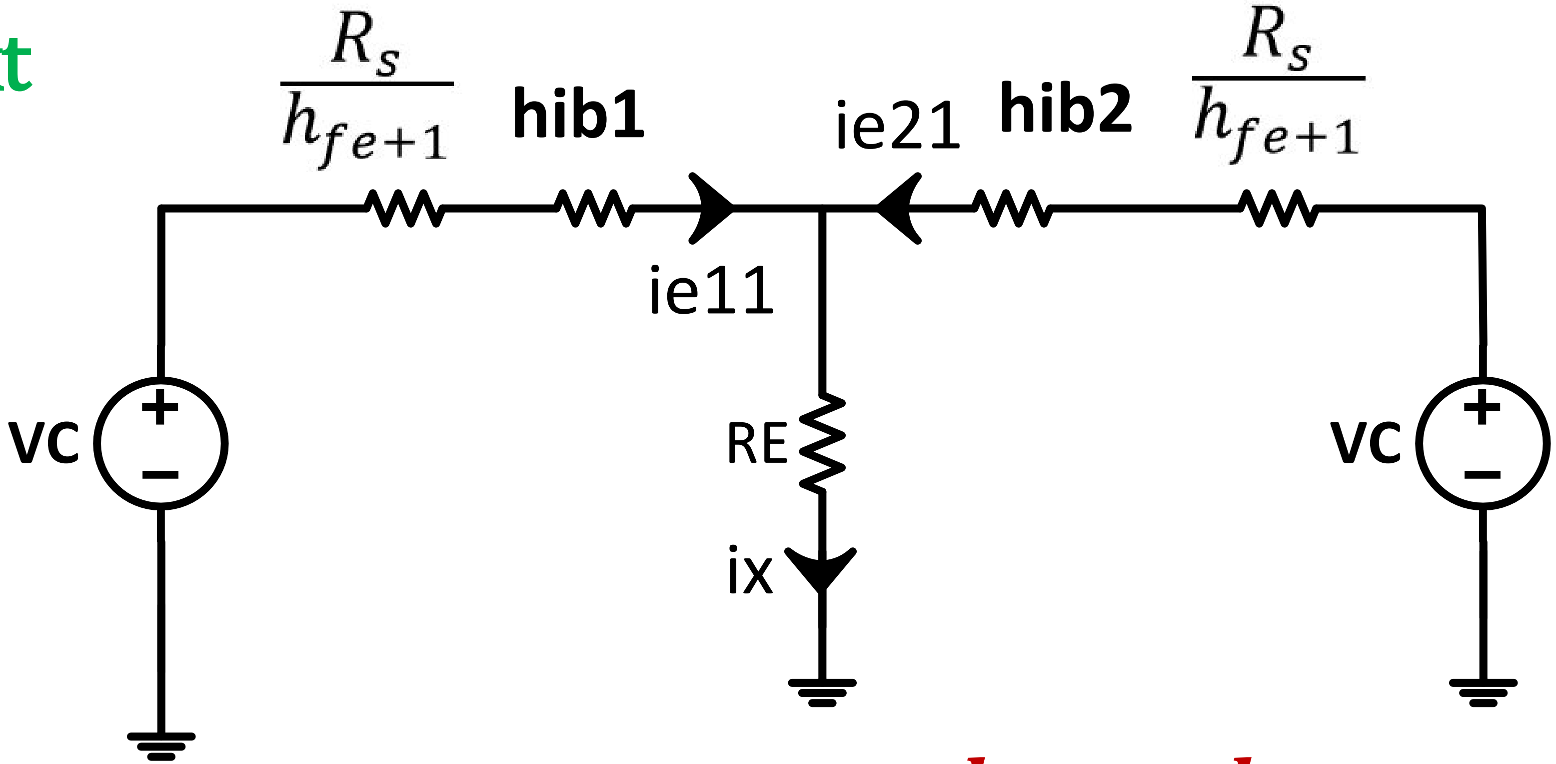
$v_{i1} = v_c \;\; ; \;\; v_{i2} = v_c$

By Symmetry

$i_{e11} = i_{e21} \;\; ; i_x = 2i_{e11}$

$$i_{e11} = \frac{v_c}{h_{ib} + \frac{R_s}{h_{fe+1}} + 2R_E}$$

$$i_{e21} = \frac{v_c}{h_{ib} + \frac{R_s}{h_{fe+1}} + 2R_E}$$



$h_{ib1} = h_{ib2}$

Differential Amplifiers

$2)\ let\ v_c = 0$

$v_1 = -\frac{v_d}{2}; \quad v_2 = \frac{v_d}{2}$

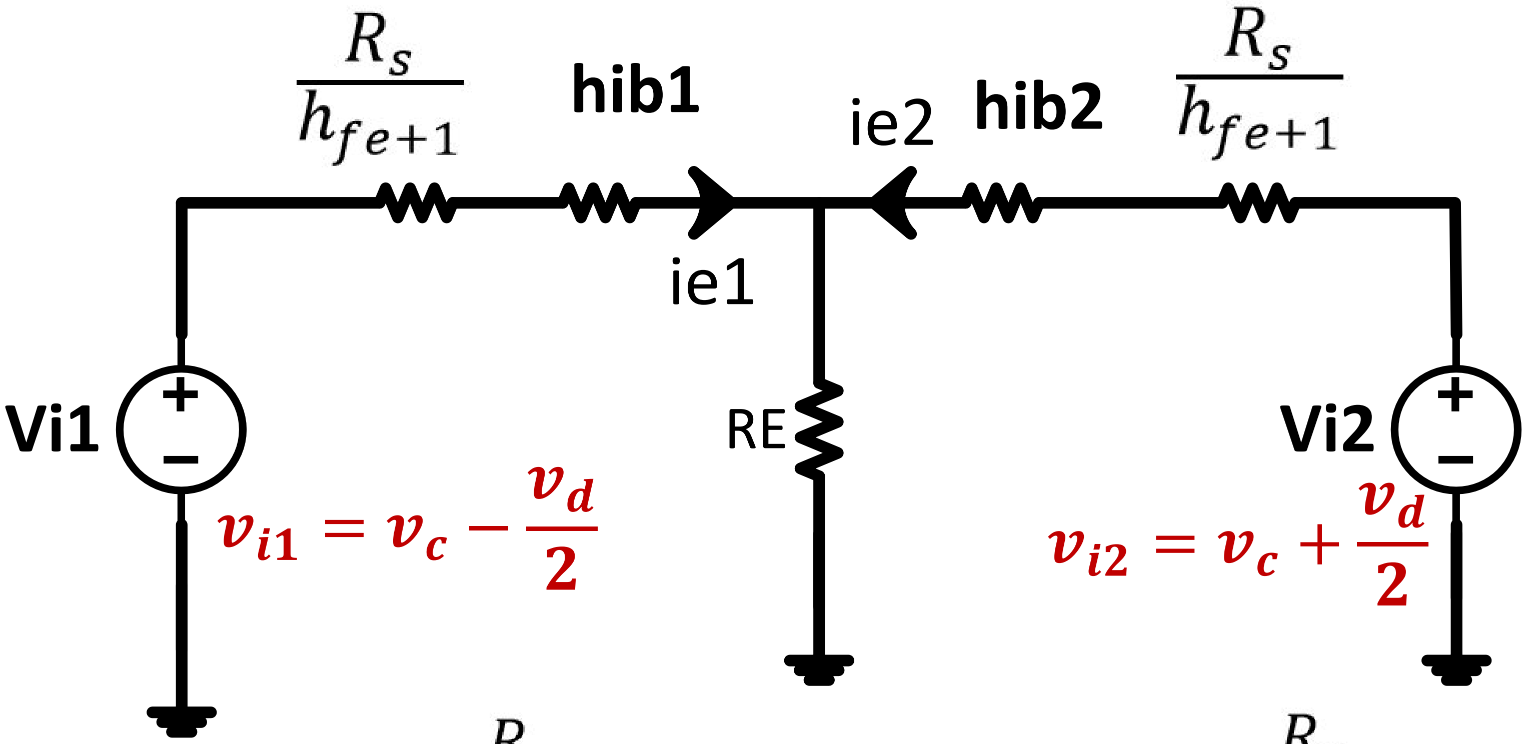
(Using *symmetry*)

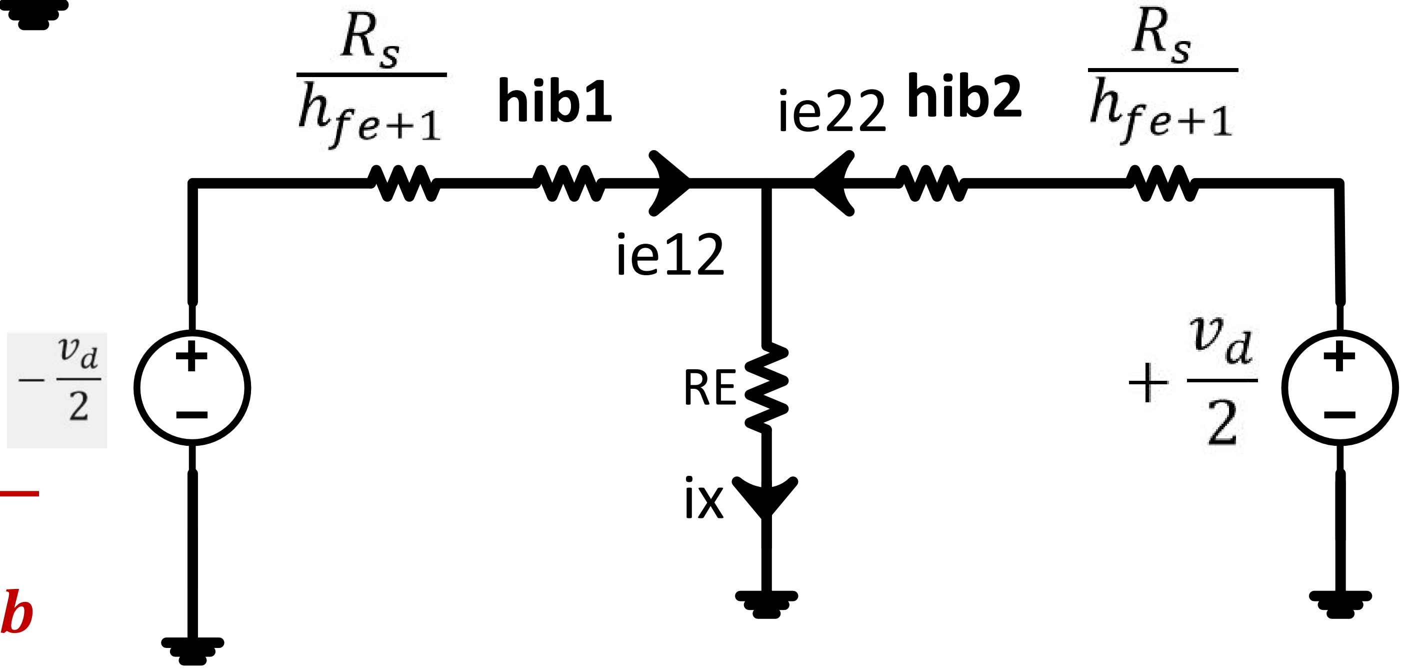
$i_{e12} = -i_{e22}$

ix = 0

$$i_{e12} = \frac{-v_d/2}{\frac{R_s}{h_{fe+1}} + h_{ib}}$$

$$i_{e22} = \frac{v_d/2}{\frac{R_s}{h_{fe+1}} + h_{ib}}$$





Differential Amplifiers

Differential Amplifier Circuit:

Using Superposition

$$i_{e1} = \frac{v_c}{h_{ib} + \frac{R_s}{h_{fe+1}} + 2R_E} - \frac{v_d/2}{\frac{R_s}{h_{fe+1}} + h_{ib}}$$

$$i_{e2} = \frac{v_c}{h_{ib} + \frac{R_s}{h_{fe+1}} + 2R_E} + \frac{v_d/2}{\frac{R_s}{h_{fe+1}} + h_{ib}}$$

$$v_{o1} = +\frac{R_c v_d}{2\left(h_{ib}+\frac{R_s}{h_{fe+1}}\right)} - \frac{R_c v_c}{h_{ib}+\frac{R_s}{h_{fe+1}}+2R_E}$$

$$v_{o2} = -\frac{R_c v_d}{2\left(h_{ib}+\frac{R_s}{h_{fe+1}}\right)} - \frac{R_c v_c}{h_{ib}+\frac{R_s}{h_{fe+1}}+2R_E}$$

$$v_{o1} - v_{o2} = \frac{R_c}{h_{ib} + \frac{R_s}{h_{fe+1}}} v_d$$

Differential Amplifiers

$$v_{o1} = +\frac{R_c v_d}{2\left(h_{ib} + \frac{R_s}{h_{fe+1}}\right)} - \frac{R_c v_c}{h_{ib} + \frac{R_s}{h_{fe+1}} + 2R_E}$$

$Ad \equiv Differential\ mode\ gain$

$$Ad = \frac{v_o}{v_d}\Big|_{v_c=0}$$

$$let\ \ v_o = v_{o1}$$

$$Ad = \frac{v_{o1}}{v_d}\Big|_{v_c=0}$$

$$Ad = \frac{R_c}{2\left(h_{ib} + \frac{R_s}{h_{fe+1}}\right)}$$

Differential Amplifiers

$$v_{o1} = +\frac{R_c v_d}{2\left(h_{ib} + \frac{R_s}{h_{fe+1}}\right)} - \frac{R_c v_c}{h_{ib} + \frac{R_s}{h_{fe+1}} + 2R_E}$$

$$Ac \equiv Common\ mode\ gain$$

$$Ac = \frac{v_o}{v_c}\Big|_{v_d=0}$$

$$let\ \ v_o = v_{o1}$$

$$Ac = \frac{v_{o1}}{v_c}\Big|_{v_d=0}$$

$$Ac\ = \frac{-R_c}{2R_E + h_{ib} + \frac{R_s}{h_{fe+1}}}$$

Differential Amplifiers

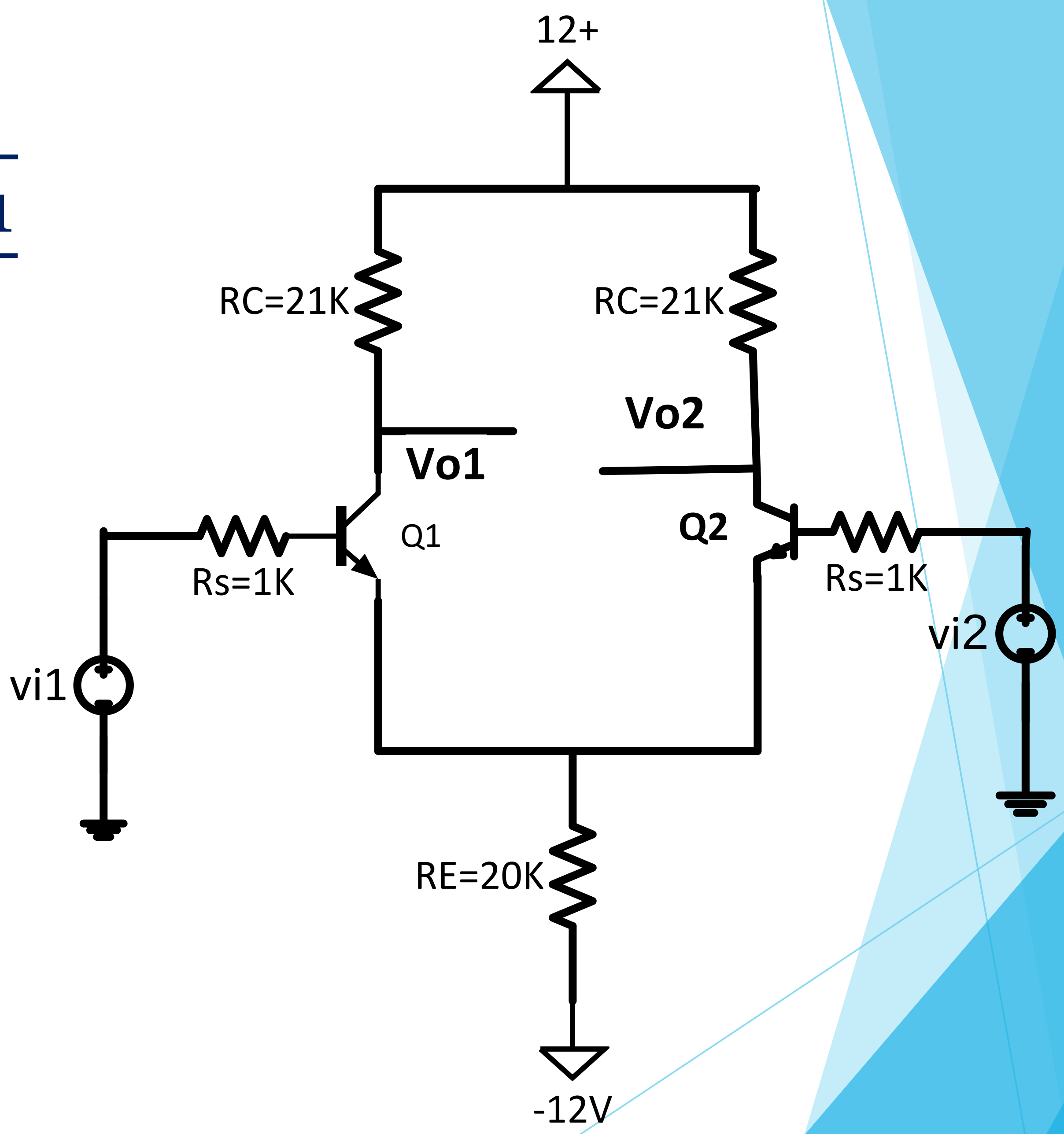
$CMRR \equiv Common\ Mode\ Rejection\ Ratio$

$$CMRR = \left|\frac{Ad}{Ac}\right|$$

$$CMRR = \frac{2R_E + h_{ib} + \frac{R_s}{h_{fe+1}}}{2\left(h_{ib} + \frac{R_s}{h_{fe+1}}\right)}$$

$To\ increase\ CMRR\ we\ need\ to\ increase\ R_E$

$$CMRR = \frac{2R_E + h_{ib} + \frac{R_s}{h_{fe+1}}}{2\left(h_{ib} + \frac{R_s}{h_{fe+1}}\right)}$$



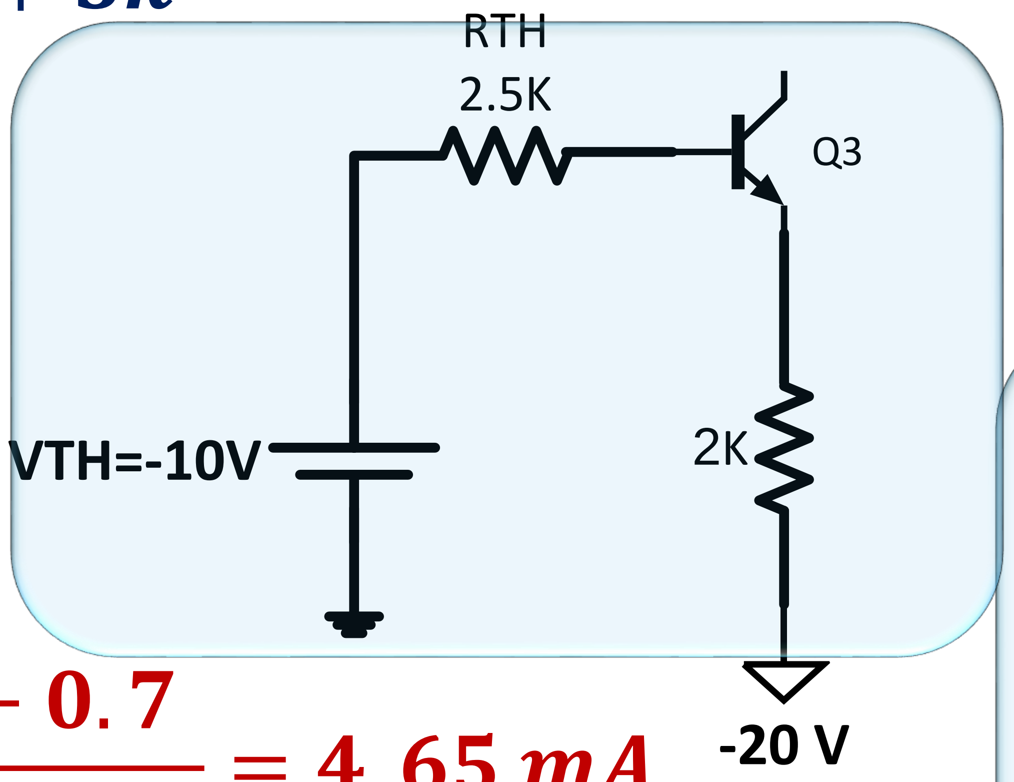
$$I_{E1} = I_{E2} = \frac{12 - 0.7}{\frac{R_s}{41} + 2R_E}$$

Differential Amplifier with constant current source:

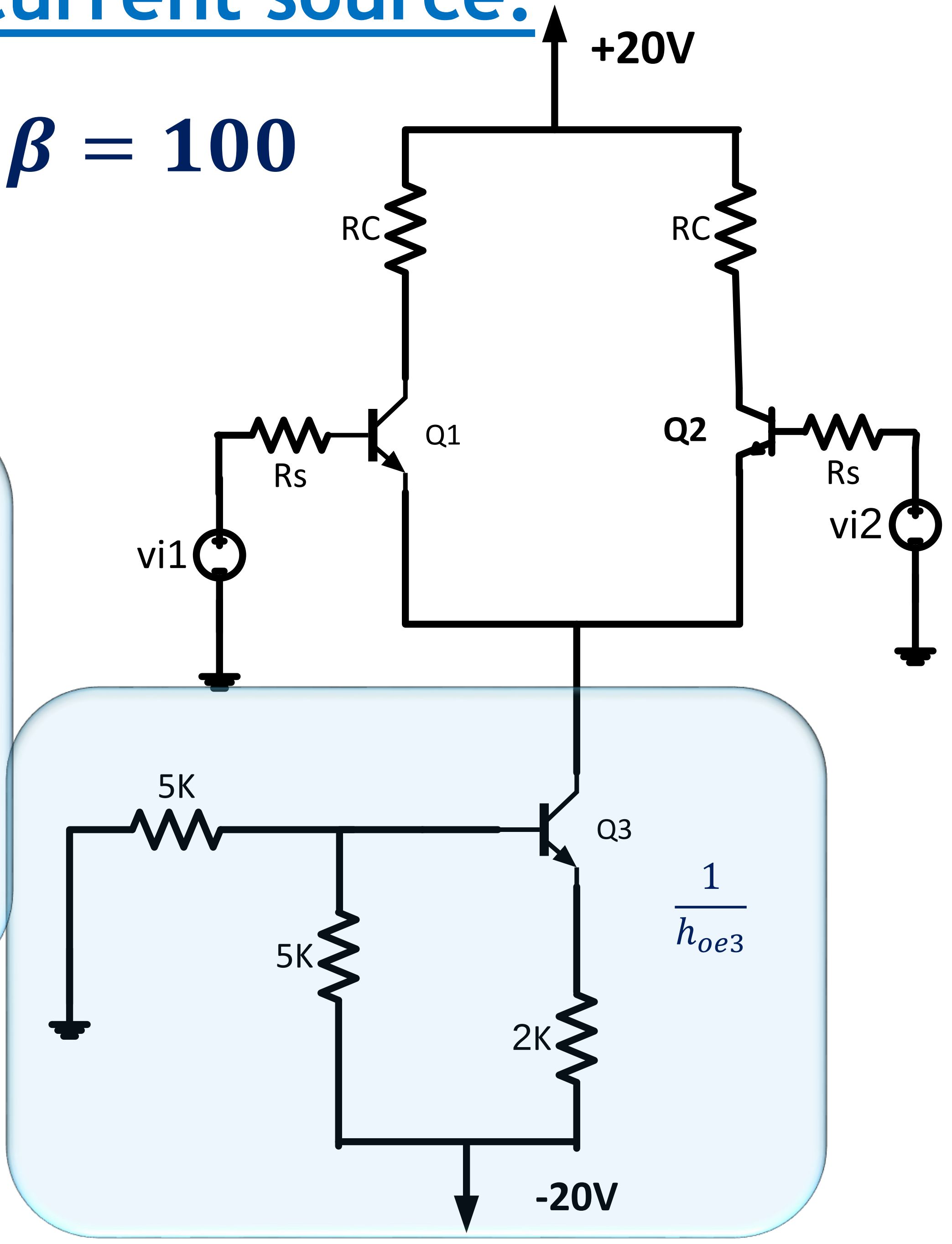
$$\beta = 100$$

$$R_{TH} = 5k \| 5k = 2.5k$$

$$V_{TH} = \frac{5k}{5k + 5k}(-20) = -10\ V$$



$$I_{E3} = \frac{10 - 0.7}{\frac{2.5k}{101} + 2k} = 4.65\ mA$$

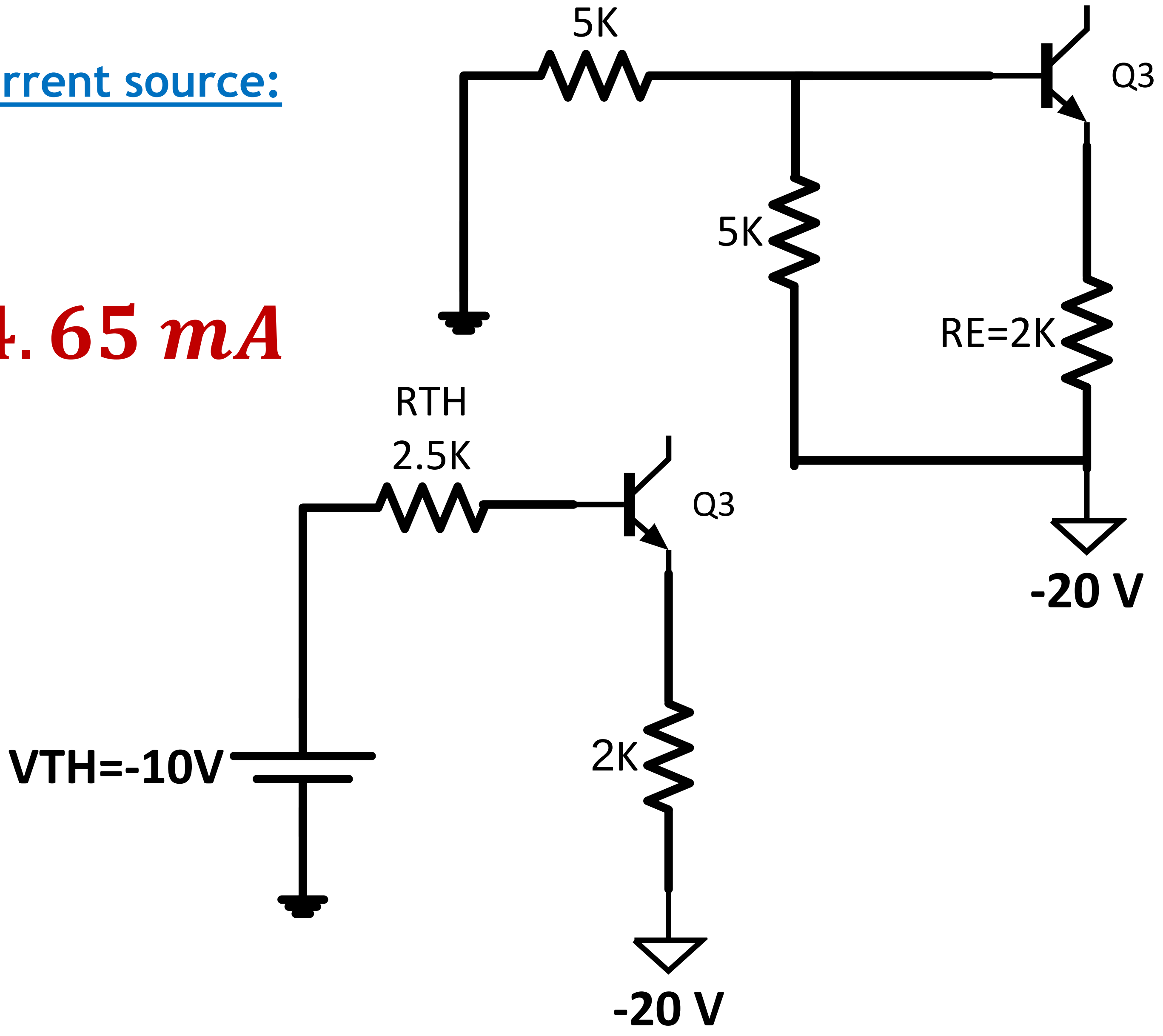


Differential Amplifiers

Differential Amplifier with constant current source:

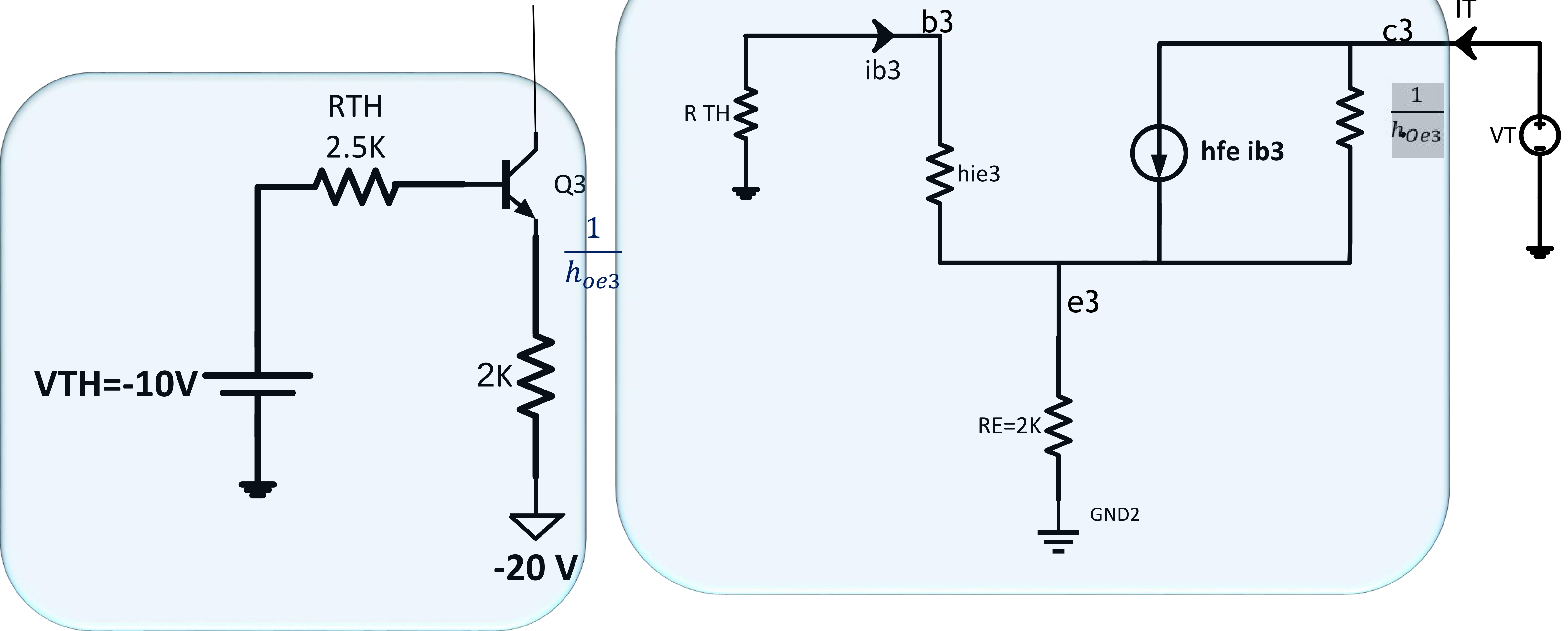
$$I_{E3} = \frac{10 - 0.7}{\frac{2.5k}{101} + 2k} = 4.65\, mA$$

$$h_{ie3} = \beta \frac{V_T}{I_{CQ3}} = 0.559K$$



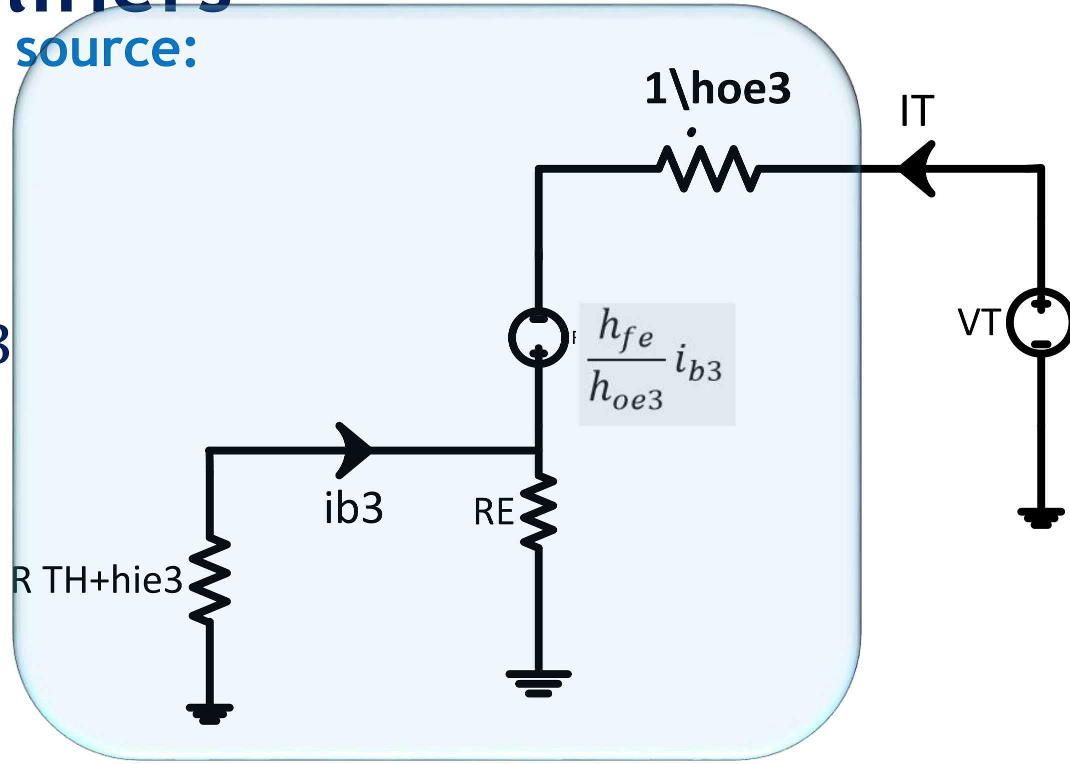
Differential Amplifiers

Ac small signal equivalent circuit for the constant current source:



Differential Amplifiers

Ac small signal equivalent circuit for the constant current source:



$$V_T = \frac{1}{h_{oe3}} I_T - \frac{h_{fe}}{h_{oe3}} i_{b3} - (h_{ie3} + R_{TH}) i_{b3}$$

$$i_{b3} = -\frac{R_E}{R_E + h_{ie3} + R_{TH}} I_T$$

$$\therefore R_o = \frac{V_T}{I_T}$$

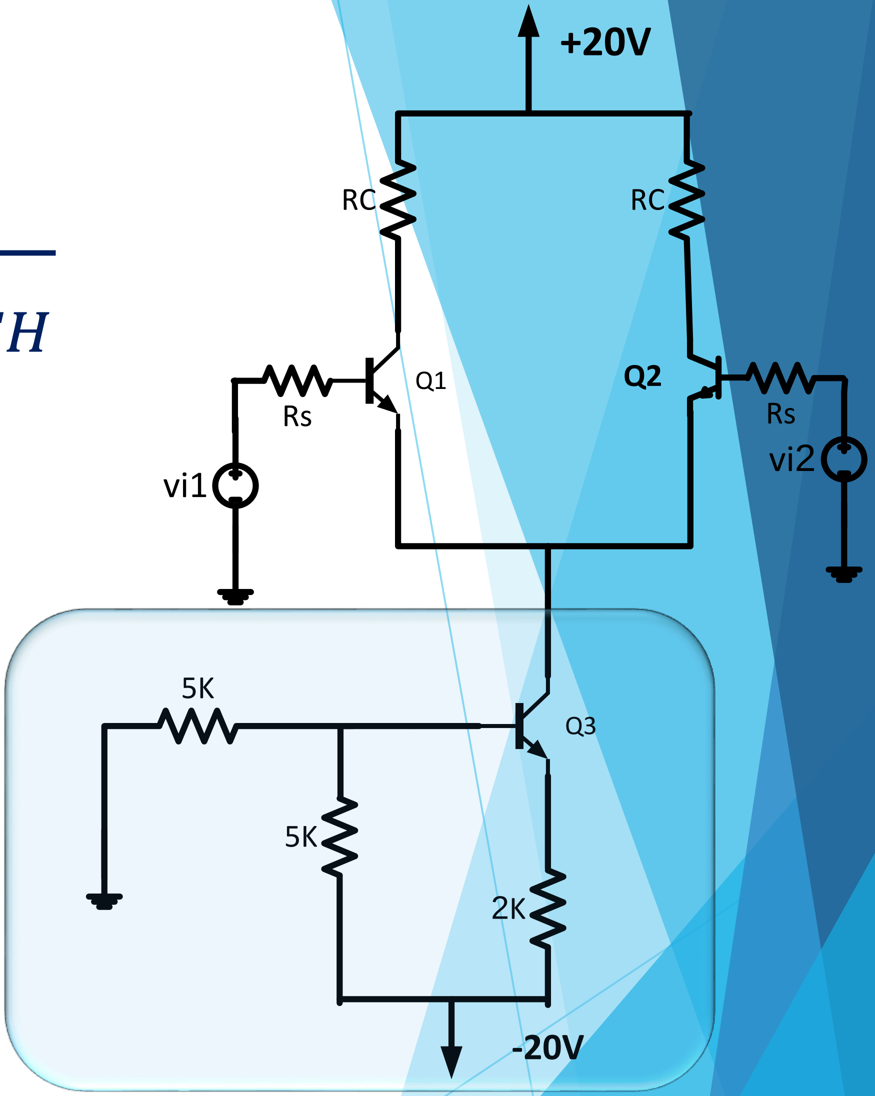
$$= \frac{1}{h_{oe3}} + \frac{h_{fe}}{h_{oe3}} \frac{R_E}{R_E + h_{ie3} + R_{TH}} + \frac{(h_{ie3} + R_{TH})}{R_E + h_{ie3} + R_{TH}} R_E$$

$$R_o \approx \frac{1}{h_{oe3}} + \frac{h_{fe}}{h_{oe3}} \frac{R_E}{R_E + h_{ie3} + R_{TH}}$$

$$R_o \approx \frac{1}{h_{oe3}} + \frac{h_{fe}}{h_{oe3}} \quad \frac{R_E}{R_E + h_{ie3} + R_{TH}}$$

- $let \ \frac{1}{h_{oe}} = 80K \ , \quad h_{ie} = 0.559k$
- $h_{fe} = 100 \ , R_E = 2k, R_{TH} = 2.5k$
- $R_o = 3.25 \ M\Omega$

$$\boldsymbol{CMRR = \frac{2R_E + h_{ib} + \frac{R_s}{h_{fe+1}}}{2\left(h_{ib} + \frac{R_s}{h_{fe+1}}\right)}}$$



$\boldsymbol{R_E} \Rightarrow \boldsymbol{R_o}$

Differential Amplifiers

Bipolar transistor current sources:

Q1 and Q2 are In the active region

1.Current mirror : Simple

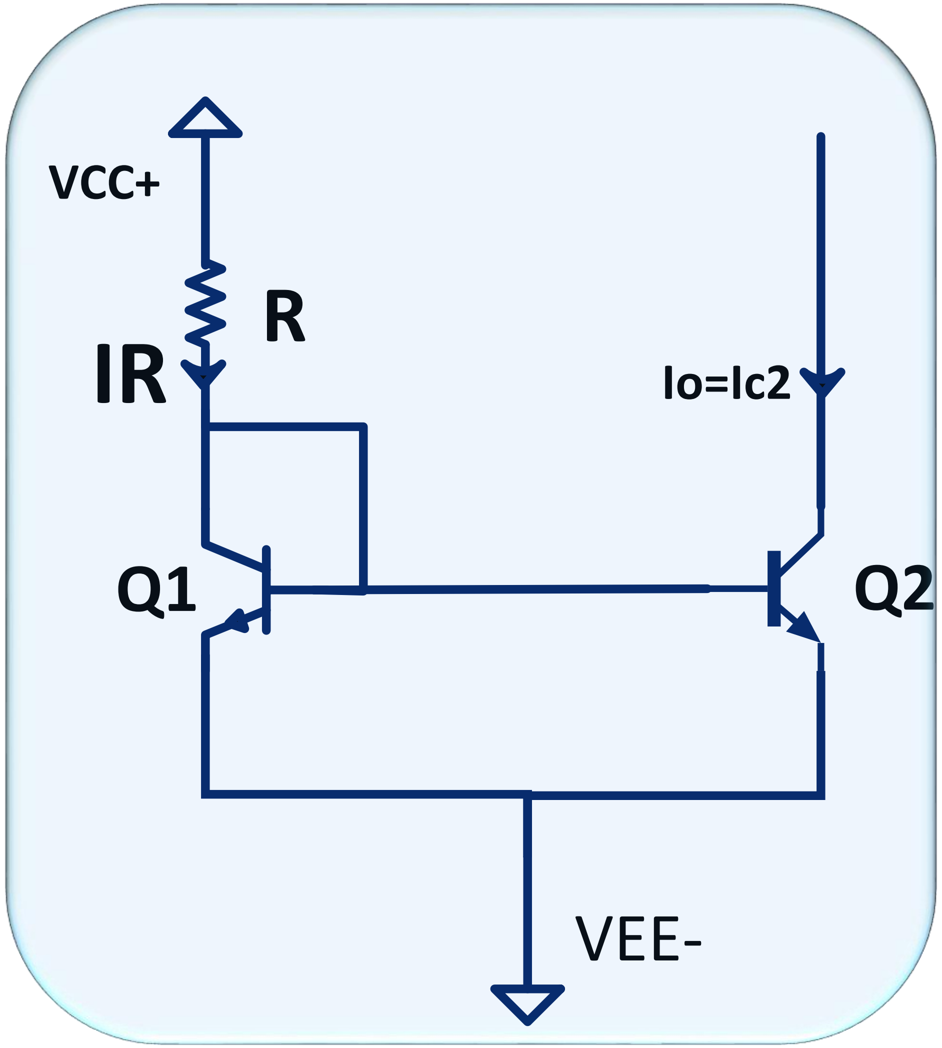
$$I_C = I_S\, e^{\frac{V_{BE}}{V_T}}$$

If Q_1 is matched to Q_2

$$\beta_1 = \beta_2\ ;\ I_{S1} = I_{S2}\ ;\ V_{T1} = V_{T2}$$

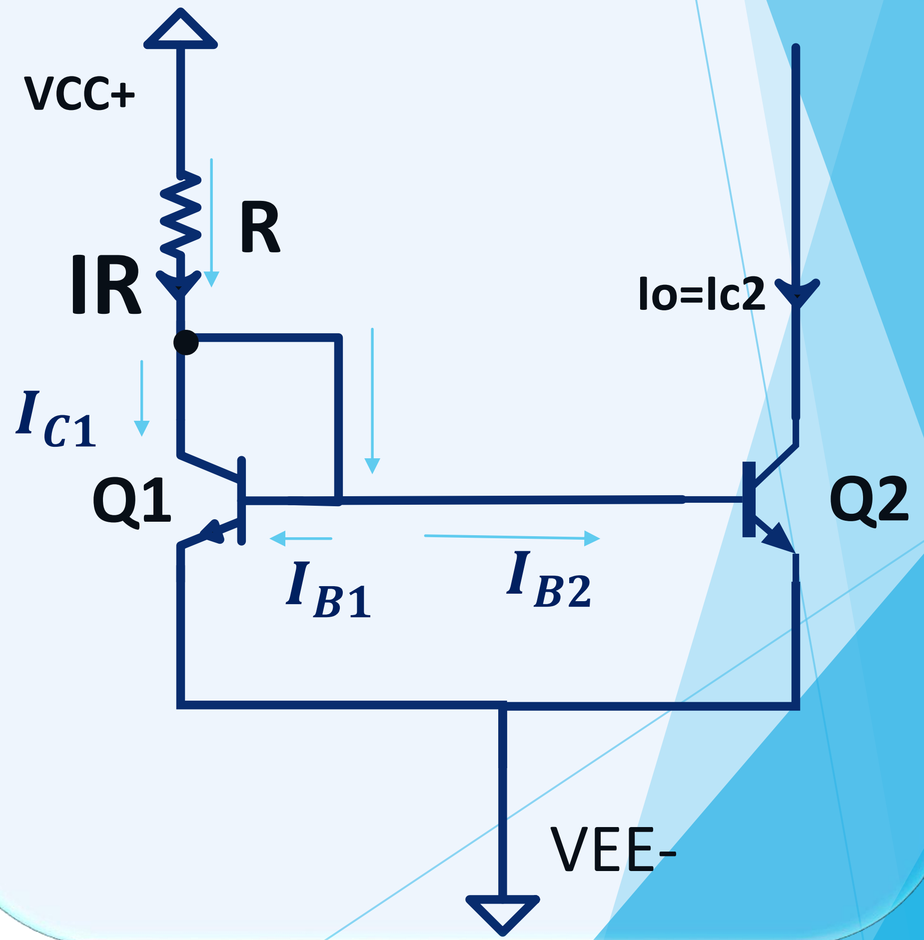
And since $V_{BE1} = V_{BE2}$

$$\therefore \quad I_{C1} = I_{C2} = I_o$$

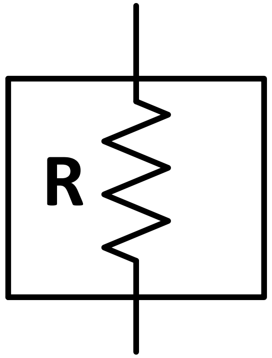


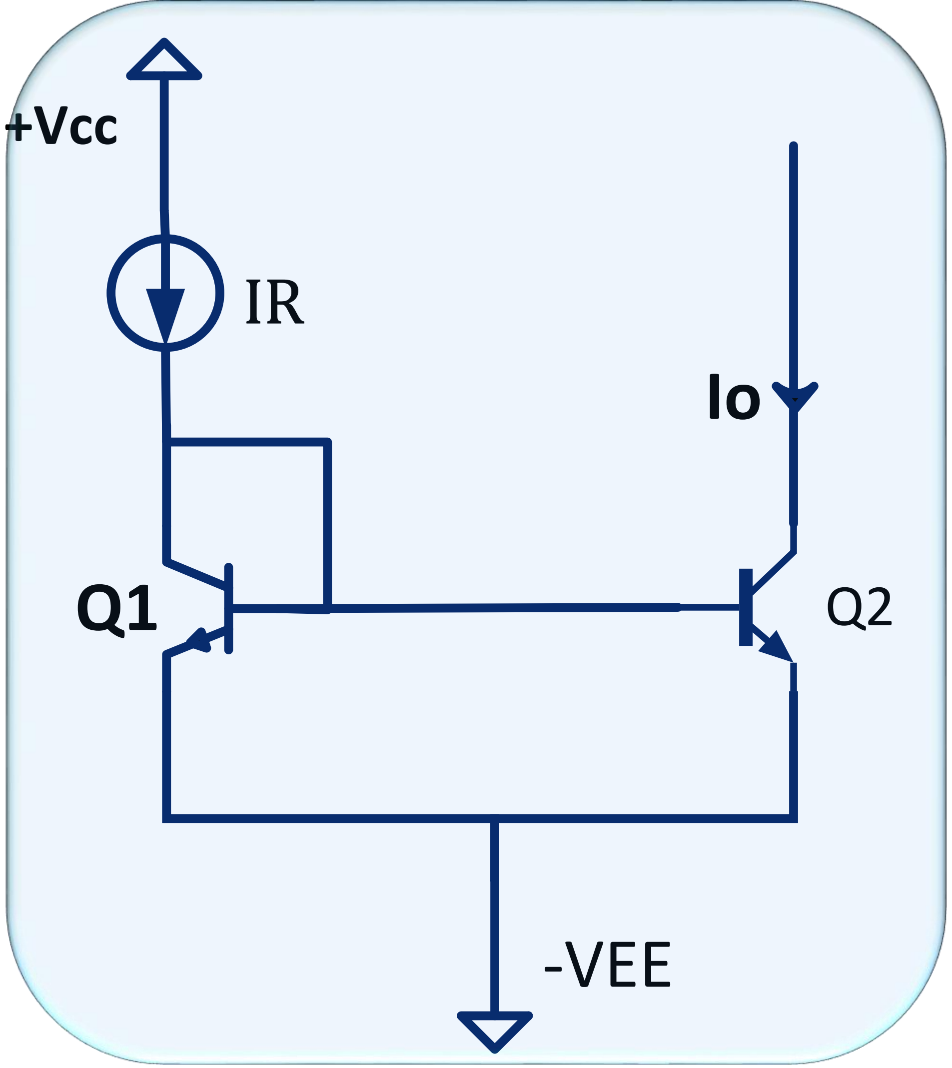
To find I_o in terms of I_R

- $KCL \quad I_R = I_{C1} + I_{B1} + I_{B2}$
- $I_{C1} = I_{C2} \quad ; \quad I_{B1} = I_{B2}$
- $\therefore \quad I_o = I_{C2} = \dfrac{I_R}{1 + \frac{2}{\beta}}$



Differential Amplifiers





Bipolar transistor current sources:

1.Current mirror : Simple

1) $if\ \ \beta = \infty$

$I_o = I_R$

2) $if\ \ \beta = 100$

$I_o = I_R \quad ; \quad 2\%\ error$

To find I_R

KVL: $V_{CC} = R\, I_R + V_{BE1} - V_{EE}$

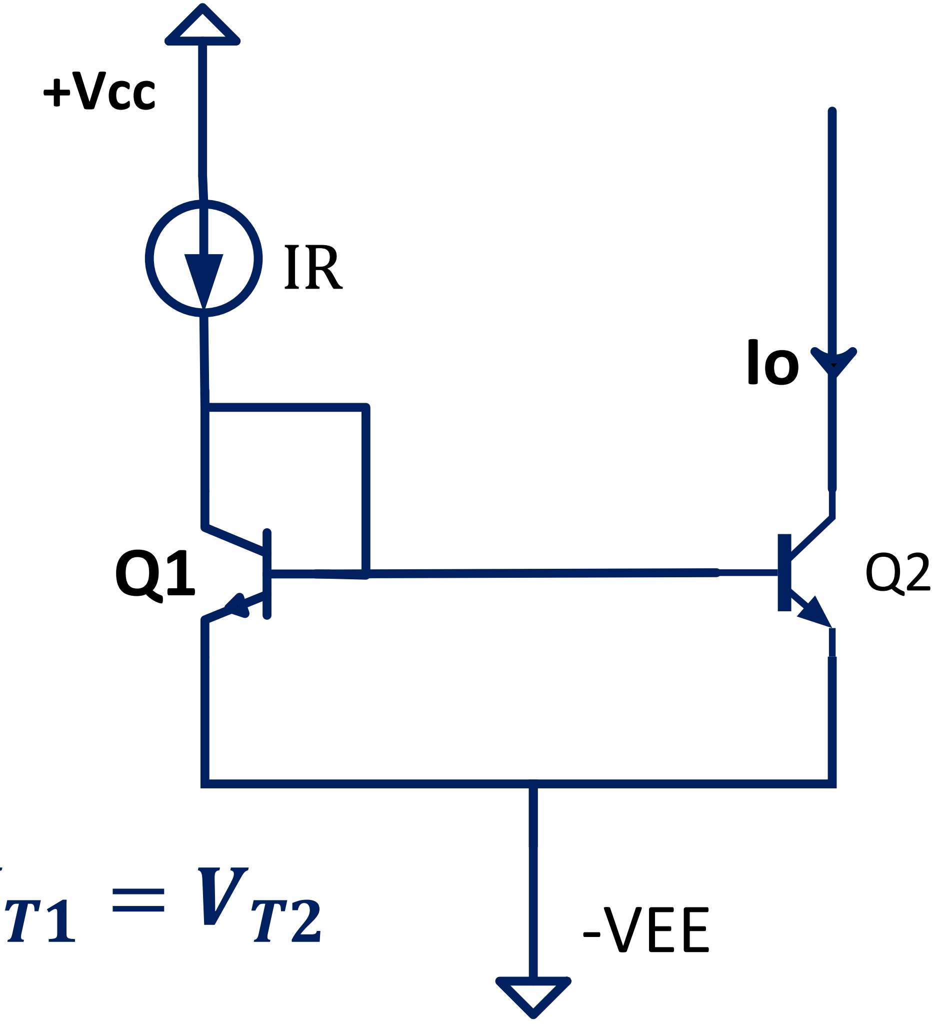
$$I_R = \frac{V_{CC} + V_{EE} - V_{BE}}{R}$$

$$I_o = I_{C2} = \frac{I_R}{1 + \frac{2}{\beta}}$$

Bipolar transistor current sources:

$$I_C = I_S\, e^{\frac{V_{BE}}{V_T}}$$

1.Current mirror : Simple



If the area of the EB junction of Q2 is m times that of Q1

$$\therefore \quad I_{S2} = mI_{S1}$$

And since $V_{BE1} = V_{BE2}$ and $\beta_1 = \beta_2$; $V_{T1} = V_{T2}$

$$\therefore I_{C2} = mI_{C1}$$

KCL: $I_R = I_{C1} + I_{B1} + I_{B2}$

$$I_R = \frac{I_{C2}}{m} + \frac{I_{C2}}{\beta m} + I_{B2}$$

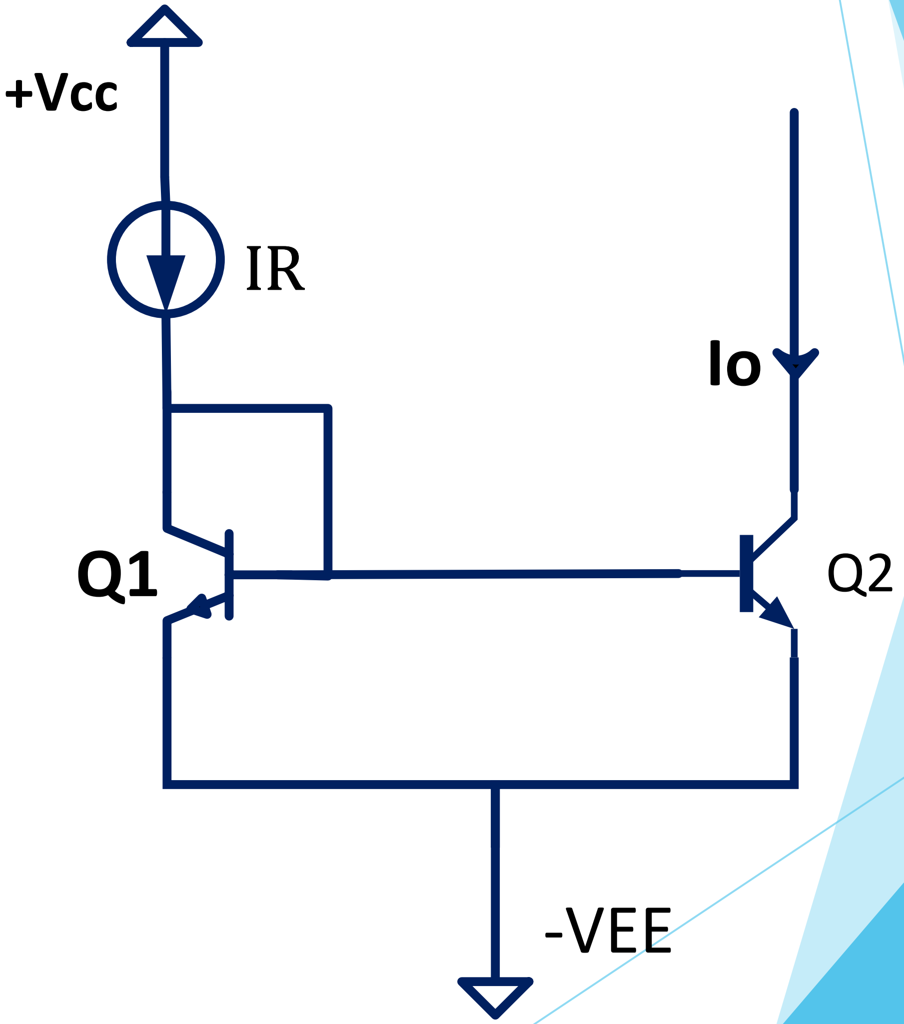
$$I_R = \frac{I_{C2}}{m} + \frac{I_{C2}}{\beta m} + I_{B2}$$

$$I_{C2} = mI_{C1}$$

$$\therefore \quad I_{C2} = I_o = I_R \frac{m}{1 + \frac{m+1}{\beta}}$$

$$if \ \beta = \infty$$

$$I_o = I_{C2} = m\,I_R$$

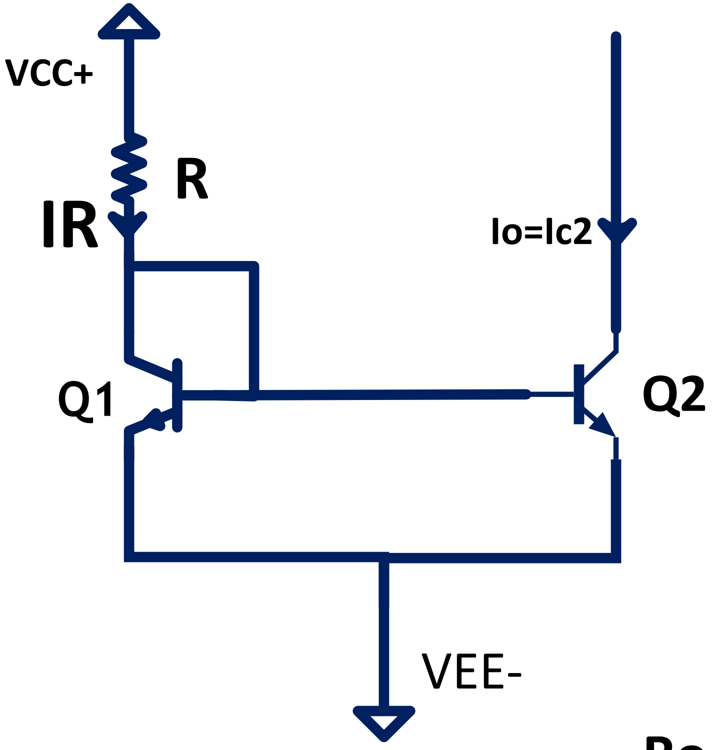


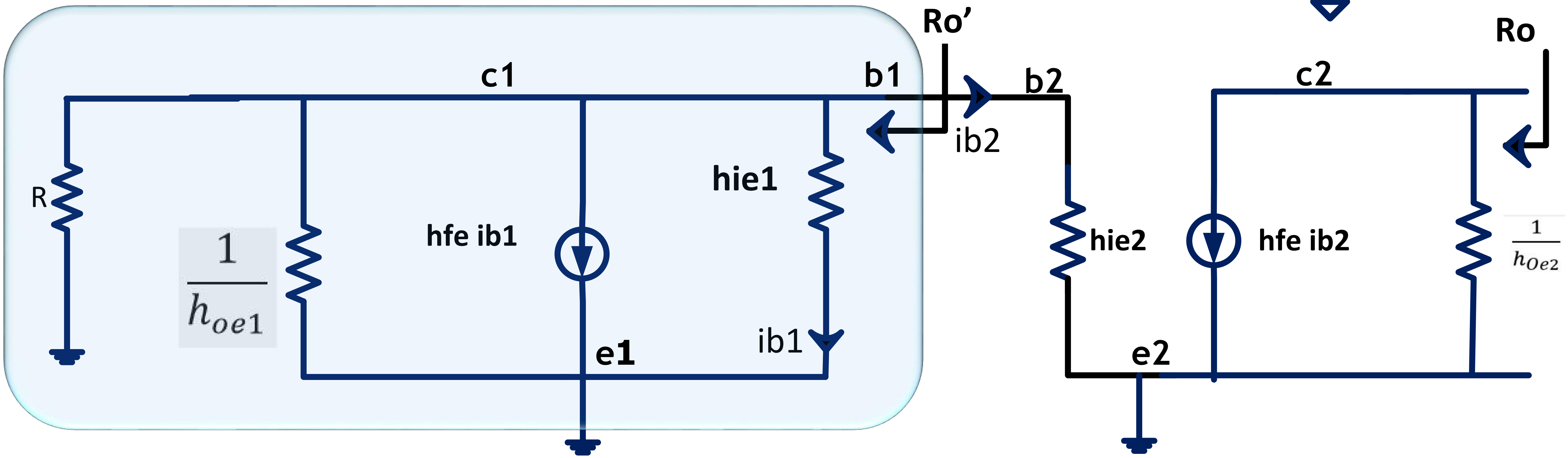
Bipolar transistor current sources:

Output - Impedance:

To find Ro = $\frac{V_T}{I_T}$

Ac small signal equivalent circuit



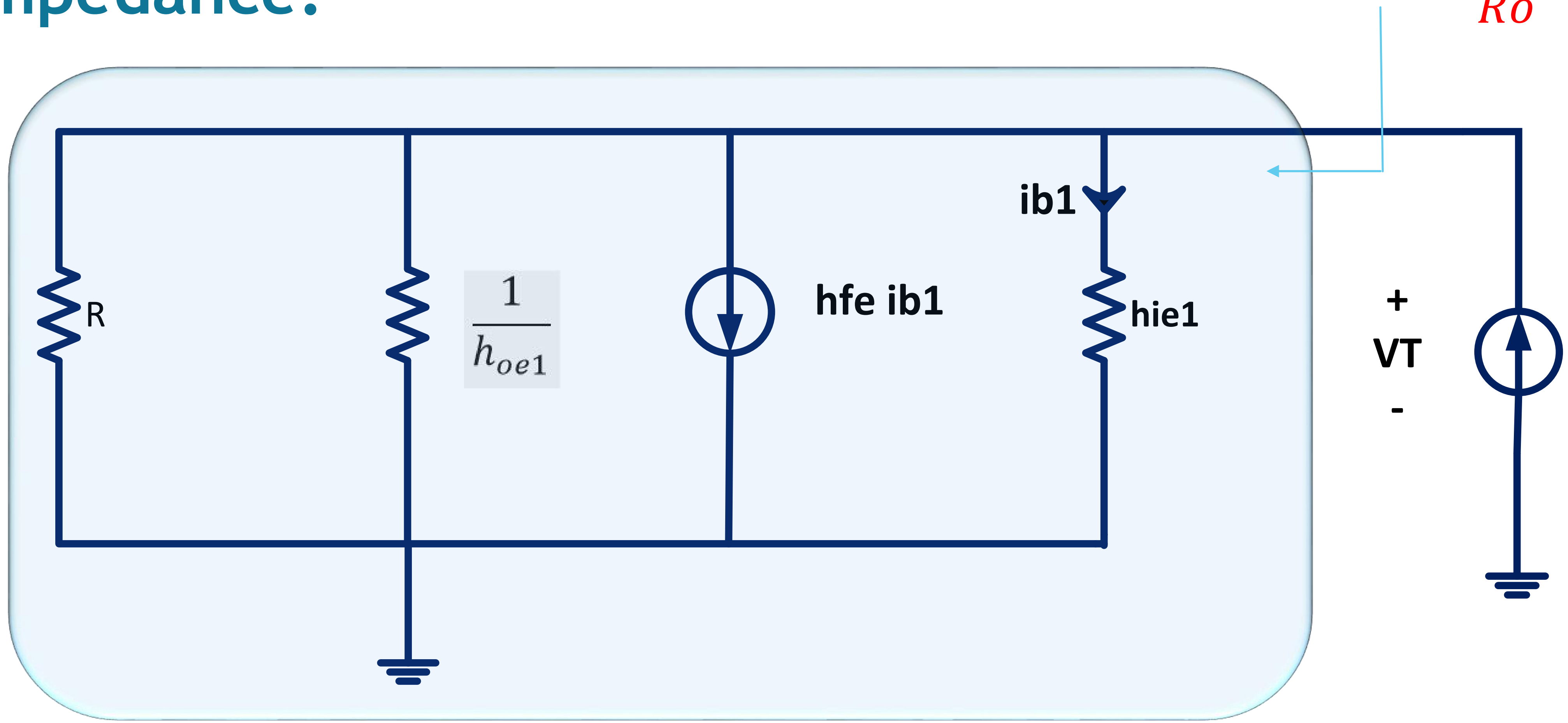


Differential Amplifiers

Bipolar transistor current sources:

Output - Impedance:

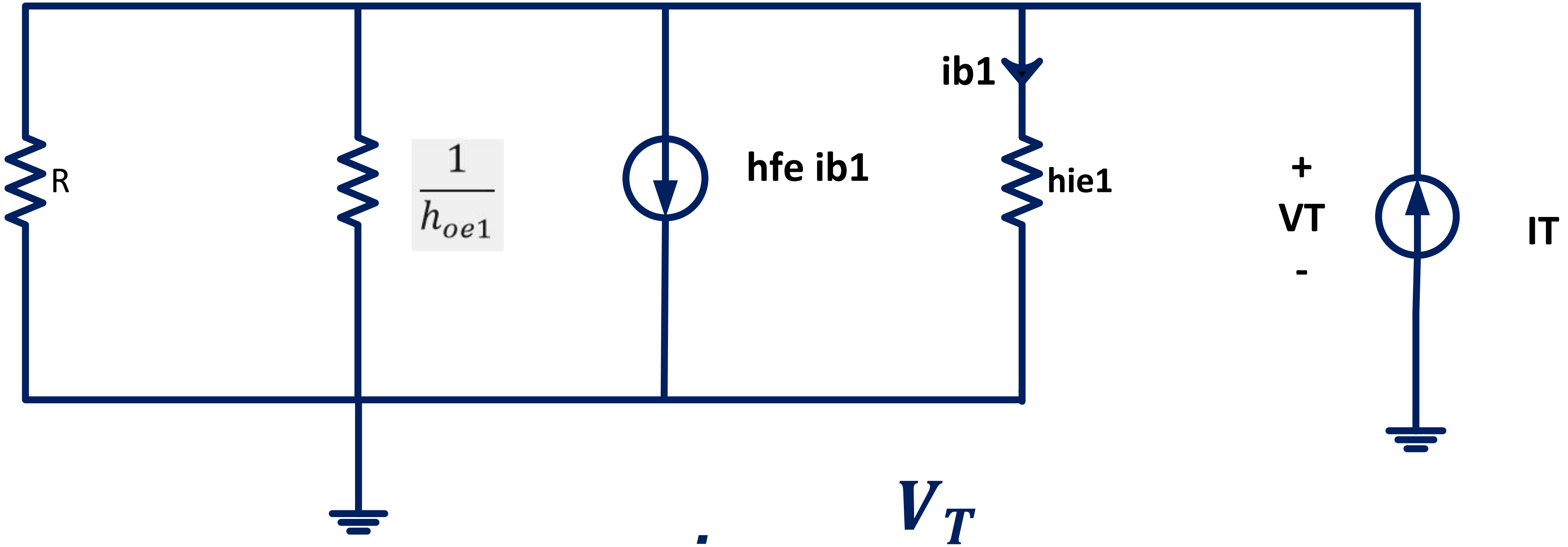
To find Ro′



Bipolar transistor current sources:

To find Ro′= $\frac{V_T}{I_T}$

Output - Impedance:



$$I_T = \frac{V_T}{R \parallel \frac{1}{h_{oe1}} \parallel h_{ie1}} + h_{fe} i_{b1}$$

$$i_{b1} = \frac{V_T}{h_{ie1}}$$

$$g_{m1} = \frac{h_{fe1}}{h_{ie1}}$$

$$I_T = \frac{h_{fe}}{h_{ie1}} V_T + \frac{V_T}{R \parallel h_{ie1} \parallel \frac{1}{h_{oe1}}}$$

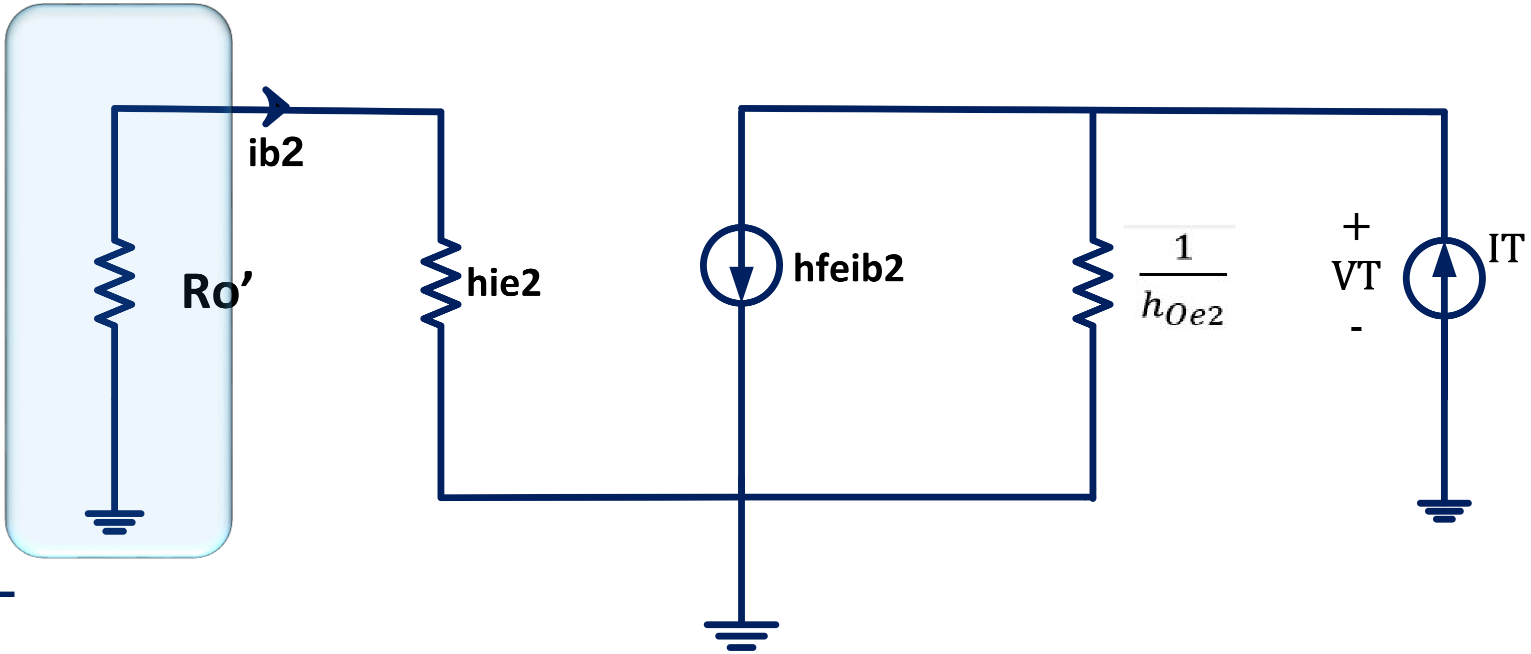
$$Ro' = R \parallel h_{ie1} \parallel \frac{1}{h_{oe1}} \parallel \frac{1}{gm1}$$

Differential Amplifiers

Bipolar transistor current sources:

Output - Impedance:

To find Ro = $\frac{V_T}{I_T}$



$$I_T = h_{fe}\, i_{b2} + \frac{V_T}{\frac{1}{h_{oe2}}}$$

$$i_{b2} = 0$$

$$\therefore \quad \frac{V_T}{I_T} = \frac{1}{h_{oe2}}$$

Bipolar transistor current sources:

2. Bipolar mirror with base-current compensation:

Reduce the B dependence

$$Q_1\,, Q_2 \; are\ matched$$

$$\beta_1 = \beta_2 \;\; ; \; I_{S1} = I_{S2} \,; \; V_{T1} = V_{T2}$$

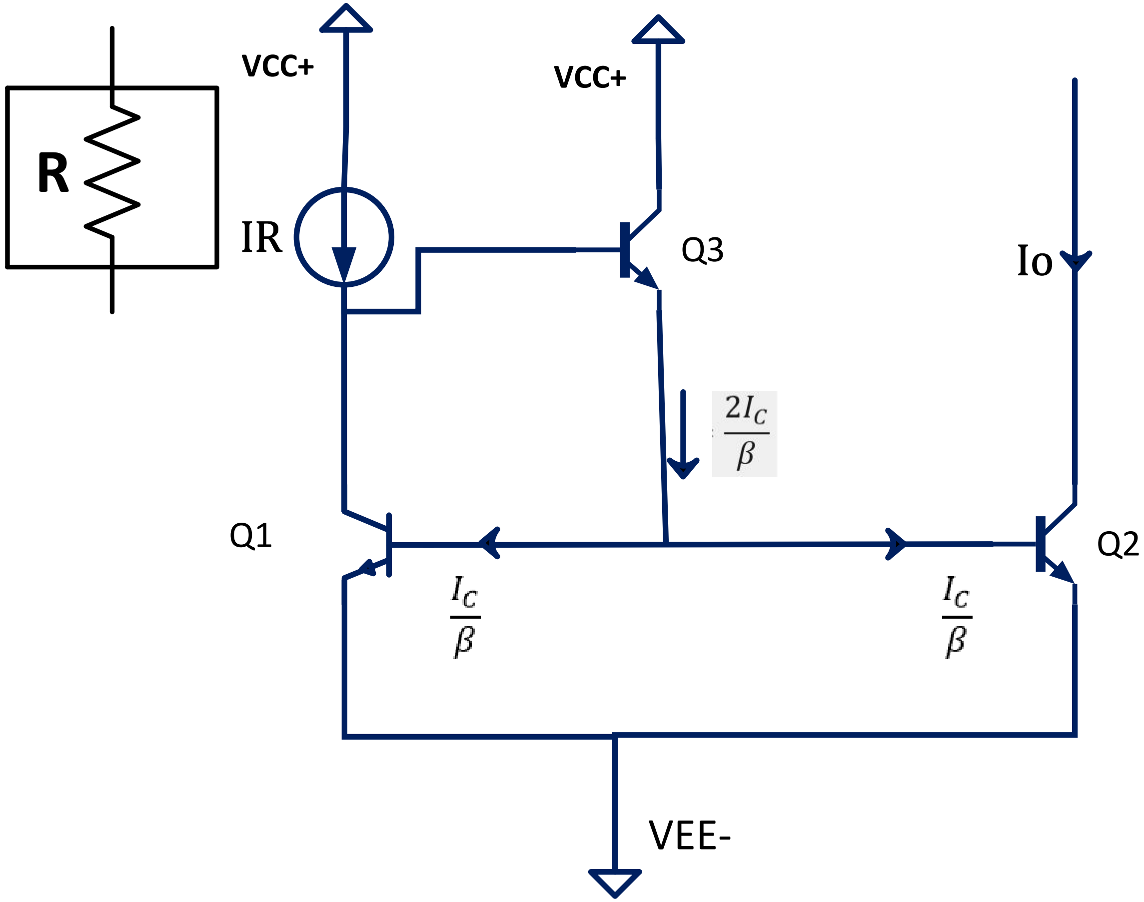
$$\text{And since } V_{BE1} = V_{BE2}$$

$$\therefore \quad I_{C1} = I_{C2} = I_o$$

$$I_{B1} = I_{B2}$$

$$\therefore \quad I_R = I_{C1} + I_{B3}$$

$$I_{B3} = \frac{I_{E3}}{\beta + 1} \qquad I_{E3} = \frac{2I_C}{\beta}$$

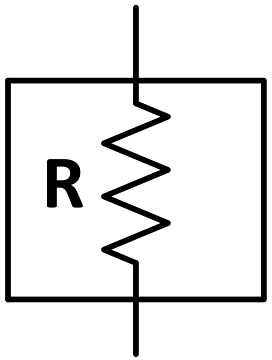


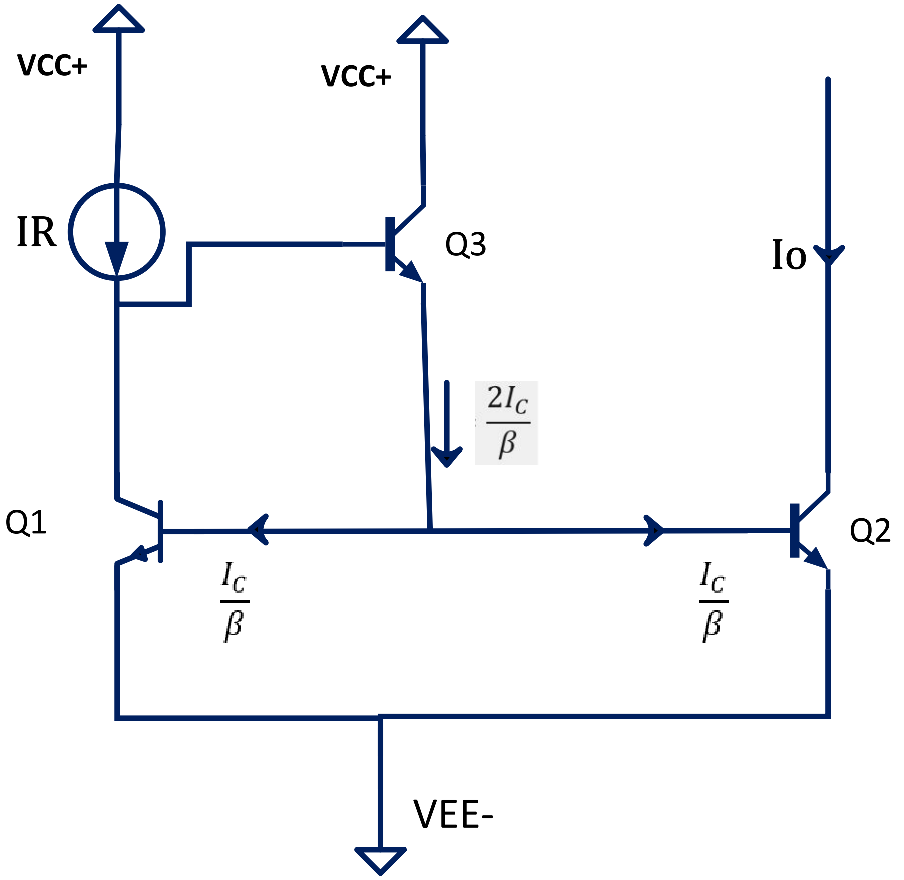
Bipolar transistor current sources:

2. Bipolar mirror with base-current compensation:

$$\therefore \quad I_R = I_C + \frac{2I_C}{\beta(\beta+1)}$$

$$\therefore \quad I_o = I_R \cdot \frac{1}{1+\frac{2}{\beta^2+\beta}}$$





Current source with a current transfer ratio that is much less dependent on B than that of the simple current mirror.

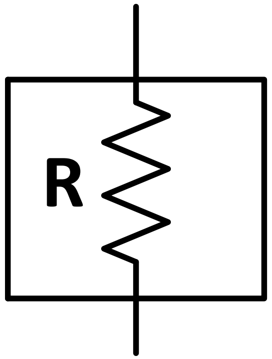
Bipolar transistor current sources:

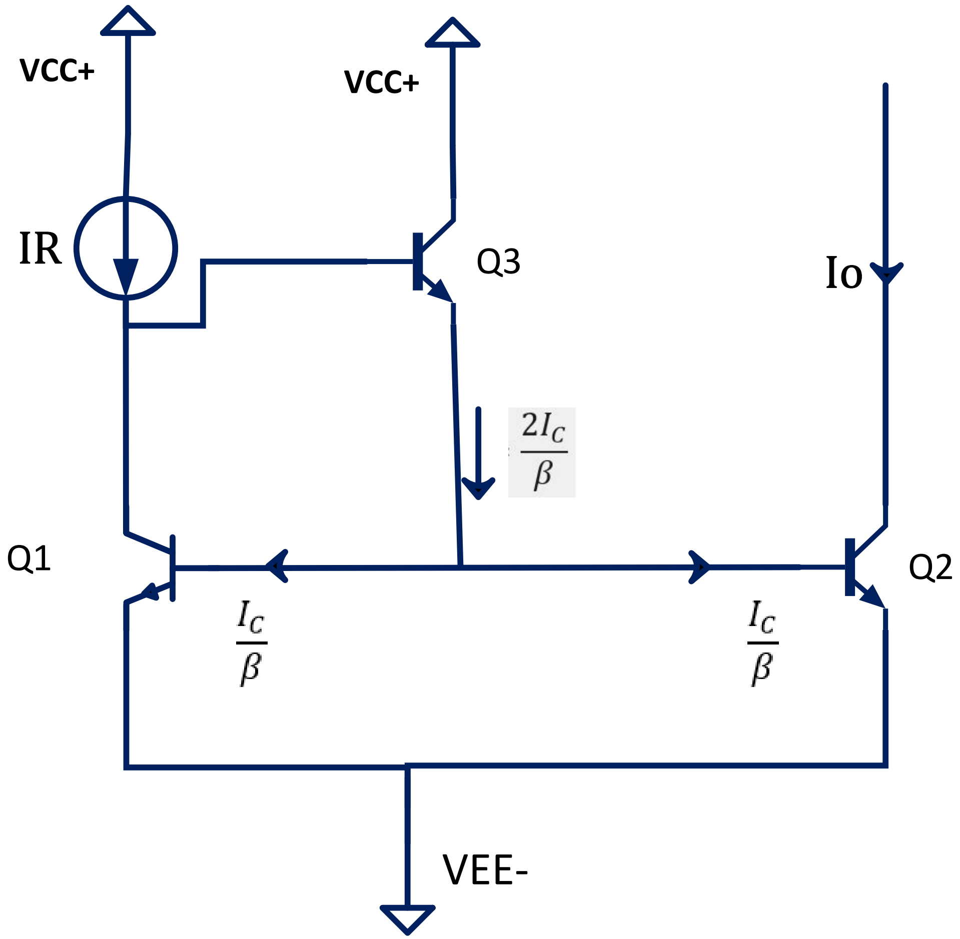
2. Bipolar mirror with base-current compensation:

Show that :

$$R_o = \frac{1}{h_{oe2}}$$

$$I_R = \frac{V_{CC} + V_{EE} - V_{BE3} - V_{BE1}}{R}$$



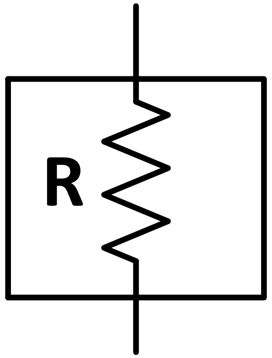


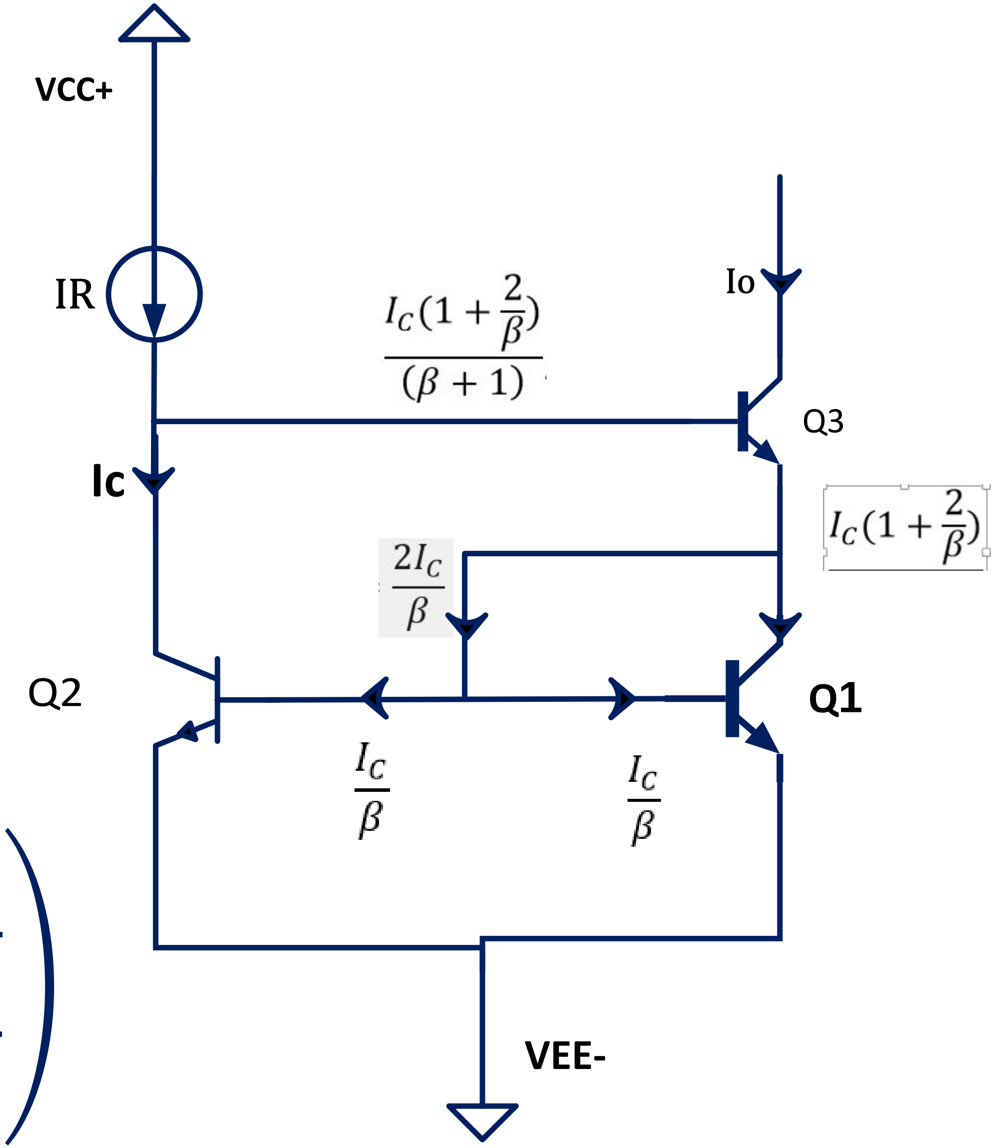
Bipolar transistor current sources:

3. The Wilson Current:

1)Reduce the B dependence

2) *Increase* $R_o = \frac{h_{fe}}{2} \frac{1}{h_{oe3}}$





$$Q_1, Q_2 \ are\ matched$$

$$I_{C1} = I_{C2} = I_C$$

$$I_R = I_C + \frac{I_C\left(1 + {}^2/_\beta\right)}{\beta + 1} = I_C\left(1 + \frac{1 + \frac{2}{\beta}}{\beta + 1}\right)$$

