ECE 2133
Electronic Circuits

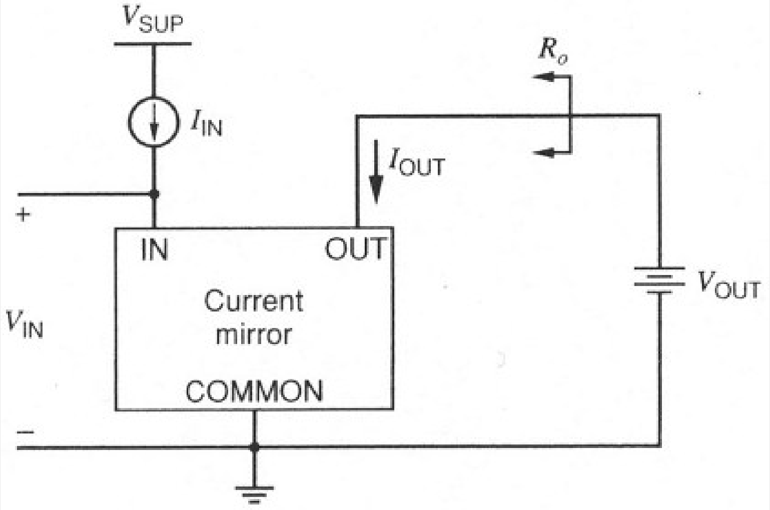
Dept. of Electrical and Computer Engineering
International Islamic University Malaysia

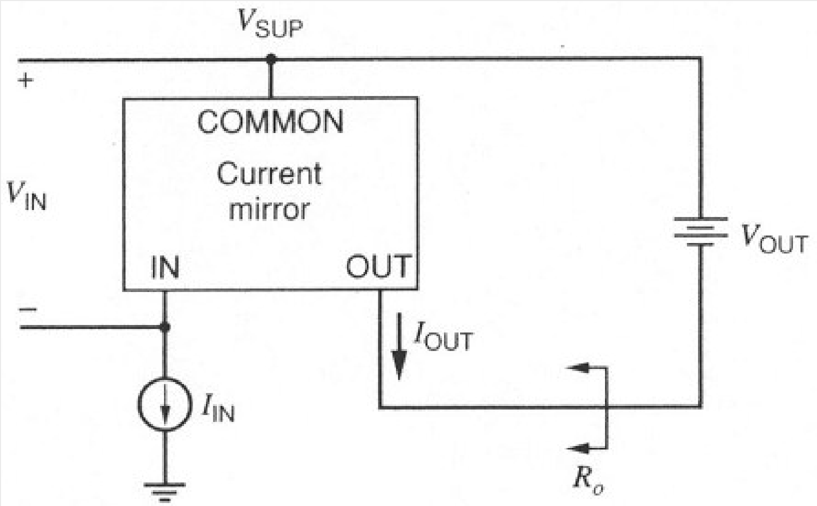
Chapter 10
Integrated Circuit Biasing

BJT Current Sources

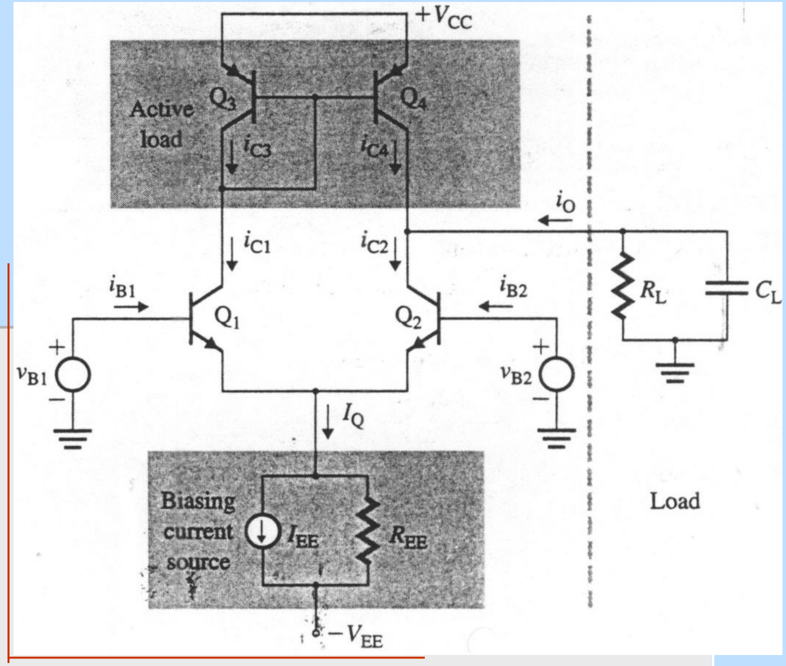
Transistor Current Mirrors, Source, and Sink

- A current source/mirror have three terminals. The common terminal is connected to a power supply or ground, and the input current source is connected to the input terminal.
- The output current is equal to the input current multiplied by a desired current gain.
- If the gain is unity, then the input current is reflected to the output and named as current mirror.





BJT Current Sources



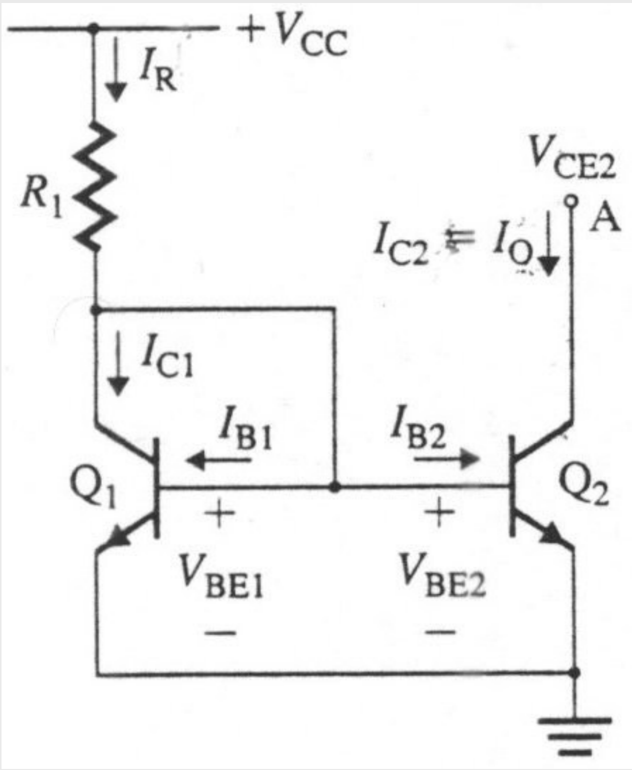
- Current sink
- Current source

Function:
Its maintain a constant current at an infinite output resistance under all operating conditions.

Uses:
- as biasing elements
- as loads for amplifying stages
- more economical than resistor in IC

Types of current sources:
- the basic current source
- the modified basic current source
- the Widlar current source
- the Wilson current source

Basic Current Source



Assume Q_1 and Q_2 are identical

$$I_R = I_{C1} + I_{B1} + I_{B2} = I_{C1} + 2I_{B1}$$

$$I_R = I_{C1} + 2I_{B1} = I_{C1} + \frac{2I_{C1}}{\beta}$$

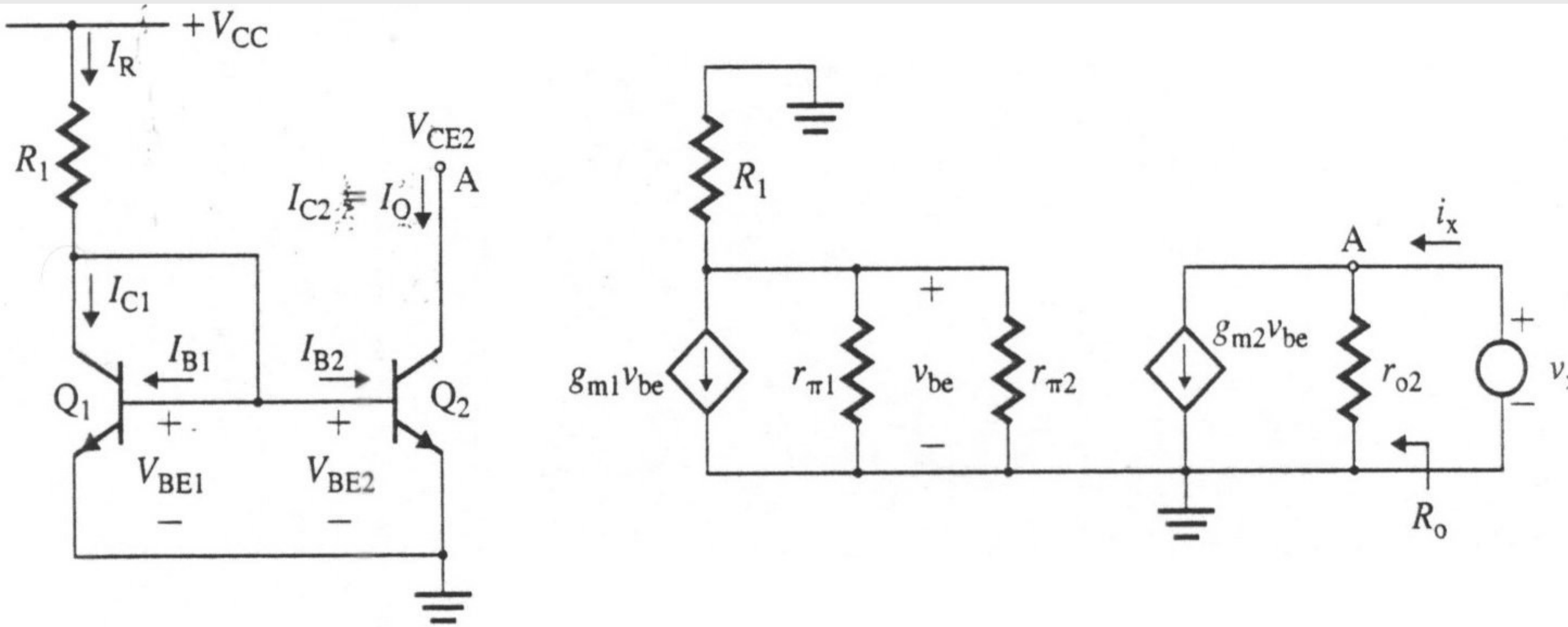
$$I_{C1} = I_{C2} = \frac{I_R}{1+\frac{2}{\beta}} = \frac{V_{CC} - V_{BE1}}{R_1} \times \frac{1}{1+\frac{2}{\beta}}$$

If the current gain $\beta >> 2$, then,

$$I_{C1} = I_{C2} \approx I_R$$

I_{C2} **is the mirror current of** I_{C1}

Basic Current Source (contd.)



