Feedback
Voltage & Transconductance Amplifiers

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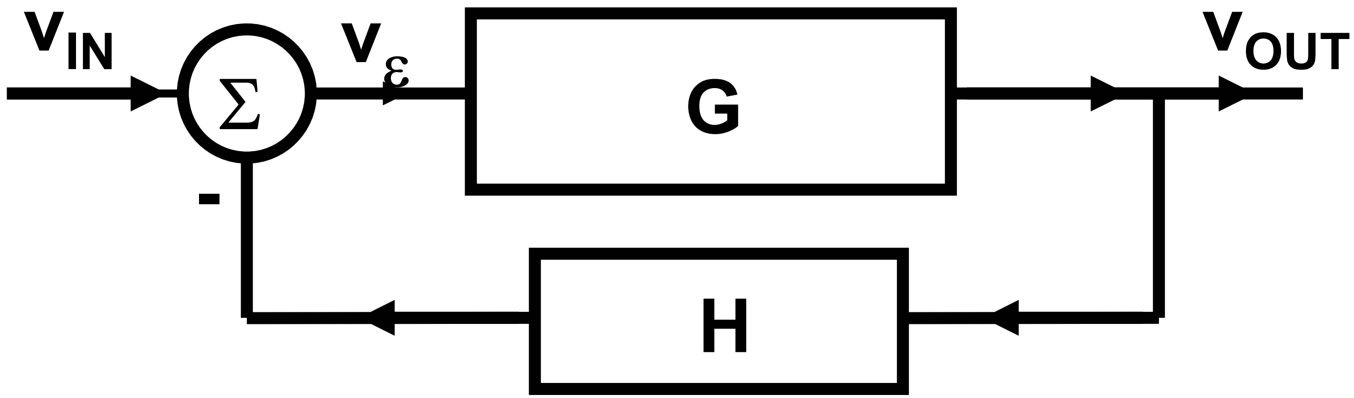
Ideal feedback

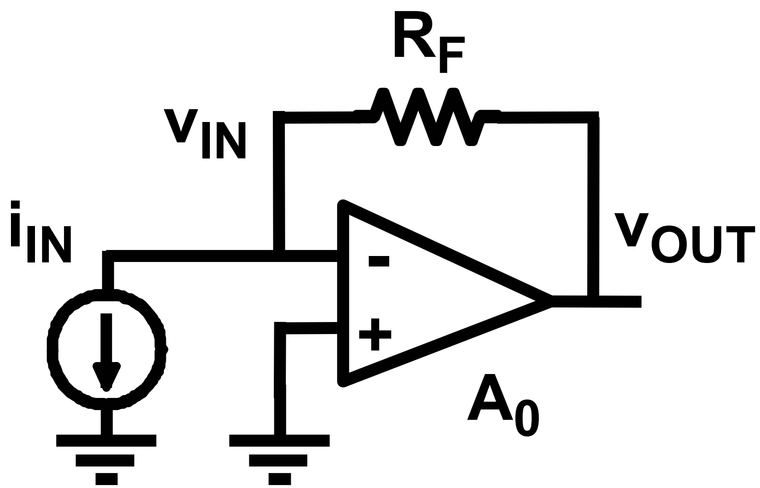


$$\left.\begin{array}{l} v_\varepsilon = v_{IN} - H\, v_{OUT} \\ v_{OUT} = G\, v_\varepsilon \end{array}\right\} \quad \frac{v_{OUT}}{v_{IN}} = \frac{G}{1 + GH} \approx \frac{1}{H}$$

if the loop gain LG = GH >> 1

Gray, Hurst, Lewis, Meyer: Design of analog integrated circuits, Wiley 2001

Shunt-shunt feedback configurations



$$LG = \frac{v_{OUT}}{v_{IN}} = A_{vOL} = A_0$$

$$A_0 \approx 10^4 \ldots 10^6$$

OL Open Loop

$$A_R = R_F$$

$$R_{IN} \approx 0$$

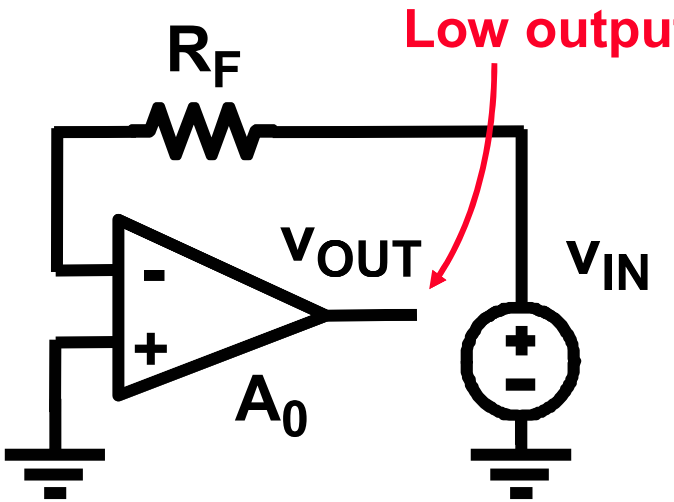
Input shunt : $R_{IN} = \dfrac{R_{INOL}}{1+LG}$

IN : shunt FB : $R_{IN} \Downarrow$

OUT : shunt FB : $R_{OUT} \Downarrow$

Output shunt : $R_{OUT} = \dfrac{R_{OUTOL}}{1+LG}$

Calculation loop gain or return ratio



$$LG = \frac{v_{OUT}}{v_{IN}} = A_{vOL} = A_0$$

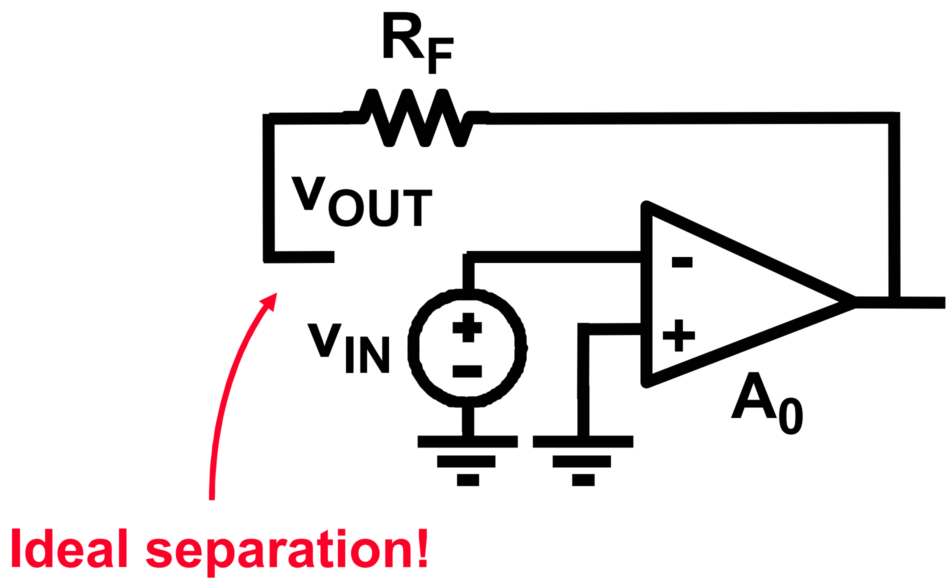
$$A_0 \approx 10^4 \ldots 10^6$$

OL Open Loop

Independent sources : voltage source to zero
current source to infinity

Break loop where impedances are very different
Find the loop gain = return ratio

Calculation loop gain - alternate

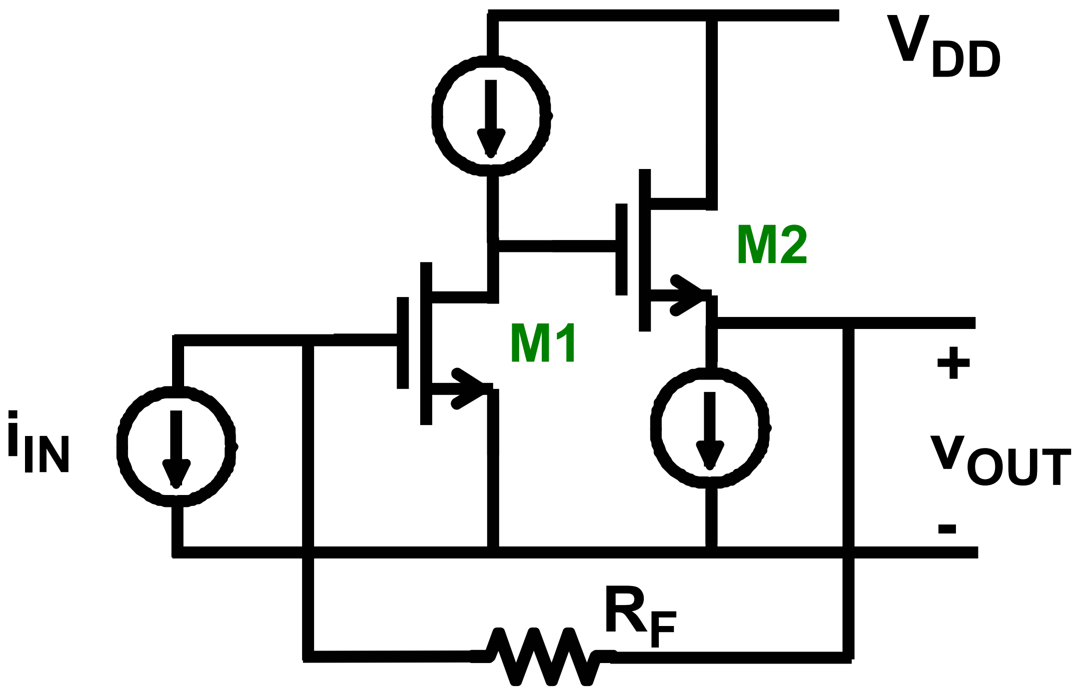


$$LG = \frac{v_{OUT}}{v_{IN}} = A_{vOL} = A_0$$

$$A_0 \approx 10^4 \ldots 10^6$$

OL Open Loop

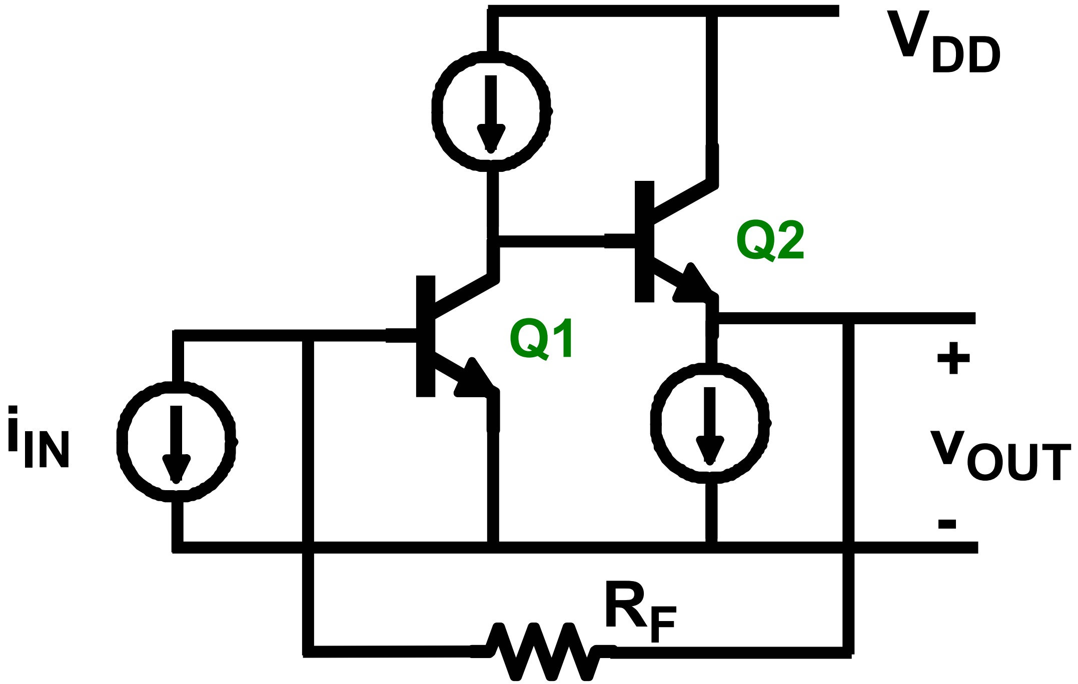
Shunt-shunt FB pair in CMOS



$$A_R = R_F$$

$$LG = g_{m1} r_{o1}$$

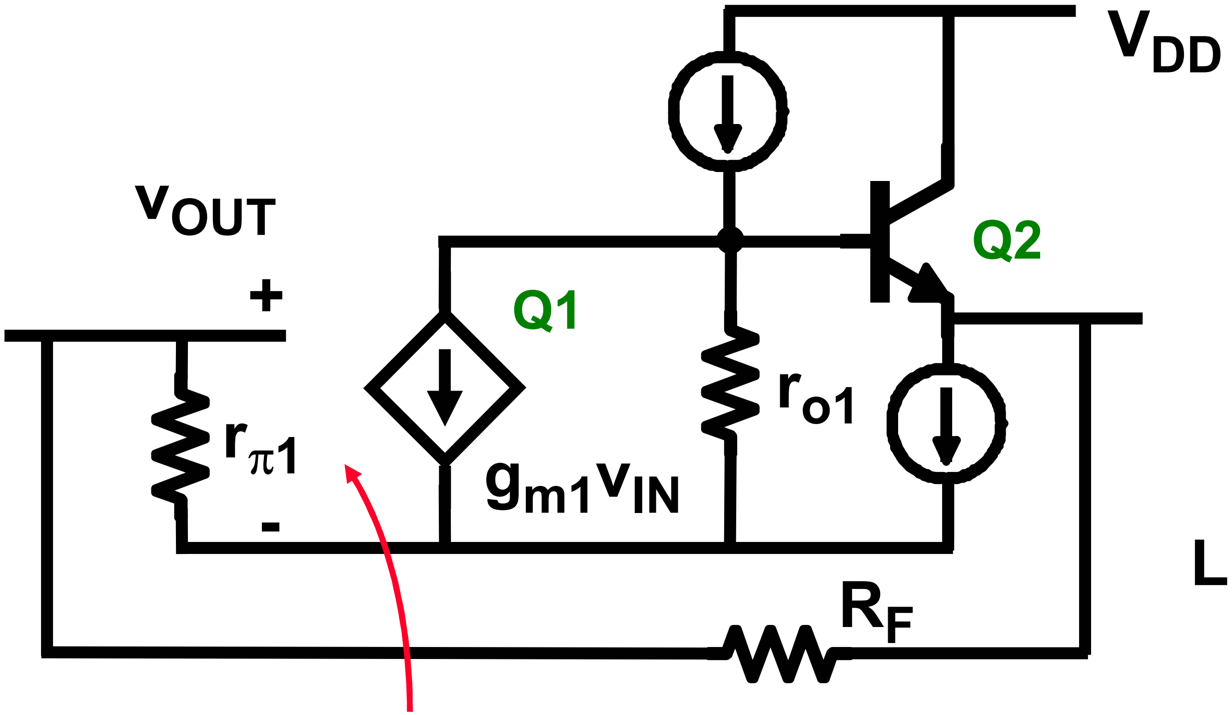
Shunt-shunt FB pair in bipolar



$$A_R = R_F$$

$$LG = g_{m1} r_{o1} \frac{r_{\pi 1}}{R_F + r_{\pi 1}}$$

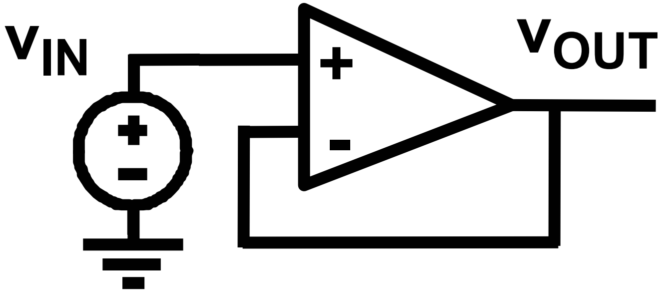
Loop gain or return ratio

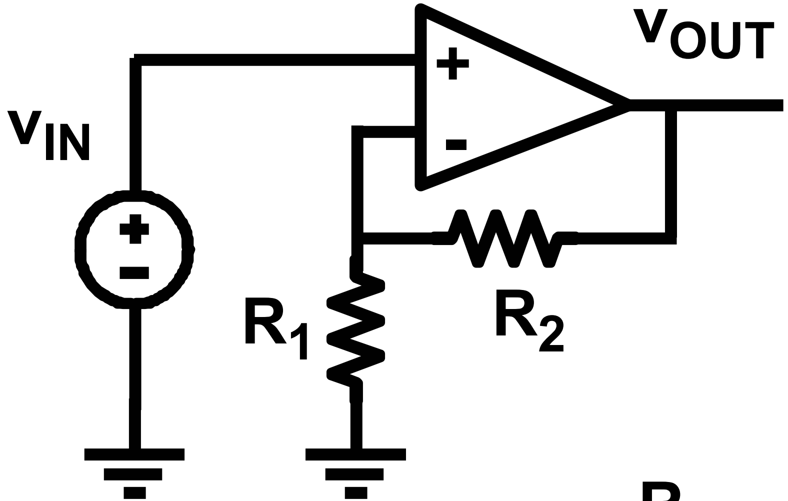


Ideal separation!

