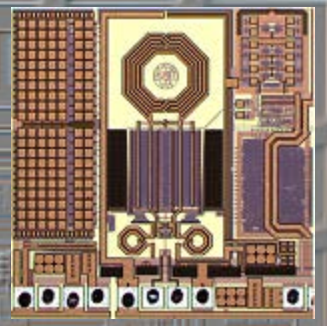

模拟集成电路设计原理

(Principle of Analog Integrated Circuit Design, INF0130025.02)

2014年12月4日

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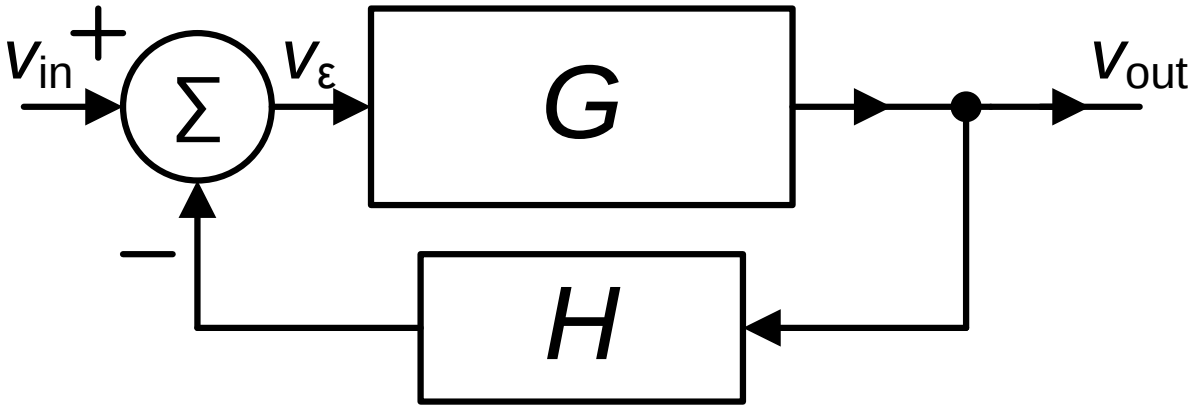
复旦大学/微电子学院/射频集成电路设计研究小组

反馈
电压放大器和跨导放大器

目录

Ref.: W. Sansen : Analog Design Essentials, Springer 2006

理想反馈

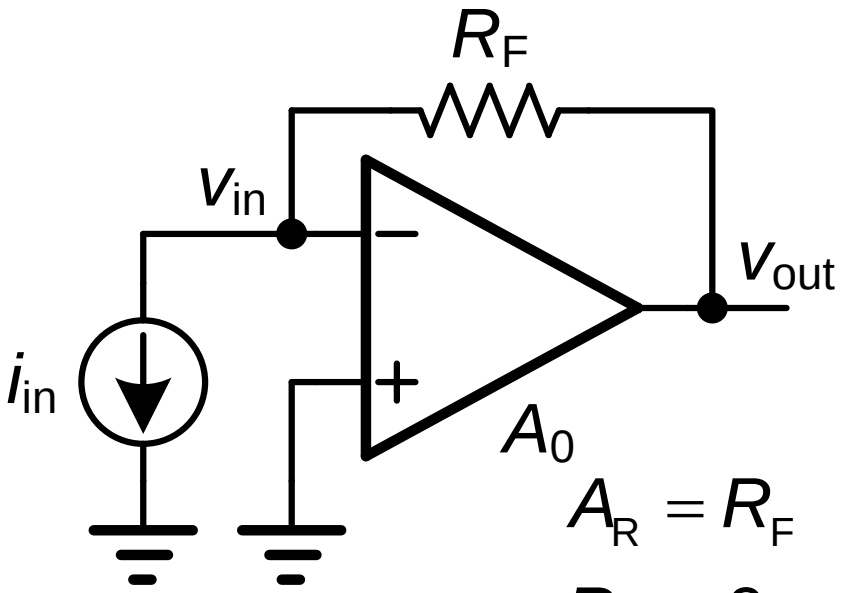


$$\left.\begin{aligned} v_\varepsilon &= v_{in} - Hv_{out} \\ v_{out} &= Gv_\varepsilon \end{aligned}\right\} \quad \frac{v_{out}}{v_{in}} = \frac{G}{1+GH} \approx \frac{1}{H}$$

如果环路增益$LG=GH>>1$

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

并联-并联结构



$$A_R = R_F$$

$$R_{in} \approx 0$$

$$LG = \frac{v_{out}}{v_{in}} = A_{VOL} = A_0$$

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

OL：Open Loop

输入：并联反馈：R_{in} ⇩

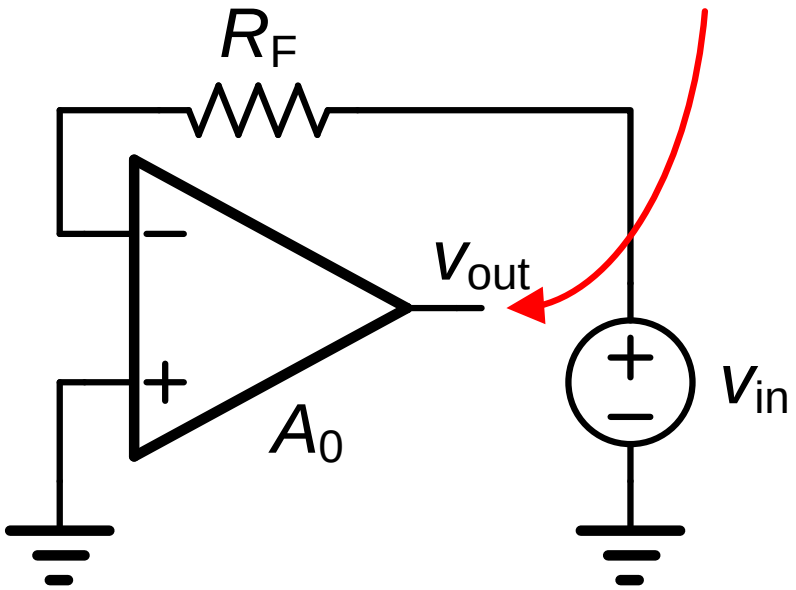
输入并联：$R_{in} = \frac{R_{inOL}}{1+LG}$

输出：并联反馈：R_{out} ⇩

输出并联：$R_{out} = \frac{R_{outOL}}{1+LG}$

计算环路增益 1

Low output resistance !



$$LG = \frac{v_{out}}{v_{in}} = A_{VOL} = A_0$$

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

OL： Open Loop

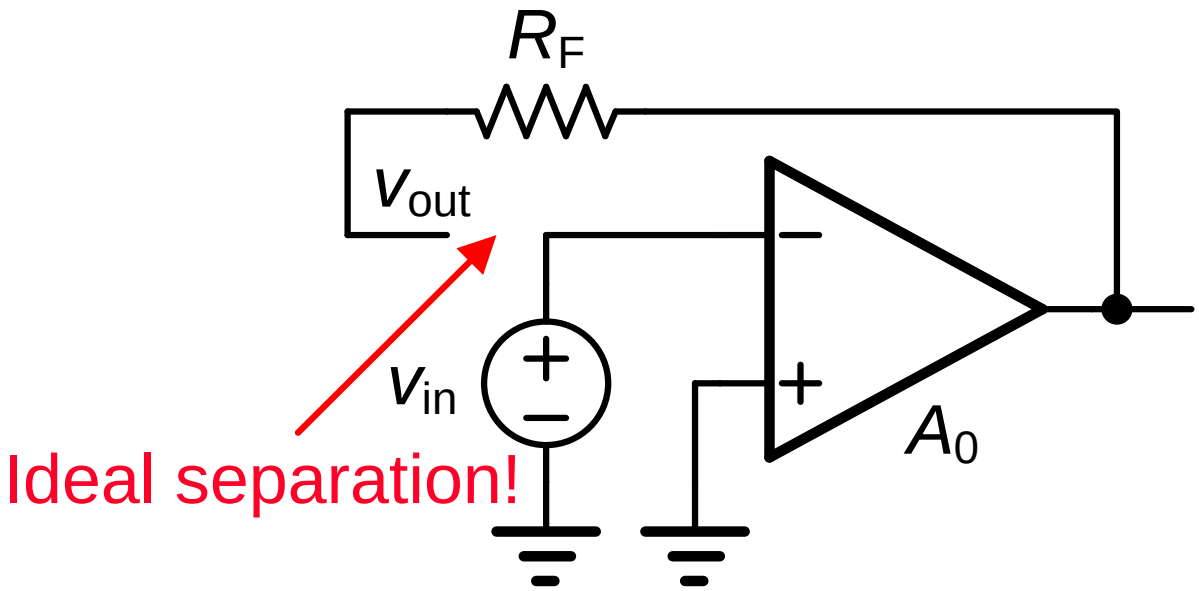
独立源置零：电压源为零电阻，短路

电流源为无穷电阻，开路

在阻抗差异较大的位置打断环路

计算环路增益

计算环路增益 2

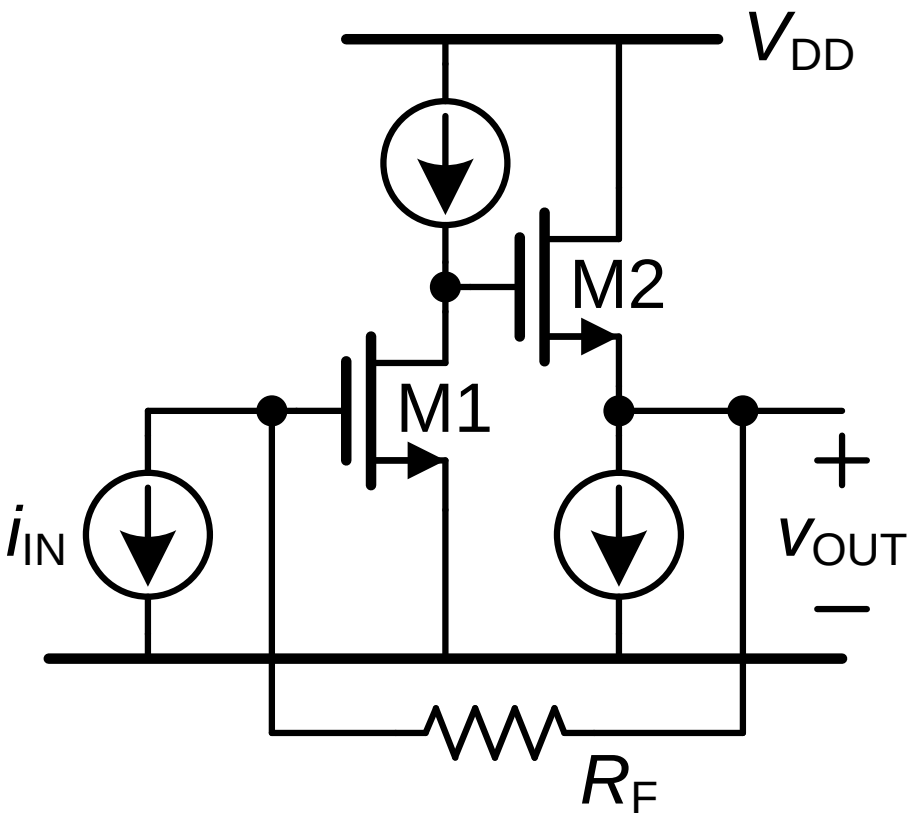


$$LG = \frac{v_{out}}{v_{in}} = A_{VOL} = A_0$$

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

OL： Open Loop

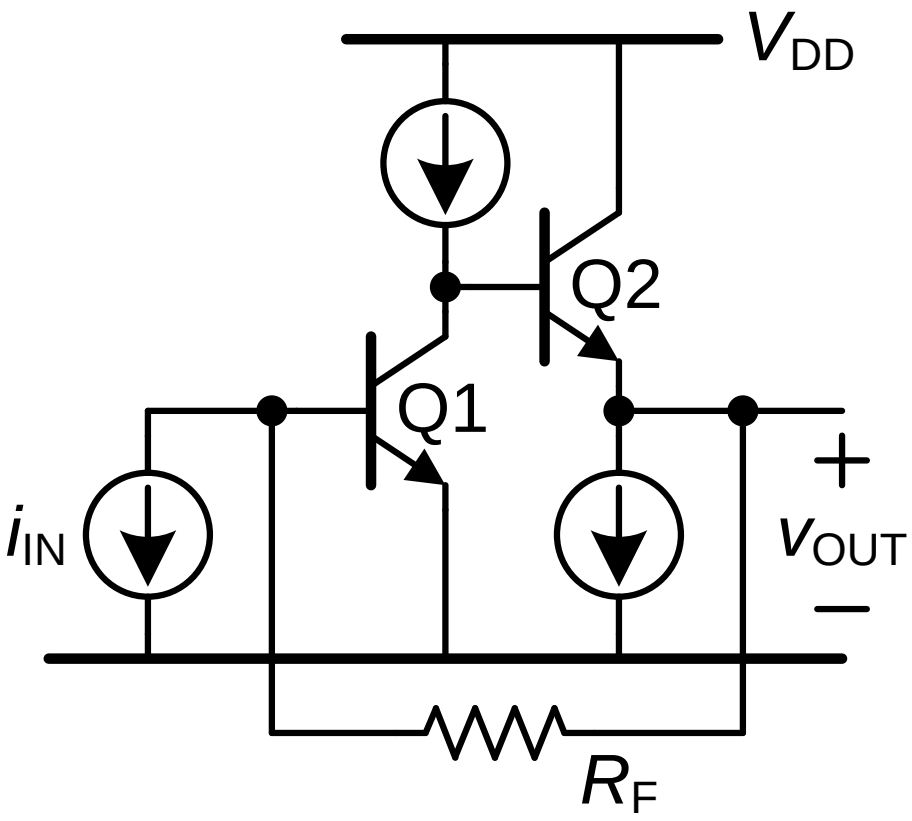
CMOS并联—并联反馈



$$A_R = R_F$$

$$LG = g_{m1} r_{DS1}$$

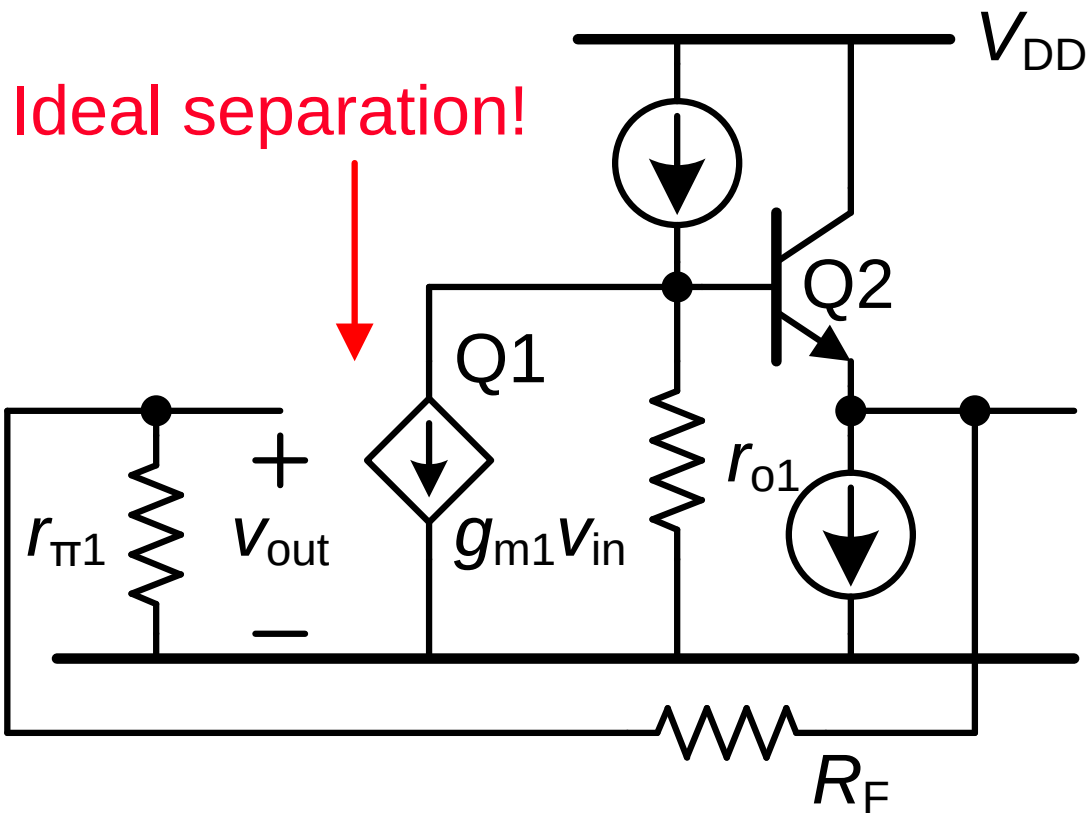
三极管并联—并联反馈



$$A_R = R_F$$

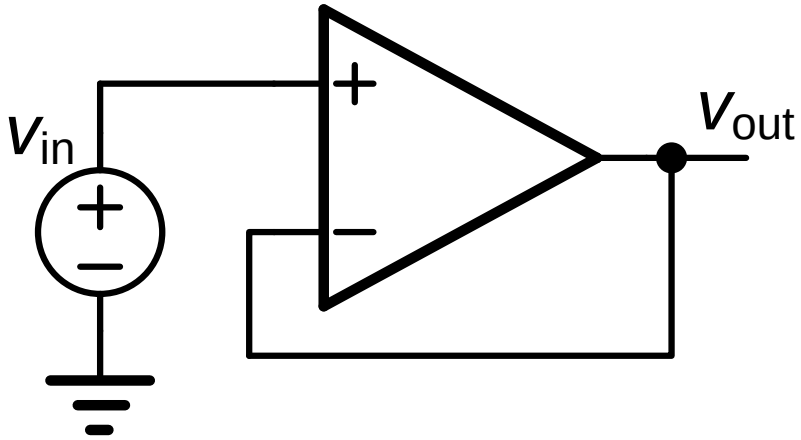
$$LG = g_{m1} r_{o1} \frac{r_{\pi 1}}{R_F + r_{\pi 1}}$$