- $I_C = I_S\left[\exp\frac{v_{BE}}{V_T} - 1\right]\left(1 + \frac{V_{CE}}{V_A}\right)$

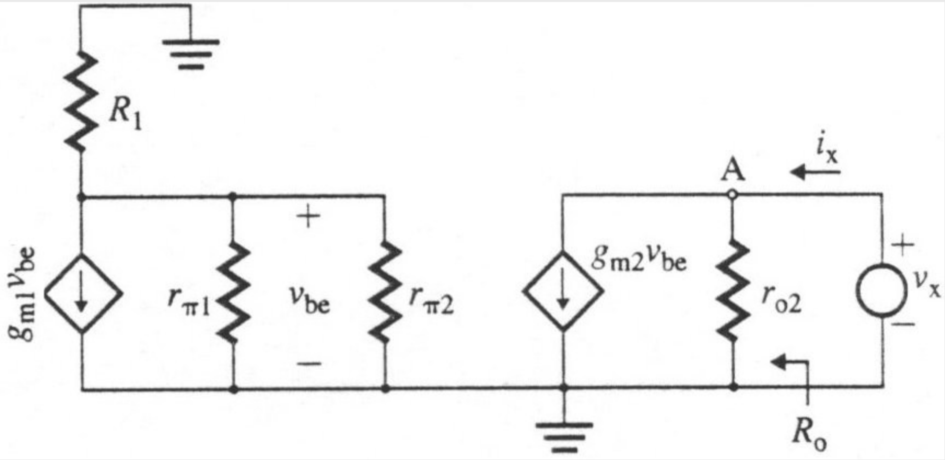
Basic Current Source

Collector current ratio:

$$\frac{I_{C2}}{I_{C1}} = \frac{1+\dfrac{V_{CE2}}{V_A}}{1+\dfrac{V_{CE1}}{V_A}}$$

Output resistance R_O**:**

$$R_O = \frac{v_x}{i_x} = r_{o2} = \frac{V_A}{I_{C2}}$$



Example 4.2.1

(a) Design the basic current source in Fig. 4.2.1 to give an output current of $I_O = 5\mu A$. The transistor parameters are $\beta = 100, V_{CC} = 30V, V_{BE1} = V_{BE2} = V_{CE1} = 0.7V$, and $V_A = 150$.

(b) Calculate the output resistance R_O, and the collector current ratio if $V_{CE2} = 20V$.

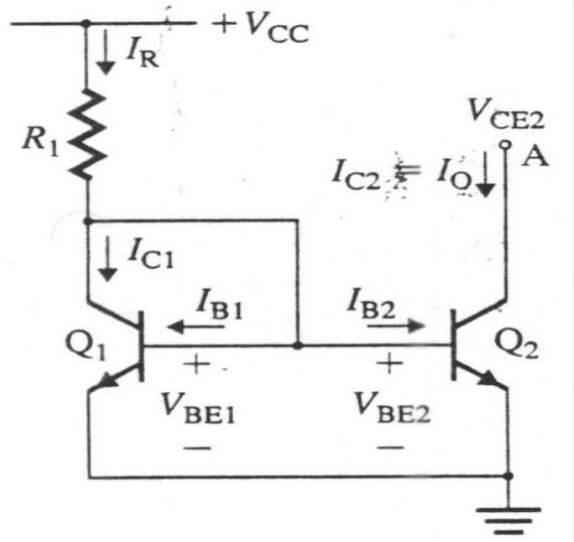
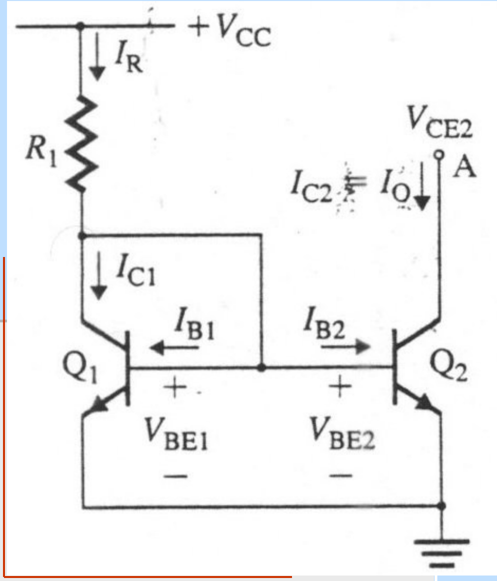


Figure 4.2.1

Example 4.2.1 (contd.)



(a)

We know,

$$I_O = I_{C1} = I_{C2} = \frac{I_R}{1+\frac{2}{\beta}}$$

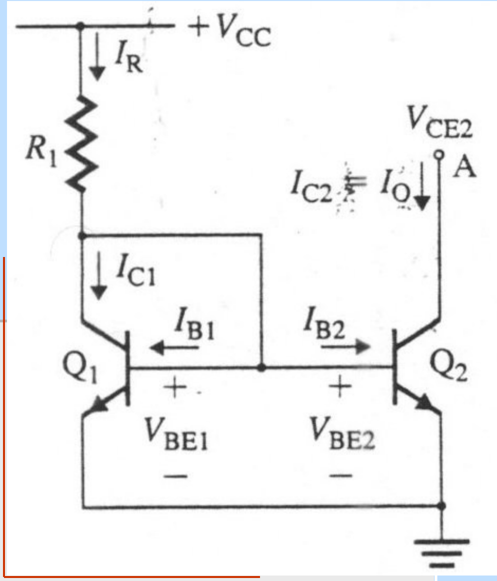
$$\Rightarrow I_R = I_O\left(1+\frac{2}{\beta}\right) = 5\mu A\left(1+\frac{2}{100}\right) = 5.1\mu A$$

Now,

$$I_R = \frac{V_{CC} - V_{BE1}}{R_1}$$

$$\Rightarrow R_1 = \frac{V_{CC} - V_{BE1}}{I_R} = \frac{30-0.7}{5.1\mu A} = 5.75M\Omega$$

Example 4.2.1 (contd.)



(b)

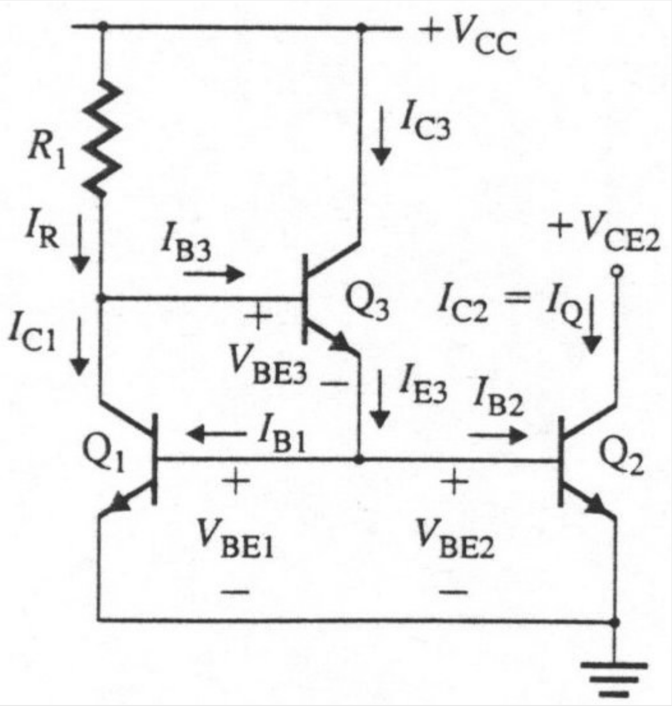
Again,

$$R_O = \frac{V_A}{I_{C2}} = \frac{150}{5\mu A} = 30M\Omega$$

The collector current ratio is,

$$\frac{I_{C2}}{I_{C1}} = \frac{1+\frac{V_{CE2}}{V_A}}{1+\frac{V_{CE1}}{V_A}} = \frac{1+\frac{20}{150}}{1+\frac{0.7}{150}} = 1.128$$

Modified Basic Current Source



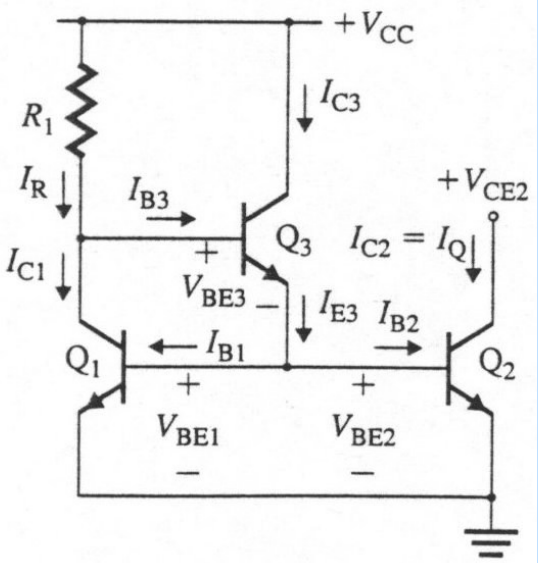
$$I_{C1} = I_{C2} = \frac{I_R}{1 + \frac{2}{\beta}}$$

Basic current source

Applying KCL at the emitter of Q_3

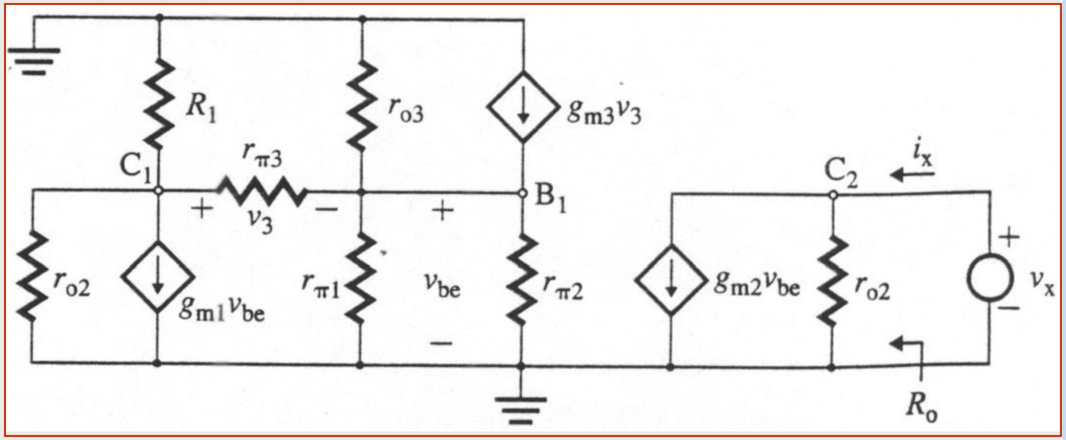
- $I_{E3} = I_{B1} + I_{B2} = \frac{I_{C1}}{\beta} + \frac{I_{C2}}{\beta} = \frac{2I_{C2}}{\beta}$
- $I_{B3} = \frac{I_{E3}}{1+\beta} = \frac{2I_{C2}}{\beta(1+\beta)}$