$$LG = g_{m1} r_{o1} \frac{r_{\pi 1}}{R_F + r_{\pi 1}}$$

Series-shunt feedback configurations





$$A_v = 1$$

$$R_{IN} = \infty$$

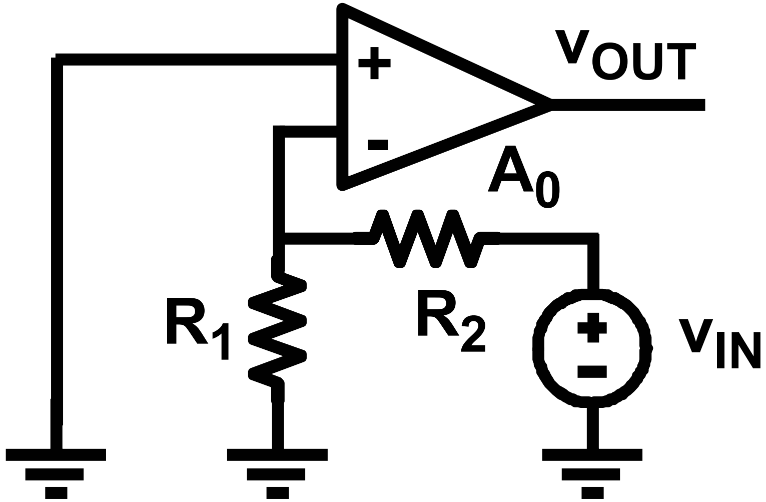
$$A_v = 1 + \frac{R_2}{R_1}$$

$$R_{IN} = \infty$$

IN : series FB : $R_{IN} \Uparrow$
OUT : shunt FB : $R_{OUT} \Downarrow$

IN : series FB : $R_{IN} \Uparrow$
OUT : shunt FB : $R_{OUT} \Downarrow$

Calculation loop gain



$$LG = \frac{v_{OUT}}{v_{IN}} = \frac{R_1}{R_1 + R_2} A_{vOL}$$

$$A_{vOL} \approx A_0 \approx 10^4 \ldots 10^6$$

OL Open Loop

$$A_v = 1 + \frac{R_2}{R_1}$$

$$R_{IN} \approx \infty$$

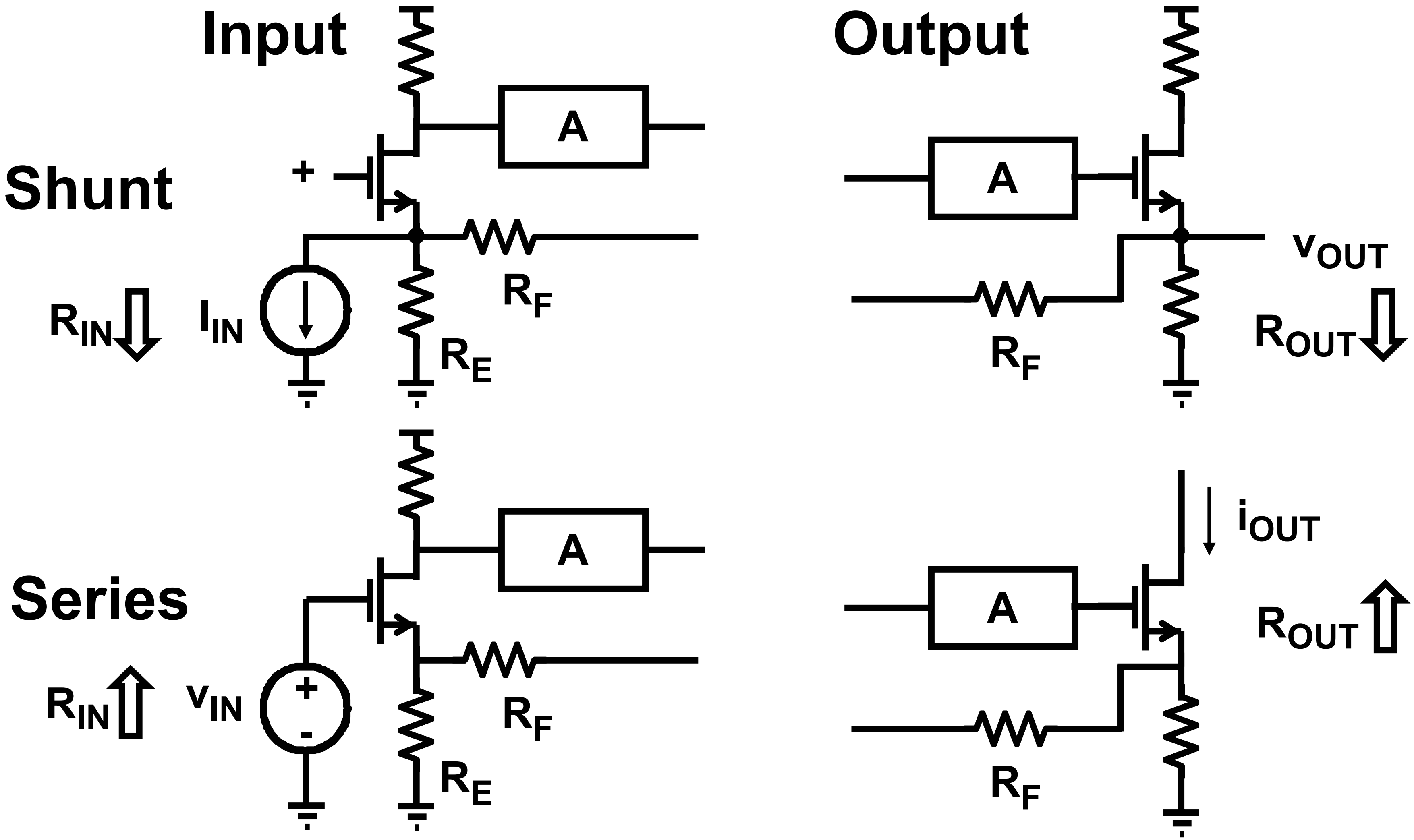
IN : series FB : $R_{IN} \Uparrow$

OUT : shunt FB : $R_{OUT} \Downarrow$

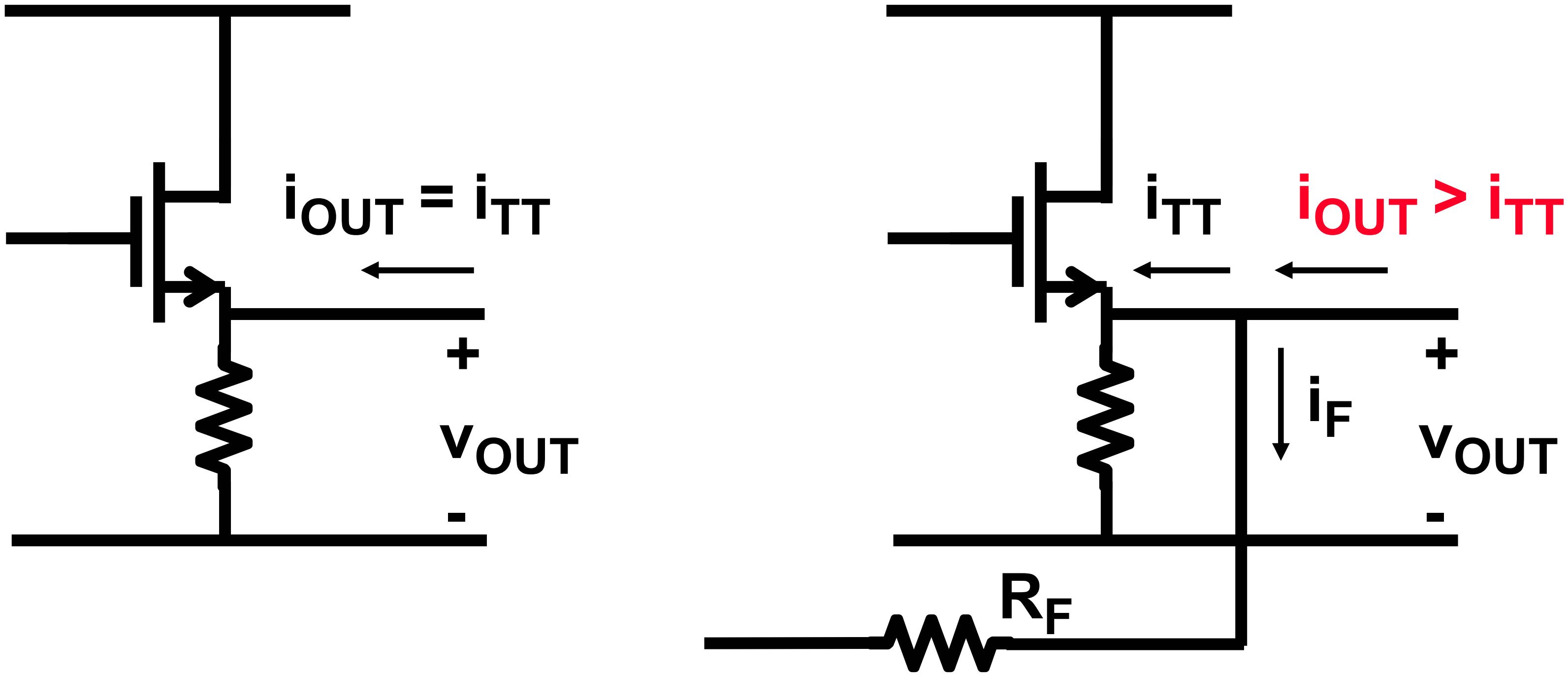
Input series : $R_{IN} = R_{INOL}\,(1+LG)$

Output shunt : $R_{OUT} = \dfrac{R_{OUTOL}}{1+LG}$

Shunt & series at input & output

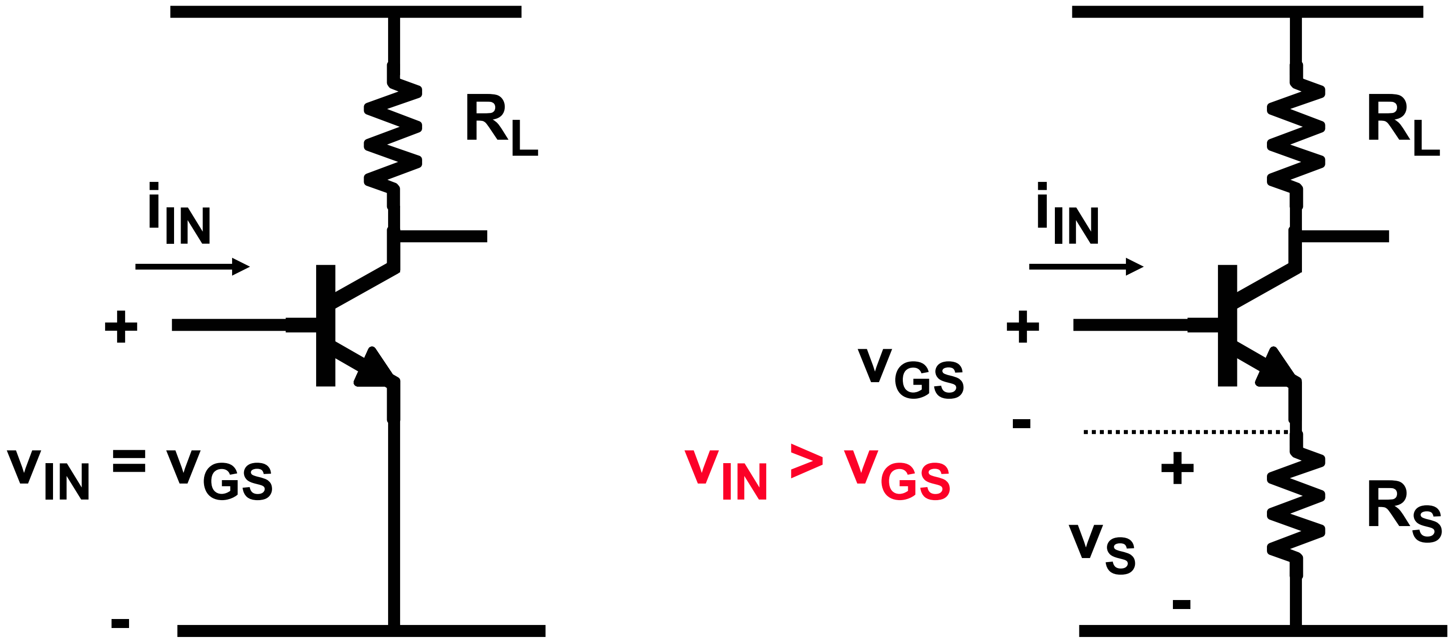


Shunt FB decreases the impedance



$$R_{OUT} = \frac{v_{OUT}}{i_{OUT}} \Downarrow$$

Series FB increases the impedance



$$R_{IN} = \frac{v_{IN}}{i_{IN}}$$

Input- & output impedances

$\frac{1}{H} =$ Output / Input		Shunt	Series
		$R_{OUT} = \frac{R_{OUTOL}}{1+LG}$	$R_{OUT} = R_{OUTOL}(1+LG)$
Shunt	$R_{IN} = \frac{R_{INOL}}{1+LG}$	$\frac{v_{OUT}}{i_{IN}} = A_R$	$\frac{i_{OUT}}{i_{IN}} = A_I$
Series	$R_{IN} = R_{INOL}(1+LG)$	$\frac{v_{OUT}}{v_{IN}} = A_V$	$\frac{i_{OUT}}{v_{IN}} = A_G$

Shunt vs series feedback

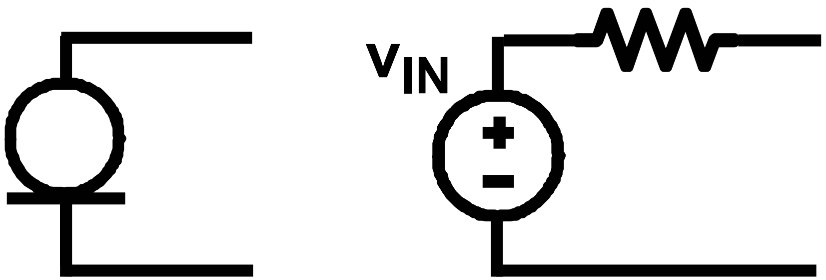
Shunt feedback
lowers impedance levels : higher bandwidths

Series feedback
increases impedances : lower node poles

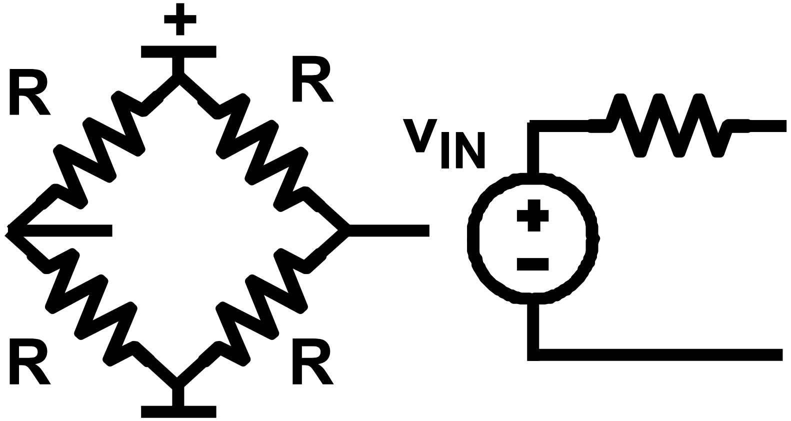
Ouput shunt best for interconnect to next stage !

Output series acts as current source !

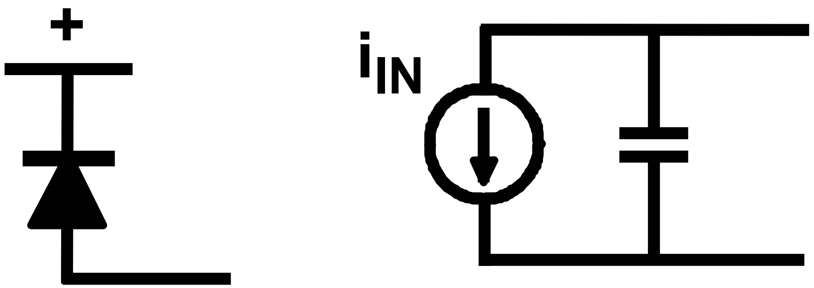
Shunt versus series for sensors



Microphone
is a voltage source
requires a high R_{in} amplifier



Pressure- , temperature
sensors are voltage sources
require a high R_{in} amp.