环路增益



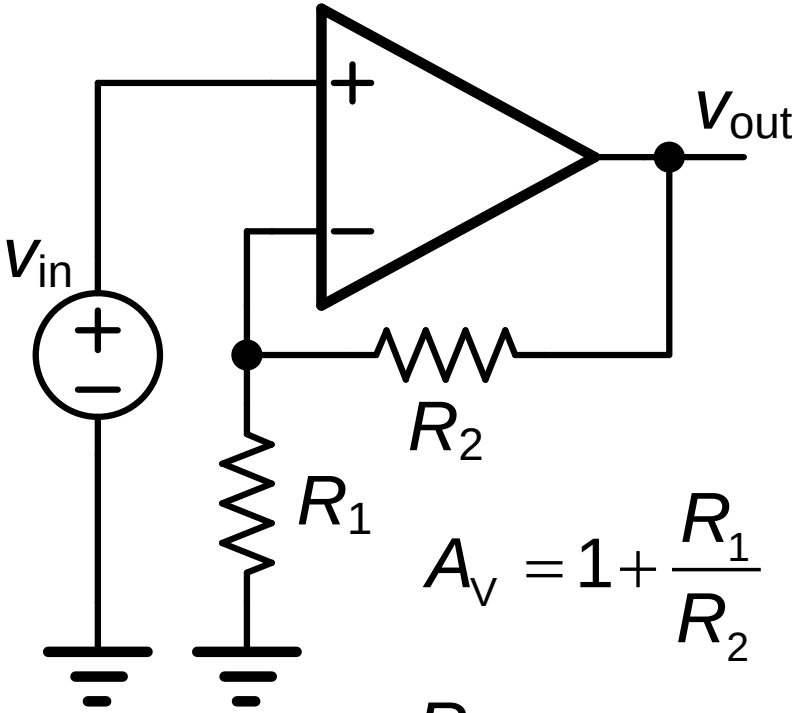
$$LG = g_{m1} r_{o1} \frac{r_{\pi 1}}{R_F + r_{\pi 1}}$$

串联—并联反馈结构



$$A_V = 1$$

$$R_{in} = \infty$$



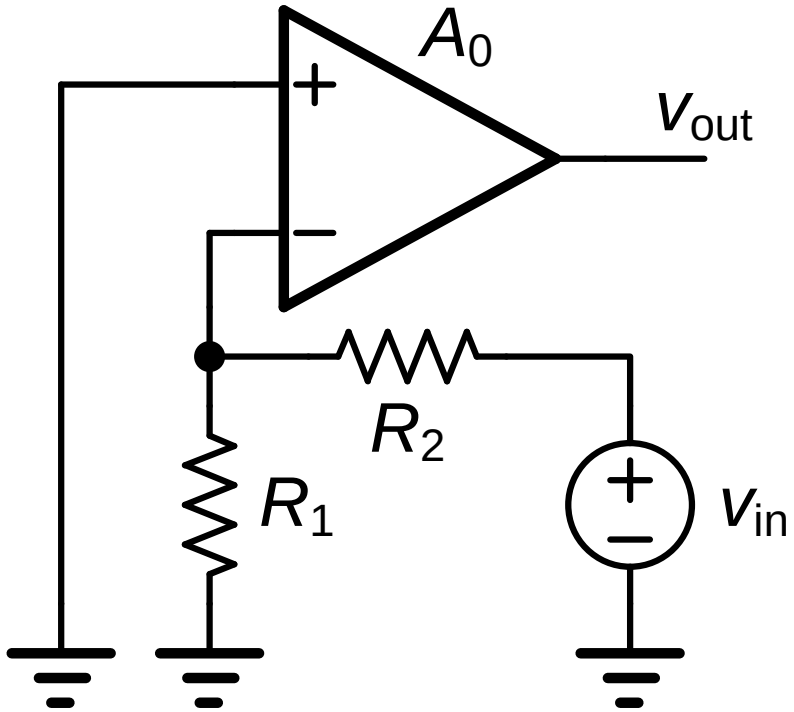
$$A_V = 1 + \frac{R_1}{R_2}$$

$$R_{in} = \infty$$

输入：串联反馈：R_{in} ⇧
输出：并联反馈：R_{out} ⇩

输入：串联反馈：R_{in} ⇧
输出：并联反馈：R_{out} ⇩

计算环路增益



$$LG = \frac{v_{out}}{v_{in}} = \frac{R_1}{R_1 + R_2} A_{VOL}$$

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

OL: Open Loop

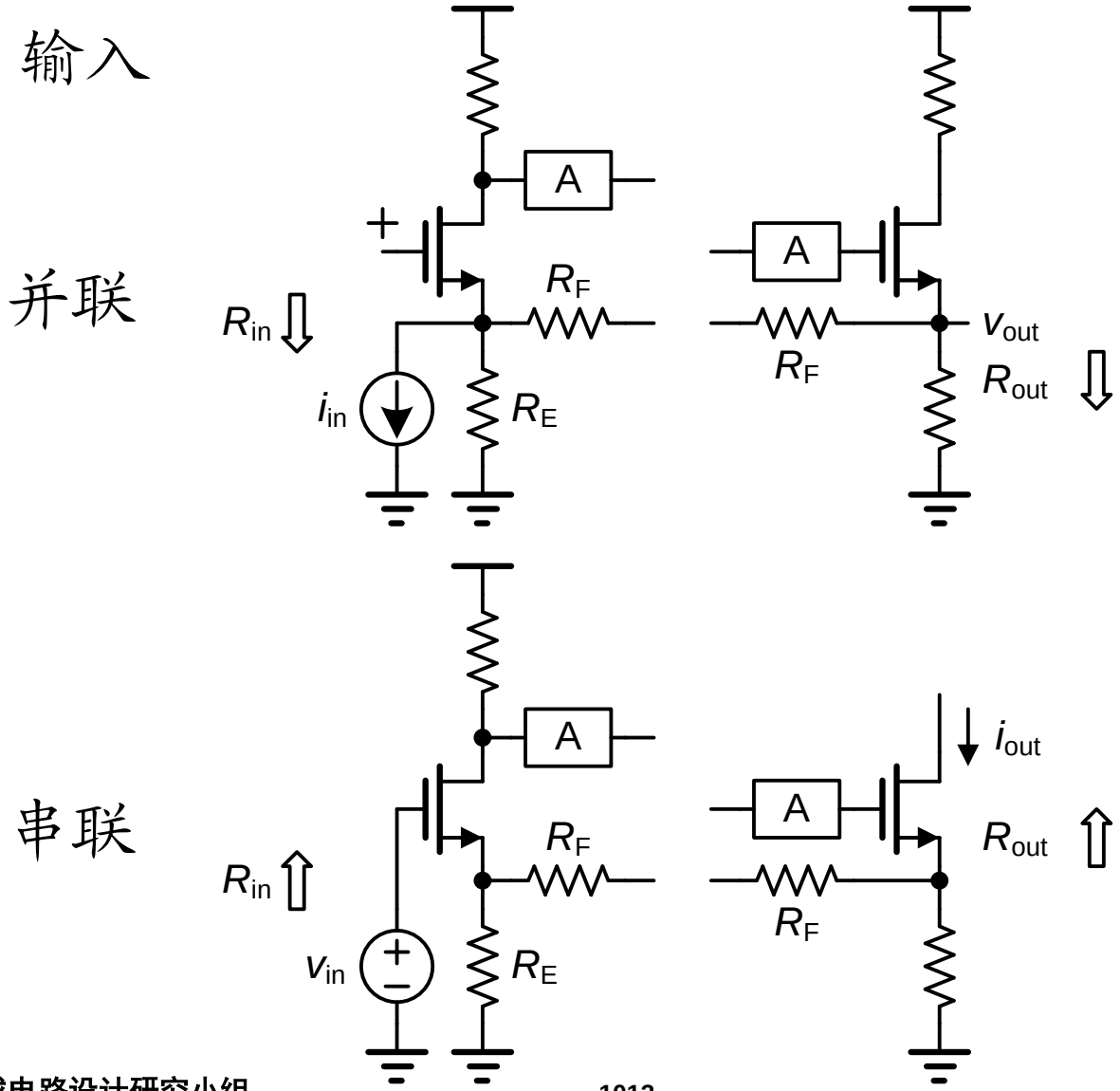
$$A_V = 1 + \frac{R_1}{R_2}$$

$$R_{in} = \infty$$

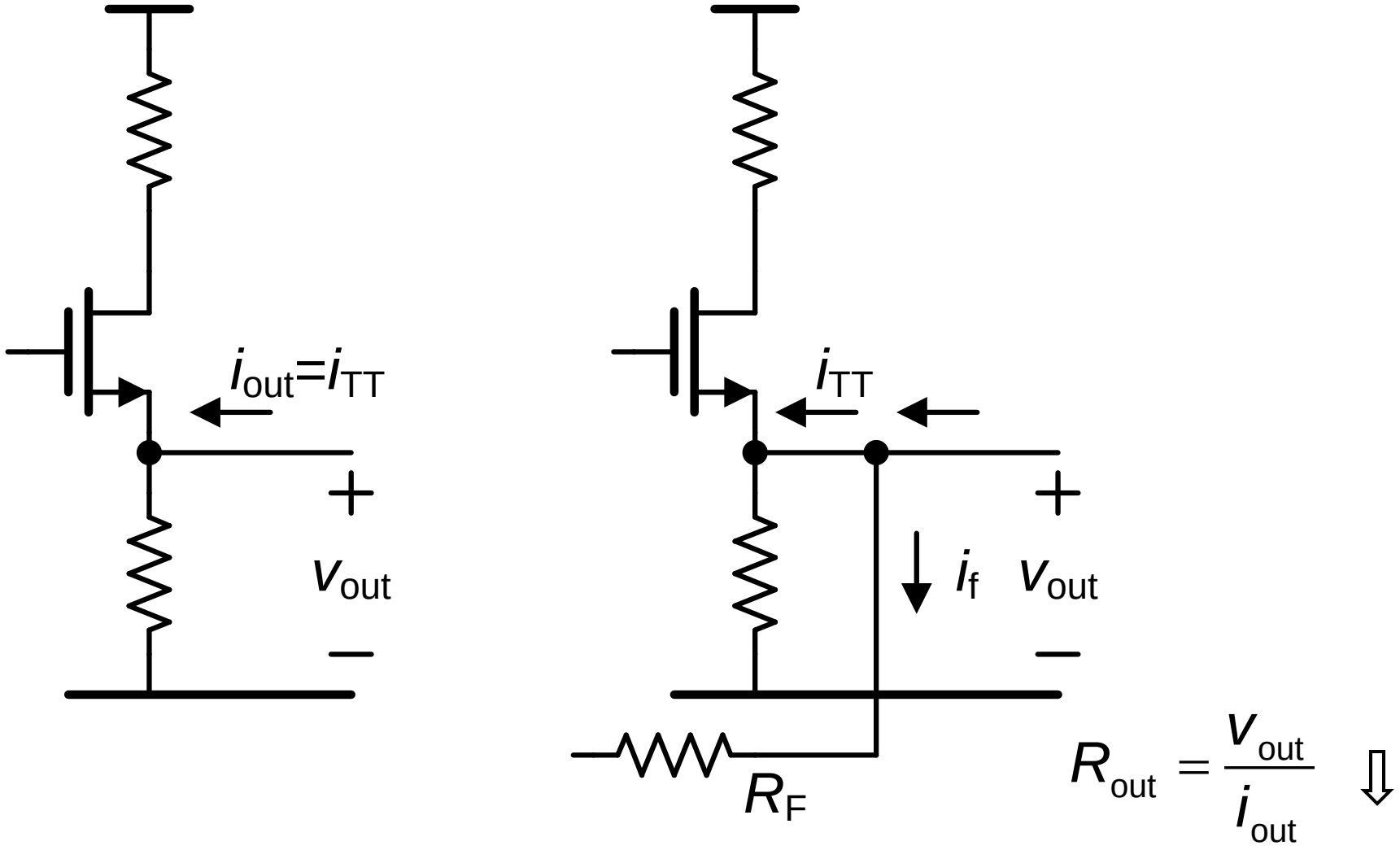
输入：串联反馈：R_{in} ⇧　　输入串联：$R_{in} = R_{inOL}(1 + LG)$

输出：并联反馈：R_{out} ⇩　　输出并联：$R_{out} = \frac{R_{outOL}}{1 + LG}$

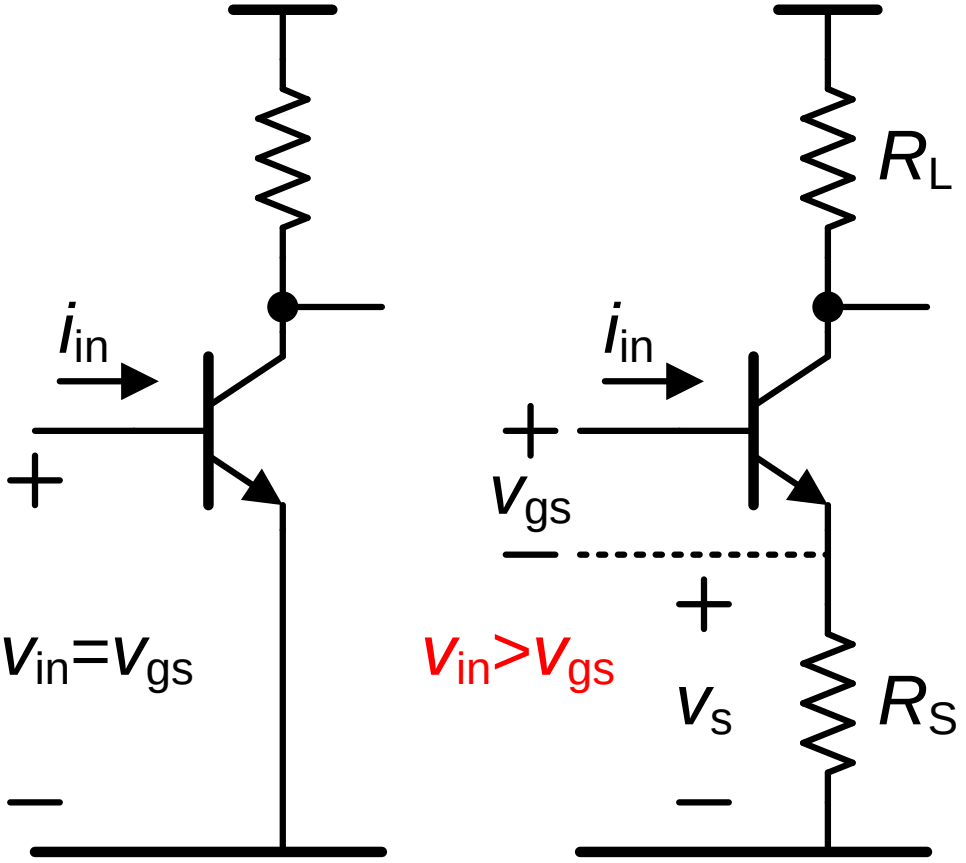
输入和输出的并联和串联



并联反馈减小阻抗



串联反馈增加阻抗



$$R_{in}=\frac{v_{in}}{i_{in}}$$ ⇧

输入和输出阻抗

$\frac{1}{H}=$	输出	并联	串联
输入		$R_{out}=\frac{R_{outOL}}{1+LG}$	$R_{out}=R_{outOL}(1+LG)$
并联	$R_{in}=\frac{R_{inOL}}{1+LG}$	$\frac{v_{out}}{i_{in}}=A_R$	$\frac{i_{out}}{i_{in}}=A_I$
串联 $R_{in}=R_{inOL}(1+LG)$		$\frac{v_{out}}{v_{in}}=A_V$	$\frac{i_{out}}{v_{in}}=A_G$