Modified Basic Current Source



Applying KCL at the collector of Q_1

- $I_R = I_{C1} + I_{B3} = I_{C1} + \dfrac{2I_{C2}}{\beta(1+\beta)}$
- $I_O = I_{C2} = \dfrac{I_R}{1 + \dfrac{2}{\beta^2 + \beta}}$
- $I_R = \dfrac{V_{CC} - V_{BE1} - V_{BE3}}{R_1}$



Output resistance R_O:

$$R_O = \frac{v_x}{i_x} = r_{o2} = \frac{V_A}{I_{C2}}$$

Example 4.2.2

(a) **Design the modified basic current source in Fig. 4.2.2 to give an output current of $I_O = 5\mu A$. The transistor parameters are $\beta = 100, V_{CC} = 30V$, $V_{BE1} = V_{BE2} = V_{BE3} = 0.7V$, and $V_A = 150$.**

(b) **Calculate the output resistance R_O, and the collector current ratio if $V_{CE2} = 20V$.**

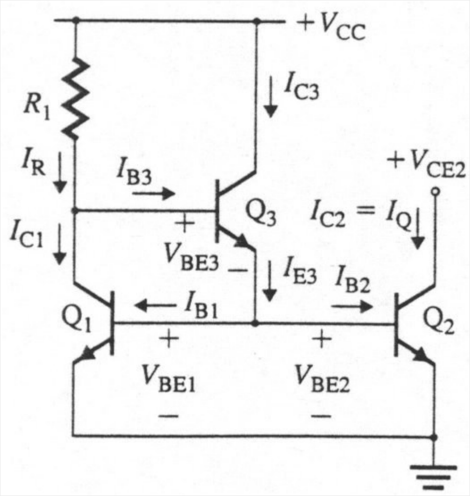
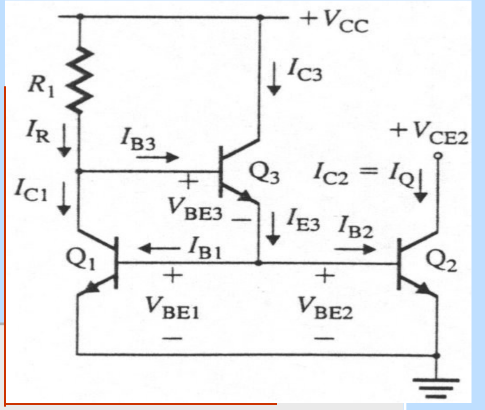


Figure 4.2.2

Example 4.2.2 (contd.)



(a)

$I_O = I_{C2} = 5\mu A,\ V_{BE1} = V_{BE2} = V_{BE3} = 0.7V,$ **and** $V_A = 150V$

The output current of modified basic current source can be given as,

$$I_O = I_{C2} = \frac{I_R}{1 + \dfrac{2}{\beta^2 + \beta}}$$

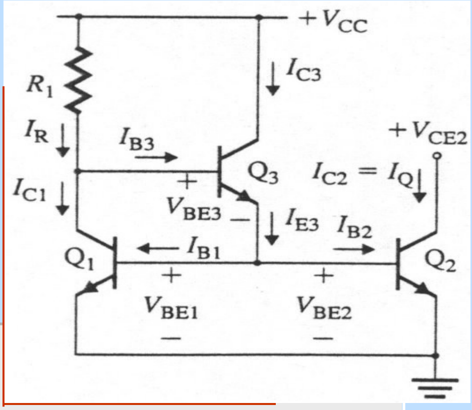
$$\Rightarrow I_R = I_O\left(1 + \frac{2}{\beta^2 + \beta}\right) = 5\mu A\left(1 + \frac{2}{100^2 + 100}\right) \approx 5\mu A$$

Now,

$$I_R = \frac{V_{CC} - V_{BE1} - V_{BE3}}{R_1}$$

$$\Rightarrow R_1 = \frac{V_{CC} - V_{BE1} - V_{BE3}}{I_R} = \frac{30 - 0.7 - 0.7}{5\mu A} = 5.72k\Omega$$

Example 4.2.2 (contd.)



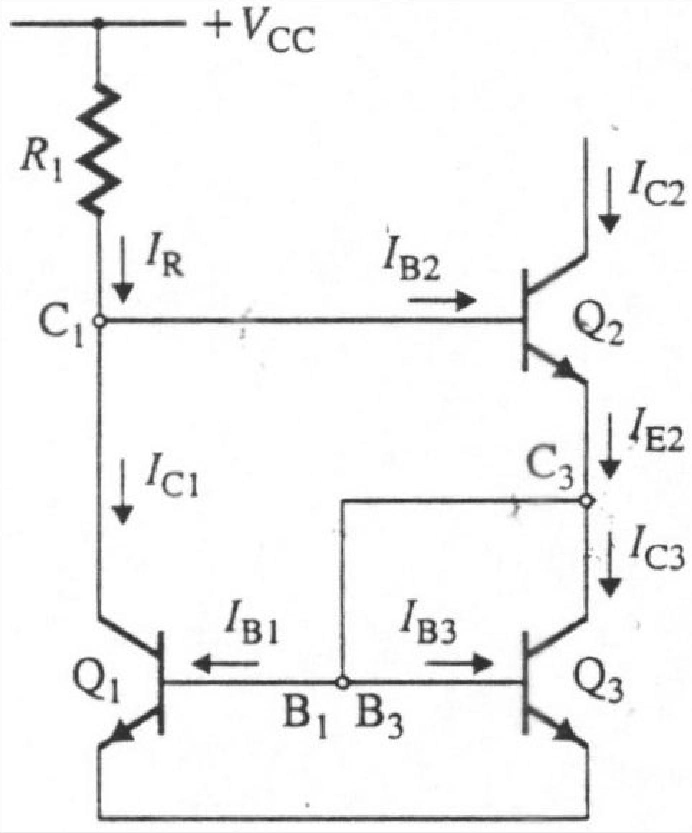
(b)
Output resistance,

$$R_O = \frac{V_A}{I_{C2}} = \frac{100}{5\mu A} = 30M\Omega$$

The ratio of two collector currents,

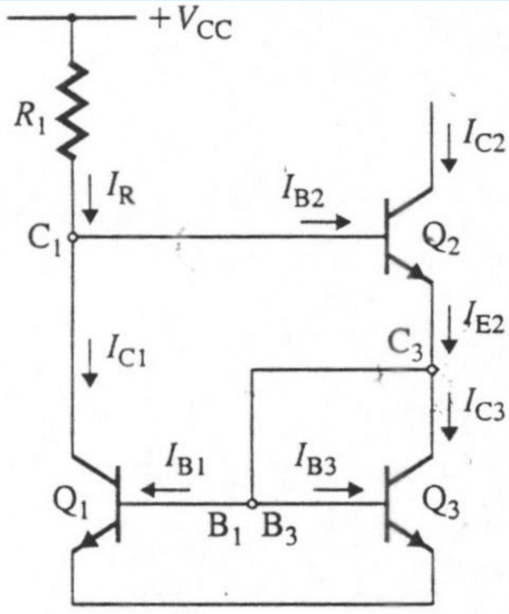
$$\frac{I_{C2}}{I_{C1}} = \frac{1+\dfrac{V_{CE2}}{V_A}}{1+\dfrac{V_{BE1}+V_{BE3}}{V_A}} = \frac{1+\dfrac{20}{150}}{1+\dfrac{0.7+0.7}{150}} = 1.123$$

Wilson Current Source



- $I_{B2} = I_R - I_{C1}$
- $I_{E2} = (1+\beta)(I_R - I_{C1})$
- $I_{C1} = I_{C3}$
- $I_{E2} \approx I_{C2}$
- $I_{C1} \approx I_{C2}$

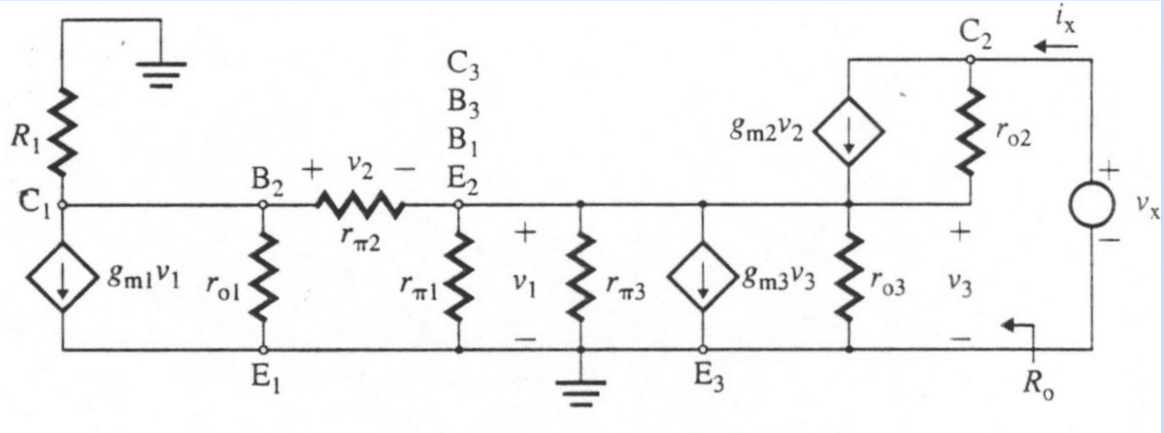
Wilson Current Source



- $I_{E2} = (1+\beta)I_{B2} = (I_R - I_{C1})(1+\beta)$

  Assume $R_O = \alpha, \quad V_A = \alpha$ **and** $I_{C1} = I_{C3}$
- $I_{E2} = I_{C3} + I_{B3} + I_{B1} = I_{C3}\left(1+\frac{1}{\beta}\right) + \frac{I_{C1}}{\beta} = I_{C3}\left(1+\frac{2}{\beta}\right)$
- $I_{C2} = I_{E2}\frac{\beta}{1+\beta} = I_{C3}\left(1+\frac{2}{\beta}\right)\frac{\beta}{1+\beta} = I_{C3}\frac{2+\beta}{1+\beta}$
- $I_{C1} = I_R - I_{B2} = I_R - \frac{I_{C2}}{\beta}$
- $I_{C1} = I_{C3} = I_{C2}\frac{1+\beta}{2+\beta} = I_R - \frac{I_{C2}}{\beta}$
- $I_O = I_{C2} = I_R\left[\frac{(2+\beta)\beta}{\beta^2+2\beta+2}\right] = I_R\left[1 - \frac{2}{\beta^2+2\beta+2}\right] \approx I_R \qquad \because \beta >> 1$