Pixel-, photodiode , radiation
detectors are current sources,
require a low R_{in} amp.

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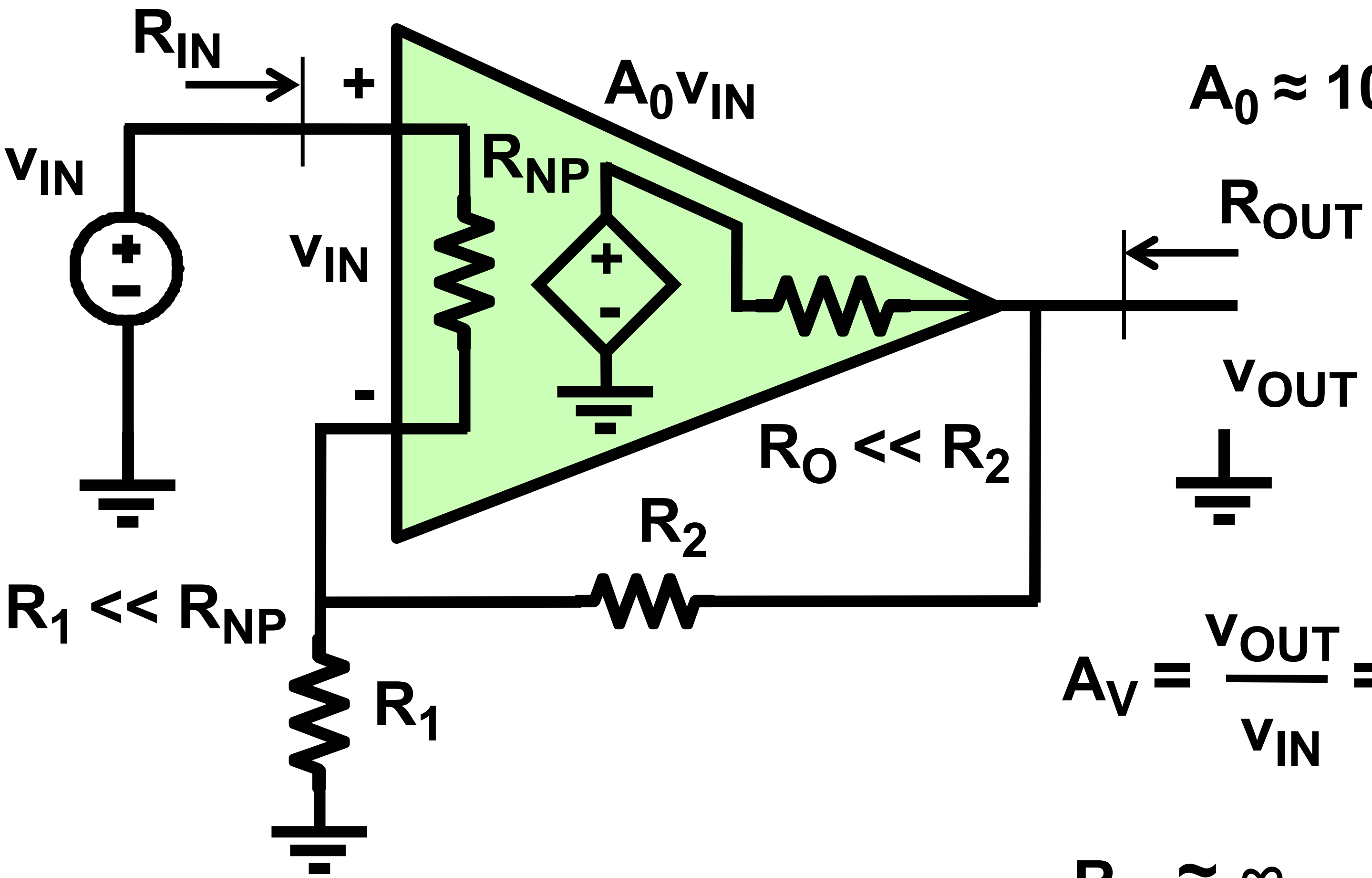
- Series-series FB for Transconductance amps