并联与串联反馈

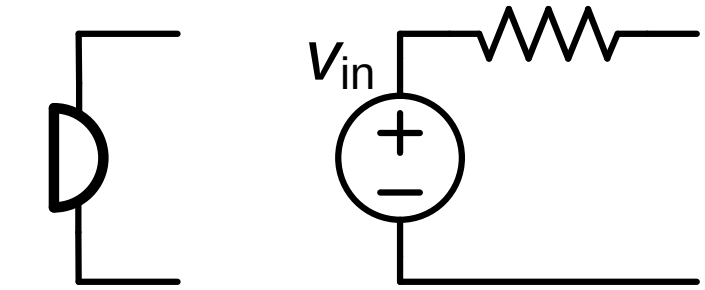
并联反馈
减低阻抗：更宽的带宽

串联反馈
增加阻抗：更低的节点极点

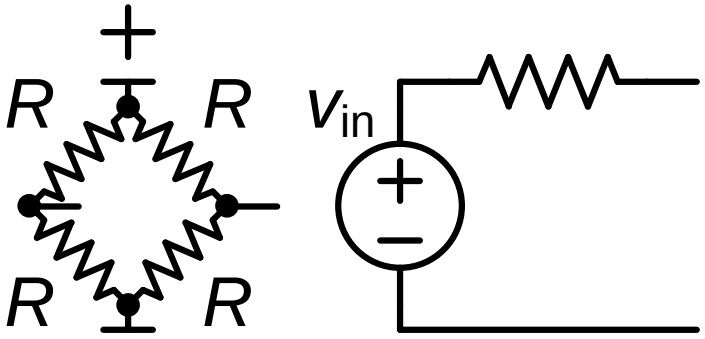
输出并联反馈更加适合与后级进行互连！

输出串联反馈作为电流源！

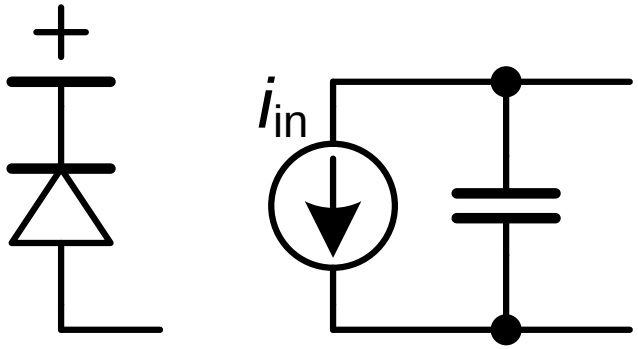
与并联及串联传感器的放大器



麦克风
是电压源
需要高R_{in}的放大器



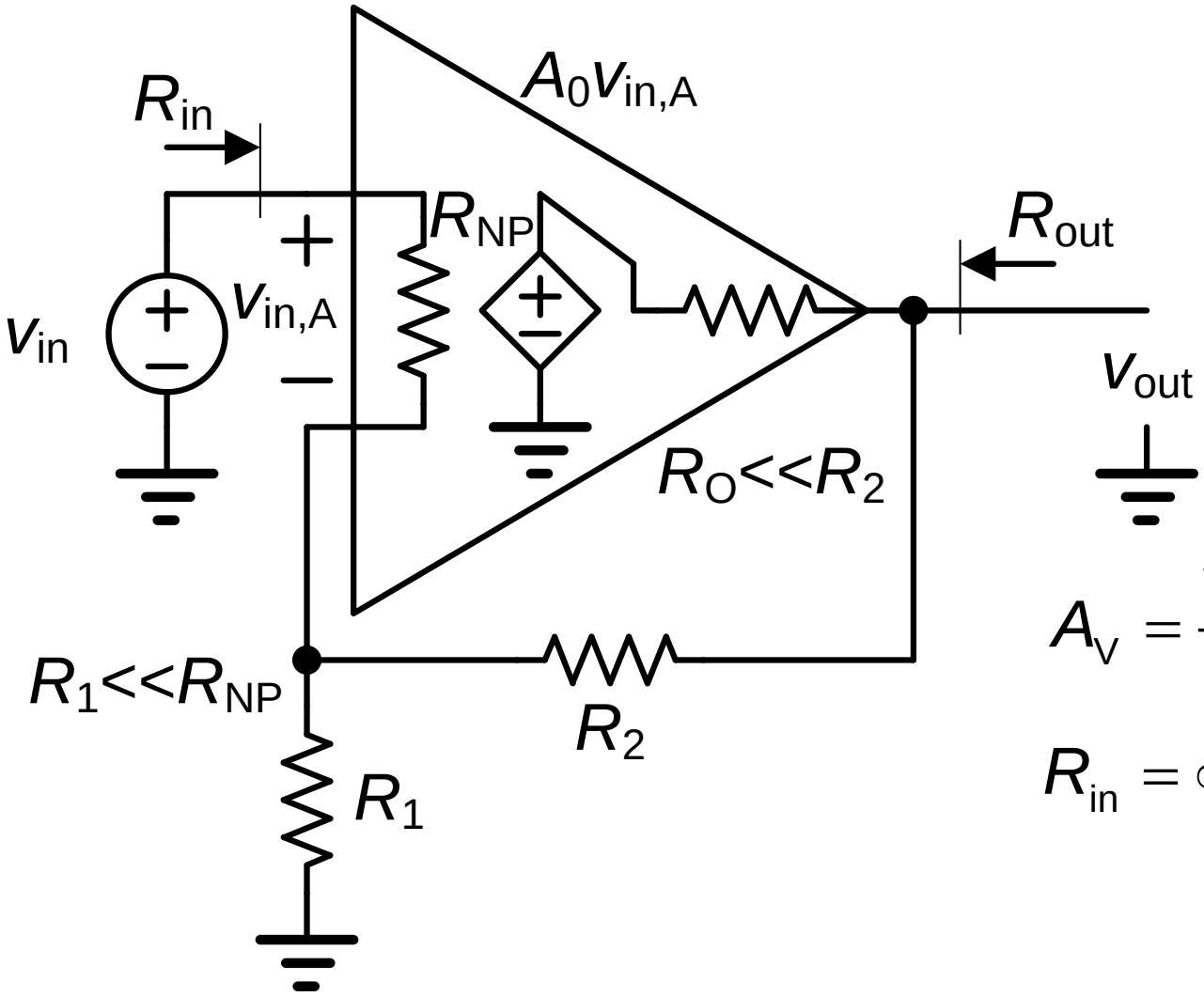
压力，温度
传感器是电压源
需要高R_{in}的放大器



像素，光敏二级管，发光二极管
检测器是电流源
需要低R_{in}的放大器

目录

串联—并联反馈结构

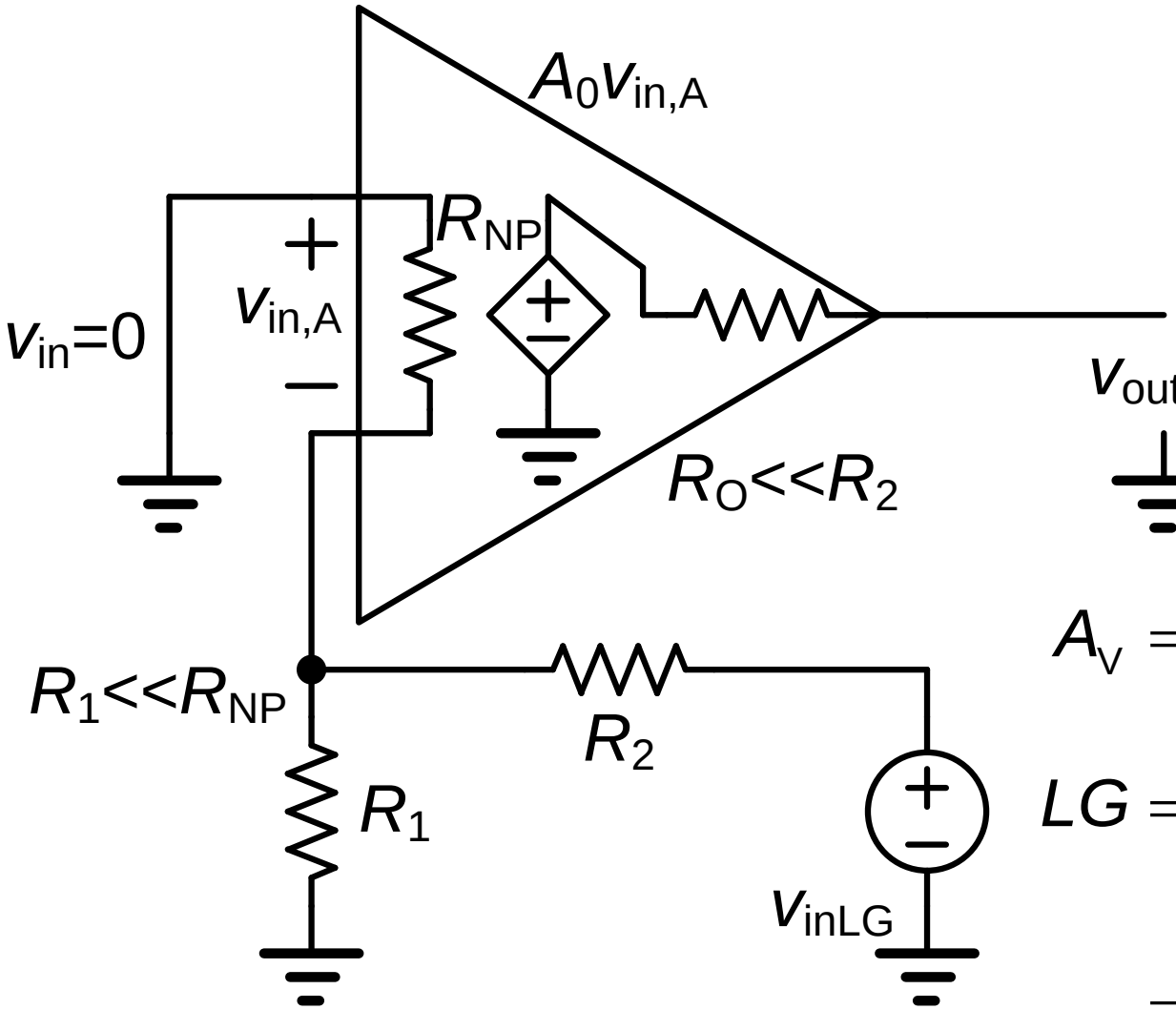


$$A_0 \approx 10^4 ... 10^6$$

$$A_V = \frac{v_{out}}{v_{in}} = \frac{R_1 + R_2}{R_1}$$

$$R_{in} = \infty \quad R_{out} = 0$$

串联—并联反馈：环路增益

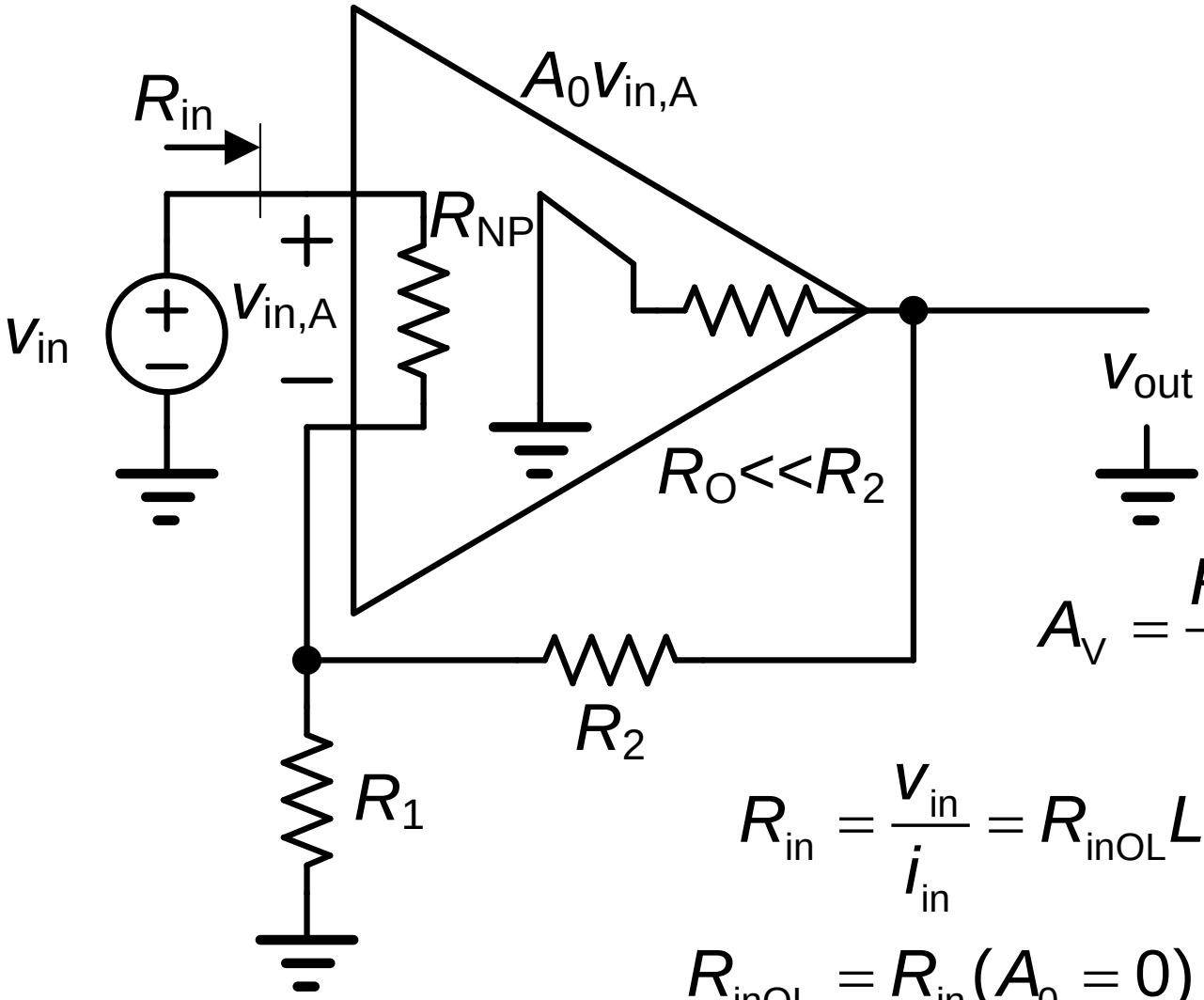


$$A_0 \approx 10^4 \ldots 10^6$$

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

$$LG = \frac{v_{outLG}}{v_{inLG}} = \frac{R_1}{R_1 + R_2} A_0$$

串联—并联反馈：输入阻抗



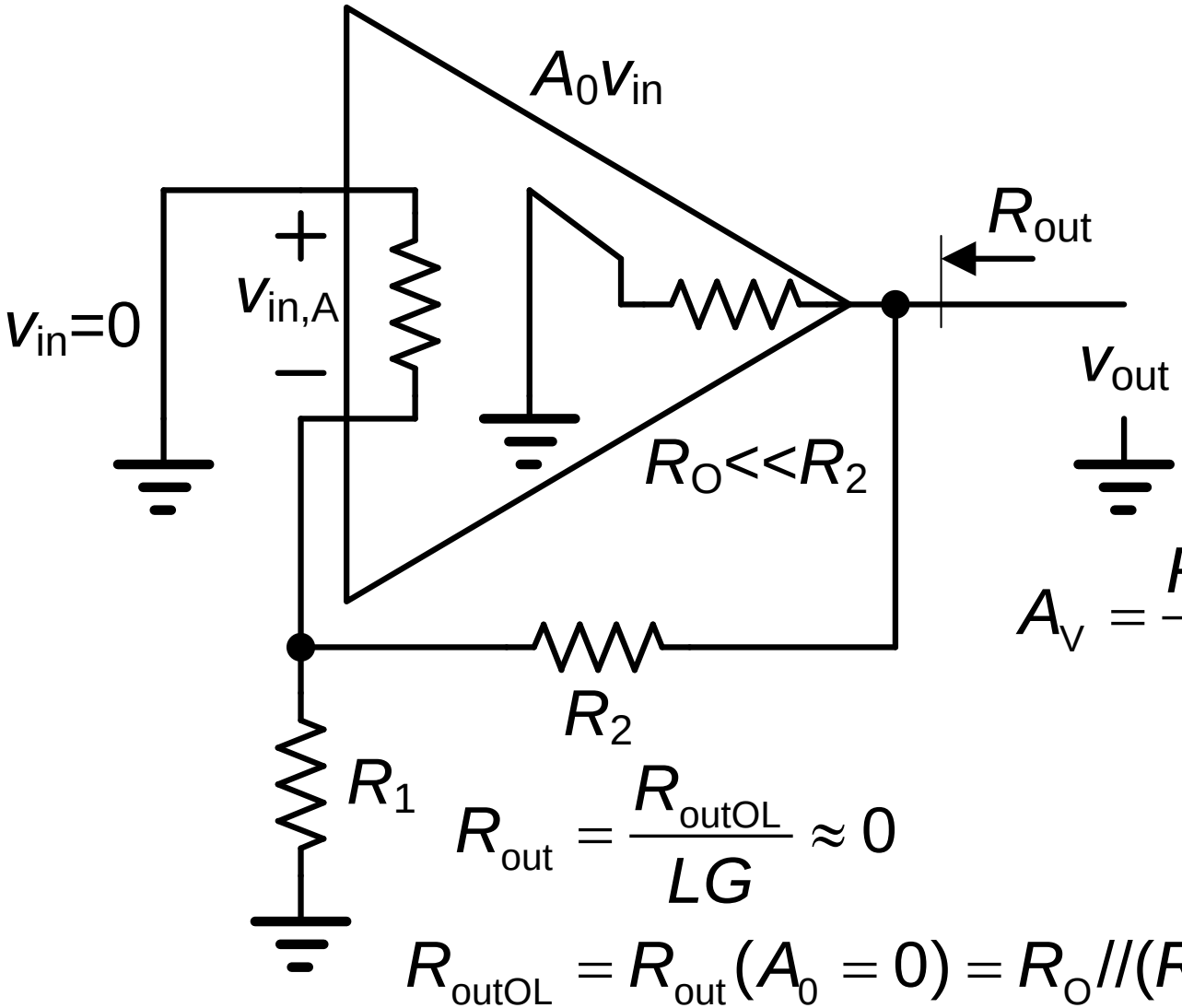
$$A_0 \approx 10^4 ... 10^6$$

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

$$R_{in} = \frac{v_{in}}{i_{in}} = R_{inOL} LG \approx \infty$$

$$R_{inOL} = R_{in}(A_0 = 0) = R_{NP} + R_1 // R_2$$

串联—并联反馈：输出阻抗



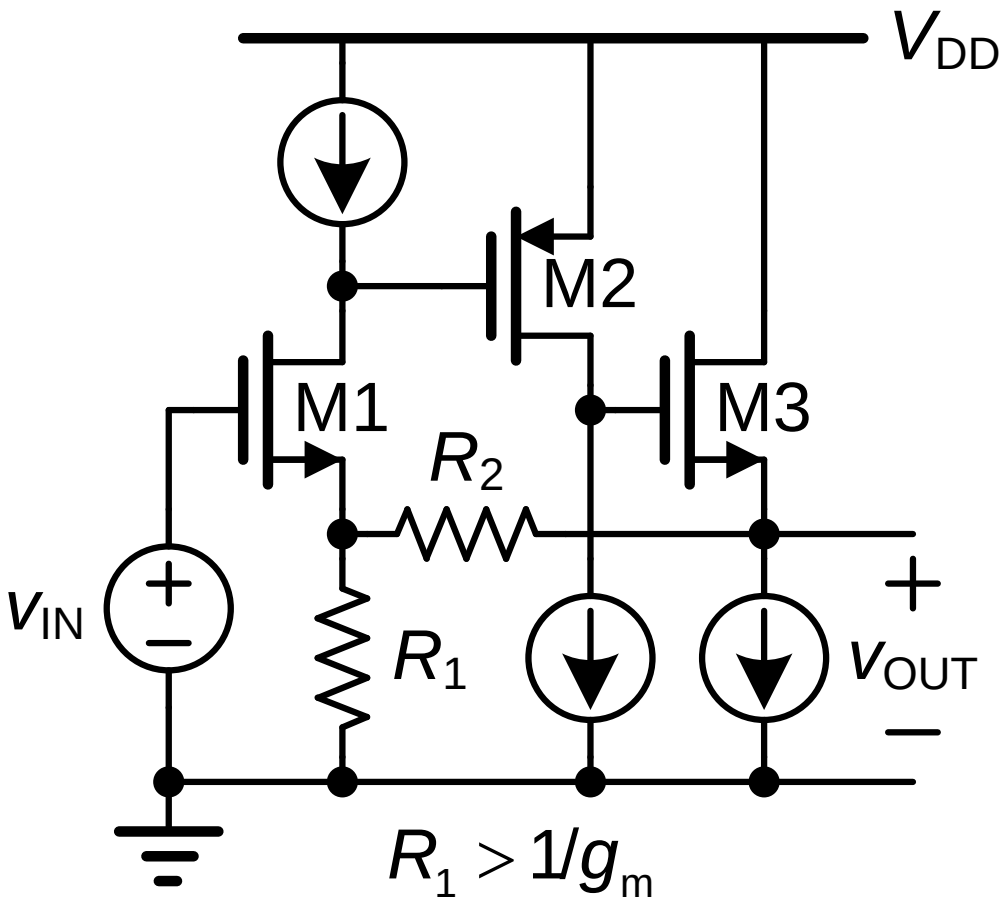
$$A_0 \approx 10^4 ... 10^6$$