Wilson Current Source



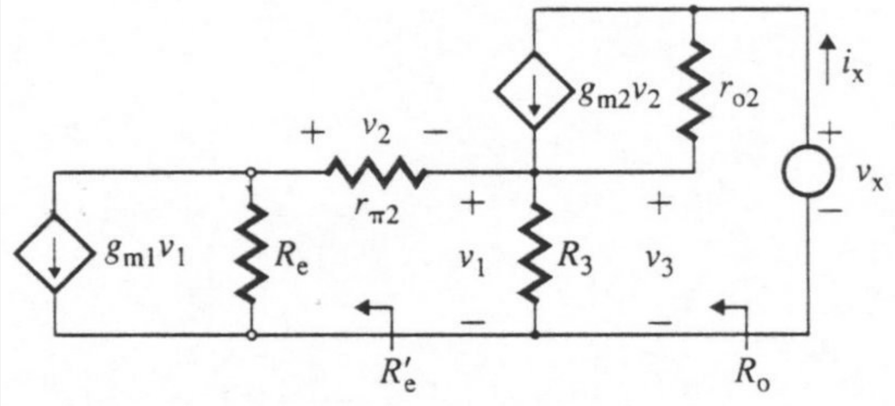
Small-signal ac equivalent circuit

Output resistance R_O:

- $R_e = r_{o1} \| R_1$
- $R_3 = r_{\pi 1} \| r_{\pi 3} \| r_{o3}$

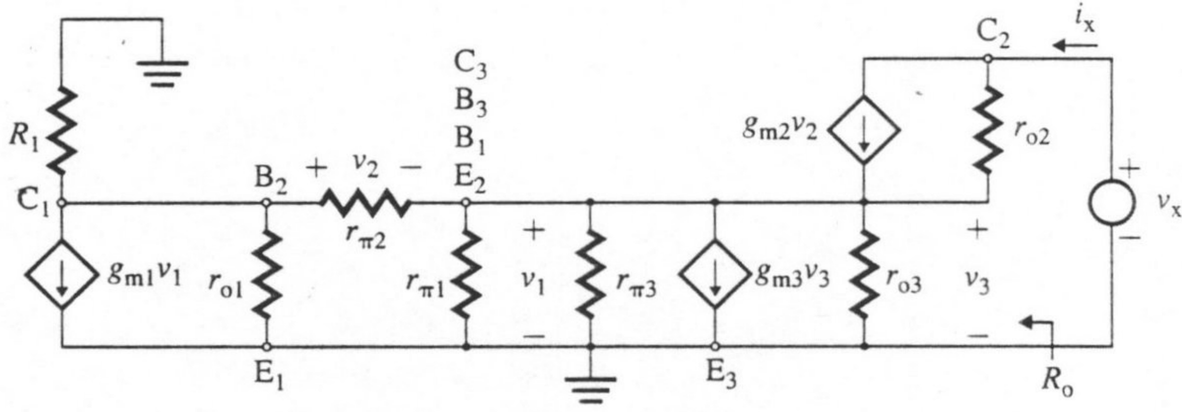
Applying KVL to the circuit left of $r_{\pi 1}$

- $v_1 = ir_{\pi 2} + (r_o \| R_1)(i - g_{m1}v_1)$
- $R_e^{'} = \dfrac{v_1}{i} = \dfrac{r_{\pi 2} + (r_{o1} \| R_1)}{1 + (r_{o1} \| R_1)g_{m1}}$
- $R_e^{'} = \dfrac{r_{\pi 2} + R_1}{1 + R_1 g_{m1}} \quad \because r_{o1} >> R_1$
- $R_e^{'} \approx \dfrac{1}{g_{m1}}$ **(For** $R_1 >> r_{\pi 2}$ **and** $g_{m1}R_1 >> 1$**)**



Equivalent circuit

Wilson Current Source

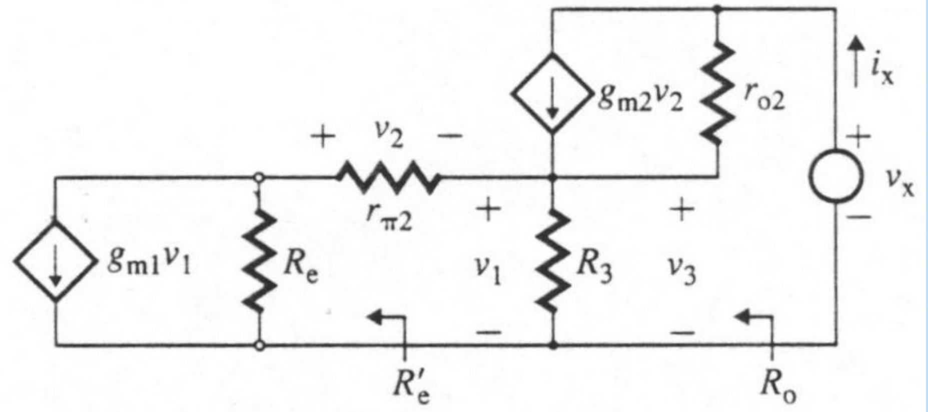


Small-signal ac equivalent circuit

- $R_O = \dfrac{v_x}{i_x} = R_3 \parallel R_e^{'} + r_{o2}\left[1 + \dfrac{g_{m2}r_{\pi 2}}{R_e^{'}} R_3 \parallel R_e^{'}\right]$
- $R_O \approx r_{o2}\left[1 + \dfrac{g_{m2}r_{\pi 2}}{R_e^{'}} R_3 \parallel R_e^{'}\right]$

Assume $\dfrac{(R_3 \parallel R_e^{'})}{R_e^{'}} = \dfrac{1}{2}$

- $R_O \approx r_{o2}\left[1 + \dfrac{g_{m2}r_{\pi 2}}{2}\right] \approx r_{o2}\left[1 + \dfrac{\beta}{2}\right]$



Equivalent circuit

Example 4.2.4

(a) **Design the Wilson current source in Fig. 4.2.4 to give an output current of** $I_O = 10\mu A$**. The transistor parameters are** $V_{CC} = 30V$, $V_{BE1} = V_{BE2} = V_{CE1} = 0.7V$, $V_T = 26mV$, $V_A = 100$ **and** $\beta = 150$**. Assume all transistors are identical.**

(b) **Calculate the output resistance** R_O.

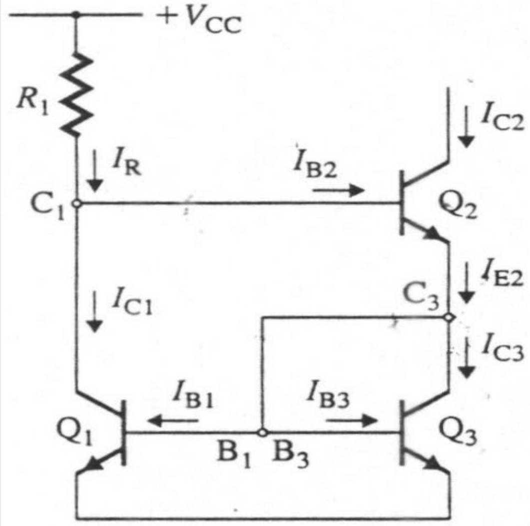
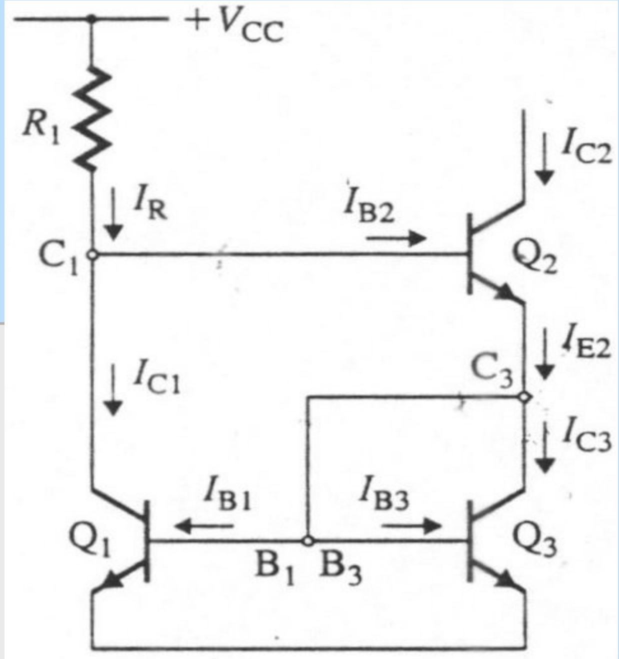


Figure 4.2.4

Example 4.2.4 (contd.)