Series-shunt FB configuration

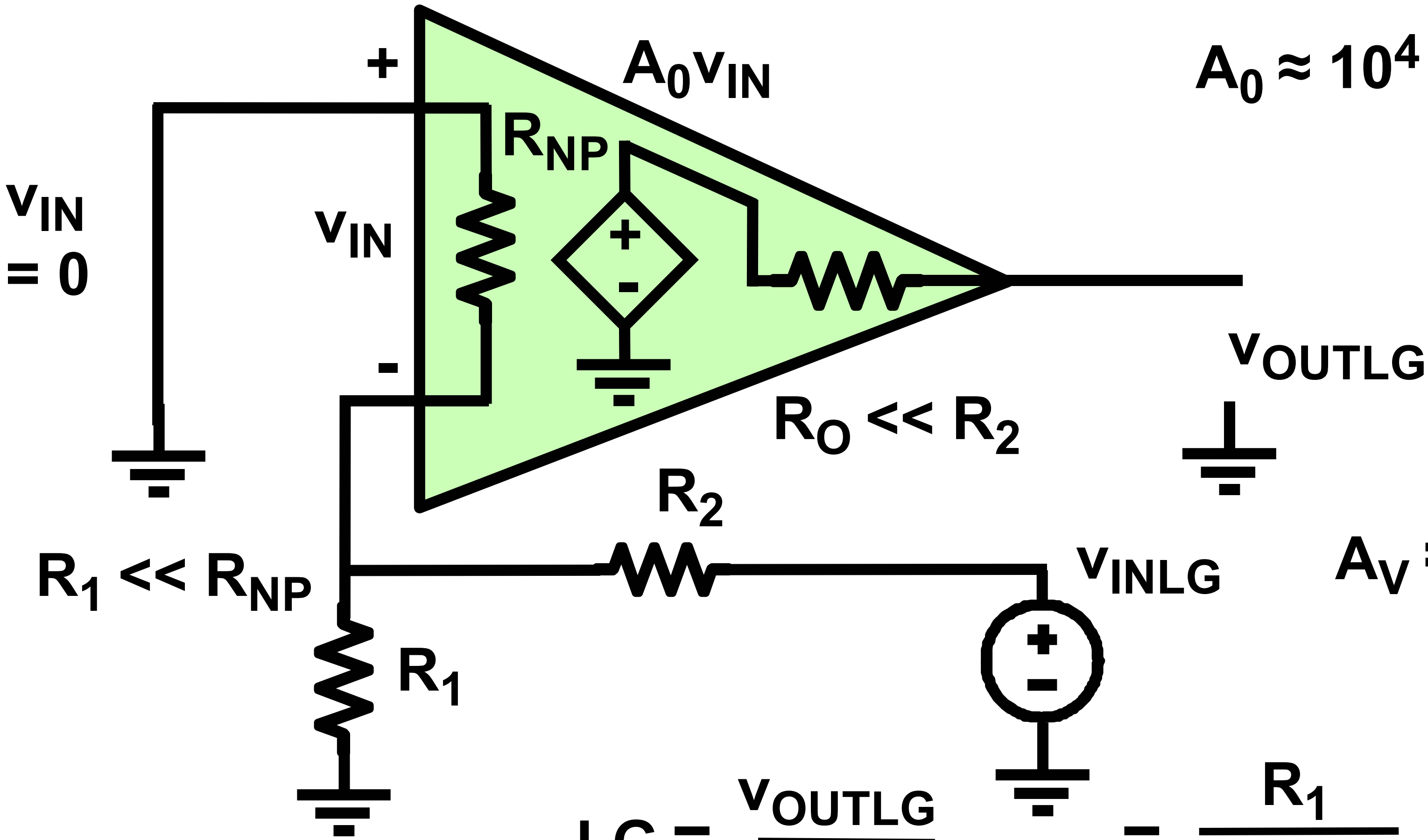


$A_0 \approx 10^4 \ldots 10^6$

$$A_V = \frac{v_{OUT}}{v_{IN}} = \frac{R_2 + R_1}{R_1}$$

$R_{IN} \approx \infty \qquad R_{OUT} \approx 0$

Series-shunt FB : loop gain

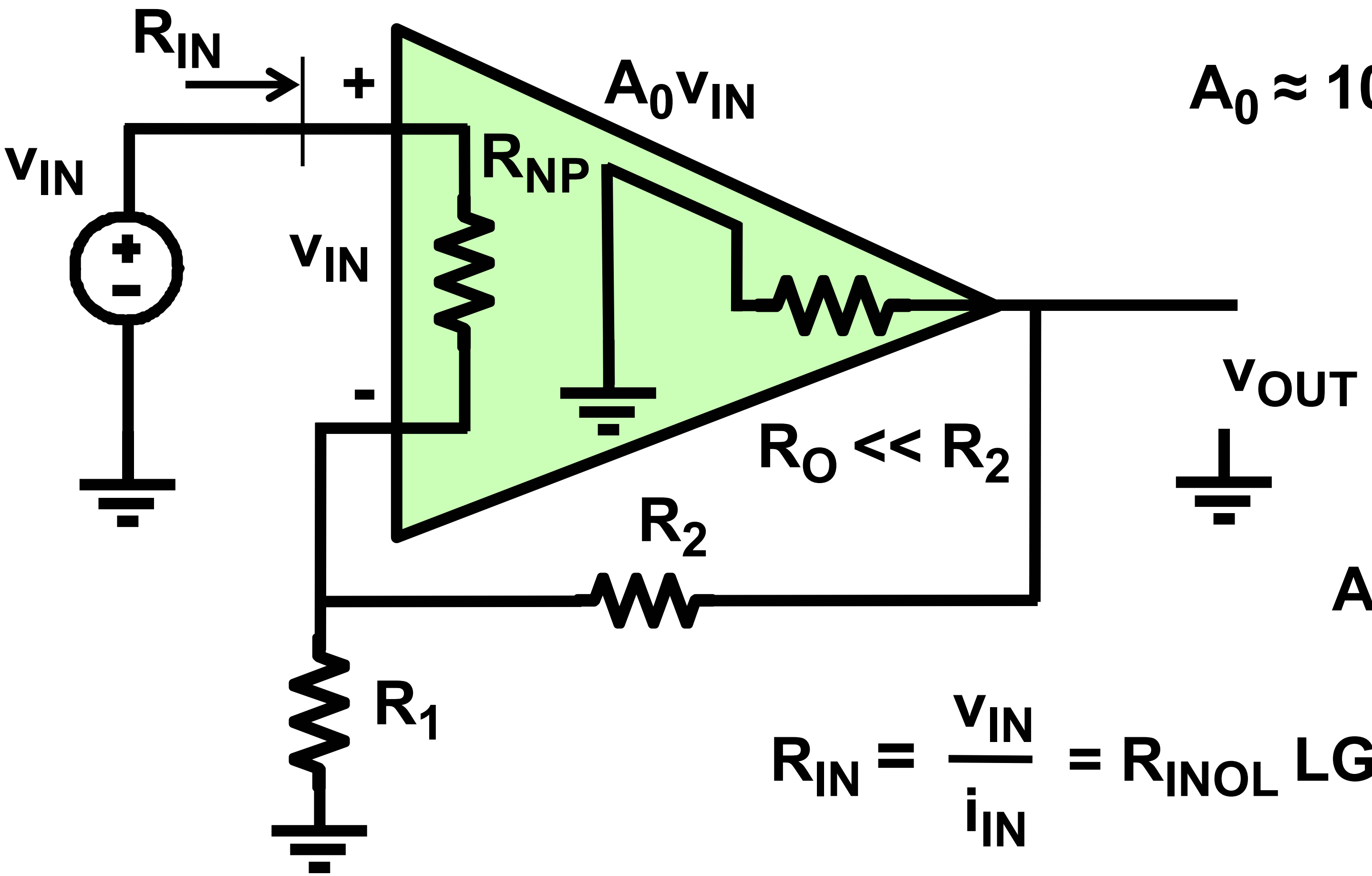


$A_0 \approx 10^4 \ldots 10^6$

$$A_V = \frac{R_2 + R_1}{R_1}$$

$$LG = \frac{v_{OUTLG}}{v_{INLG}} = \frac{R_1}{R_2 + R_1} A_0$$

Series-shunt FB : input resistance



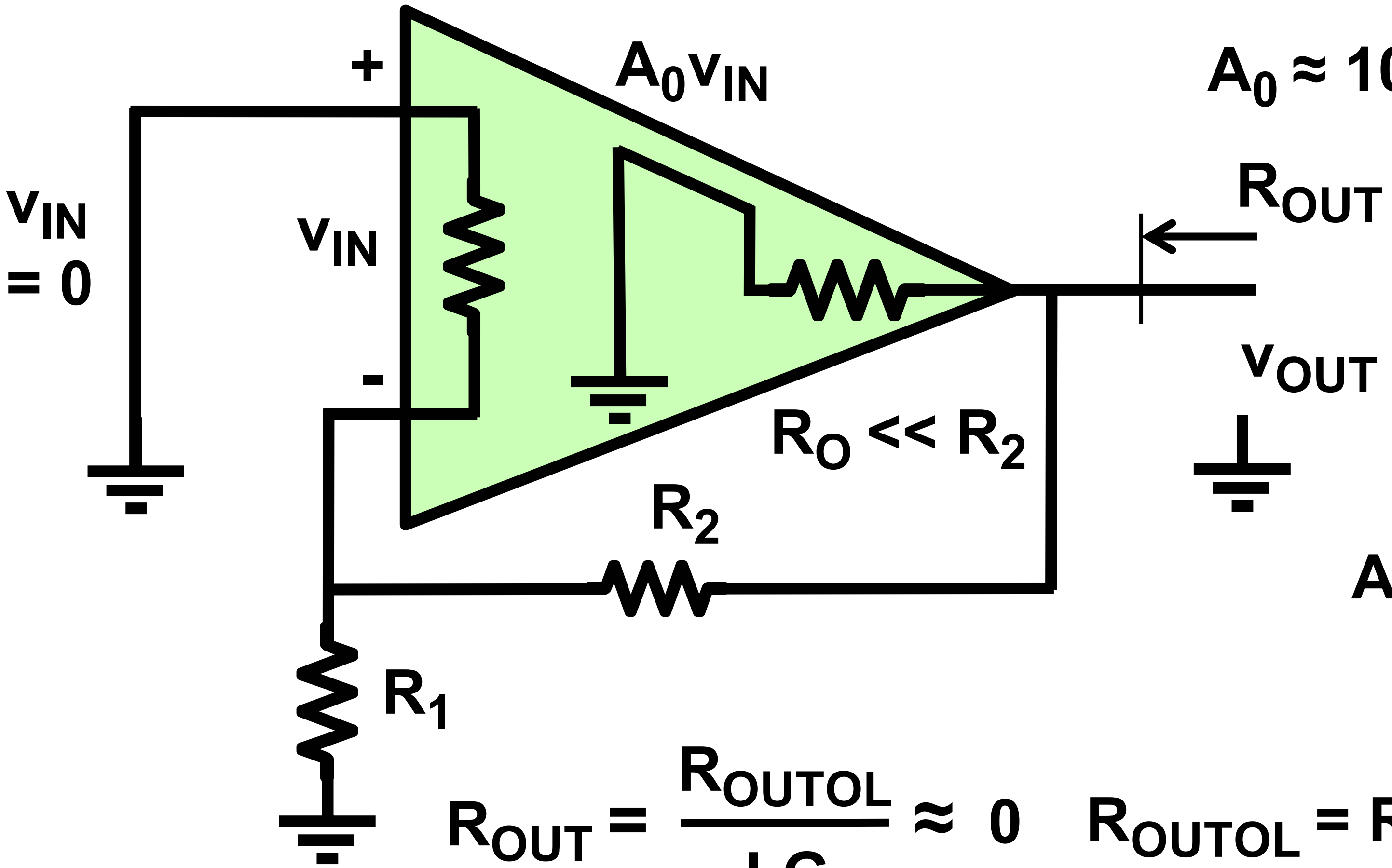
$A_0 \approx 10^4 \dots 10^6$

$$A_V = \frac{R_2 + R_1}{R_1}$$

$$R_{IN} = \frac{v_{IN}}{i_{IN}} = R_{INOL}\,LG \approx \infty$$

$$R_{INOL} = R_{IN}\,(A_0 = 0) = R_{NP} + R_1//R_2$$

Series-shunt FB : output resistance



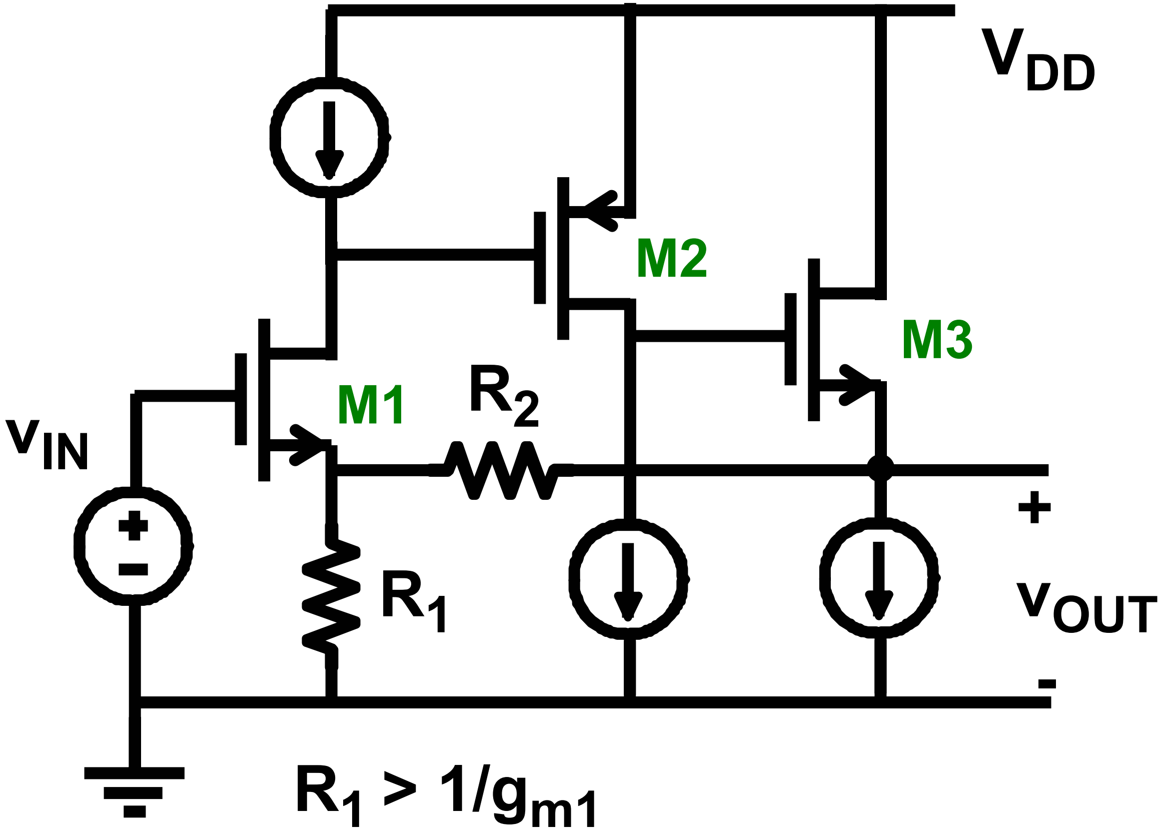
$A_0 \approx 10^4 \ldots 10^6$

$$A_V = \frac{R_2 + R_1}{R_1}$$

$$R_{OUT} = \frac{R_{OUTOL}}{LG} \approx 0 \qquad R_{OUTOL} = R_{OUT}\,(A_0 = 0)$$

$$= R_O // (R_2 + \ldots) \approx R_O$$

Series-shunt FB pair : loop gain



$R_1 > 1/g_{m1}$

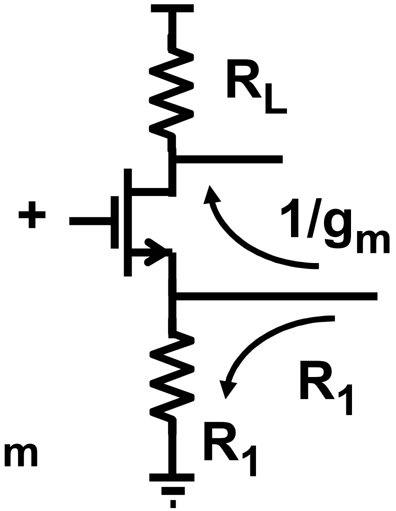
$$A_V = \frac{R_2 + R_1}{R_1}$$

LG = ?

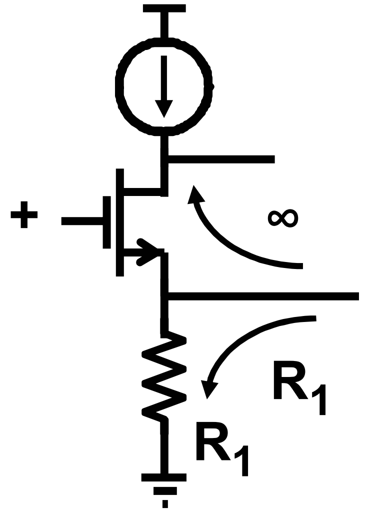
Series-shunt FB pair : series input

$R_L < r_o$

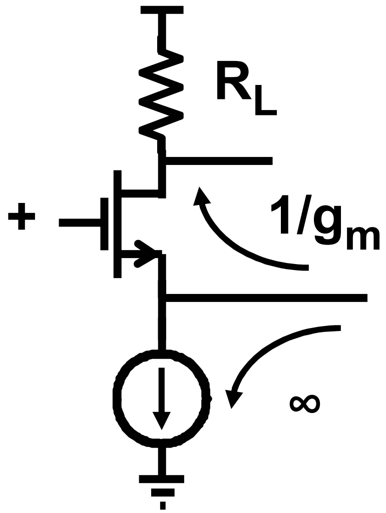
$R_1 > 1/g_m$



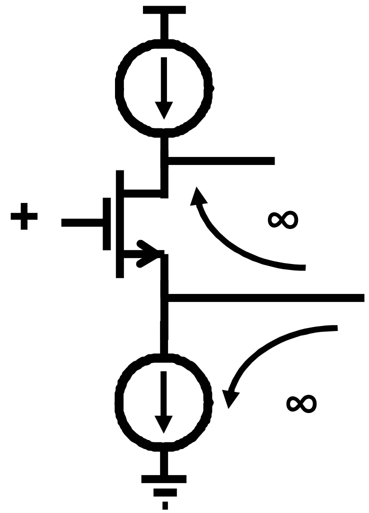
$R_{IN} \approx 1/g_m$



$R_{IN} = R_1$



$R_{IN} = 1/g_m$



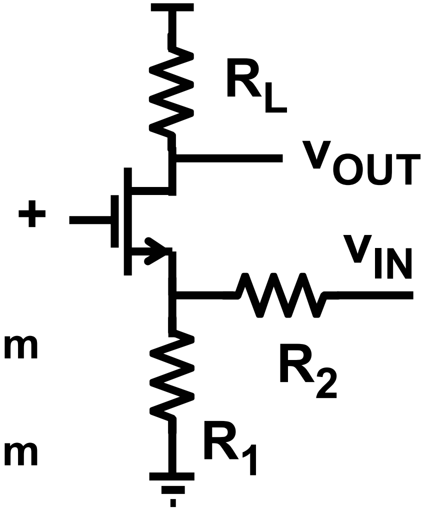
$R_{IN} = \infty$

Series-shunt FB pair : gain input stage

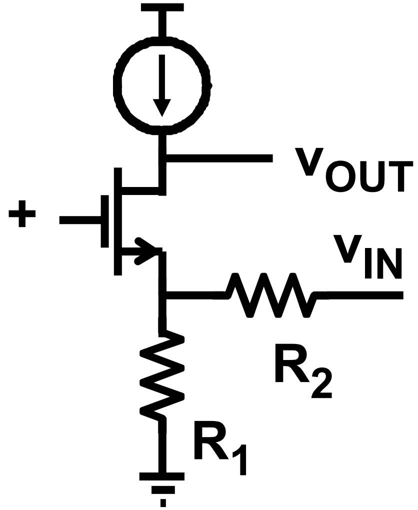
$R_L < r_o$

$R_2 > 1/g_m$

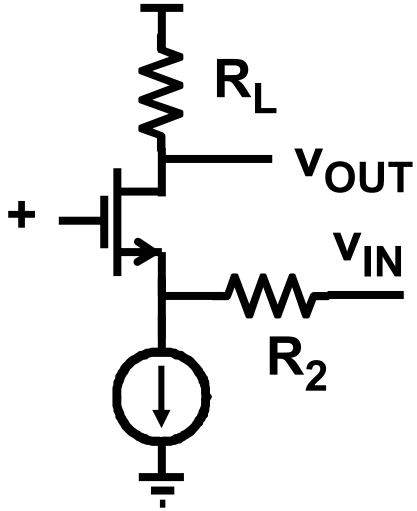
$R_1 > 1/g_m$



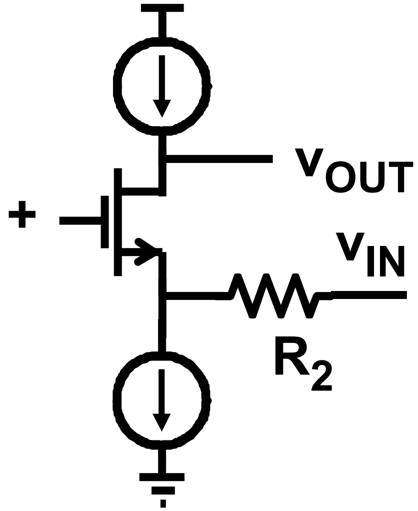
$$\frac{v_{OUT}}{v_{IN}} = \frac{R_L}{R_2}$$



$$= \frac{R_1}{R_1+R_2}\, g_m r_o$$

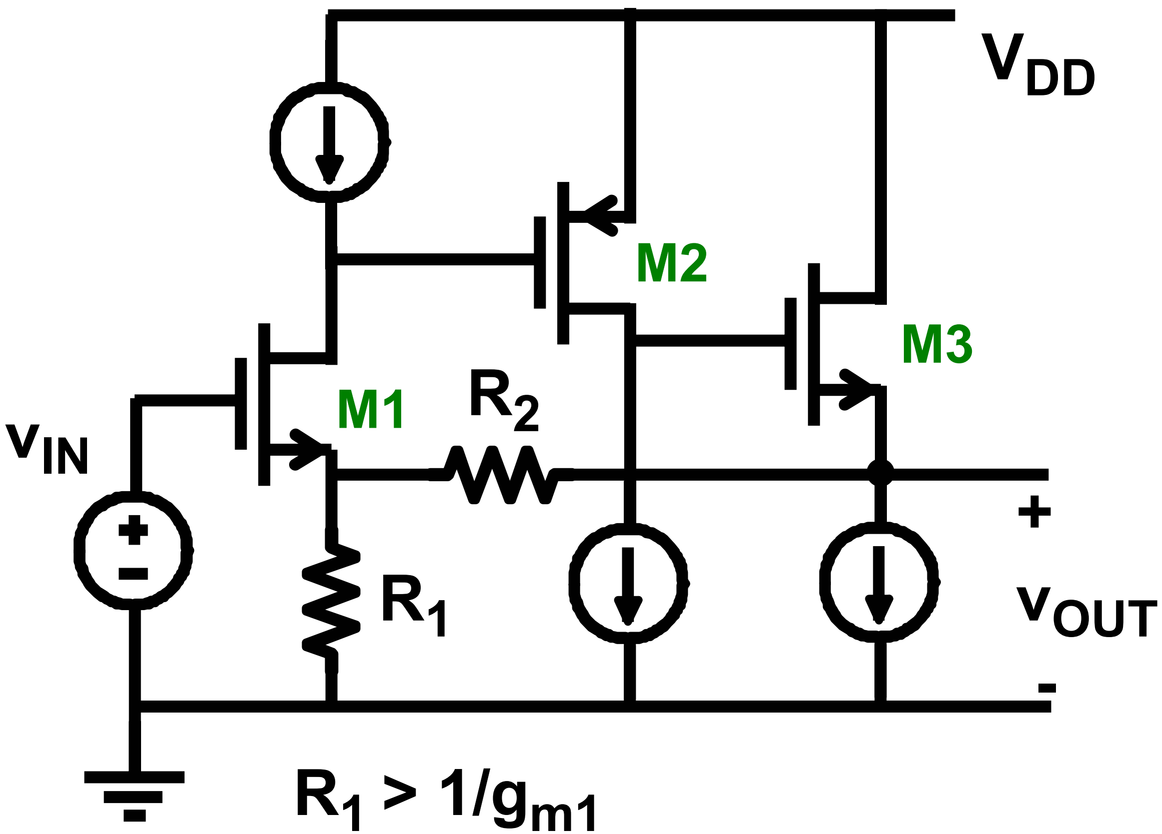


$$= \frac{R_L}{R_2}$$



$$= g_m r_o$$

Series-shunt FB pair : input & output resistance



$R_1 > 1/g_{m1}$

$$A_V = \frac{R_2 + R_1}{R_1}$$

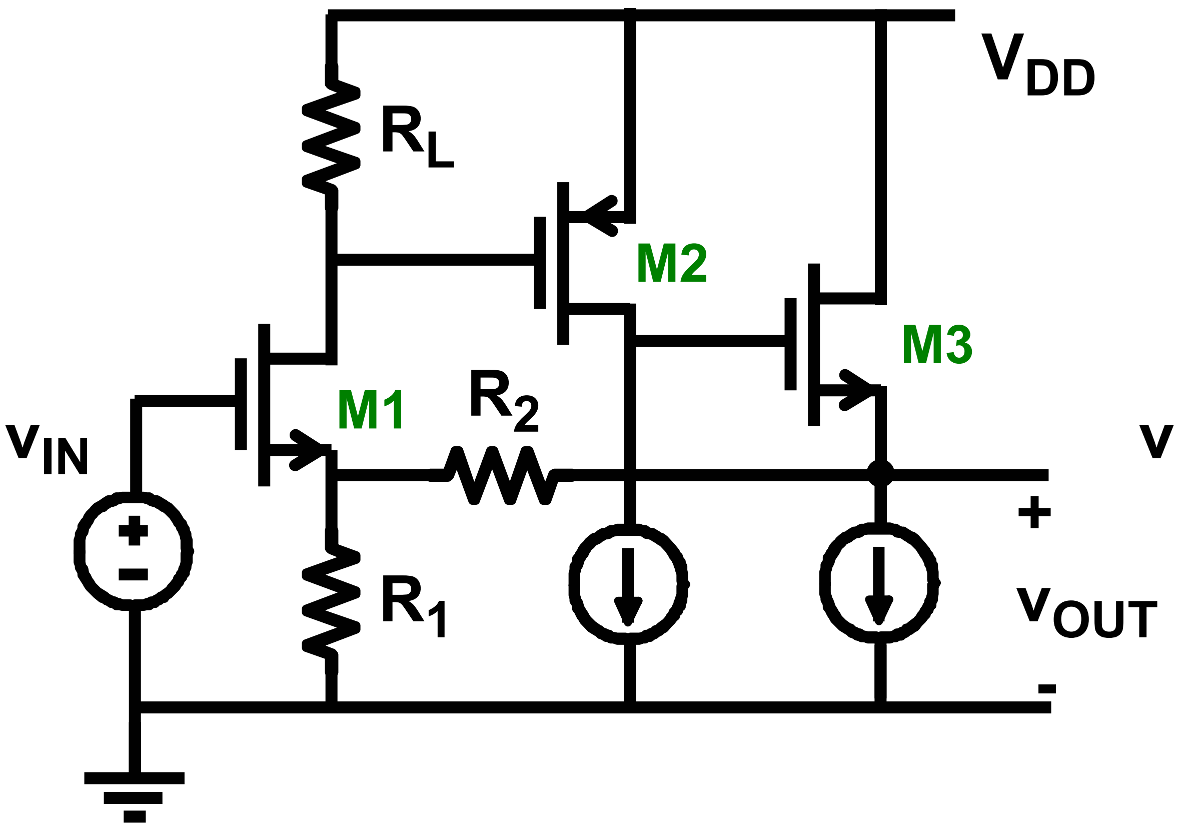
LG =

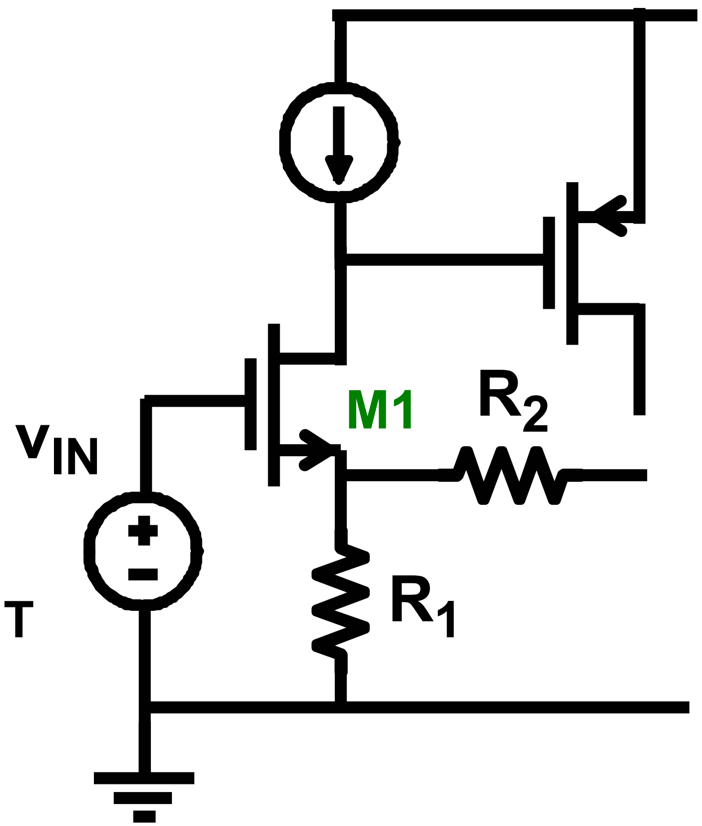
$$g_{m1}r_{o1}\, g_{m2}r_{o2}\, \frac{R_1}{R_1+R_2}$$