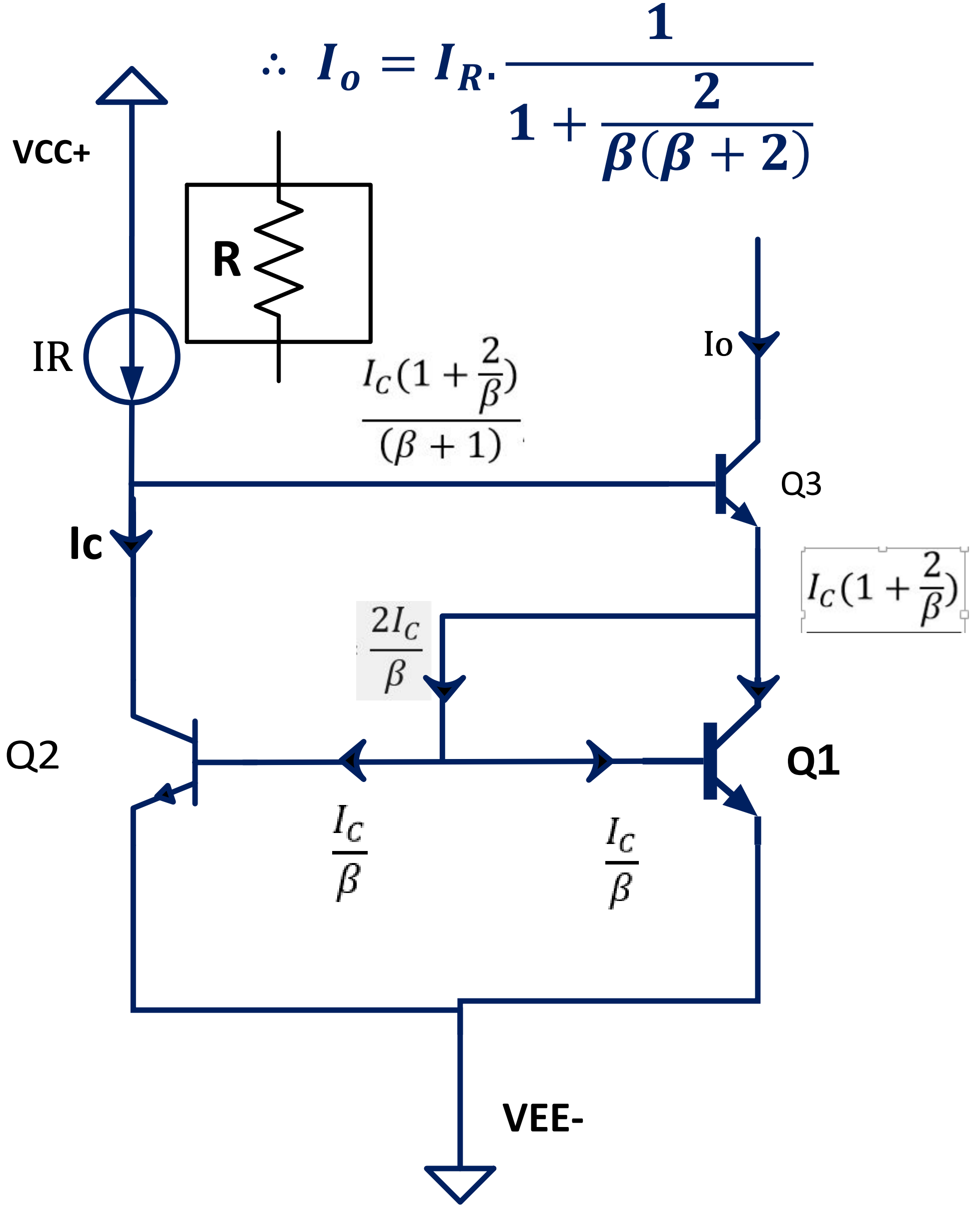
Bipolar transistor current sources:

3. The Wilson Current:

$$I_o = I_{C3} = \frac{\beta}{\beta+1} I_{E3} = \frac{\beta\left(1+\frac{2}{\beta}\right)}{\beta+1} I_C$$

$$\frac{I_o}{I_R} = \frac{I_C\left(1+{}^{2}/_{\beta}\right)\left({}^{\beta}/_{\beta+1}\right)}{I_C\left(1+\frac{1+{}^{2}/_{\beta}}{\beta+1}\right)}$$

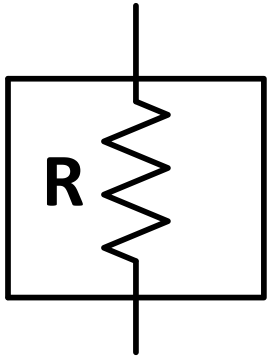
$$I_o = I_R \frac{1}{1+\frac{2}{\beta(\beta+2)}}$$

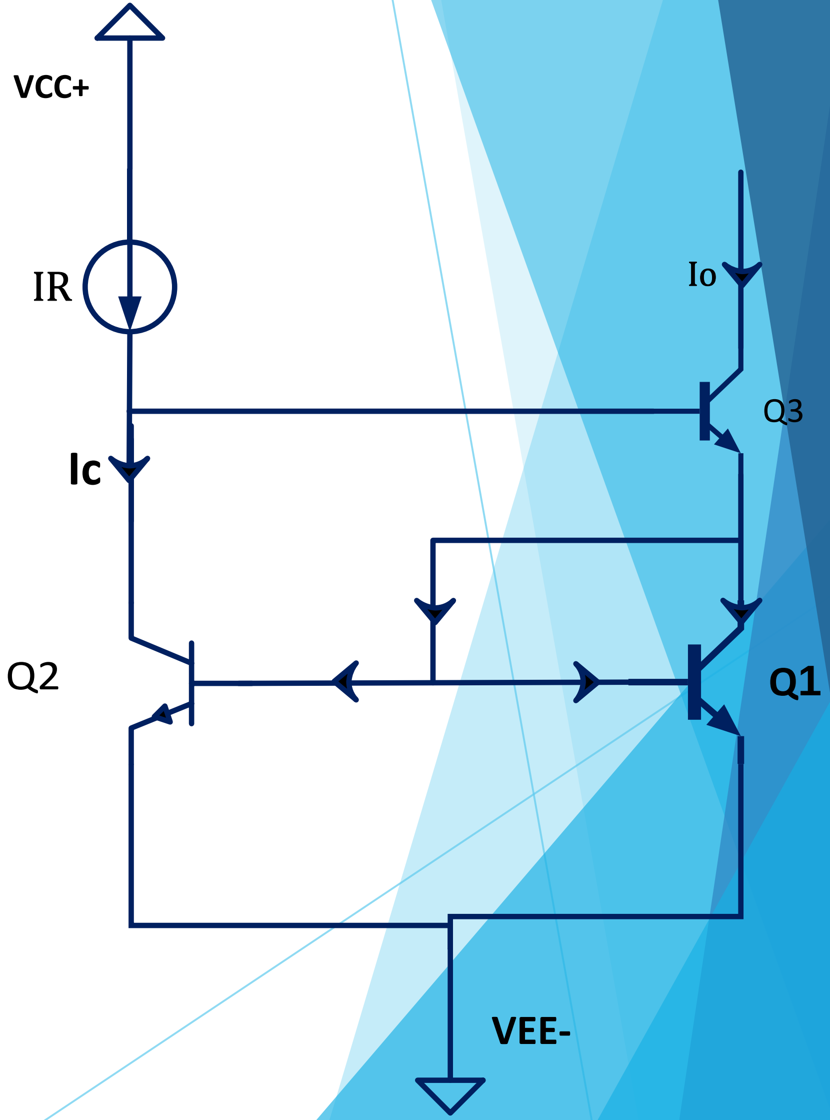


Differential Amplifiers

The Wilson current mirror

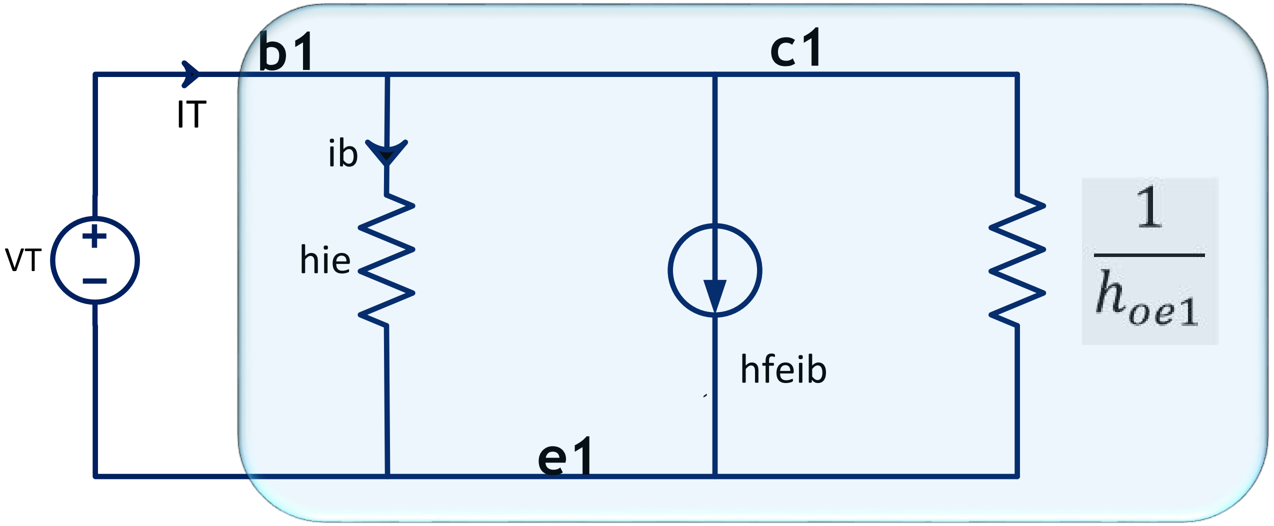
To proof that $R_o \approx \frac{h_{fe}}{2}\frac{1}{h_{oe}}$

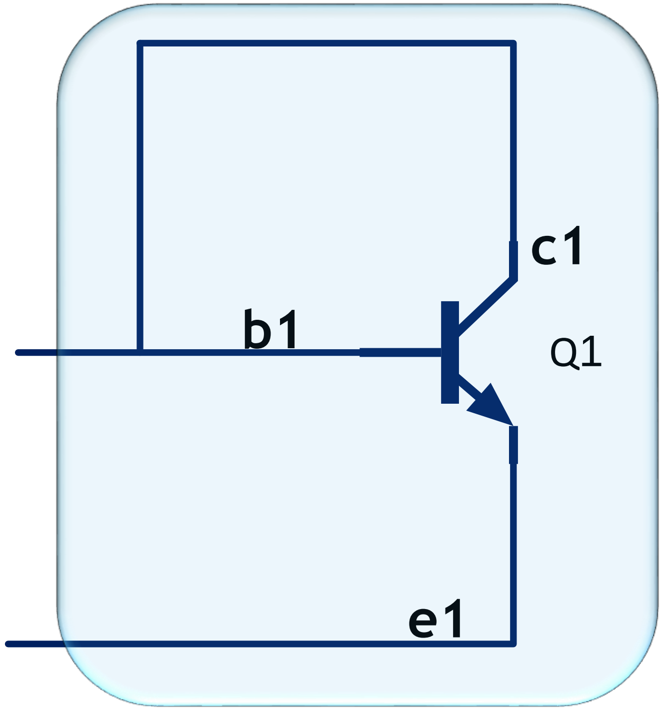




Bipolar transistor current sources:

The Equivalent circuit for a diode connected transistor





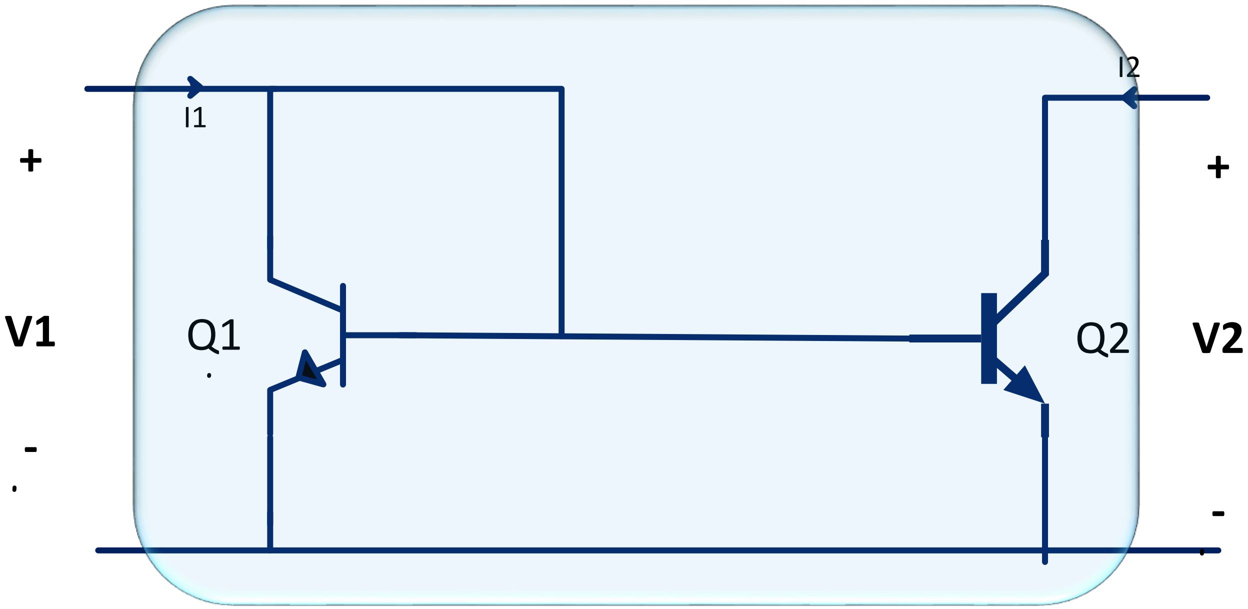
$$I_T = h_{fe1} i_{b1} + \frac{V_T}{h_{ie1} \parallel \frac{1}{h_{oe1}}}$$

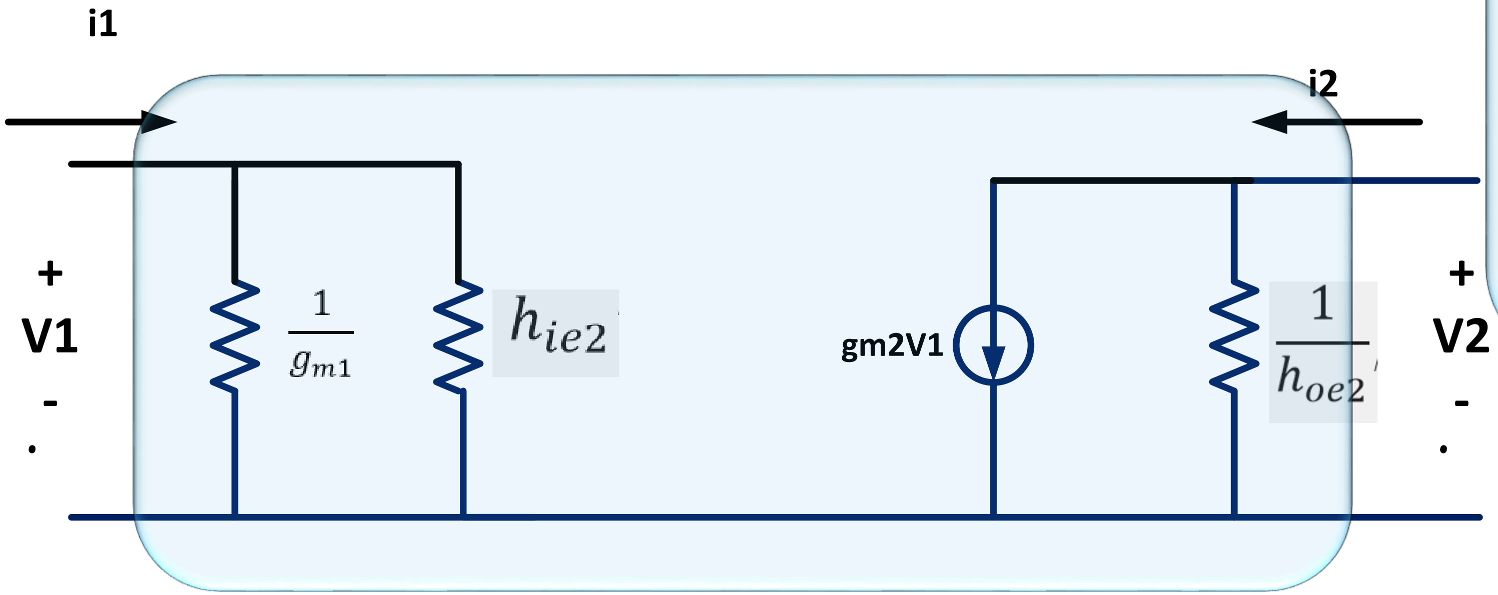
$$\therefore \quad \frac{V_T}{I_T} = \frac{1}{g_{m1}} \parallel h_{ie1} \parallel \frac{1}{h_{oe1}}$$

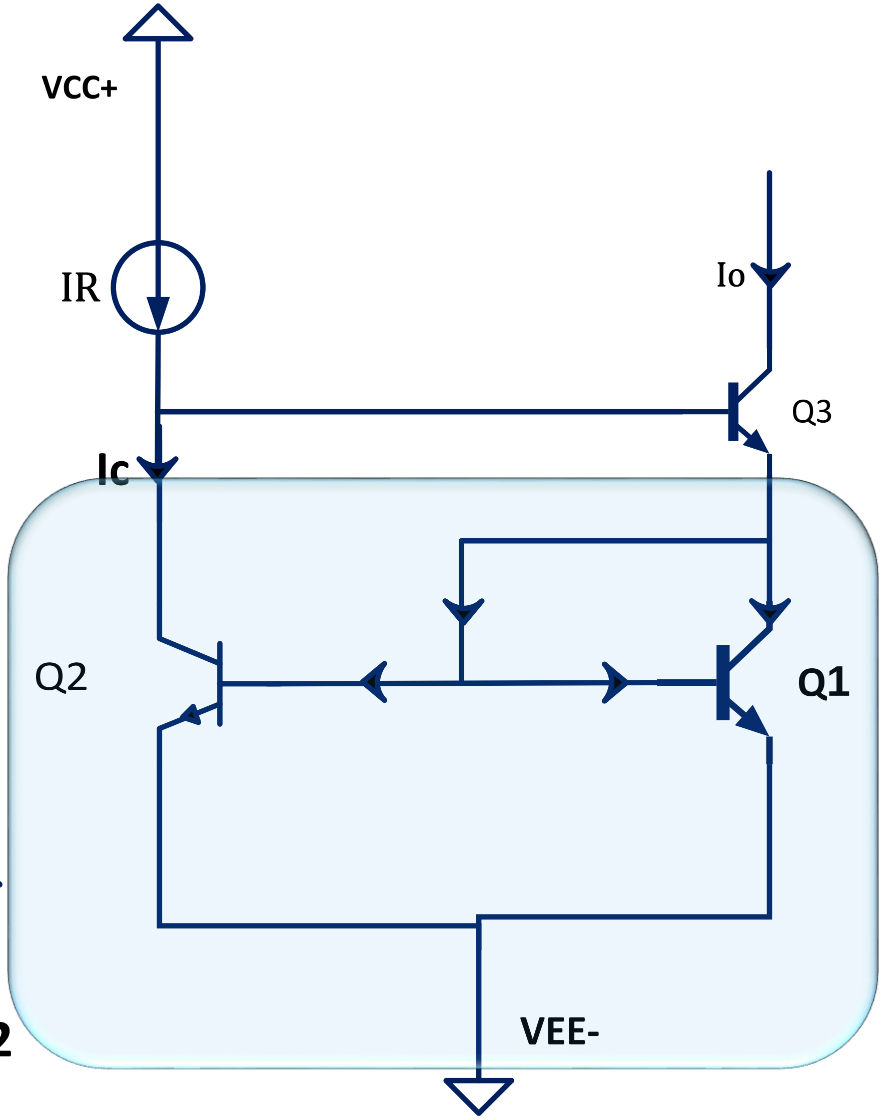
$$i_{b1} = \frac{V_T}{h_{ie1}}$$

$$R_{TH} \approx \frac{1}{g_{m1}} \approx h_{ib1}$$

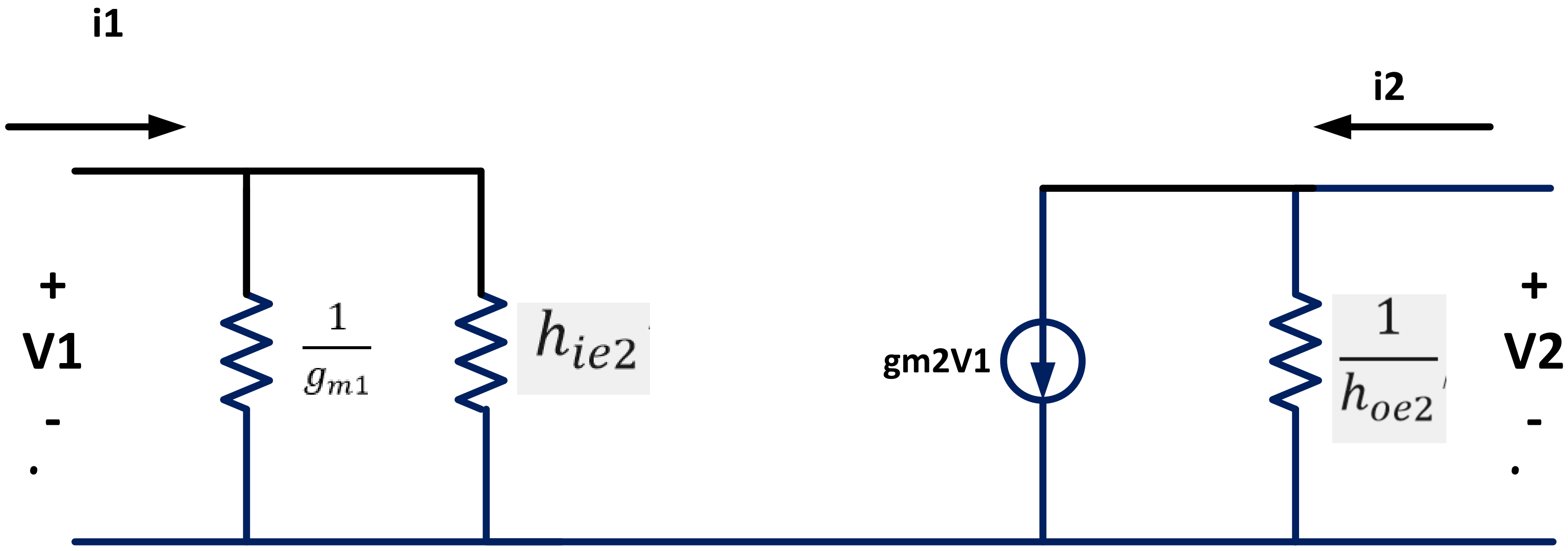
Two Port Model for the current mirror







Two Port Model for the current mirror



$$V_1 = h_{11}\ i_1 + h_{12}\,V_2$$
$$i_2 = h_{21}\ i_1 + h_{22}\,V_2$$

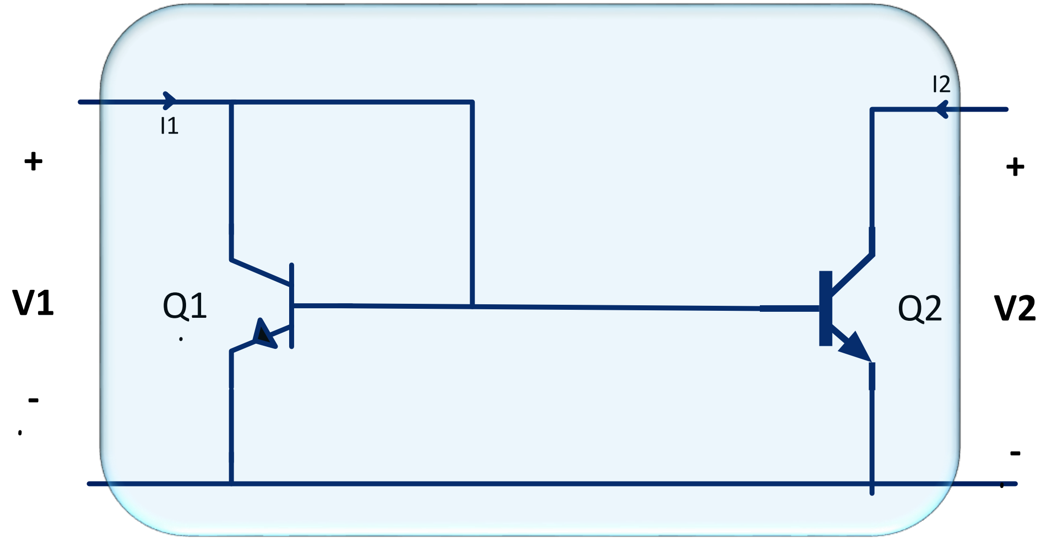
$$h_{11} = \frac{v_1}{i_1}\Big|_{v_2=0} = \frac{1}{g_{m1}} \,\|\, h_{ie2} \approx \frac{1}{g_{m1}}$$

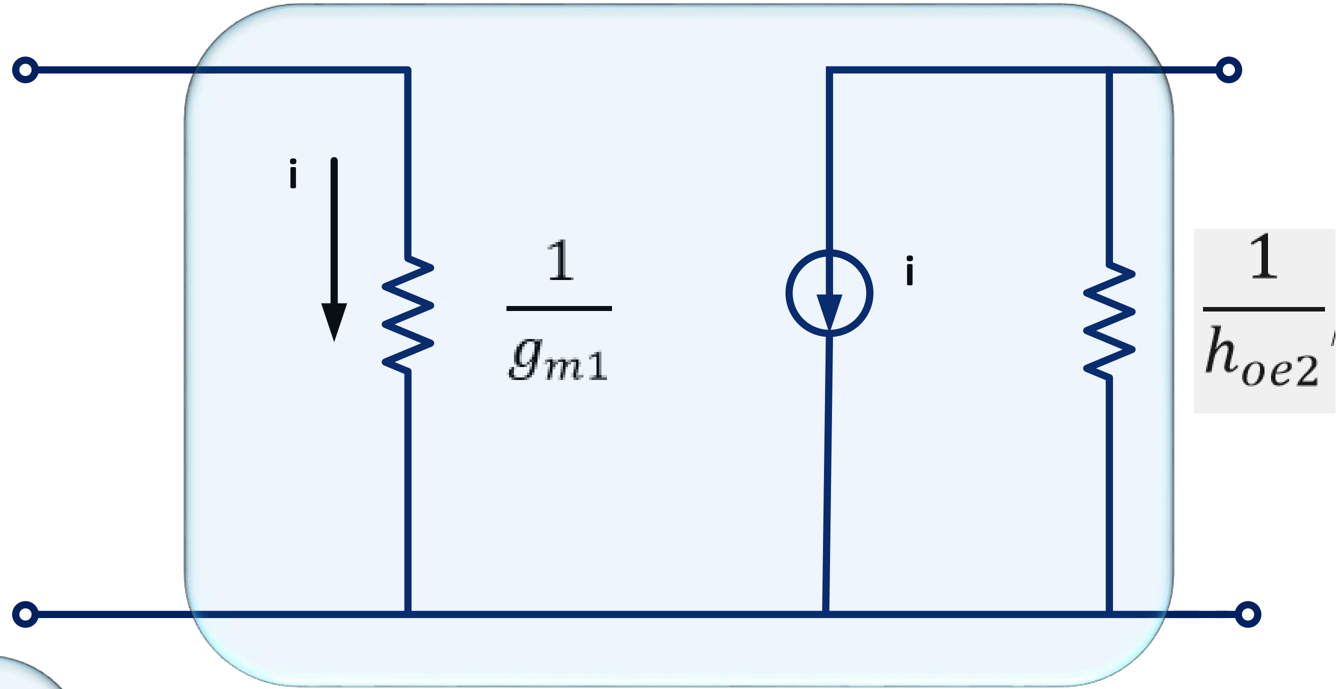
$$h_{12} = \frac{v_1}{v_2}\Big|_{i_1=0} = 0$$

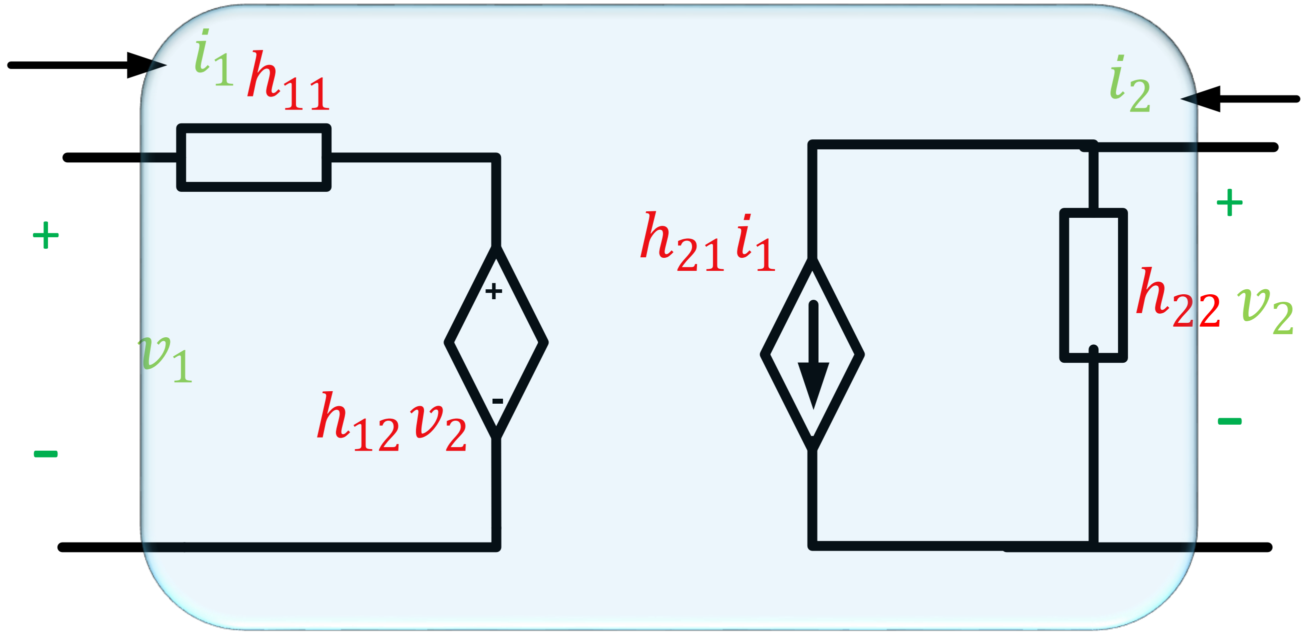
$$h_{22} = \frac{i_2}{v_2}\Big|_{i_1=0} = h_{oe2}$$

$$h_{21} = \frac{i_2}{i_1}\Big|_{v_2=0} = \frac{g_{m2}\ h_{ie2}}{1 + g_{m1}\ h_{ie1}} \approx \frac{g_{m2}}{g_{m1}} = 1$$

Two Port Model for the current mirror







$$h_{11} = \frac{1}{g_{m1}}$$

$$h_{12} = 0$$

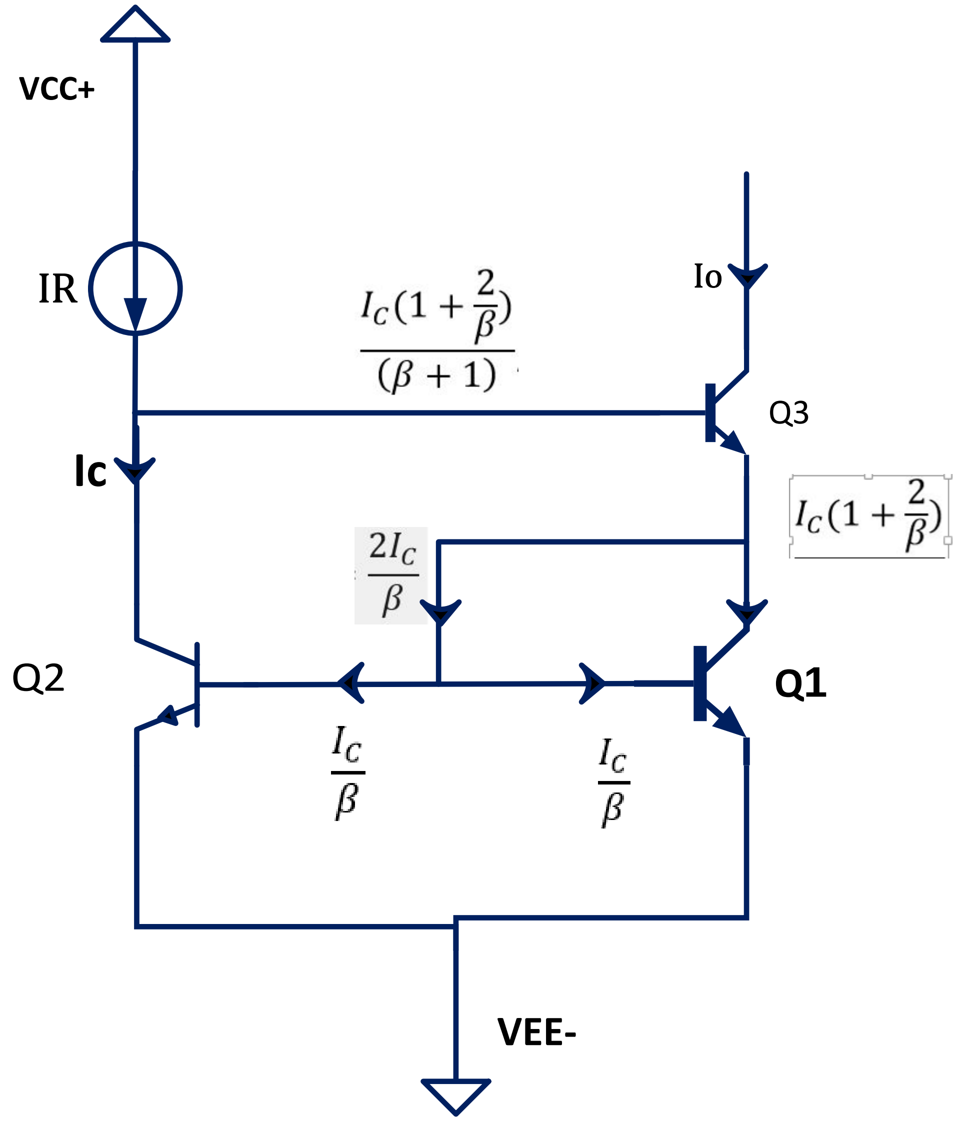
$$h_{21} = 1$$

$$h_{22} = h_{oe2}$$

Differential Amplifiers

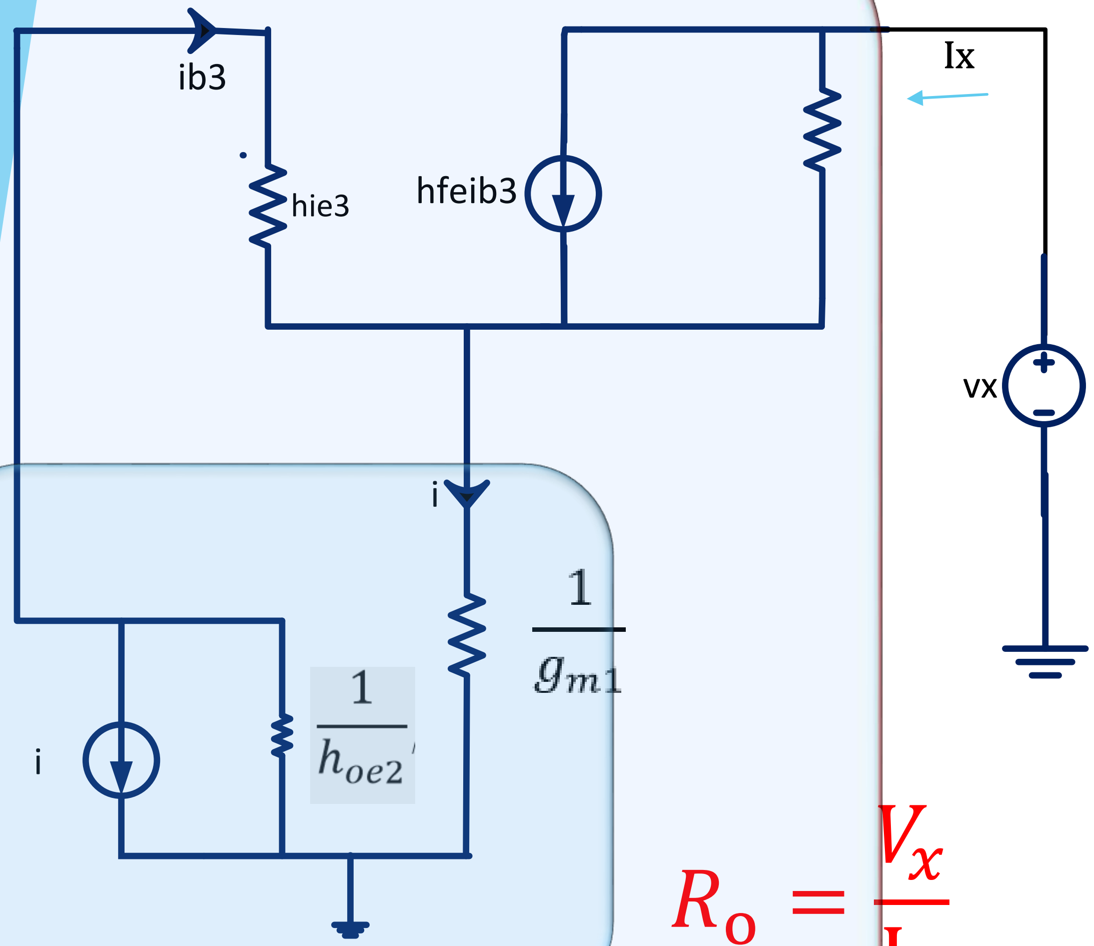
The Wilson Current:

$$To\ proof\quad R_o \cong \frac{h_{fe}}{2} \cdot \frac{1}{h_{oe3}}$$

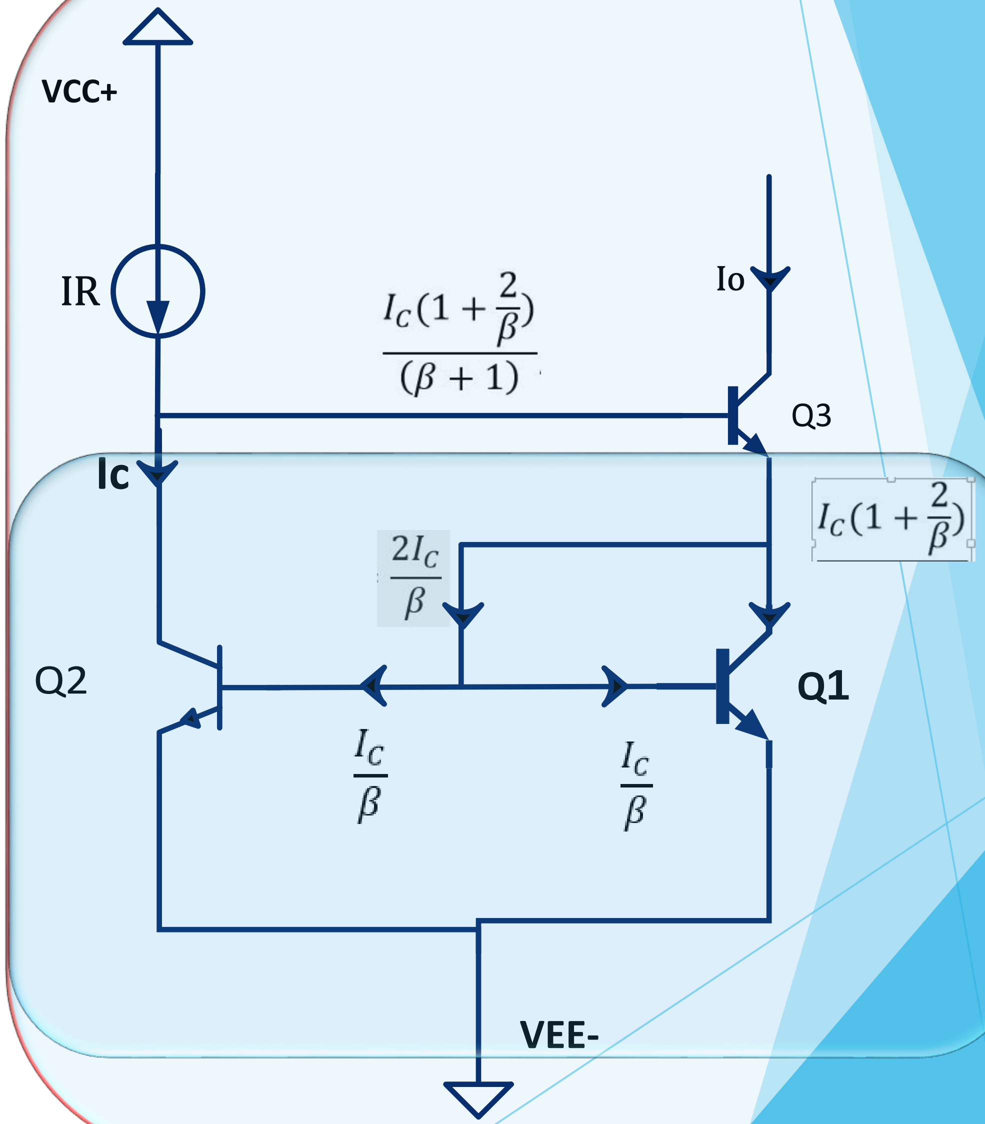


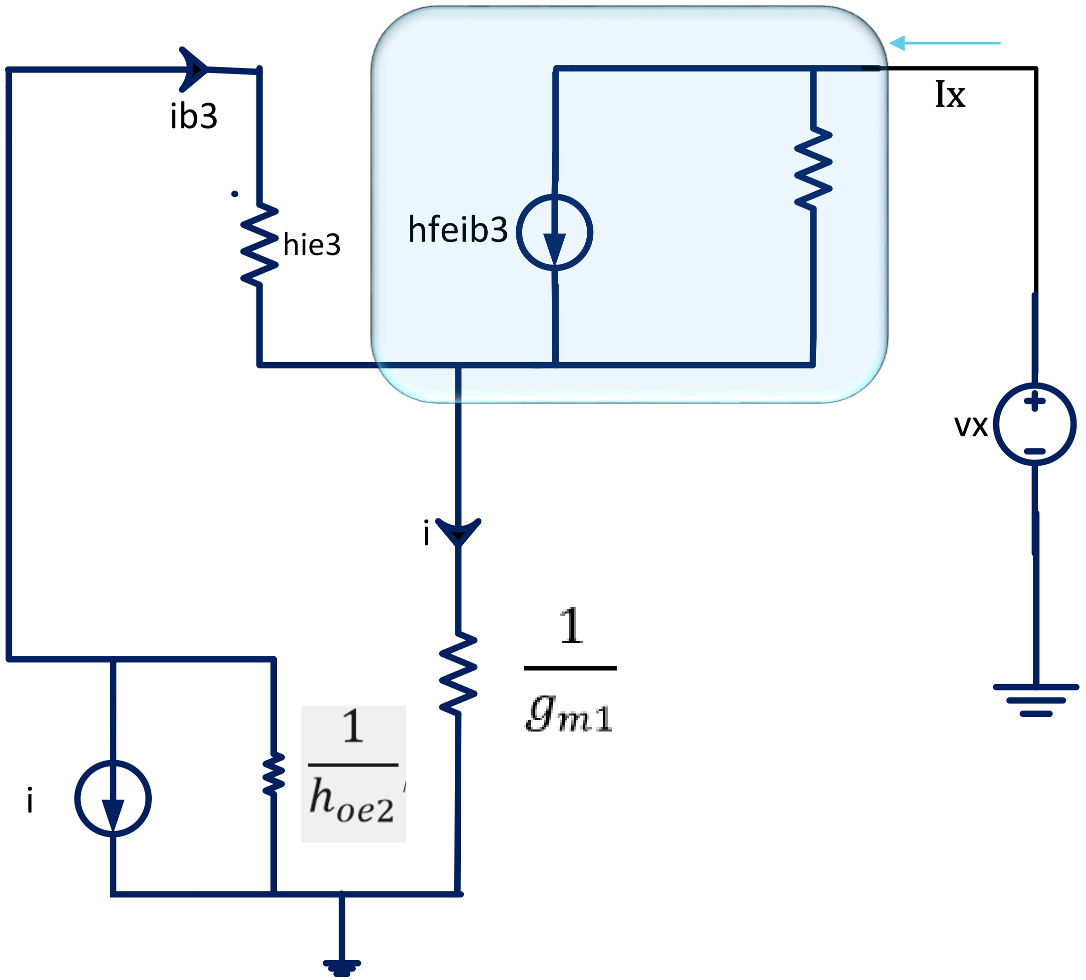
Differential Amplifiers

The Wilson current mirror

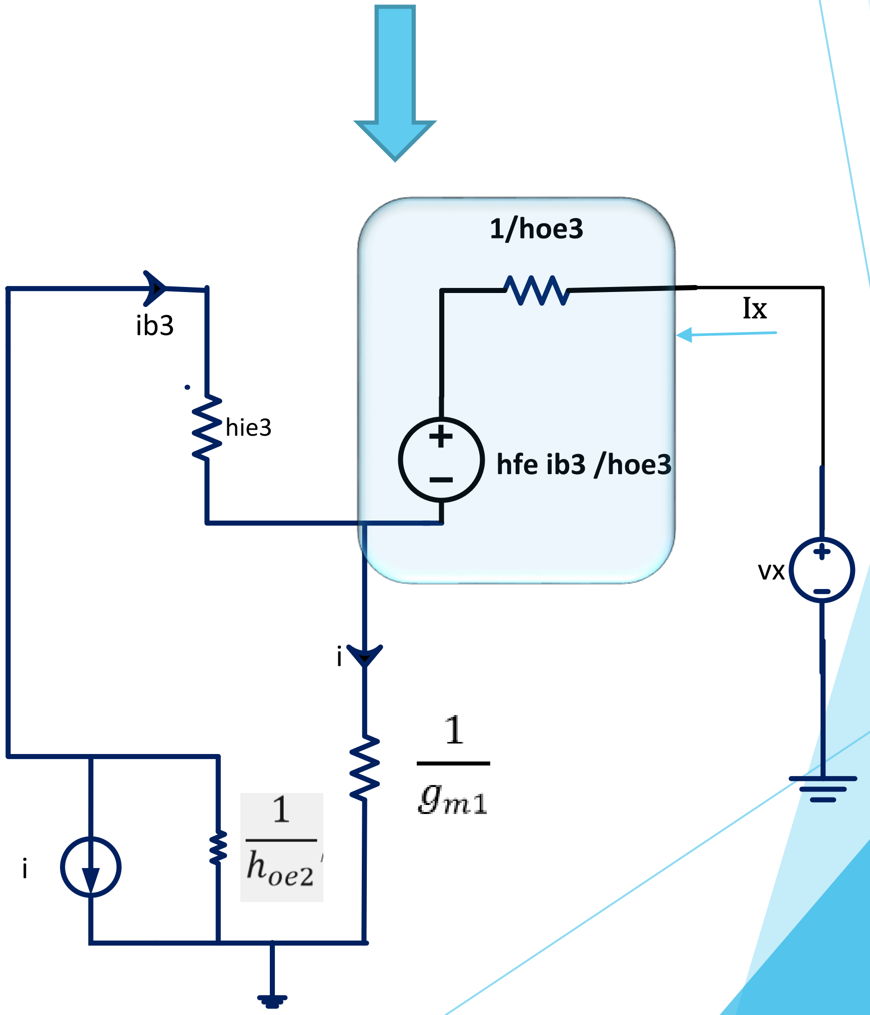


$$R_o = \frac{V_x}{I_x}$$





Source transformation



The Wilson current mirror

$$V_X + \frac{h_{fe}}{h_{oe3}}\,ib_3 = \left(\frac{1}{h_{oe3}} + \frac{1}{g_{m1}}\right) I_X + \frac{1}{g_{m1}}\,ib_3$$