(a)

$$I_O = I_{C2} = 10\mu A$$

The output current,

$$I_O = I_R\left[1 - \frac{2}{\beta^2 + 2\beta + 2}\right]$$

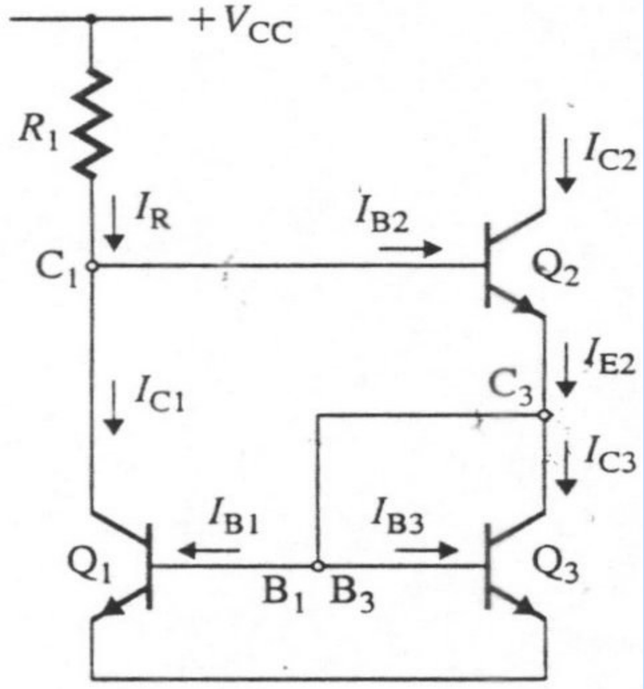
$$10\mu A = I_R\left[1 - \frac{2}{150^2 + 2\times150 + 2}\right] \Rightarrow I_R = 10\mu A$$

The reference current can be found from,

$$I_R = \frac{V_{CC} - V_{BE1} - V_{BE2}}{R_1}$$

$$\Rightarrow R_1 = \frac{V_{CC} - V_{BE1} - V_{BE2}}{I_R} = \frac{30 - 0.7 - 0.7}{10\mu A} = 2.86M\Omega$$

Example 4.2.4 (contd.)



(b)

$$I_{C1} = I_{C3} = I_{C2}\frac{1+\beta}{2+\beta} = 10\mu A\frac{1+150}{2+150} = 9.93\mu A$$

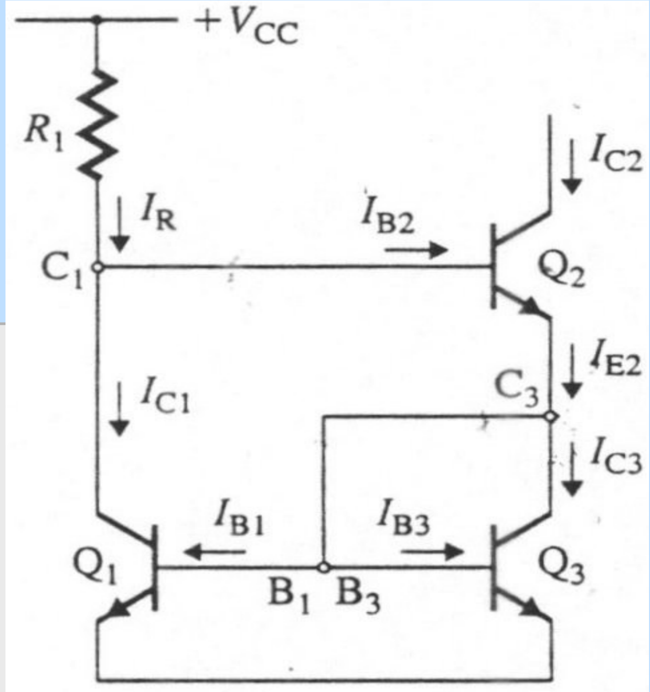
$$r_{o1} = r_{o3} = \frac{V_A}{I_{C1}} = \frac{100}{9.93\mu A} = 10.07M\Omega$$

$$r_{o2} = \frac{V_A}{I_{C2}} = \frac{100}{10\mu A} = 10M\Omega$$

$$g_{m1} = g_{m3} = \frac{I_{C1}}{V_T} = \frac{9.93\mu A}{26mV} = 381.9\,\mu A/V$$

$$g_{m2} = \frac{I_{C2}}{V_T} = \frac{10\mu A}{26mV} = 384.6\,\mu A/V$$

Example 4.2.4 (contd.)



Then,

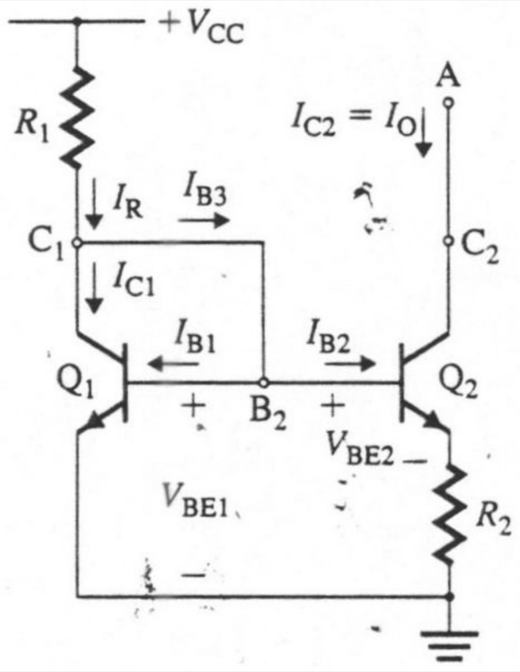
$$r_{\pi 1} = r_{\pi 3} = \frac{\beta}{g_{m1}} = \frac{150}{381.9} = 393k\Omega$$

$$r_{\pi 2} = \frac{\beta}{g_{m2}} = \frac{150}{384.6} = 390k\Omega$$

$$R_O = r_{o2}\left[1 + \frac{g_{m2} r_{\pi 2}}{2}\right] = 10M\left[1 + \frac{384.6 \times 390k}{2}\right] = 750M\Omega$$

Widlar Current Source

Widlar current source which provides biasing currents of low magnitudes, typically $5\mu A$.



- $I_{C2} \neq I_R$
- $I_{C2} << I_{C1}$ **(in** μA **range,** $R < 50k\Omega$**)**

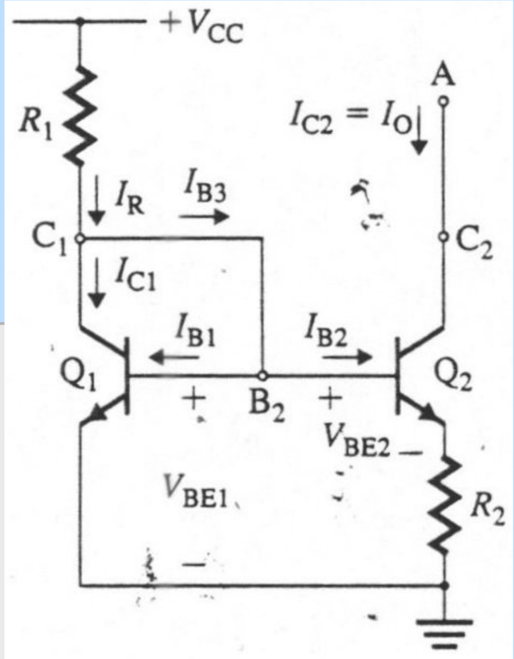
Applying KVL at the base-emitter loop

- $V_{BE1} - V_{BE2} - (I_{C2} + I_{B2})R_2 = 0$

Since $I_{C2} >> I_{B2}$

- $V_{BE1} - V_{BE2} - I_{C2}R_2 = 0$ …… **(1)**

Widlar Current Source



Assume $R_O = \alpha, \quad \therefore V_A = \alpha$

- $I_C = I_S\left[\exp\frac{v_{BE}}{V_T} - 1\right]\left(1 + \frac{V_{CE}}{V_A}\right) \approx I_S \exp\frac{v_{BE}}{V_T}$

$$\Rightarrow V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right)$$

Applying this value into eqn. (1),

- $V_T \ln\left(\frac{I_{C1}}{I_{S1}}\right) - V_T \ln\left(\frac{I_{C2}}{I_{S2}}\right) - I_{C2}R_2 = 0$

For identical transistor, i.e. $I_{S1} = I_{S2}$

- $V_T \ln\left(\frac{I_{C1}}{I_{S1}} \times \frac{I_{S2}}{I_{C2}}\right) - I_{C2}R_2 = 0$

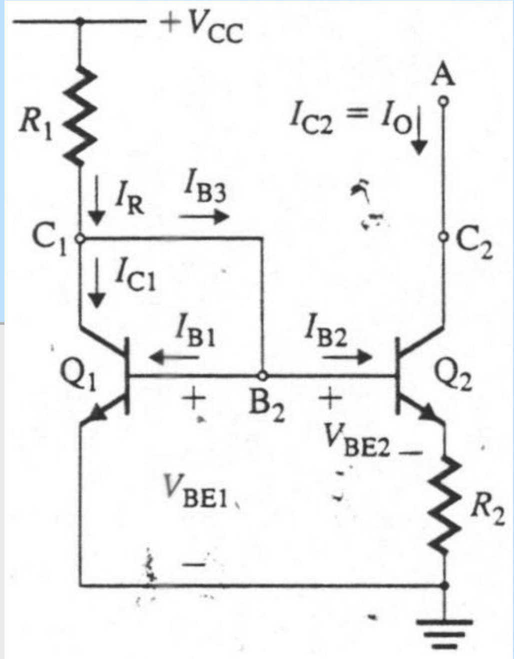
or,

- $V_T \ln\left(\frac{I_{C1}}{I_{C2}}\right) = I_{C2}R_2$

or,

- $I_{C1} = I_{C2} \exp\frac{I_{C2}R_2}{V_T}$ .. .. **(2)**

Widlar Current Source



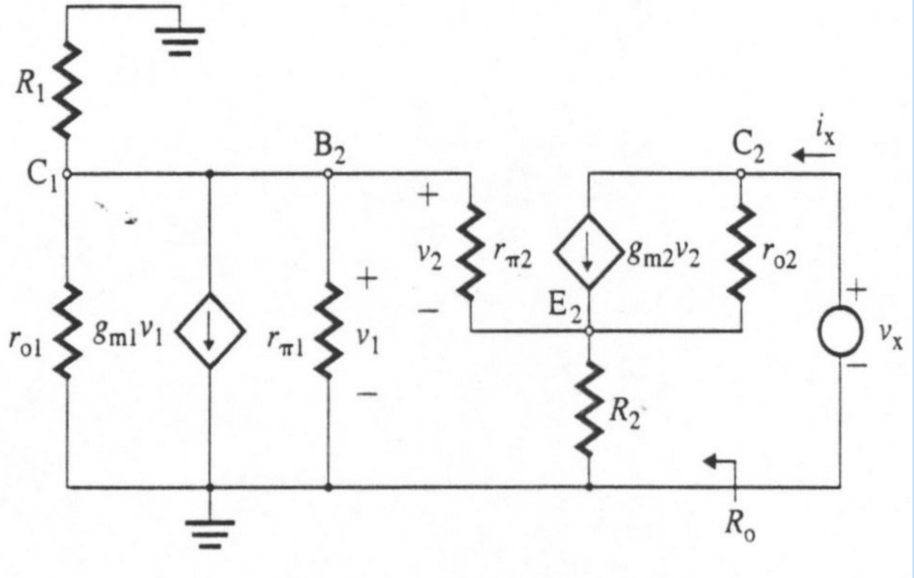
- $I_R = \dfrac{V_{CC} - V_{BE1}}{R_1}$
- $I_R = I_{C1} + I_{B1} + I_{B2} = I_{C1}\left(1 + \dfrac{1}{\beta}\right) + \dfrac{I_{C2}}{\beta}$