$$R_{IN} \approx \infty$$

$$R_{OUT} = \frac{1/g_{m3}}{LG} \approx 0$$

Series-shunt FB pair : loop gain

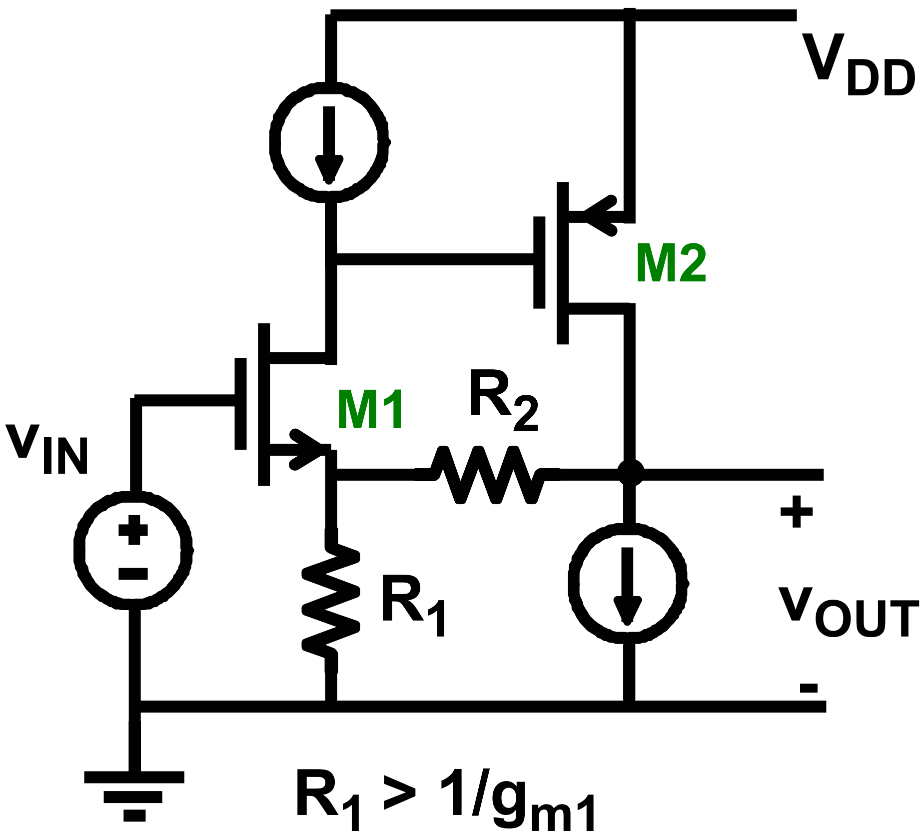




$$LG = g_{m2} r_{o2} \frac{R_L}{R_2}$$

$$LG = g_{m1} r_{o1} \, g_{m2} r_{o2} \frac{R_1}{R_1 + R_2}$$

Series-shunt FB pair : output loading



$R_1 > 1/g_{m1}$

$$A_V = \frac{R_2 + R_1}{R_1}$$

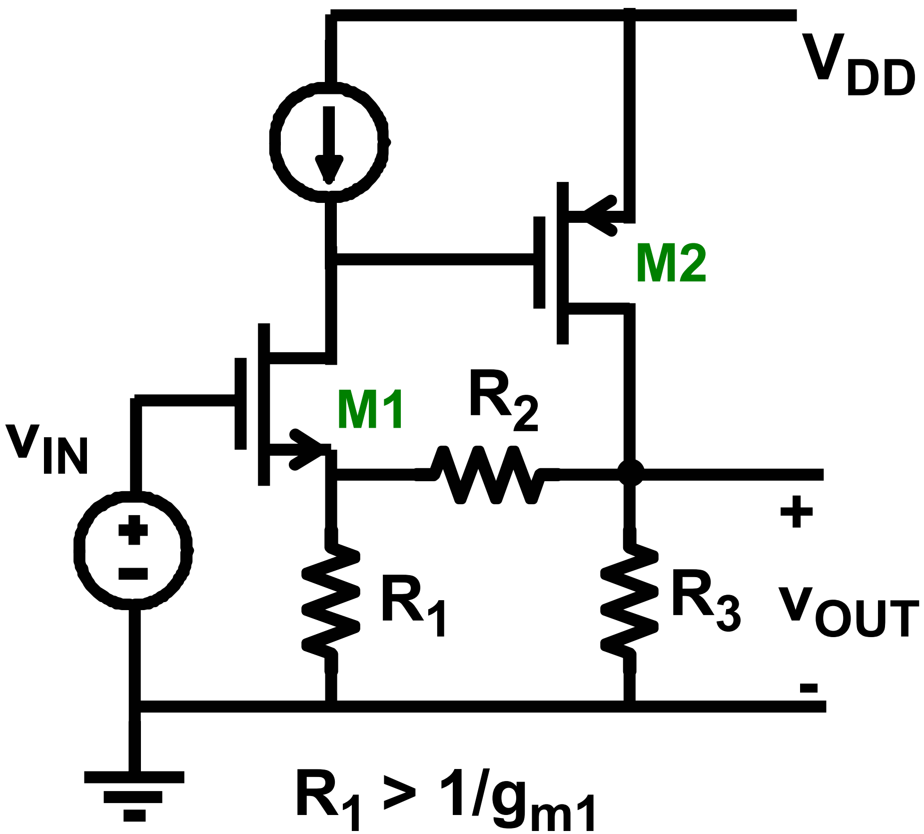
$$LG = g_{m1} r_{o1}\, g_{m2} \frac{r_{o2} R_1}{R_1 + R_2 + r_{o2}}$$

$$R_{IN} \approx \infty$$

$$R_{OUT} = \frac{(R_1 + R_2) // r_{o2}}{LG} \approx 0 \ ??$$

Output loading : $R_2 \approx r_{o2}$

Series-shunt FB pair : output loading with R



$R_1 > 1/g_{m1}$

$$A_V = \frac{R_2 + R_1}{R_1}$$

LG =

$$g_{m1} r_{o1}\, g_{m2} \frac{r_{o2}//R_3 \;\; R_1}{R_1 + R_2 + r_{o2}//R_3}$$

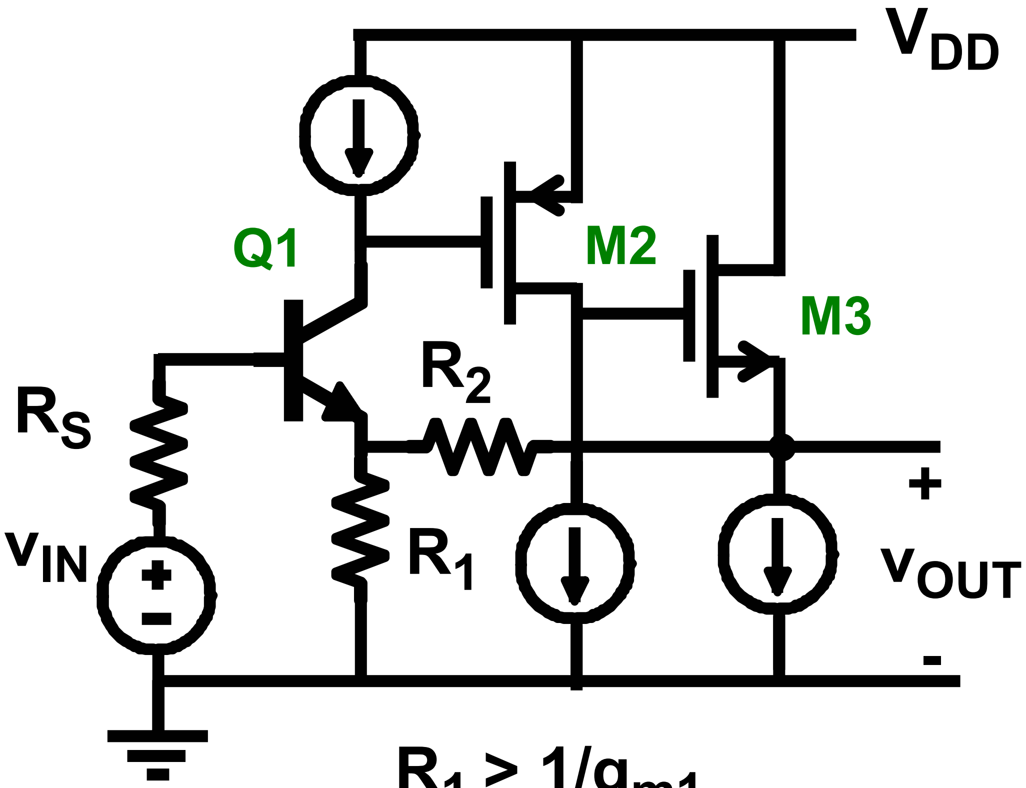
$R_{IN} \approx \infty$

$$R_{OUT} = \frac{(R_2+R_1)//r_{o2}//R_3}{LG}$$

$\approx$ 0 ??

Output loading : $R_2 \approx R_3 \approx r_{o2}$

Series-shunt pair in BiCMOS



$R_1 > 1/g_{m1}$

Input loading : $R_{IN} < \infty$

$$A_V = \frac{R_2 + R_1}{R_1}$$

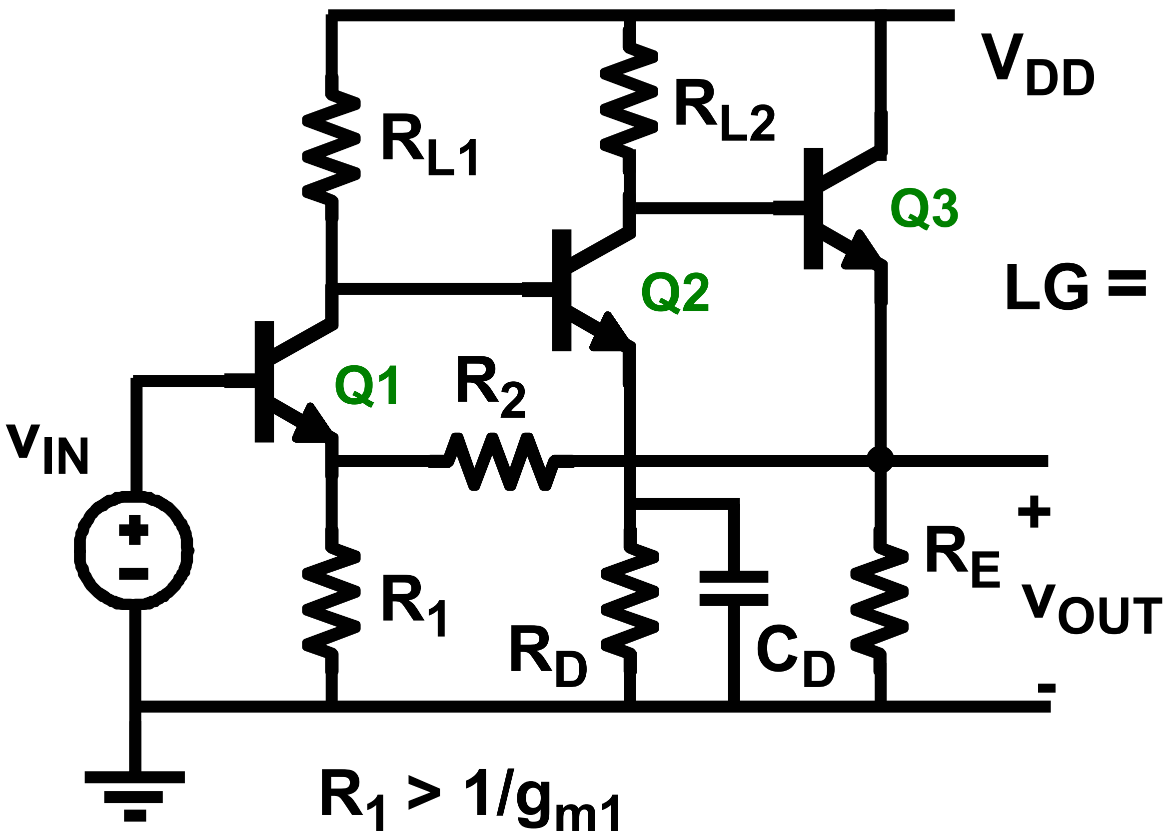
$$LG = g_{m1}r_{o1}\, g_{m2}r_{o2} \frac{R_1}{R_1+R_2}$$

$$R_{IN} = R_{INOL}\, LG \approx \infty$$

$$R_{INOL} = r_{\pi 1} + \beta\,(R_1//R_2)$$

$$R_{OUT} = \frac{1/g_{m3}}{LG} \approx 0$$

Series-shunt FB pair with resistances



$R_1 > 1/g_{m1}$

$$A_V = \frac{R_2 + R_1}{R_1}$$

$$LG = \frac{R_{L1}//r_{\pi 2}}{R_2}\, g_{m2} r_{o2} \frac{R_{L2}}{R_{L2} + r_{o2}}$$

$$R_{IN} = R_{INOL}\, LG \approx \infty$$

$$R_{INOL} = r_{\pi 1} + \beta\,(R_1//R_2)$$

$$R_{OUT} = \frac{R_{OUTOL}}{LG} \approx 0$$

$$R_{OUTOL} = \frac{1}{g_{m3}} + \frac{R_{L2}//r_{o2}}{\beta}$$

Input loading : $R_{IN} < \infty$

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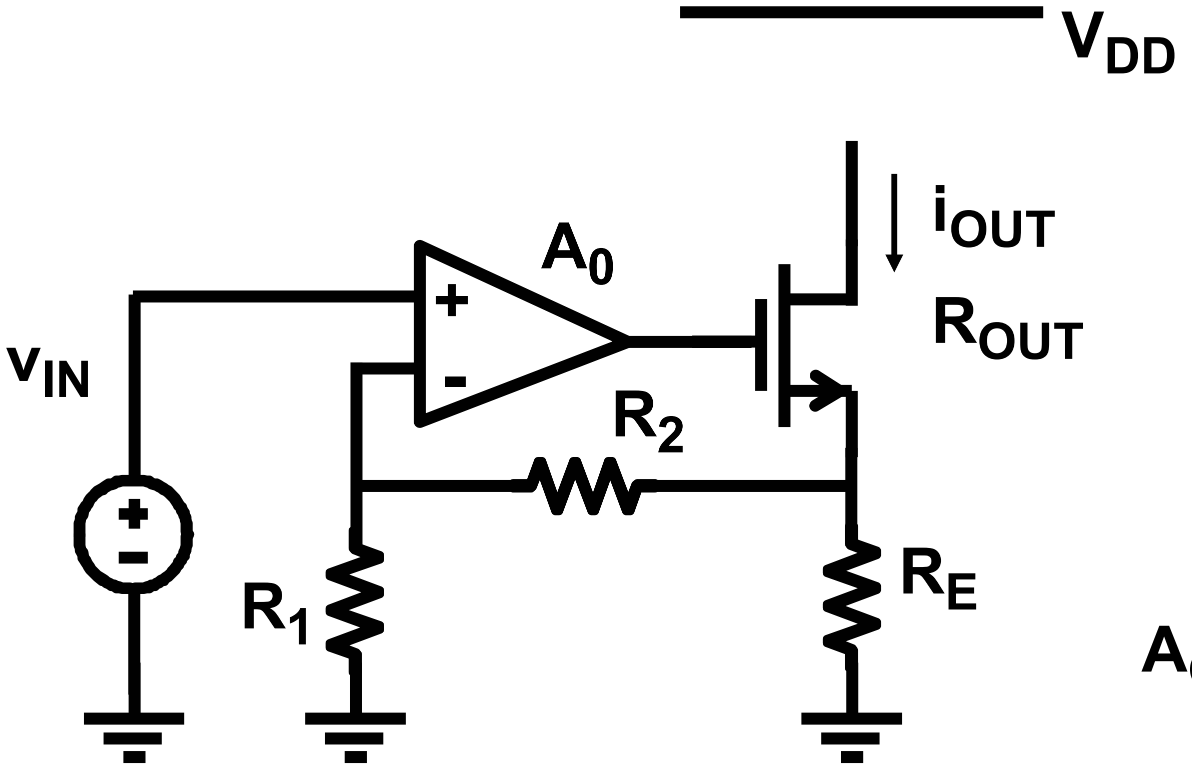
Series-series feedback : gain