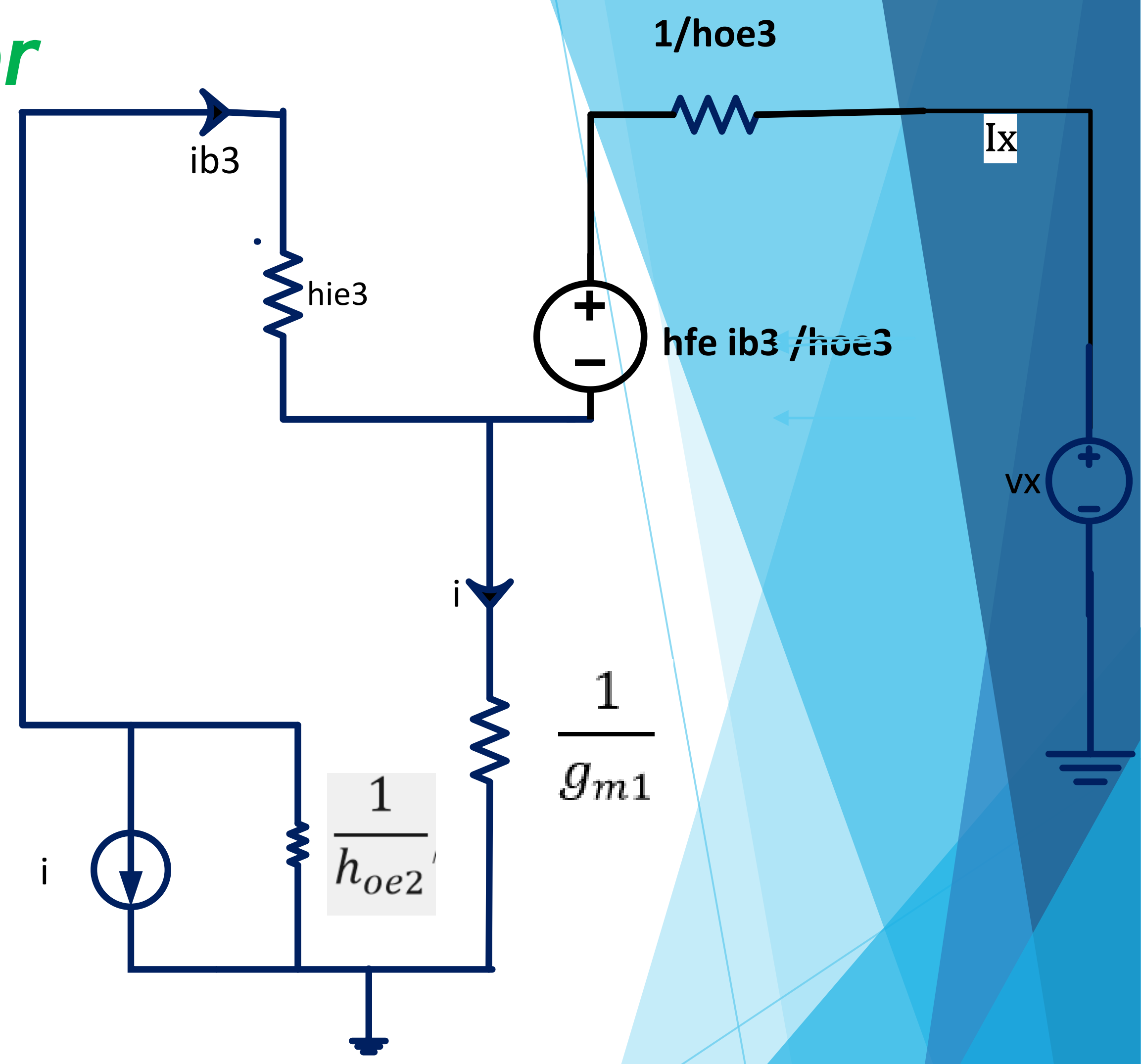
$$V_X = \left(\frac{1}{h_{oe3}} + \frac{1}{g_{m1}}\right) I_X + \left(\frac{1}{g_{m1}} - \frac{h_{fe}}{h_{oe3}}\right) ib_3$$

$$since \quad \frac{1}{h_{oe3}} \gg \frac{1}{g_{m1}} \quad and \quad \frac{h_{fe}}{h_{oe3}} \gg \frac{1}{g_{m1}}$$

$$V_X = \frac{1}{h_{oe3}}\,I_X - \frac{h_{fe}}{h_{oe3}}\,ib_3 \quad \rightarrow (1)$$

$$-\frac{i}{h_{oe2}} = \frac{1}{g_{m1}}\,I_X + \left(h_{ie3} + \frac{1}{g_{m1}} + \frac{1}{h_{oe2}}\right) ib_3 \quad \rightarrow (2)$$

$$i = ib_3 + I_X \quad \rightarrow (3)$$

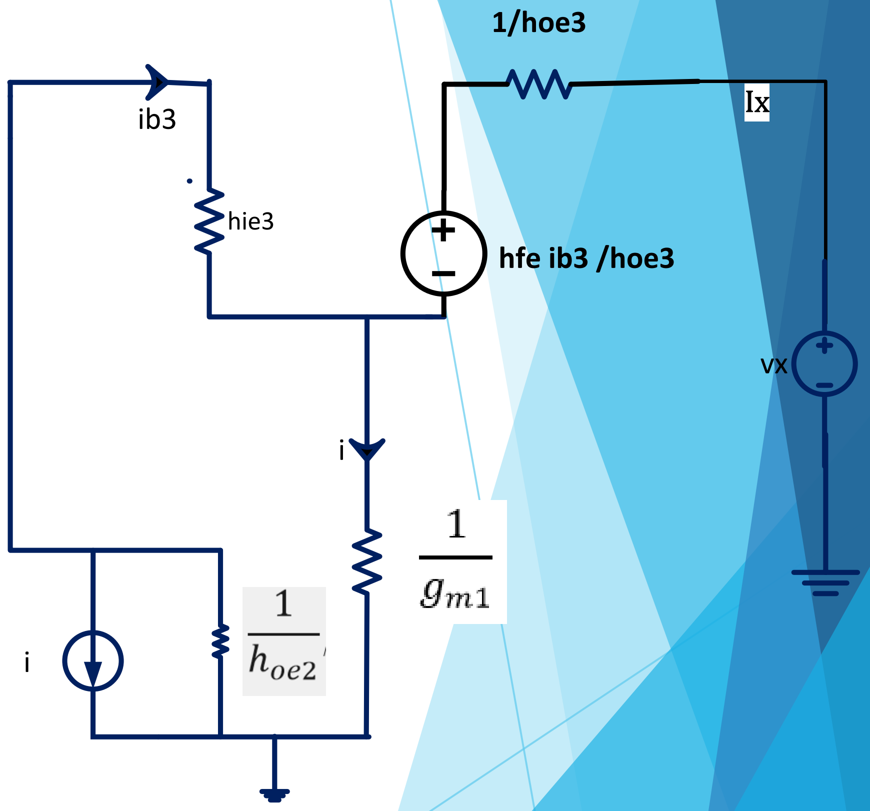


$$sub\ (3)\ into\ (2)$$

$$0 = \left(\frac{1}{h_{oe2}} + \frac{1}{g_{m1}}\right)\ I_X + \left(\frac{1}{g_{m1}} + h_{ie3} + \frac{2}{h_{oe2}}\right) ib_3$$

$$since\ \frac{1}{h_{oe2}} \gg \frac{1}{g_{m1}} \quad and \quad \frac{2}{h_{oe2}} \gg \frac{1}{g_{m1}} + h_{ie3}$$

$$0 = \frac{1}{h_{oe2}}\ I_X + \frac{2}{h_{oe2}}\ ib_3 \quad \rightarrow (4)$$



The Wilson current mirror

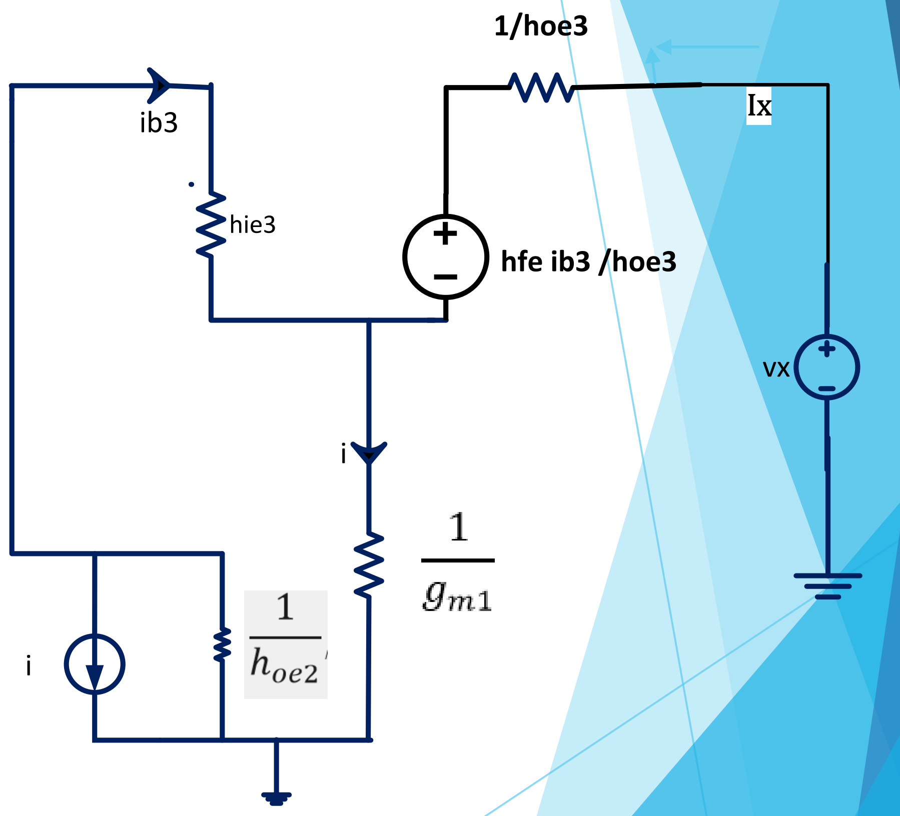
$$V_X = \frac{1}{h_{oe3}} I_X - \frac{h_{fe}}{h_{oe3}} ib_3 \quad \rightarrow (1)$$

$$using\ (4)\ we\ get \quad ib_3 = -\frac{I_X}{2}$$

$$\therefore \quad V_X = \frac{1}{h_{oe3}} I_X + \frac{h_{fe}}{2} \; \frac{1}{h_{oe3}} \; I_X$$

$$\therefore \quad \frac{V_X}{I_X} = \left(\frac{h_{fe}}{2} + 1\right) \frac{1}{h_{oe3}}$$

$$\therefore \quad R_o = \frac{V_X}{I_X} \approx \frac{h_{fe}}{2} \; \frac{1}{h_{oe3}}$$



$$I_{C1} > I_{C2} = I_0 \qquad I_C = I_S\, e^{\frac{V_{BE}}{V_T}}$$

4. Widlar Current Source:

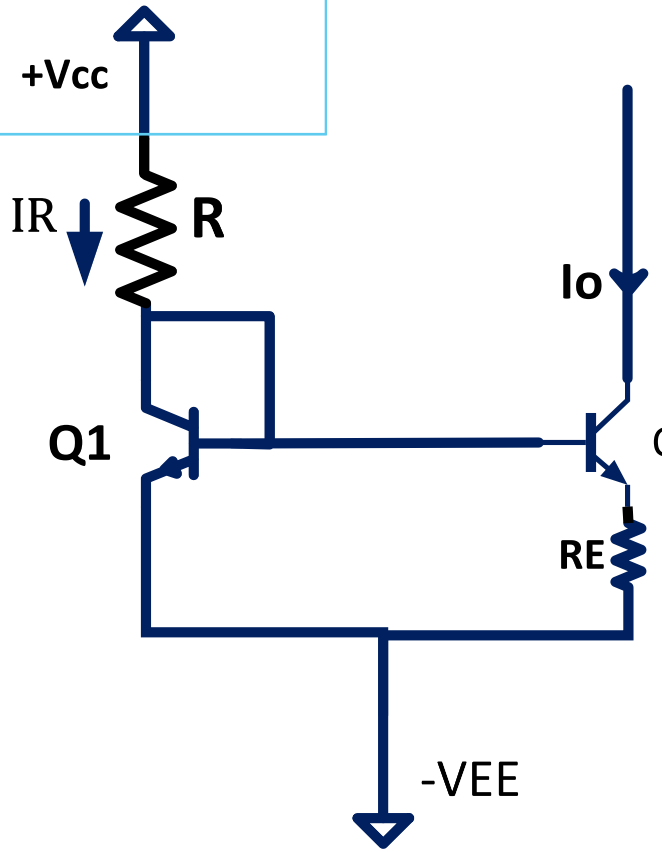
- To Produce Very small Io
- To increase Ro

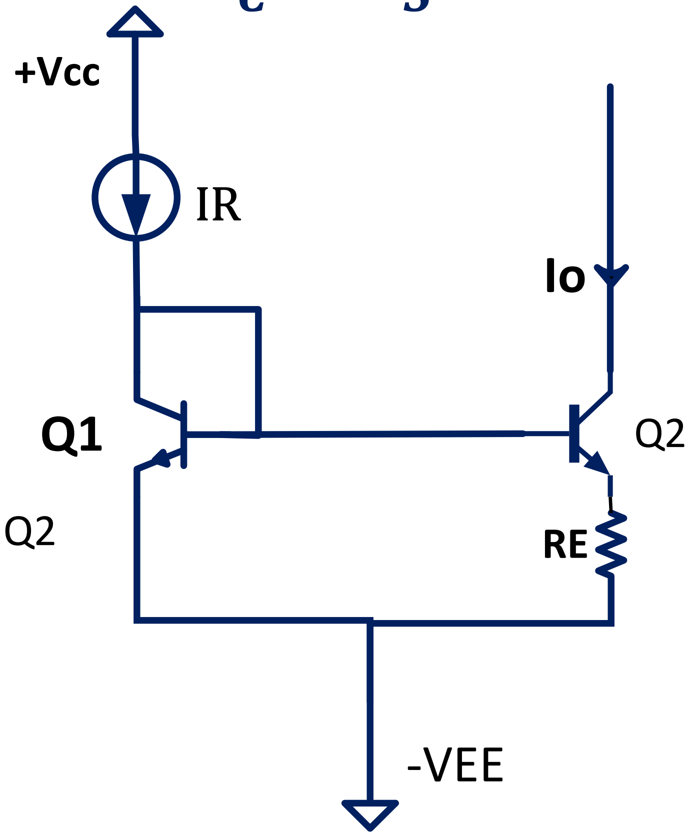
$$KVL: \quad V_{BE1} = V_{BE2} + R_E I_{E2}$$

$$V_T \ln\frac{I_{C1}}{I_{S1}} = V_T \ln\frac{I_{C2}}{I_{S2}} + R_E I_{E2}$$

$$V_T \ln\frac{I_{C1}}{I_{S1}} - V_T \ln\frac{I_{C2}}{I_{S2}} = R_E I_{E2}$$

$if \quad Q_1 \; and \; Q_2 \; are \; matched$





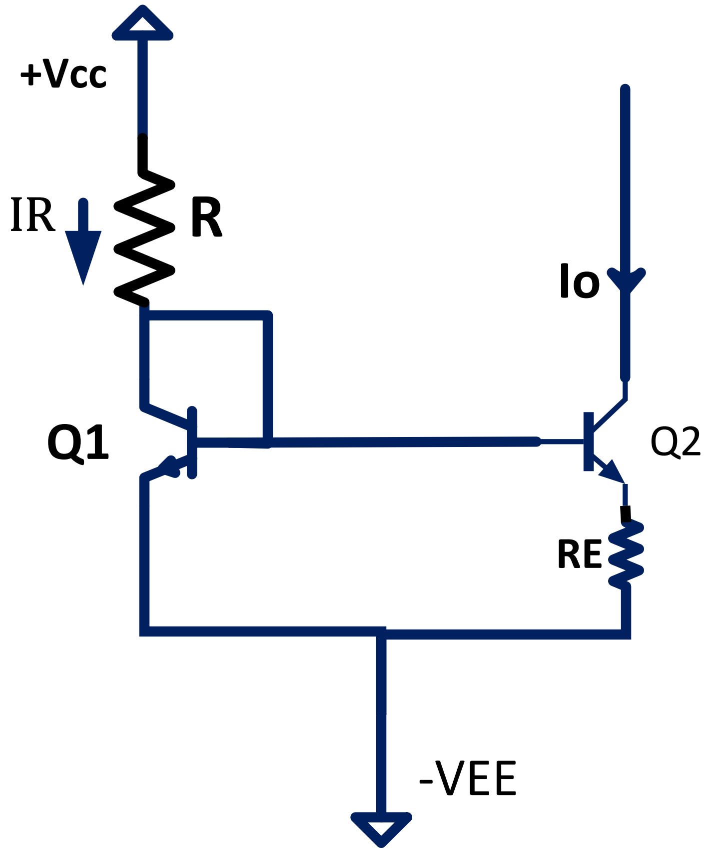
$$V_T \ln\frac{I_{C1}}{I_{C2}} = R_E I_{E2}$$

$$V_T \ln \frac{I_{C1}}{I_{C2}} = R_E I_{E2}$$

$$\boldsymbol{if\ \beta = \infty}$$

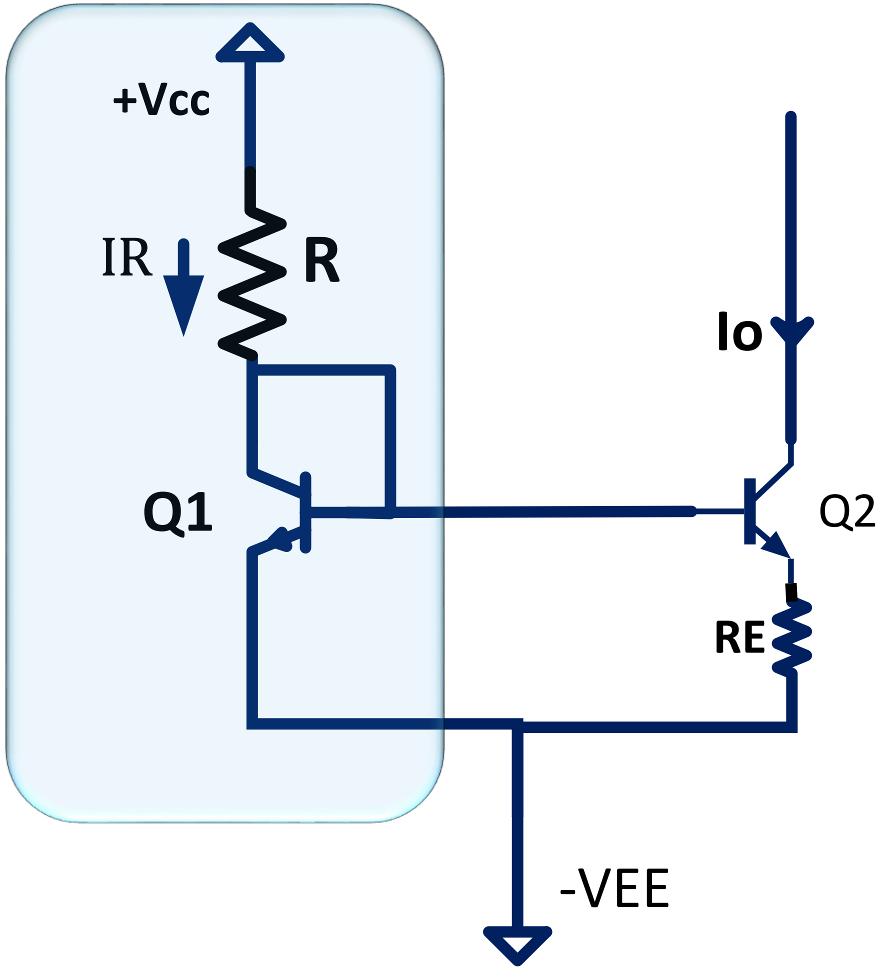
$$V_T \ln \frac{I_R}{I_0} = R_E I_O$$

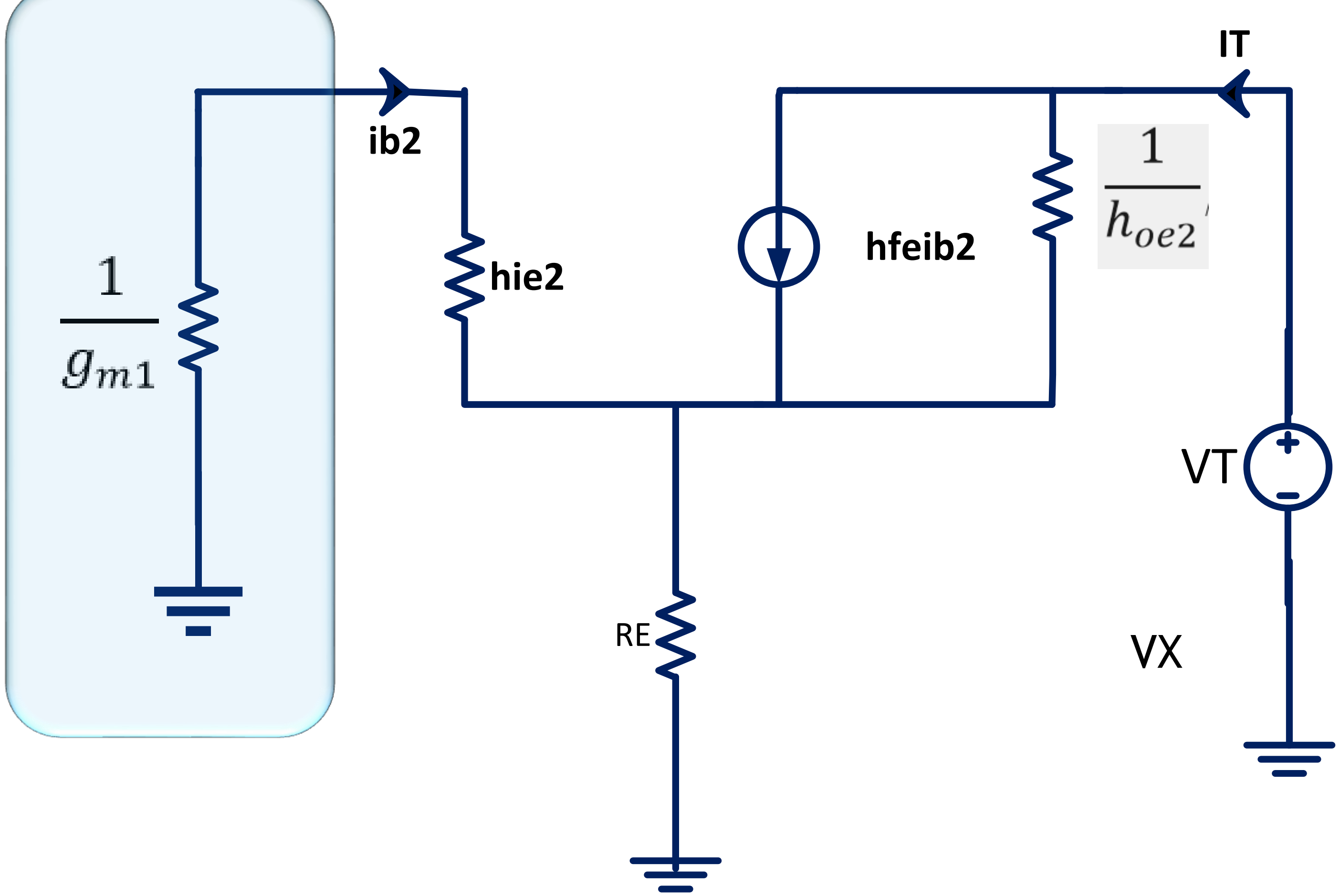
$$I_R = \frac{V_{CC} + V_{EE} - V_{BE1}}{R}$$



4. Widlar Current Source:

- To Find Ro:





$$R_o \approx \frac{1}{h_{oe2}} + \frac{h_{fe}}{h_{oe2}} \quad \frac{R_E}{R_E + h_{ie2} + \frac{1}{gm1}}$$

Design a simple current mirror to generate Io= 10uA given that V_{BE} = 0.7 V @ 1mA

Assume B = ∞ , V_{CC} = 10V and V_{EE} = 0V

We need to find the value of V_{BE} @10uA

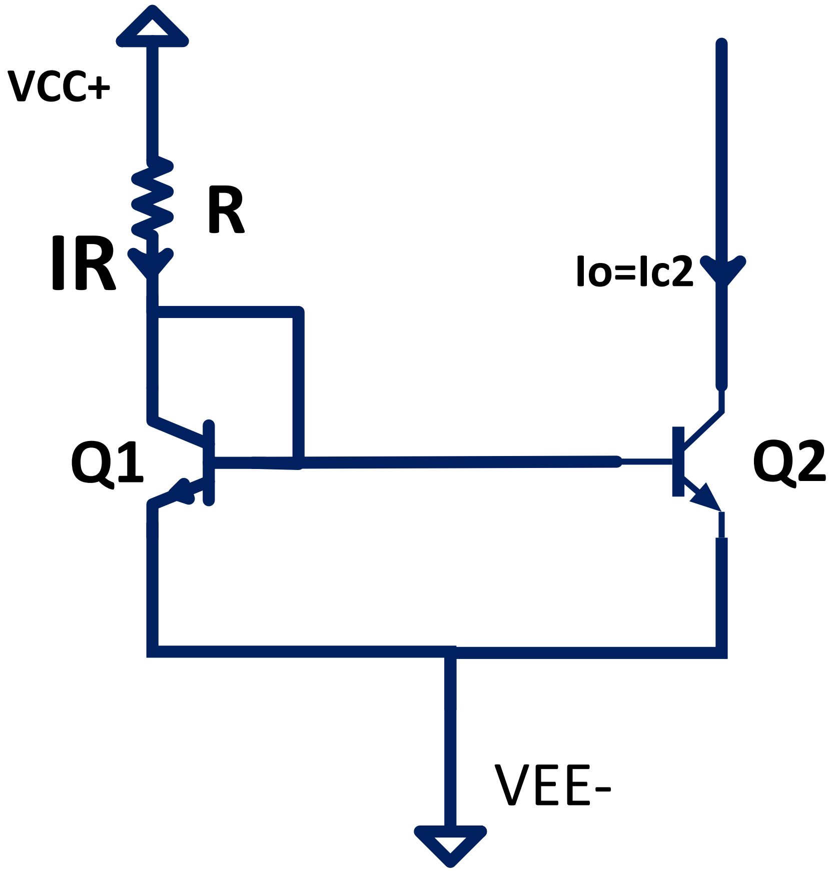
$$V_{BE} = V_T \ln \frac{I_C}{I_S}$$

$$V_{BE2} - V_{BE1} = V_T \ln \frac{I_{C2}}{I_{C1}}$$

$$V_{BE2} = V_{BE1} + V_T \ln \frac{I_{C2}}{I_{C1}}$$

$$= 0.7 + V_T \ln \frac{10HA}{1mA}$$

$$= 0.58\ V$$



Differential Amplifiers

Design a simple current mirror to generate Io= 10uA given that VBE = 0.7 V @ 1mA

Assume B=∞ , V_{CC} = 10V and V_{EE} = 0V

$$V_{BE} = 0.7\,V\ @\ I_C = 1mA$$

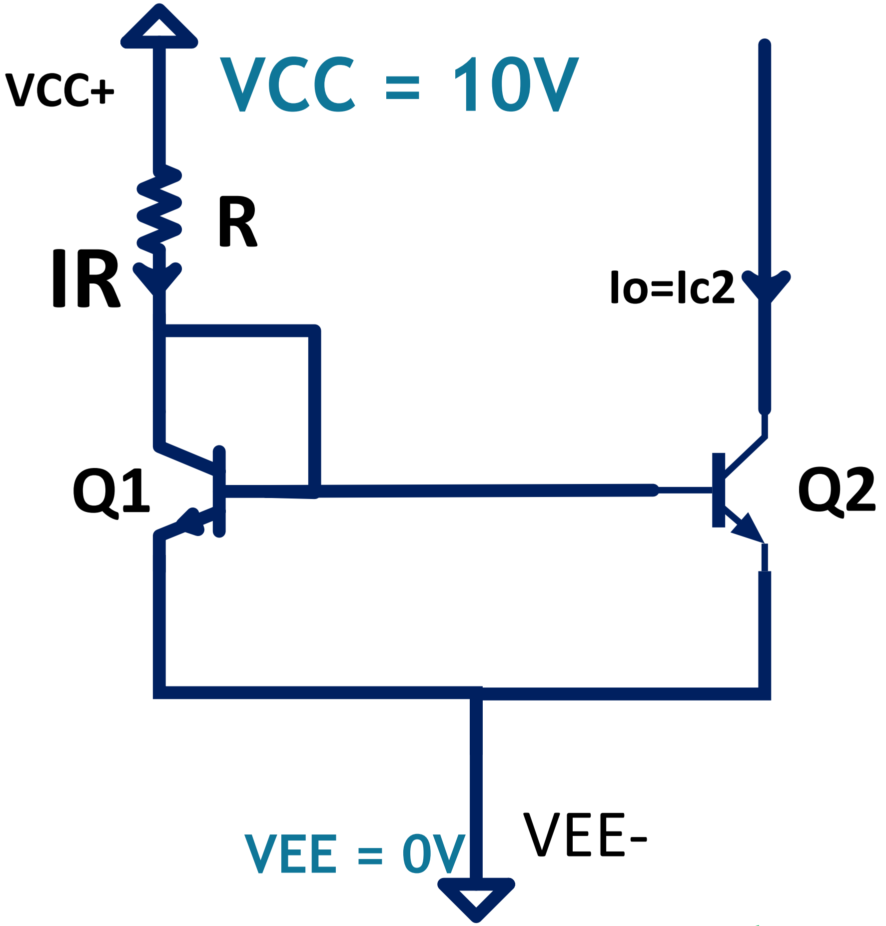
$$V_{BE} = 0.58\,V\ @\ I_C = 10\mu A$$

$$KVL: \ V_{CC} = R\,I_R + V_{BE}$$

$$since \quad \beta = \infty$$

$$I_R = I_o = 10\mu A$$

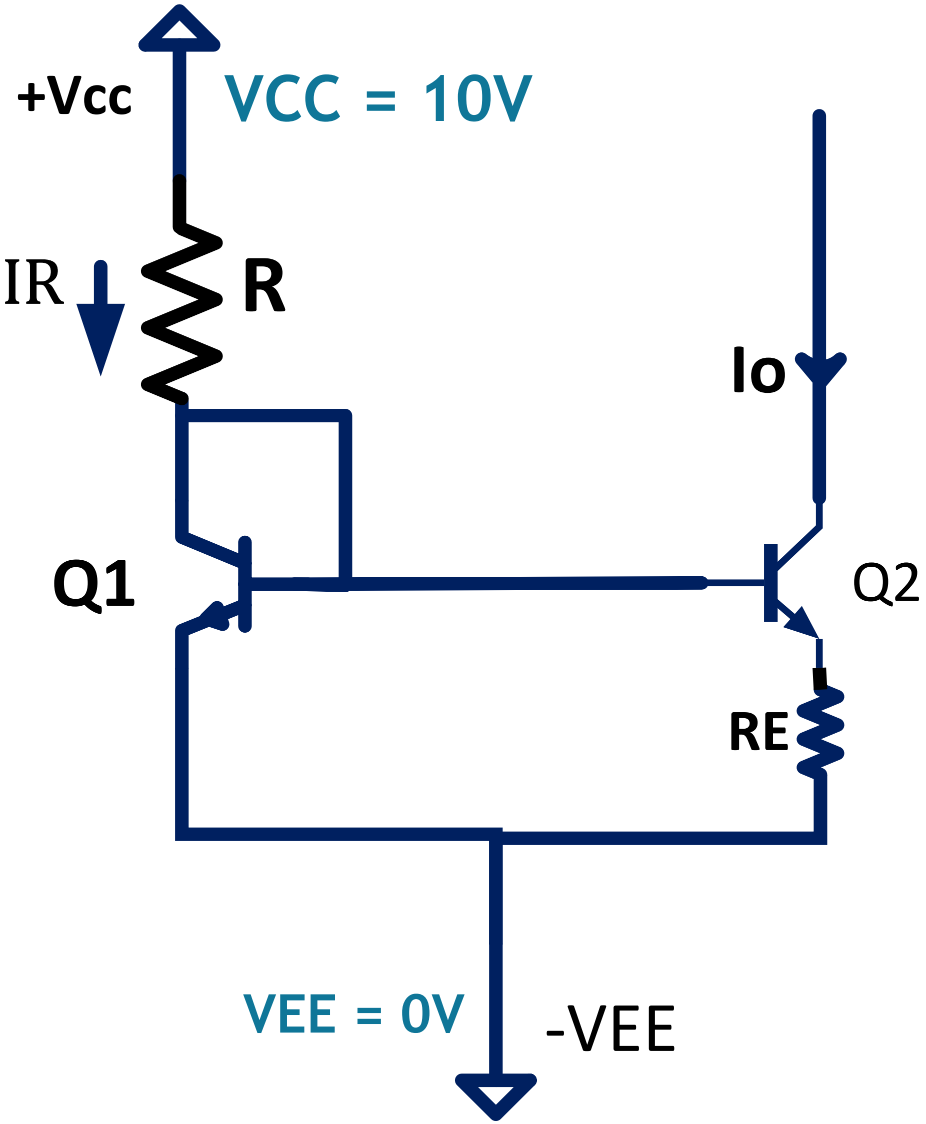
$$\therefore R = 942K$$



Too Large , Not Practical

Design a Wedlar current source to generate Io= 10uA given that V_{BE} = 0.7 V @ Ic=1mA

Assume B=∞ , Vcc = 10V and VEE = 0V



$\underline{Assume\ that\ I_R = 1mA}$

$$\therefore \quad V_{BE1} = 0.7\,V$$

$$R = \frac{V_{CC} - V_{BE1}}{I_R} = 9.3k$$

$$I_o\ R_E = V_T\, ln \frac{I_R}{I_o}$$

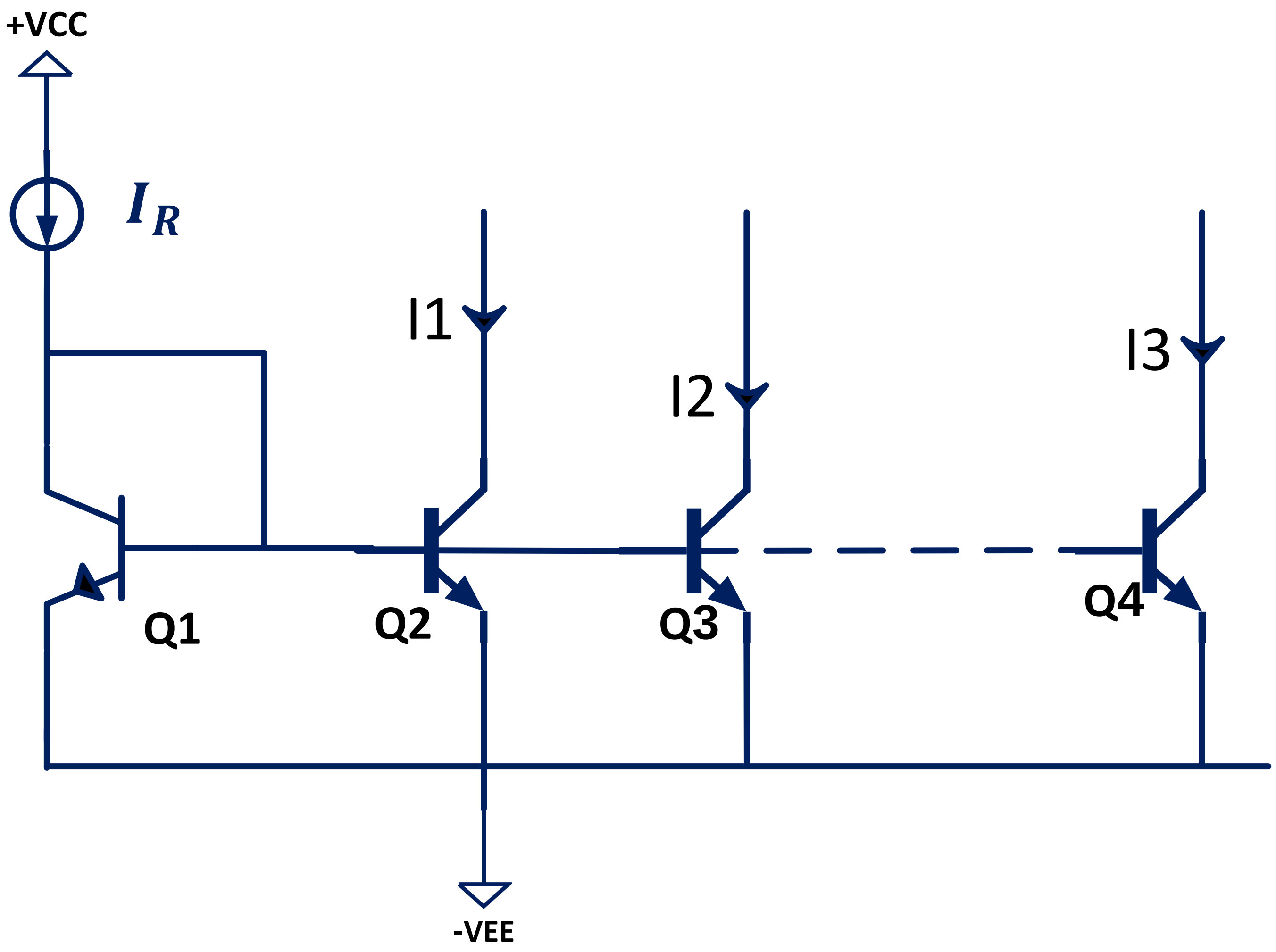
$$\therefore \quad R_E = 11.5k$$

smaller resistor ; smaller chip area

Multitransistor Current Mirror

If β is finite and all the transistors are matched:

$$I_1 = I_2 = I_3 = \frac{I_R}{1 + \frac{(N+1)}{\beta}}$$



Generalized Current Mirror

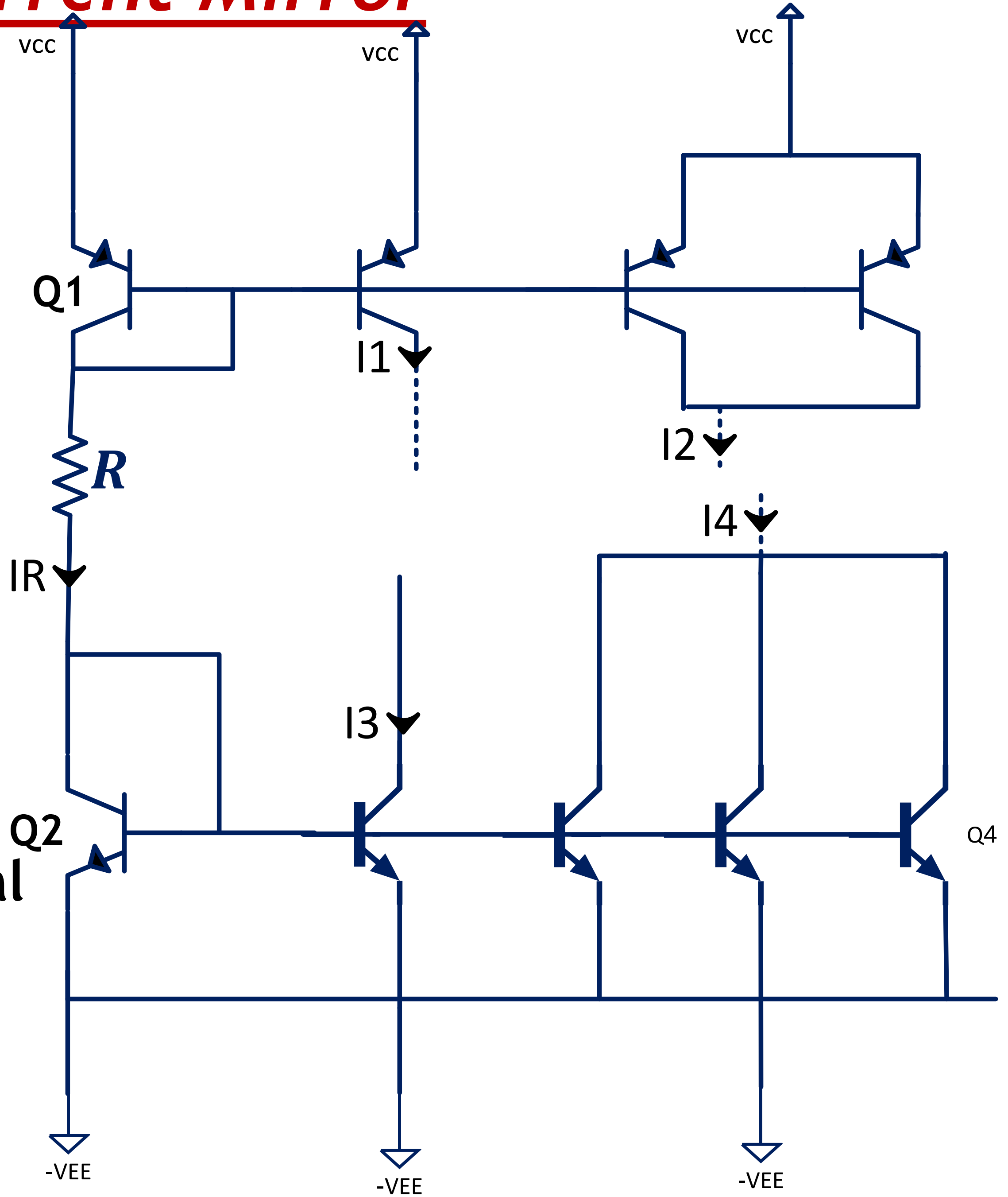
To Generate bias currents for different amplifier stages in an IC

$$I_R = \frac{V_{CC} + V_{EE} - V_{EB1} - V_{BE2}}{R}$$

$$if \quad \beta \rightarrow \infty$$

Since |VBE| For all the transistors are equal

$$I_1 = I_R\,; I_2 = 2I_R\;;\; I_4 = 3I_R$$



Mosfet Current Sources:

The Basic mosfet Current Source

$$Since\ V_{G1} = V_{D1}\ and\ V_{GS} = V_{D\ S}$$

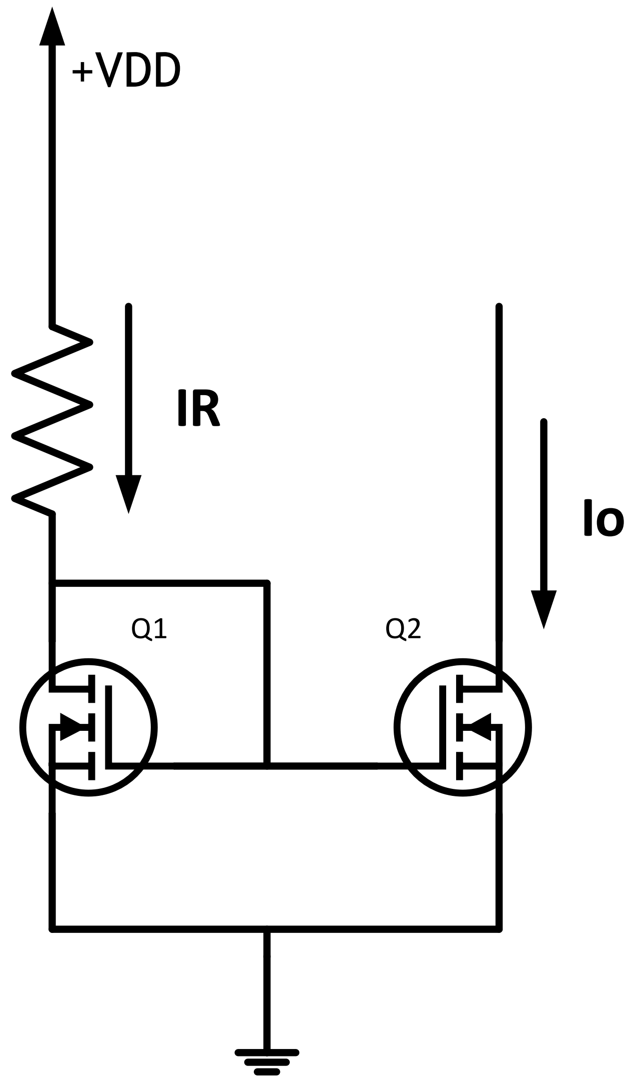
$$|V_{DS}| > |V_{GS} - V_T|$$

$\therefore$ *Q1 is operated in the pinch off region*

$$I_{DS1} = \frac{1}{2}\bar{K}_{n1}\left(\frac{W}{L}\right)_1 (V_{GS1} - V_T)^2$$

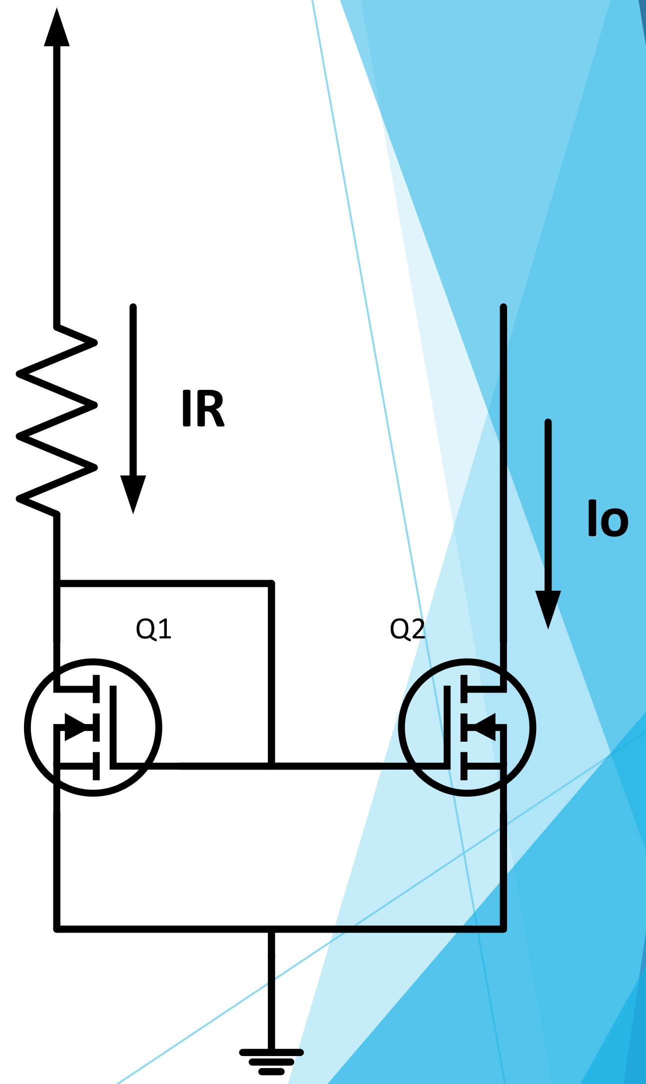
$$I_o = I_{DS2} = \frac{1}{2}\bar{K}_{n2}\left(\frac{W}{L}\right)_2 (V_{GS2} - V_T)^2$$

$$I_R = I_{DS1} + I_{G1} + I_{G2} = I_{DS1}$$



$$I_R = I_{DS1} = \frac{1}{2}\bar{K}_{n1}\left(\frac{W}{L}\right)_1 (V_{GS1} - V_T)^2$$

$$I_o = I_{DS2} = \frac{1}{2}\bar{K}_{n2}\left(\frac{W}{L}\right)_2 (V_{GS2} - V_T)^2$$



$$Since \quad V_{GS1} = V_{GS2}$$

$and \; V_{T1} = V_{T1}$, and $\bar{K}_{n1} = \bar{K}_{n2}$

$$\therefore \quad \frac{I_o}{I_R} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1} \equiv \quad current\ gain$$

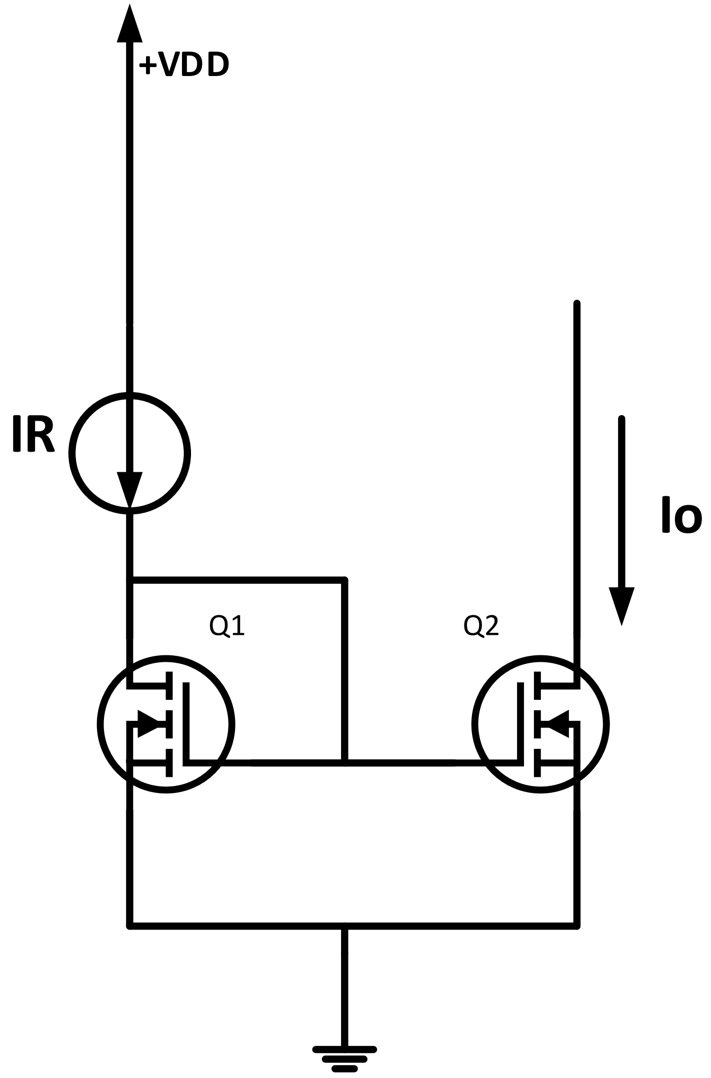
Mosfet Current Sources:

The Basic mosfet Current Source

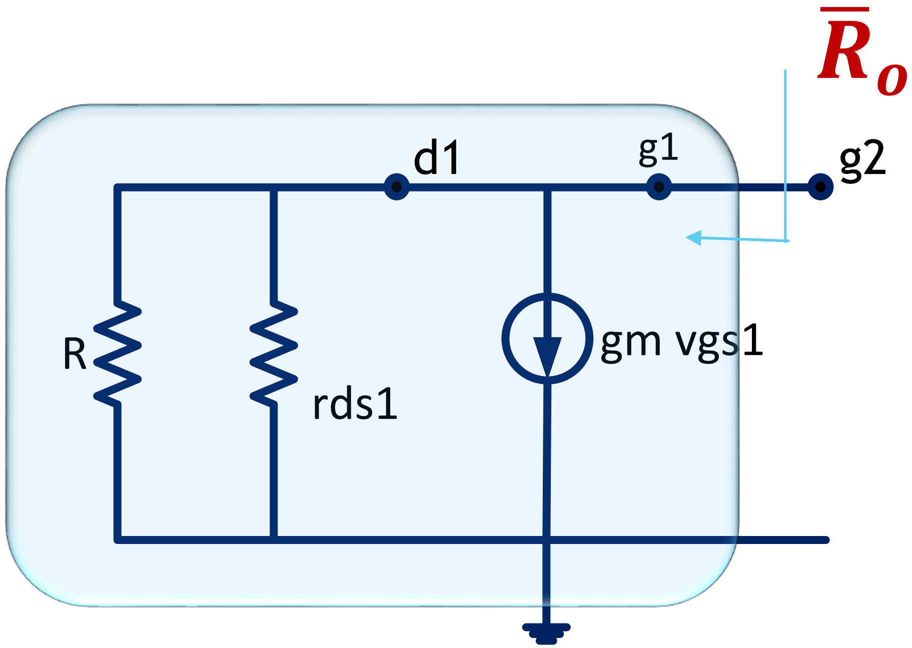
If we have matched Transistors

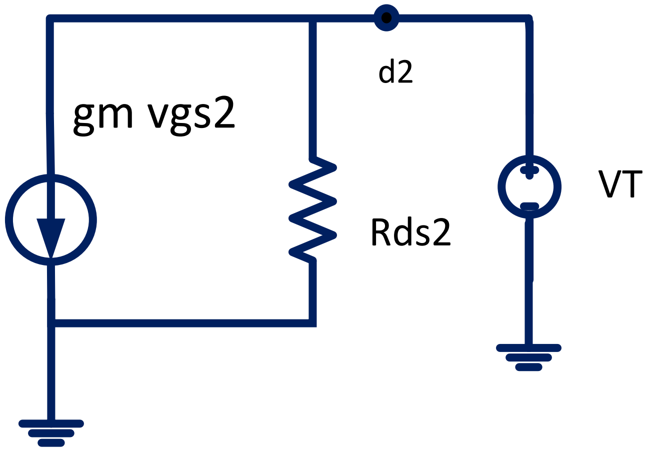
$$\frac{I_o}{I_R} = 1$$

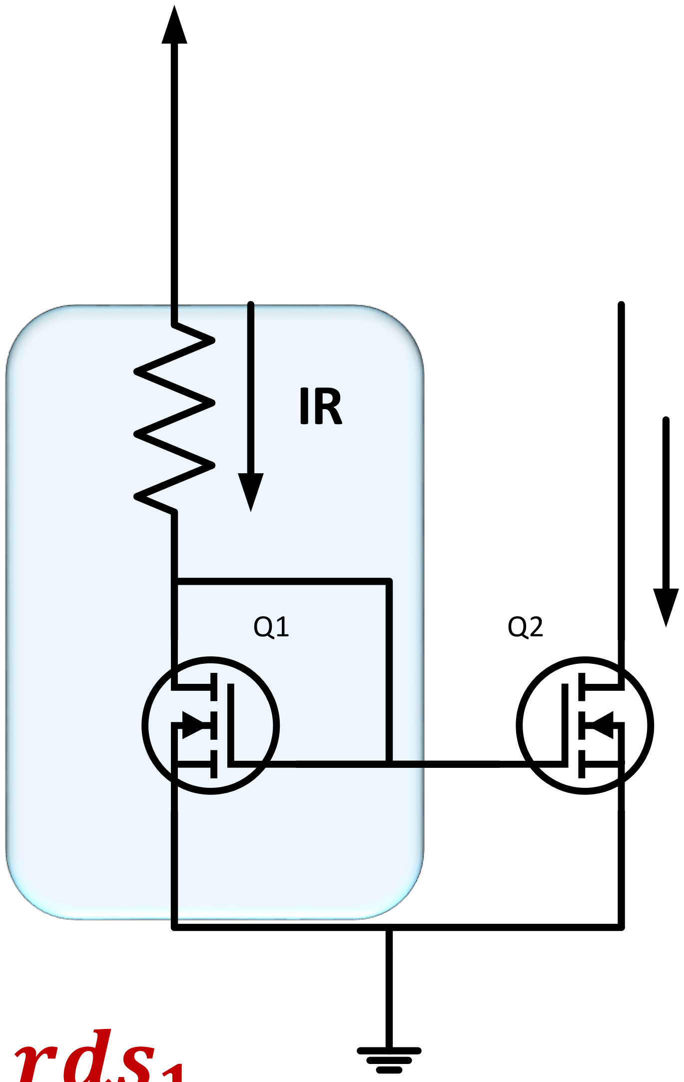
$$I_o = I_R \ \ current\ mirror$$

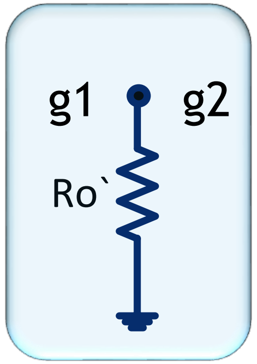


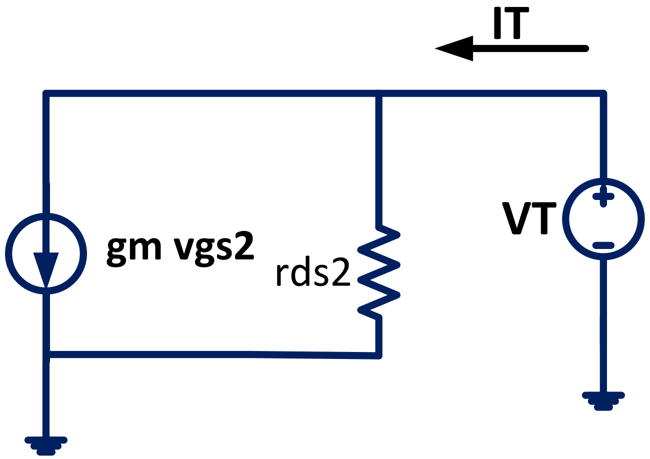
Mosfet Current Sources:











$$\bar{R}_o = \frac{1}{g_{m1}} \| \mathrm{R} \| rds_1$$

$$R_o = \frac{V_T}{I_T} = rds_2$$

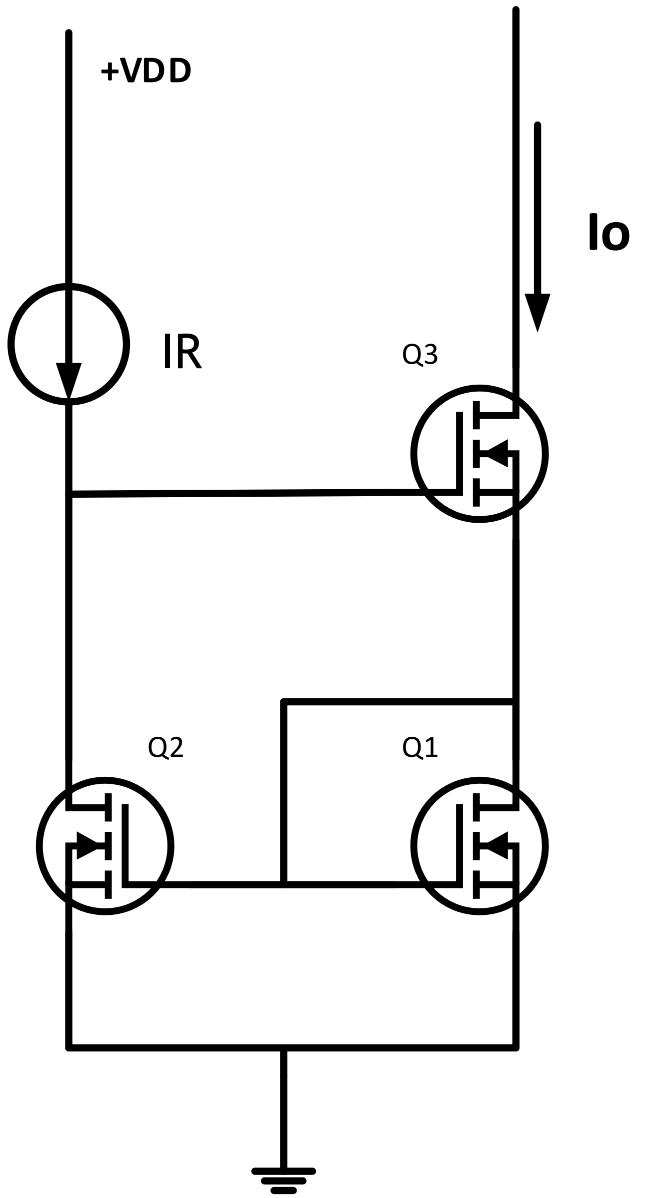
Mosfet Current Sources:

The Wilson mosfet current mirror

$$Q_1, Q_2 \ are \ matched$$

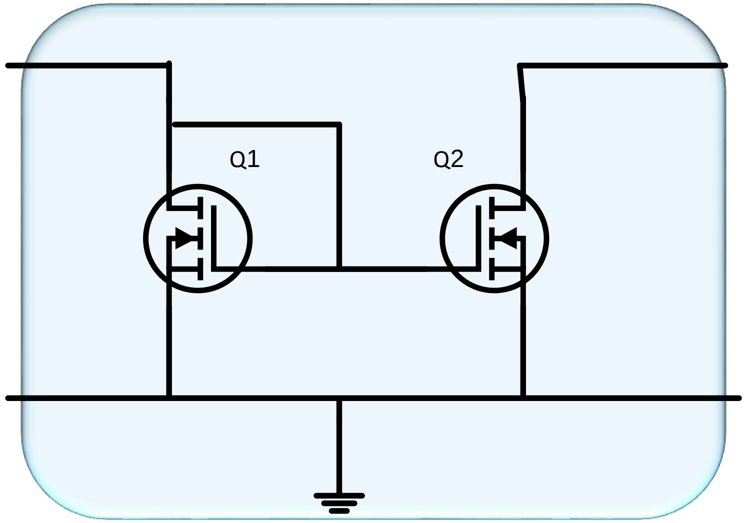
$$\therefore \quad I_o = I_R$$

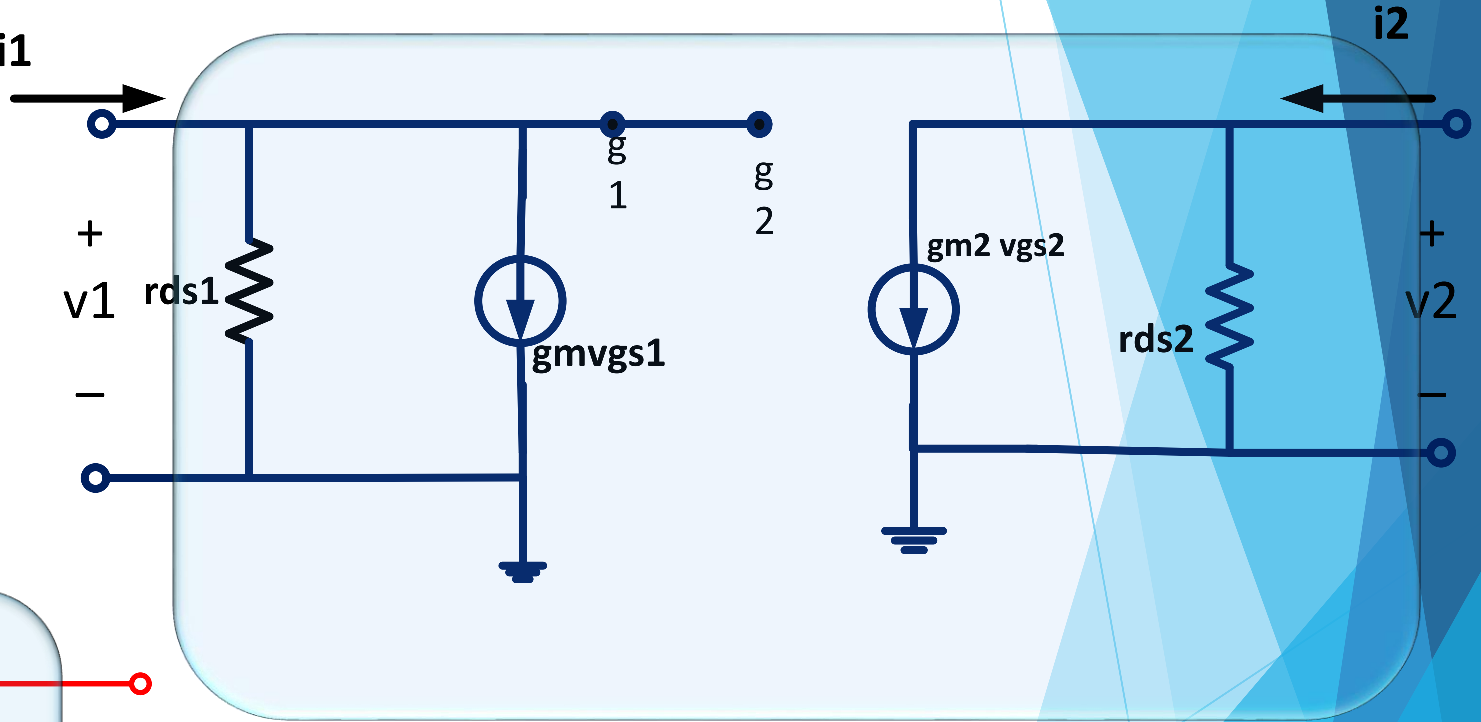
$$R_o \cong gm_3 \, rds_3 \, rds_2$$

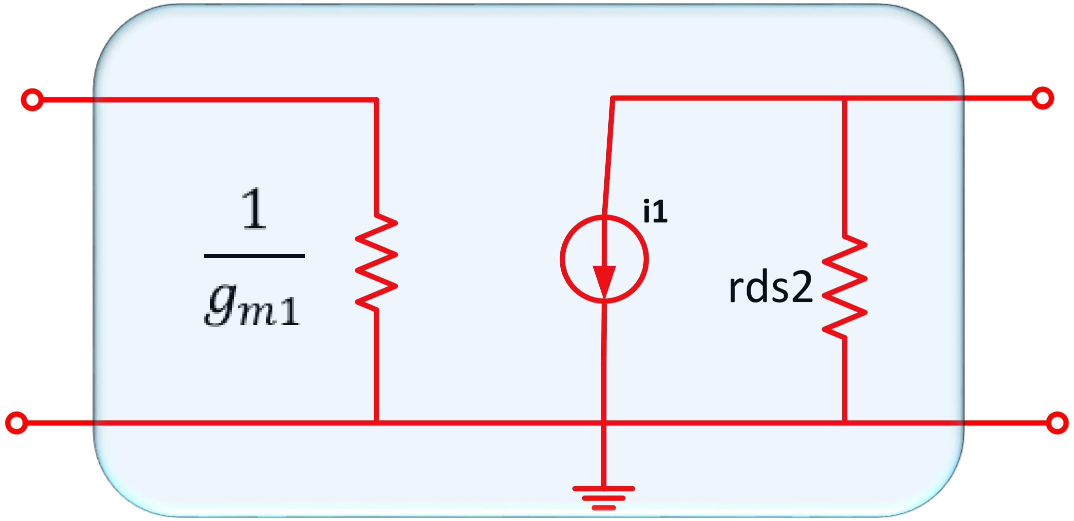


Mosfet Current Sources:

Two Port Model for Mosfet Current Mirror







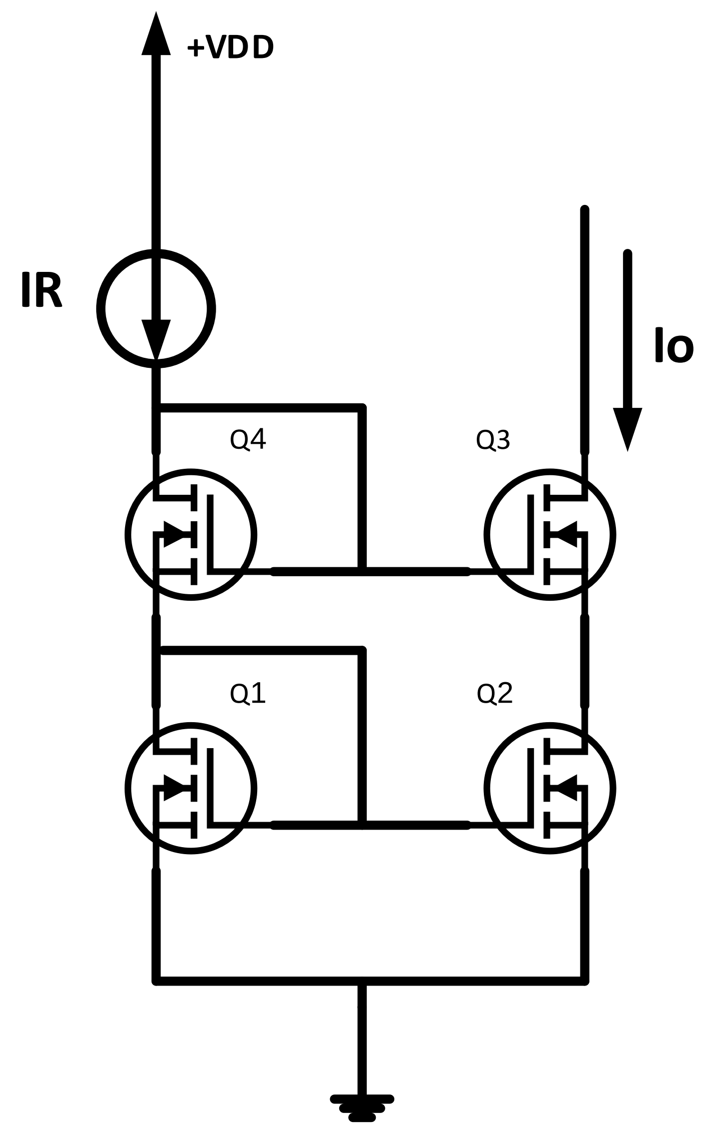
Mosfet Current Sources:

Cascode mosfet current mirror

$$I_{DS1} = \frac{1}{2}\bar{K}_n(V_{GS1} - V_T)^2\left(\frac{W}{L}\right)_1 = I_R$$

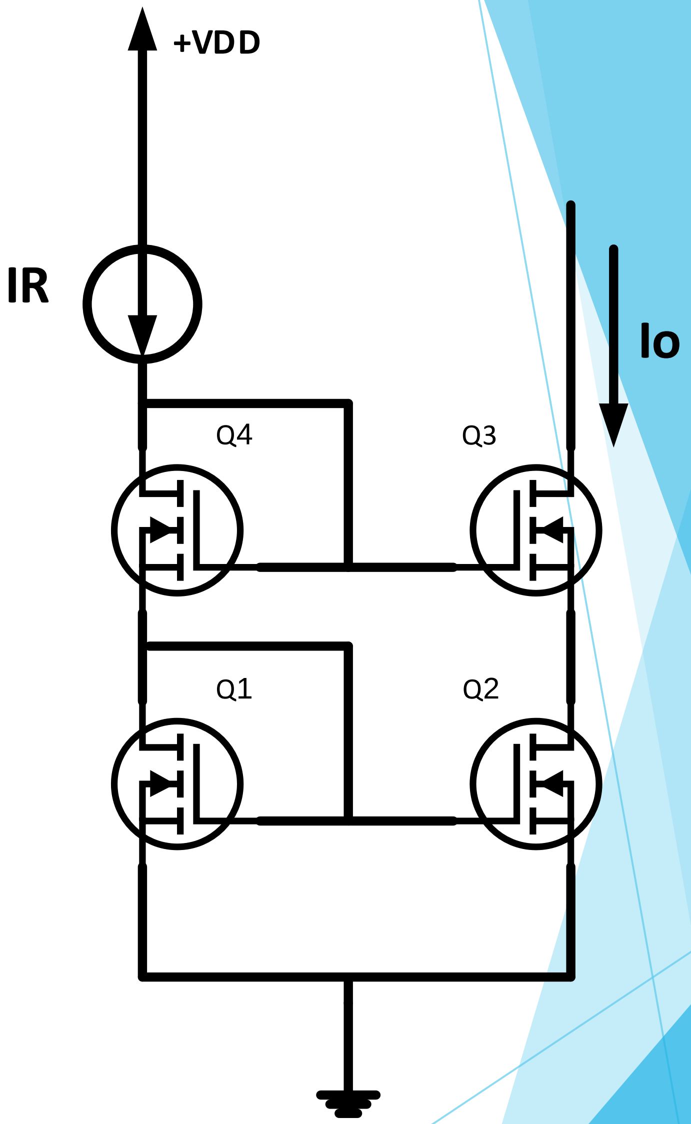
$$I_{DS2} = \frac{1}{2}\bar{K}_n(V_{GS2} - V_T)^2\left(\frac{W}{L}\right)_2 = I_o$$

$$\frac{I_o}{I_R} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}$$



- $R_o = rds_3 + rds_2(1 + gm\, rds_3)$

$R_o \approx rds_2\, rds_3\, gm$



Circuits With Active Load

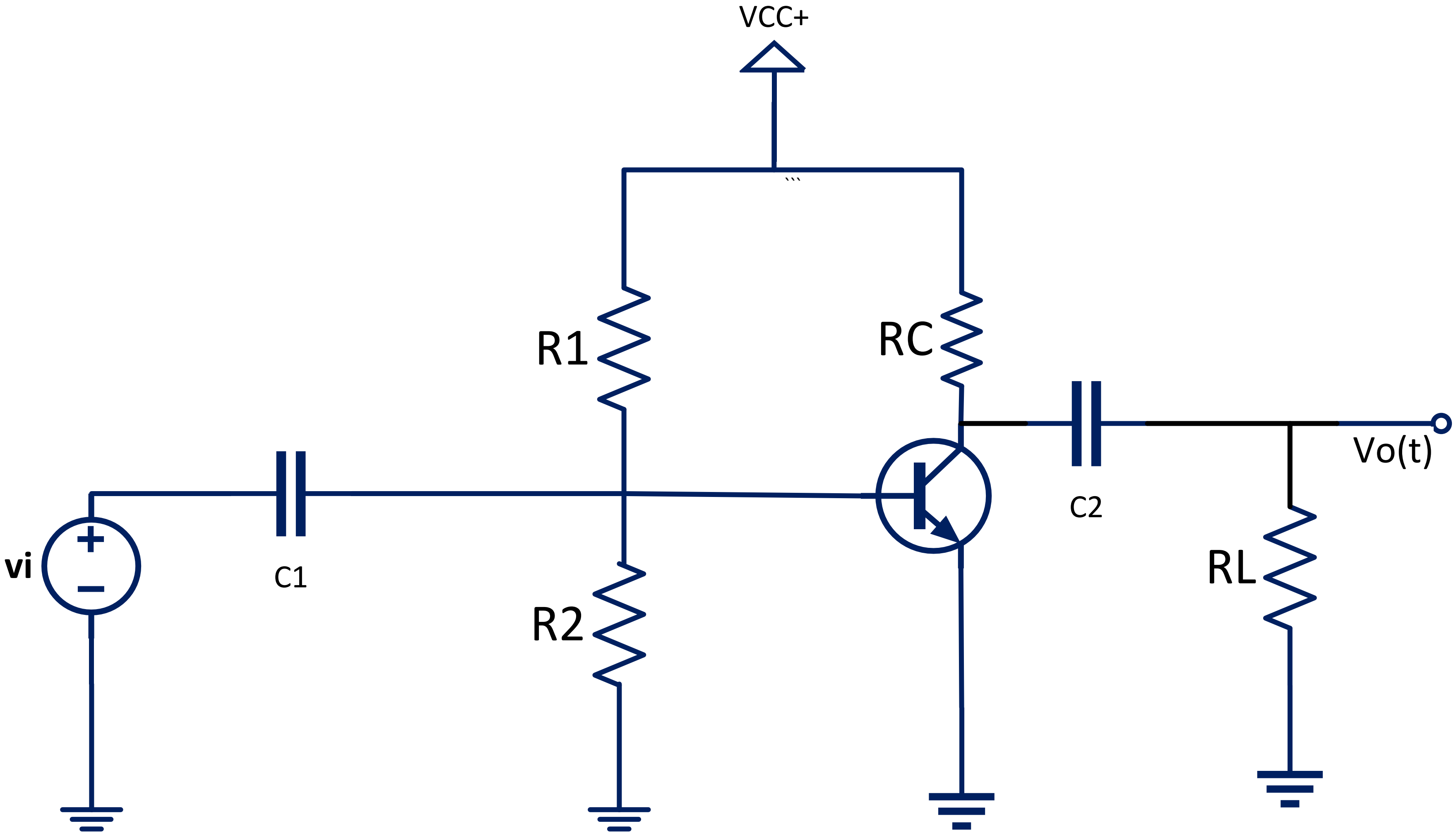
Find Av = $\frac{V_o}{V_i}$

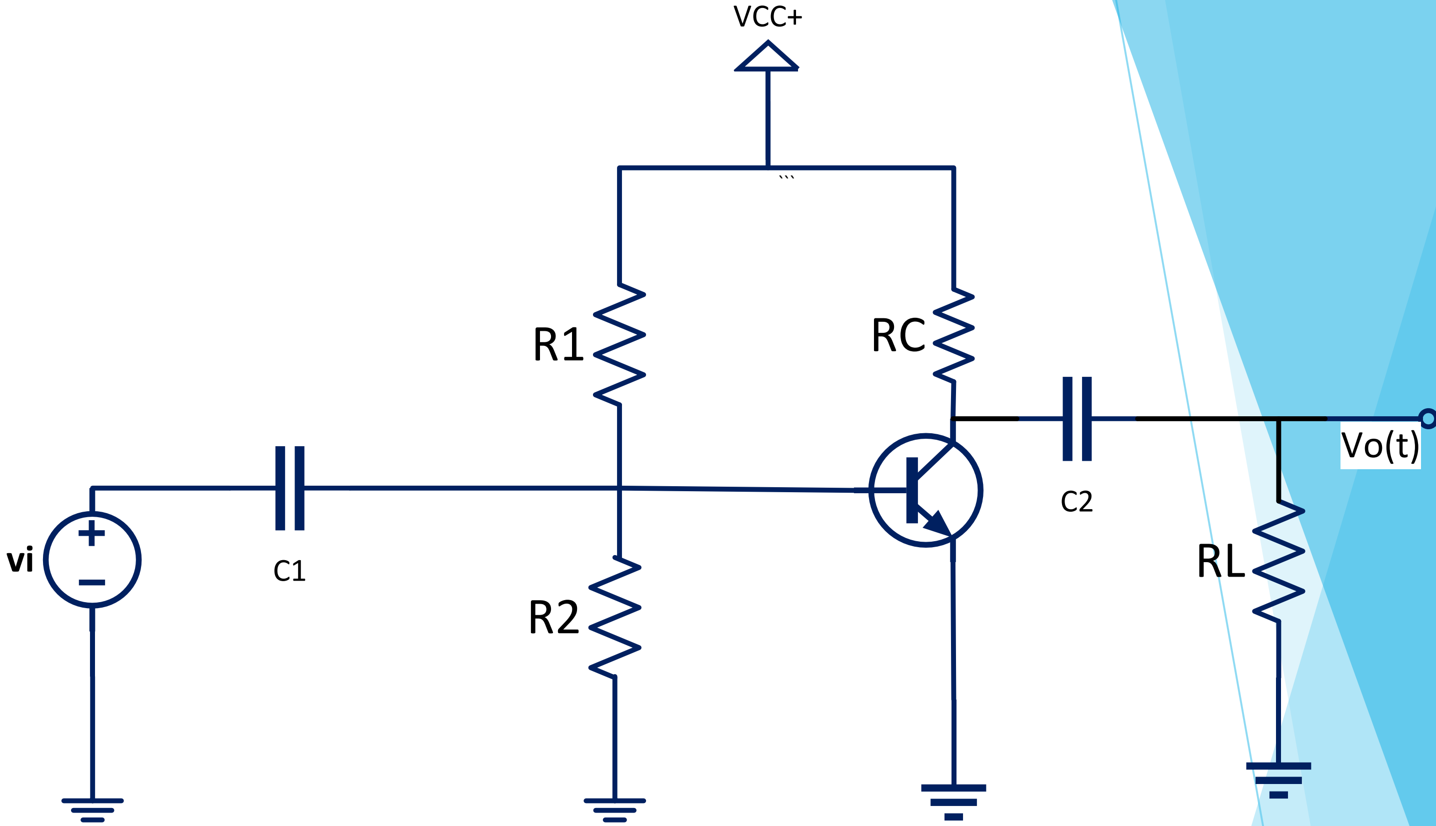
$Let\ R_C = 5k\ ,$

$I_{CQ} = 1mA,$

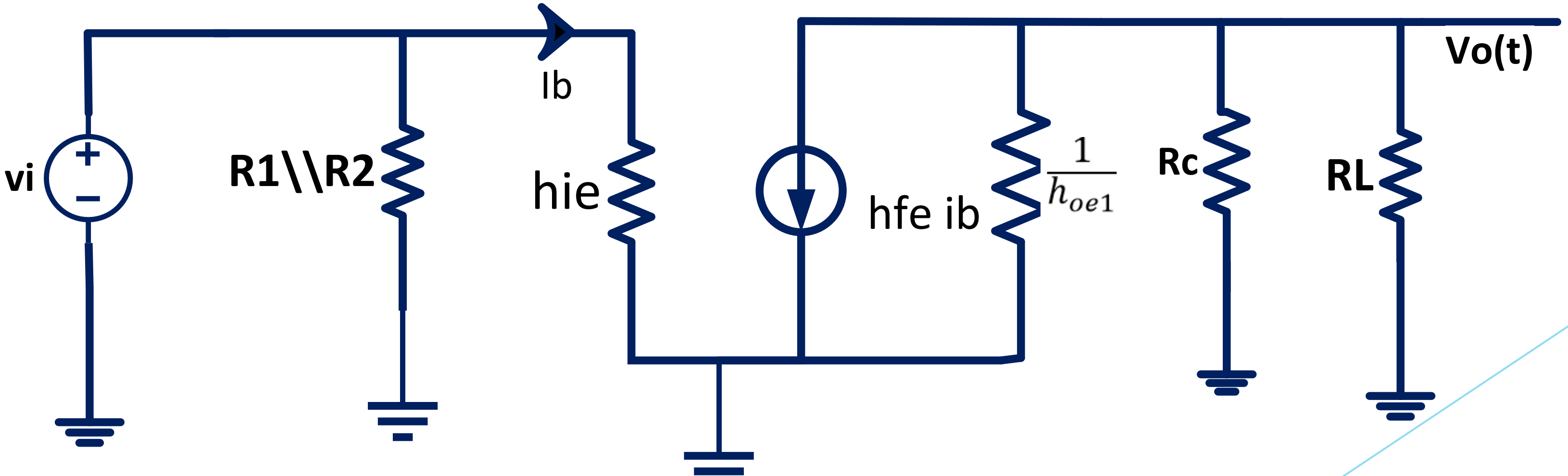
$and\ \frac{1}{h_{oe}} = 120k$

$Rl = 10k$

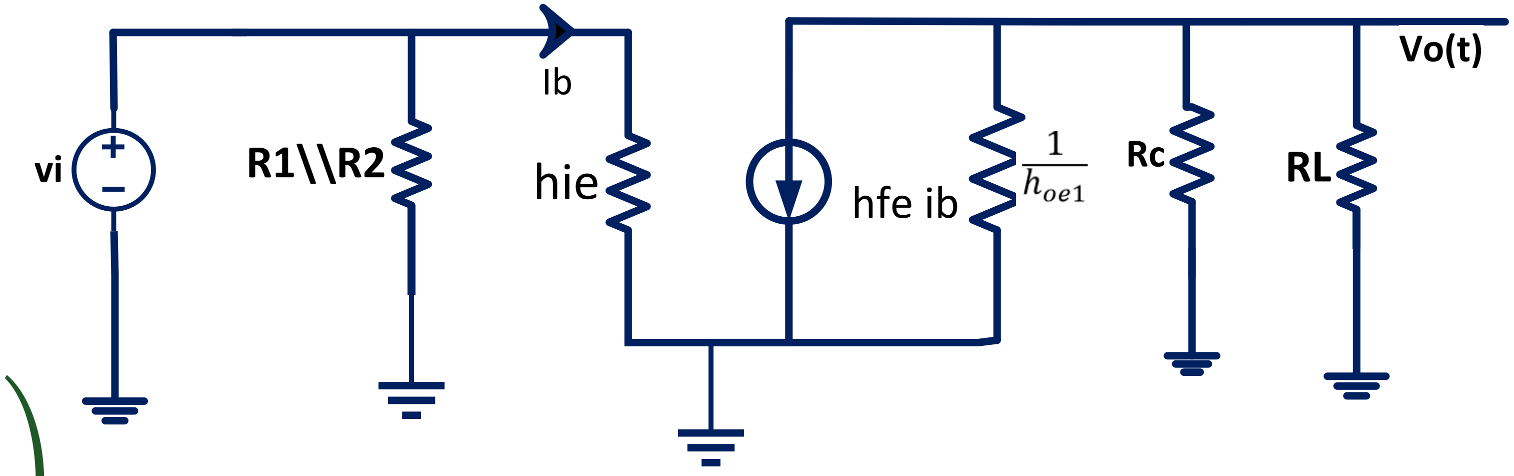




Ac Small signal equivalent Circuit



Circuits With Active Load



$$V_o = -h_{fe} i_b \left(R_C \| R_L \| \frac{1}{h_{oe}} \right)$$

$$i_b = \frac{v_i}{h_{ie}}$$

$$\text{To increase } |Av|, R_C \uparrow, V_{CE} \downarrow$$
$$\rightarrow \text{Transistor enters saturation}$$