Putting the value of I_{C1} from eqn. (2),

- $I_R = \dfrac{1+\beta}{\beta} I_{C2} \exp \dfrac{I_{C2} R_2}{V_T} + \dfrac{I_{C2}}{\beta}$

$\Rightarrow$ I_{C2} **is nonlinear function of I_R and R_2.**

Widlar Current Source



Small-signal equivalent circuit

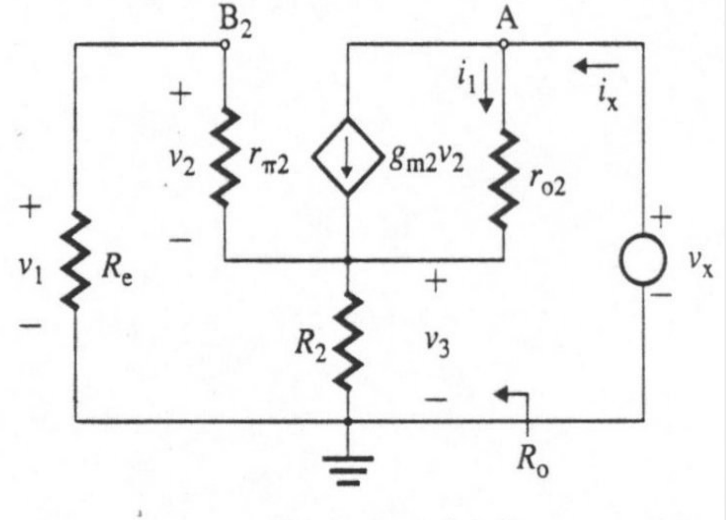
Output resistance R_O:

- $R_e = r_{\pi 1} \parallel \dfrac{1}{g_{m1}} \parallel R_1 \parallel r_{o1}$

$$g_m = \frac{\beta I_B}{V_T} = \frac{\beta}{r_\pi} \Rightarrow r_{\pi 1} = \frac{\beta}{g_{m1}}$$

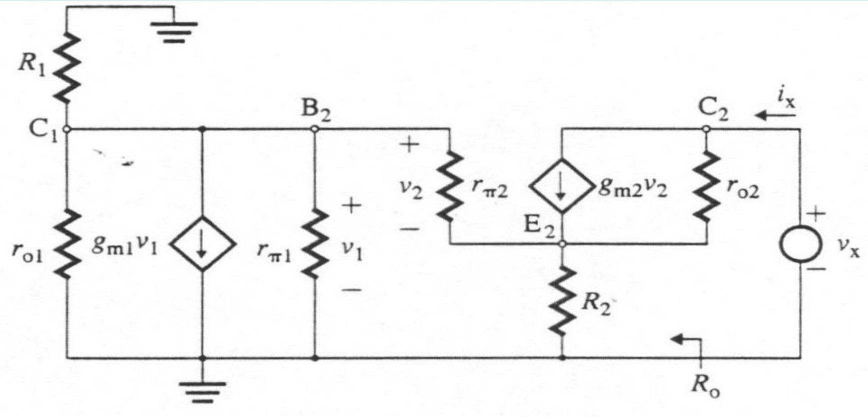
Since $\beta >> 1$, $r_{\pi 1} >> \dfrac{1}{g_{m1}}$ and $R_1 >> \dfrac{1}{g_{m1}}$

- $R_e \approx \dfrac{1}{g_{m1}}$
- $v_3 = i_x [R_2 \parallel (r_{\pi 2} + R_e)]$
- $v_2 = -\dfrac{v_3 r_{\pi 2}}{r_{\pi 2} + R_e} = -\dfrac{i_x r_{\pi 2} R_2 \parallel (r_{\pi 2} + R_e)}{r_{\pi 2} + R_e}$

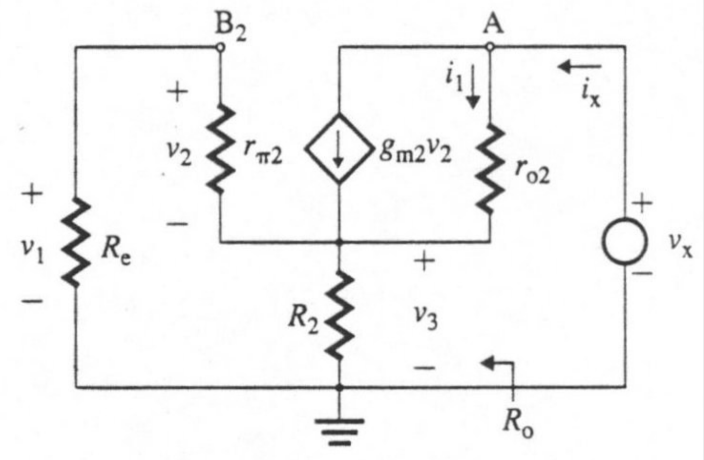


Equivalent circuit

Widlar Current Source



Small-signal equivalent circuit



Equivalent circuit

- $i_1 = i_x - g_{m2} v_2$

$$v_x = v_3 + r_{o2} i_1 = v_3 + r_{o2} i_x - r_{o2} g_{m2} v_2$$
$$= v_3 + r_{o2} i_x + \frac{r_{o2} g_{m2} v_3 r_{\pi 2}}{r_{\pi 2} + R_e}$$

Putting value of v_3

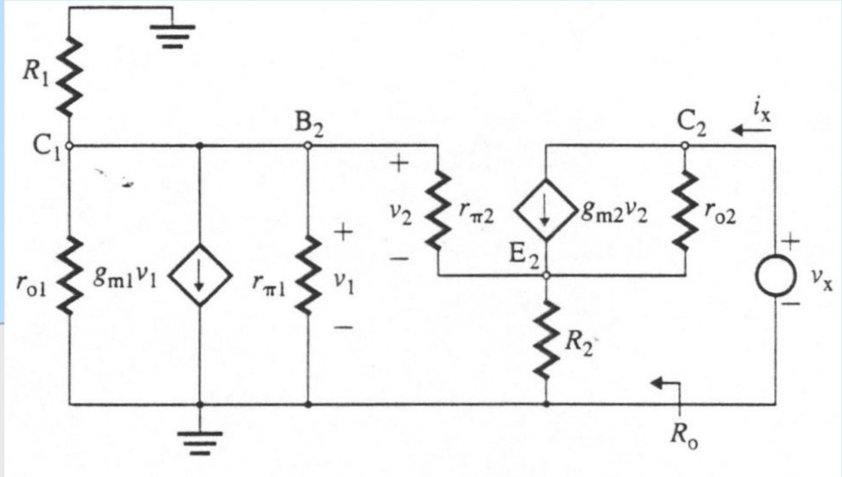
- $R_O = \dfrac{v_x}{i_x}$

$$= R_2 \| (r_{\pi 2} + R_e) + r_{o2} \left[1 + \frac{g_{m2} r_{\pi 2}}{r_{\pi 2} + R_e} R_2 \| (r_{\pi 2} + R_e) \right]$$

- $R_O \approx r_{o2} \left[1 + \dfrac{g_{m2} r_{\pi 2}}{r_{\pi 2} + R_e} R_2 \| (r_{\pi 2} + R_e) \right] \qquad \because r_{o2} >>$

Widlar Current Source

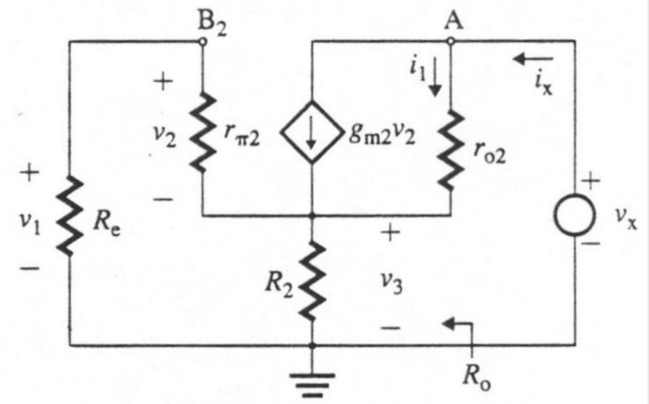
$$g_m = \frac{I_C}{V_T} = \frac{\beta I_B}{V_T} = \frac{\beta}{r_\pi} \quad \Rightarrow \quad \frac{1}{g_{m1}} = \frac{V_T}{I_{C1}}$$



Small-signal equivalent circuit

- $r_{\pi2} = \dfrac{\beta}{g_{m2}} = V_T \dfrac{\beta}{I_{C2}} = \beta \dfrac{V_T}{I_{C1}} \times \dfrac{I_{C1}}{I_{C2}} = \dfrac{\beta}{g_{m1}} \times \dfrac{I_{C1}}{I_{C2}}$

$I_{C1} >> I_{C2}$, $r_{\pi2} >> \dfrac{1}{g_{m1}}$ **and** $r_{\pi2} >> R_e$



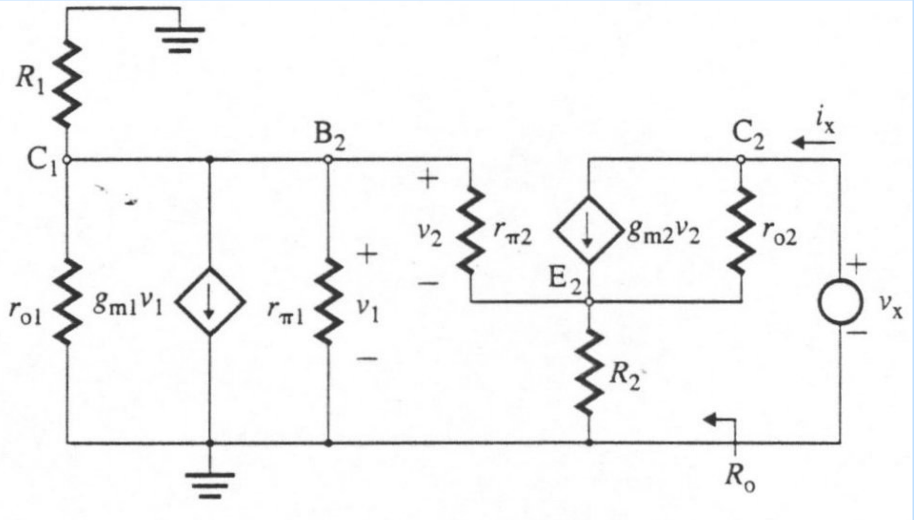
Equivalent circuit

- $R_e + r_{\pi2} \approx r_{\pi2}$
- $R_O \approx r_{o2}[1 + g_{m2}(R_2 \| r_{\pi2})]$

