电子电路与系统基础

习题课第十五讲

1、运算放大器复习
2、第十五讲作业讲解

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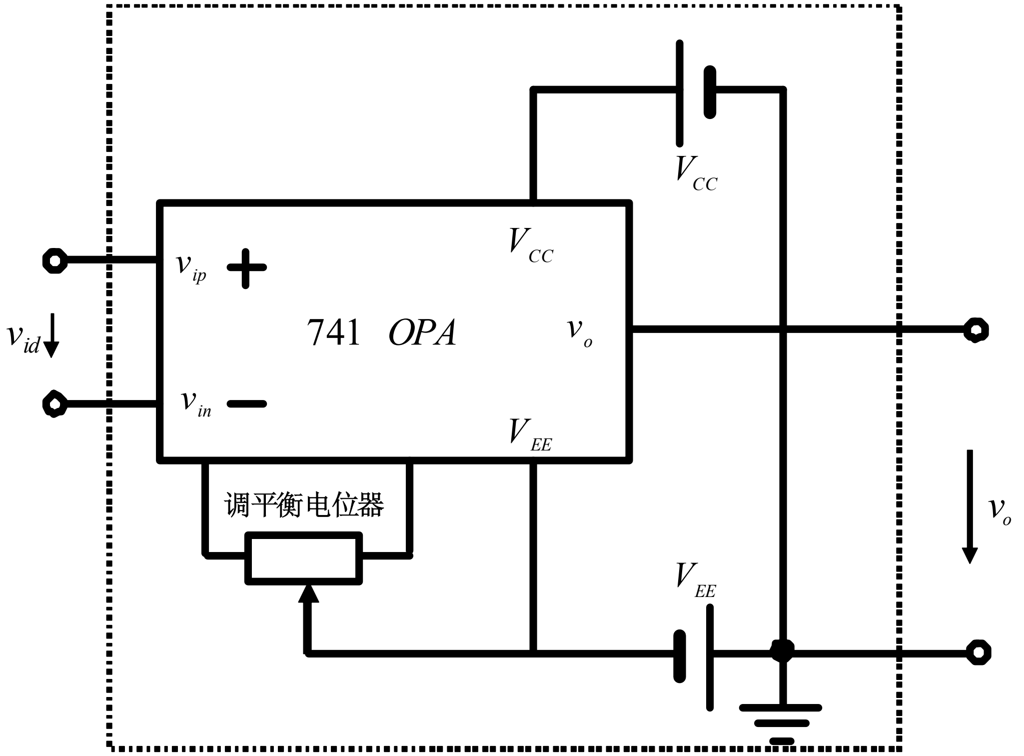
运算放大器复习

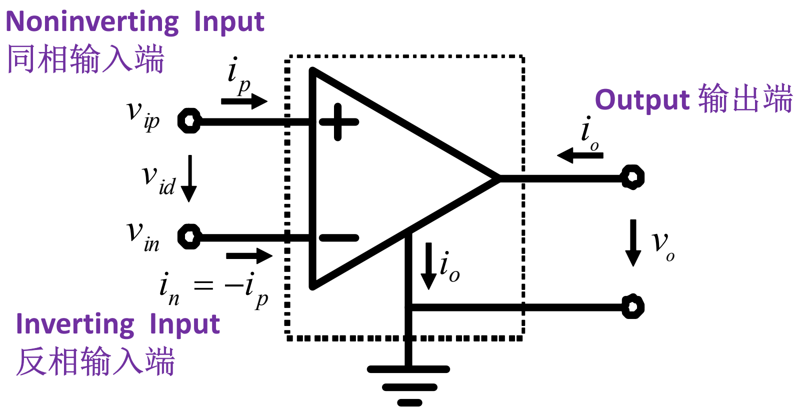
基本要求
1、基本电路模型
2、虚短虚断应用
3、负反馈类型判定
4、正反馈分析

- 运放转移特性曲线
  - 具有明显的分区特性：三段折线等效电路模型
- 在运放转移特性曲线的放大区，运放等效为压控压源
  - 放大倍数抽象为无穷大
    - 虚短、虚断特性：熟练运用
  - 运放保持在放大区，绝大多数靠负反馈实现
    - 什么是负反馈，什么是正反馈？
- 运放转移特性曲线的饱和区，运放等效电路为恒压源
  - 负反馈运放电路
    - 如果输出幅度预算超过饱和电压则必进入饱和区
  - 正反馈运放电路
    - 大多进入饱和区，个别通过适当控制（形成负反馈效应）则可工作在线性区（等效为负阻）

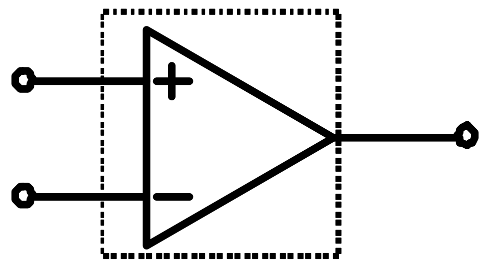
运放是高度抽象的二端口网络



（a）实际运放外部连接关系



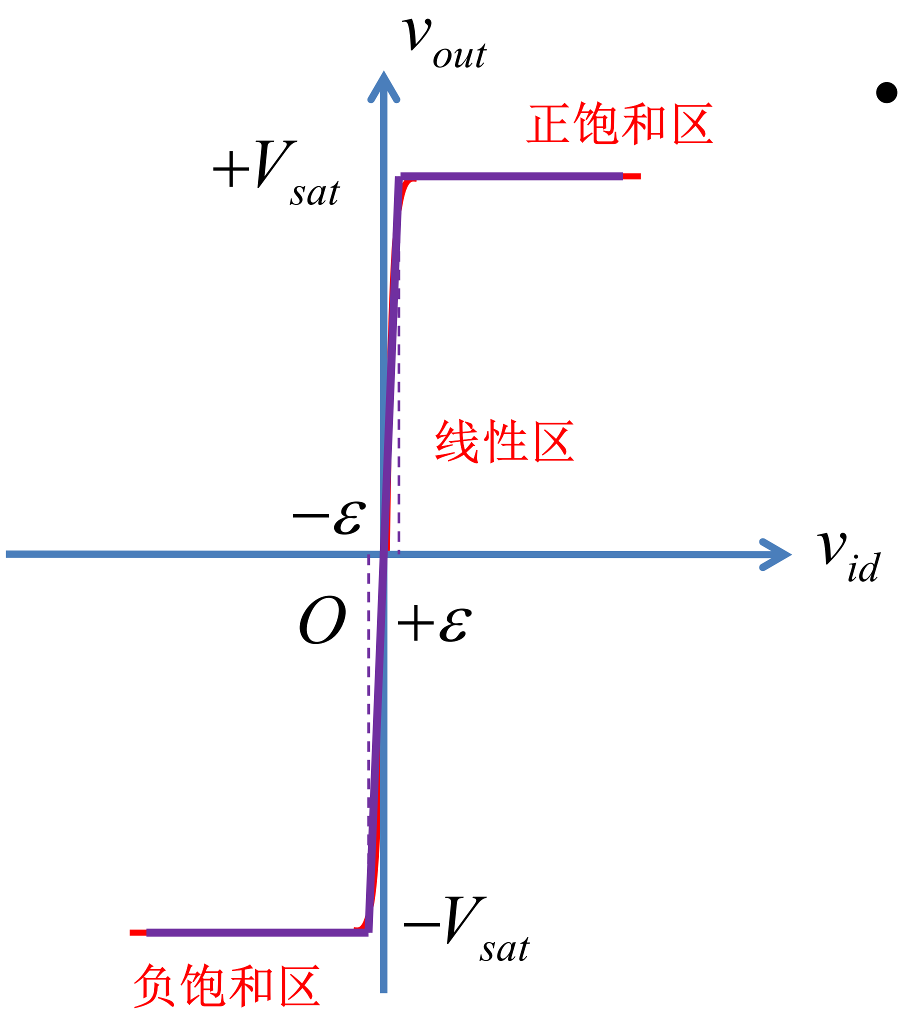
（b）运放符号：（带地）



（c）运放符号：（默认带地）

$$v_{out} = f(v_{id}) = f(v_{ip} - v_{in}) \overset{\text{线性放大区}}{\triangleq} A_{v0}(v_{ip} - v_{in})$$

三段折线模型



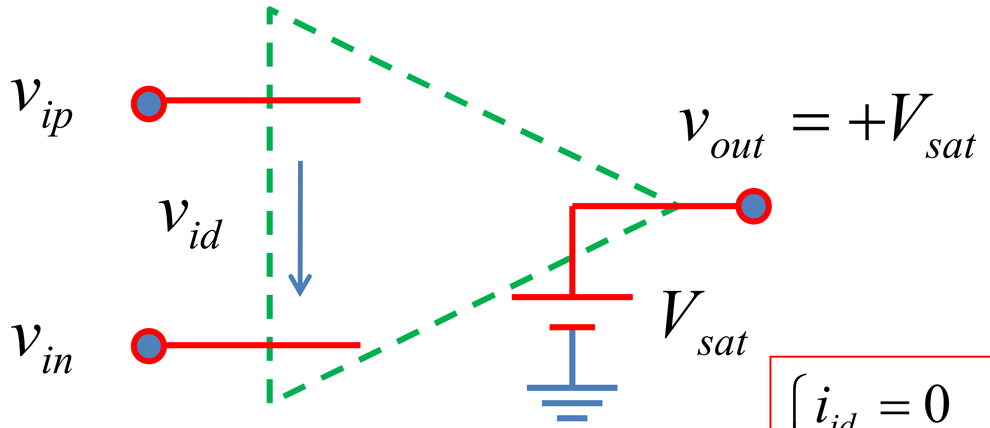
- 分段线性是对强非线性的常见处理手法
  - 运放转移特性曲线

$$v_{out} = \begin{cases} -V_{sat} & v_{id} < -\varepsilon \\ A_{v0} v_{id} & -\varepsilon < v_{id} < +\varepsilon \\ +V_{sat} & v_{id} > +\varepsilon \end{cases}$$

$$\varepsilon = \frac{V_{sat}}{A_{v0}}$$

A_{v0}极大
ε很小

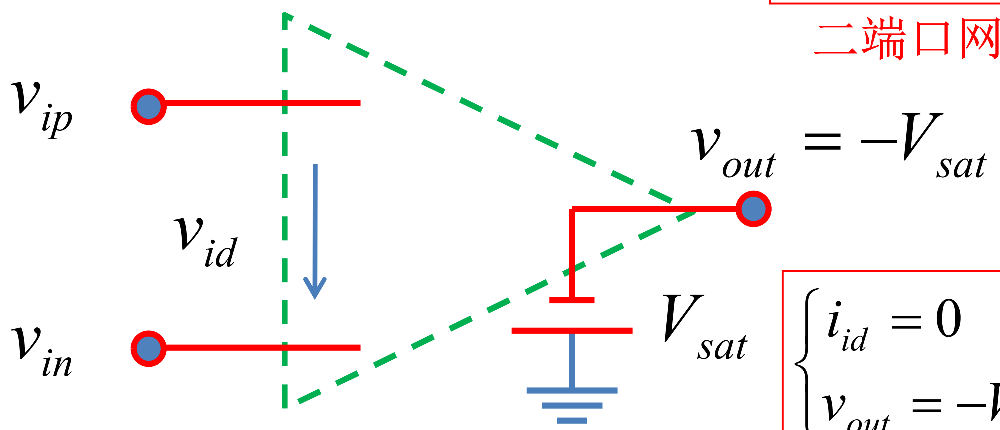
饱和区恒压源模型



正饱和区等效电路

$$\begin{cases} i_{id} = 0 \\ v_{out} = +V_{sat} \end{cases} \quad (v_{id} > +\varepsilon)$$

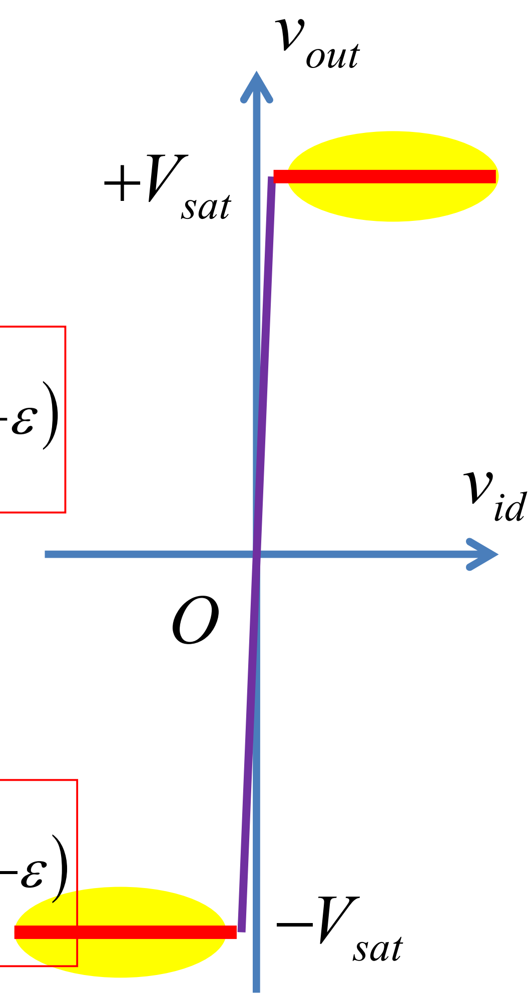
二端口网络描述方程



负饱和区等效电路

$$\begin{cases} i_{id} = 0 \\ v_{out} = -V_{sat} \end{cases} \quad (v_{id} < -\varepsilon)$$

二端口网络描述方程



线性区
压控压源模型

$$\begin{cases} i_{id} = v_{id}/R_{in} \\ v_{out} = A_{v0}v_{id} - R_{out}i_{out} \end{cases}$$

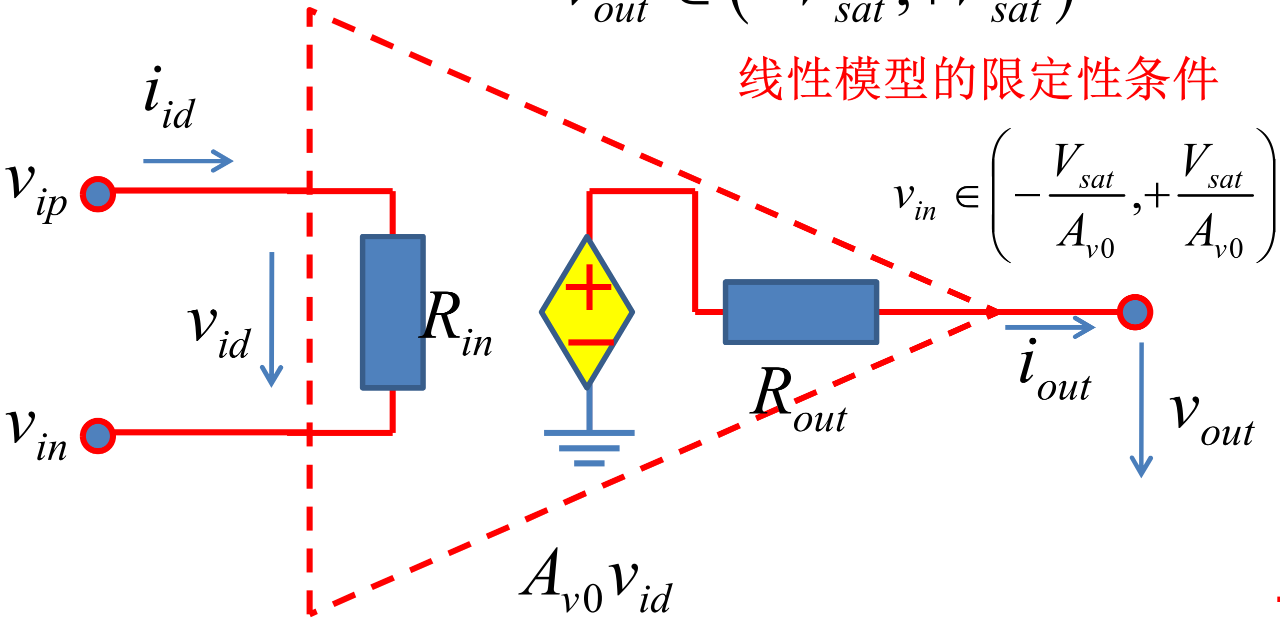
二端口网络描述方程

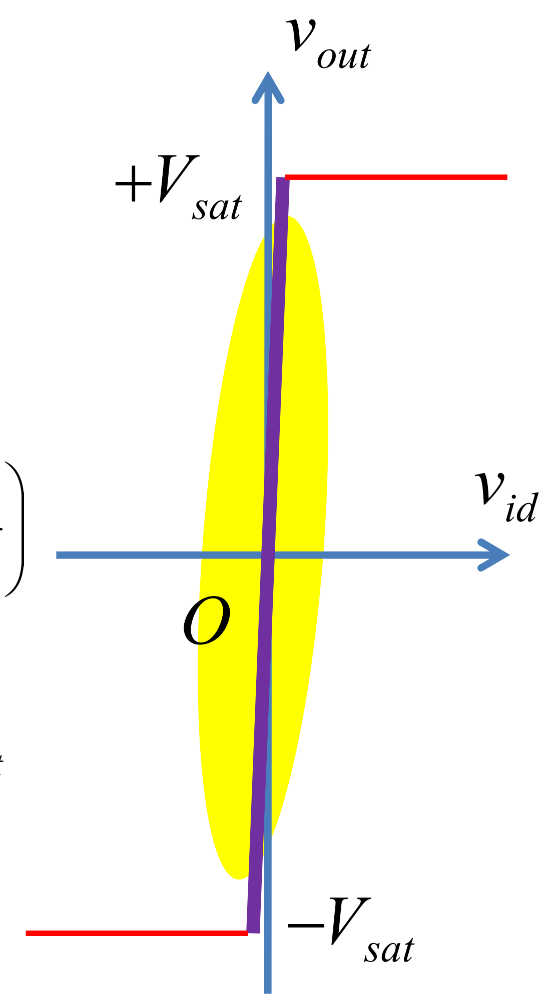
- 既然是电压放大器，除了电压增益（传输特性）外，还有端口阻抗特性

$$v_{out} \in \left(-V_{sat}, +V_{sat}\right)$$

线性模型的限定性条件

$$v_{in} \in \left(-\frac{V_{sat}}{A_{v0}}, +\frac{V_{sat}}{A_{v0}}\right)$$





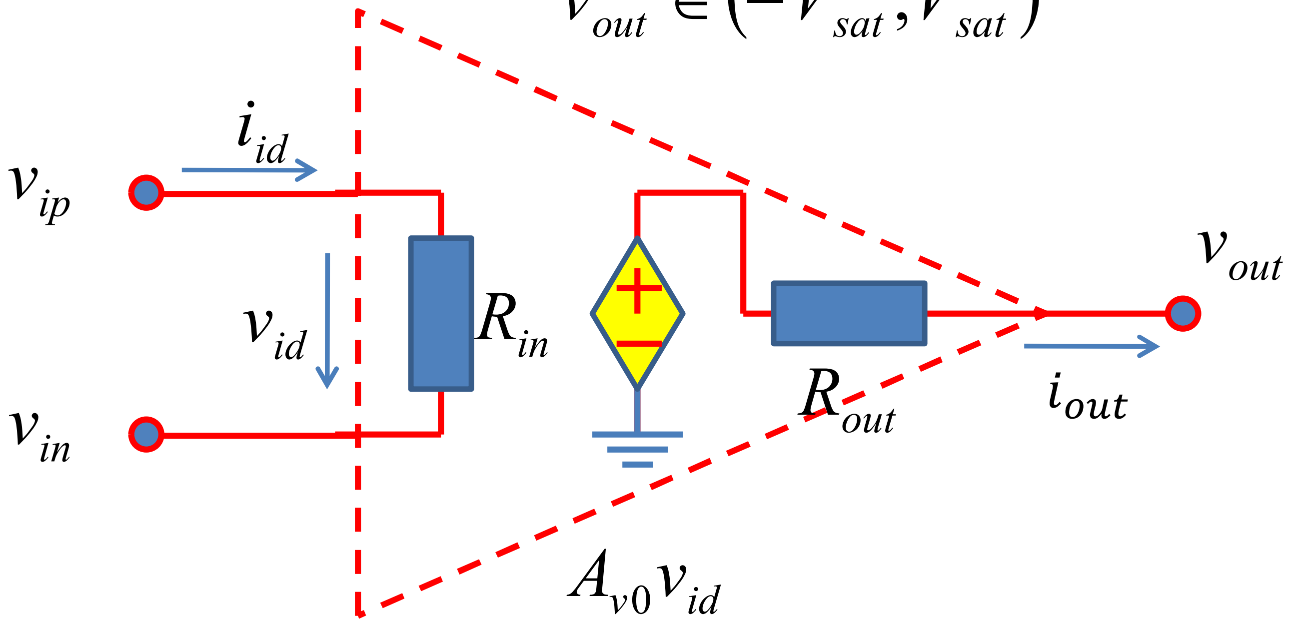
理想运放电路模型

$$A_{v0} \to \infty$$

传输参量

$$ABCD = \begin{bmatrix} \frac{1}{A_{v0}} & \frac{R_{out}}{A_{v0}} \\ \frac{1}{A_{v0}R_{in}} & \frac{R_{out}}{A_{v0}R_{in}} \end{bmatrix}$$

$$v_{out} \in \left(-V_{sat}, V_{sat}\right)$$



$$\begin{bmatrix} v_{id} \\ i_{id} \end{bmatrix} = ABCD \begin{bmatrix} v_{out} \\ i_{out} \end{bmatrix}$$

$$A_{v0} \to \infty$$

$$\begin{cases} i_{id} = 0 \\ v_{id} = 0 \end{cases}$$

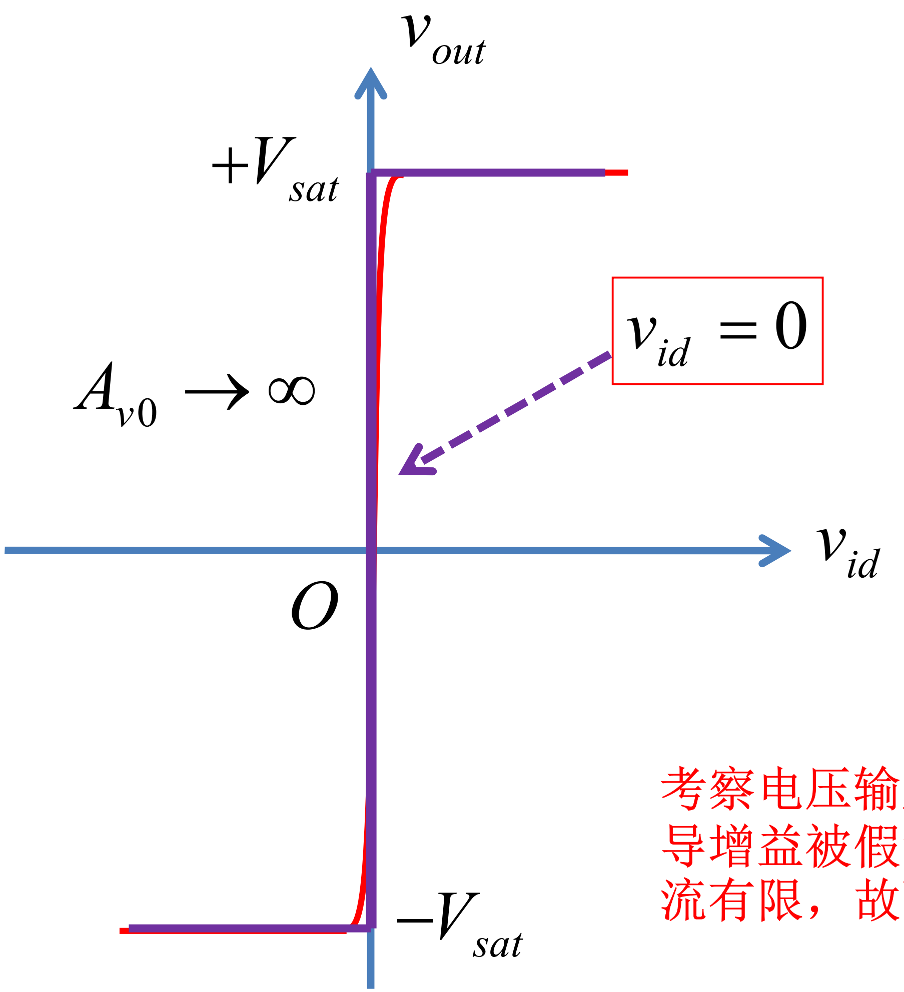
二端口网络描述方程
限定性条件:

$$i_{out} \in \left(-I_{sc}, I_{sc}\right)$$
$$v_{out} \in \left(-V_{sat}, V_{sat}\right)$$