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

$$R_{out} = \frac{R_{outOL}}{LG} \approx 0$$

$$R_{outOL} = R_{out}(A_0 = 0) = R_O // (R_2 + R_1 // R_{NP}) \approx R_O$$

串联—并联反馈：环路增益



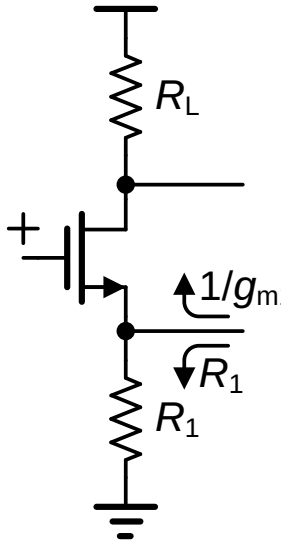
$$A_V = \frac{R_1 + R_2}{R_1}$$

$$LG = ?$$

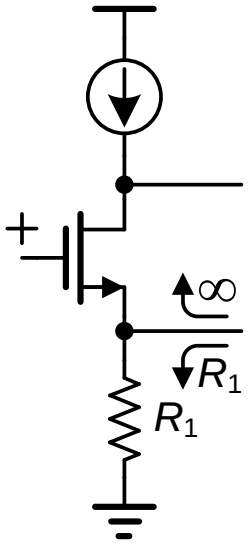
串联—并联反馈：串联输入

$R_L < r_{DS}$

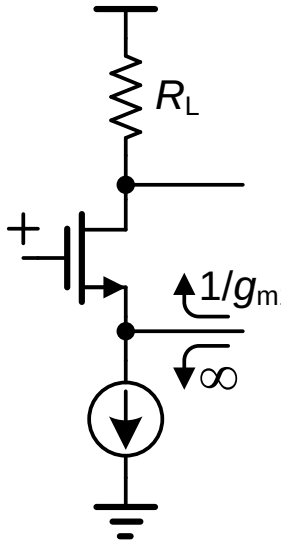
$R_1 > 1/g_m$



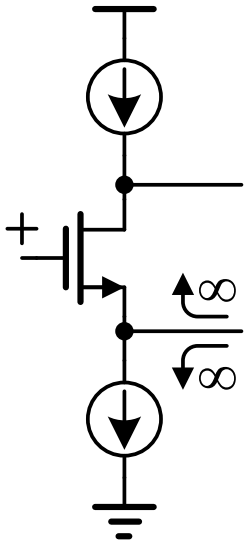
$R_{in} \approx 1/g_m$



$R_{in} = R_1$



$R_{in} = 1/g_m$



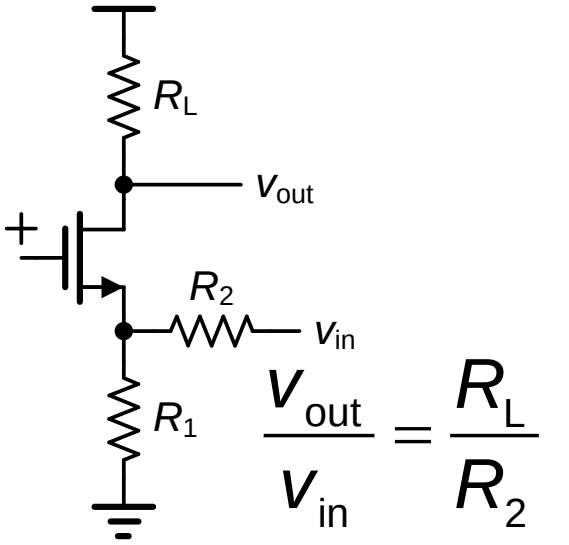
$R_{in} = \infty$

串联—并联反馈：增益输入级

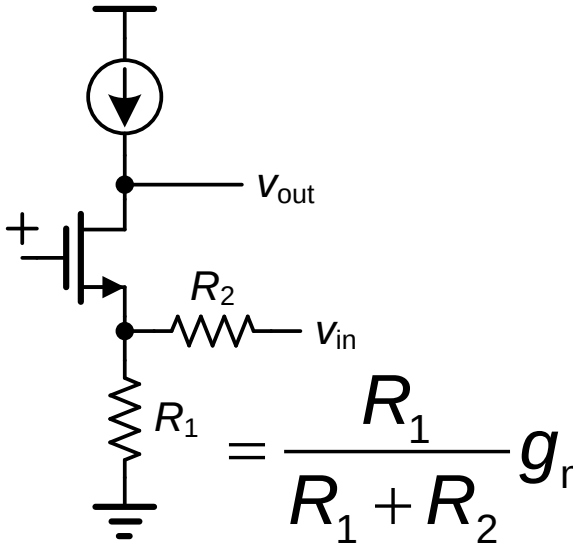
$R_L < r_{DS}$

$R_2 > 1/g_m$

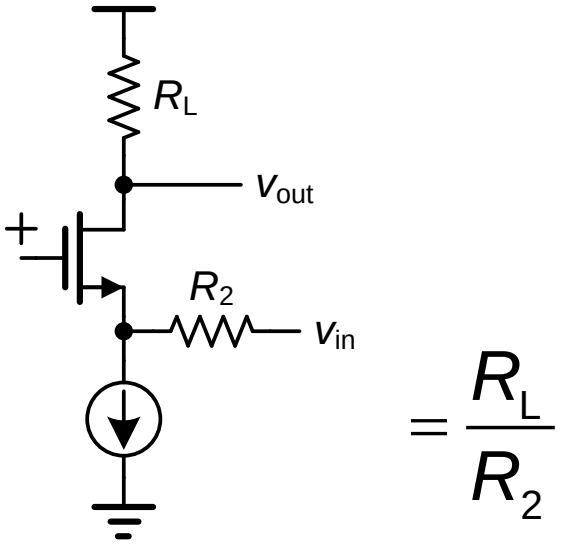
$R_1 > 1/g_m$



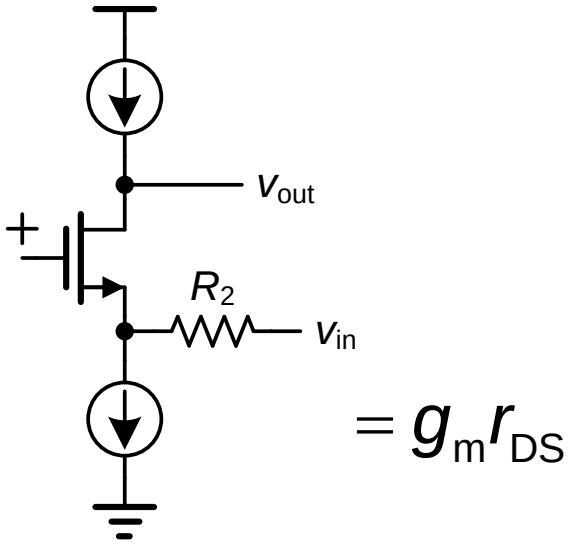
$$\frac{v_{out}}{v_{in}} = \frac{R_L}{R_2}$$



$$= \frac{R_1}{R_1 + R_2} g_m r_{DS}$$

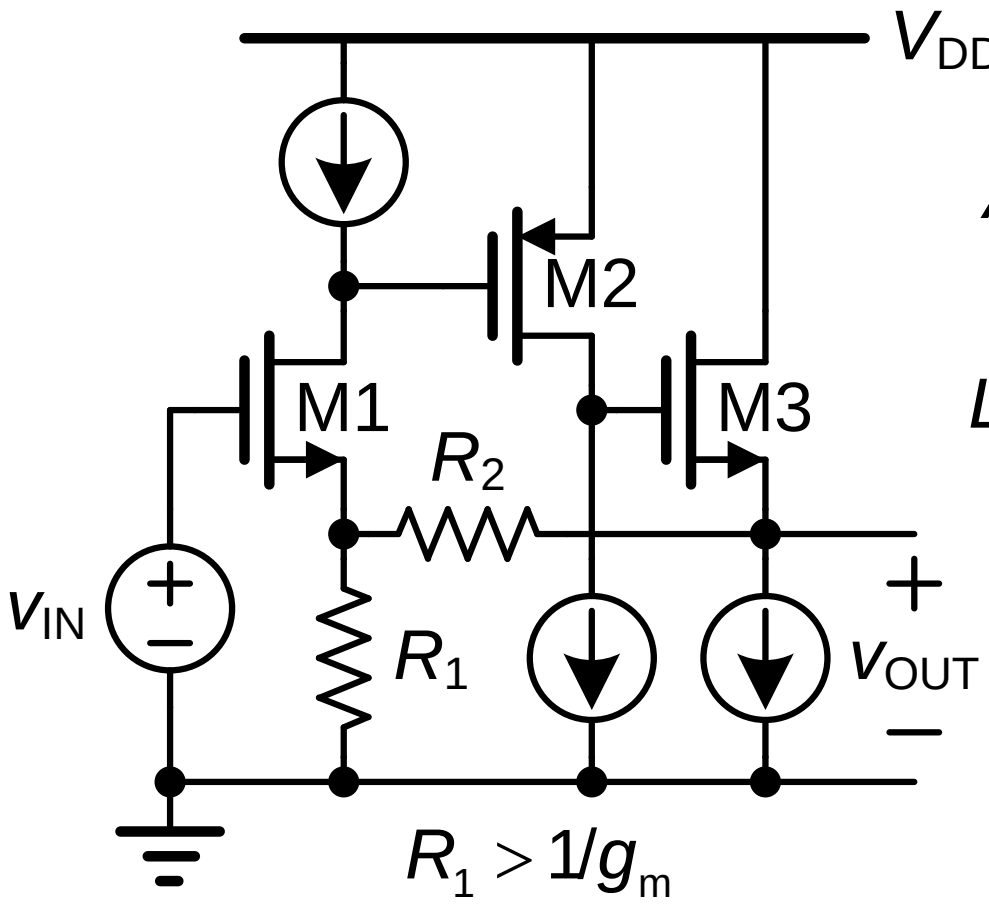


$$= \frac{R_L}{R_2}$$



$$= g_m r_{DS}$$

串联—并联反馈：输入与输出阻抗



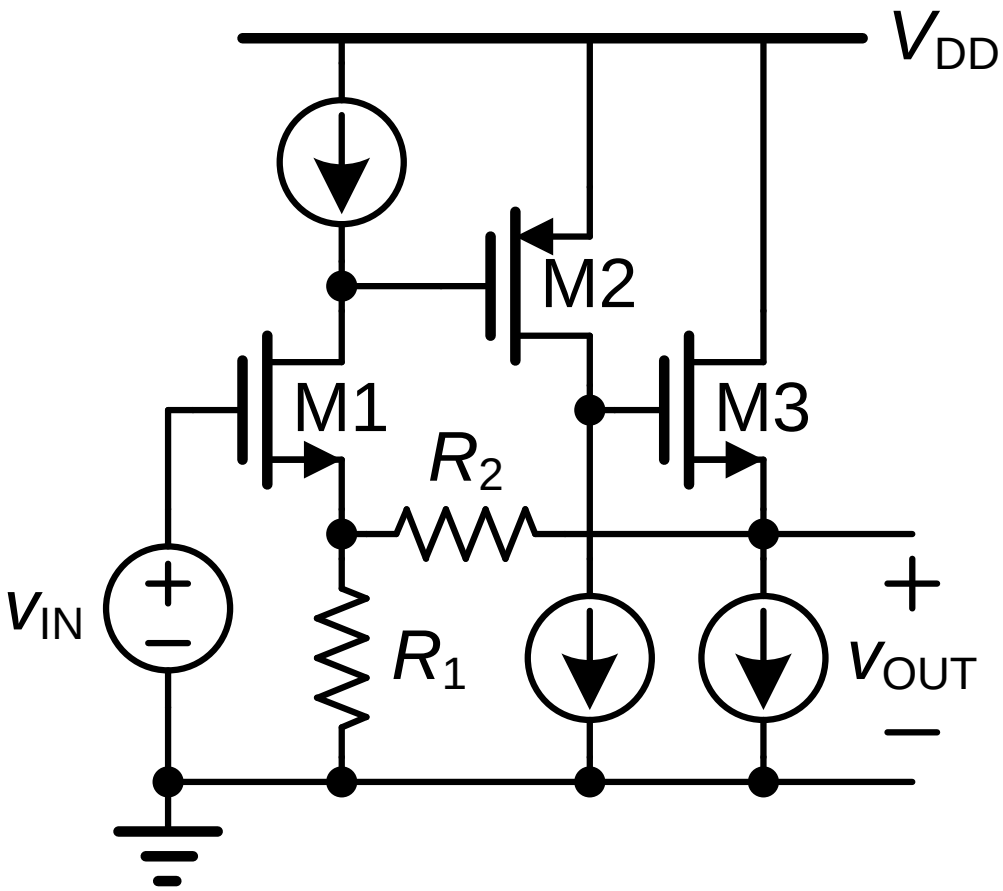
$$A_V = \frac{R_1 + R_2}{R_1}$$

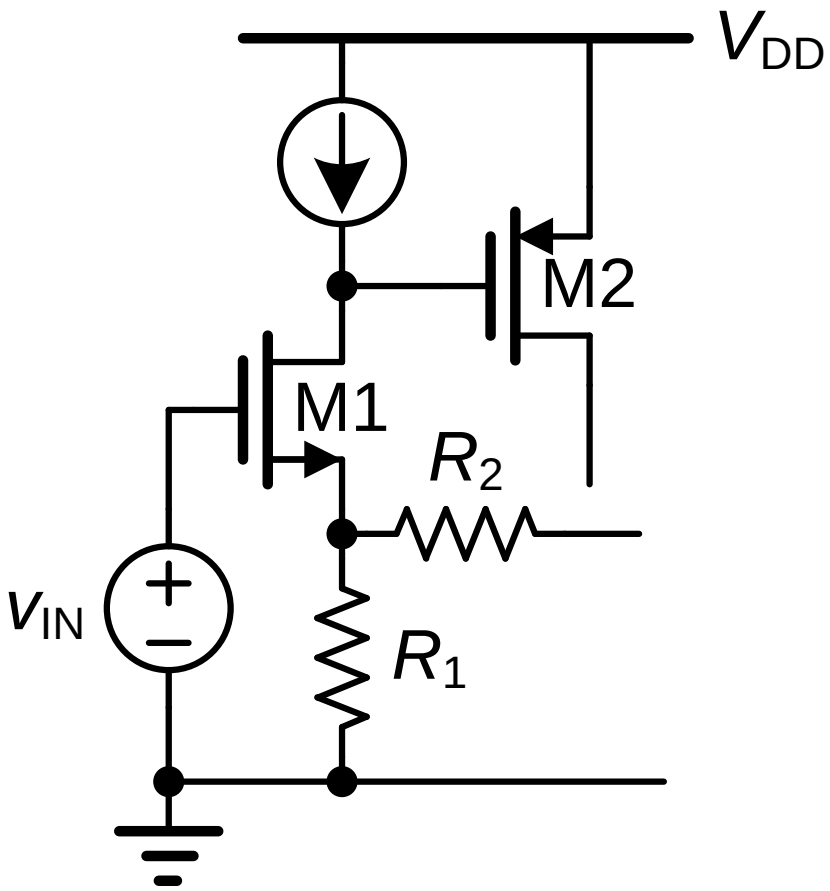
$$LG = g_{m1} r_{DS1} g_{m2} r_{DS2} \frac{R_1}{R_1 + R_2}$$