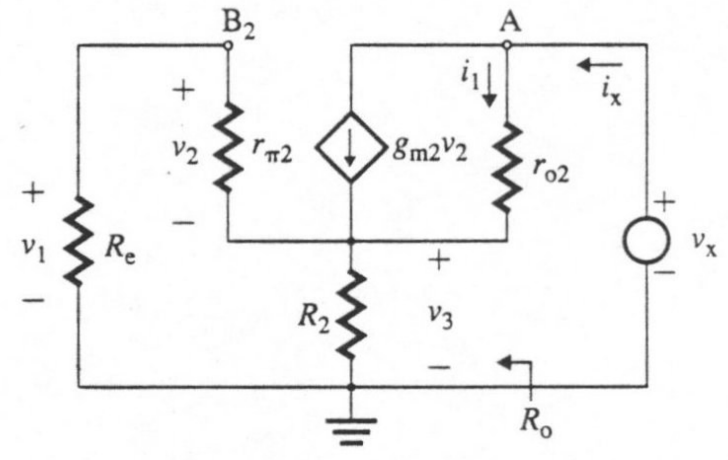
$\beta >> 1$ **and** $r_{\pi2} = \dfrac{\beta}{g_{m2}}$

- $$R_O = r_{o2} \frac{g_{m2}R_2(1+\beta)+\beta}{g_{m2}R_2+\beta} = r_{o2}\left[\frac{1+g_{m2}R_2}{1+\dfrac{g_{m2}R_2}{\beta}}\right]$$

Widlar Current Source



Small-signal equivalent circuit



Equivalent circuit

$$\beta >> g_{m2}R_2$$

- $R_O \approx r_{o2}(1+g_{m2}R_2) \approx r_{o2}\left(1+\frac{I_{C2}R_2}{V_T}\right)$

$\Rightarrow$ R_O **depends on** $I_{C2}R_2$**, i.e. the dc voltage drop across** R_2**.**

Example 4.2.3

(a) Design the Widlar current source in Fig. 4.2.3 to give an output current of $I_O = 5\mu A$ and $I_R = 1mA$. The transistor parameters are $V_{CC} = 30V$, $V_{BE1} = 0.7V$, $V_T = 26mV$, $V_A = 150$ and $\beta = 100$.

(b) Calculate the output resistance R_O. Assume $V_T = 26mV$.

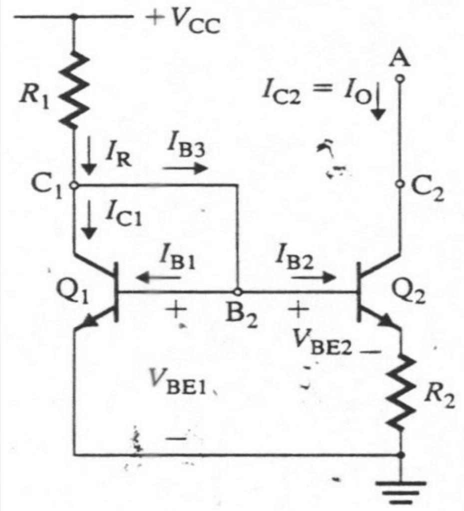
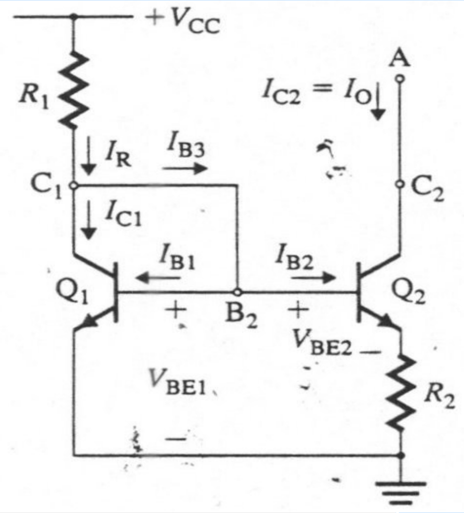


Figure 4.2.3

Example 4.2.3 (contd.)



We know,

$$I_R = \frac{V_{CC} - V_{BE1}}{R_1}$$

$$R_1 = \frac{V_{CC} - V_{BE1}}{I_R} = \frac{30 - 0.7}{1mA} = 29.3k\Omega$$

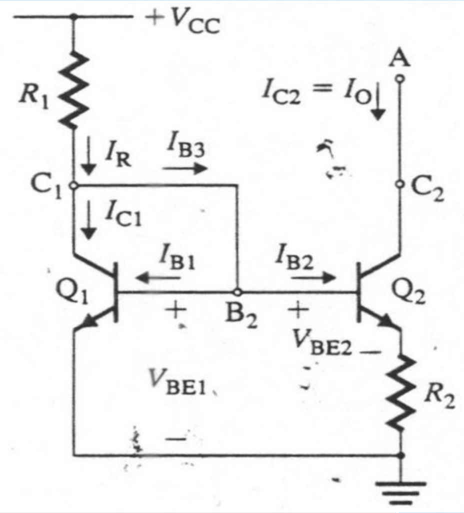
We know,

$$I_R = I_{C1}\left(1 + \frac{1}{\beta}\right) + \frac{I_{C2}}{\beta} \Rightarrow 1mA = I_{C1}\left(1 + \frac{1}{100}\right) + \frac{5\mu A}{100} \Rightarrow I_{C1} = 990\mu A$$

Again,

$$V_T \ln\left(\frac{I_{C1}}{I_{C2}}\right) = I_{C2}R_2 \Rightarrow 26mV \ln\left(\frac{990\mu A}{5\mu A}\right) = 5\mu A \times R_2 \Rightarrow R_2 = 27.5k\Omega$$

Example 4.2.3 (contd.)



Since,

$$r_{o2} = \frac{V_A}{I_{C2}} = \frac{150}{5\mu A} = 30M\Omega, \quad r_{\pi 2} = \frac{V_T \beta}{I_{C2}} = \frac{26mV \times 100}{5\mu A} = 520k\Omega$$

and,

$$g_{m2} = \frac{I_{C2}}{V_T} = \frac{5\mu A}{26mV} = 192.3\,\mu A/V$$

Therefore, the output resistance,

$$R_O \approx r_{o2}\left[1 + g_{m2}(R_2 \parallel r_{\pi 2})\right] = 30M\Omega[1 + 192.3\,\mu A/V(27.5k\Omega \parallel 520k\Omega)]$$

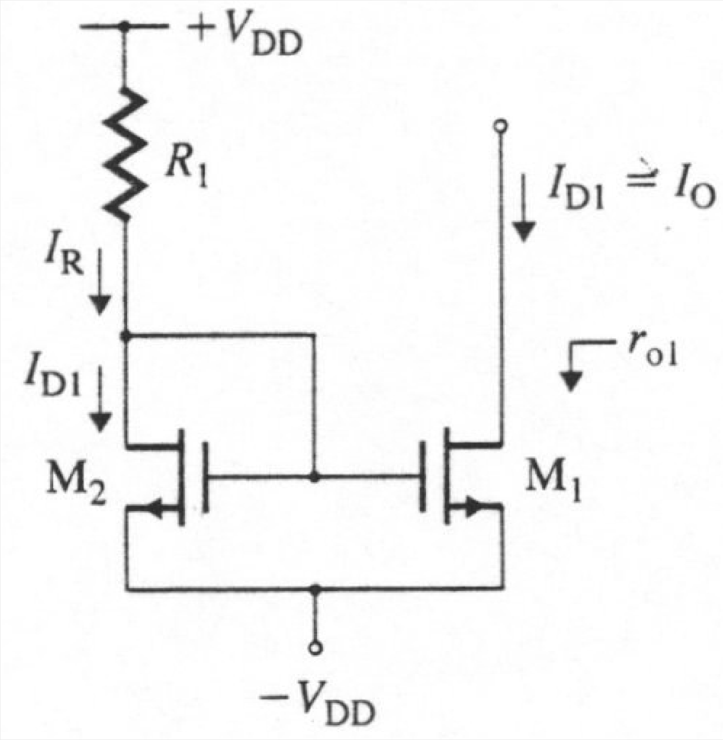
$$= 180.68M\Omega$$

FET Current Sources

MOSFET Current Source

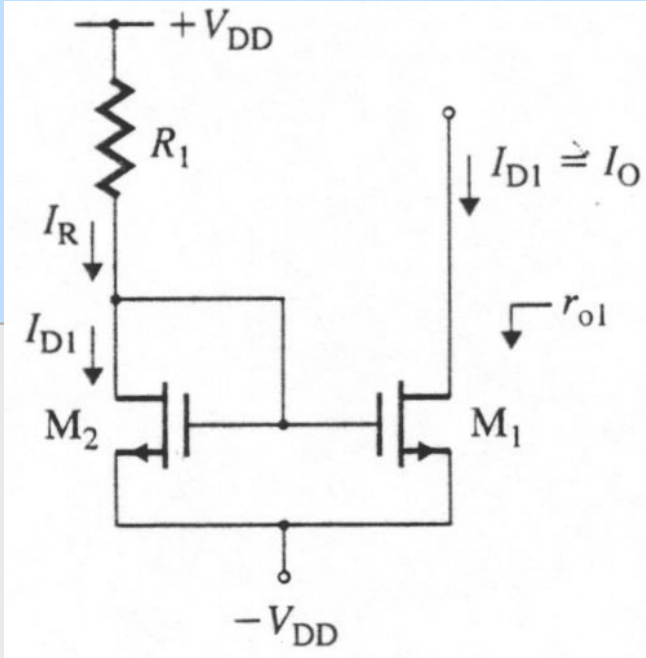
MOSFET current sources are analogous to BJT current sources. We can convert a BJT current source to an equivalent MOSFET current source by assuming that the β of the BJTs is finite. Since MOSFETs do not draw any gate current, there is no need for base current compensation as there is with BJTs. The choice of a BJT source or a MOSFET source generally depends on the type of integrated circuit involved (e.g., bipolar or MOS). BJT sources have some advantages over MOSFET sources, such as a wider compliance range and a higher output resistance. However, a higher output resistance can be obtained by cascode-like connections of MOSFETs.