虚短 virtual short circuit

$$\boxed{\begin{cases} i_{id} = 0 \\ v_{id} = 0 \end{cases}}$$

理想运放二端口描述方程



$$-V_{sat} < v_{out} < +V_{sat}$$

$$\boxed{v_{ip} = v_{in}}$$

$$v_{out,open} = A_{v0} v_{id}$$

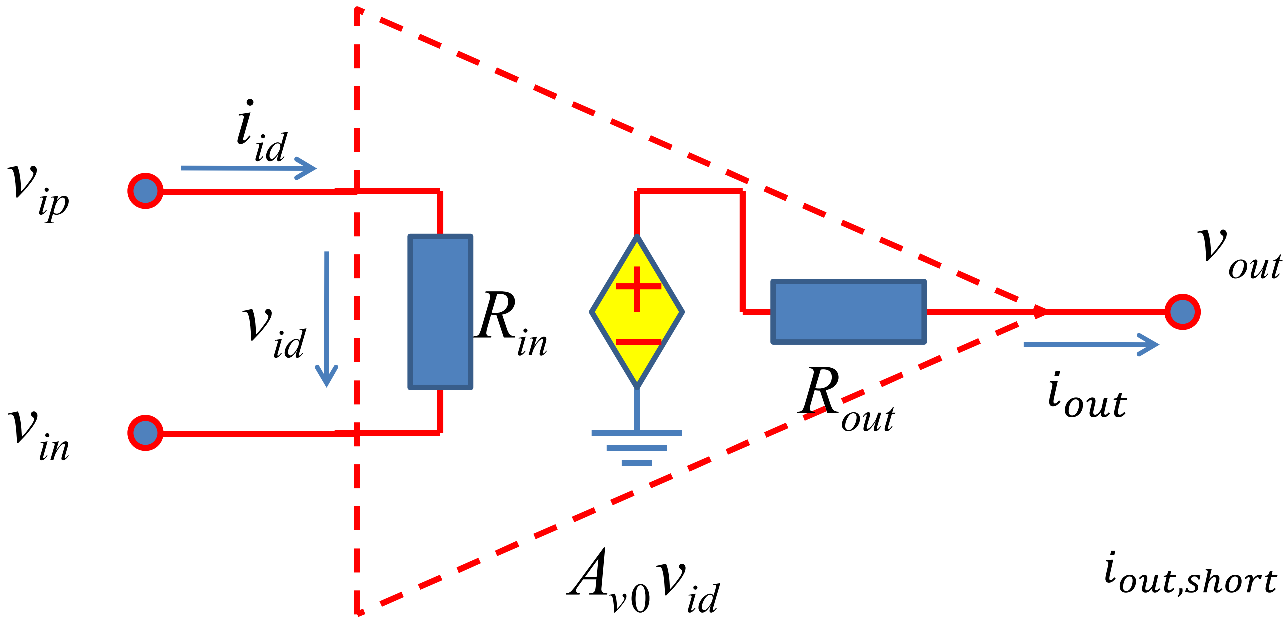
$$i_{out,short} = G_{m0} v_{id} = \frac{A_{v0}}{R_{out}} v_{id}$$

考察电压输入时，由于本征电压增益和本征跨导增益被假设为无穷大，而输出电压和输出电流有限，故而输入电压虚拟为**0**（虚短）

虚断 virtual open circuit

$$\begin{cases} i_{id} = 0 \\ v_{id} = 0 \end{cases}$$

理想运放二端口描述方程



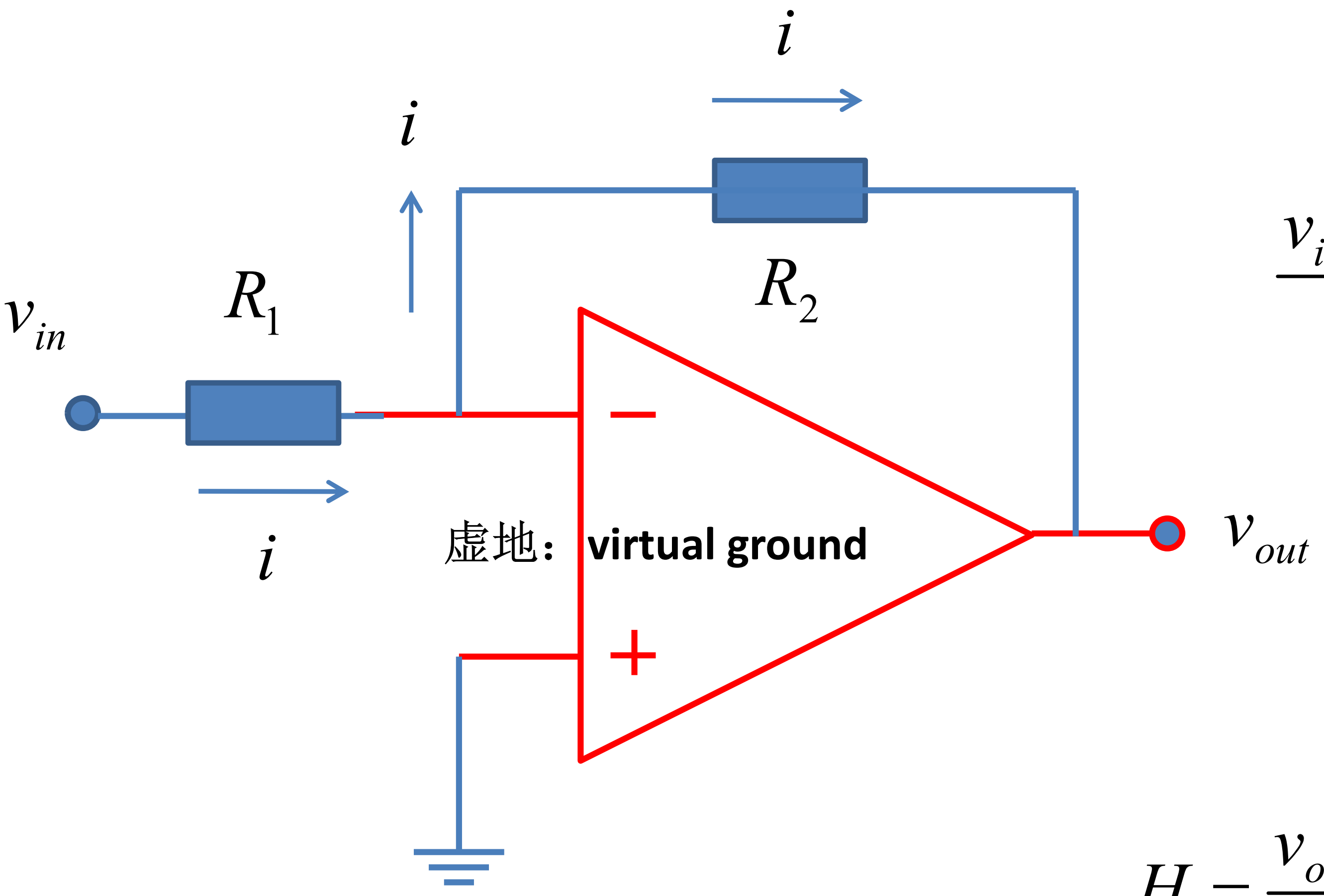
$$i_{out} \in \left(-I_{sc}, I_{sc}\right)$$
$$v_{out} \in \left(-V_{sat}, V_{sat}\right)$$

$$i_{out,short} = A_{i0} i_{id} = \frac{A_{v0} R_{in}}{R_{out}} i_{id}$$
$$v_{out,open} = R_{m0} i_{id} = A_{v0} R_{in} i_{id}$$

考察电流输入时，由于本征跨阻增益和本征电流增益假设无穷大，而输出电压和输出电流有限，故而输入电流虚拟为**0**（虚断）

虚短、虚断简化分析要求熟练掌握

大多数的负反馈运放电路分析流程：首先判断负反馈，之后假设虚短和虚断



$$\frac{v_{in}-0}{R_1}=i=\frac{0-v_{out}}{R_2}$$

$$\frac{v_{in}}{R_1}=-\frac{v_{out}}{R_2}$$

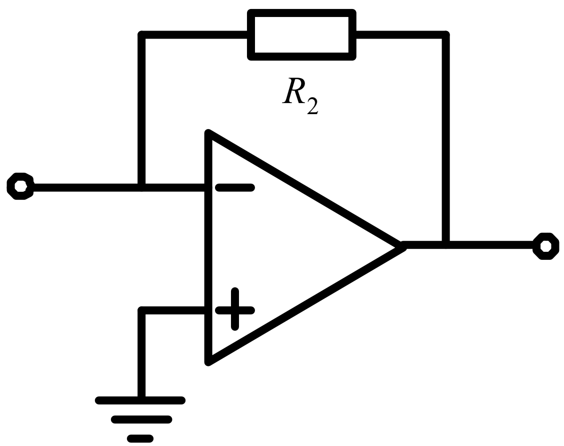
$$H=\frac{v_{out}}{v_{in}}=-\frac{R_2}{R_1}$$

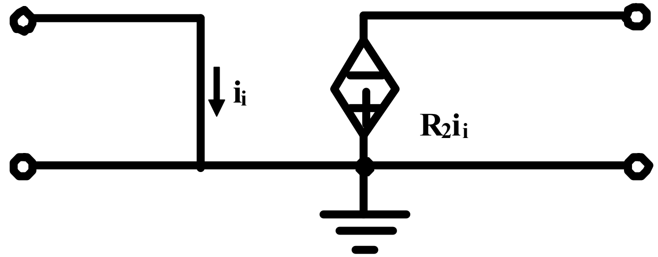
理想运放线性区的虚短、虚断特性：
反相输入端虚拟接地，但无电流流入

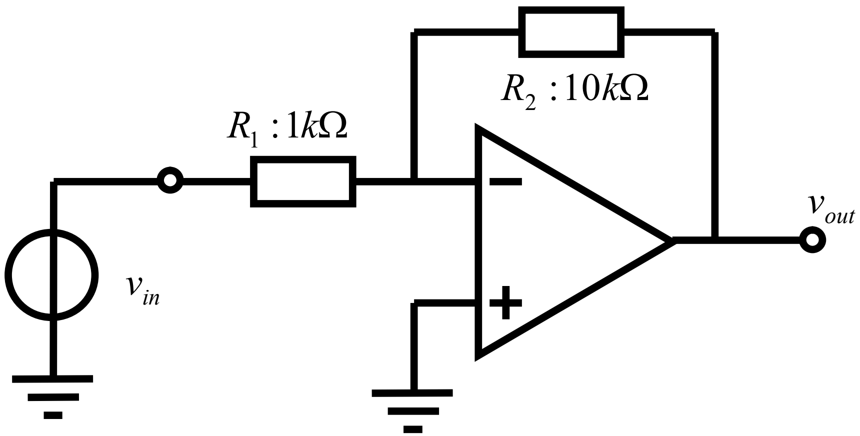
运放外围电路是正反馈还是负反馈？

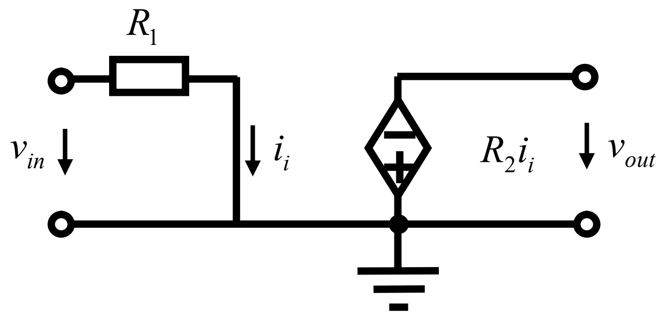
- 只要从输出端连接到反相输入端，则是负反馈连接方式
  - 如果反馈网络是电阻网络，一阶阻容网络，则为负反馈
  - 如果反馈网络为二阶或二阶以上阻容网络，由于阻容网络或可形成**180°**移相，有可能将负反馈连接变成正反馈连接（下学期振荡器设计）
- 只要从输出端连接到同相输入端，则是正反馈连接方式
- 如果输出端同时有连接到同相输入端和反相输入端
  - 考察$F_p=\Delta v_p/\Delta v_o$，$F_n=\Delta v_n/\Delta v_o$两个反馈系数
    - $F_p>F_n$，正反馈占优，则为正反馈
    - $F_p<F_n$，负反馈占优，则为负反馈
- 如果确定为负反馈，运放则可假定工作在线性区，用虚短、虚断分析，如果分析结果中的输出电压超过饱和电压，运放则工作在饱和区
- 如果确定为正反馈，运放则可假定工作在正负饱和区

并并连接负反馈：应用最多

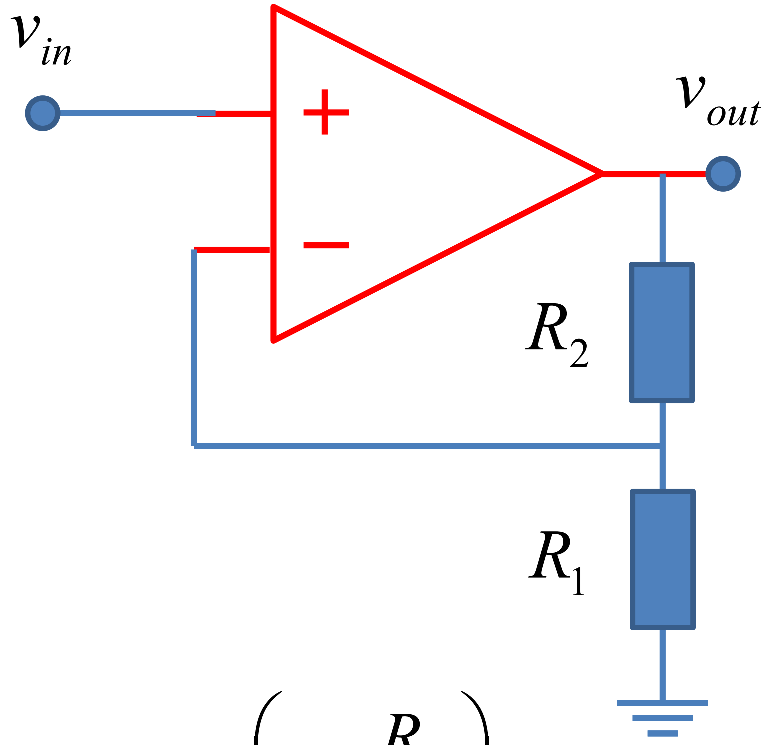




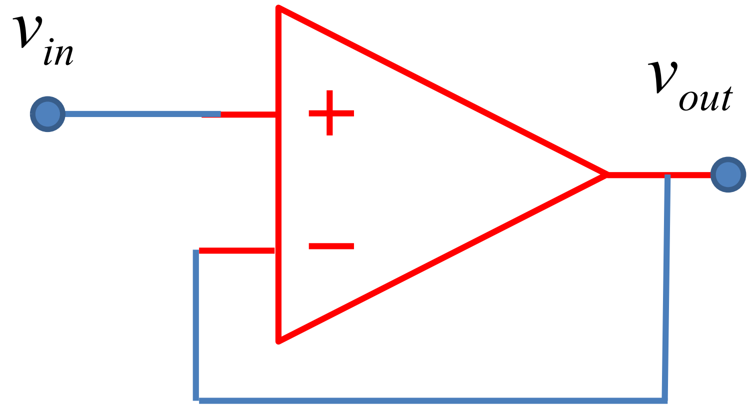




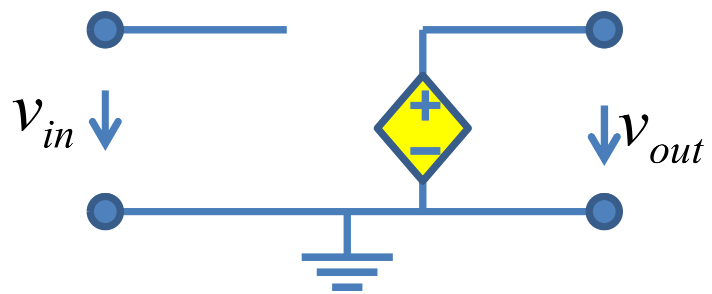
串并连接负反馈：电压缓冲器



$$v_{out} = \left(1 + \frac{R_2}{R_1}\right) v_{in}$$



$$v_{out} = v_{in}$$

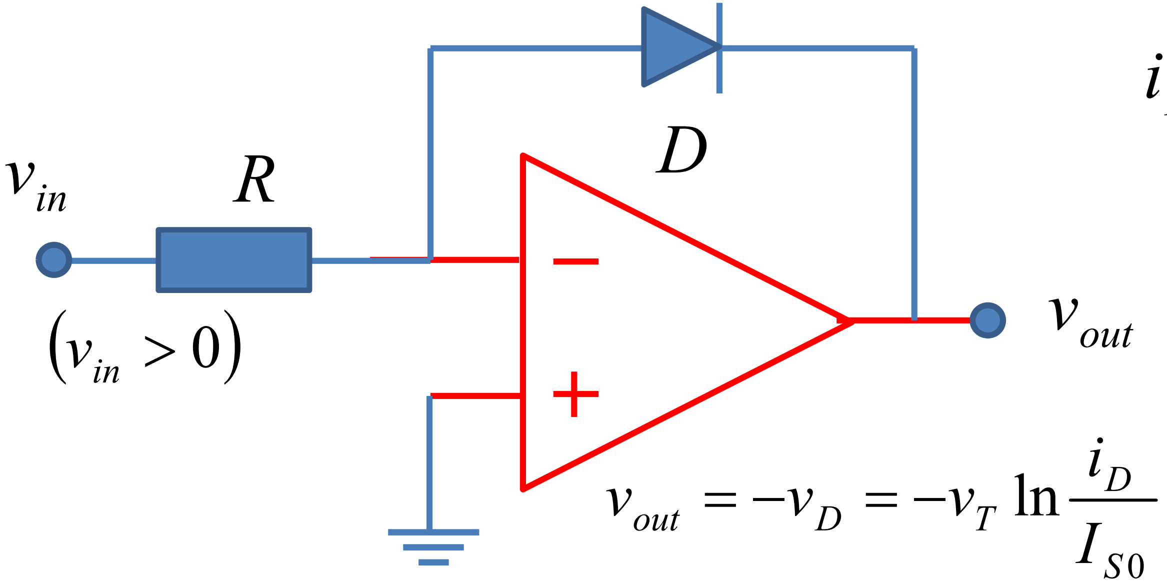


隔离，缓冲

单向传输，解除反向耦合

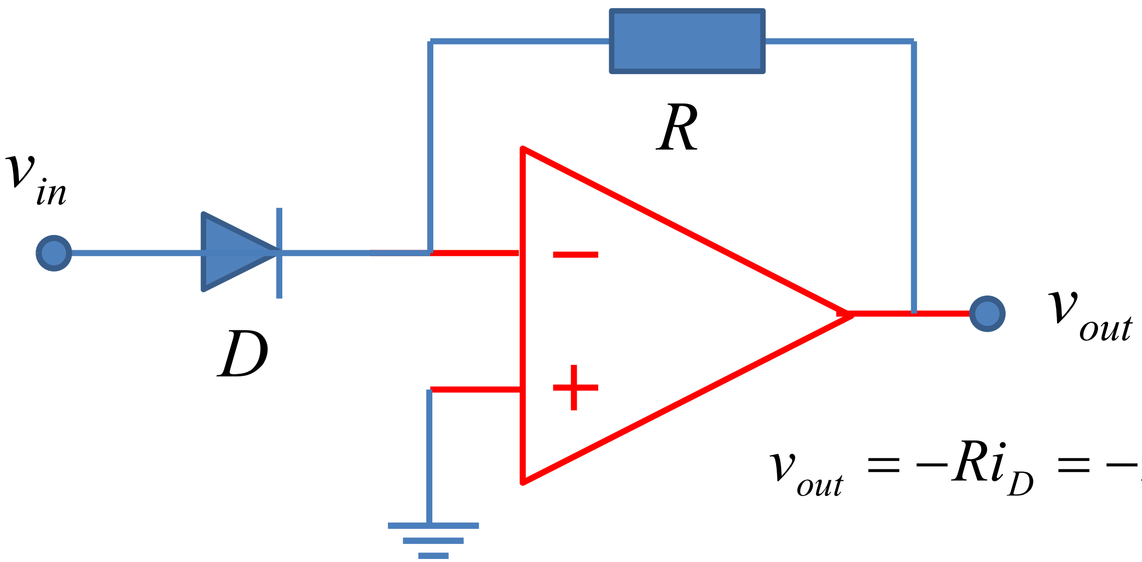
负反馈非线性应用

$$i_D \approx I_{S0} e^{\frac{v_D}{v_T}}$$



$$v_{out} = -v_D = -v_T \ln \frac{i_D}{I_{S0}} = -v_T \ln \frac{v_{in}}{R I_{S0}}$$