$$R_{E12} = R_E \, // \, (R_1 + R_2)$$

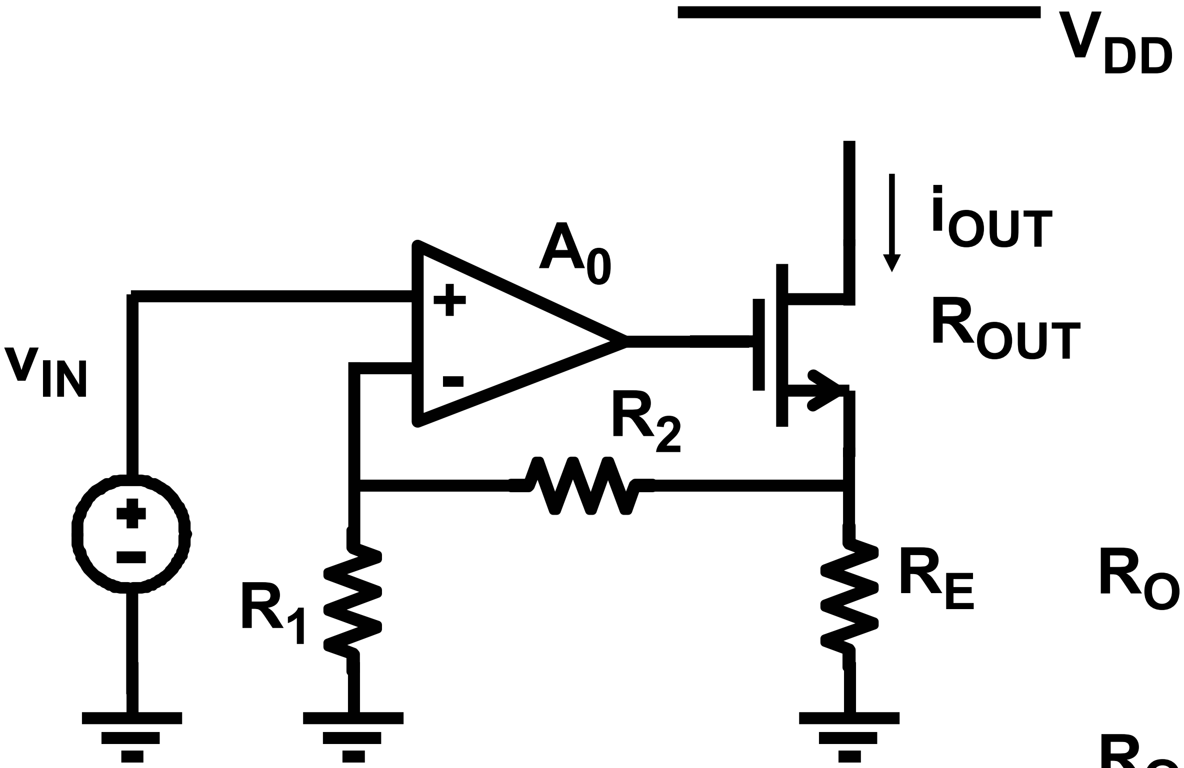
$$LG = A_0 \frac{R_1}{R_2 + R_1}$$

$$A_{GOL} = A_0 \frac{1}{R_{E12}}$$

$$A_G = \frac{R_2 + R_1}{R_1} \frac{1}{R_{E12}}$$

$$= \frac{R_2 + R_1 + R_E}{R_1} \frac{1}{R_E}$$

Series-series feedback : in- & output resistances



$$LG = A_0 \frac{R_1}{R_2 + R_1}$$

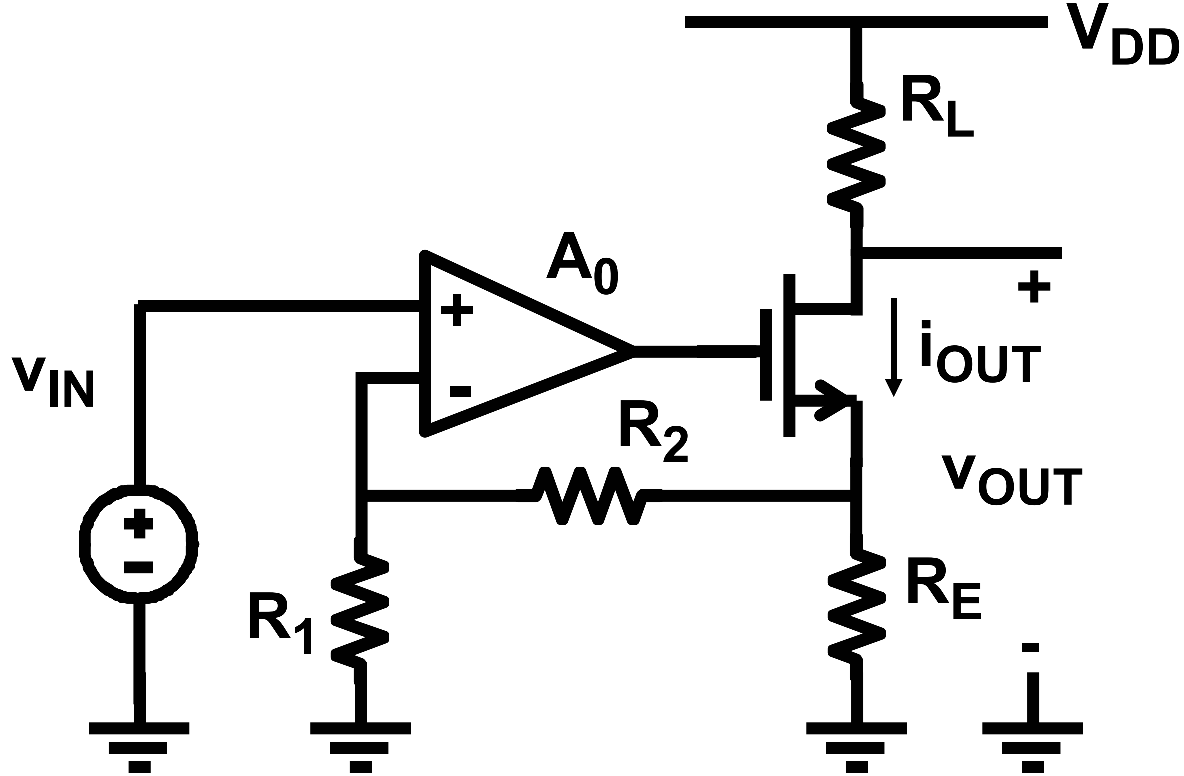
$$R_{IN} = \infty$$

$$R_{OUTOL} = r_o (1 + g_m R_{E12})$$

$$R_{OUT} = R_{OUTOL}\, LG \approx \infty$$

$$R_{E12} = R_E \,//\, (R_1 + R_2)$$

Series-series feedback with load RL



$$R_{E12} = R_E \;//\; (R_1 + R_2)$$

$$A_G = \frac{R_2 + R_1}{R_1} \frac{1}{R_{E12}}$$

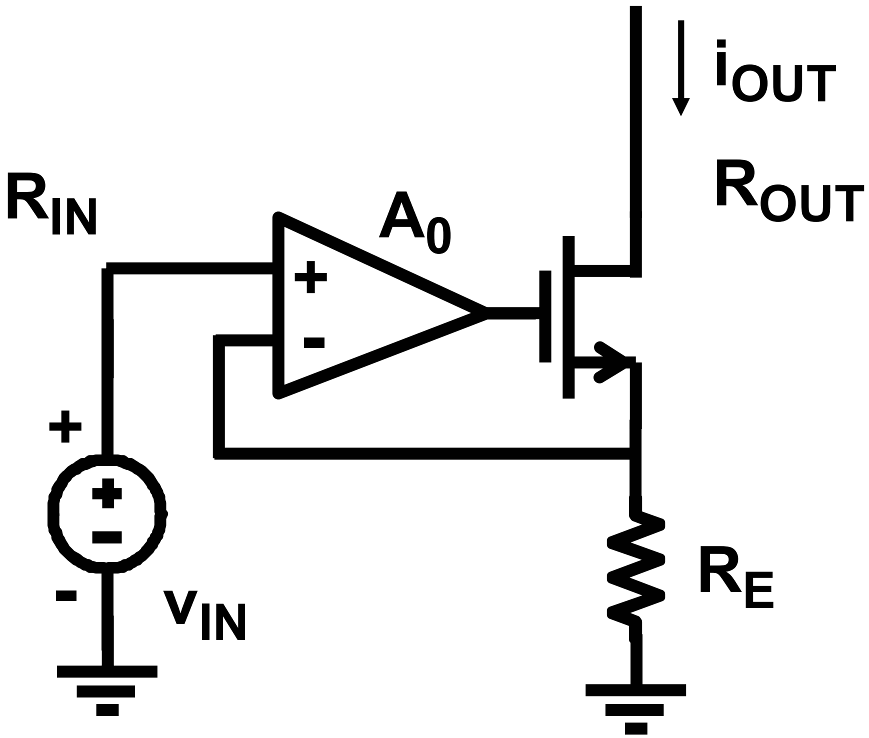
$$A_V = - \frac{R_2 + R_1}{R_1} \frac{R_L}{R_{E12}}$$