Basic Current Source



- Assume M_1 and M_2 are identical.
  - $I_{D1} = I_{D2} \quad \because V_{GS1} = V_{GS2}$
- Thus, $I_O (= I_{D1})$ will be the mirror of I_{D2}
- M_2 will be in saturation $\because V_{DS2} = V_{GS2}$
- M_1 will be in saturation for $(V_{GS2} - V_{t2}) \leq V_{DS1} > (V_{GS1} - V_{t1})$

Basic Current Source (contd.)



$$I_D = \frac{1}{2}\frac{WK_x}{L}(V_{GS} - V_t)^2(1 + \lambda V_{DS})$$

$$= K_P(V_{GS} - V_t)^2\left(1 + \frac{V_{DS}}{V_M}\right)$$

where V_t = threshold voltage

W = width of the channel, typically $10\mu m - 500\mu m$

L = length of the channel, typically $10\mu m - 500\mu m$

λ = channel modulation length, typically $0.01V^{-1}$

$V_M = \frac{1}{\lambda}$ = channel modulation voltage, in V

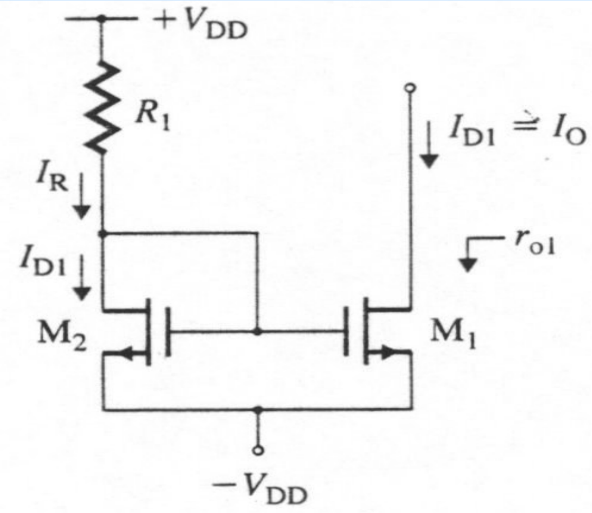
$K_x = \mu_x C_{ox}$ = channel constant, typically $20\mu A/V^2$

μ_x = mobility of electrons, typically $500cm^2/V$

C_{ox} = capacitance per unit area, typically $3.5\times10^{-4}\ pF/\mu m^2$

K_P is a constant given by, $K_P = \frac{1}{2}\frac{WK_x}{L}$

Basic Current Source (contd.)



- $I_{D1} = I_O = K_{P1}(V_{GS1} - V_{t1})^2(1+\lambda V_{DS1})$
- $I_{D2} = I_R = K_{P2}(V_{GS2} - V_{t2})^2(1+\lambda V_{DS2})$

As all the components of the current source are processed on the same integrated circuit, therefore K_x and V_t are identical for both devices, thus, the ratio of I_O to I_R is given by

- $$\frac{I_O}{I_R} = \frac{K_{P1}(1+\lambda V_{DS1})}{K_{P2}(1+\lambda V_{DS2})} = \frac{(W/L)_1}{W/L)_2} \times \frac{(1+\lambda V_{DS1})}{(1+\lambda V_{DS2})} = \frac{(W/L)_1}{W/L)_2} \quad \because \lambda V_{DS} << 1$$

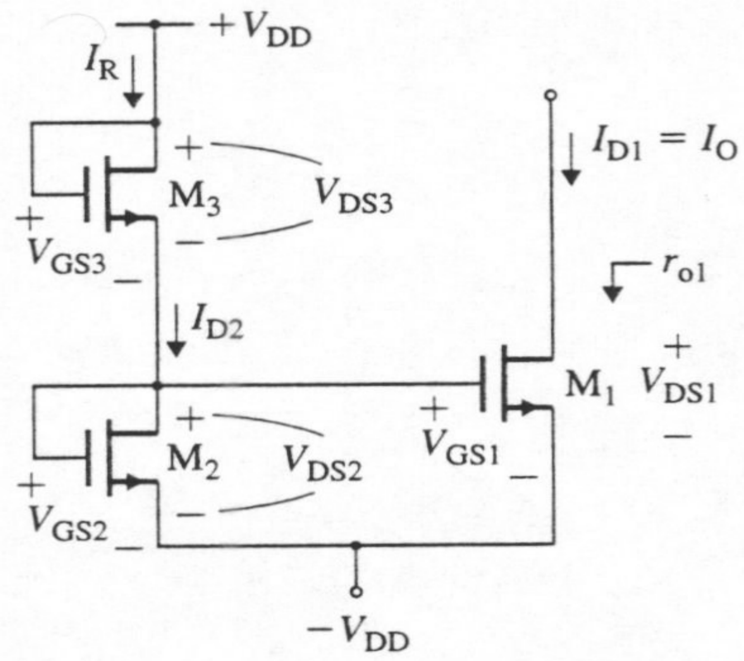
We can change I_O by controlling W/L. L is usually fixed, W varies from device to device to give the desired current ratio I_O/I_R. With $W_1 = W_2$ and $L_1 = L_2$ one can ensure that $I_O = I_R$.

Since $V_{GS2} = V_{DD} - R_1 I_R$ and $V_{DS2} = V_{GS2}$

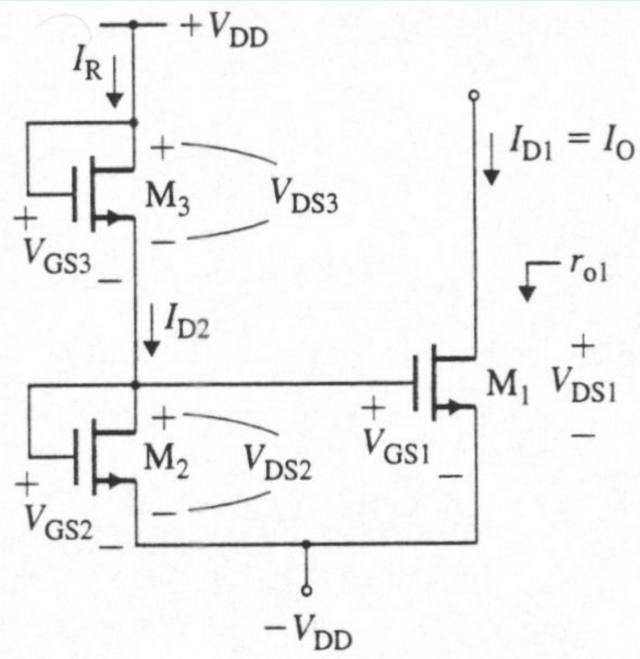
- $I_R = I_{D2} = K_{P2}(V_{DD} - R_1 I_R - V_{t2})^2$

Basic Current Source (contd.)

Transistors M_2 and M_3 are used as voltage dividers to control the gate-source voltage of transistor M_1. If M_1 and M_2 are identical, the output current I_O exactly mirrors the drain current through M_2 and M_3. The value of V_{GS1} should be made as low as possible without taking M_1 out of the saturation region.



Basic Current Source (contd.)



Since $V_{DS2} = V_{GS2}$,

$$I_{D2} = I_R = K_{P2}(V_{GS2} - V_{t2})^2(1 + \lambda V_{GS2})$$

Since $V_{GS3} = V_{DD} - V_{GS2}$,

$$I_{D3} = I_R = K_{P3}(V_{GS3} - V_{t3})^2(1 + \lambda V_{DS3})$$

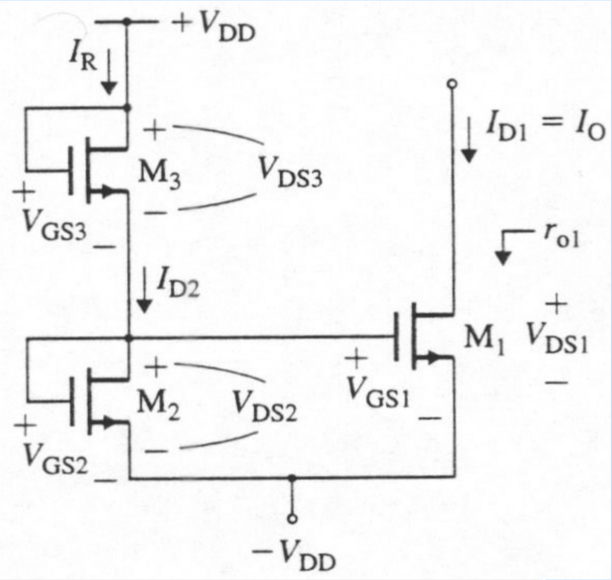
$$= K_{P3}(V_{DD} - V_{GS2} - V_{t3})^2[1 + \lambda(V_{DD} - V_{GS2})]$$

Since $I_{D2} = I_{D3} = I_R$,

$$\frac{K_{P2}(V_{GS2} - V_{t2})^2(1 + \lambda V_{GS2})}{K_{P3}(V_{DD} - V_{GS2} - V_{t3})^2[1 + \lambda(V_{DD} - V_{GS2})]} = 1$$

Thus, by controlling the constants K_{P2} and K_{P3}, we can obtain the desired value of $V_{GS2} = V_{GS1}$.

Basic Current Source (contd.)



Output Resistance R_O:

The small-signal drain-source resistance r_{ds1} can be derived from the equation,

$$I_D = \frac{1}{2}\frac{WK_x}{L}(V_{GS} - V_t)^2(1 + \lambda V_{DS}) = K_P(V_{GS} - V_t)^2(1 + \frac{V_{DS}}{V_M})$$

$$\Rightarrow \frac{1}{r_{ds1}} = \frac{\delta i_{D1}}{\delta v_{DS1}} = \frac{K_{P1}}{V_M}(V_{GS} - V_t)^2 \approx \frac{I_{D1}}{V_M}$$

Thus, the small-signal output resistance of the current source becomes

$$R_O = r_{ds1} = \frac{V_M}{I_{D1}} = \frac{1}{\lambda I_{D1}}$$

which is relatively small. This small output resistance is a disadvantage of having only one MOSFET M_1 at the output side of a current source.