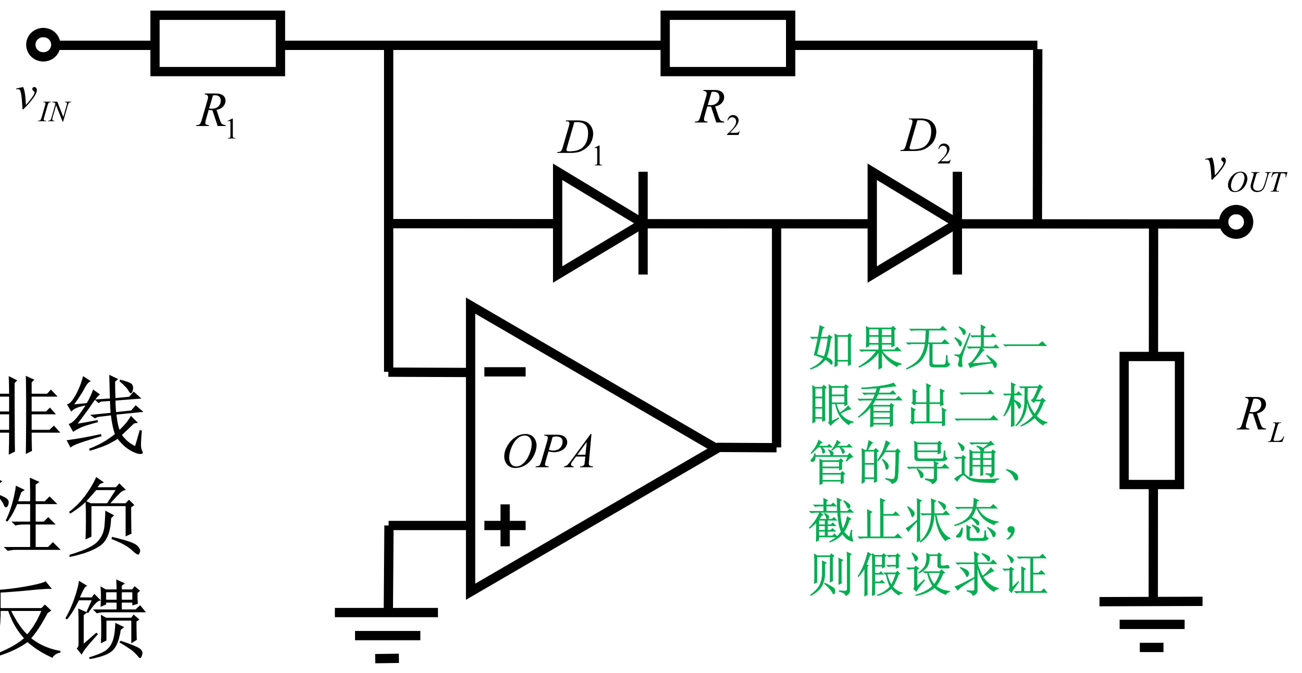
$$(v_{in} > 0)$$

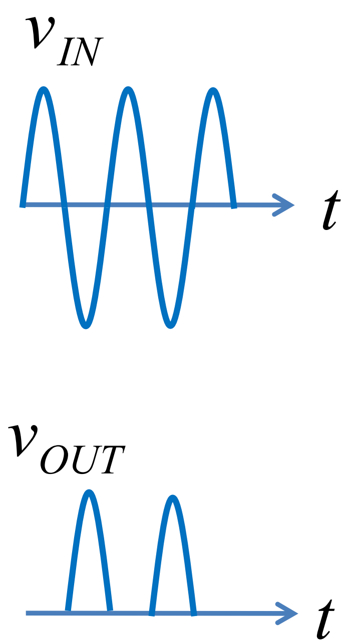


$$v_{out} = -R i_D = -R I_{S0} e^{\frac{v_{in}}{v_T}}$$

$$(v_{in} > 0)$$

非线性负反馈应用

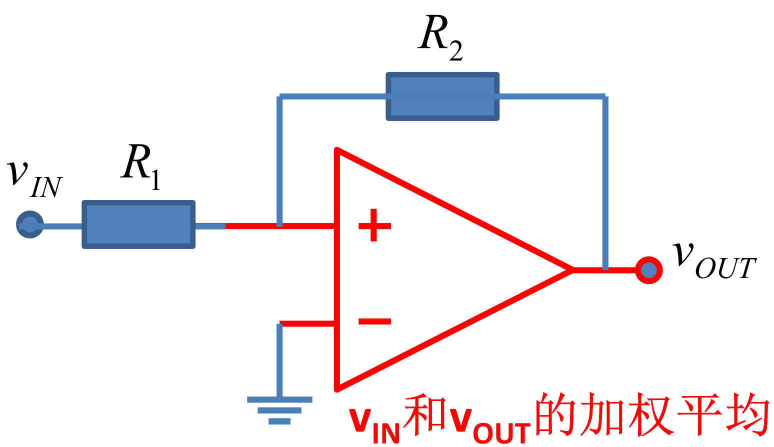




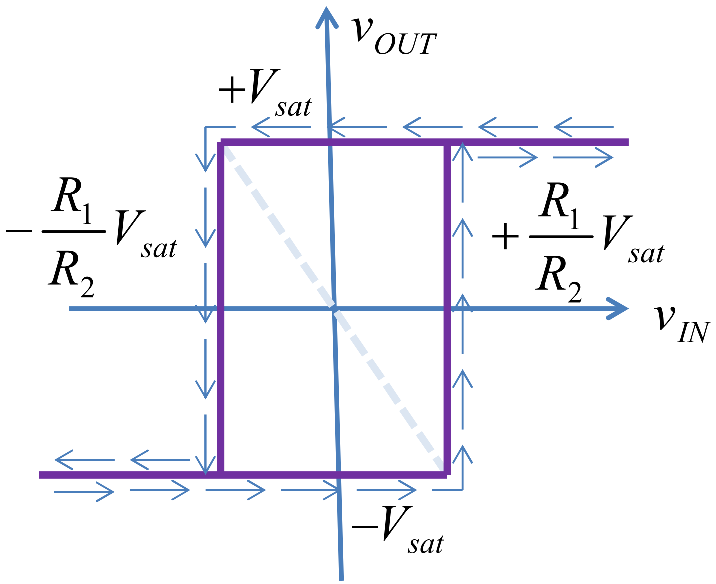
$v_{IN} > 0$　　D_1导通　　$v_{OUT} = 0$　　$v_{OPA,O} = -0.7V$

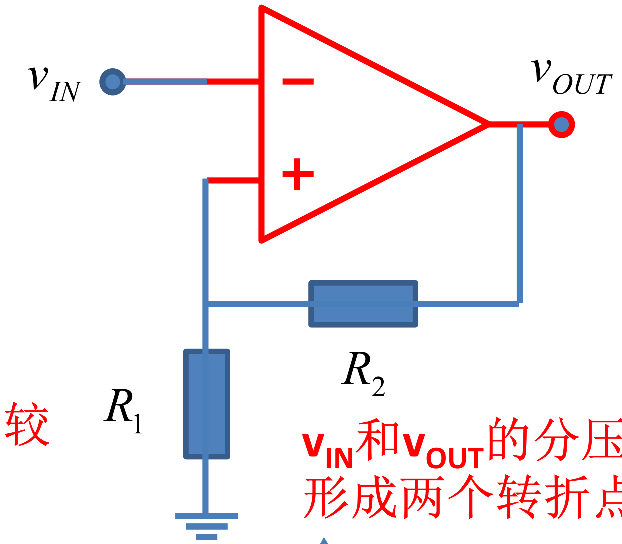
$v_{IN} < 0$　　D_2导通　　$v_{OUT} = -\dfrac{R_2}{R_1} v_{IN}$　　$v_{OPA,O} = v_{OUT} + 0.7V$