$$= - \frac{R_2 + R_1 + R_E}{R_1} \frac{R_L}{R_E}$$

$$R_{IN} = \infty$$

$$R_{OUT} = R_L$$

Ideal current source



$$i_{OUT} = \frac{v_{IN}}{R_E}$$

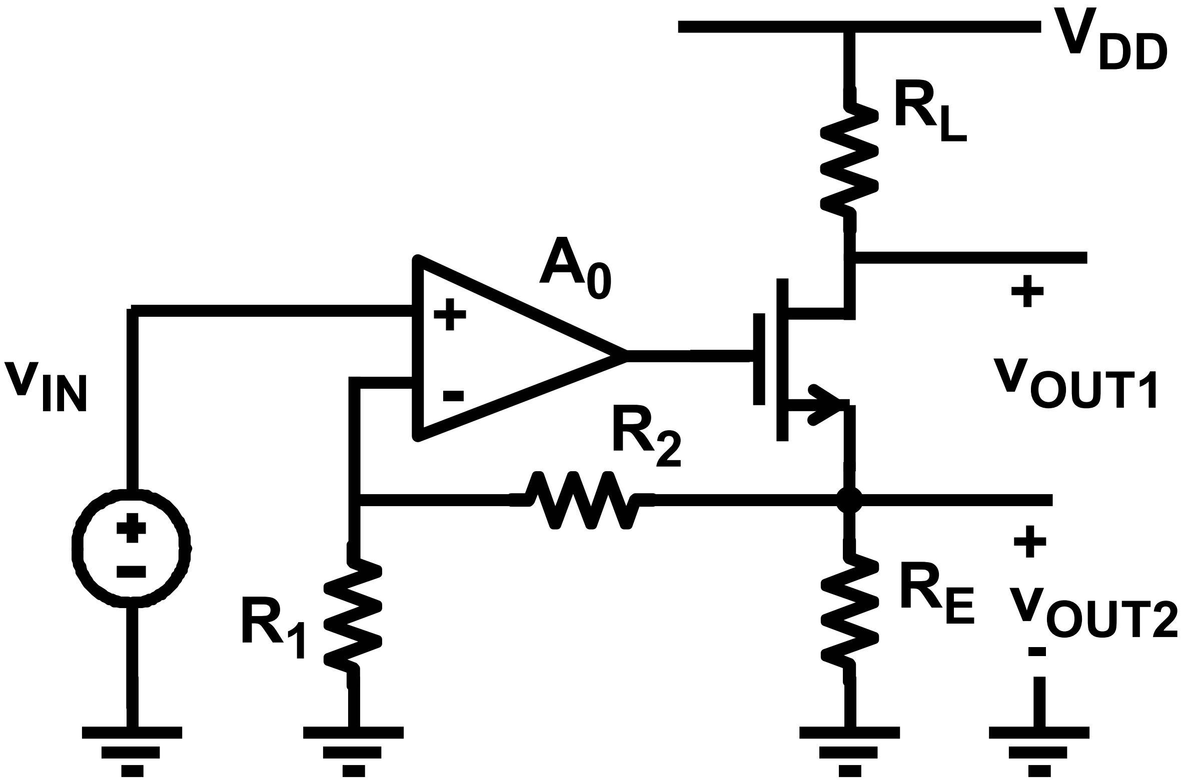
$LG = A_0$

$R_{IN} \approx \infty$

$R_{OUT} = R_{OUTOL}\, LG$

$R_{OUTOL} \approx r_o\,(1+g_m R_E\,)$

Series-series feedback : two outputs



$$LG = A_0 \frac{R_1}{R_2 + R_1}$$

$$A_{V1} = -\frac{R_2 + R_1}{R_1} \frac{R_L}{R_{E12}}$$

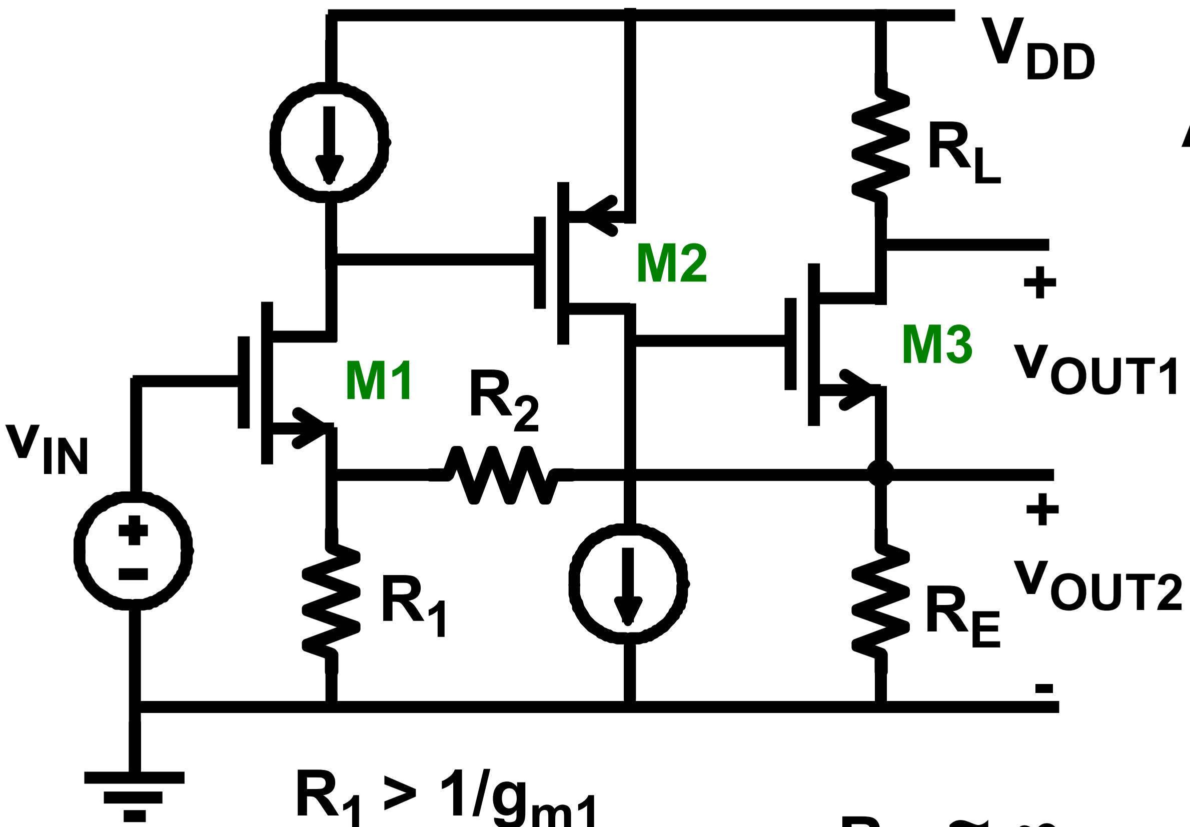
$$A_{V2} = \frac{R_2 + R_1}{R_1}$$

$$R_{OUT1} = R_L$$

$$R_{OUT2} = \frac{1/g_m}{LG}$$

$$R_{E12} = R_E \,//\, (R_1 + R_2)$$

Series-series FB triple



$$A_{V1} = -\frac{R_2 + R_1}{R_1}\,\frac{R_L}{R_{E12}}$$

$$A_{V2} = \frac{R_2 + R_1}{R_1}$$

$$LG = A_1 A_2 \frac{R_1}{R_2 + R_1}$$

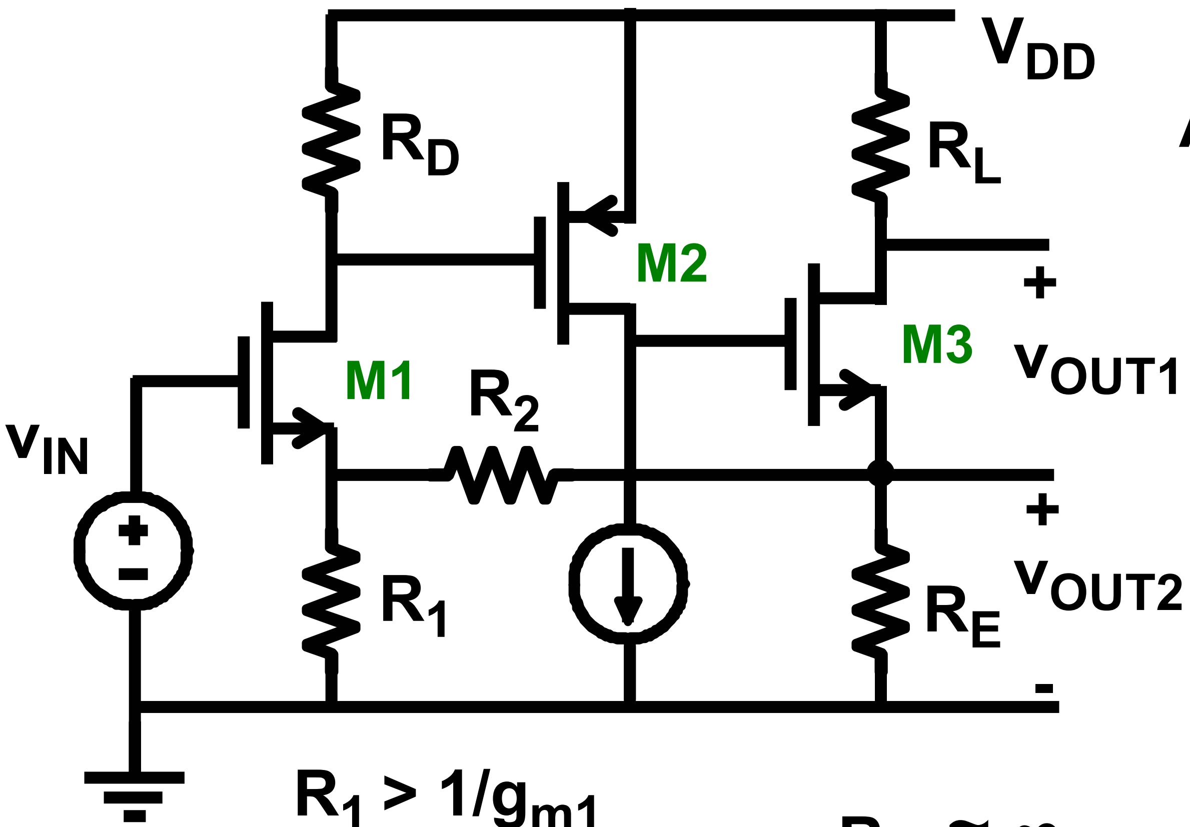
$$A_i = g_{mi} r_{oi}$$

$R_1 > 1/g_{m1}$

$R_{IN} \approx \infty$

$R_{E12} = R_E \,//\, (R_1 + R_2)$ $\quad R_{OUT1} = R_L$ $\quad R_{OUT2} = \dfrac{1/g_{m2}}{LG} \approx 0$

Series-series FB triple



$$A_{V1} = -\frac{R_2 + R_1}{R_1}\,\frac{R_L}{R_{E12}}$$

$$A_{V2} = \frac{R_2 + R_1}{R_1}$$

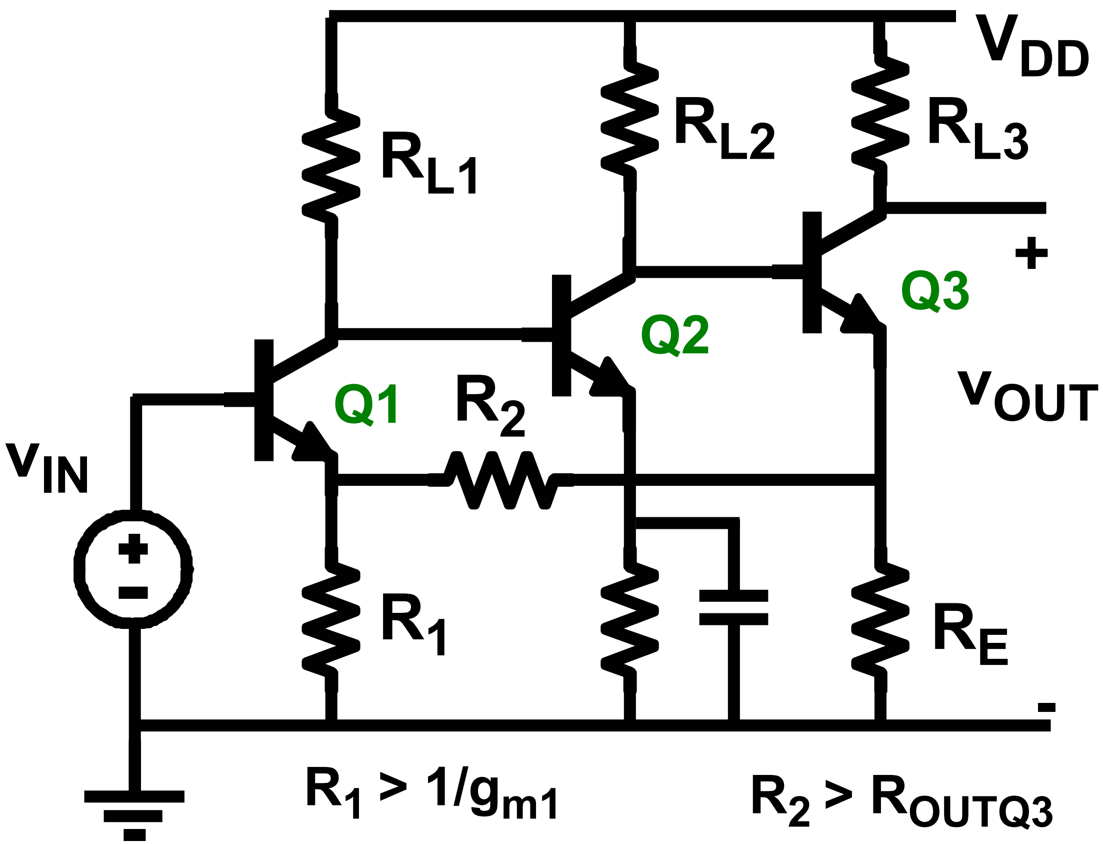
$$LG = g_{m2} r_{o2}\,\frac{R_D}{R_2}$$

$R_1 > 1/g_{m1}$

$R_{IN} \approx \infty$

$R_{E12} = R_E \,//\, (R_1 + R_2)$ $\quad R_{OUT1} = R_L$ $\quad R_{OUT2} = \dfrac{1/g_{m2}}{LG} \approx 0$

Series-series triple



$R_1 > 1/g_{m1}$ $R_2 > R_{OUTQ3}$

$$A_V = -\frac{R_2 + R_1}{R_1}\frac{R_{L3}}{R_{E12}}$$

$$R_{E12} = R_E // (R_1 + R_2)$$

$$LG \approx g_{m2}(r_{o2}//R_{L2})\frac{R_{L1}//r_{\pi 2}}{R_2}$$

$$R_{IN} = R_{INOL}\ LG \approx \infty$$

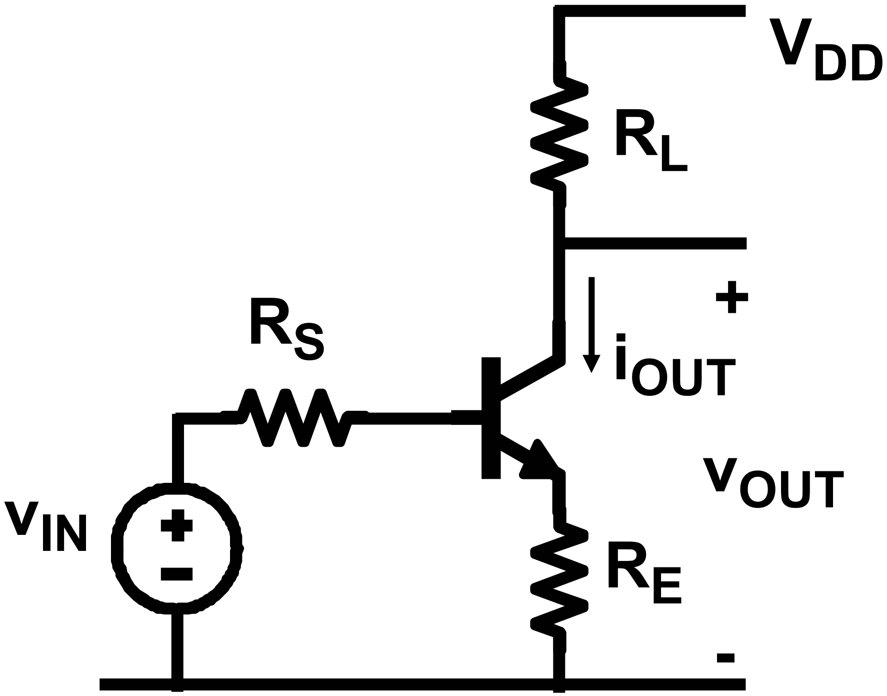
$$R_{INOL} = r_{\pi 1} + \beta\,(R_1//R_2)$$

$$R_{OUT} = R_{L3}$$

Input loading : $R_{IN} < \infty$

Wooley, JSSC Feb.71, 24-34

Nonideal single-transistor FB



$$A_G \approx \frac{1}{R_E} \quad A_v \approx -\frac{R_L}{R_E}$$

$$LG = g_m R_E \quad (>>1)$$

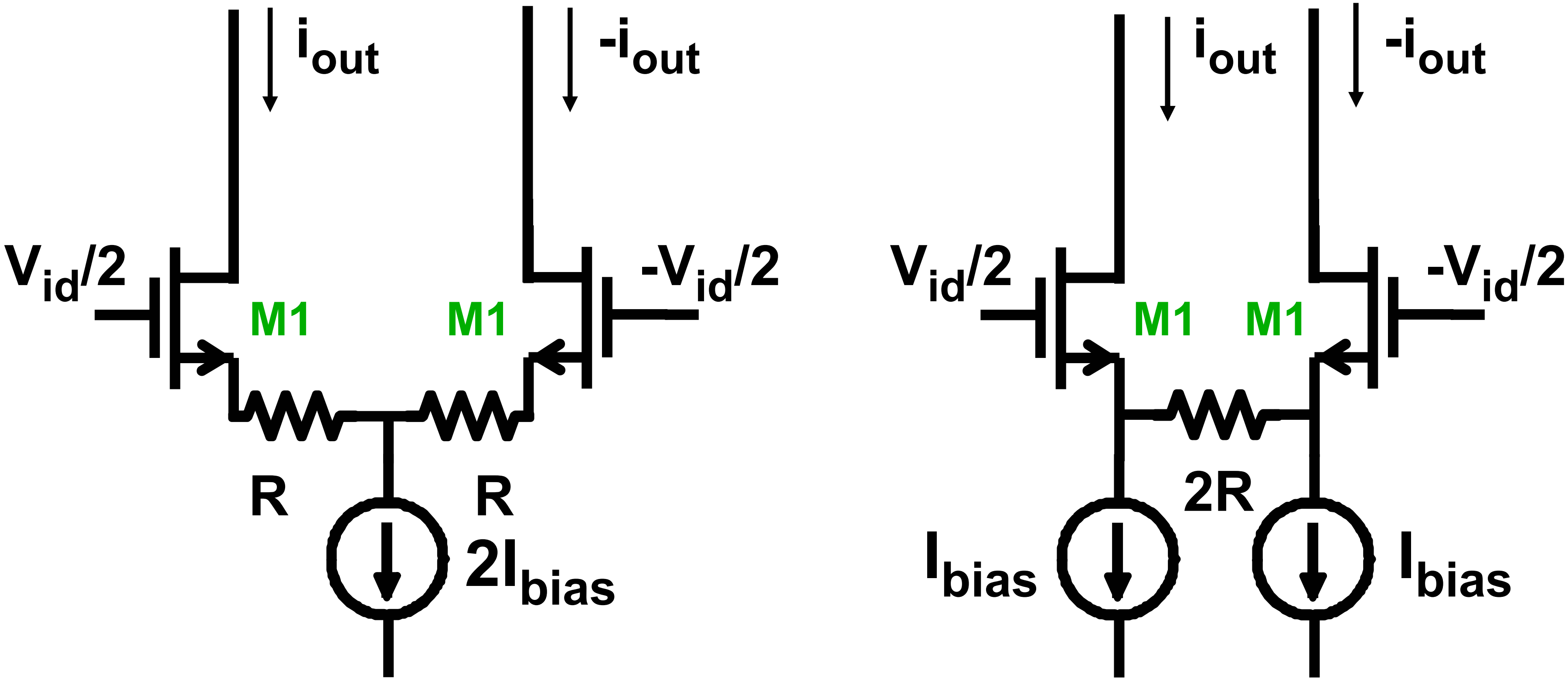
$$R_{IN} = r_\pi + \beta\, R_E$$

$$R_{OUT} = R_L // r_{oL}$$

Output loading : $R_L \approx r_{oL}$ $\quad r_{oL} = r_o\,(g_m R_E)$

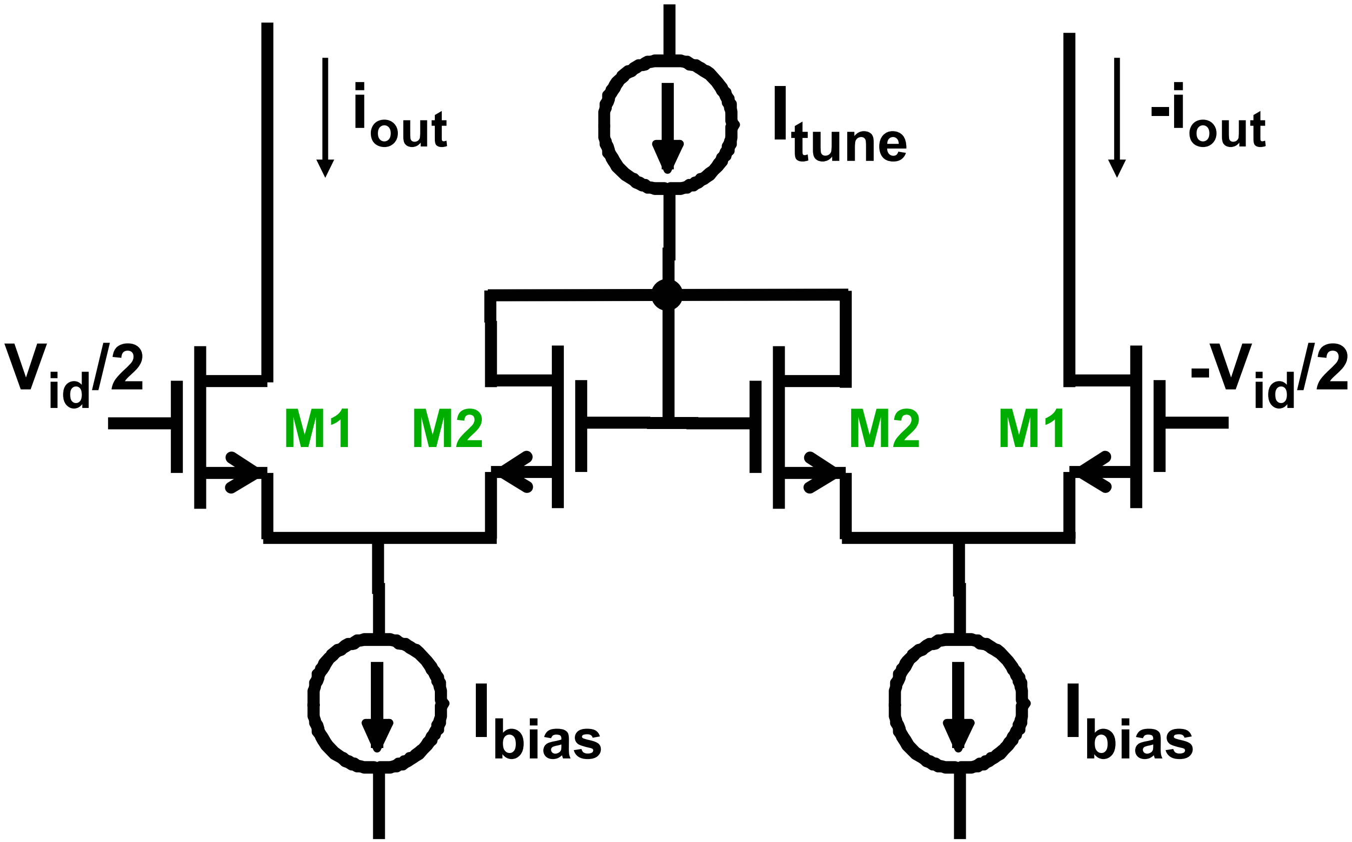
Input loading : $R_S < R_{IN}$ $\quad R_{IN} = r_\pi + \beta R_E$