$$R_{in} \approx \infty$$

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

串联—并联反馈：环路增益

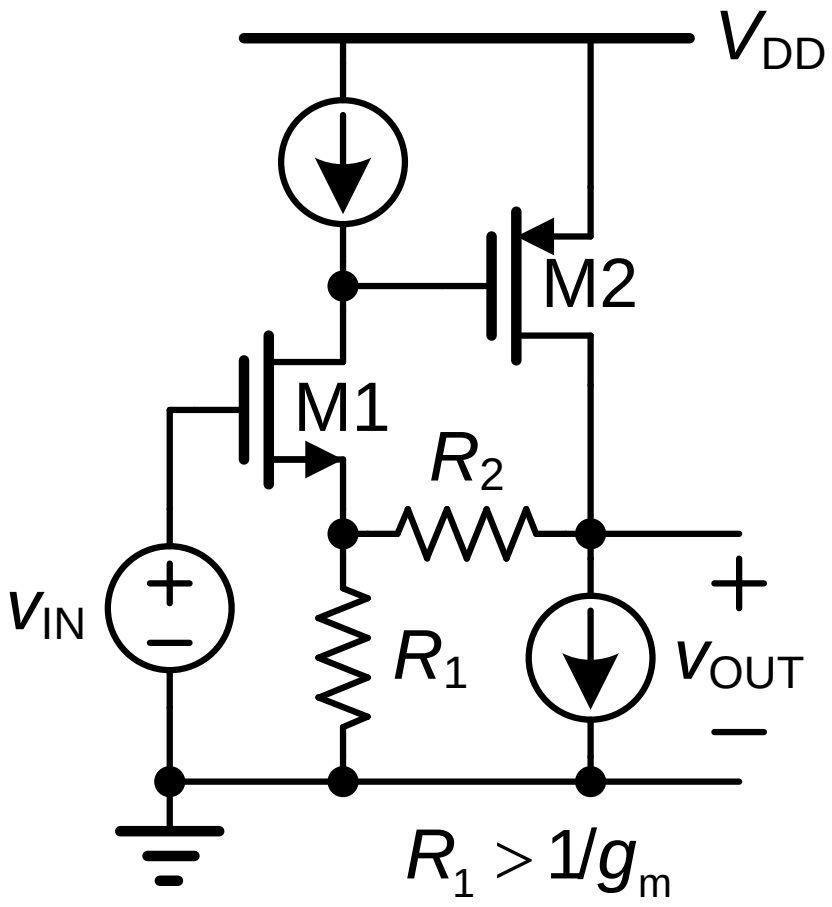




$$LG = g_{m2} r_{DS2} \frac{R_L}{R_2}$$

$$LG = g_{m1} r_{DS1} g_{m2} r_{DS2} \frac{R_1}{R_1 + R_2}$$

串联—并联反馈：输出负载效应



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

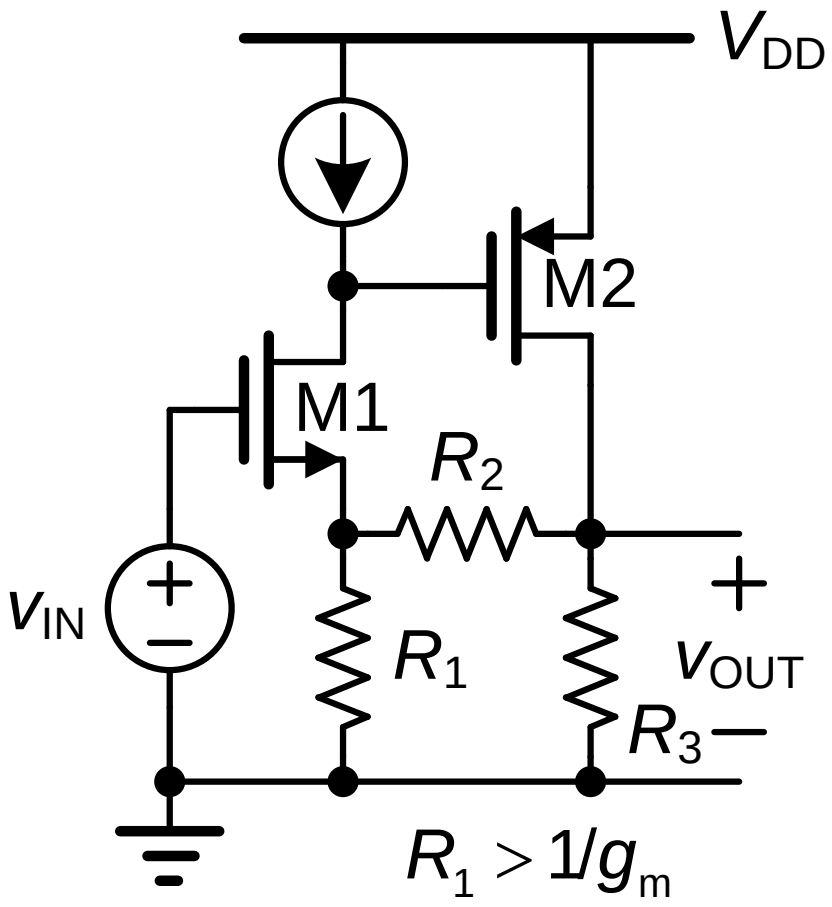
$$LG = g_{m1} r_{DS1} g_{m2} \frac{r_{DS2} R_1}{R_1 + R_2 + r_{DS2}}$$

$$R_{in} \approx \infty$$

$$R_{out} = \frac{(R_1 + R_2) // r_{DS2}}{LG} \approx 0 \; ??$$

输出负载：$R_2 \approx r_{DS2}$

串联—并联反馈：接R的输出负载



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

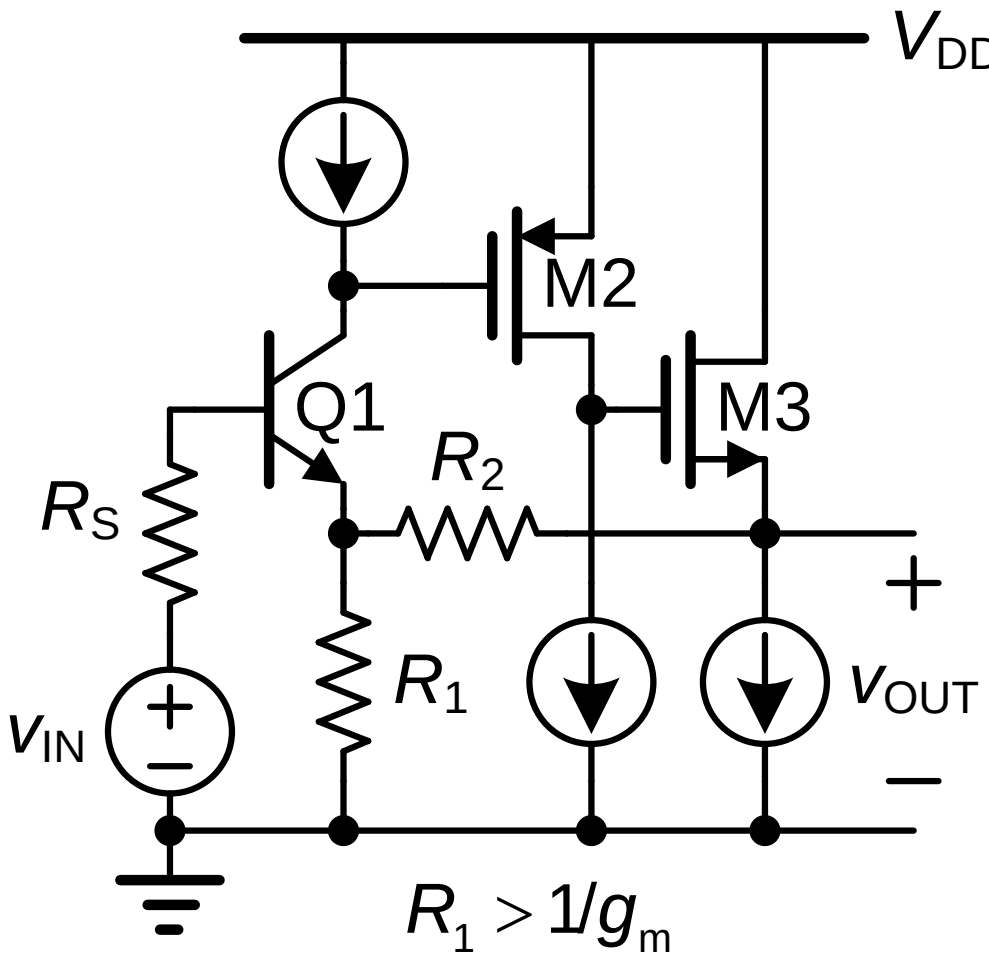
$$LG = g_{m1} r_{DS1} g_{m2} \frac{(r_{DS2} // R_3) R_1}{R_1 + R_2 + r_{DS2} // R_3}$$

$$R_{in} \approx \infty$$

$$R_{out} = \frac{(R_1 + R_2) // r_{DS2} // R_3}{LG} \approx 0 \; ??$$

输出负载：$R_2 \approx R_3 \approx r_{DS2}$

BiCMOS串联—并联



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

$$LG = g_{m1} r_{o1} g_{m2} r_{DS2} \frac{R_1}{R_1 + R_2}$$

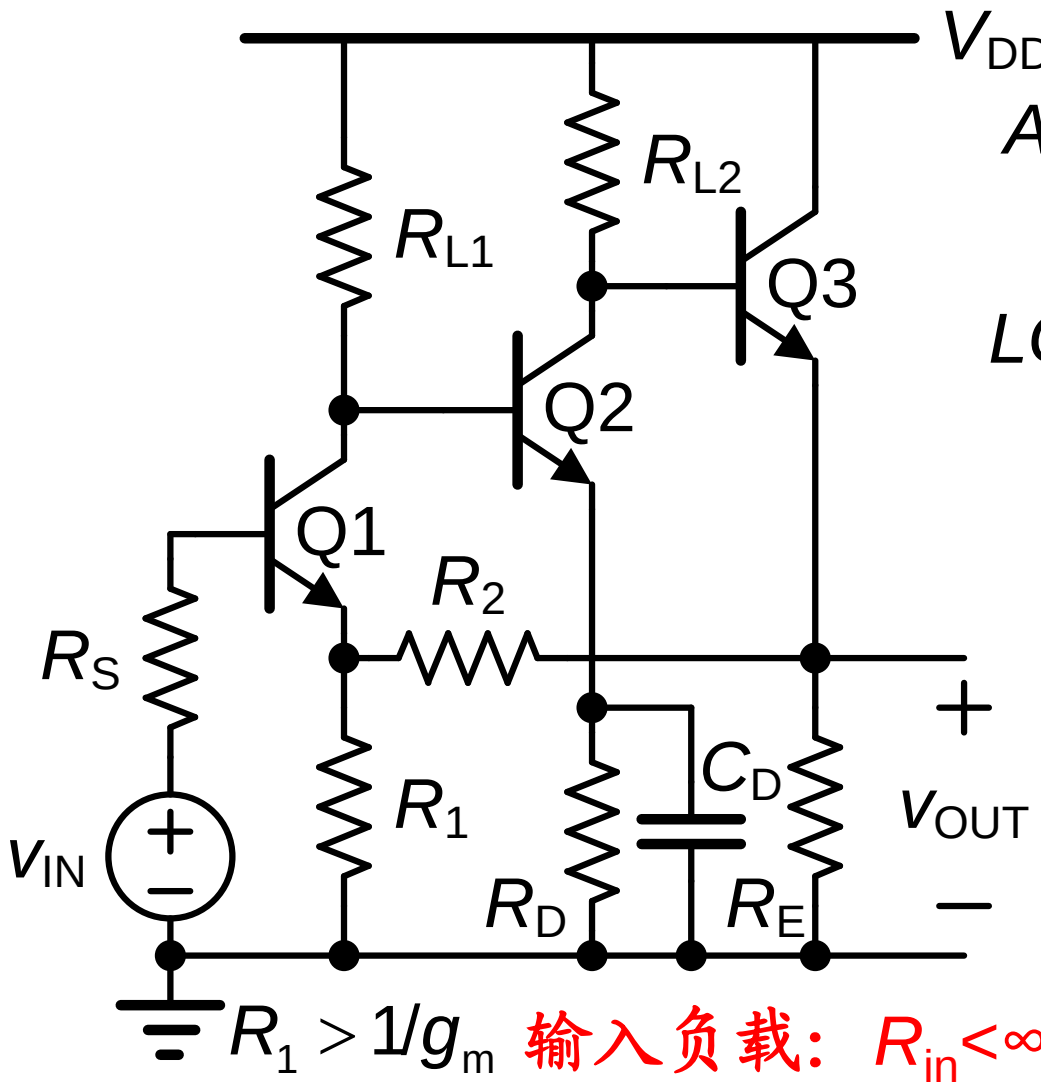
$$R_{in} = R_{inOL} LG \approx \infty$$

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

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

输入负载：$R_{in} < \infty$

接电阻的串联—并联反馈



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

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

$$R_{in} = R_{inOL} LG \approx \infty$$

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

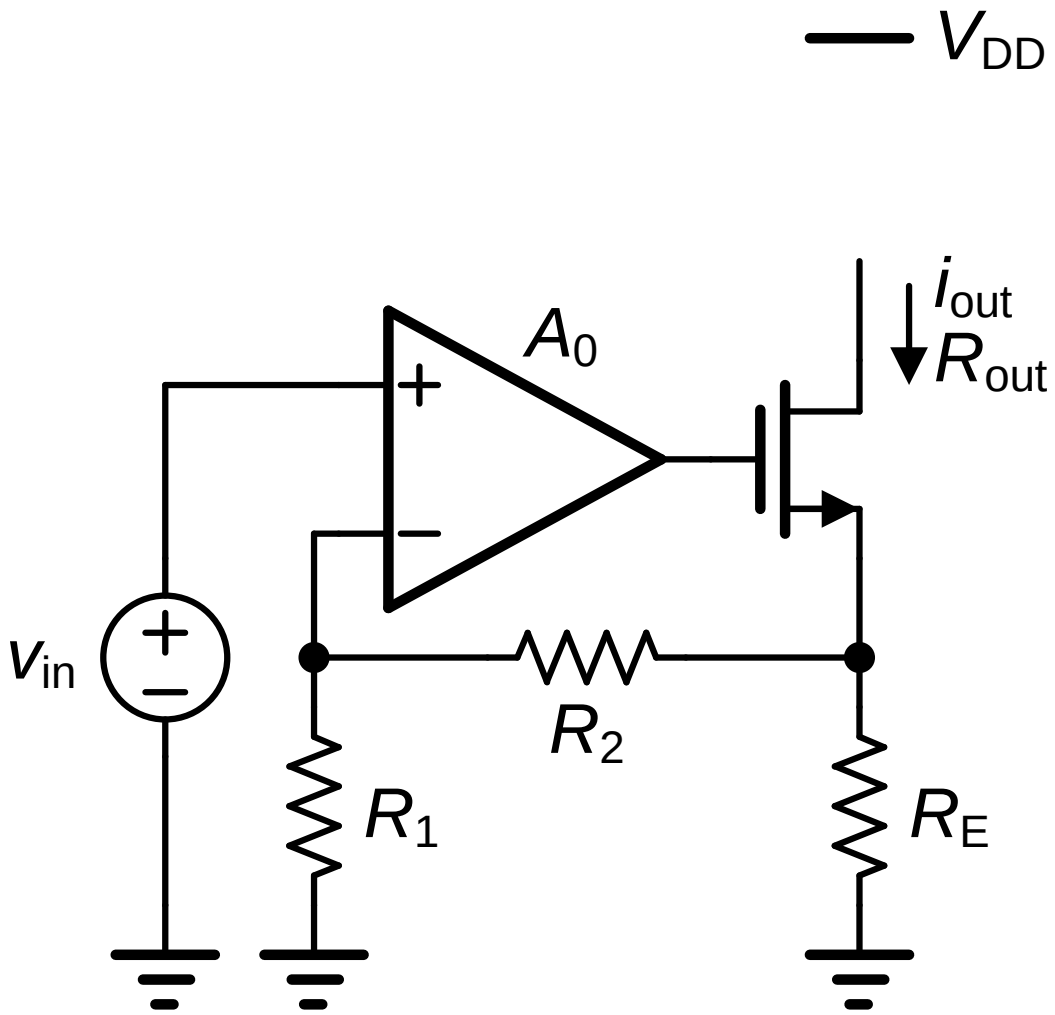
$$R_{out} = \frac{R_{outOL}}{LG} \approx 0$$