两个最基本的正反馈：施密特触发器

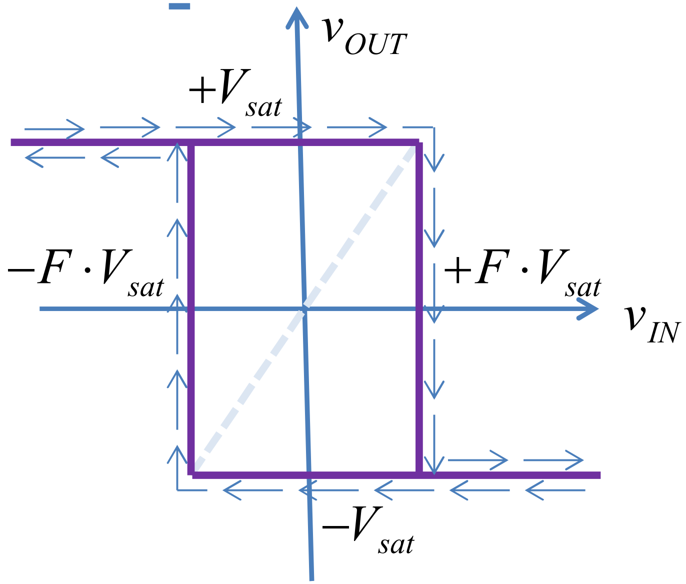


v_{IN}和v_{OUT}的加权平均和0进行比较
形成两个转折点





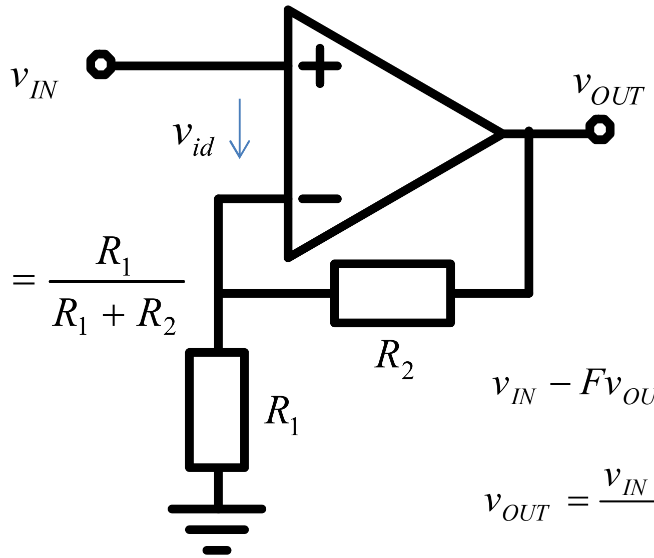
v_{IN}和v_{OUT}的分压进行比较
形成两个转折点



线性负反馈

唯一输出

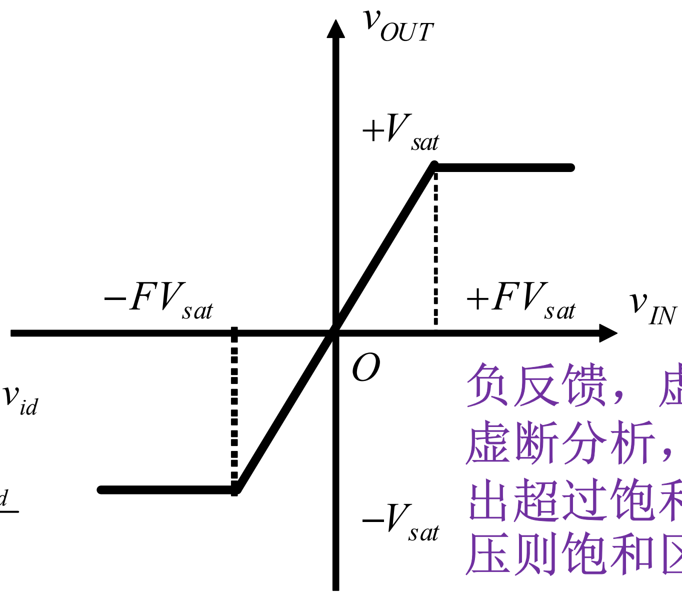
线性正反馈与线性负反馈的区别



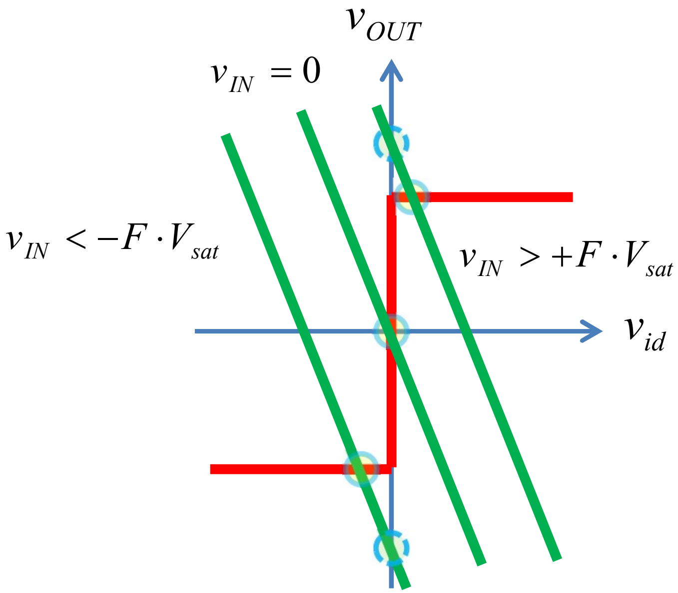
$$F = \frac{R_1}{R_1 + R_2}$$

$$v_{IN} - F v_{OUT} = v_{id}$$

$$v_{OUT} = \frac{v_{IN} - v_{id}}{F}$$



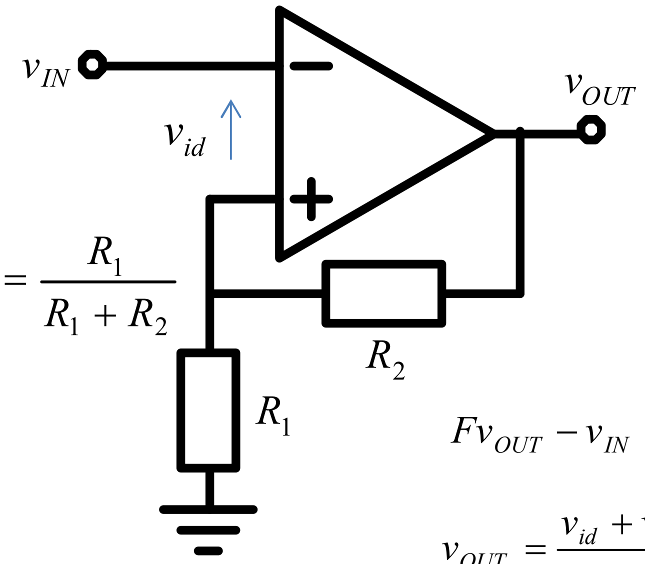
负反馈，虚短虚断分析，输出超过饱和电压则饱和区



线性区 $v_{IN} = F \cdot v_{OUT}$

$$v_{OUT} = \frac{1}{F} v_{IN} = \left(1 + \frac{R_2}{R_1}\right) v_{IN}$$

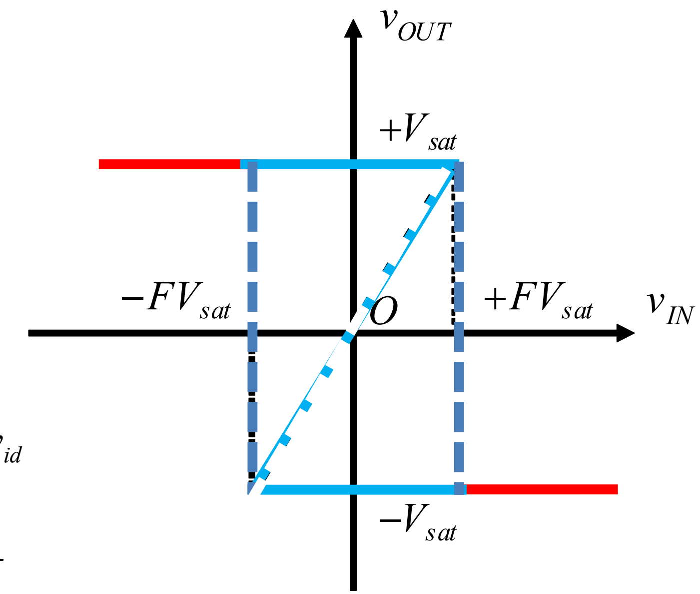
线性正反馈



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

$$Fv_{OUT}-v_{IN}=v_{id}$$

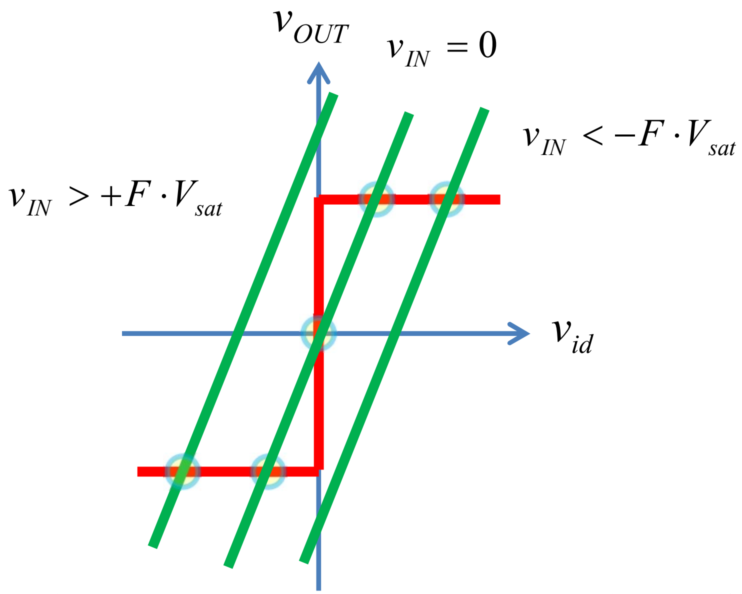
$$v_{OUT}=\frac{v_{id}+v_{IN}}{F}$$



线性区 $v_{IN}=F\cdot v_{OUT}$

$$v_{OUT}=\frac{1}{F}v_{IN}=\left(1+\frac{R_2}{R_1}\right)v_{IN}$$

非唯一输出

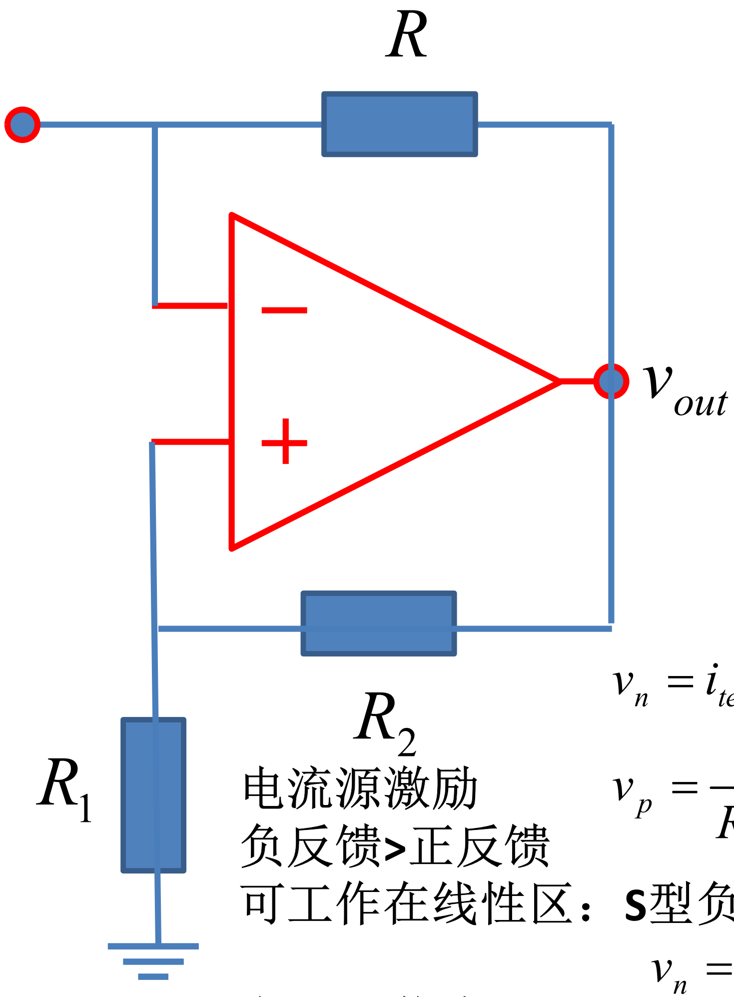


不稳定区：待不住

理论转移特性曲线
实际转移特性曲线：滞回曲线

同时有正反馈和负反馈

不能再用连接关系判断受控源类型：不再是用负反馈稳定输出



$$v_n = i_{test} R + v_o$$

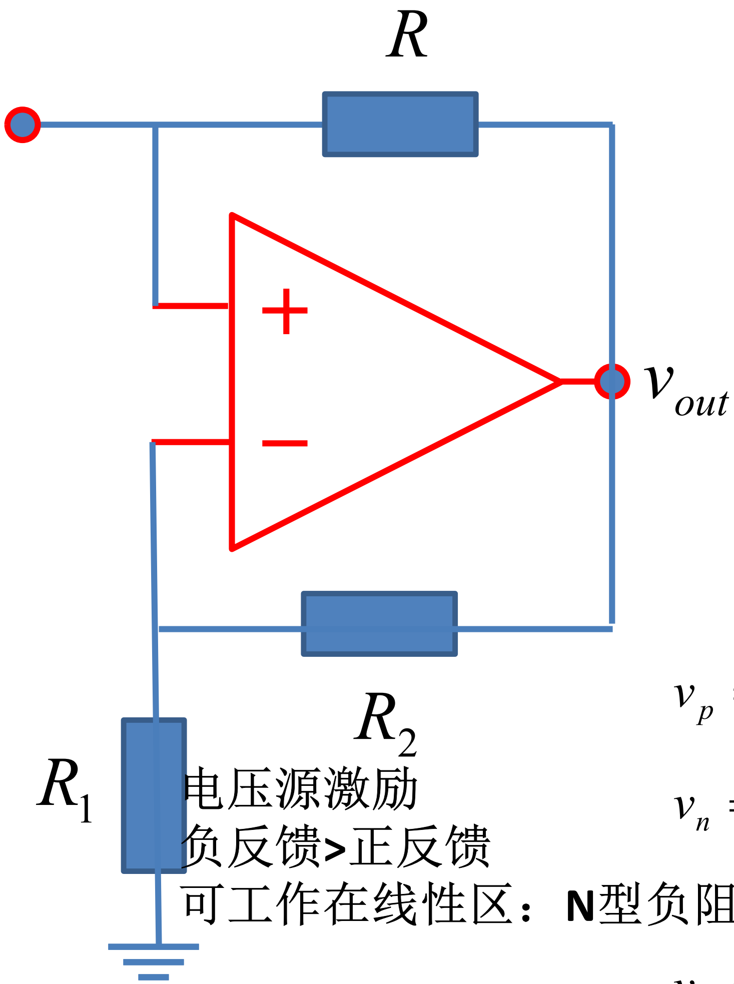
$$v_p = \frac{R_1}{R_1 + R_2} v_o$$

电流源激励
负反馈>正反馈
可工作在线性区：**S**型负阻

$$v_n = v_{test}$$

$$v_p = \frac{R_1}{R_1 + R_2} v_o$$

电压源激励
正反馈>负反馈
只能工作在正负饱和区



$$v_p = v_{test}$$

$$v_n = \frac{R_1}{R_1 + R_2} v_o$$

电压源激励
负反馈>正反馈
可工作在线性区：**N**型负阻

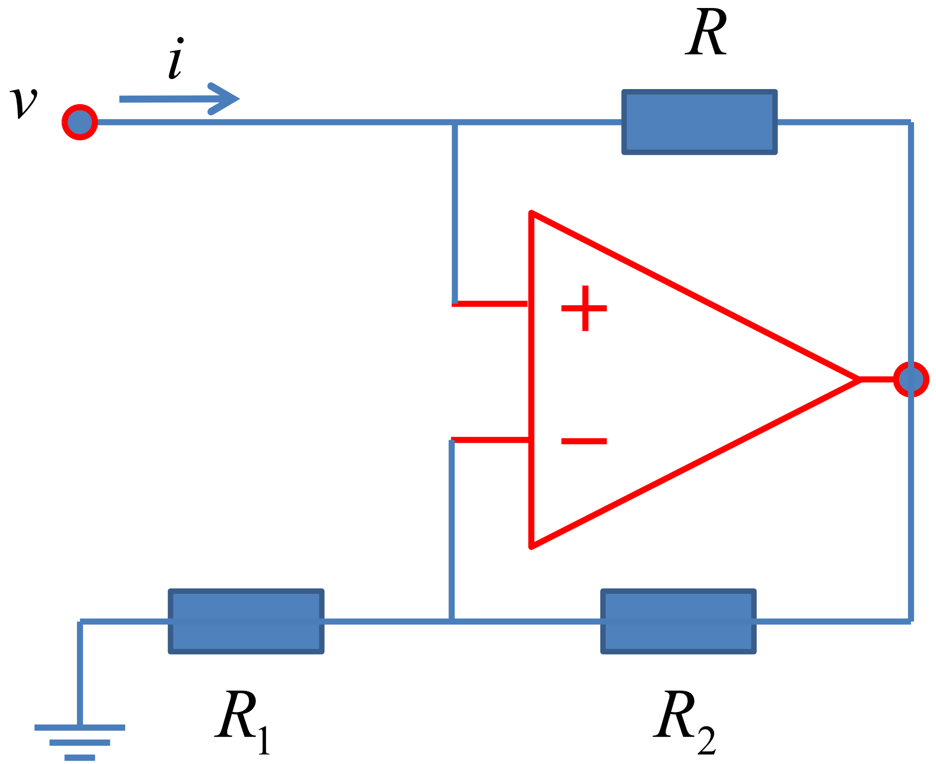
$$v_p = i_{test} R + v_o$$

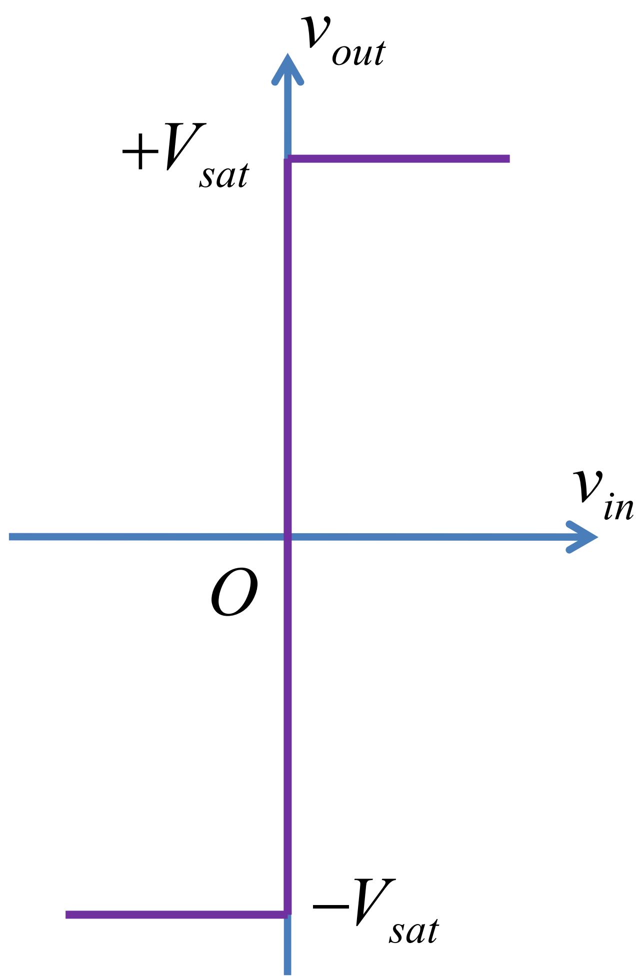
$$v_n = \frac{R_1}{R_1 + R_2} v_o$$

电流源激励
正反馈>负反馈
只能工作在正负饱和区

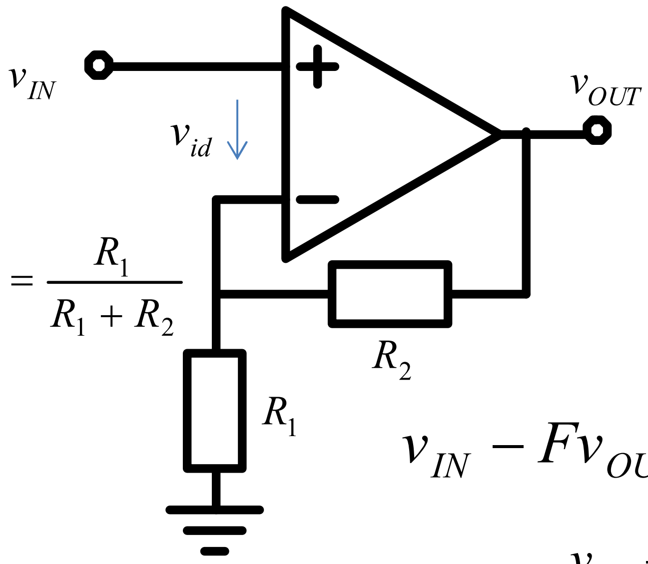
作业2 N型负阻

- 已知理想运放的转移特性，分析确认如图所示单端口网络的伏安特性为N型负阻
  - 提示1：假设在线性区，假设在正饱和区，假设在负饱和区，分别考察
  - 提示2：电压源驱动，N型具有唯一解
    - 电压源驱动，确保负反馈

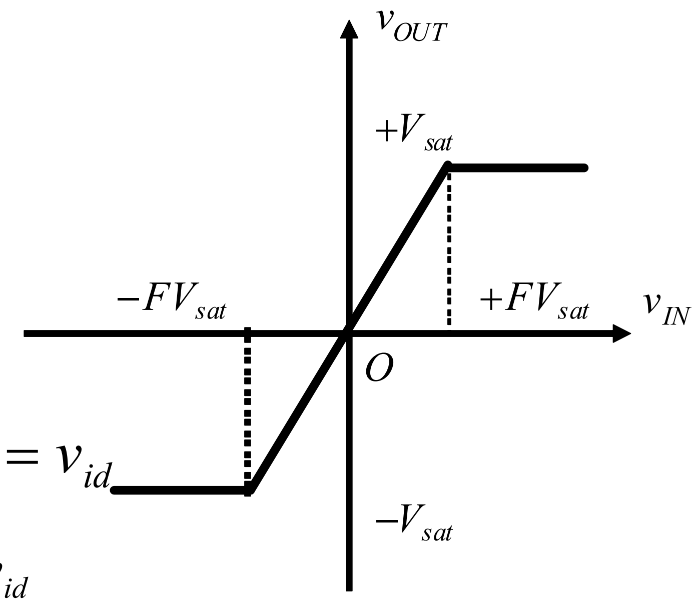




同相电压放大器

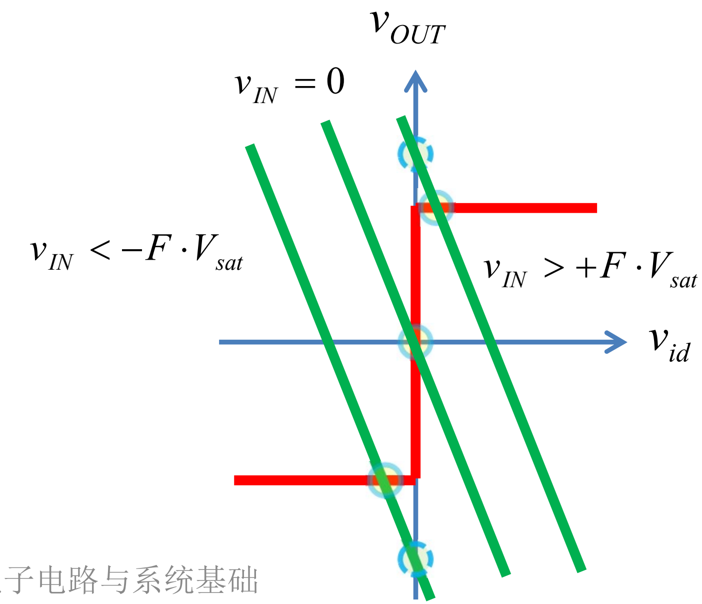


$$F = \frac{R_1}{R_1 + R_2}$$



$$v_{IN} - Fv_{OUT} = v_{id}$$

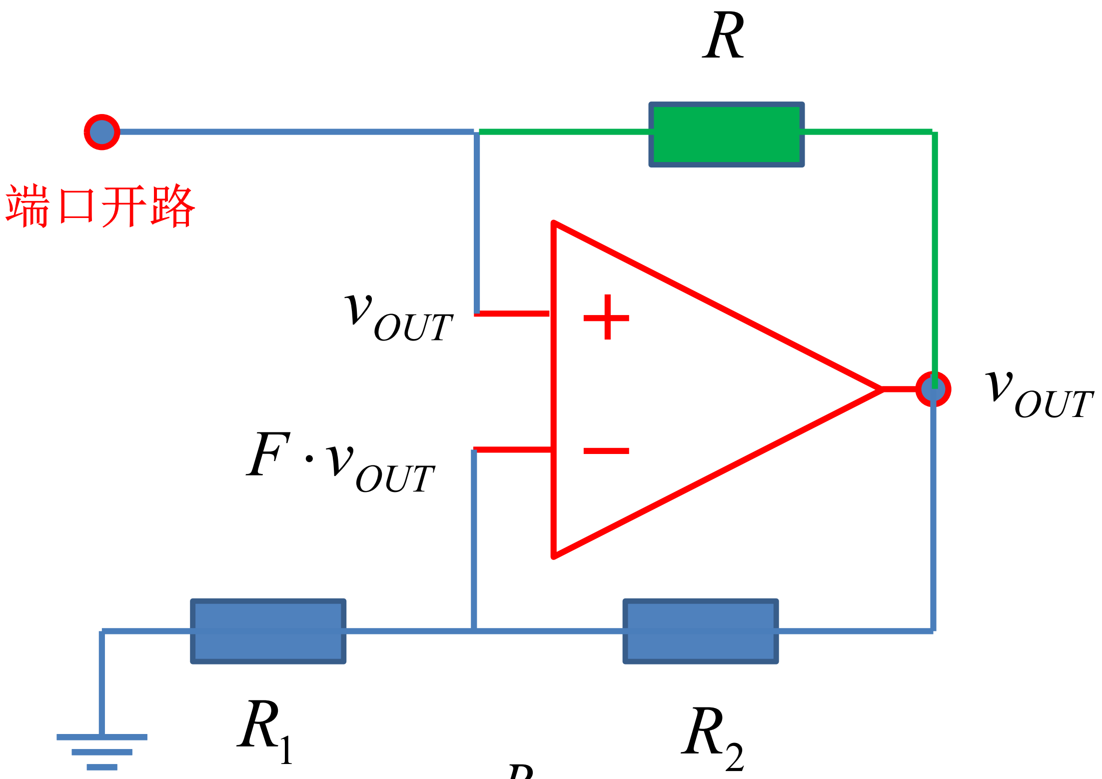
$$v_{OUT} = \frac{v_{IN} - v_{id}}{F}$$



线性区 $v_{IN} = F \cdot v_{OUT}$

$$v_{OUT} = \frac{1}{F} v_{IN} = \left(1 + \frac{R_2}{R_1}\right) v_{IN}$$

正反馈则无法待在线性区



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

可能性1：运放线性区

$$v_{OUT} = F \cdot v_{OUT}$$

$$v_{OUT} = 0$$

可能性2：运放正饱和区

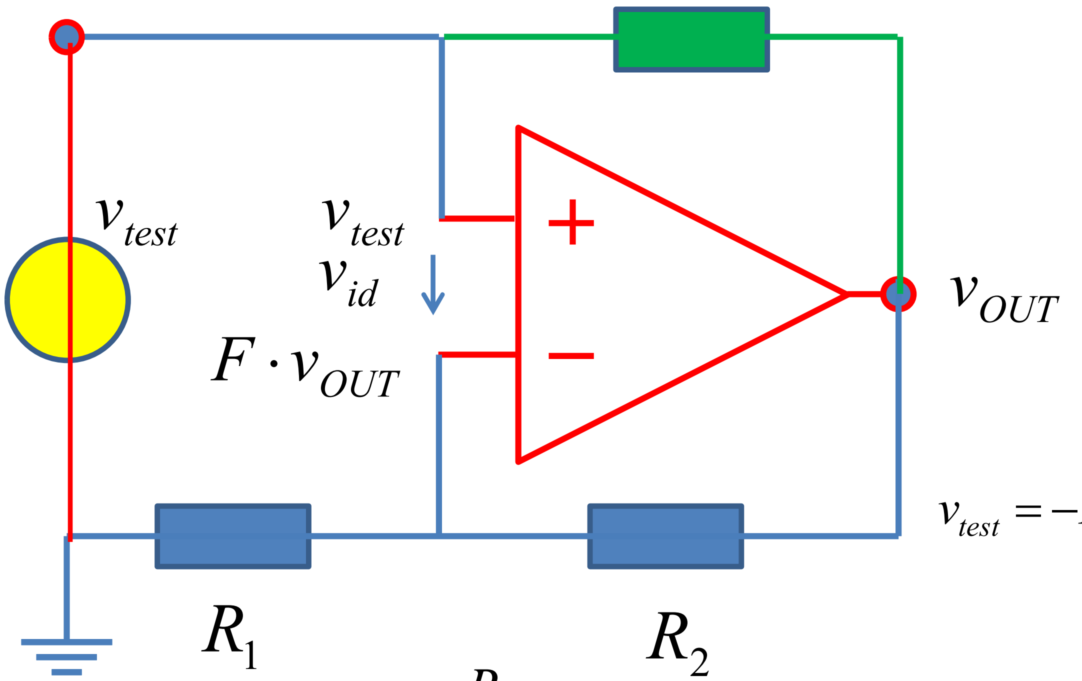
$$V_{sat} > F \cdot V_{sat}$$

可能性3：运放负饱和区

$$F \cdot \left(-V_{sat}\right) > -V_{sat}$$

输入端口开路，正反馈高于负反馈，电路中的噪声，将导致运放无法待在线性区

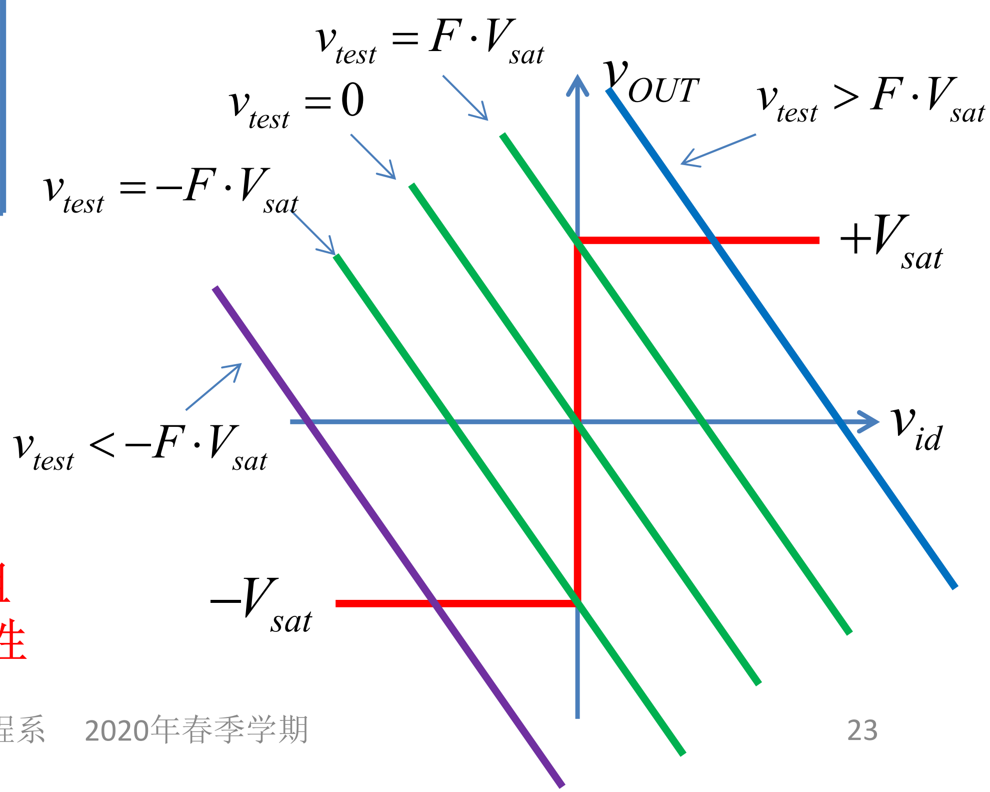
同相输入端恒压源取消正反馈



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

$$v_{id} = v_{test} - F \cdot v_{OUT}$$

$$v_{OUT} = \frac{1}{F} v_{test} - \frac{1}{F} v_{id}$$

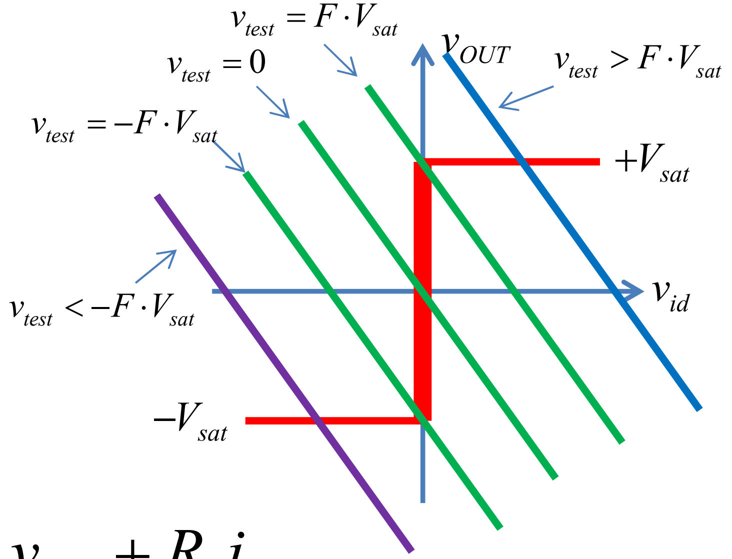


加压测试负反馈：**N**型负阻
加流测试正反馈：滞回特性

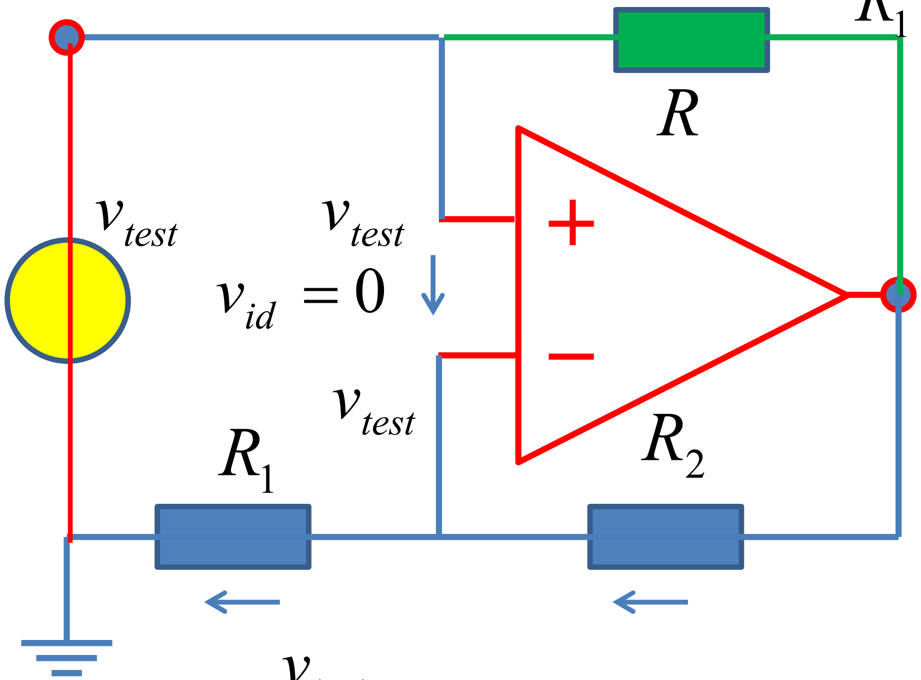
运放线性区

$$\boxed{-F \cdot V_{sat} < v_{test} < +F \cdot V_{sat}}$$

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



$$i = \frac{R_2}{R_1}\frac{v_{test}}{R}$$



$$i_1 = \frac{v_{test}}{R_1}$$

$$i_2 = i_1$$

$$v_{OUT} = v_{test} + R_2 i_2$$

$$= v_{test} + \frac{R_2}{R_1} v_{test}$$

$$= \frac{v_{test}}{F} \in \left(-V_{sat}, V_{sat}\right)$$

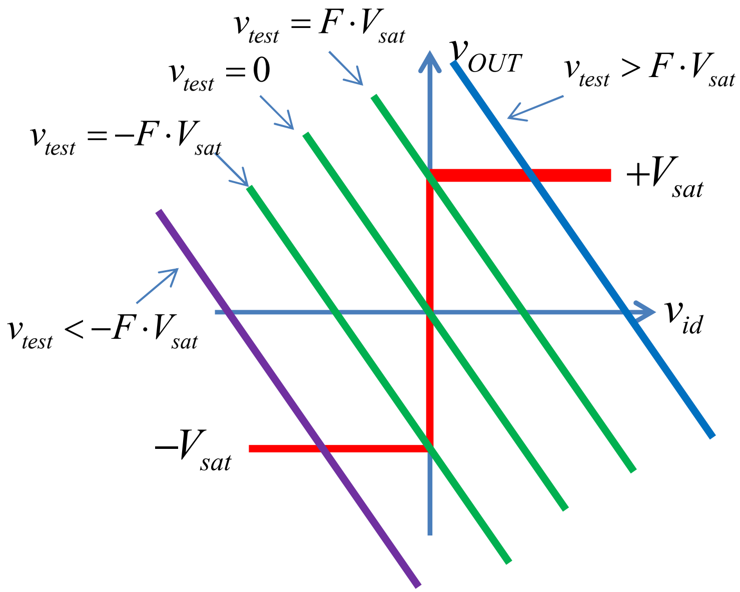
$$i = \frac{R_2}{R_1}\frac{v_{test}}{R} = -i_{test}$$