Decreasing distortion by feedback



$LG = g_m R \quad (>>1)$ $\qquad A_G \approx \dfrac{1}{R}$

By tunable feedback



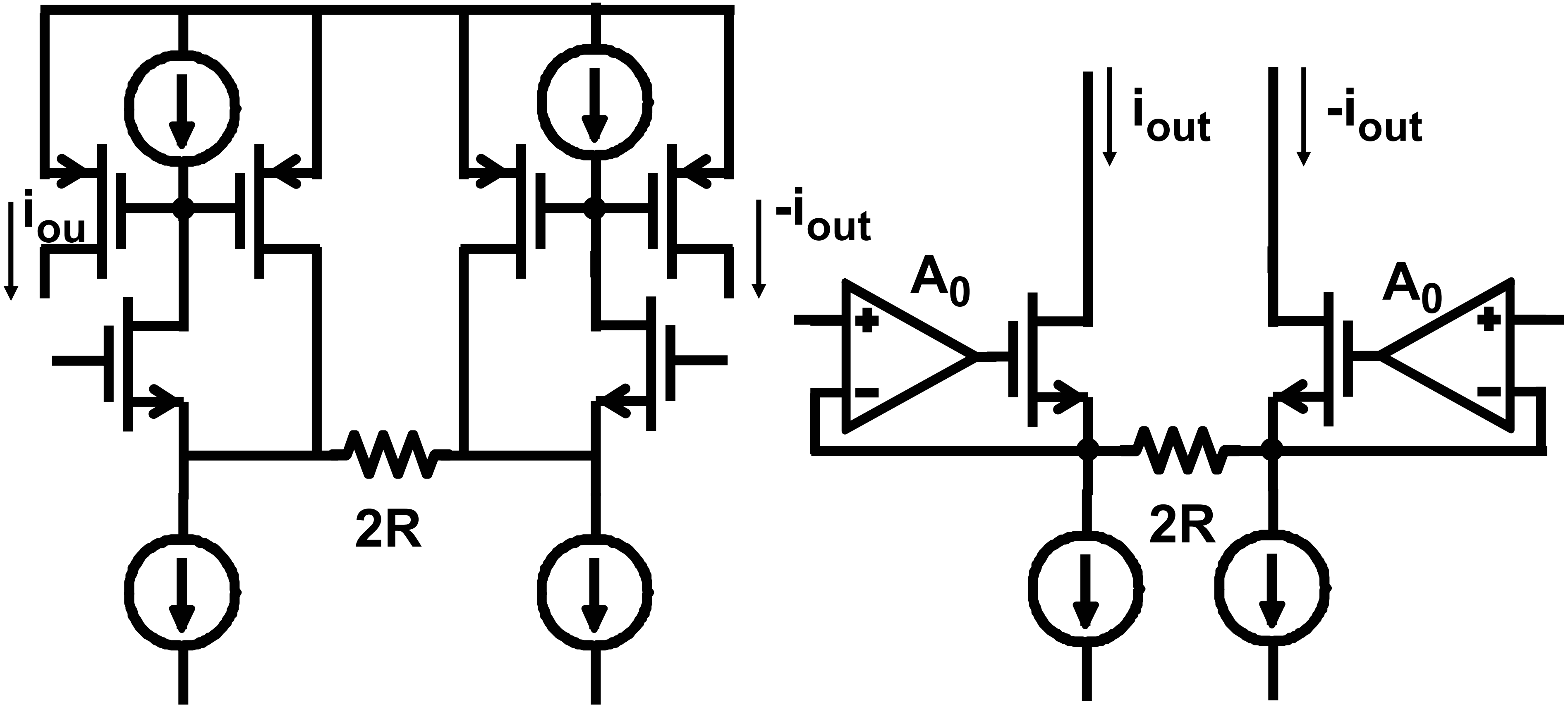
$R = 1/g_{m2}$

$A_G \approx \frac{1}{R}$

$LG = g_m R \quad (>>1)$

Ref.Torrance etal CAS Nov.85, 1097-1104

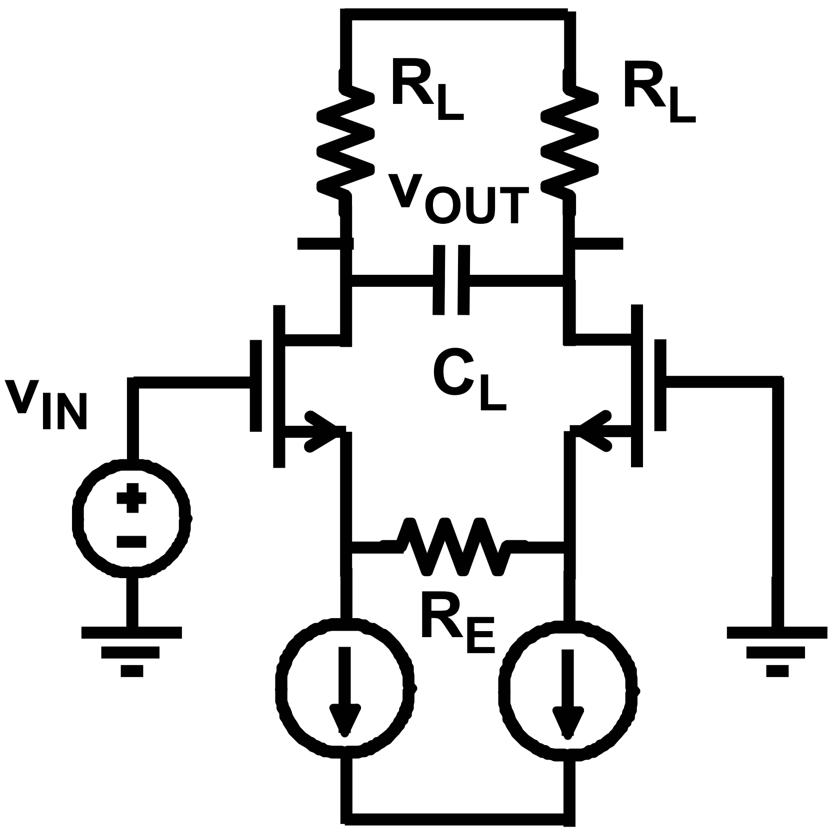
Decreasing distortion by more feedback

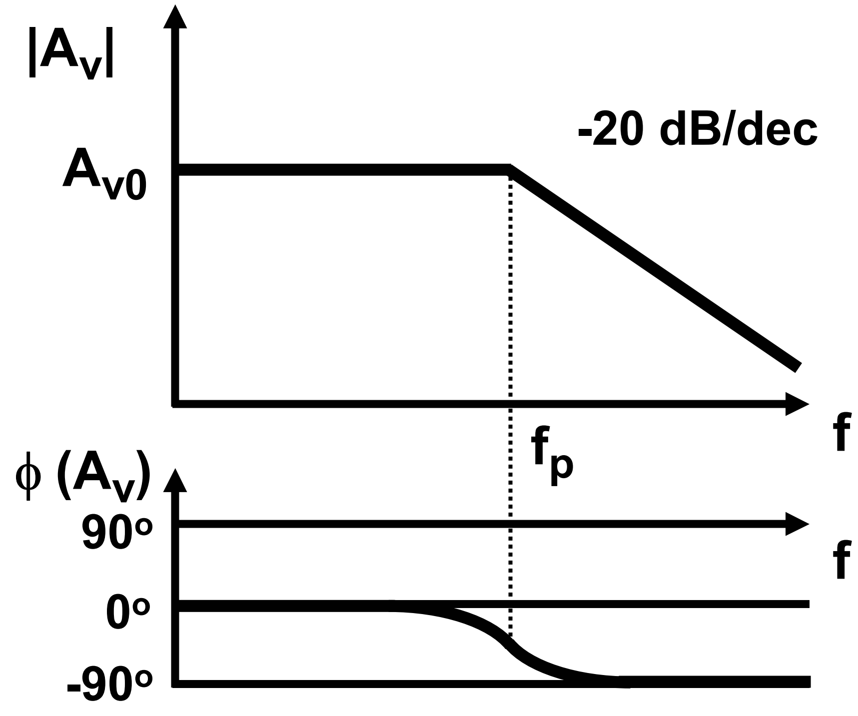


Additional local FB

More FB with opamps

Low-pass filter



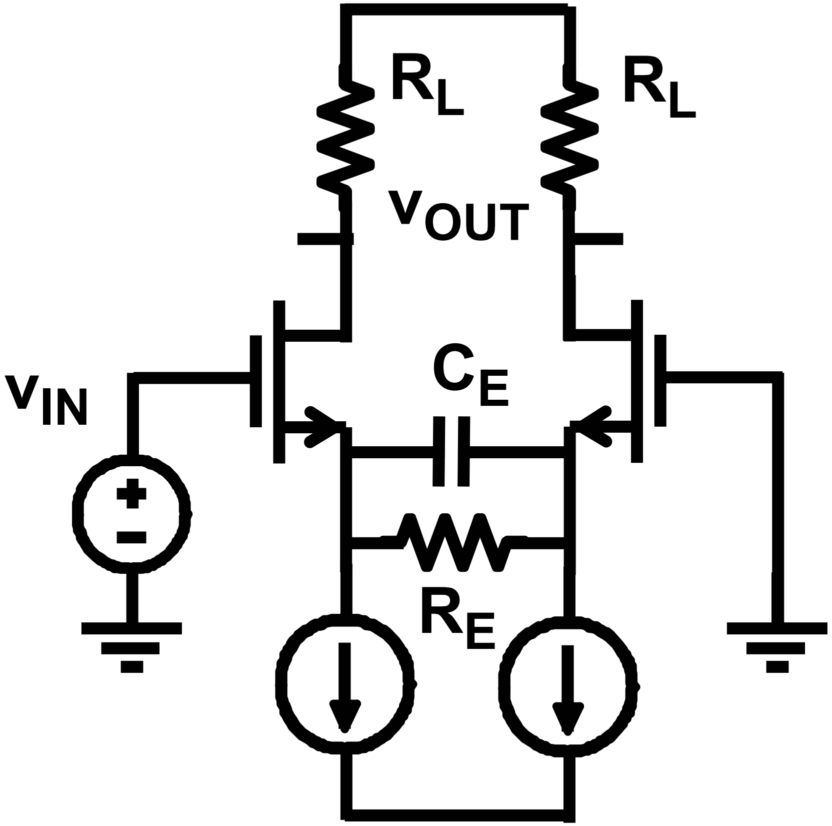


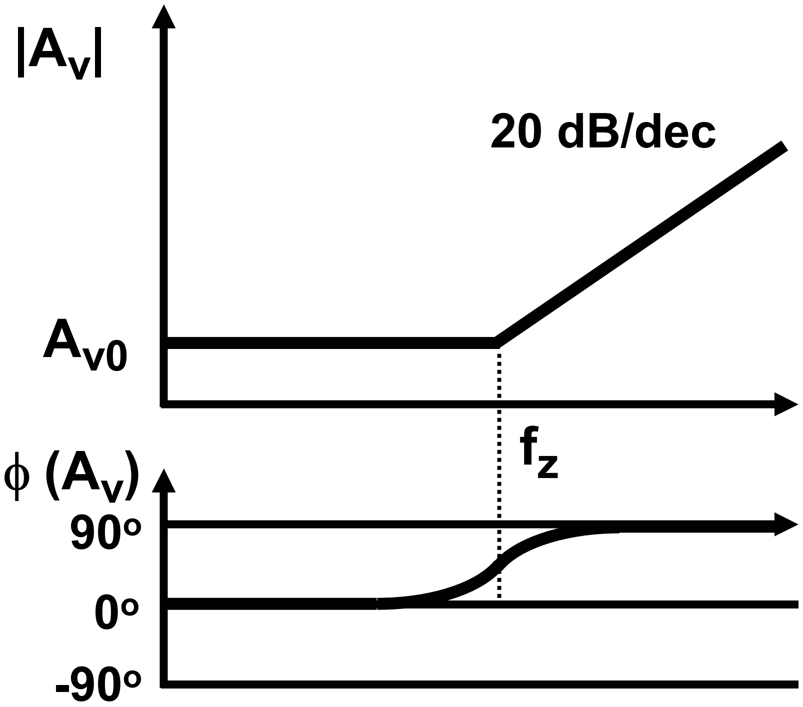
$$A_{v0} = 2\ R_L/R_E$$

$$A_v = \frac{A_{v0}}{(1 + j\frac{f}{f_p})}$$

$$f_p = \frac{1}{2\pi\ 2R_LC_L}$$

High-frequency booster



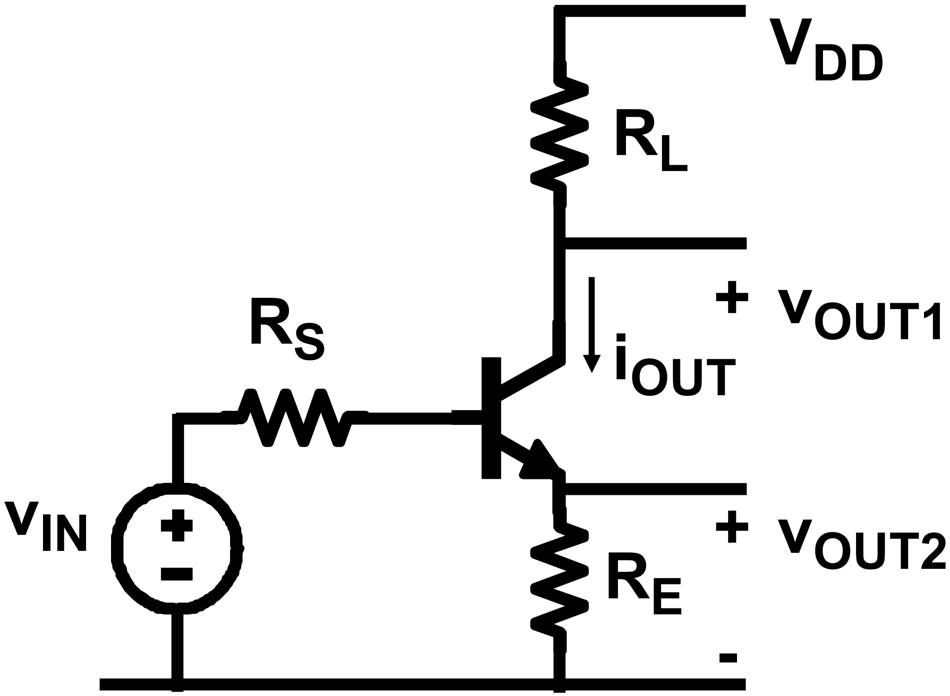


$$A_{v0} = 2\ R_L/R_E$$

$$A_v = A_{v0}\left(1 + j\frac{f}{f_z}\right)$$

$$f_z = \frac{1}{2\pi\ R_E C_E}$$

Single-transistor FB with two outputs



$A_{v1} \approx -\frac{R_L}{R_E}$ $\quad A_{v2} \approx 1$

$LG = g_m R_E \quad (>>1)$

$R_{IN} = r_\pi + \beta R_E$

$R_{OUT1} = R_L // r_{oL}$

$R_{OUT2} = 1/g_m + R_S/\beta$

Output loading : $R_L \approx r_{oL} \qquad r_{oL} = r_o\,(g_m R_E)$

Input loading : $R_S < R_{IN} \qquad R_{IN} = r_\pi + \beta R_E$

Table of contents

- Definitions
- Series-shunt FB for Voltage amplifiers.
- Series-series FB for Transconductance amps.