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

$R_1 > 1/g_m$ 输入负载：$R_{in} < \infty$

目录

串联—串联反馈：增益



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

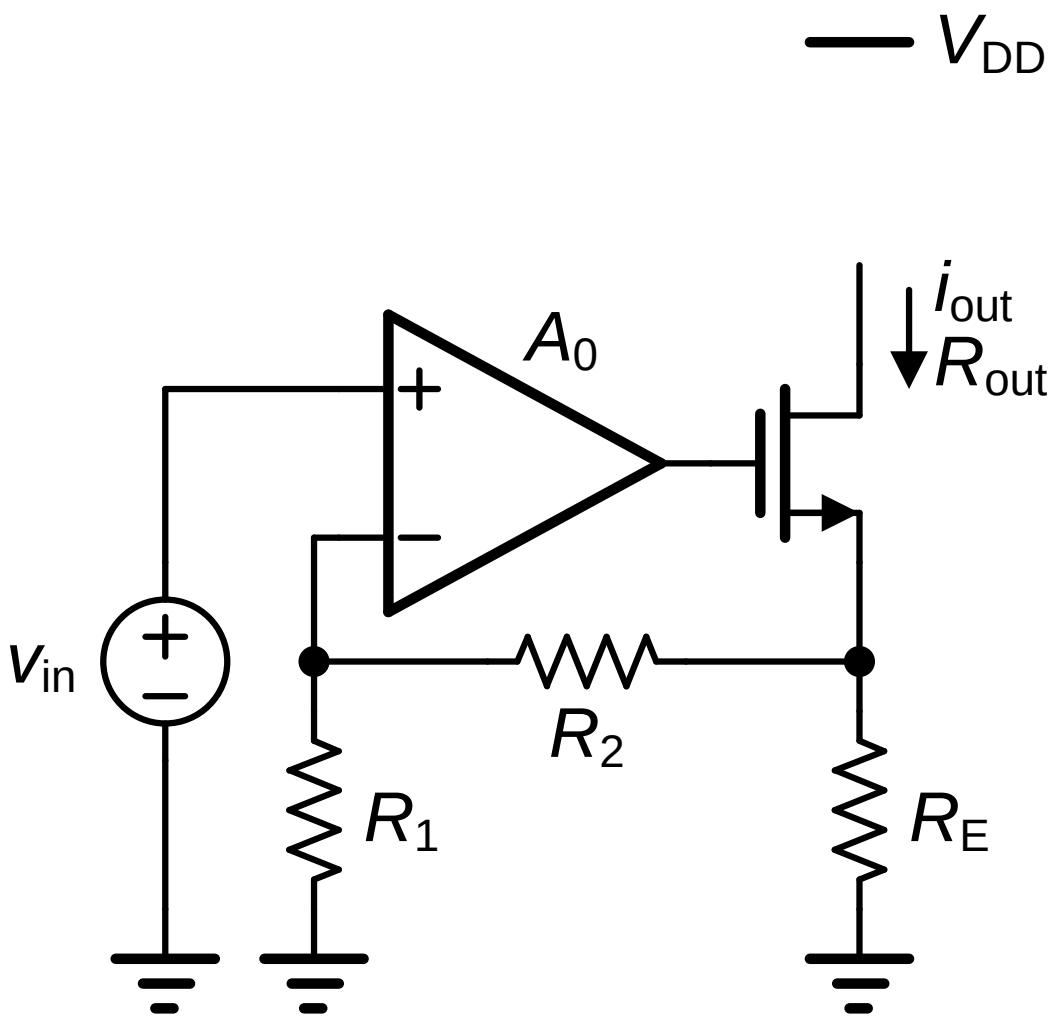
$$A_{GOL} = A_0 \frac{1}{R_{E12}}$$

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

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

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

串联—串联反馈：输入和输出电阻



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

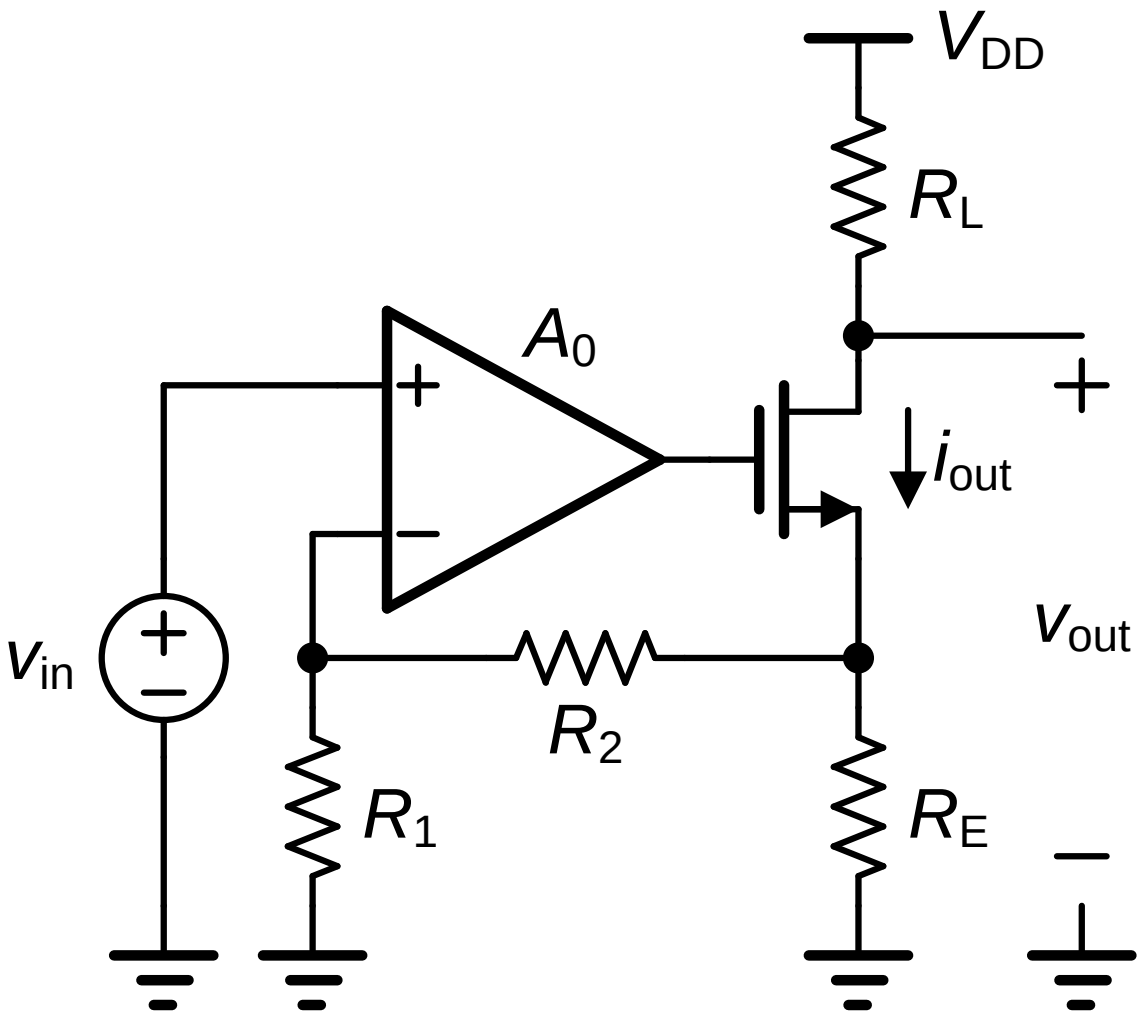
$$R_{in} \approx \infty$$

$$R_{outOL} = r_{DS}(1 + g_m R_{E12})$$

$$R_{out} = R_{OUTOL} LG \approx \infty$$

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

接R_L负载的串联—串联反馈



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

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

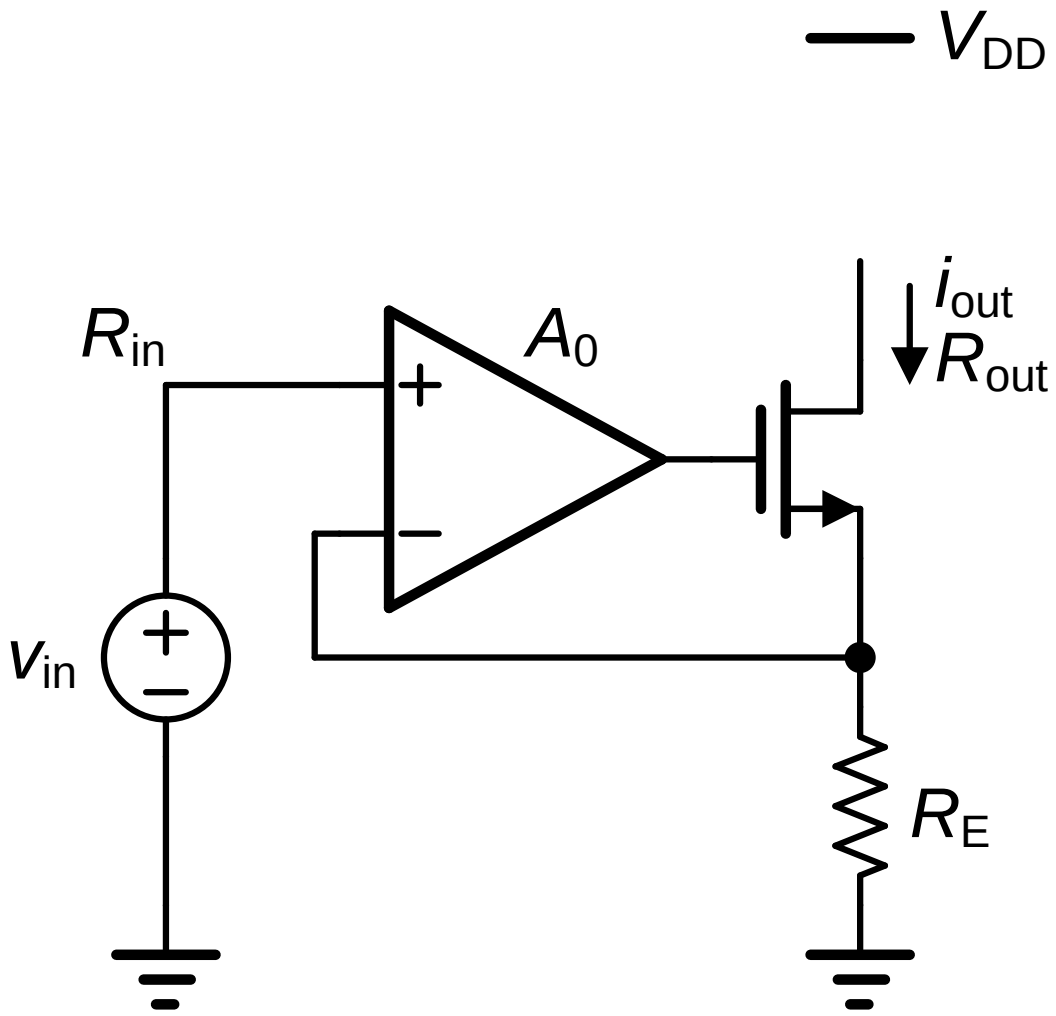
$$= -\frac{R_1 + R_2 + R_E}{R_1}\frac{R_L}{R_E}$$