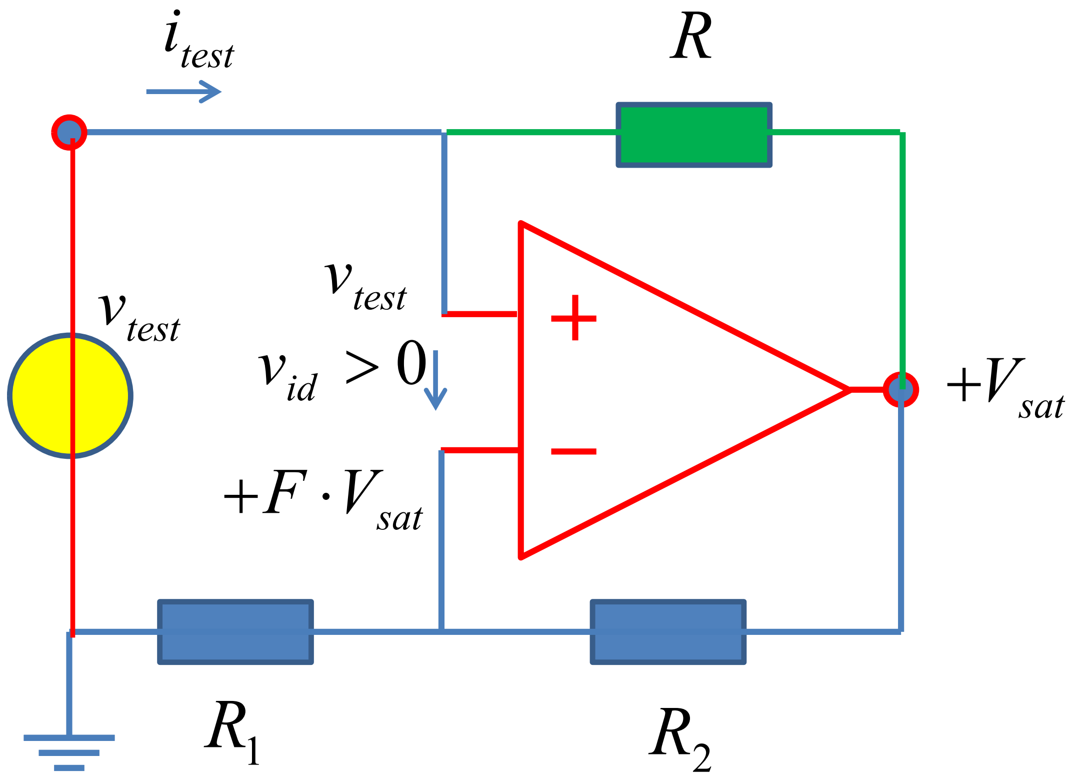
$$v_{test} = -i_{test}\frac{R_1}{R_2}R$$

运放正饱和区

$$\boxed{v_{test} > +F \cdot V_{sat}}$$

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



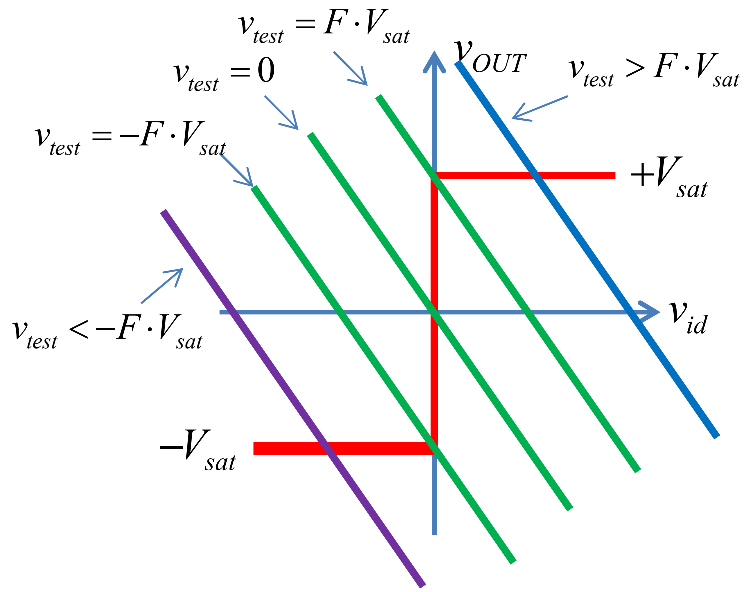


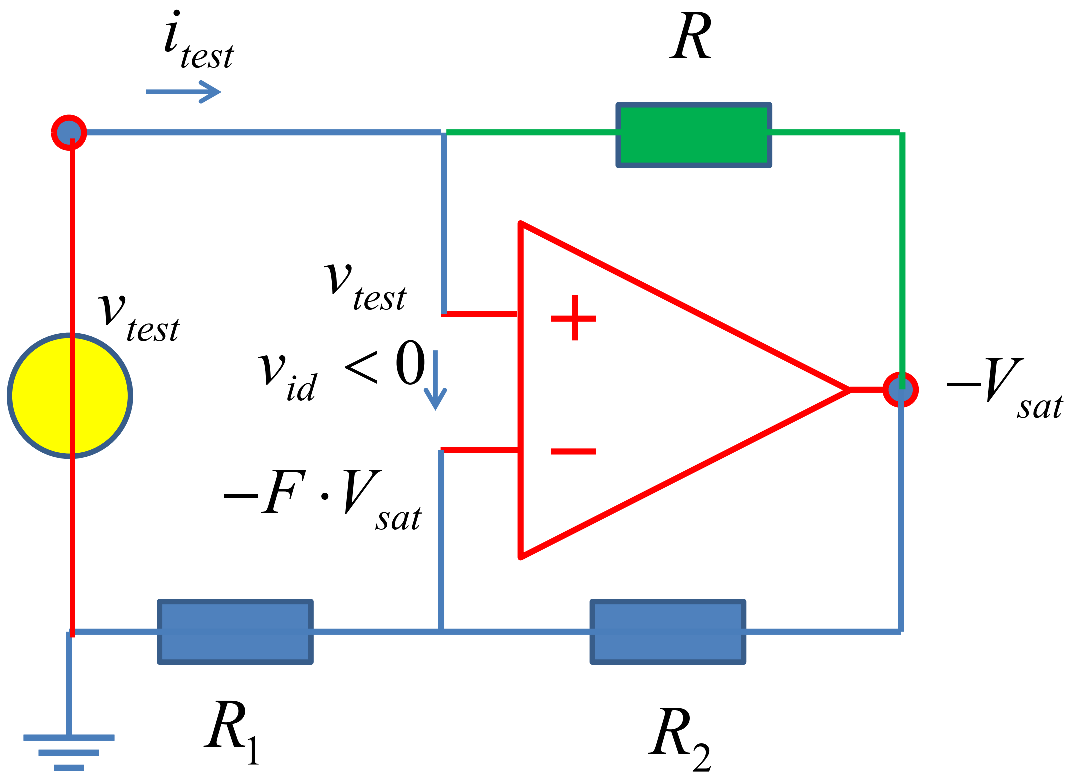
$$v_{test} = i_{test} R + V_{sat}$$

运放负饱和区

$$\boxed{v_{test} < -F \cdot V_{sat}}$$

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





$$v_{test} = i_{test} R - V_{sat}$$

N型负阻
压控器件

运放线性区

$$\boxed{-F\cdot V_{sat} < v_{test} < +F\cdot V_{sat}}$$

$$v_{test} = -i_{test}\frac{R_1}{R_2}R$$

$$i_{test} = -\frac{R_2}{R_1}\frac{v_{test}}{R}$$

运放正饱和区

$$\boxed{v_{test} > +F\cdot V_{sat}}$$

$$v_{test} = i_{test}R + V_{sat}$$

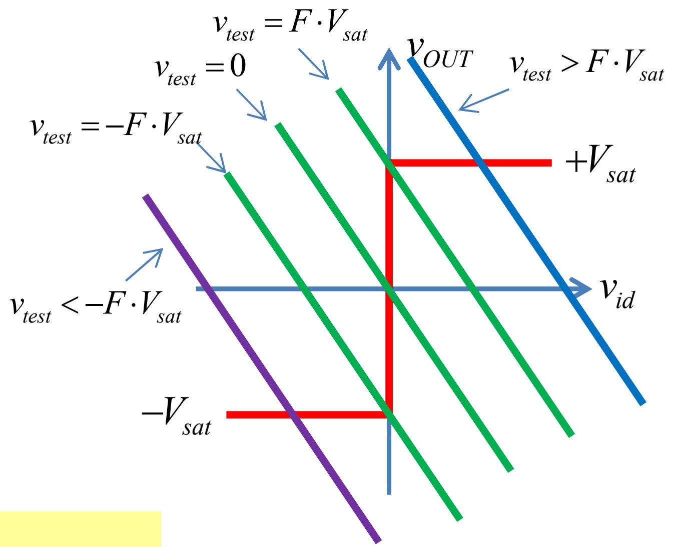
运放负饱和区

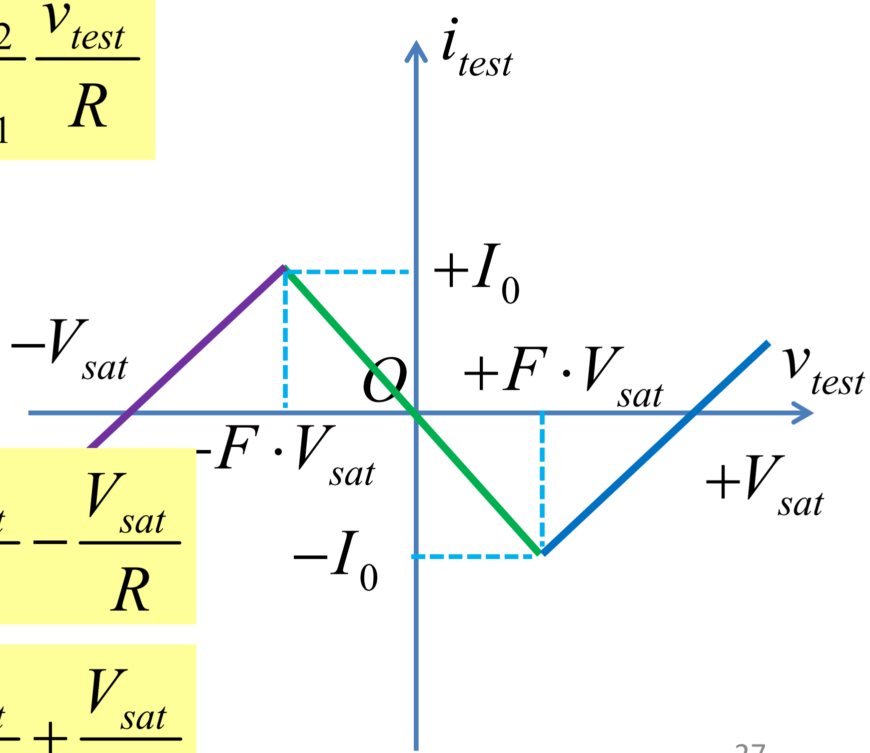
$$\boxed{v_{test} < -F\cdot V_{sat}}$$

$$v_{test} = i_{test}R - V_{sat}$$

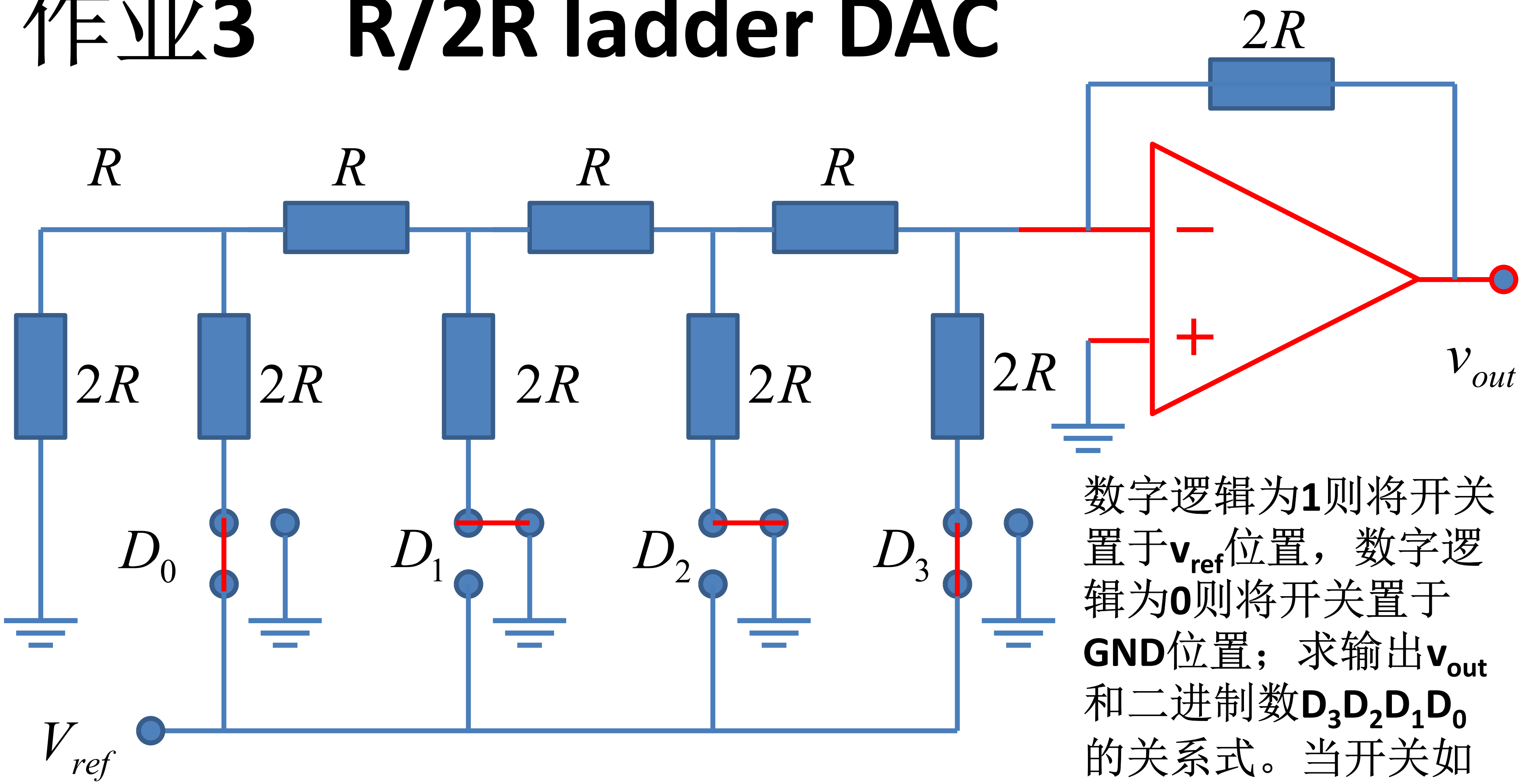
$$i_{test} = \frac{v_{test}}{R} - \frac{V_{sat}}{R}$$

$$i_{test} = \frac{v_{test}}{R} + \frac{V_{sat}}{R}$$



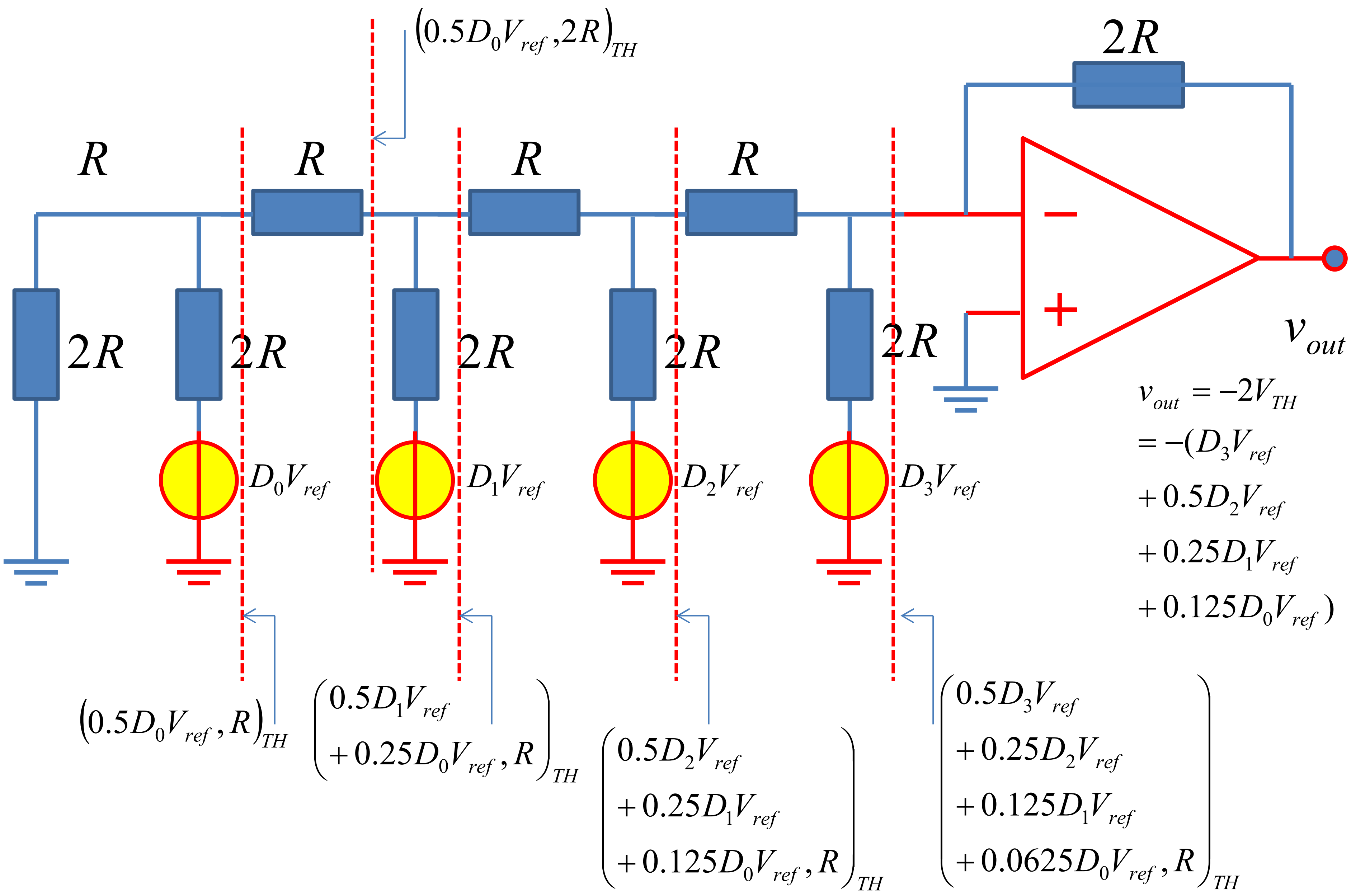


作业3　R/2R ladder DAC



数字逻辑为**1**则将开关置于v_{ref}位置，数字逻辑为**0**则将开关置于**GND**位置；求输出v_{out}和二进制数$D_3D_2D_1D_0$的关系式。当开关如图所示时，二进制数是多少？对应输出电压为多少？假设v_{ref}**=5V**。