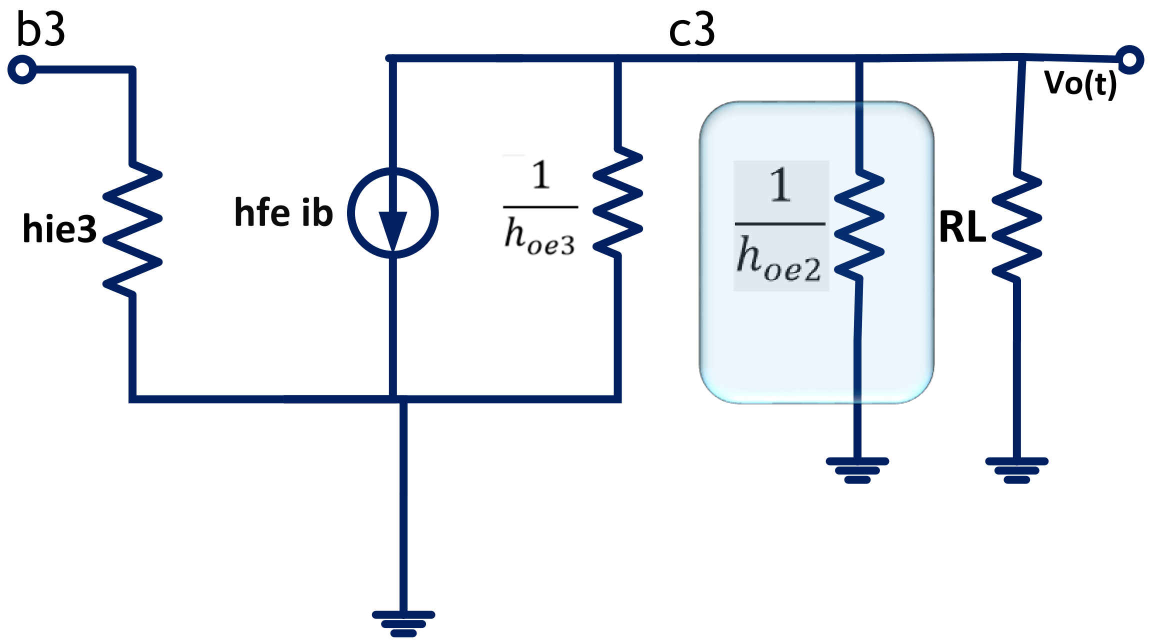
$$\therefore Av = -\frac{h_{fe}}{h_{ie}} \left(R_C \| R_L \| \frac{1}{h_{oe}} \right)$$

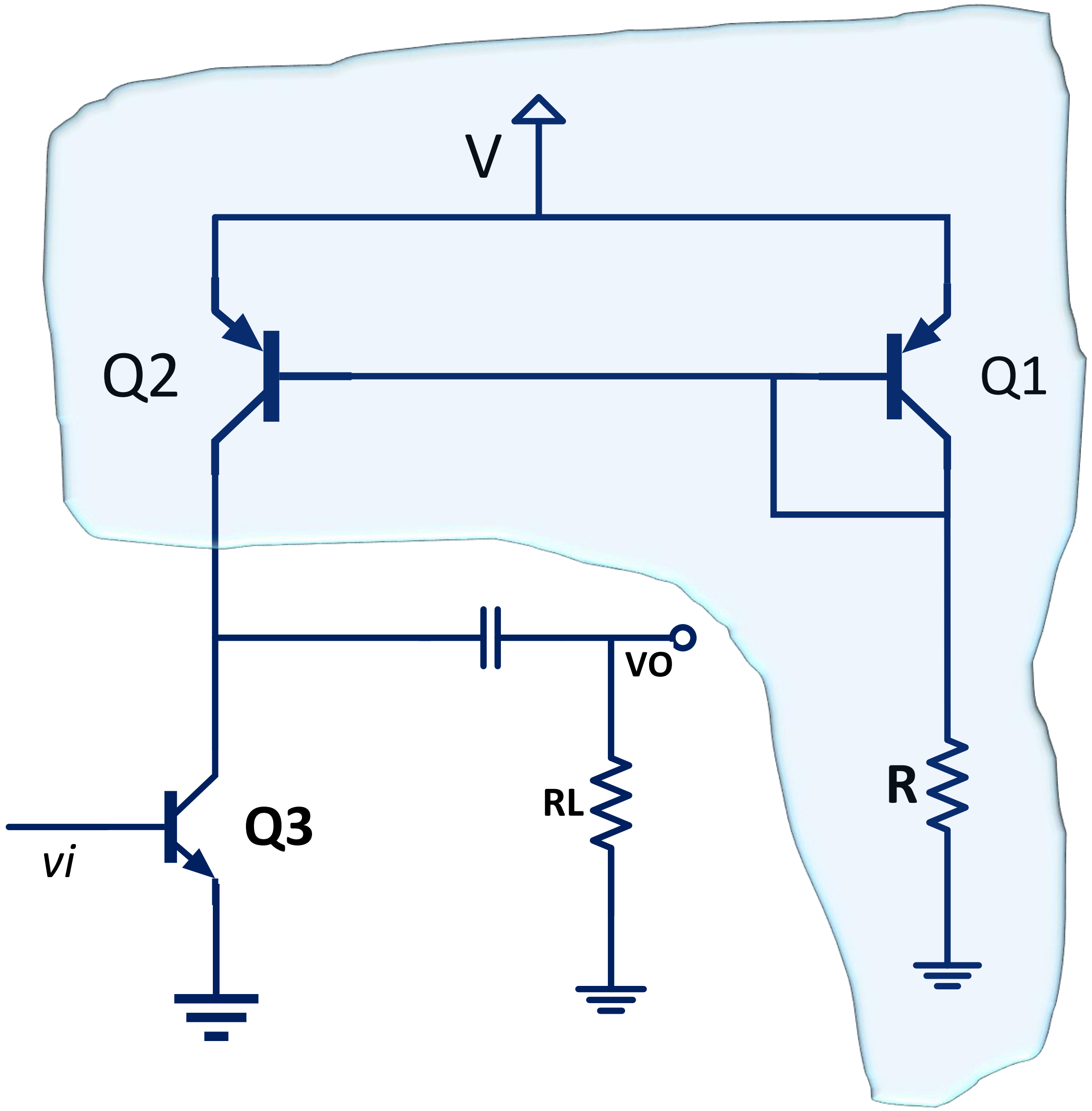
$$Av = -gm \left(R_C \| R_L \| \frac{1}{h_{oe}} \right) = -125$$

$$V_{CE} = V_{CC} - R_C \; I_{CQ}$$

Amplifier With an Active Load

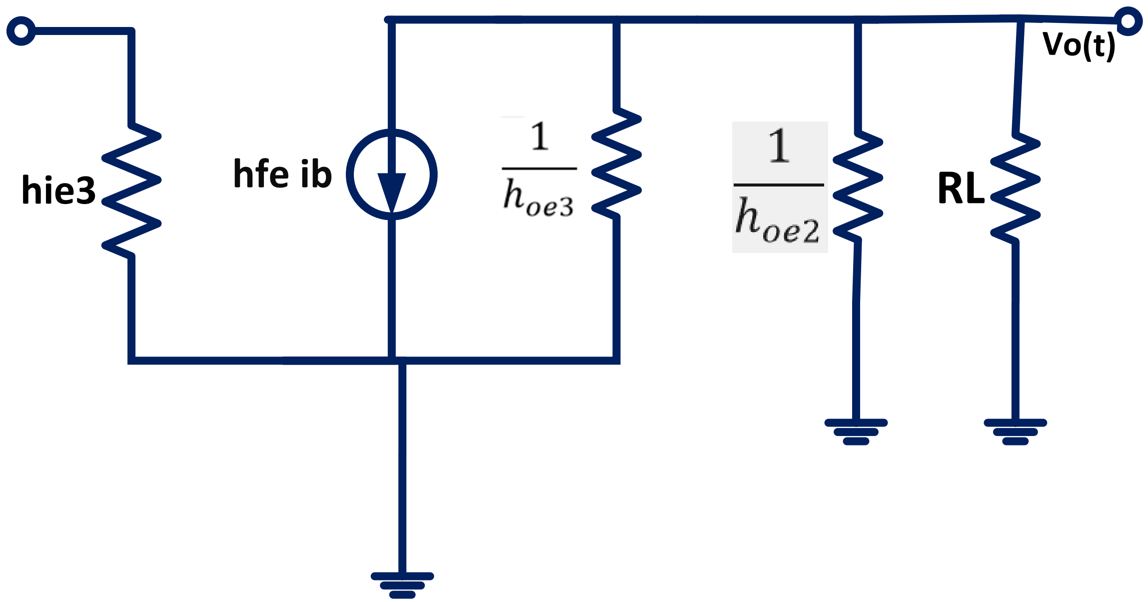
Ac Small signal equivalent Circuit





Amplifier With an Active Load

$$Av = -gm\left(\frac{1}{h_{oe3}} \parallel \frac{1}{h_{oe3}} \parallel R_L\right)$$



$$let\ \frac{1}{h_{oe3}} = 120k$$

$$\frac{1}{h_{oe2}} = 80k$$

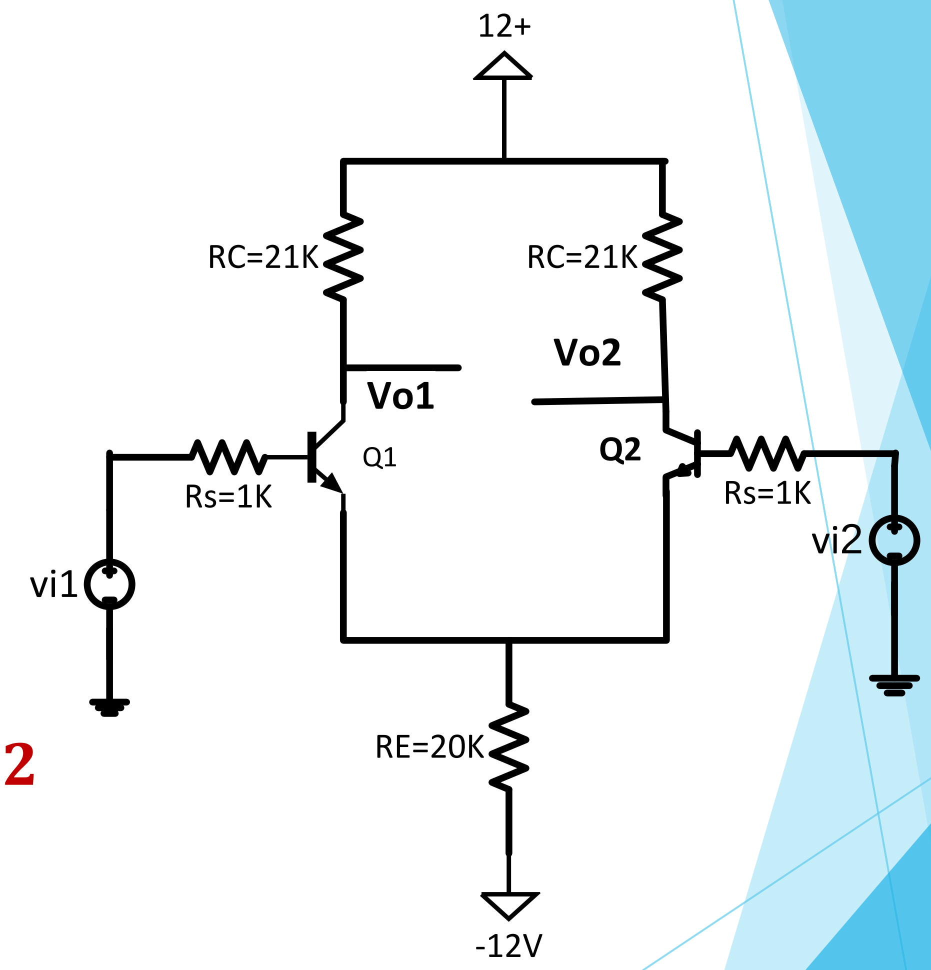
$$, I_{CQ} = 1mA$$

$$V_o = \begin{cases} -1846\ v_i\ ; R_L = \infty \\ -1247\ v_i\ ; R_L = 100k \\ -318\ v_i\ ; R_L = 10k \end{cases}$$

$$\therefore gm = \frac{h_{fe3}}{h_{ie3}} = \frac{I_{CQ}}{V_T} = 38.46\ \Omega$$

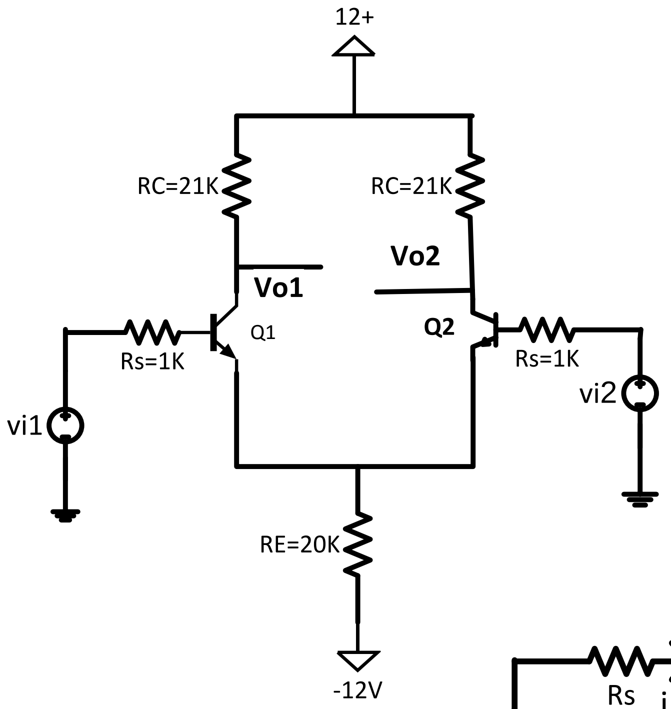
Differential Amplifiers

AC Analysis: ***Input Impedance***

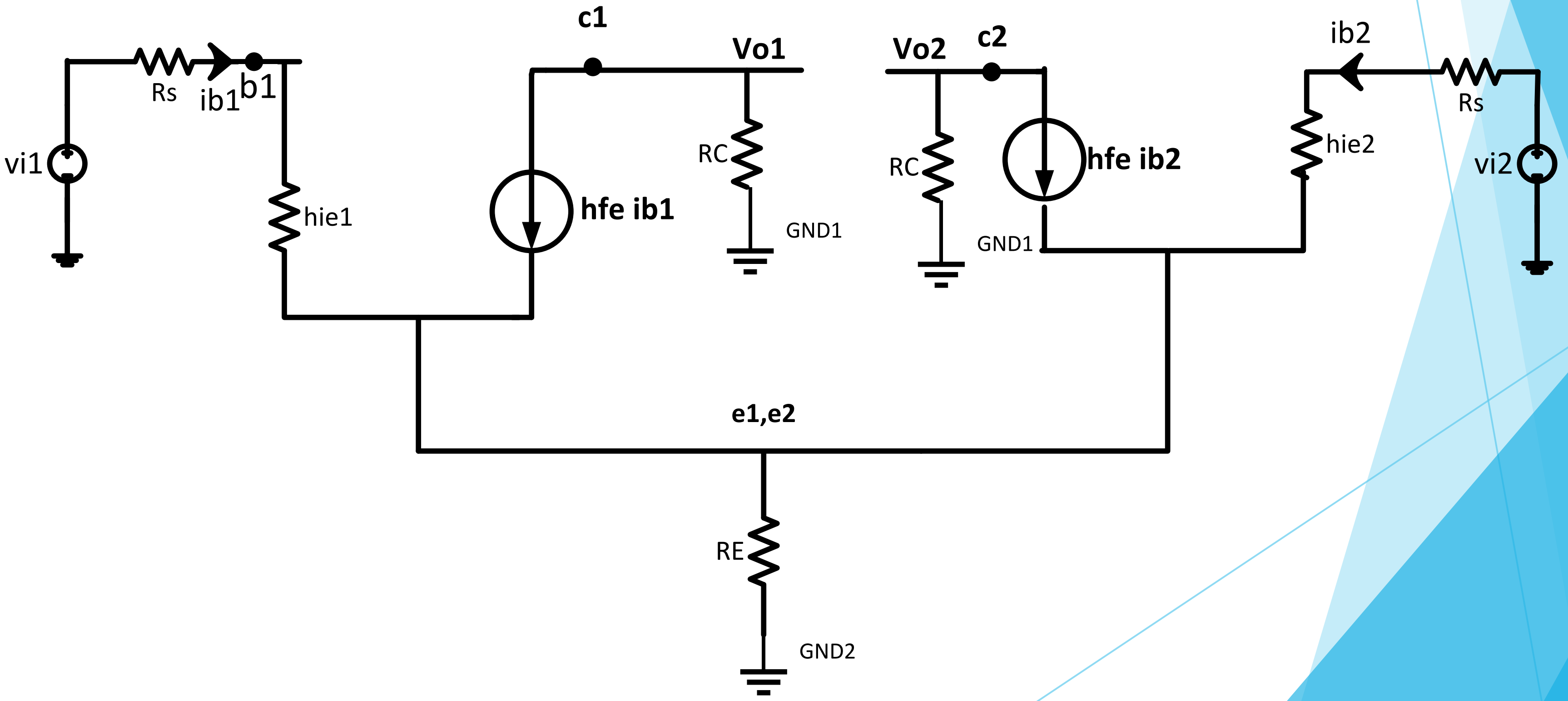


$$\text{since} \quad I_{E1} = I_{E2} \ \text{and} \ \beta_1 = \beta_2$$

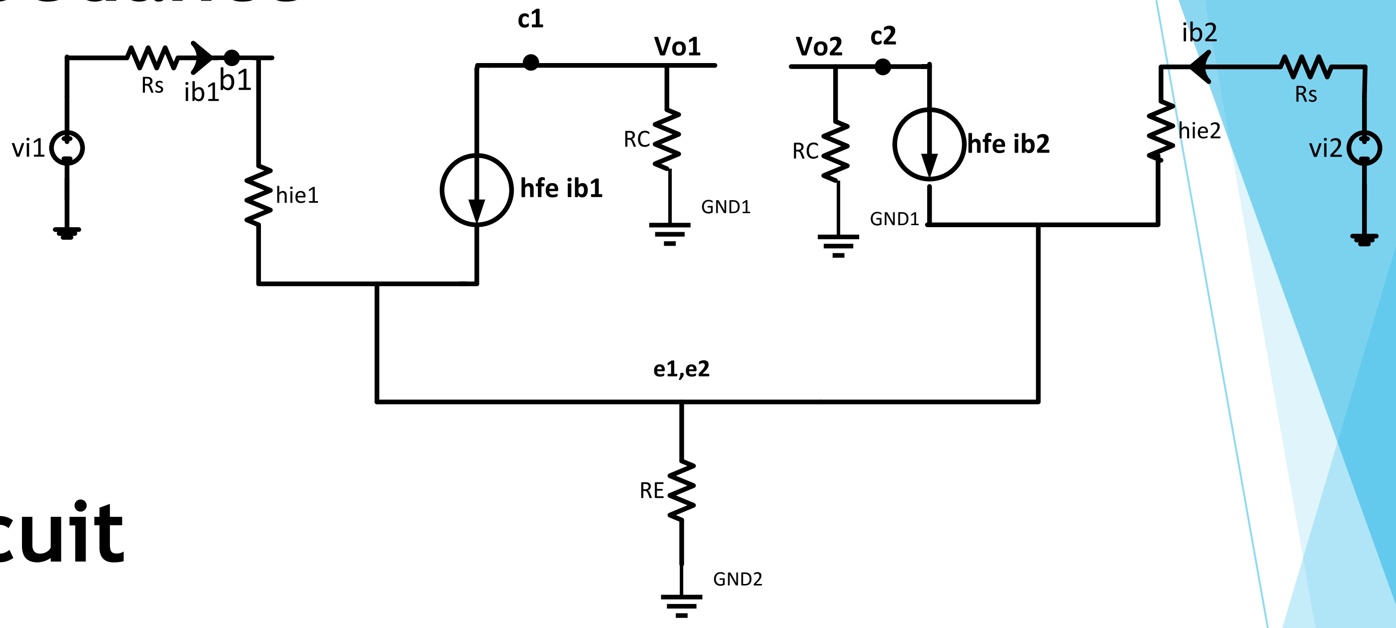
$$h_{ie1} = h_{ie2} = h_{ie}$$
$$h_{ib1} = h_{ib2} = h_{ib}$$



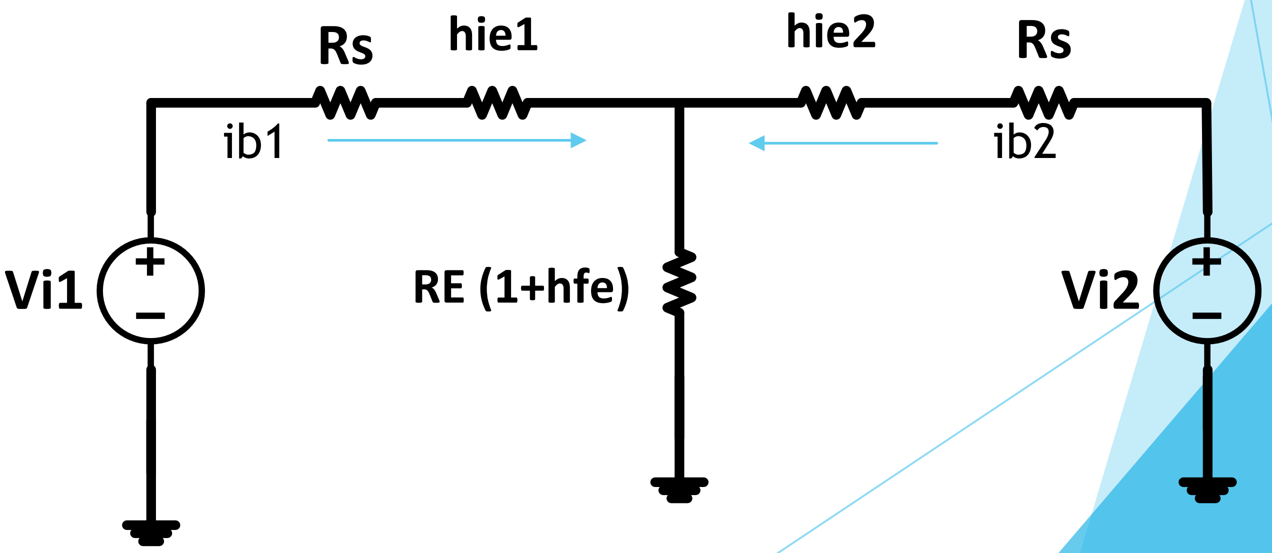
Ac small signal equivalent circuit



To find the input impedance



Base equivalent circuit



Input Impedance:

Base equivalent circuit

$$Differential\ mode\ input\ impedance \equiv Z_{id}$$

$$Z_{id} = \left.\frac{v_d}{i_b}\right|_{v_c=0}$$

$$Common\ mode\ input\ impedance \equiv Z_{ic}$$

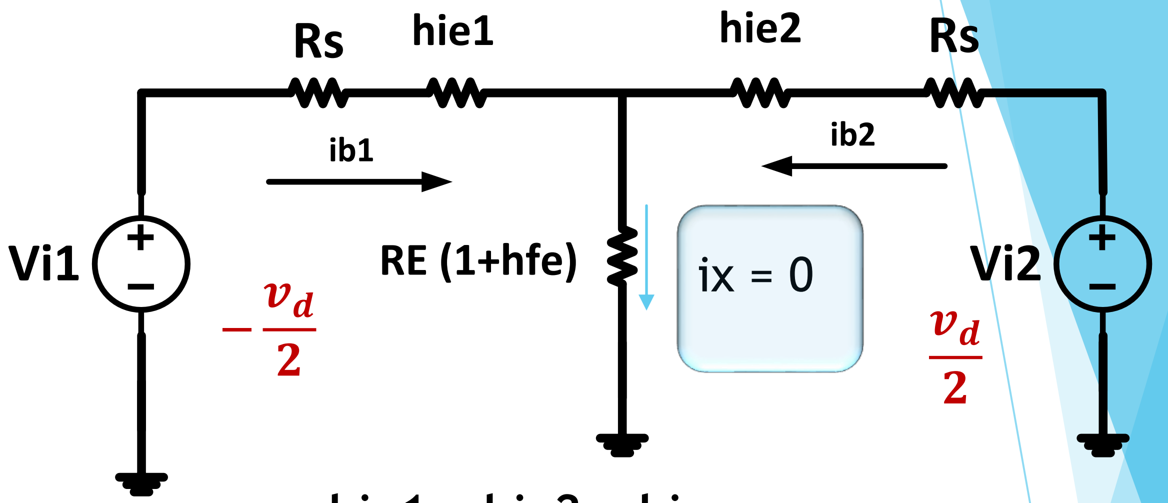
$$Z_{ic} = \left.\frac{v_c}{i_b}\right|_{v_d=0}$$

Input impedance

$$Z_{id} = \left.\frac{v_d}{i_b}\right|_{v_c=0}$$

$$v_{i1} = -\frac{v_d}{2}\,;\, v_{i2} = \frac{v_d}{2}$$

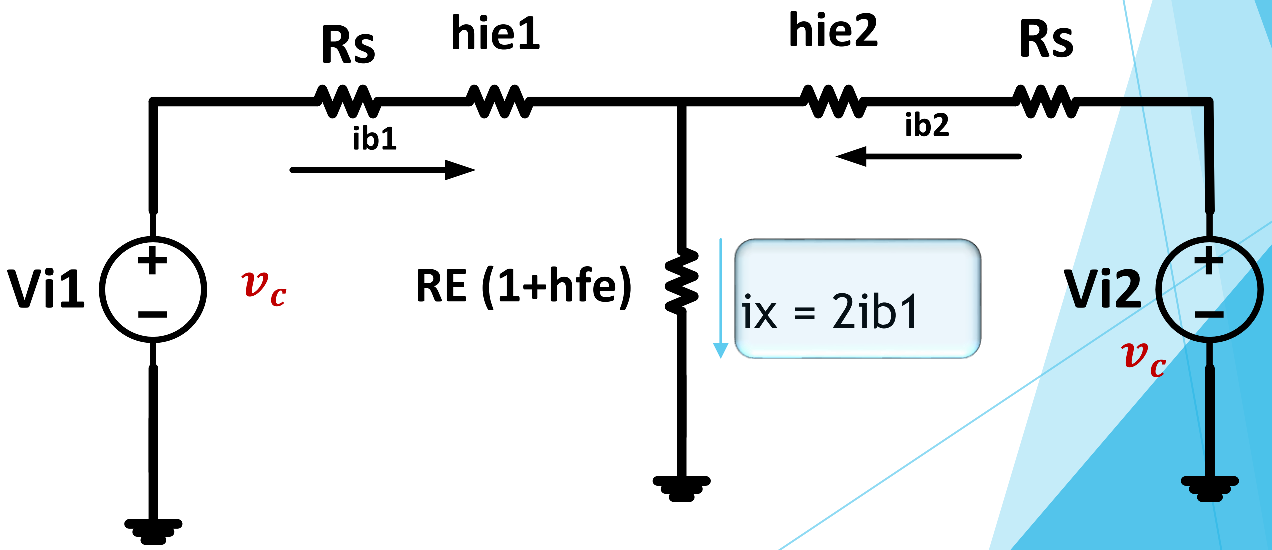
$$Z_{id} = 2(R_S + h_{ie})$$



hie1 = hie2 = hie

$$Z_{ic} = \left.\frac{v_c}{i_b}\right|_{v_d=0}$$

$$v_{i1} = v_c \;\;;\;\; v_{i2} = v_c$$



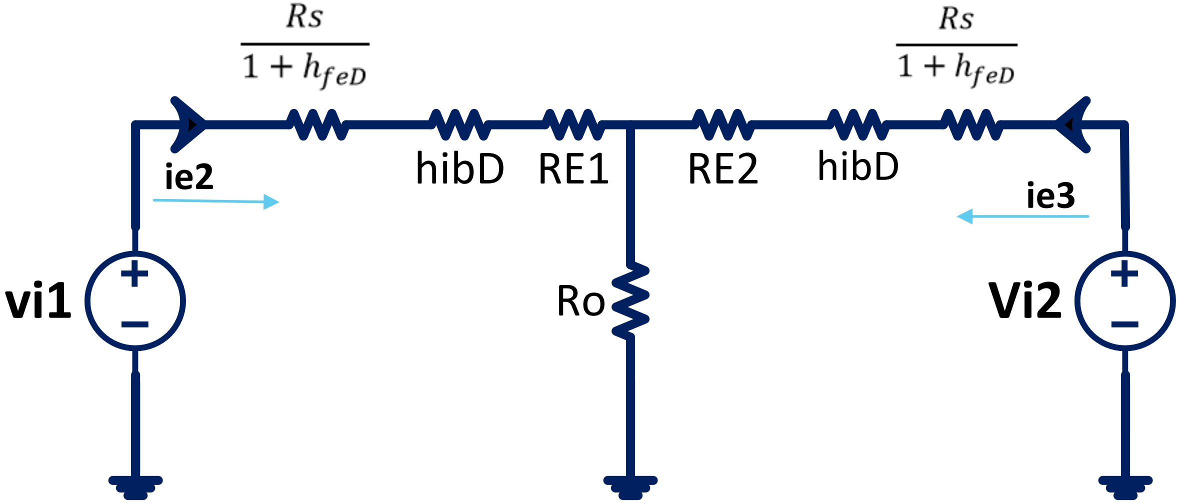
$$Z_{ic} = R_S + h_{ie} + 2(1 + h_{fe})RE$$

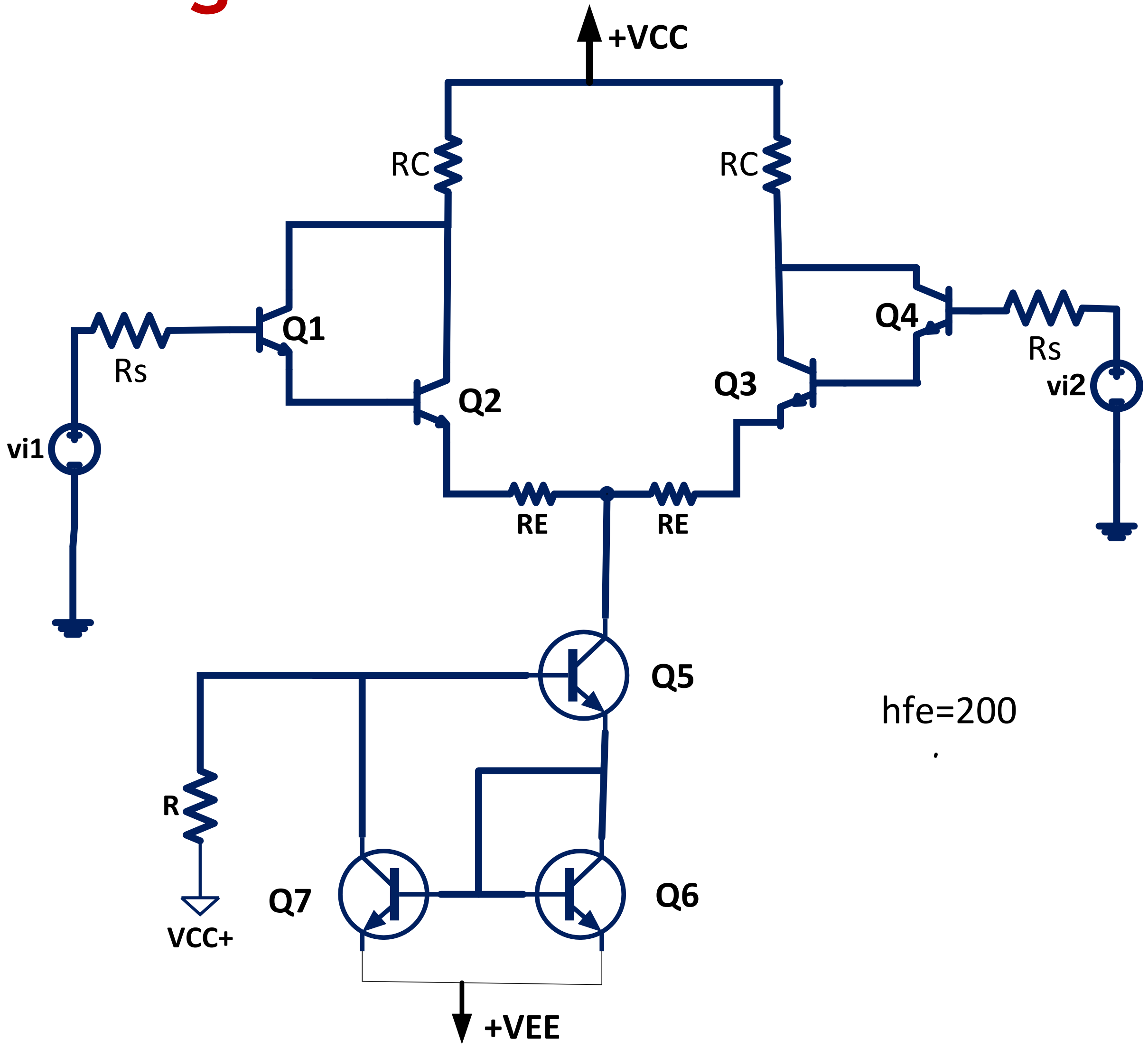
Differential Amplifiers Using Darlington and FET

Differential Amplifiers Using Darlington

To find Ac & Ad:

Emitter equivalent circuit





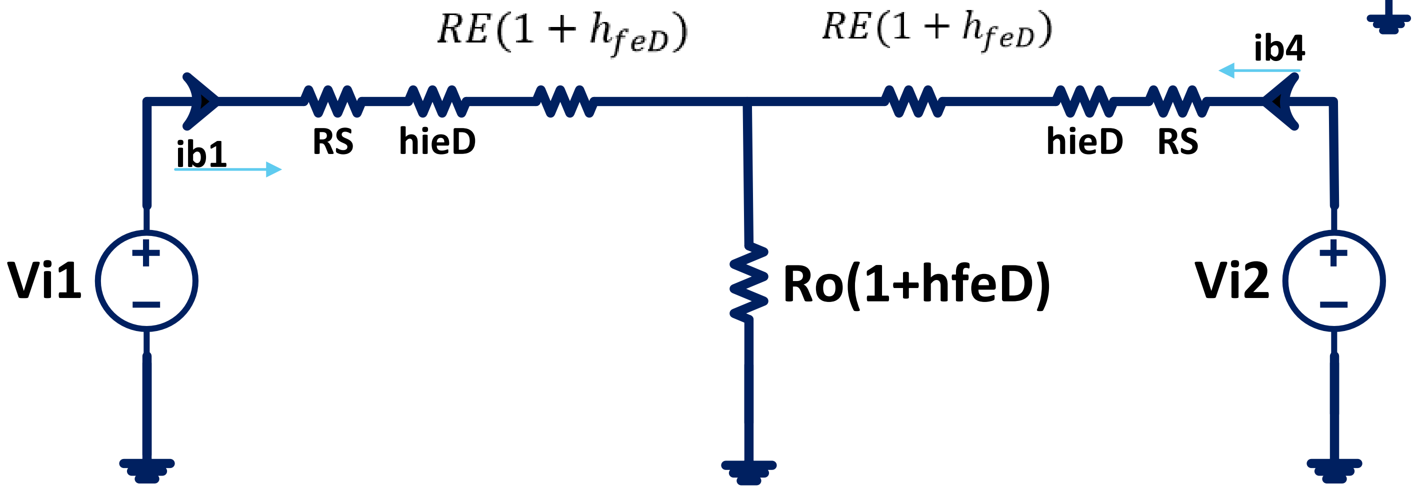
hfe=200

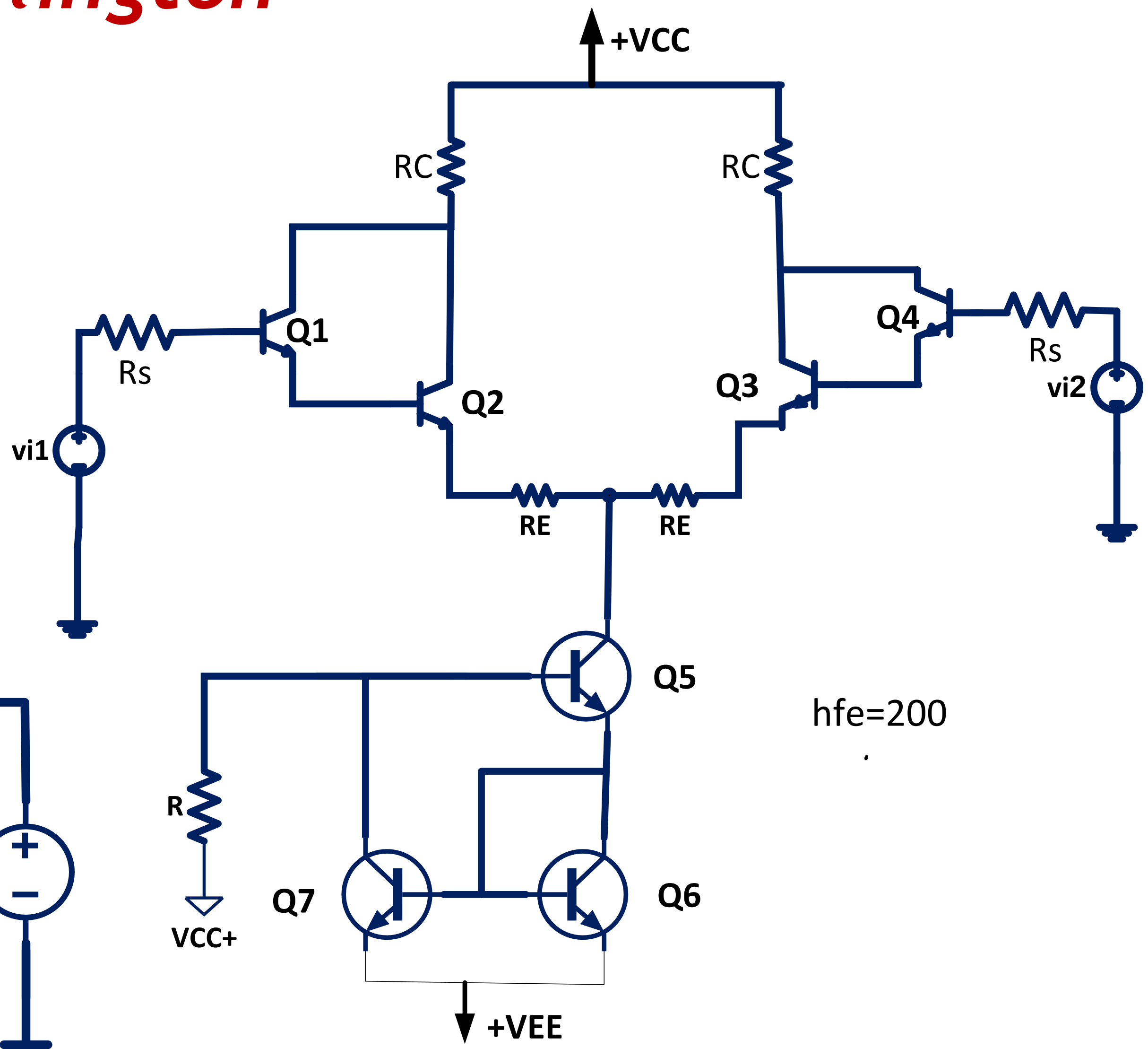
Differential Amplifiers Using Darlington and FET

Differential Amplifiers Using Darlington

***To find Zid*:**

Base equivalent circuit

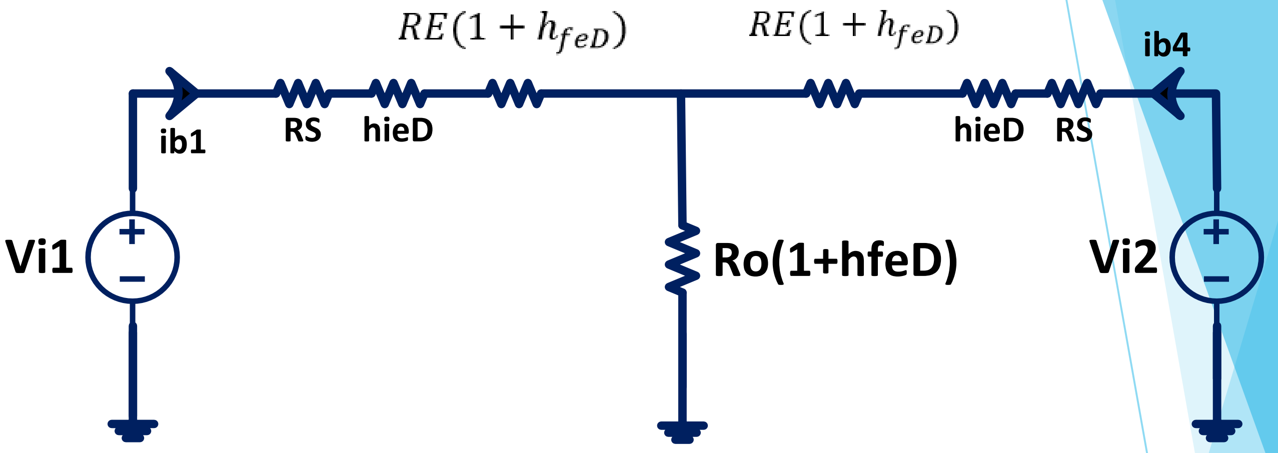




Input Impedance:

Base equivalent circuit

$$Z_{id} = \left.\frac{v_d}{i_{b1}}\right|_{v_c=0}$$



$$v_{i1} = -\frac{v_d}{2}\,;\, v_{i2} = \frac{v_d}{2}$$

$$Z_{id} = 2\left(R_S + h_{ieD} + R_E(1 + h_{feD})\right)$$

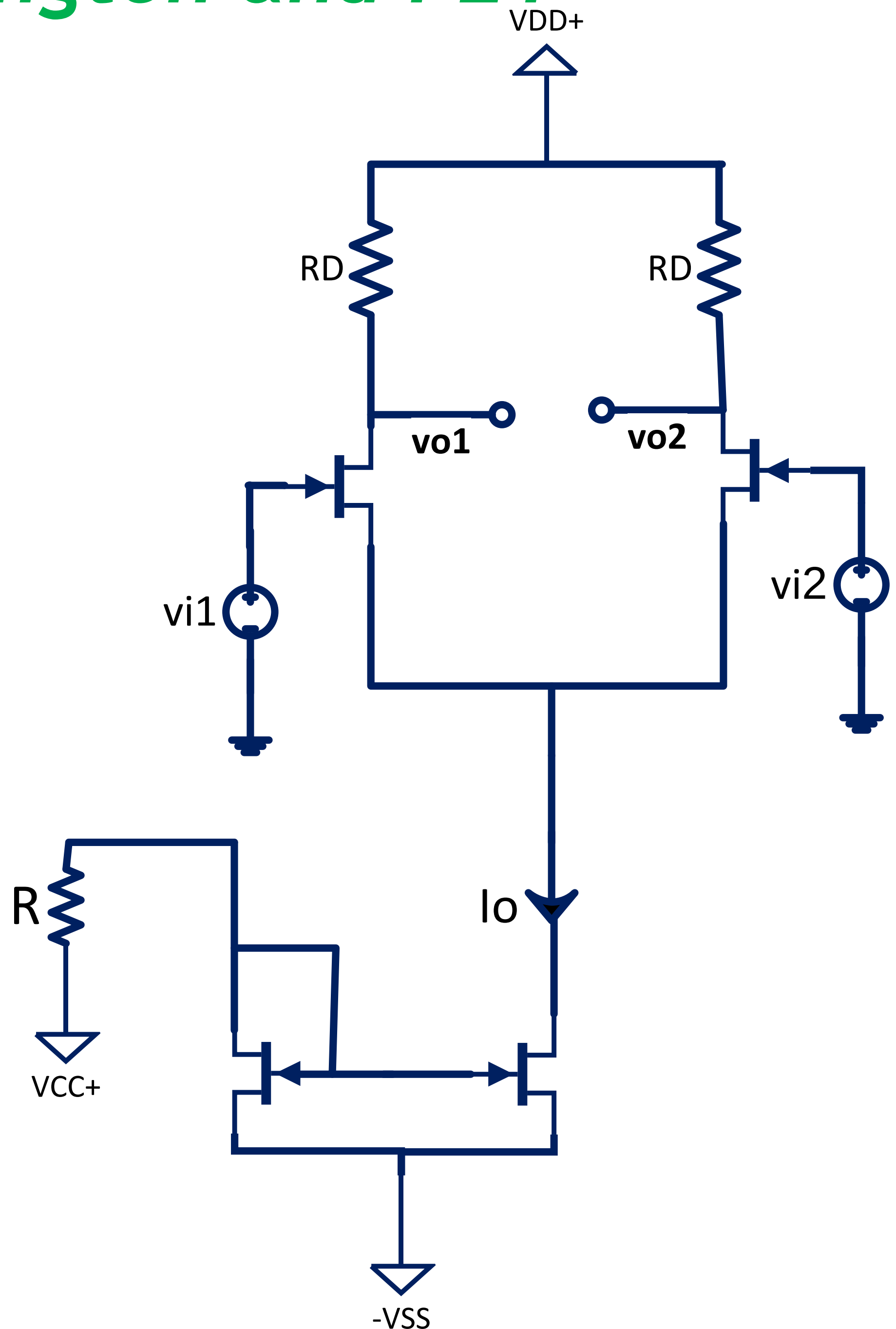
$$Z_{ic} = \left.\frac{v_c}{i_b}\right|_{v_d=0}$$

$$v_{i1} = v_c \;\;;\;\; v_{i2} = v_c$$

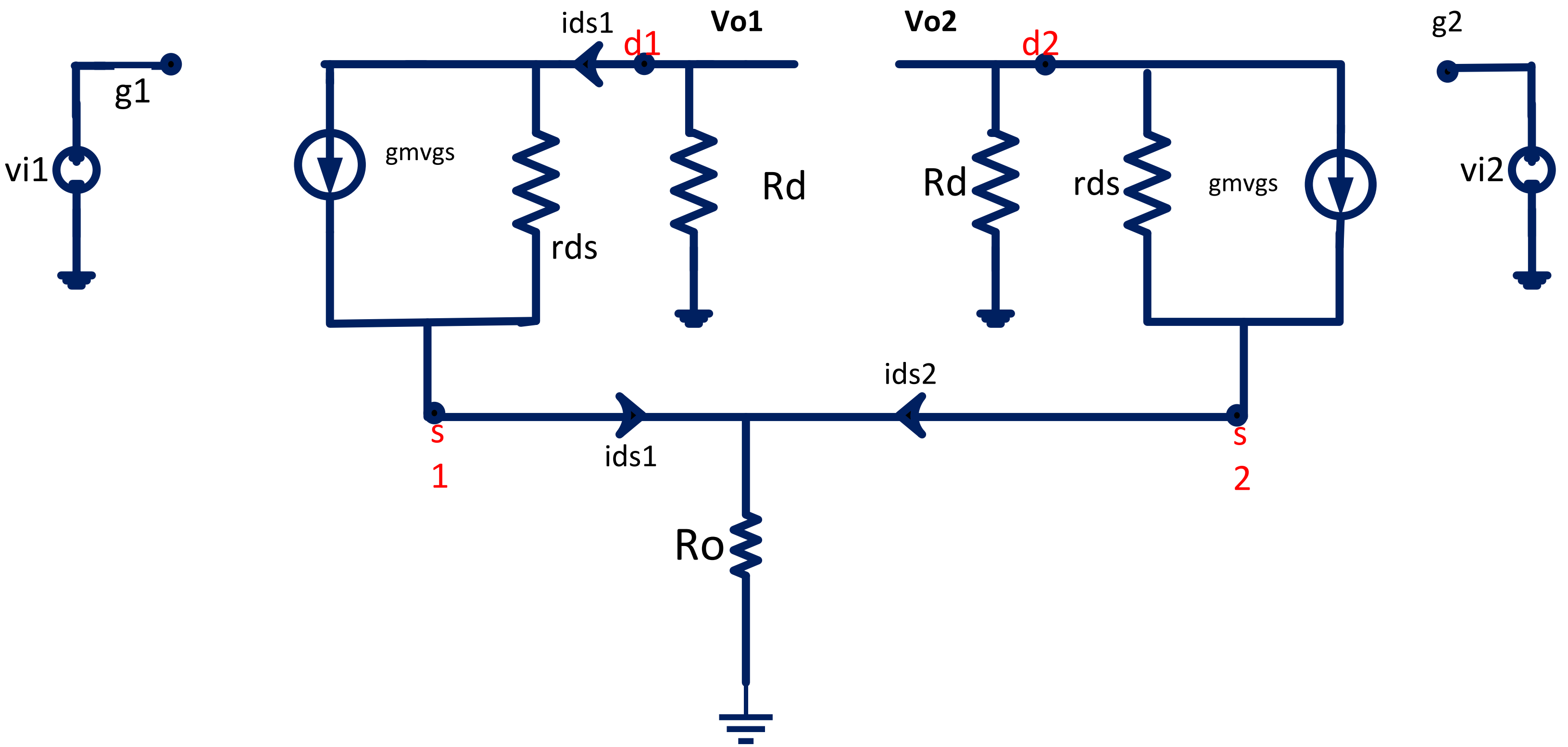
$$Z_{ic} = R_S + h_{ieD} + R_E(1 + h_{feD}) + 2R_o(1 + h_{feD})$$

Differential Amplifiers Using Darlington and FET

Differential Amplifiers Using FET

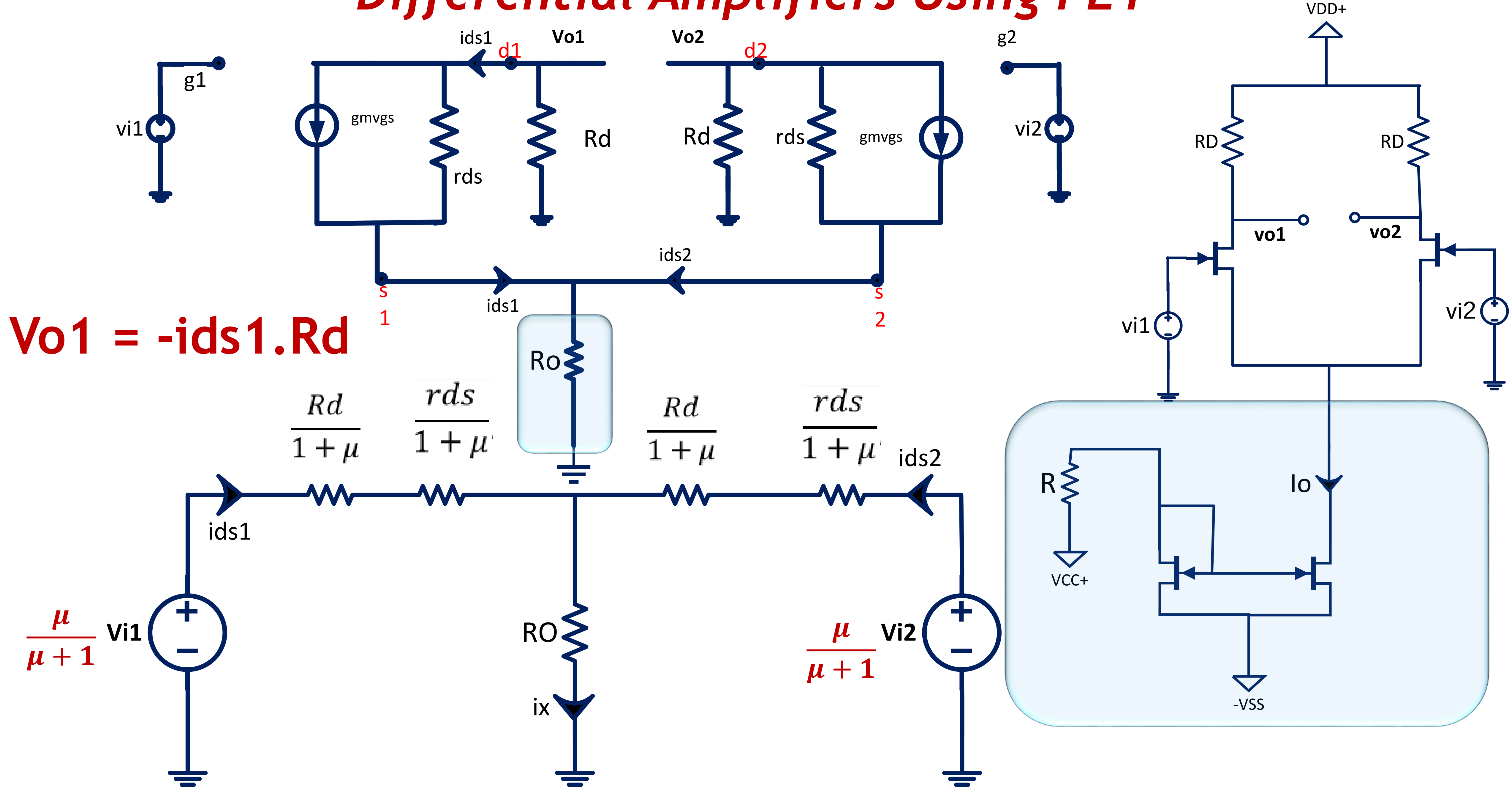


Ac Small signal equivalent Circuit:



Differential Amplifiers Using FET

$$Vo1 = -ids1.Rd$$

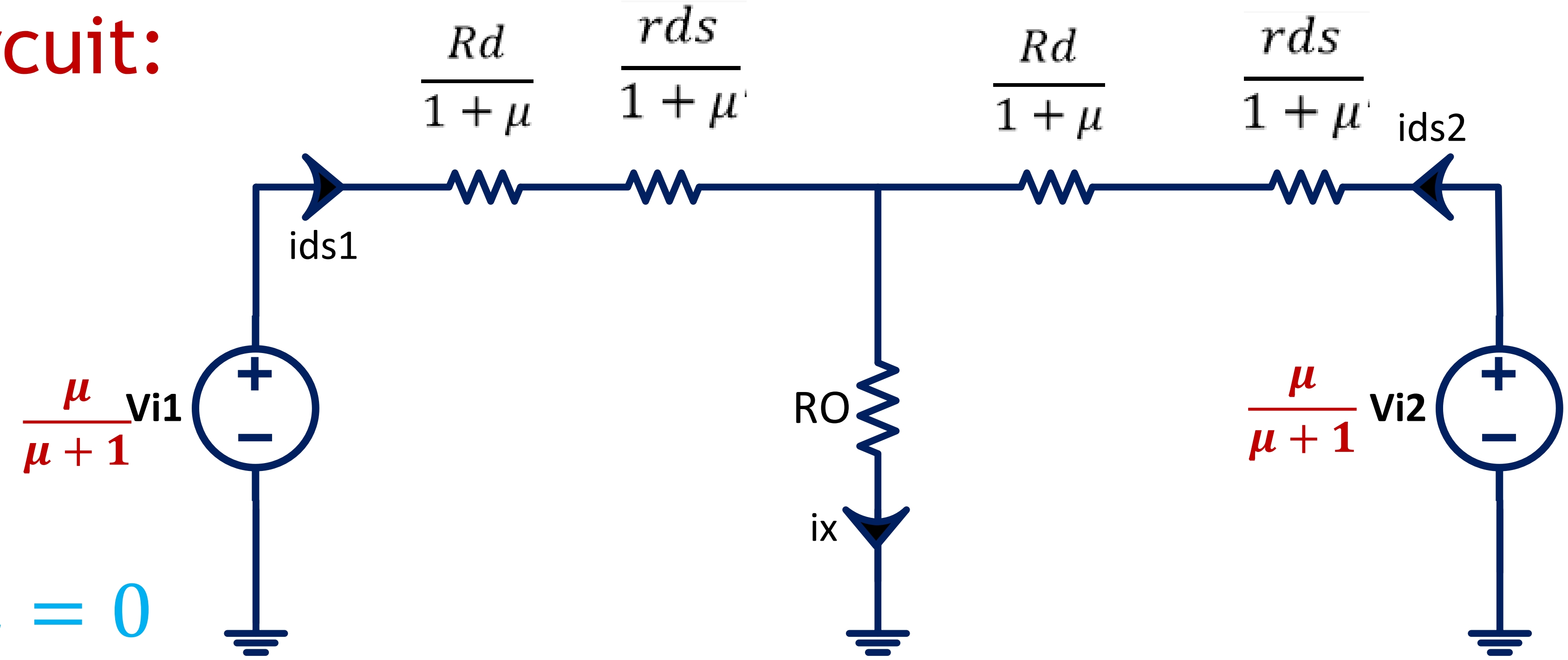


Differential Amplifiers Using FET

Source equivalent Circuit:

$$vi_1 = v_c - \frac{v_d}{2}$$

$$v_{i2} = v_c + \frac{v_d}{2}$$



$1)\ To\ find\quad A_d\,;set\ v_c = 0$

$$v_{i1} = -\frac{v_d}{2}$$

$$ids_1 = -ids_2$$

$$vi_2 = \frac{v_d}{2}$$

$$ids_1 = \frac{\frac{\mu}{\mu+1}\left(-\frac{v_d}{2}\right)}{\frac{R_d + rds}{\mu+1}}$$

$$v_{o1} = \frac{R_d \frac{\mu}{\mu+1} v_d}{2\left(\frac{R_d + rds}{\mu+1}\right)}$$

$$i_x = 0 \quad symmetry$$

$$v_{o1} = \frac{R_d \frac{\mu}{\mu+1} v_d}{2\left(\frac{R_d + rds}{\mu+1}\right)}$$

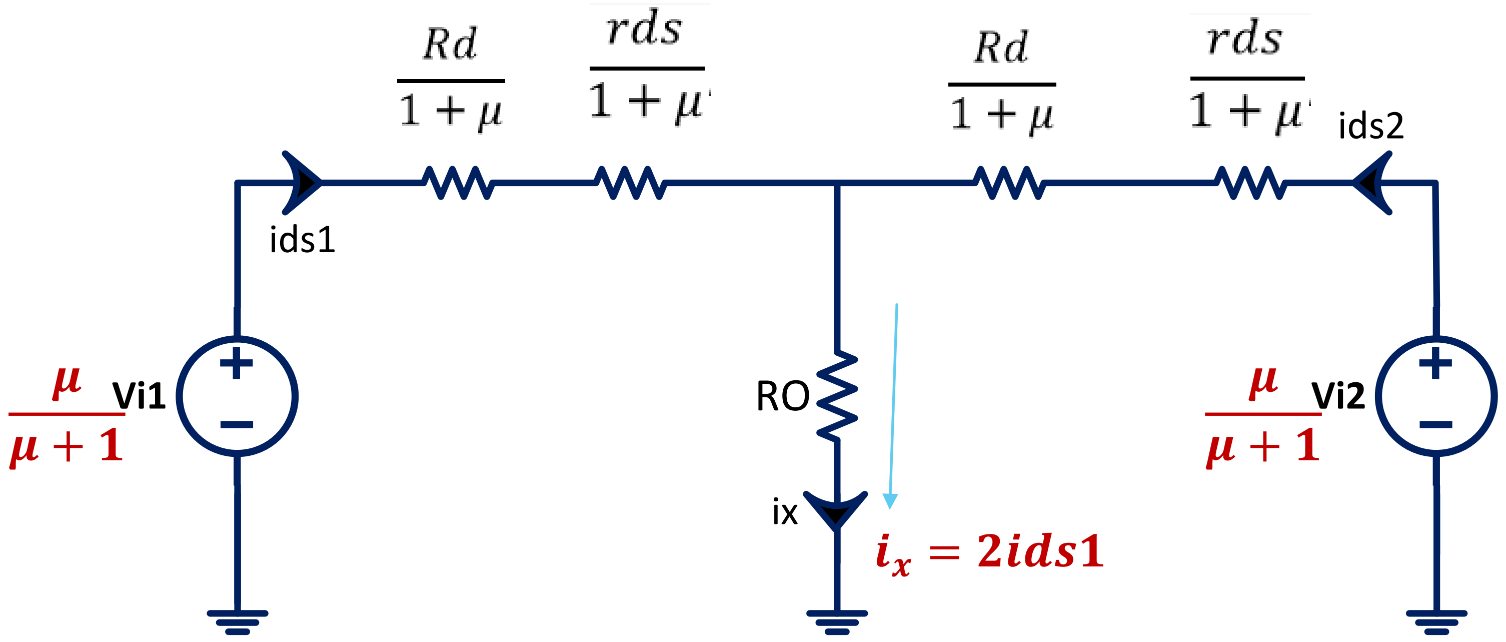
$$A_d = \left.\frac{v_{o1}}{v_d}\right|_{v_c=0}$$

$$A_d = \frac{R_d \frac{\mu}{\mu+1}}{2\left(\frac{R_d + rds}{\mu+1}\right)}$$

Differential Amplifiers Using FET

Ac Small signal equivalent Circuit:

$$2)\ To\ find\ A_c = \left.\frac{v_{o1}}{v_c}\right|_{v_d=0}$$



$$vi_1 = v_c$$
$$vi_2 = v_c$$

$$ids_1 = ids_2$$

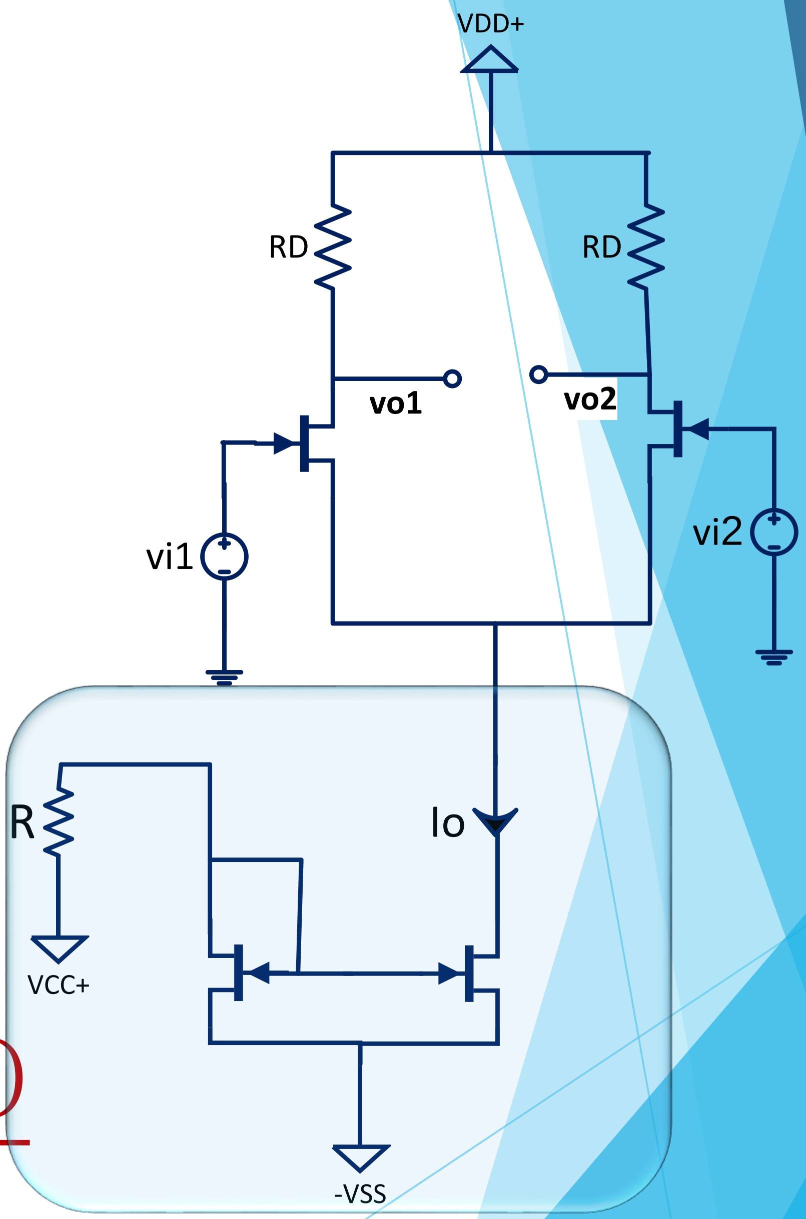
$$i_x = 2ids1$$

$$i_{ds1} = \frac{v_c \frac{\mu}{\mu+1}}{\left(\frac{R_d + rds}{\mu+1}\right) + 2R_o}$$

$$v_{o1} = \frac{-R_d \frac{\mu}{\mu+1}}{\left(\frac{R_d + rds}{\mu+1}\right) + 2R_o} v_c$$

$$\therefore \quad A_c = \frac{R_d \frac{\mu}{\mu+1}}{\left(\frac{R_d + rds}{\mu+1}\right) + 2R_o}$$

$$CMRR = \left|\frac{A_d}{A_c}\right| = \frac{rds + R_d + 2R_o(\mu+1)}{2(R_d + rds)}$$



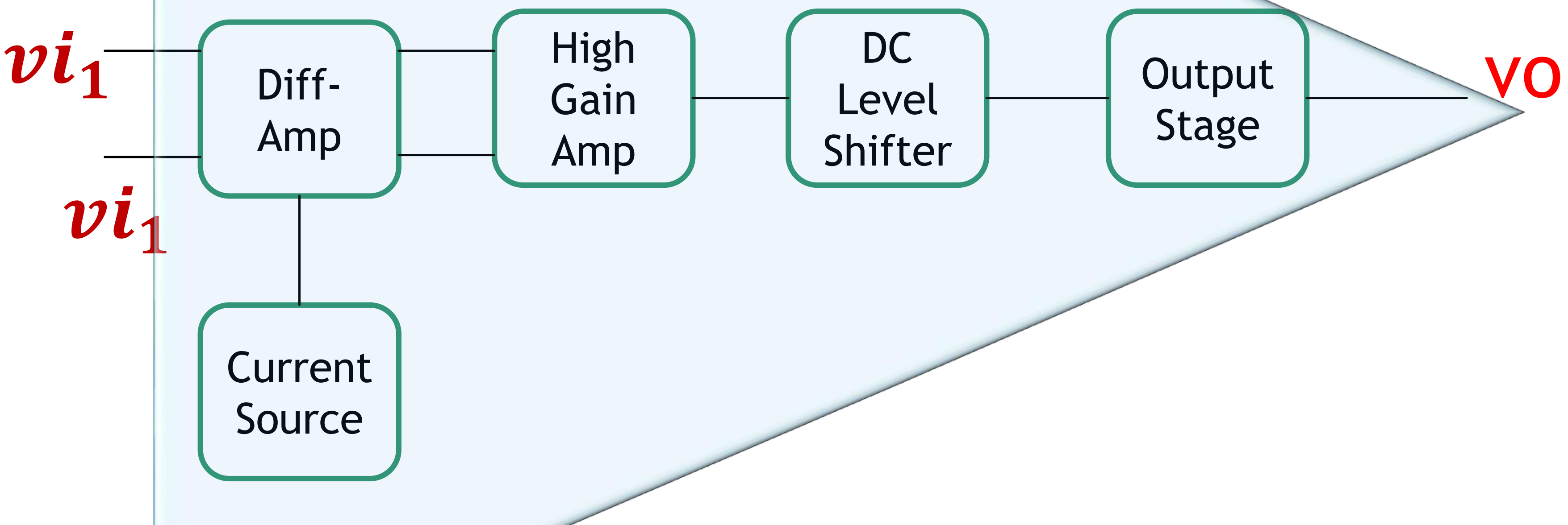
The Operational Amplifier

Very high voltage gain ; 200,000

Very High input impedance ; 10M ohm

Very small output impedance ; 75ohm

Designed to do mathematical operations such as addition , subtraction ….



The Operational Amplifier

DC Level Shifter

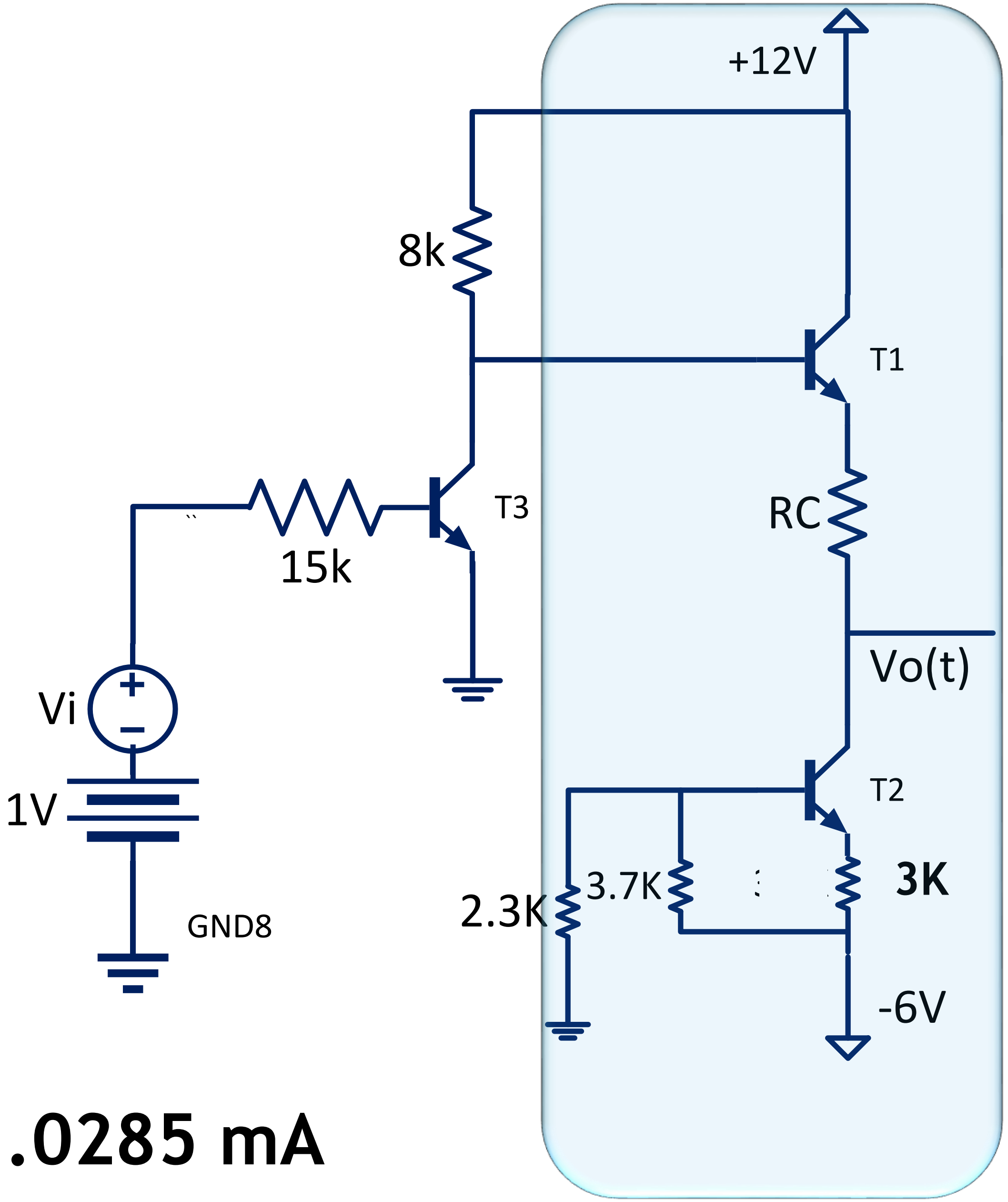
$$To\ make\ v_o = 0, when$$
$$v_{i1} = v_{i2} = 0$$

$$R_C \quad = \quad ?????$$

$$R_{TH} = 2.3k \| 3.7k = 1.418\ k$$

$$V_{TH} = \frac{2.3k}{2.3k + 3.7k}(-6) = -2.2\ V$$

$$I_{E2} = \frac{V_{TH} - 0.7 + 6}{3k + \frac{R_{TH}}{\beta + 1}}$$



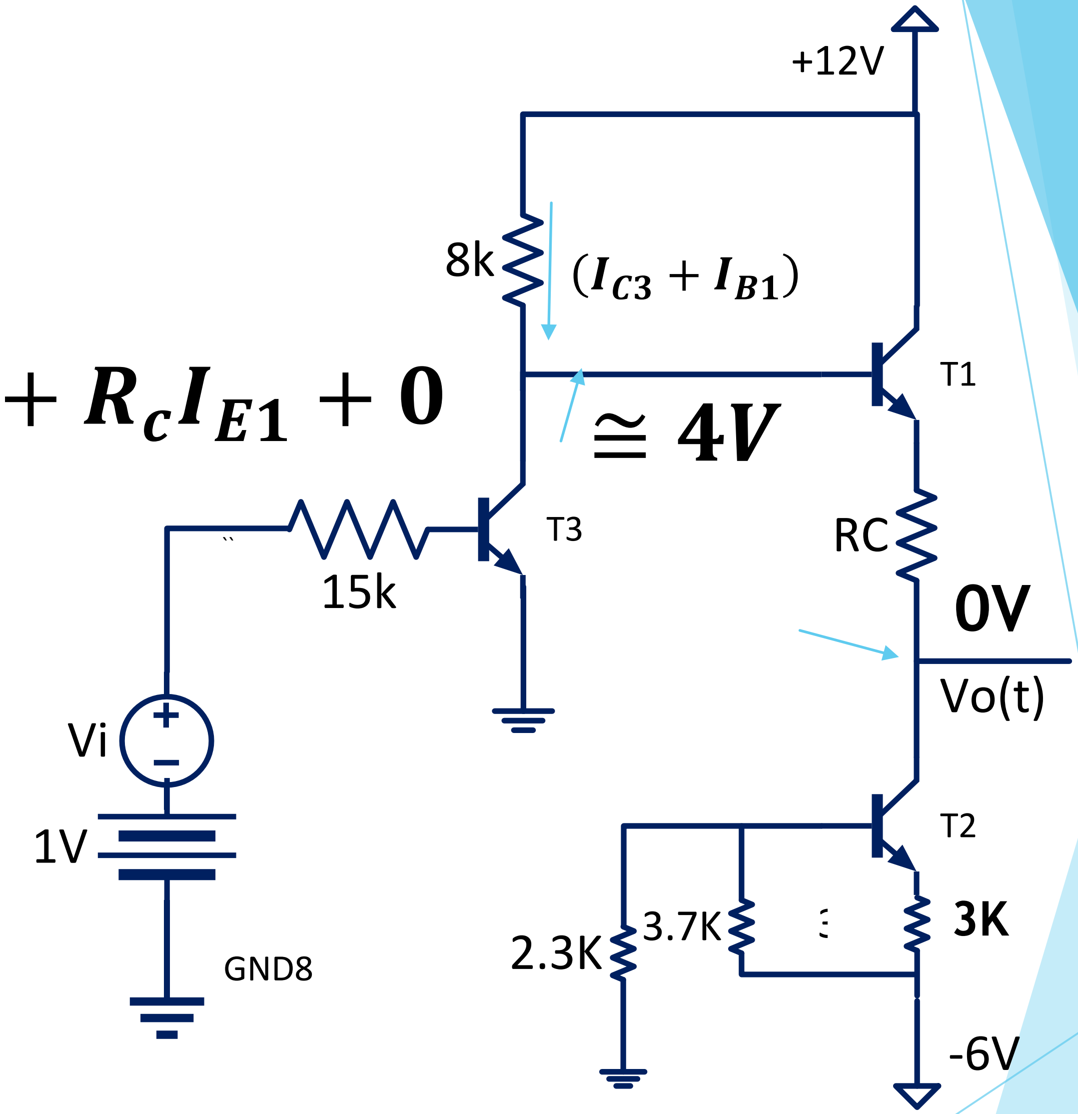
$$I_{E2} = 1.0285\ \text{mA}$$

$$I_{B3} = \frac{1-0.7}{15k} = 0.02mA$$

$$I_{C3} = 1mA$$

$$12 = 8k(I_{C3} + I_{B1}) + 0.7 + R_c I_{E1} + 0$$

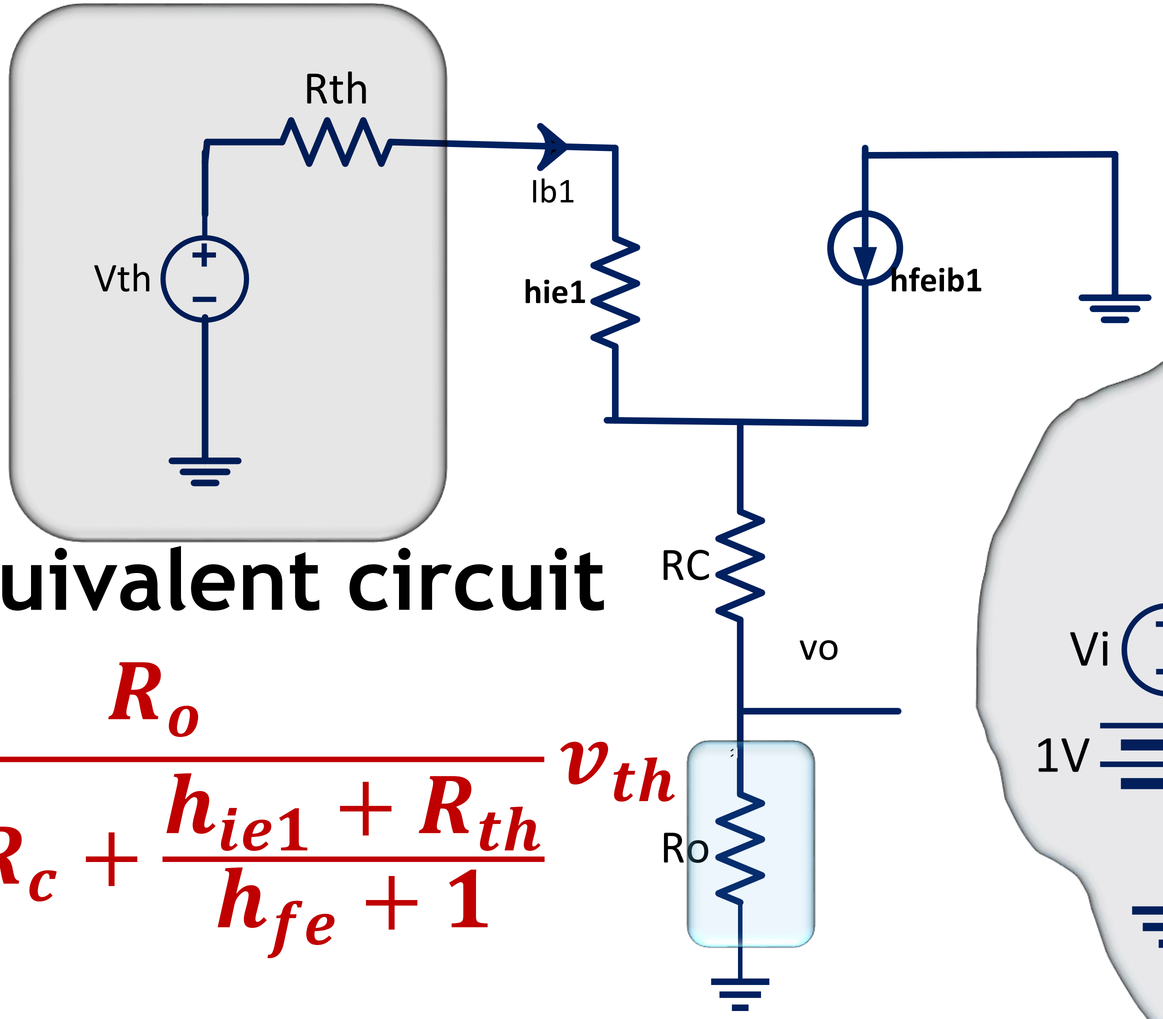
$$\therefore\ R_c \cong 3.3k$$

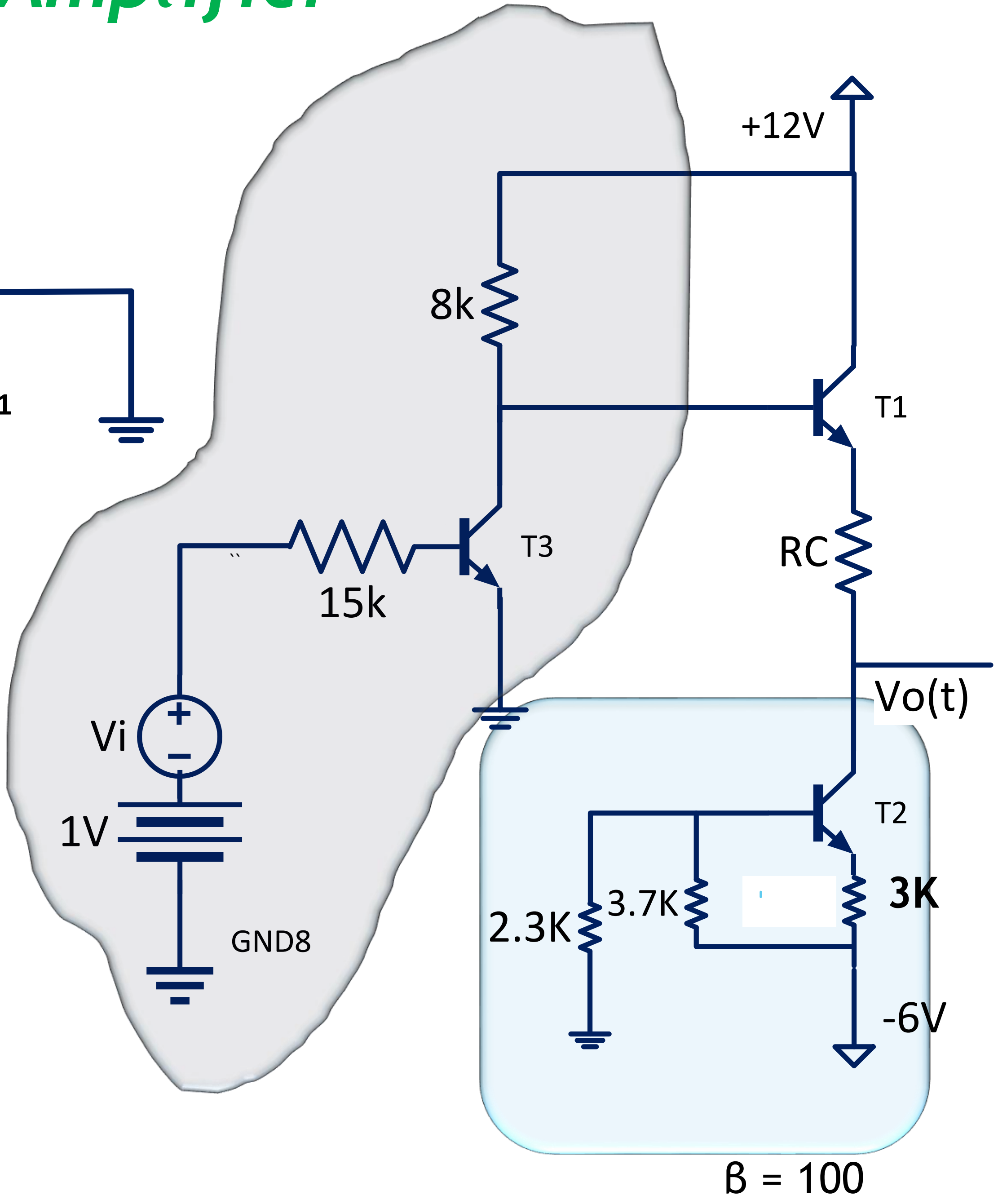


THE FUNCTION OF THE CAPACITOR

The Operational Amplifier

Ac Small signal equivalent Circuit:



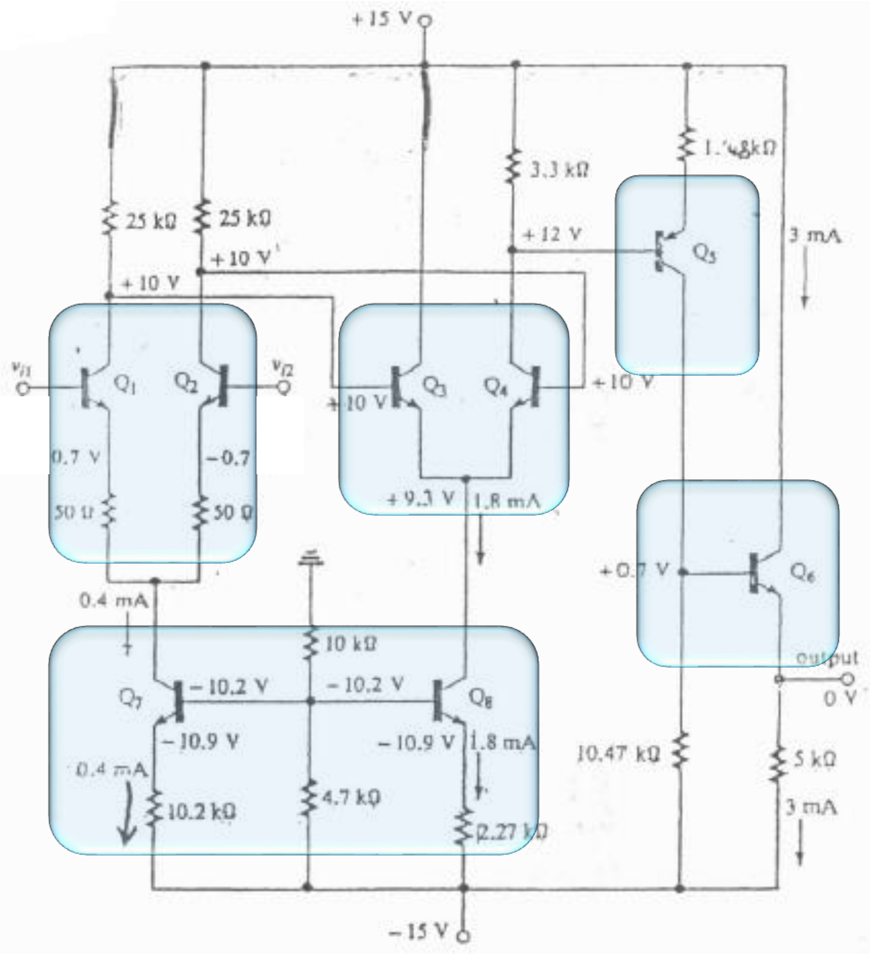


Emitter equivalent circuit

$$v_o = \frac{R_o}{R_o + R_c + \frac{h_{ie1} + R_{th}}{h_{fe} + 1}} v_{th}$$

$$v_o \approx v_{th}$$

Complete Operational Amplifier



Q5 pnp DC Level Shifter

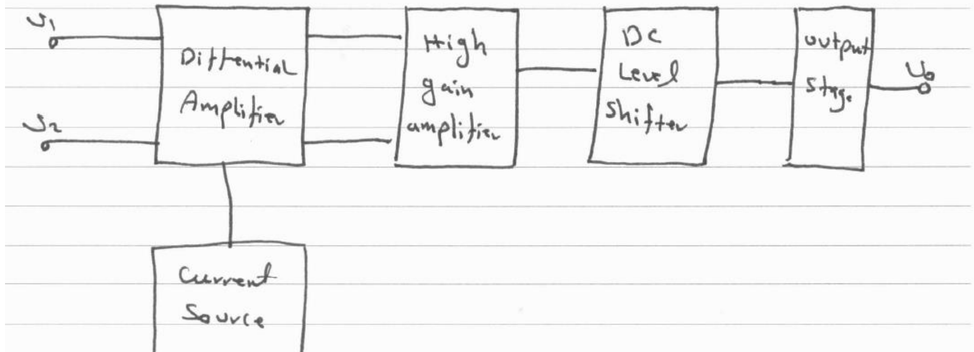
ALL β = 100

Q6 Output Stage CC

Q1and Q2 Differential Amplifier

Q3 and Q4 High Gain Amplifier

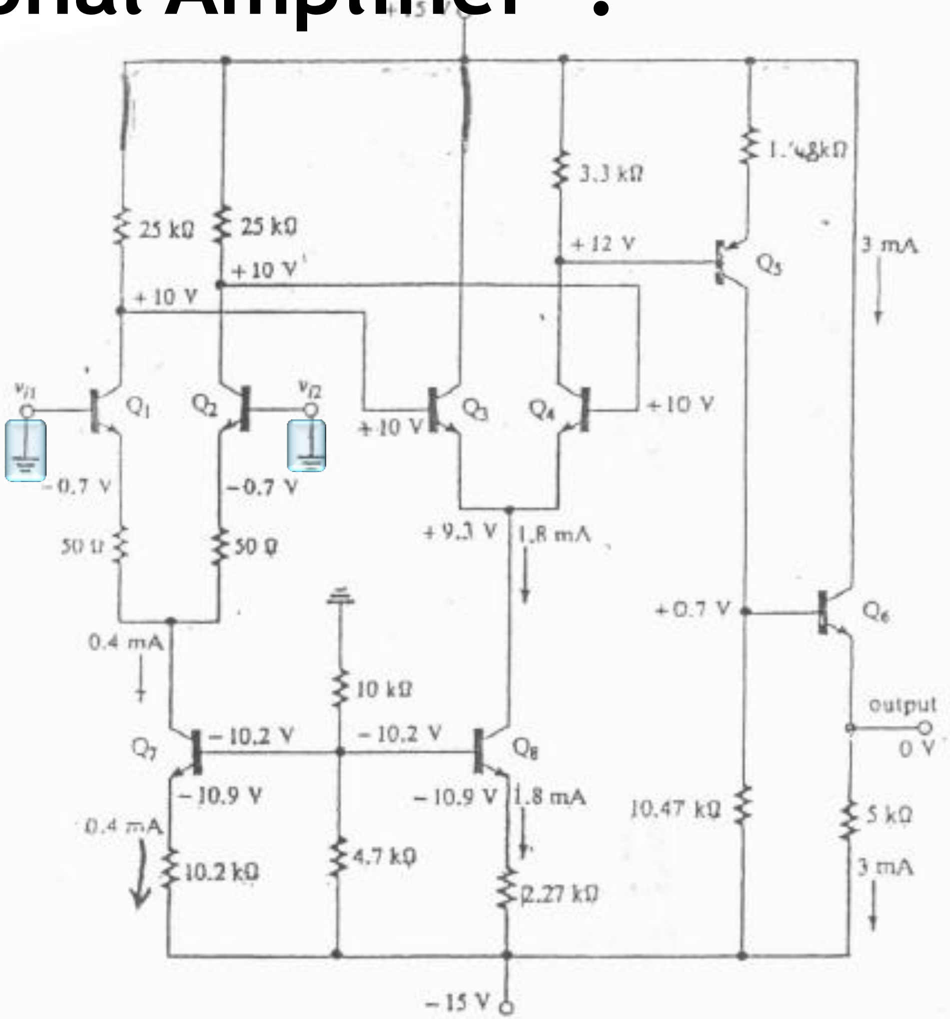
Q7 and Q8 Current Source



Complete Operational Amplifier :

DC Analysis :

Vi2 = Vi1 = 0



All ß = 100

ALL ß = 100

VB7 = VB8 = (10K) . (-15V)/(10K+4.7K = -10.2 V

VE7 = VE8 = -10.2V - 0.7V = - 10.9V

IE7 = (+15 - 10.9)/RE7 = 0.4mA

IE8 =(+15 -10.9)/RE8 = 1.8mA

ICQ1 = ICQ2 = 0.5 IE7 = 0.2mA

ICQ3 = ICQ4 = 0.5 IE8 = 0.9mA

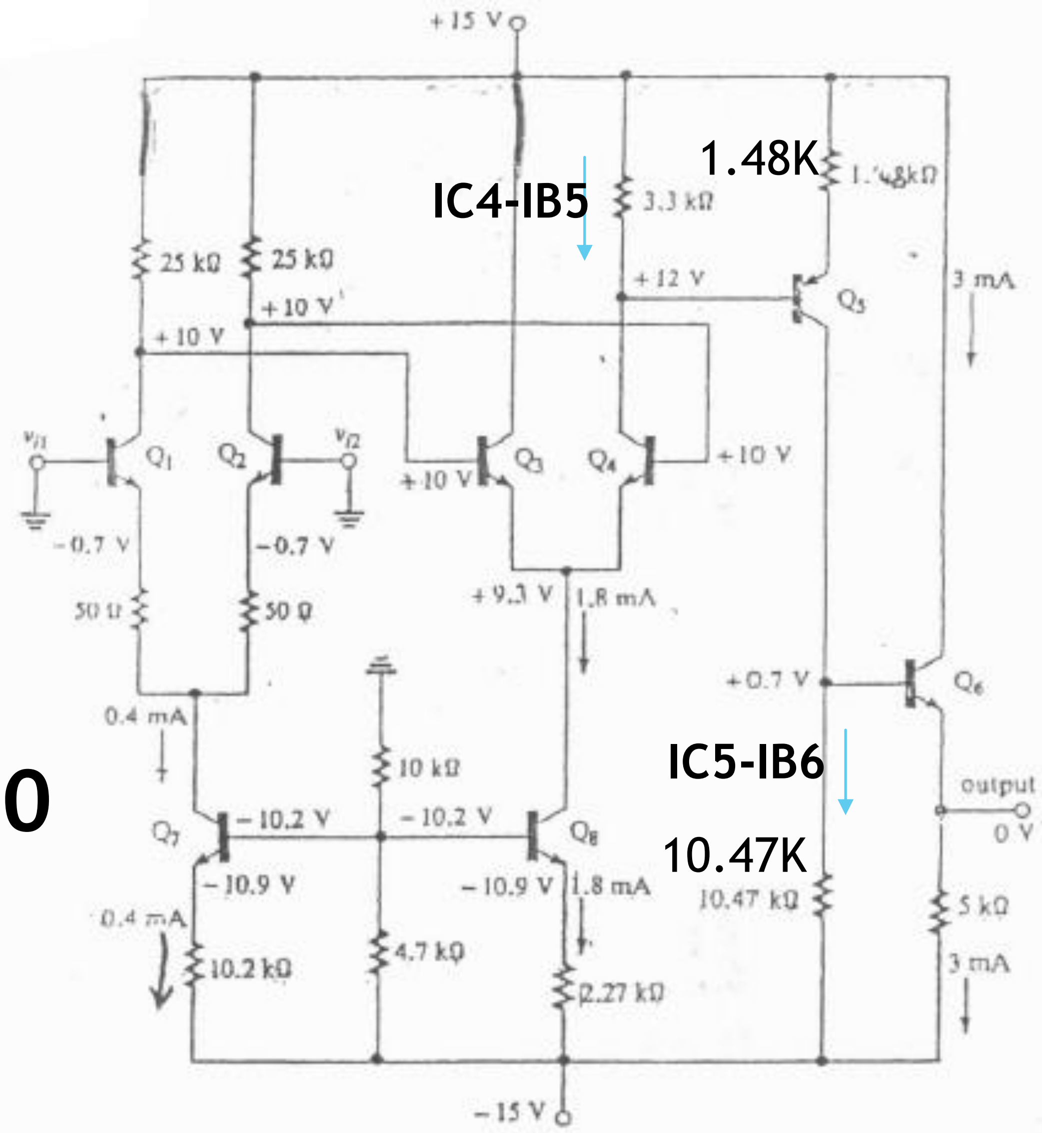
0 = 3.3K (IC4-IB5) + VBE5 - 1.48K IE5

IE5 = 1.53 mA

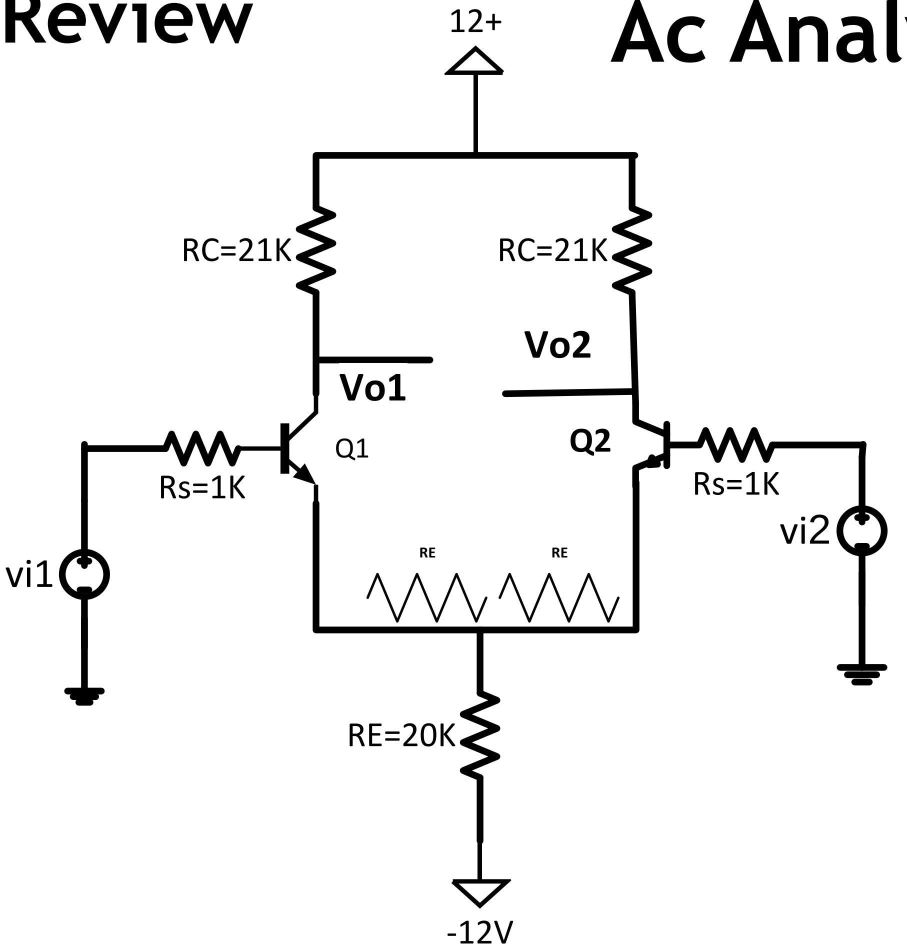
VBE6+5K IE6 - 10.47K (IC5-IB6) = 0

IE6 = 3mA

Or IE6 = $\frac{0-(-15)}{5K}$ = 3mA



Review



Ac Analysis :Differential Mode Analysis

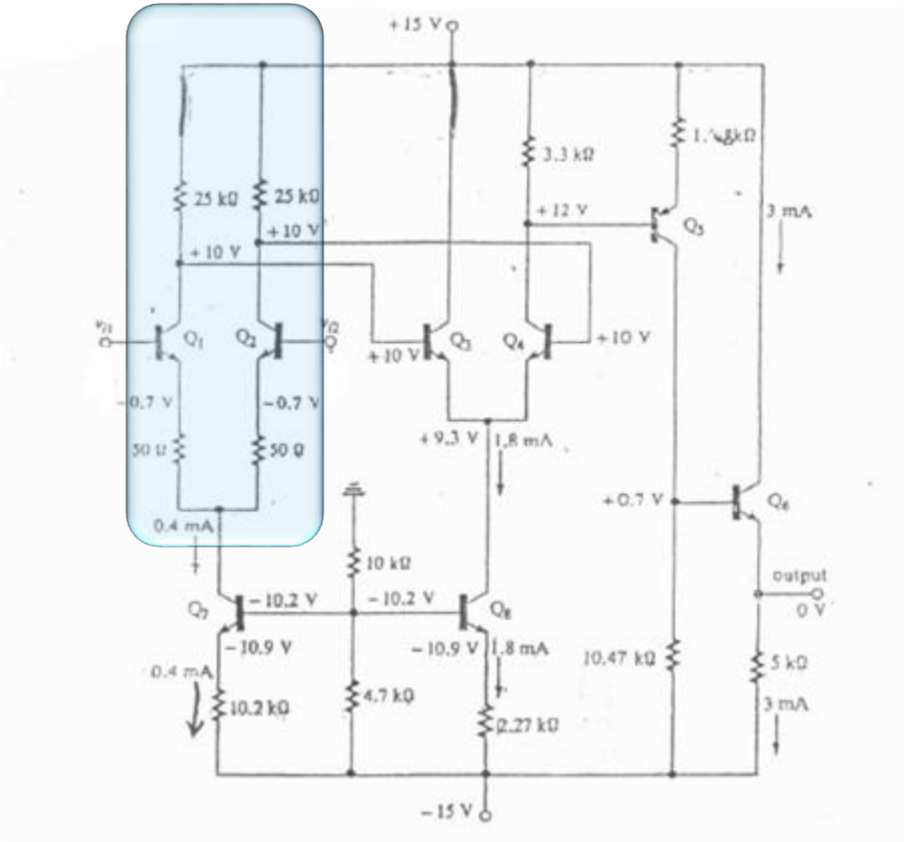
If we have RE1= RE2

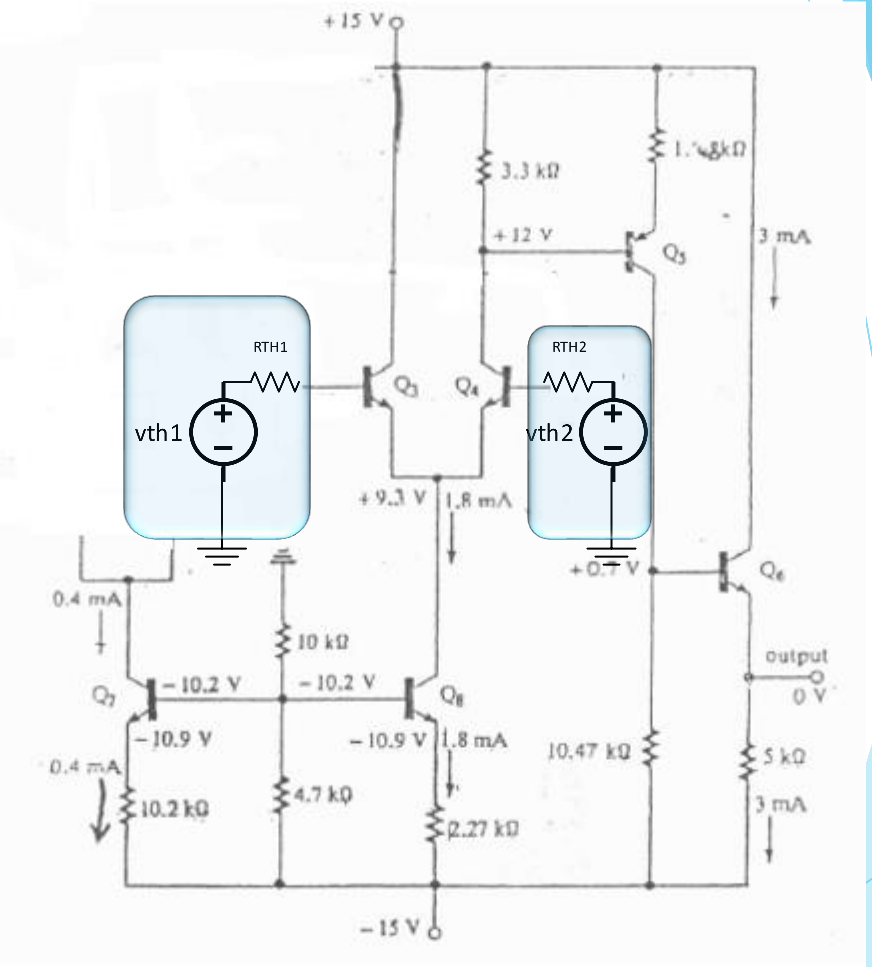
$$v_{o1} = \frac{R_c v_d}{2\left(h_{ib} + RE1 + \frac{R_s}{h_{fe+1}}\right)}$$

$$v_{o2} = -\frac{R_c v_d}{2\left(h_{ib} + RE1 + \frac{R_s}{h_{fe+1}}\right)}$$

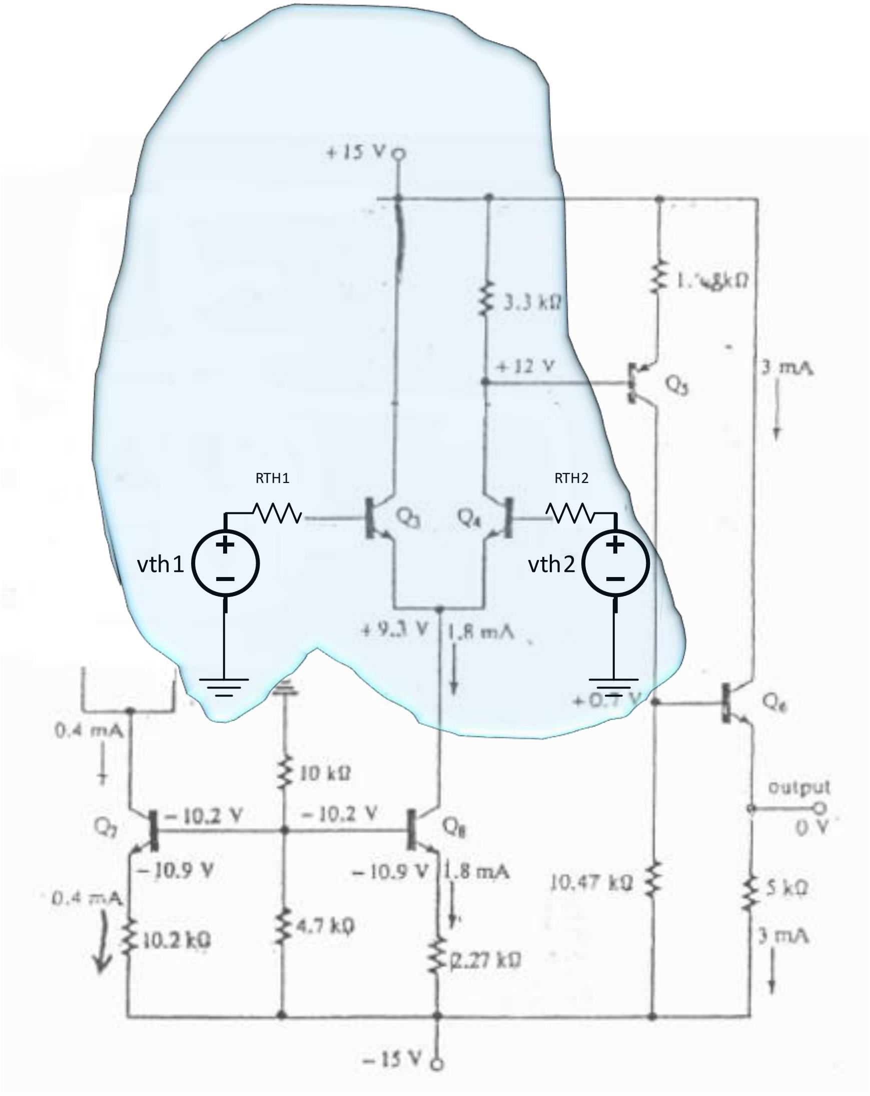
$$v_{o1} = \frac{R_c v_d}{2\left(h_{ib} + \frac{R_s}{h_{fe+1}}\right)}$$

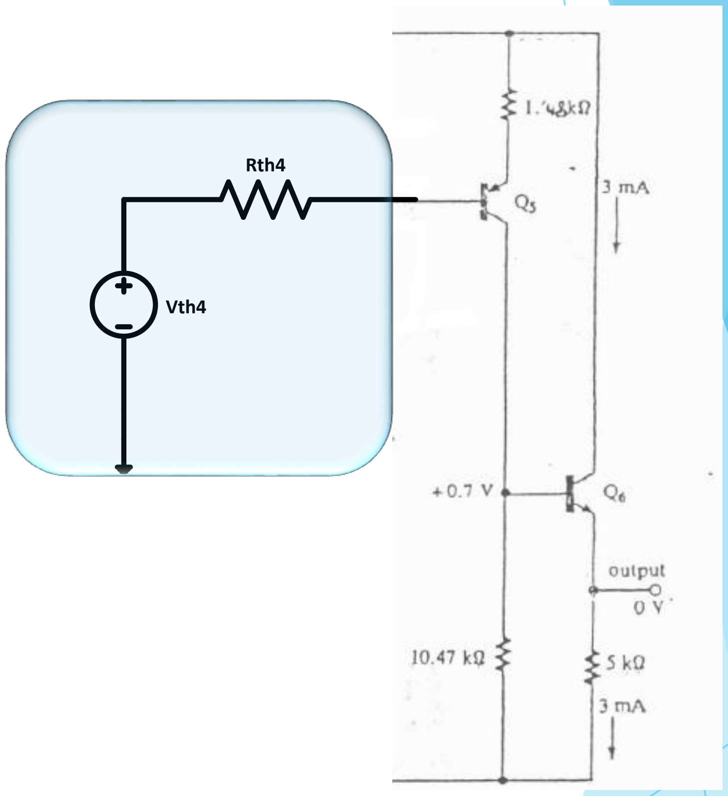
$$v_{o2} = -\frac{R_c v_d}{2\left(h_{ib} + \frac{R_s}{h_{fe+1}}\right)}$$


+15 V
25 kΩ
25 kΩ
+10 V
+10 V
3.3 kΩ
+12 V
Q5
3 mA
Q1
Q2
Q3
Q4
+10 V
+10 V
−0.7 V
−0.7 V
50 Ω
50 Ω
+9.3 V
1.8 mA
+0.7 V
Q6
0.4 mA
10 kΩ
output
0 V
Q7
−10.2 V
−10.2 V
Q8
−10.9 V
−10.9 V
1.8 mA
0.4 mA
10.2 kΩ
4.7 kΩ
2.27 kΩ
10.47 kΩ
5 kΩ
3 mA
−15 V


+15 V
3.3 kΩ
+12 V
Q5
3 mA
RTH1
RTH2
vth1
vth2
Q3
Q4
+9.3 V
1.8 mA
Q6
0.4 mA
10 kΩ
output
0 V
Q7
−10.2 V
−10.2 V
Q8
−10.9 V
−10.9 V
1.8 mA
0.4 mA
10.2 kΩ
4.7 kΩ
2.27 kΩ
10.47 kΩ
5 kΩ
3 mA
−15 V

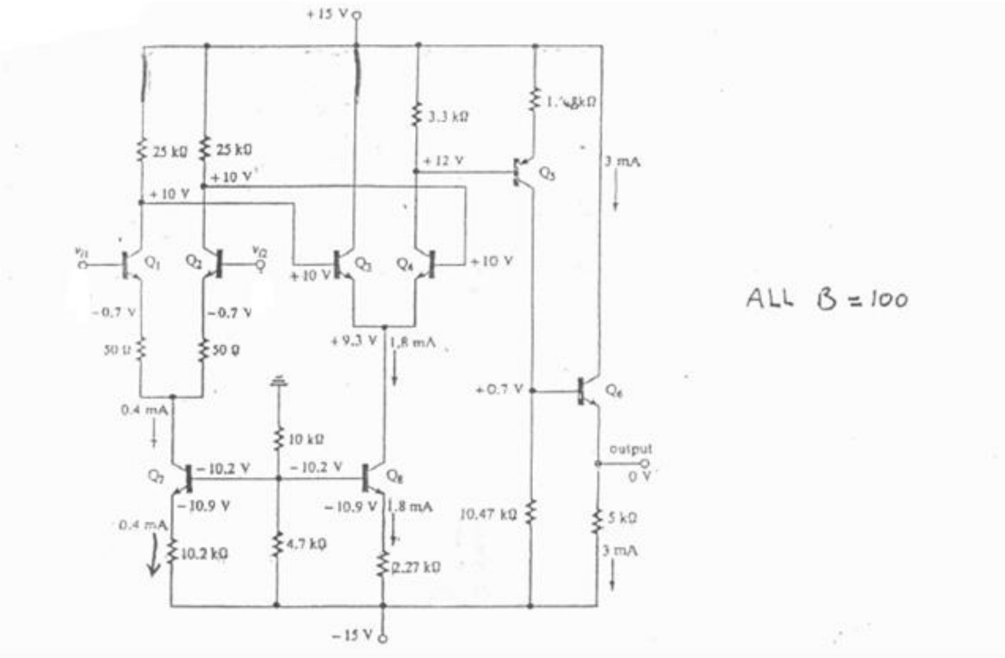
All β = 100


+15 V
3.3 kΩ
1.'‰8kΩ
+12 V
Q5
3 mA
RTH1
RTH2
Q3
Q4
vth1
vth2
+9.3 V
1.8 mA
+0.7 V
Q6
0.4 mA
10 kΩ
output
0 V
Q7
−10.2 V
−10.2 V
Q8
−10.9 V
−10.9 V
1.8 mA
0.4 mA
10.47 kΩ
5 kΩ
10.2 kΩ
4.7 kΩ
2.27 kΩ
3 mA
−15 V


Rth4
Vth4
1.'‰8kΩ
Q5
3 mA
+0.7 V
Q6
output
0 V
10.47 kΩ
5 kΩ
3 mA

All β = 100

Ac Small signal Analys



hie1 = 13kΩ
hie2 = 13kΩ
hie3 = 2.89KΩ
hie4 =2.89KΩ
hie5 = 1. 7KΩ
hie6 = 0.87KΩ

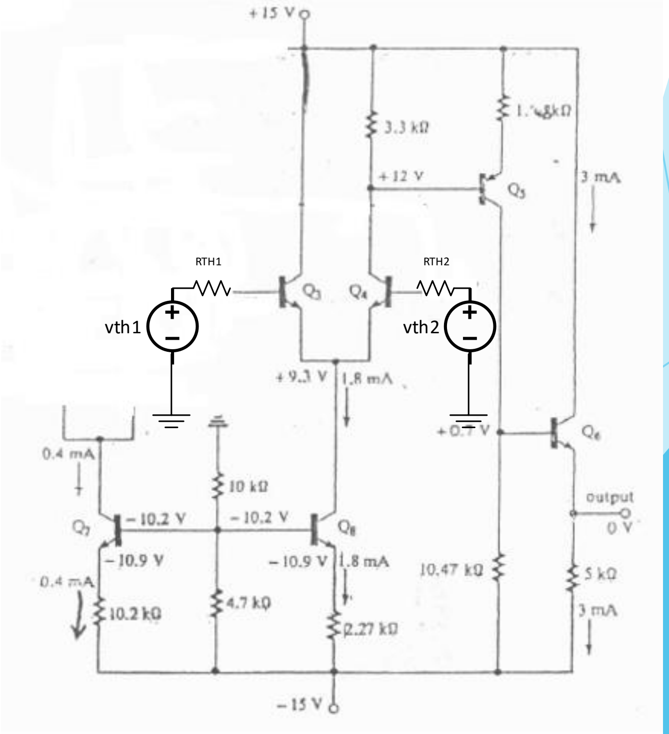
$$Vth1 = \frac{\left(+\frac{vd1}{2}\right)Rc1}{Re1+hib1+Rs1/(hfe+1)}$$

Rs1 = 0 vd1= Vi2 - Vi1

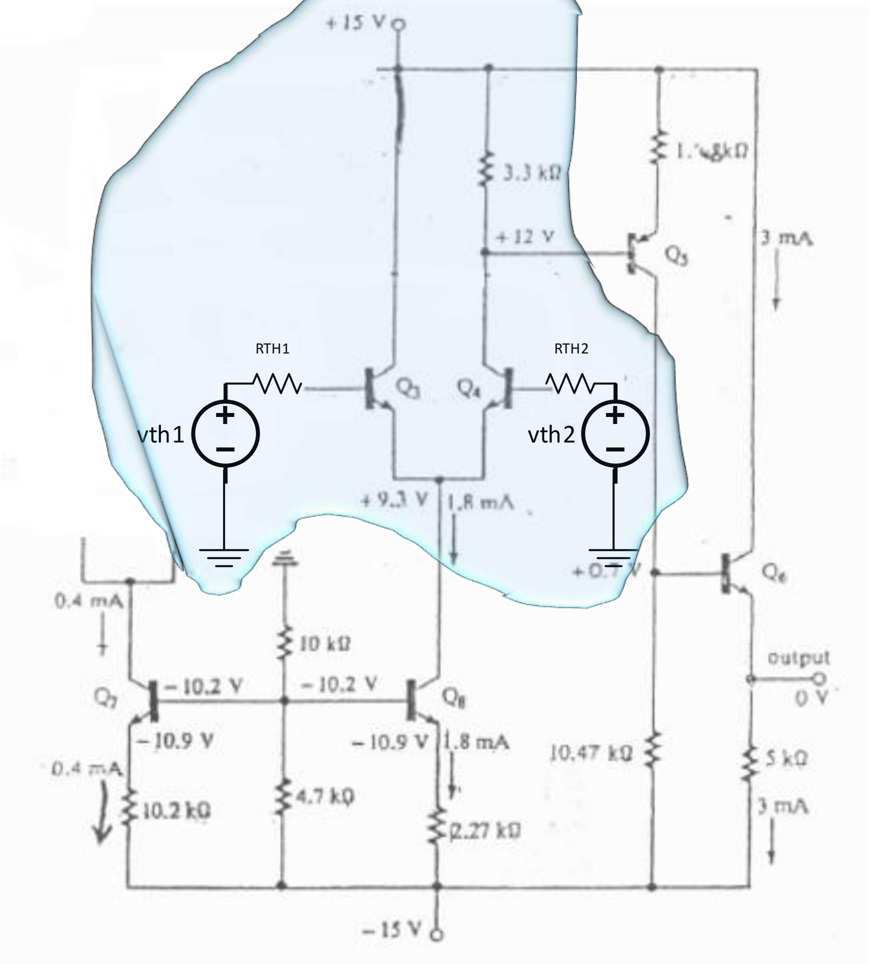
Vth1 = 69.4 Vd1 Rth1 = Rc1 = 25K

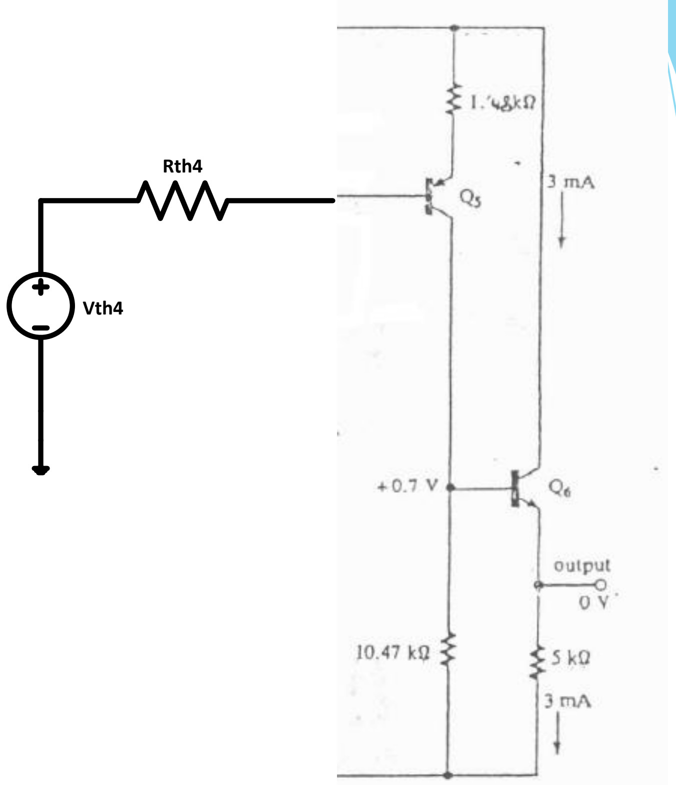
$$Vth2 = -Vth1 = \frac{-\left(+\frac{vd1}{2}\right)Rc1}{Re1+hib1+Rs1/(hfe+1)}$$

Vth2 = -69.4 $Vd1$



Rth2 = 25K





$$\text{Vth4} = \frac{-\left(+\frac{vd4}{2}\right)RC4}{Re4+hib4+Rs4/(hfe+1)} = 829\,Vd4$$

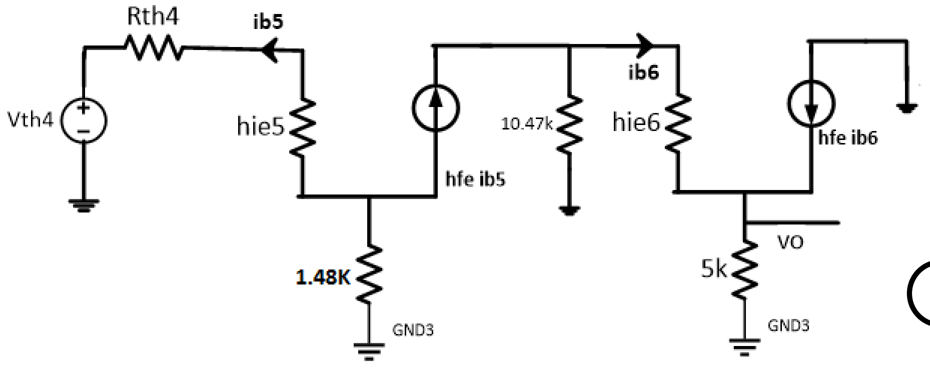
Rth4 = 3.3k

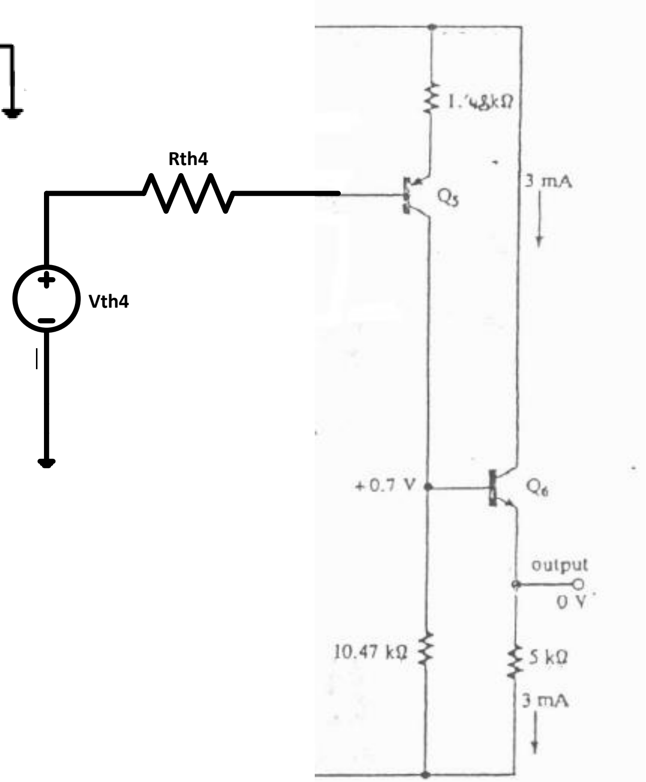
Re4 = 0

Rs4 = 25K

Vd4 = (Vth2 – Vth1)

Ac Small Signal Equivalent Circuit Of the DC Level Shifter and the Output Stages :



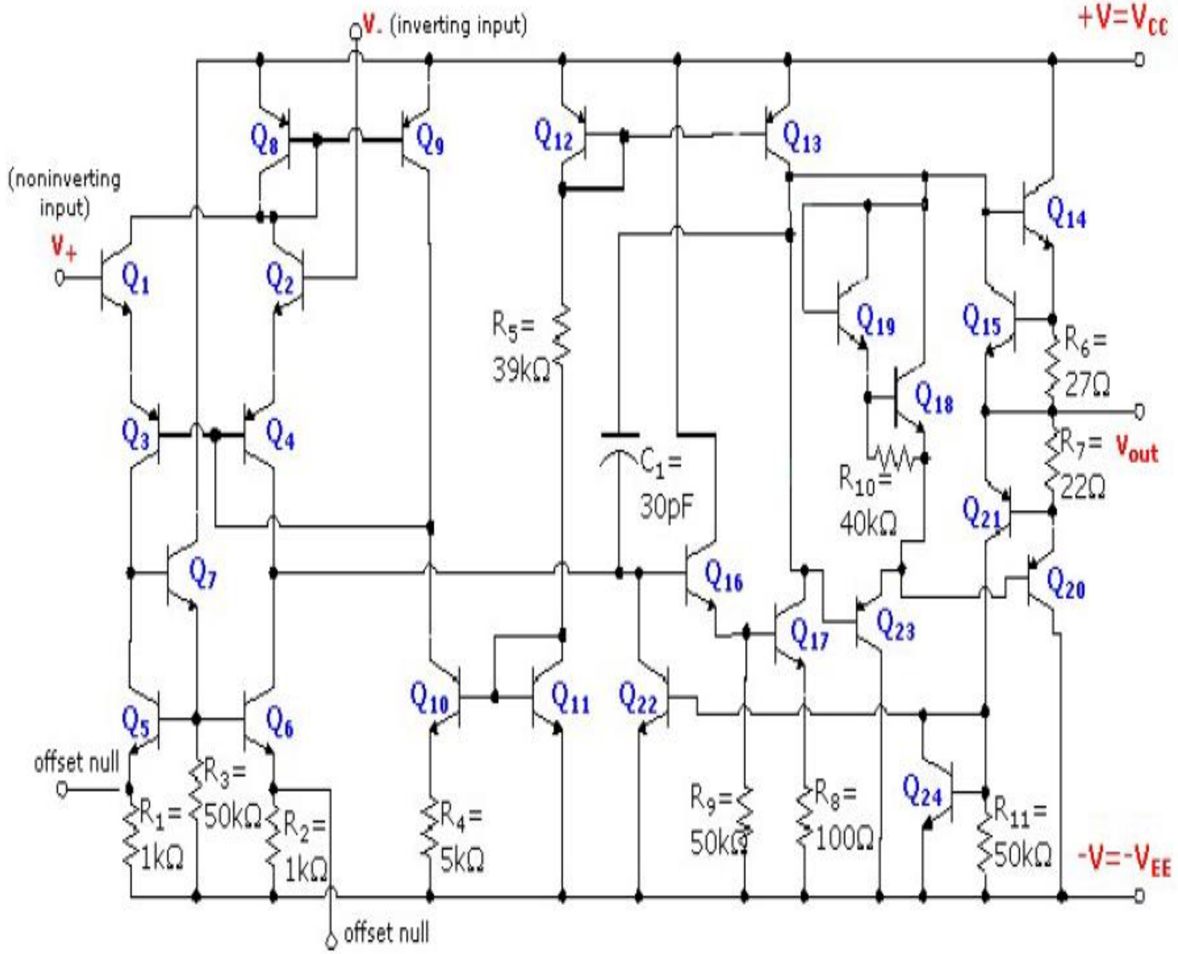


$vo = 5k\ ie6$; $ie6 = (1+hfe)\ ib6$

$$ib6 = \frac{10.47k \cdot hfe\ ib5}{10.47k + hie6 + 5k(1+hfe)}$$

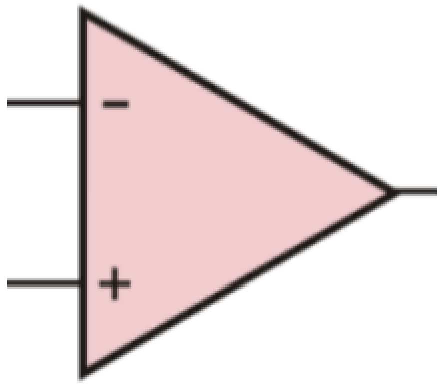
$$ib5 = \frac{-vth4}{Rth4 + hie5 + 1.48k(1+hfe)}$$

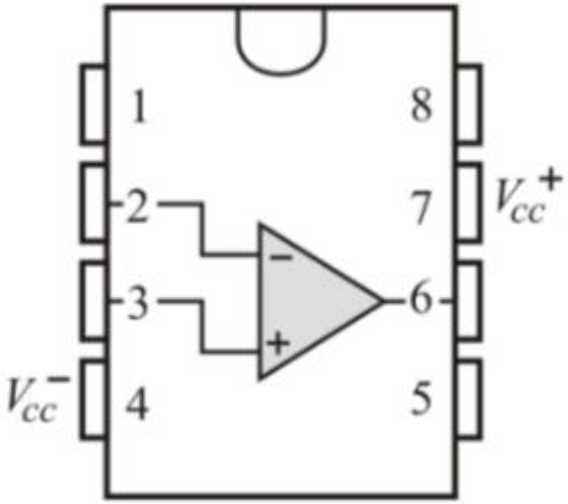
$Vo = -5540\ vd1 = +5540\ (vi1 - vi2)$



V- (inverting input)
+V=Vcc
(noninverting input)
V+
Q1
Q2
Q3
Q4
Q5
Q6
Q7
Q8
Q9
Q10
Q11
Q12
Q13
Q14
Q15
Q16
Q17
Q18
Q19
Q20
Q21
Q22
Q23
Q24
R5= 39kΩ
C1= 30pF
R10= 40kΩ
R6= 27Ω
R7= 22Ω
Vout
offset null
R1= 1kΩ
R3= 50kΩ
R2= 1kΩ
R4= 5kΩ
R9= 50kΩ
R8= 100Ω
R11= 50kΩ
-V=-VEE
offset null

Operational Amplifier





741 Op-Amp Pin out