$$R_{in} \approx \infty$$

$$R_{out} = R_L$$

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

理想电流源



$$i_{out} = \frac{v_{in}}{R_E}$$

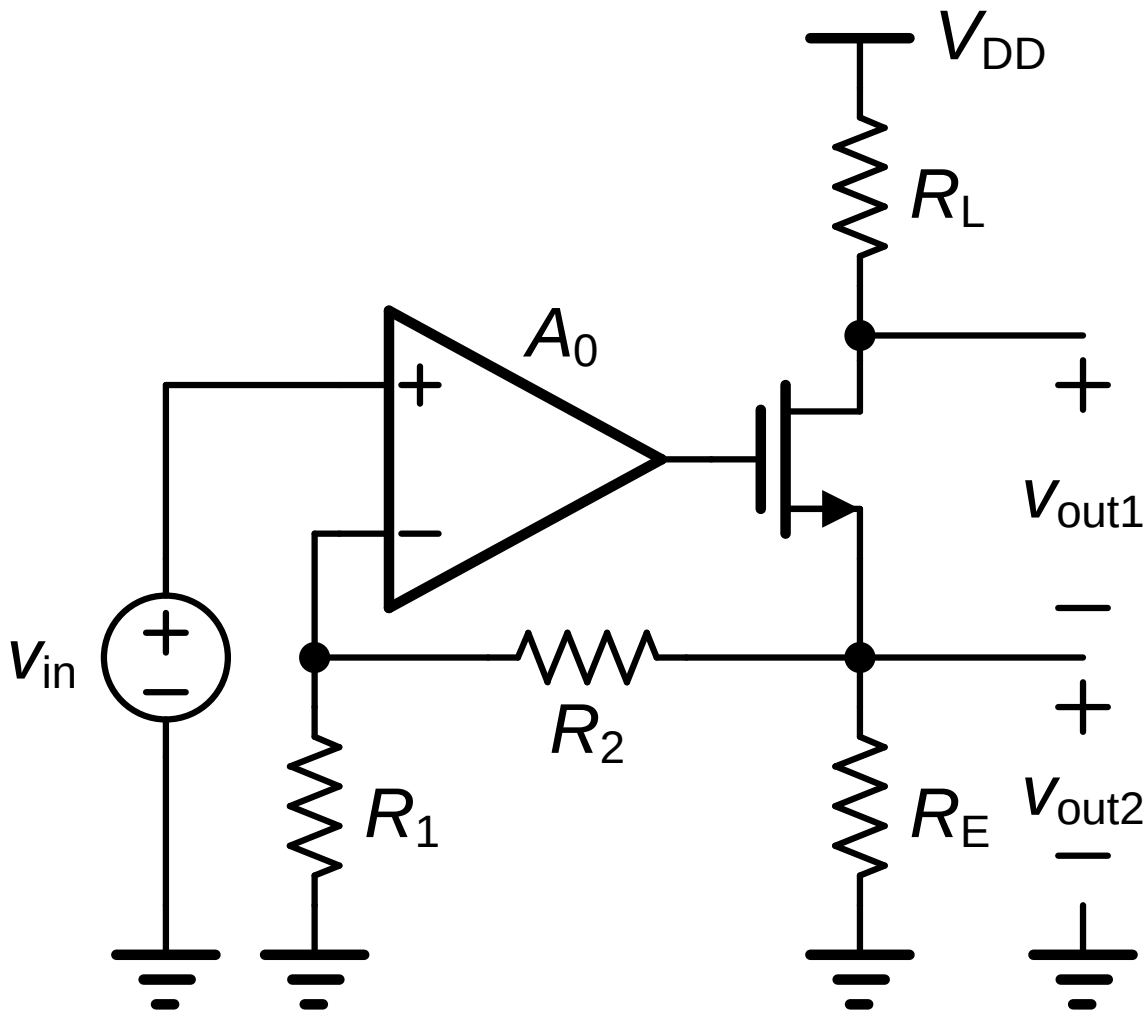
$$LG = A_0$$

$$R_{in} \approx \infty$$

$$R_{out} = R_{outOL} LG$$

$$R_{outOL} \approx r_{DS}(1 + g_m R_E)$$

串联—串联反馈：双输出



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

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

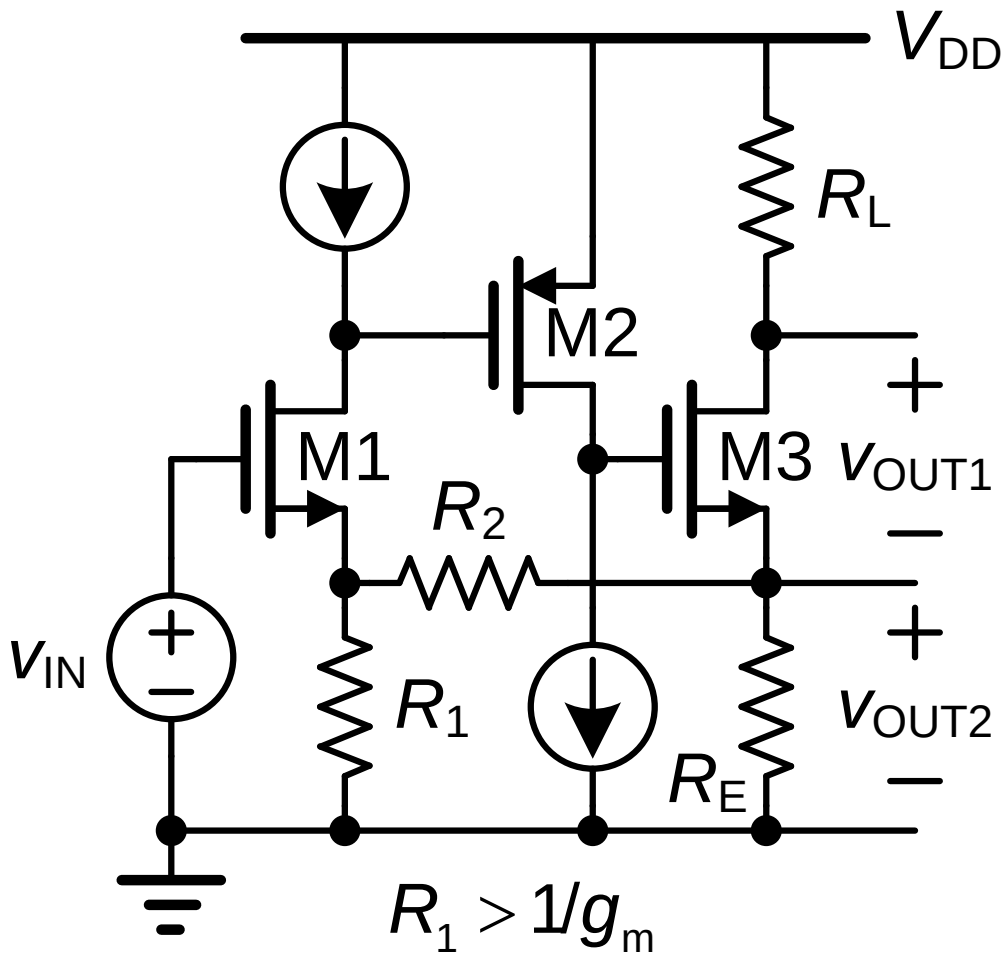
$$LG = A_0 \frac{R_1}{R_1 + R_2}$$

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

$$R_{out1} = R_L$$

$$R_{out2} = \frac{1/g_m}{LG}$$

接电流源负载的串联—串联反馈



$$R_1 > 1/g_m$$

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

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

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

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

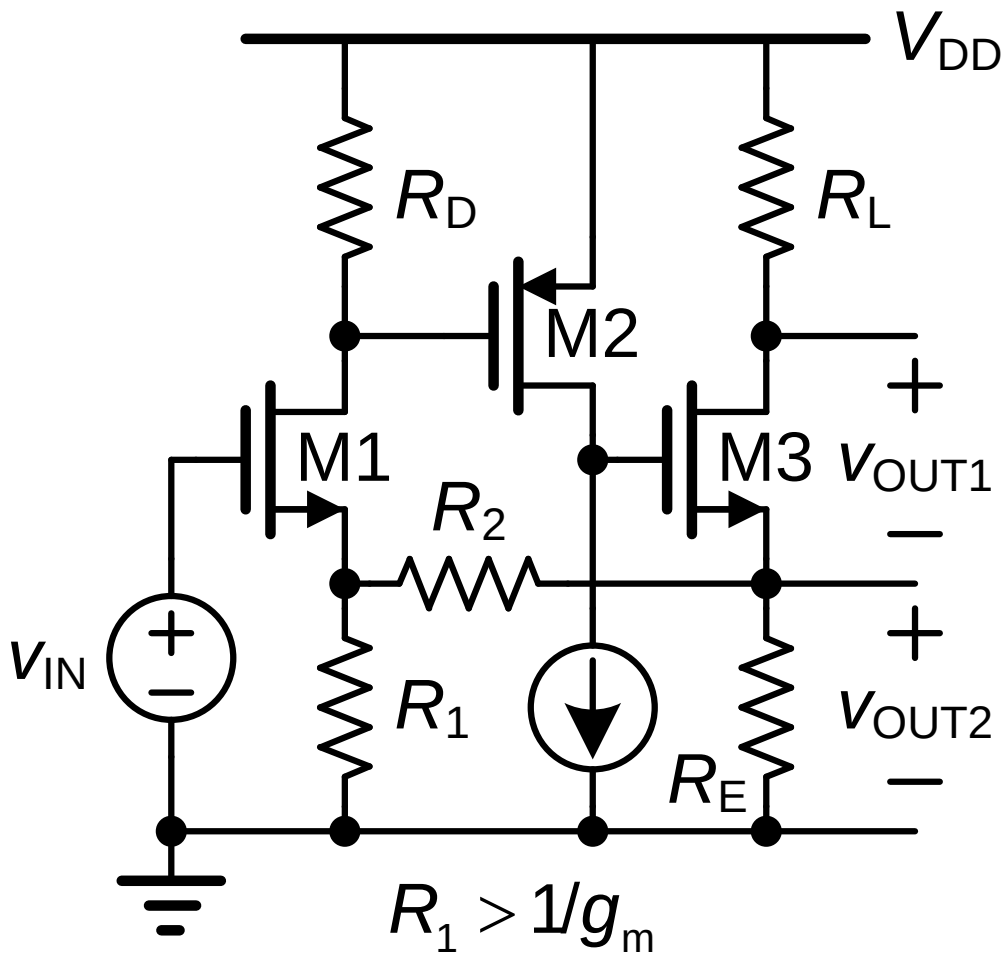
$$A_i = g_{mi} r_{DSi}$$

$$R_{in} \approx \infty$$

$$R_{out1} = R_L$$

$$R_{out2} = \frac{1/g_{m2}}{LG} \approx 0$$

接电阻负载的串联—串联反馈



$$R_1 > 1/g_m$$

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

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

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

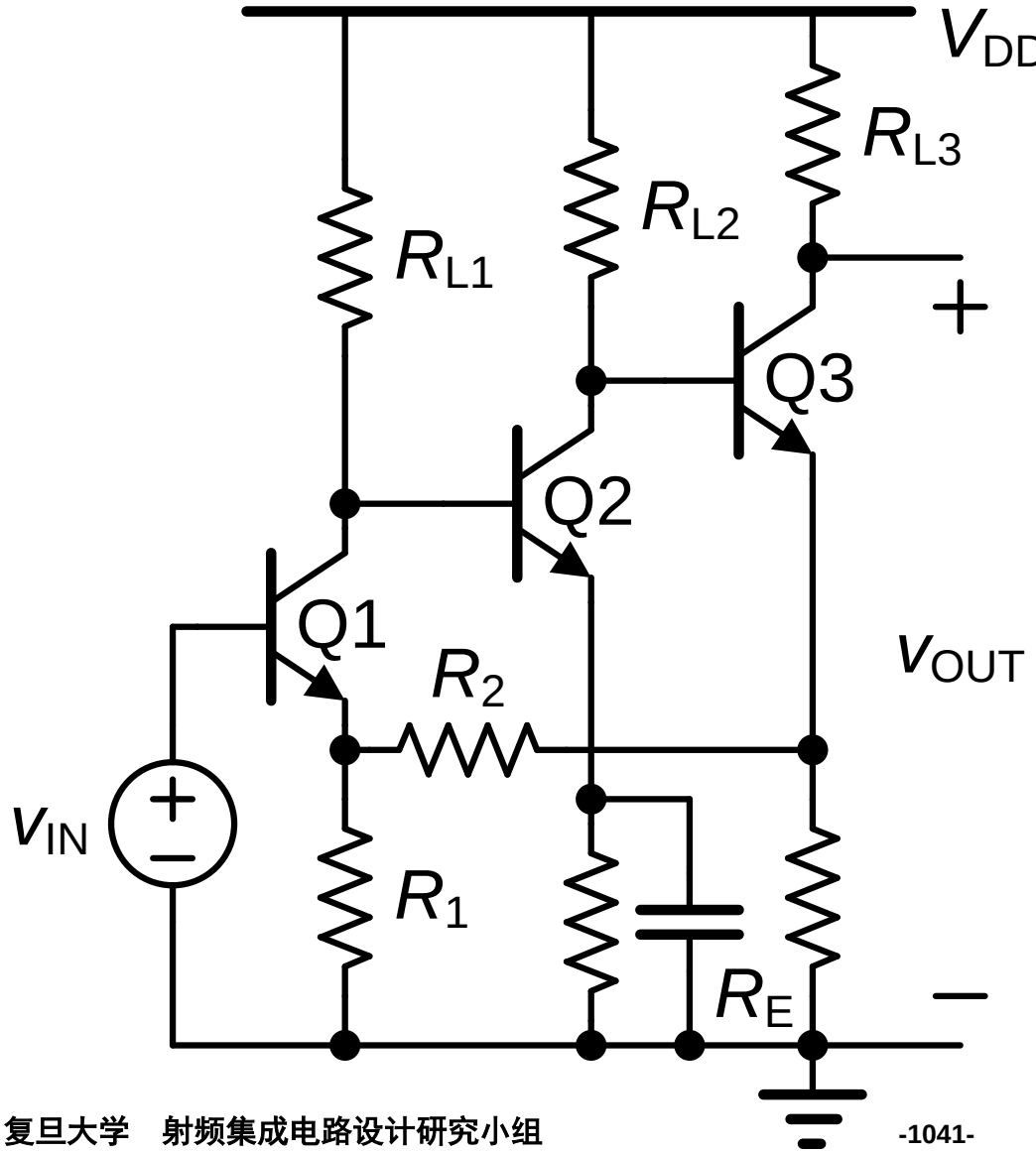
$$LG = g_{m2} r_{DS2} \frac{R_D}{R_2}$$

$$R_{in} \approx \infty$$

$$R_{out1} = R_L$$

$$R_{out2} = \frac{1/g_{m2}}{LG} \approx 0$$

三极管并联—并联反馈



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

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

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

$$R_{in} = R_{inOL} LG \approx \infty$$

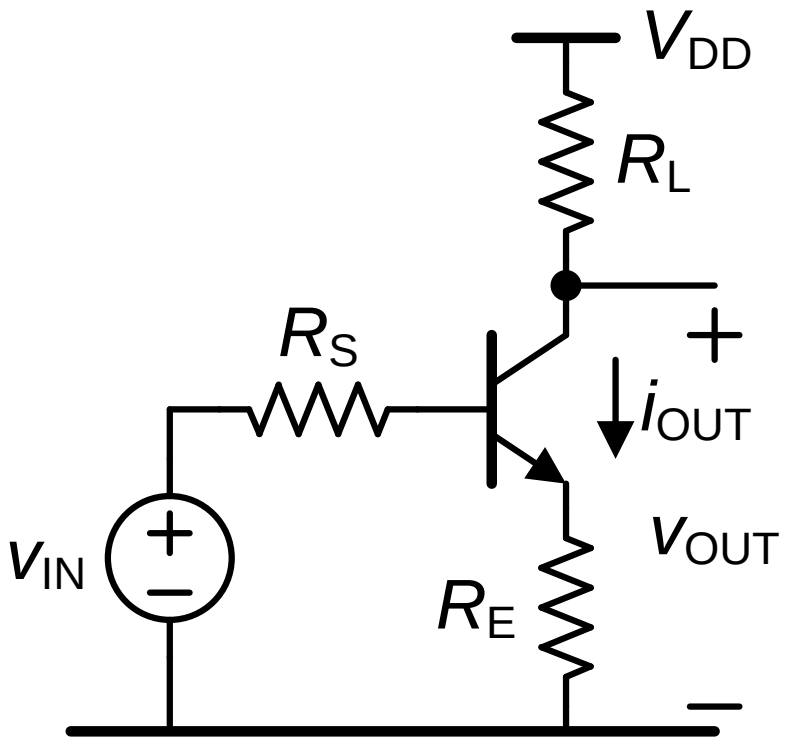
$$R_{inOL} = r_{\pi 1} + \beta(R_1 // R_2)$$