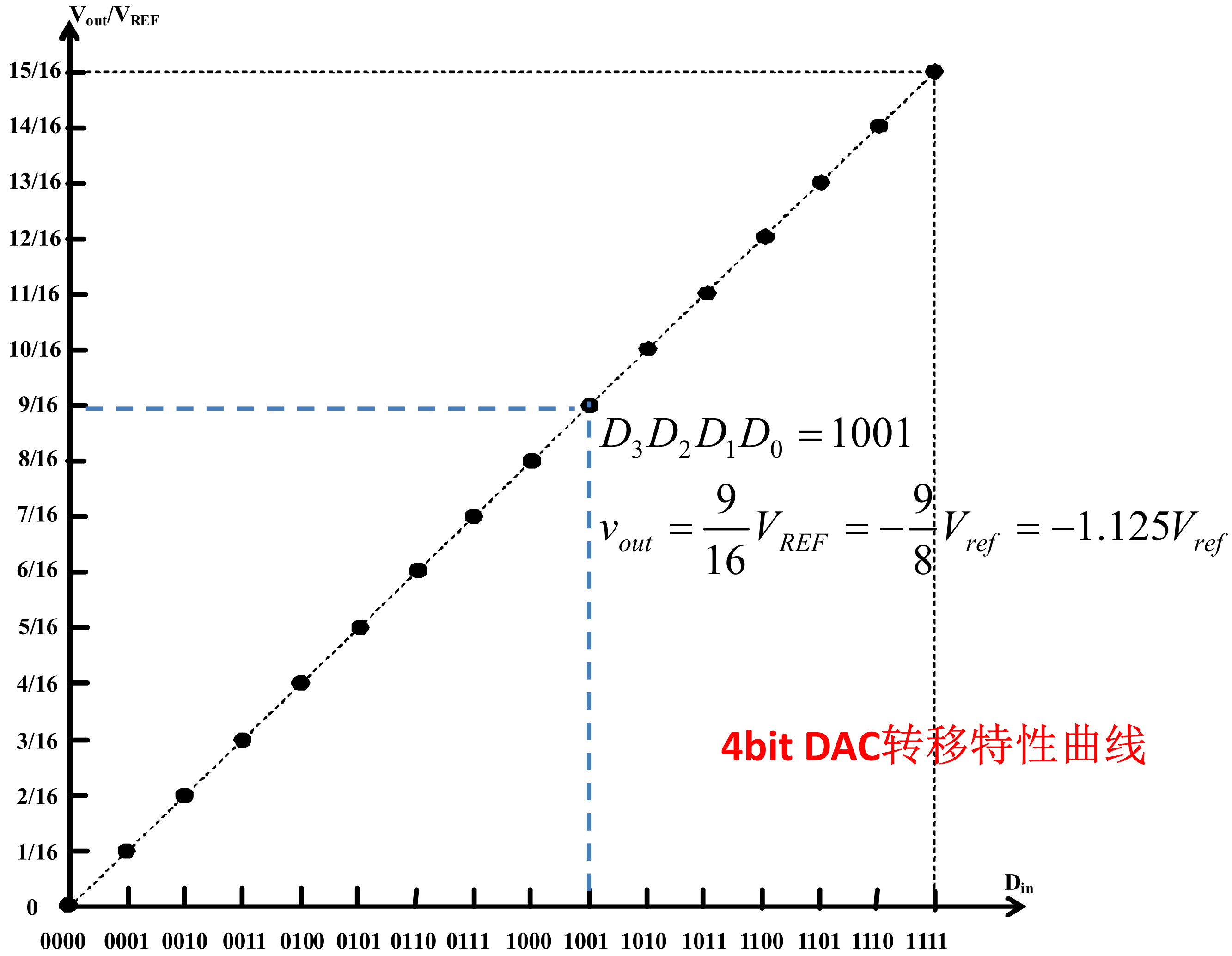
提示：将**D0-D3**处理为电压源，**…**


$(0.5D_0V_{ref}, 2R)_{TH}$
$2R$
R
R
R
R
$2R$
$2R$
$2R$
$2R$
$2R$
v_{out}
D_0V_{ref}
D_1V_{ref}
D_2V_{ref}
D_3V_{ref}
$v_{out} = -2V_{TH}$
$= -(D_3V_{ref}$
$+ 0.5D_2V_{ref}$
$+ 0.25D_1V_{ref}$
$+ 0.125D_0V_{ref})$
$(0.5D_0V_{ref}, R)_{TH}$
$\begin{pmatrix} 0.5D_1V_{ref} \\ +0.25D_0V_{ref}, R \end{pmatrix}_{TH}$
$\begin{pmatrix} 0.5D_2V_{ref} \\ +0.25D_1V_{ref} \\ +0.125D_0V_{ref}, R \end{pmatrix}_{TH}$
$\begin{pmatrix} 0.5D_3V_{ref} \\ +0.25D_2V_{ref} \\ +0.125D_1V_{ref} \\ +0.0625D_0V_{ref}, R \end{pmatrix}_{TH}$

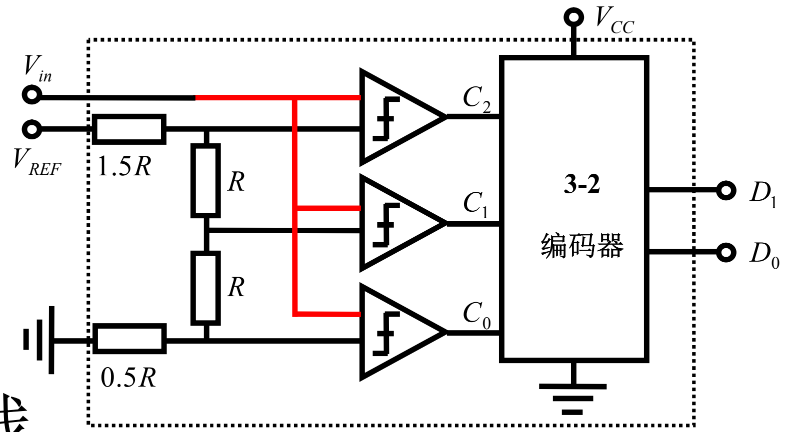
$$v_{out} = -(D_3V_{ref} + 0.5D_2V_{ref} + 0.25D_1V_{ref} + 0.125D_0V_{ref})$$

$$= -\frac{2}{16}V_{ref}\left(2^3D_3 + 2^2D_2 + 2^1D_1 + 2^0D_0\right)$$

$$= \frac{V_{REF}}{2^4}\sum_{k=0}^{3}2^kD_k$$



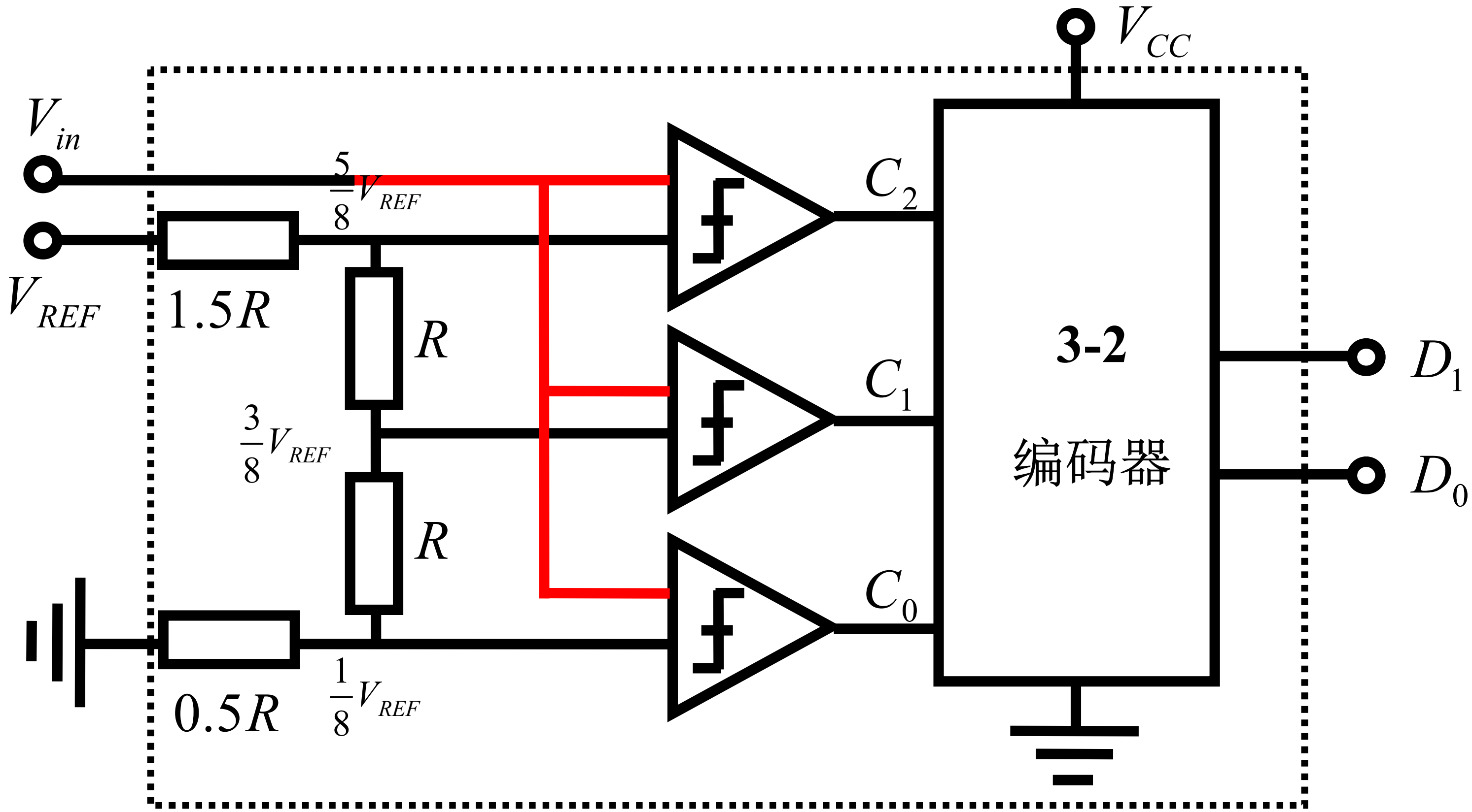
作业4
Flash-ADC编码表



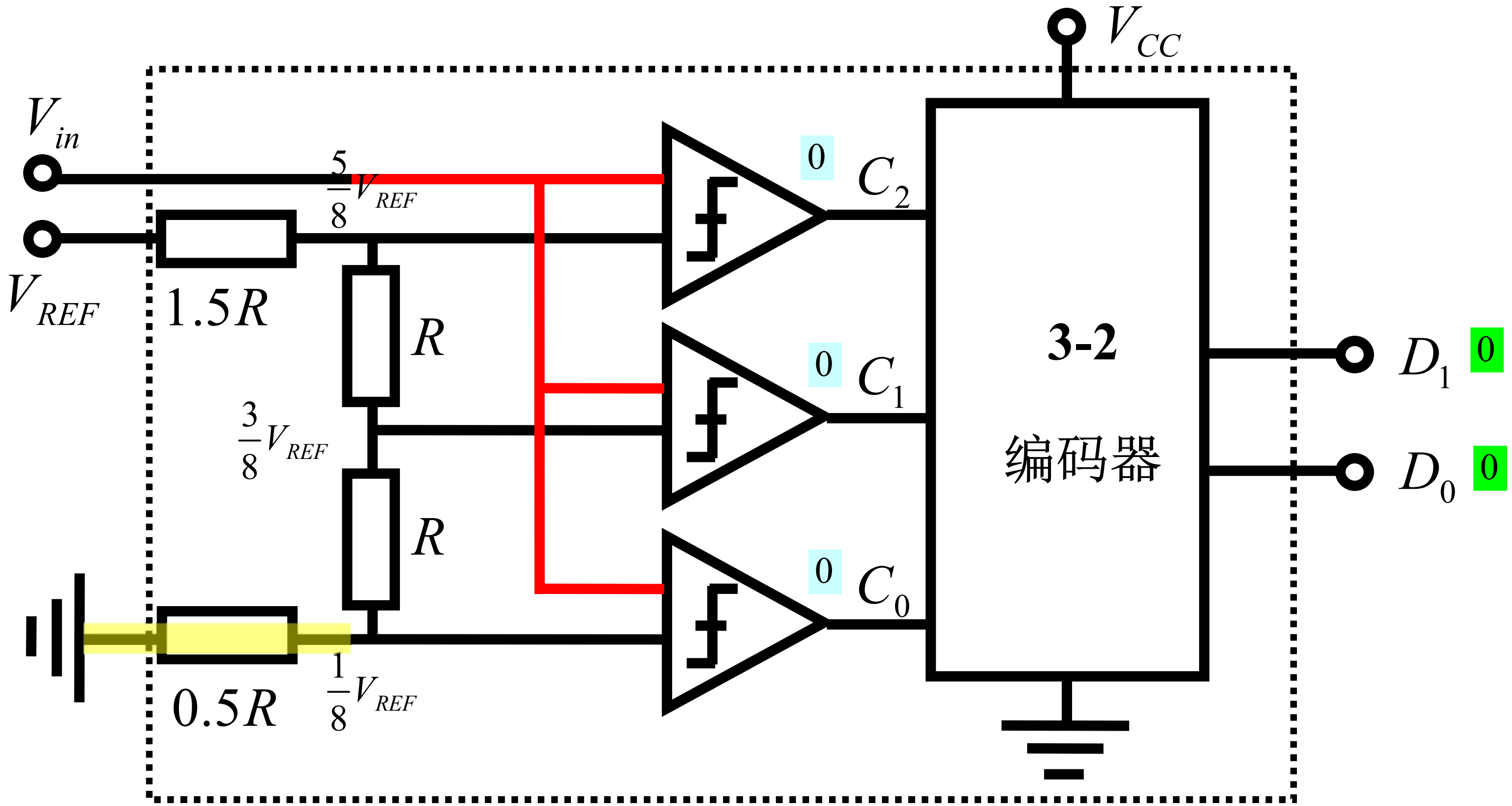
- 填写flash-ADC编码的码表
- 画出输入V_{in}输出D_{out}转移特性曲线

模拟输入电压	$C_2C_1C_0$	数字输出码D_1D_0
	000	00
		01
		10
		11

电阻分压网络提供比较电压基准

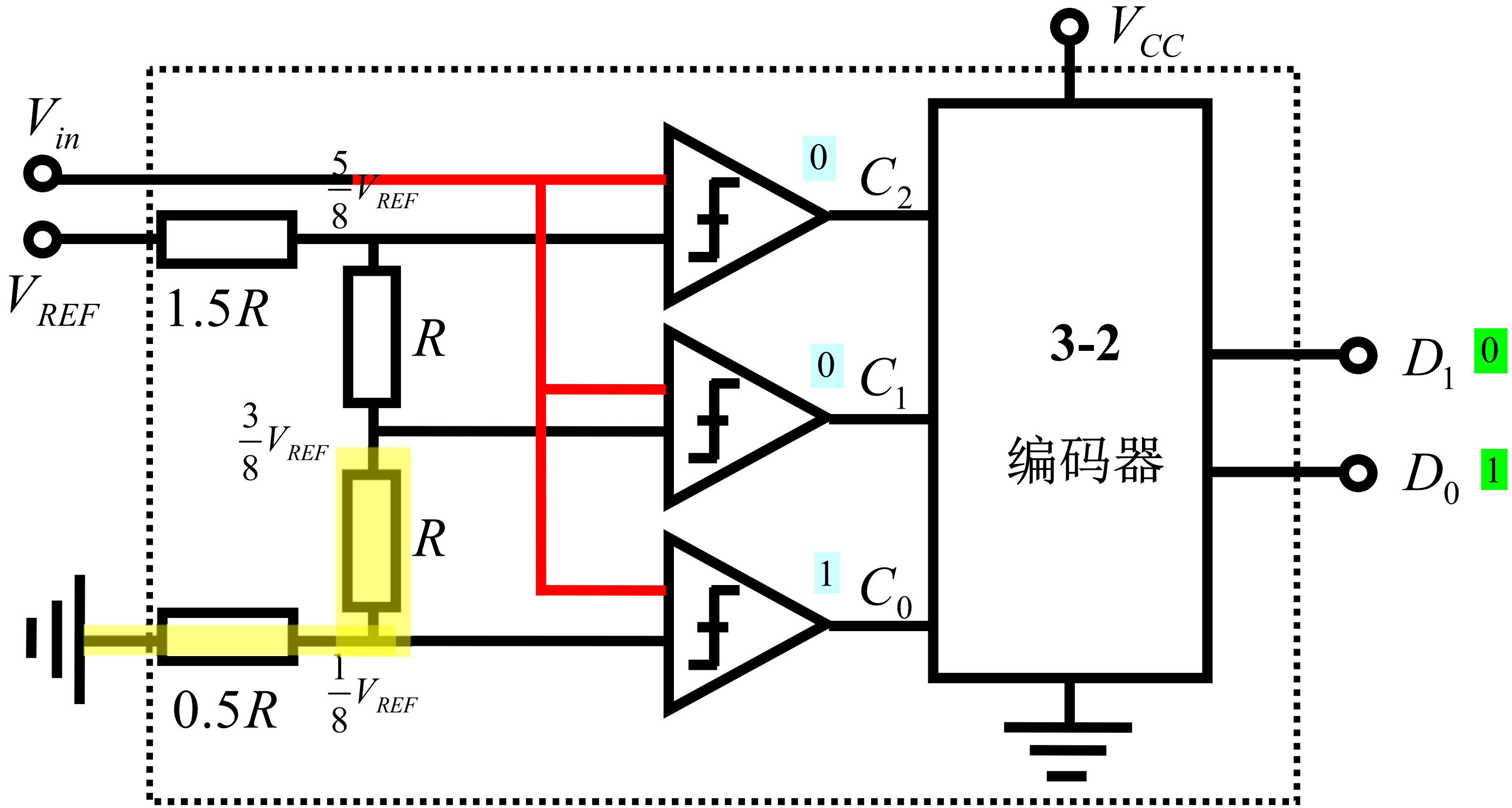


$V_{in}<V_{REF}/8$

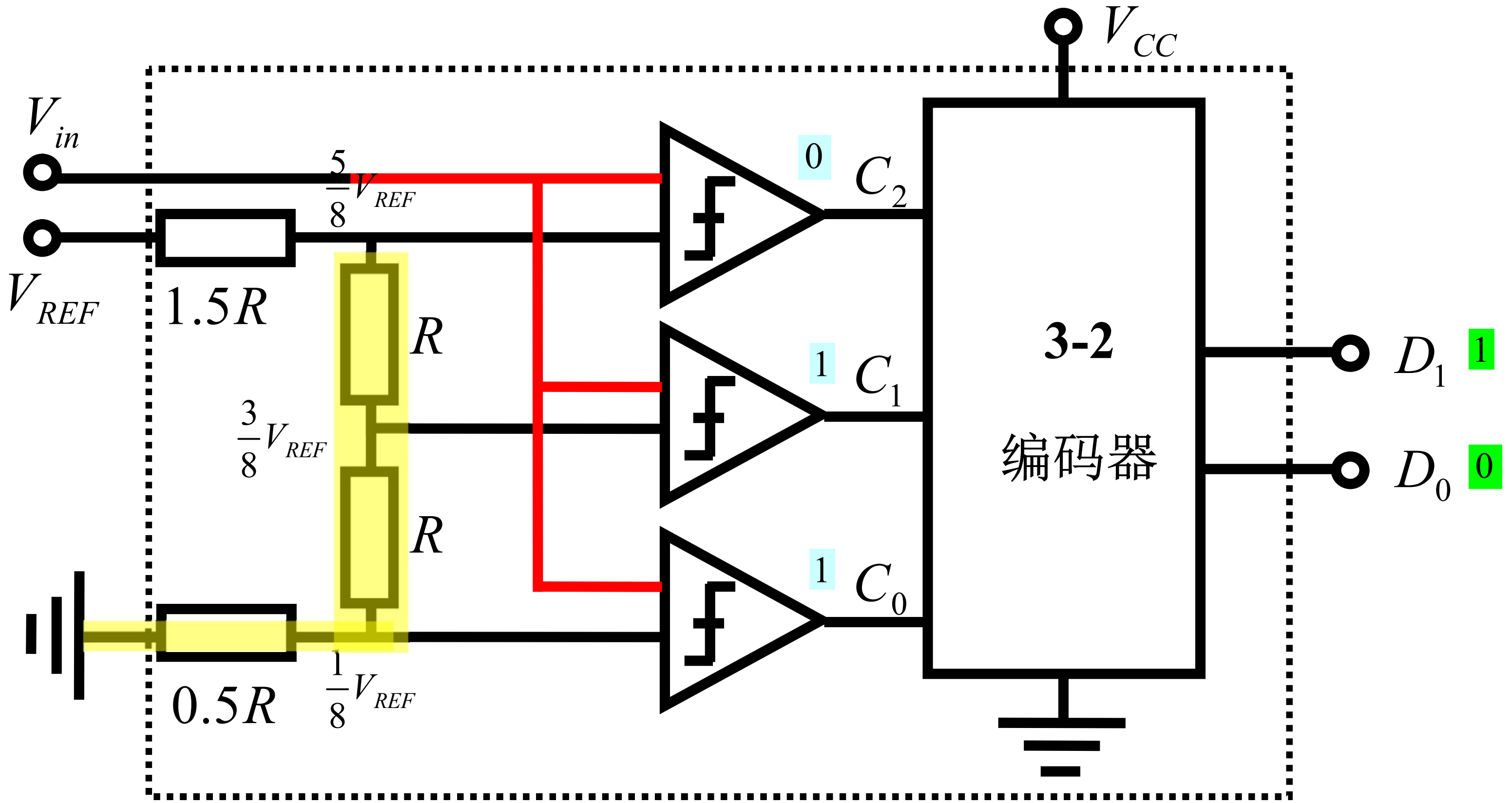


V_{CC}
V_{in}
$\frac{5}{8}V_{REF}$
0
C_2
V_{REF}
1.5R
R
$\frac{3}{8}V_{REF}$
0
C_1
3-2
编码器
D_1
0
D_0
0
R
0
C_0
0.5R
$\frac{1}{8}V_{REF}$

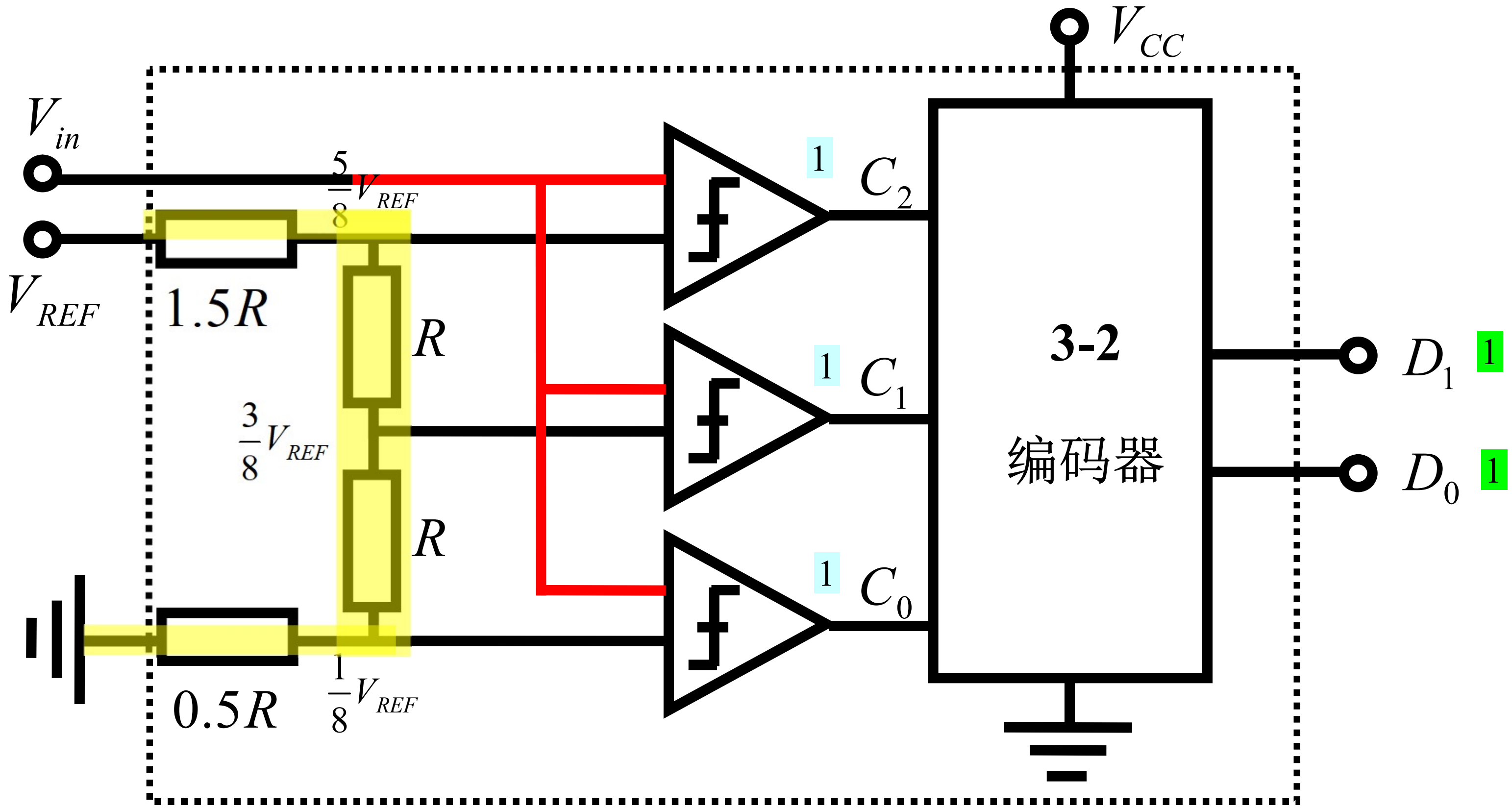
$V_{REF}/8<V_{in}<V_{REF}3/8$



$V_{REF}3/8<V_{in}<V_{REF}5/8$

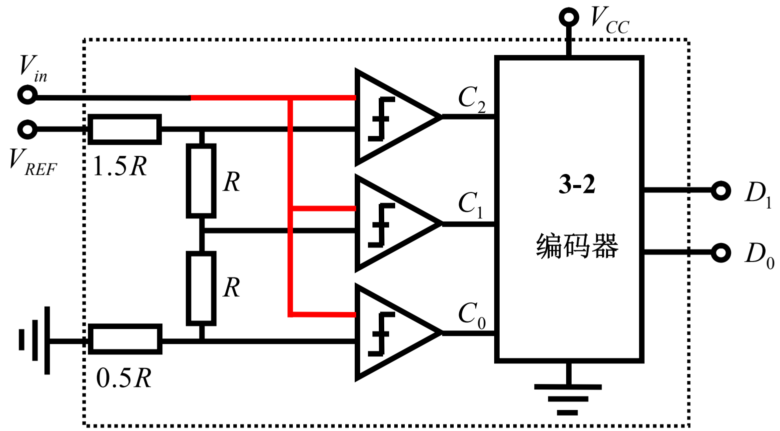


$V_{in} > V_{REF} 5/8$



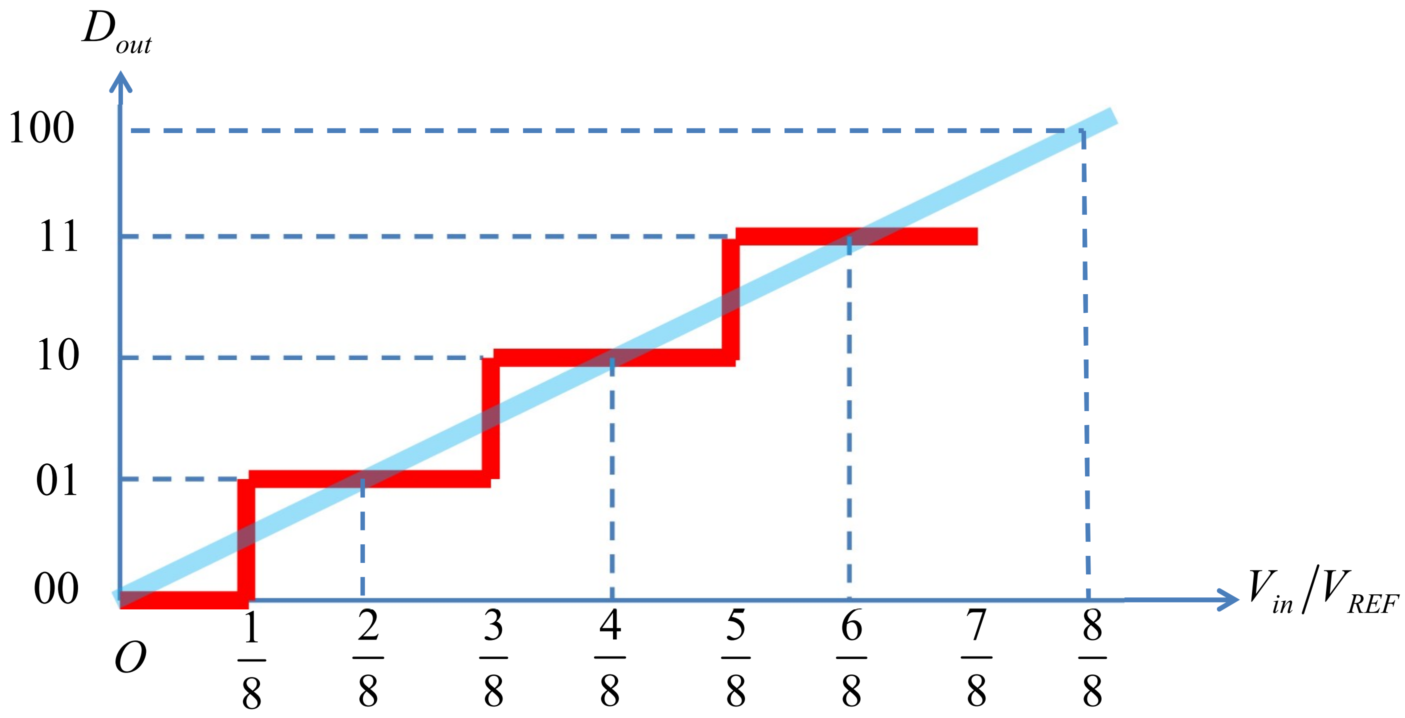
V_{CC}
V_{in}
$\frac{5}{8}V_{REF}$
1
C_2
V_{REF}
1.5R
R
$\frac{3}{8}V_{REF}$
1
C_1
3-2
编码器
D_1
1
D_0
1
R
1
C_0
0.5R
$\frac{1}{8}V_{REF}$

码表



模拟输入电压	$C_2C_1C_0$	数字输出码D_1D_0
$V_{in} < \frac{1}{8}V_{REF}$	**000**	**00**
$\frac{1}{8}V_{REF} < V_{in} < \frac{3}{8}V_{REF}$	**001**	**01**
$\frac{3}{8}V_{REF} < V_{in} < \frac{5}{8}V_{REF}$	**011**	**10**
$V_{in} > \frac{5}{8}V_{REF}$	**111**	**11**

转移特性曲线



2bit ADC转移特性曲线

作业5 CMRR

- 假设运放理想，证明：
- 回答：要想获得80dB的CMRR，对外部电阻精度提出什么要求？

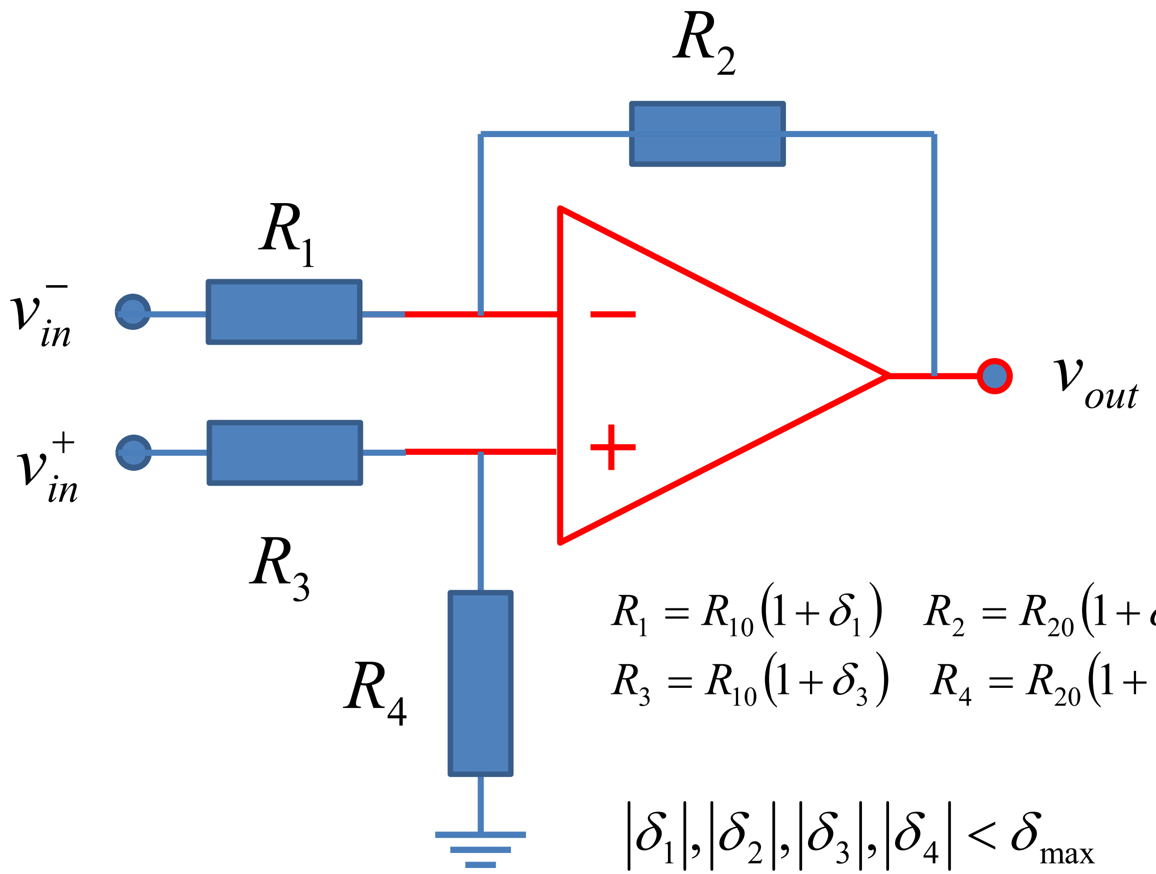
$$CMRR_{\min} = \frac{1}{4\delta_{\max}}$$

$$v_{in}^{+} = v_c + 0.5v_d$$

$$v_{in}^{-} = v_c - 0.5v_d$$

$$v_{out} = A_{vd}v_d + A_{vc}v_c$$

$$CMRR = \left|\frac{A_{vd}}{A_{vc}}\right|$$

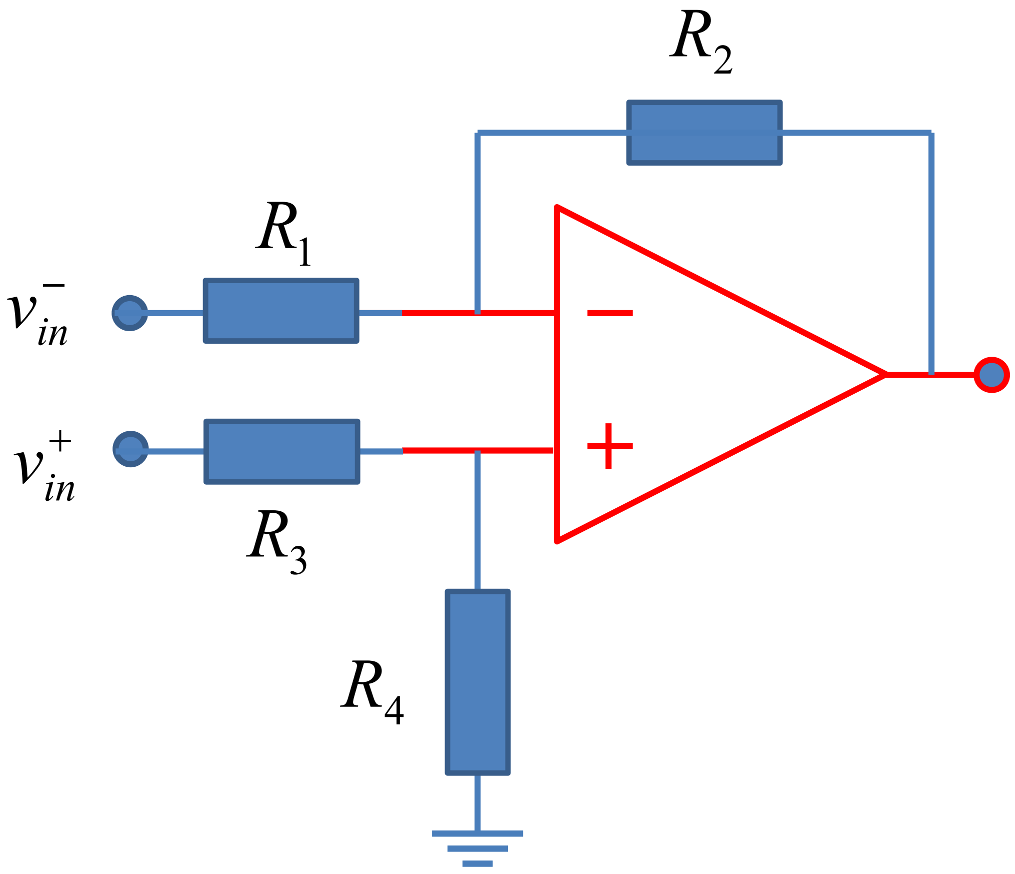


$$R_1 = R_{10}(1+\delta_1) \quad R_2 = R_{20}(1+\delta_2)$$

$$R_3 = R_{10}(1+\delta_3) \quad R_4 = R_{20}(1+\delta_4)$$

$$|\delta_1|, |\delta_2|, |\delta_3|, |\delta_4| < \delta_{\max}$$

CMRR



$$v_{out} = A_v^- \cdot v_{in}^- + A_v^+ \cdot v_{in}^+$$

$$A_v^- = -\frac{R_2}{R_1}$$

$$A_v^+ = \left(\frac{R_2}{R_1} + 1\right)\frac{R_4}{R_3 + R_4}$$

$$v_{in}^+ = v_c + 0.5v_d$$

$$v_{in}^- = v_c - 0.5v_d$$

$$R_1 = R_{10}(1+\delta_1) \quad R_2 = R_{20}(1+\delta_2)$$

$$R_3 = R_{10}(1+\delta_3) \quad R_4 = R_{20}(1+\delta_4)$$

$$CMRR = \left|\frac{A_{vd}}{A_{vc}}\right|$$

$$v_{out} = A_{vd}v_d + A_{vc}v_c$$

先求两个电压增益

$$v_{out} = A_v^- \cdot v_{in}^- + A_v^+ \cdot v_{in}^+$$

$$= -\frac{R_2}{R_1}(v_c - 0.5v_d) + \left(\frac{R_2}{R_1} + 1\right)\frac{R_4}{R_3 + R_4}(v_c + 0.5v_d)$$

$$= \left(\left(\frac{R_2}{R_1} + 1\right)\frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1}\right)v_c + \left(\left(\frac{R_2}{R_1} + 1\right)\frac{R_4}{R_3 + R_4} + \frac{R_2}{R_1}\right)0.5v_d$$

$$= \left(\frac{R_2 + R_1}{R_1}\frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1}\right)v_c + \left(\frac{R_2 + R_1}{R_1}\frac{R_4}{R_3 + R_4} + \frac{R_2}{R_1}\right)0.5v_d$$

$$= \left(\frac{R_1R_4 - R_2R_3}{R_1(R_3 + R_4)}\right)v_c + \left(\frac{2R_2R_4 + R_1R_4 + R_2R_3}{R_1(R_3 + R_4)}\right)0.5v_d$$

$$CMRR = \left|\frac{A_{vd}}{A_{vc}}\right| = \left|0.5\frac{2R_2R_4 + R_1R_4 + R_2R_3}{R_1R_4 - R_2R_3}\right| = \ldots$$

$$CMRR=\left|\frac{A_{vd}}{A_{vc}}\right|=\left|0.5\frac{2R_2R_4+R_1R_4+R_2R_3}{R_1R_4-R_2R_3}\right|$$

留大弃小

$$=\left|0.5\frac{2R_{20}\left(1+\delta_2\right)R_{20}\left(1+\delta_4\right)+R_{10}\left(1+\delta_1\right)R_{20}\left(1+\delta_4\right)+R_{20}\left(1+\delta_2\right)R_{10}\left(1+\delta_3\right)}{R_{10}\left(1+\delta_1\right)R_{20}\left(1+\delta_4\right)-R_{20}\left(1+\delta_2\right)R_{10}\left(1+\delta_3\right)}\right|$$

$$=0.5\left|\frac{2\frac{R_{20}}{R_{10}}\left(1+\delta_2\right)\left(1+\delta_4\right)+\left(1+\delta_1\right)\left(1+\delta_4\right)+\left(1+\delta_2\right)\left(1+\delta_3\right)}{\left(1+\delta_1\right)\left(1+\delta_4\right)-\left(1+\delta_2\right)\left(1+\delta_3\right)}\right|$$

$$=0.5\left|\frac{2\frac{R_{20}}{R_{10}}\left(1+\delta_2+\delta_4+\delta_2\delta_4\right)+\left(1+\delta_1+\delta_4+\delta_1\delta_4\right)+\left(1+\delta_2+\delta_3+\delta_2\delta_3\right)}{\left(1+\delta_1+\delta_4+\delta_1\delta_4\right)-\left(1+\delta_2+\delta_3+\delta_2\delta_3\right)}\right|$$

$$\approx 0.5\left|\frac{2\frac{R_{20}}{R_{10}}+2}{\delta_1+\delta_4-\delta_2-\delta_3}\right|=\left|\frac{\frac{R_{20}}{R_{10}}+1}{\delta_1+\delta_4-\delta_2-\delta_3}\right|\geq\left|\frac{1}{\delta_1+\delta_4-\delta_2-\delta_3}\right|\geq\frac{1}{4\delta_{\max}}=CMRR_{\min}$$

高精度意味着高成本

$$CMRR=\left|\frac{A_{vd}}{A_{vc}}\right|\approx\frac{R_{10}+R_{20}}{R_{10}}\frac{1}{\left|\delta_4-\delta_2+\delta_1-\delta_3\right|}\geq\frac{1}{4\delta_{\max}}=CMRR_{\min}$$

$$CMRR\geq 80dB$$

$$CMRR_{\min}\geq 80dB$$

$$20\log\frac{1}{4\delta_{\max}}\geq 80dB$$

$$\frac{1}{4\delta_{\max}}\geq 10^4$$

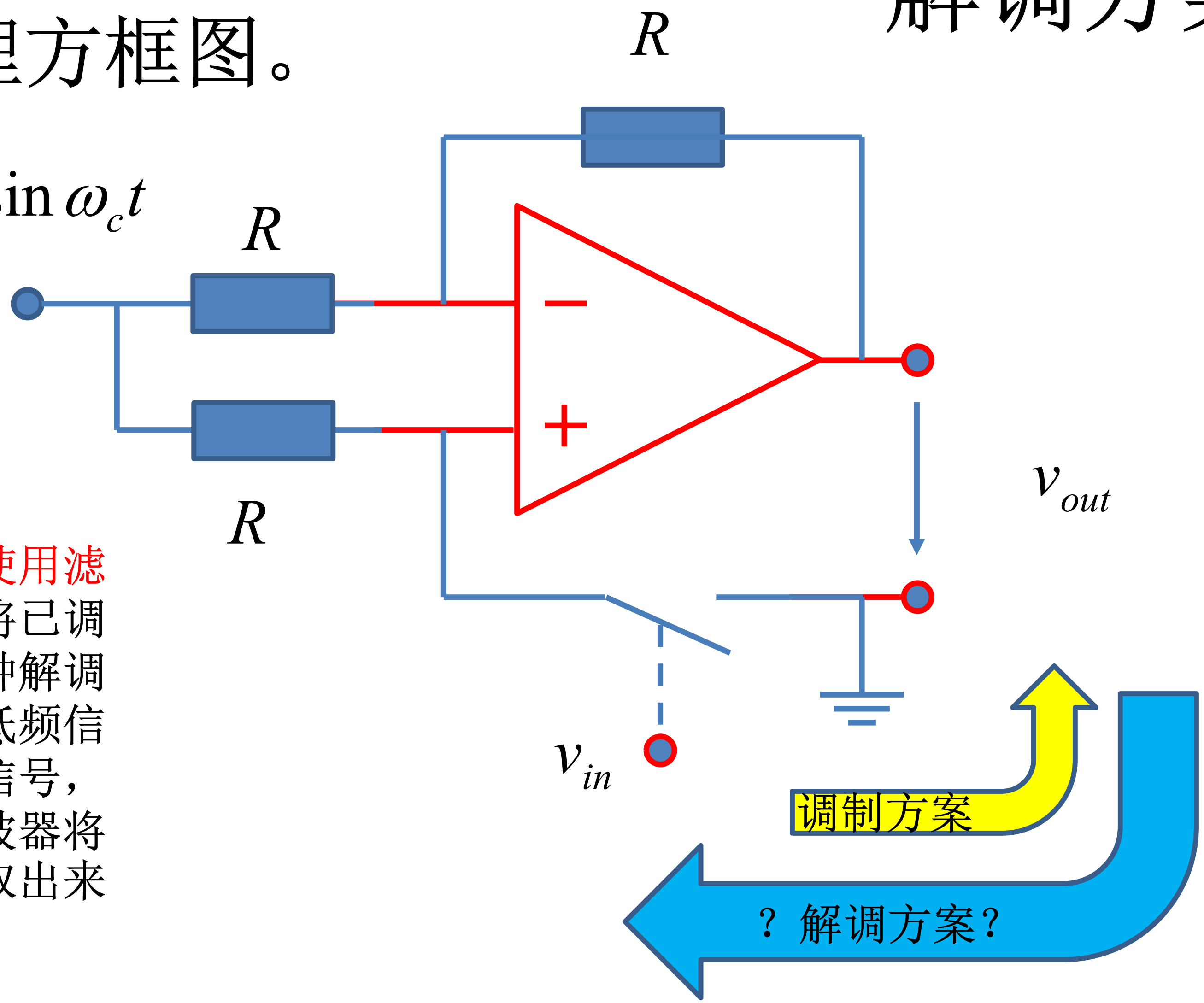
$$\delta_{\max}\leq\frac{1}{4\times 10^4}=2.5\times 10^{-5}=0.25\%\%$$