$$R_{out} = R_{L3}$$

输入负载：$R_{in}<\infty$

Ref.: Wooley, JSSC Feb.71, 24-34

非理想单管反馈



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

$$A_V \approx -\frac{R_L}{R_E}$$

$$LG = g_m R_E (\gg 1)$$

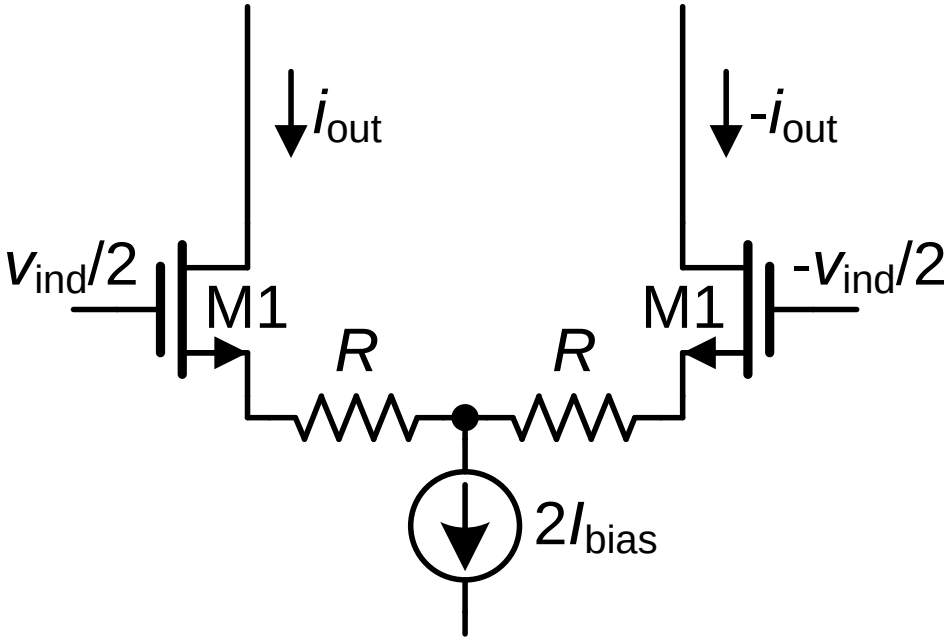
$$R_{in} = r_\pi + \beta R_E$$

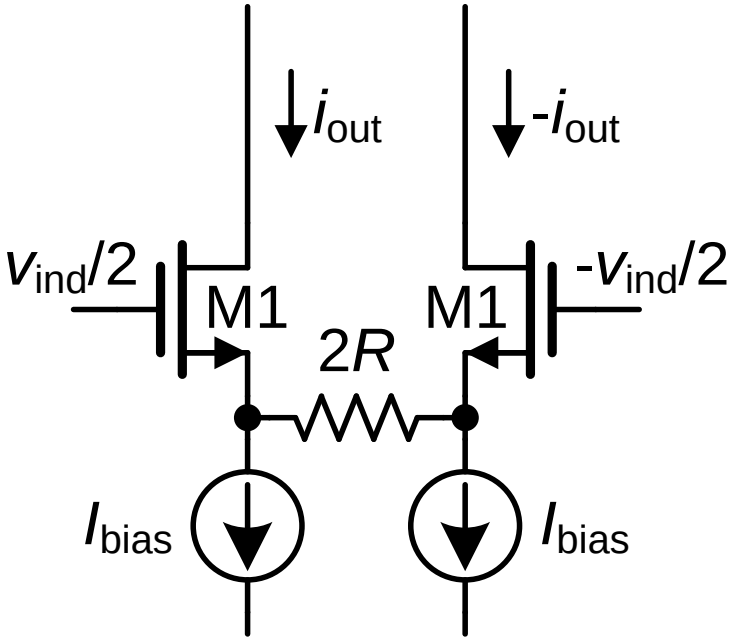
$$R_{out} = R_L // r_{oL}$$

输出负载：$R_L \approx r_{oL}$　$r_{oL}=r_o(g_m R_E)$

输入负载：$R_S < R_{in}$　$R_{in}=r_\pi+\beta R_E$

利用反馈减小失真

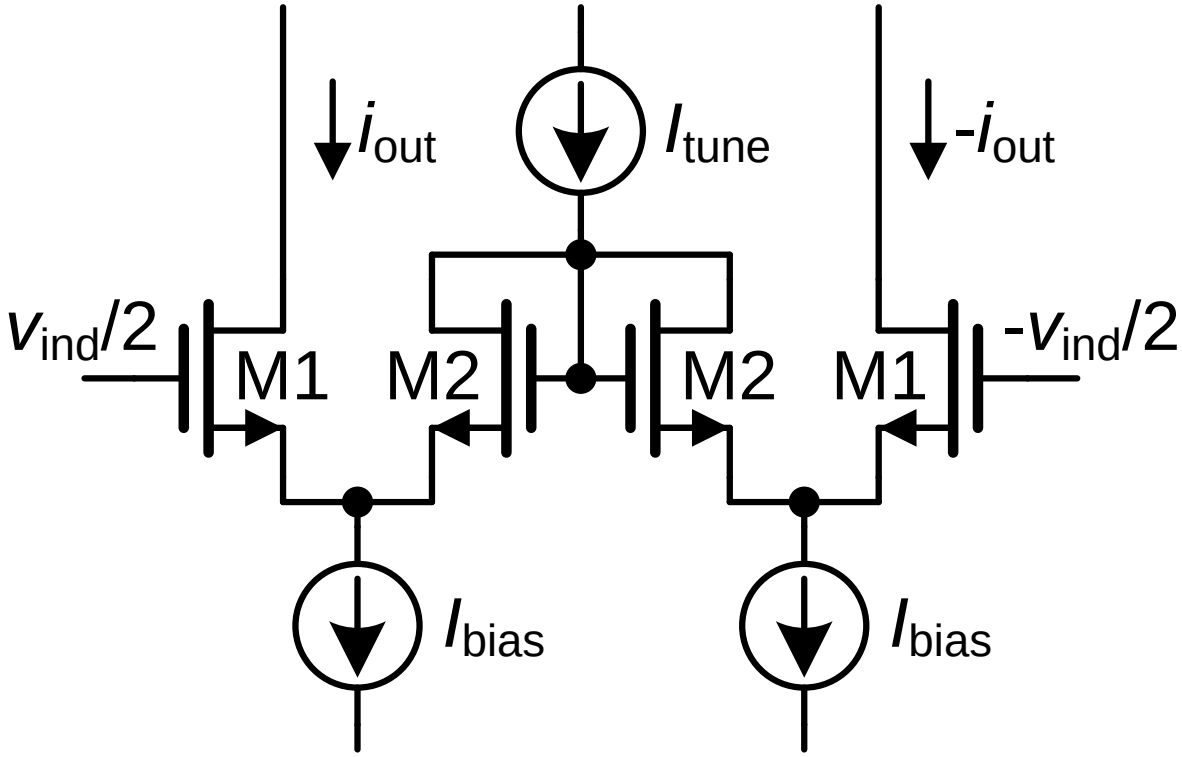




$$LG = g_m R (\gg 1)$$

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

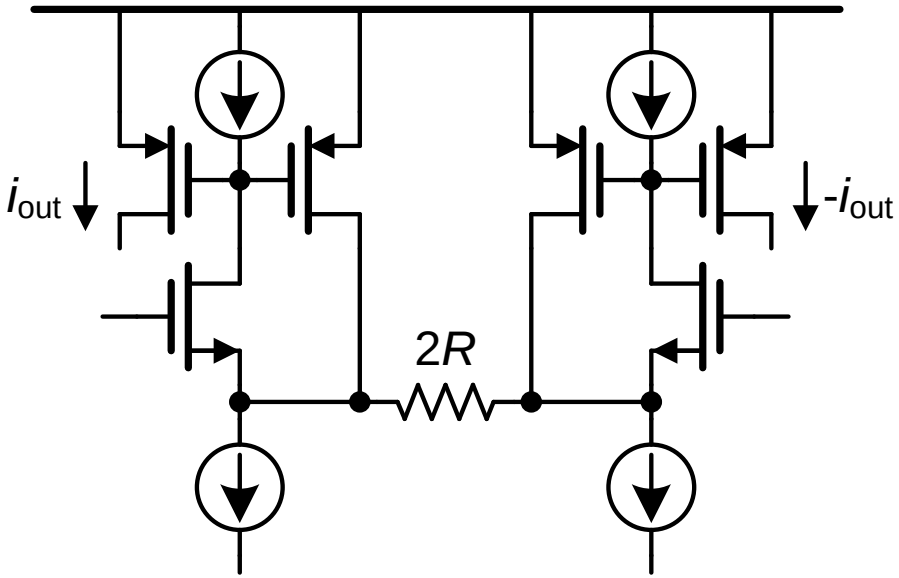
可调反馈



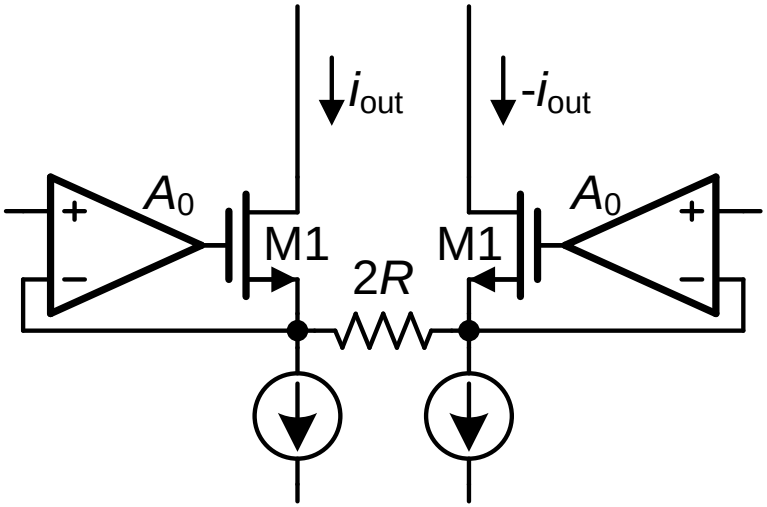
$$LG = g_m R (\gg 1) \quad R = 1/g_{m2} \qquad A_G \approx \frac{1}{R}$$

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

利用反馈减小失真

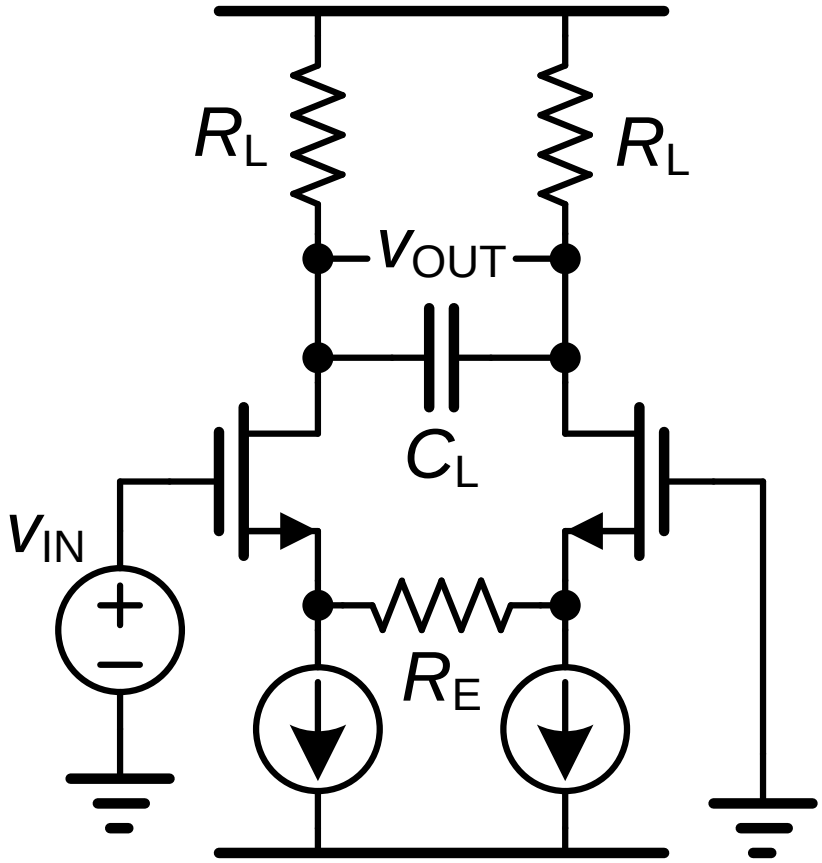


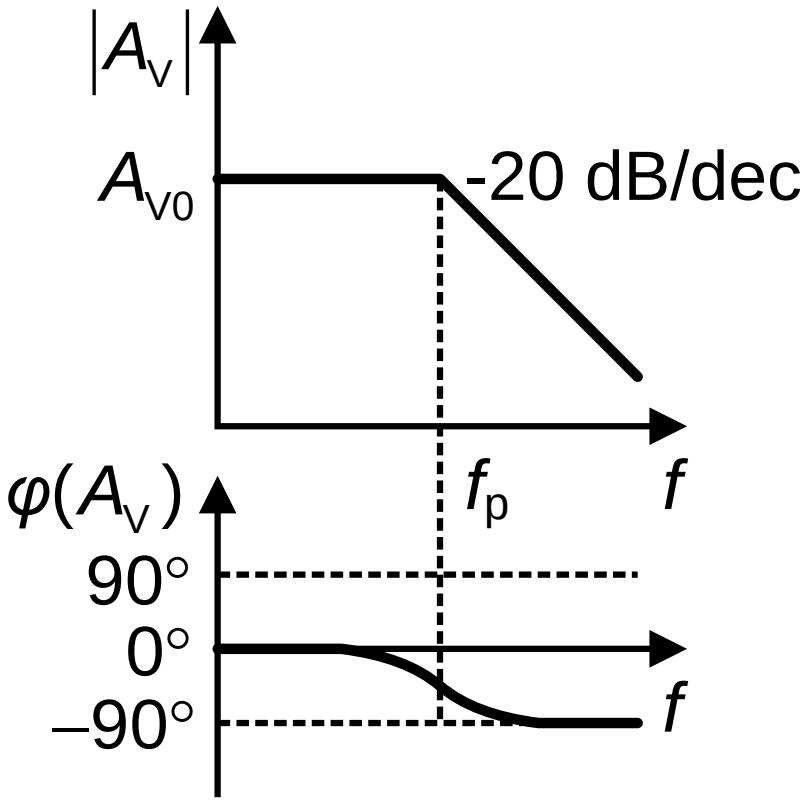
附加局部反馈



运放构建反馈

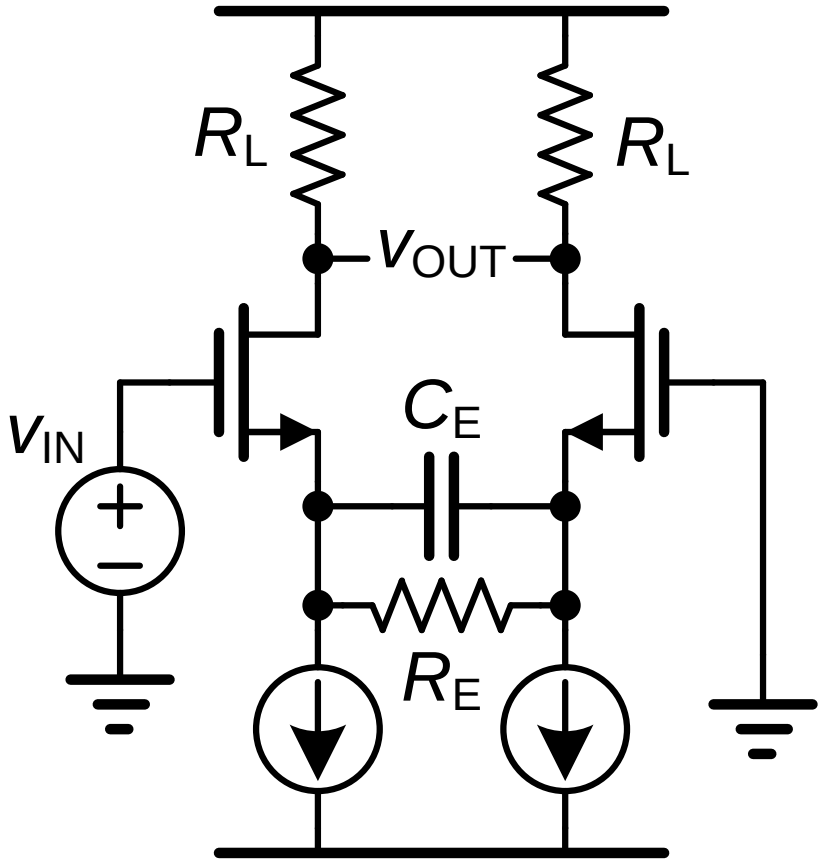
低通滤波器

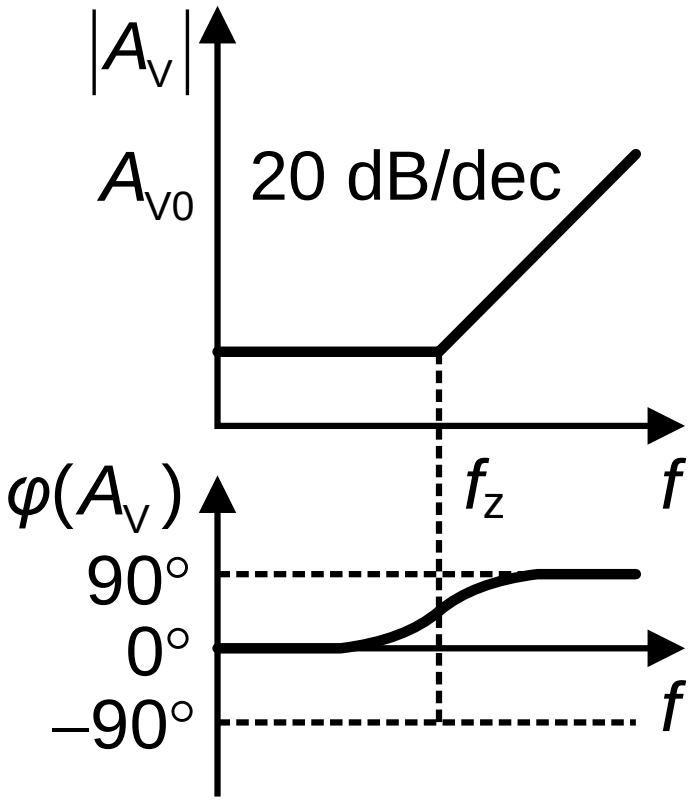




$$A_{V0} = -2R_L // R_E \qquad A_V = A_{V0}\frac{1}{1+\mathrm{j}\frac{f}{f_p}} \qquad f_p = \frac{1}{2\pi 2R_L C_L}$$

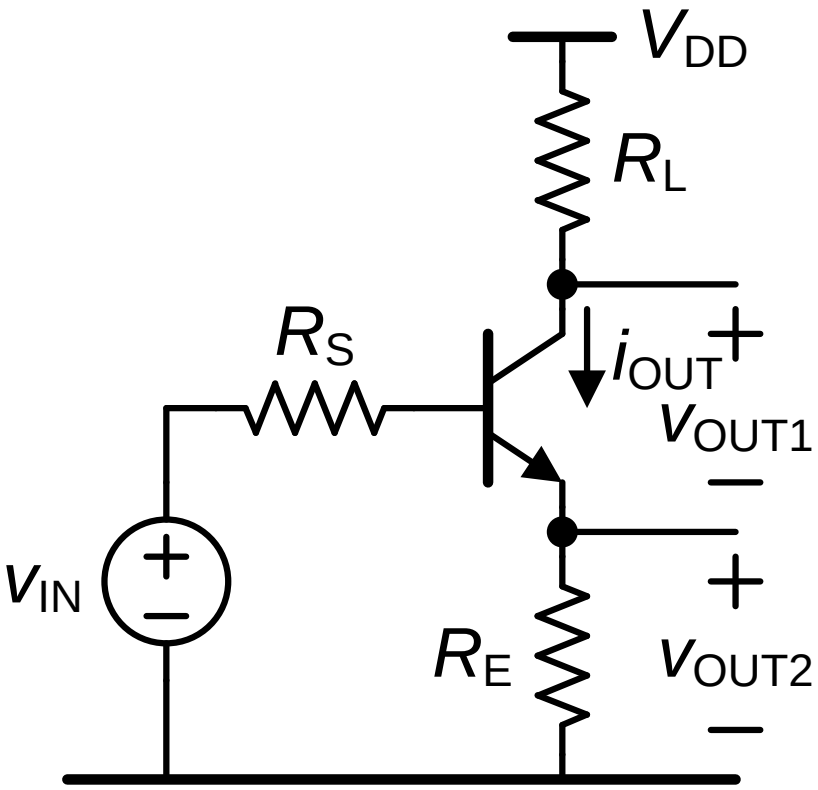
高频提升





$$A_{V0} = -2R_L // R_E \qquad A_V = A_{V0}\left(1 + \mathrm{j}\frac{f}{f_z}\right) \qquad f_z = \frac{1}{2\pi R_E C_E}$$

双输出的单管反馈



$$A_{V1} \approx -\frac{R_L}{R_E}$$

$$A_{V2} \approx 1$$

$$LG = g_m R_E (\gg 1)$$

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

$$R_{out1} = R_L // r_{oL}$$

$$R_{out2} = 1/g_m + R_S/\beta$$

输出负载：$R_L \approx r_{oL}$　$r_{oL}=r_o(g_m R_E)$

输入负载：$R_S < R_{in}$　$R_{in}=r_\pi+\beta R_E$