极高的精度要求，成本将会急剧提高

作业6
解调方案

- 给出你的解调方案，画出电路图或原理方框图。

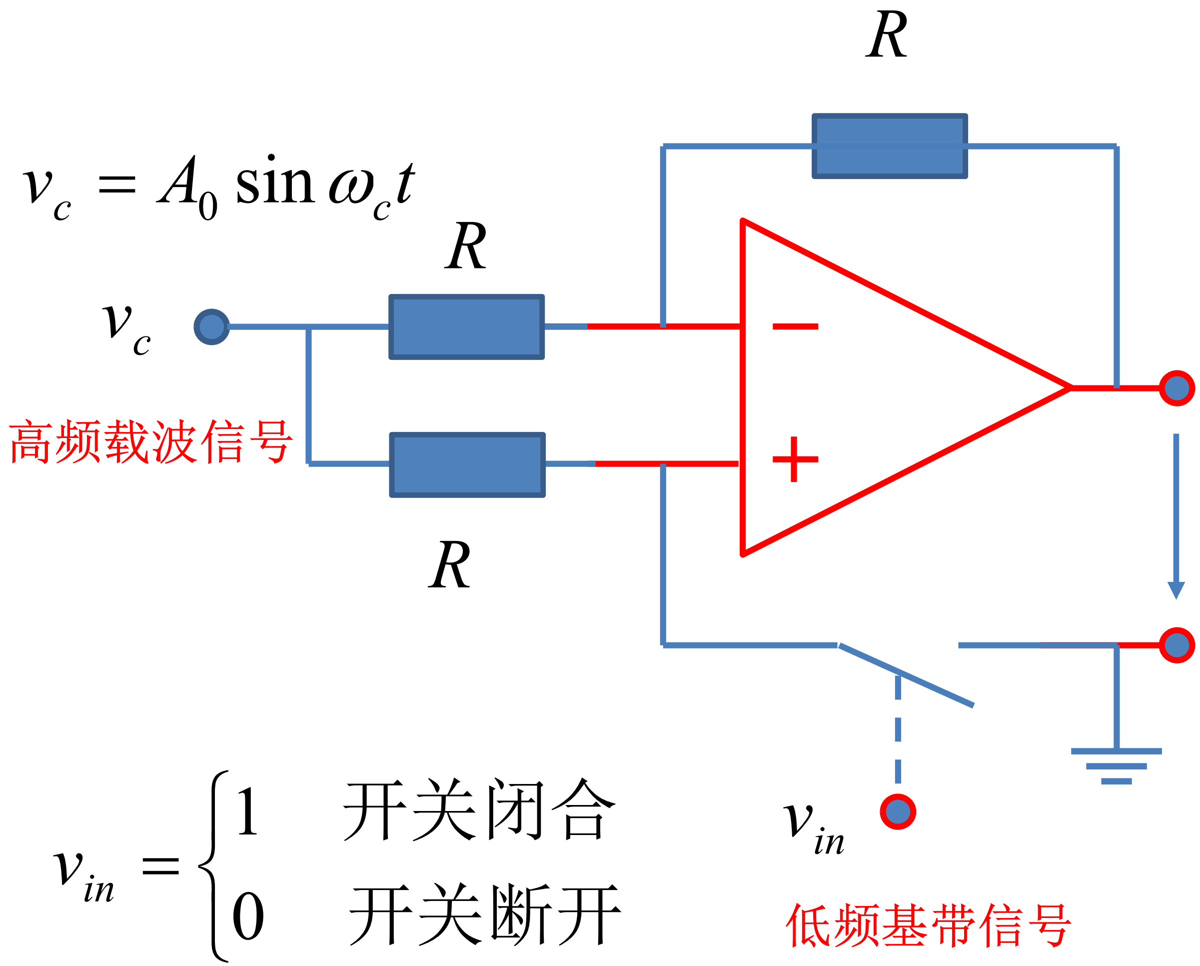
$$v_c = A_0 \sin \omega_c t$$



提示：可以使用滤波器：首先将已调制信号用某种解调方式变换为低频信号加上高频信号，再用低通滤波器将低频信号提取出来

简单调制电路

$$v_c = A_0 \sin \omega_c t$$



低频基带信号被调制到高频载波信号的幅度或相位上：信息装载到载波的幅度或相位上

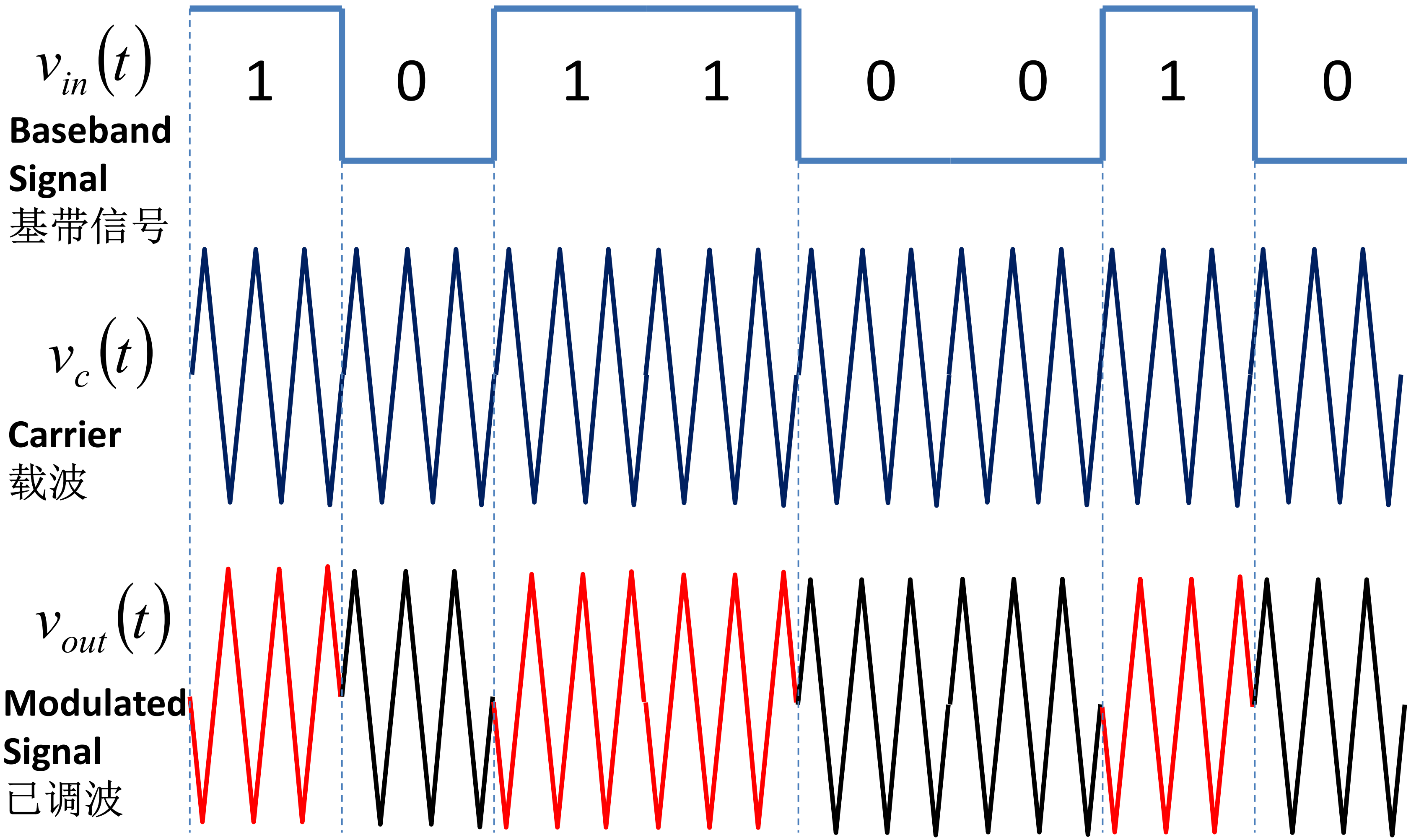
$$v_{out} = \begin{cases} -v_c & v_{in} = 1 \\ +v_c & v_{in} = 0 \end{cases}$$

$$= (1 - 2v_{in}) \cdot A_0 \sin \omega_c t$$

$$= A_0 \sin(\omega_c t + v_{in} \cdot \pi)$$

$$v_{in} = \begin{cases} 1 & \text{开关闭合} \\ 0 & \text{开关断开} \end{cases}$$

已调波波形 $v_{out}=\begin{cases}-v_c & v_{in}=1\\ +v_c & v_{in}=0\end{cases}=(1-2v_{in})\cdot A_0\sin\omega_c t=A_0\sin(\omega_c t+v_{in}\cdot\pi)$



解调原理：乘以载波信号

$$v_{out}(t)=(1-2v_{in}(t))\cdot A_0\sin(\omega_c t+\varphi_e)$$ 幅度调制

$$v_{out}(t)\cdot v_c'(t)=(1-2v_{in}(t))\cdot A_0\sin\omega_c t\cdot A_1\sin(\omega_c t+\varphi_e)$$

$$=(1-2v_{in}(t))\cdot A_0A_1\sin\omega_c t\cdot\sin(\omega_c t+\varphi_e)$$

幅度解调

$$=(1-2v_{in}(t))\cdot A_0A_1\frac{\cos\varphi_e-\cos(2\omega_c t+\varphi_e)}{2}$$

$$=\frac{A_0A_1}{2}(1-2v_{in}(t))(\cos\varphi_e-\cos(2\omega_c t+\varphi_e))$$

$$=\frac{A_0A_1}{2}\cos\varphi_e(1-2v_{in}(t))-\frac{A_0A_1}{2}(1-2v_{in}(t))\cos(2\omega_c t+\varphi_e)$$

$$v_d(t)=f_{Lowpassfilter}(v_{out}(t)\cdot v_c'(t))$$ 低通滤波

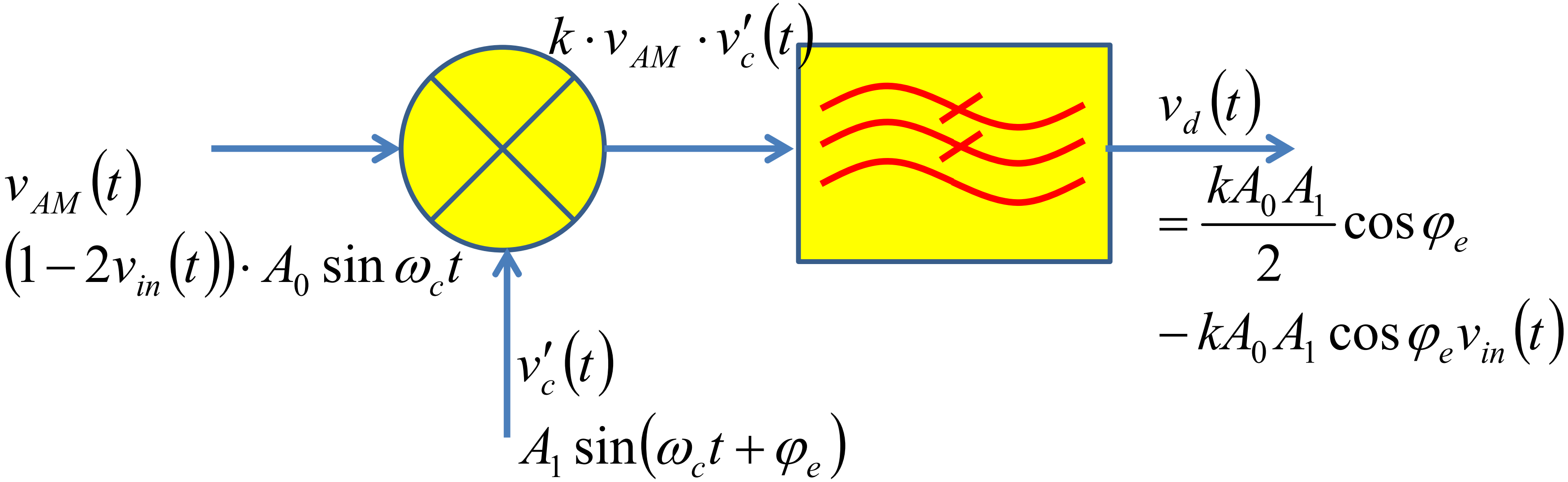
$$=f_{Lowpassfilter}\left(\frac{A_0A_1}{2}\cos\varphi_e(1-2v_{in}(t))-\frac{A_0A_1}{2}(1-2v_{in}(t))\cos(2\omega_c t+\varphi_e)\right)$$

$$=\frac{A_0A_1}{2}\cos\varphi_e(1-2v_{in}(t-\tau_0))=\frac{A_0A_1}{2}\cos\varphi_e-A_0A_1\cos\varphi_e v_{in}(t-\tau_0)$$

低通滤波器引入的延时
空间传输也会引入延时

理想传输、理想
滤波无失真

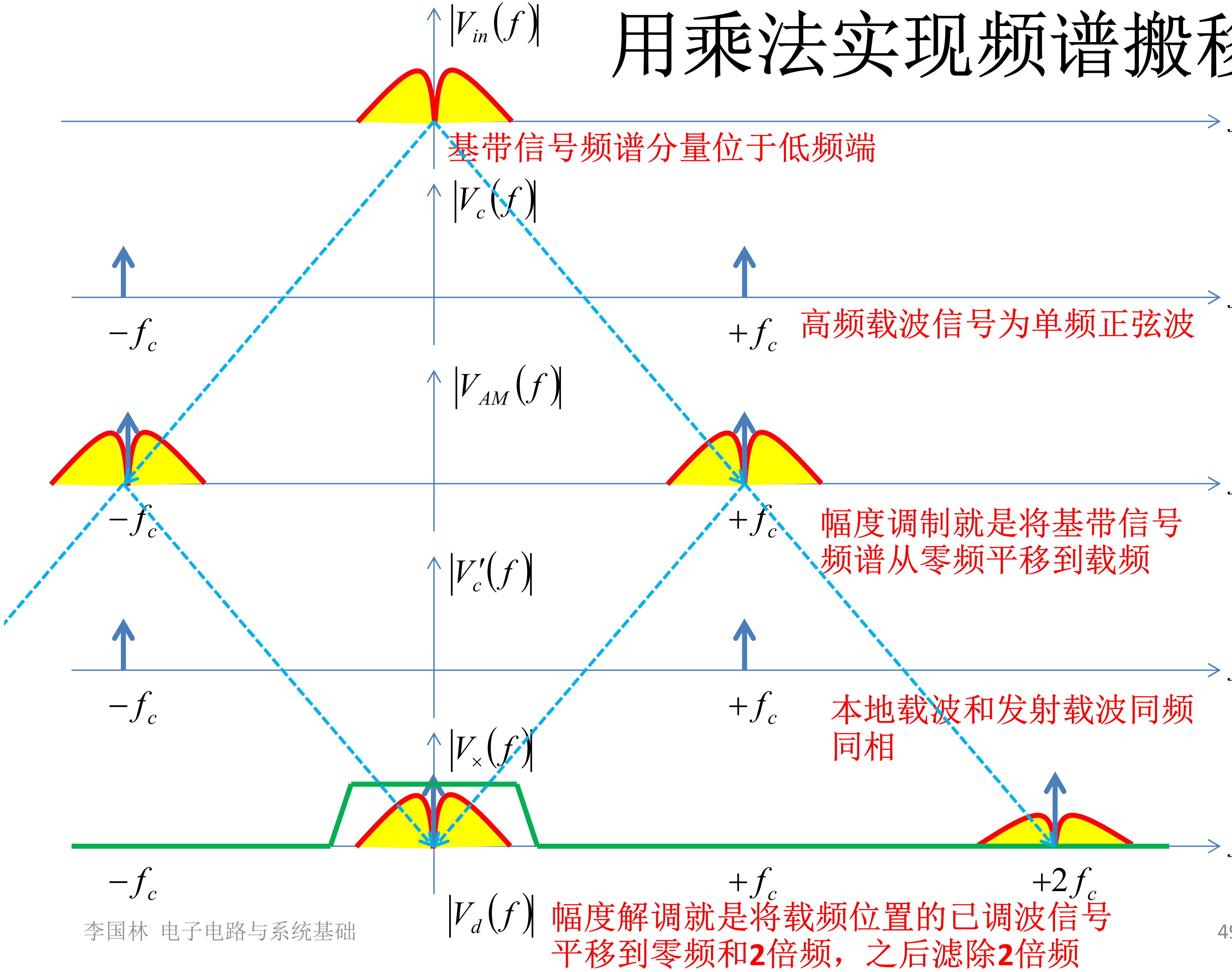
幅度解调器原理性方案



同频同相本地载波的产生是解调的关键技术

《通信电路》课程讨论锁相环技术，可实现同频同相本地载波的产生

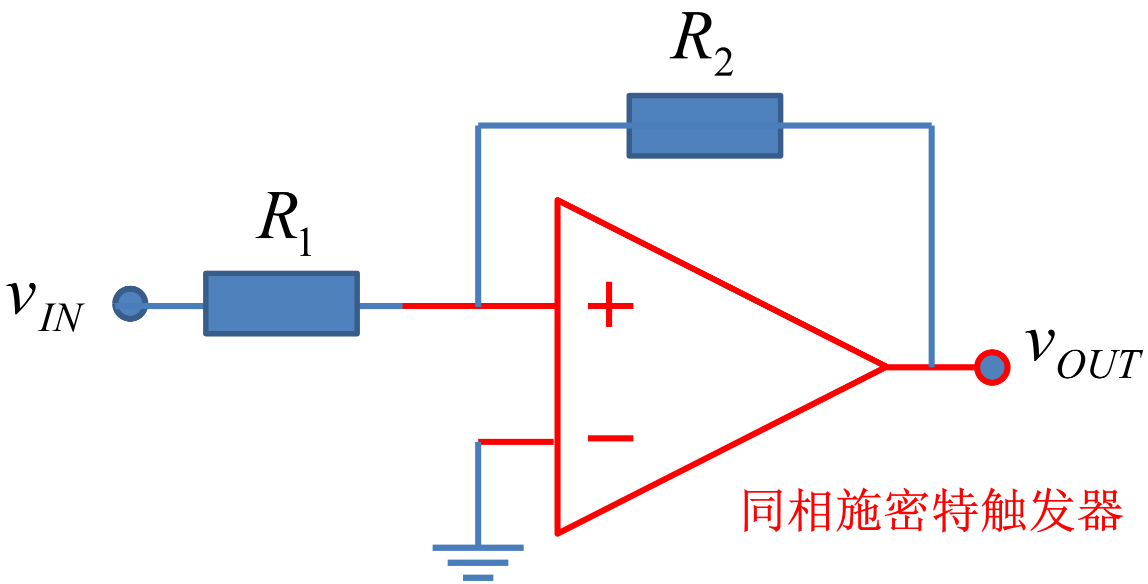
用乘法实现频谱搬移

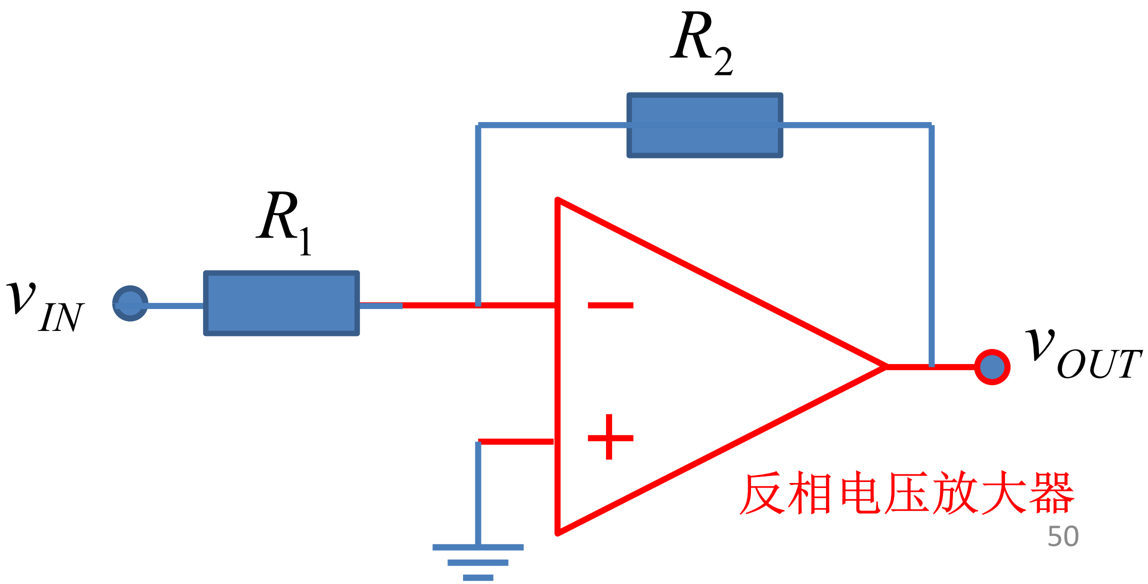


$|V_{in}(f)|$
f
基带信号频谱分量位于低频端
$|V_c(f)|$
f
$-f_c$
$+f_c$
高频载波信号为单频正弦波
$|V_{AM}(f)|$
f
$-f_c$
$+f_c$
幅度调制就是将基带信号
频谱从零频平移到载频
$|V_c'(f)|$
f
$-f_c$
$+f_c$
本地载波和发射载波同频
同相
$|V_\times(f)|$
f
$-f_c$
$+f_c$
$+2f_c$
$|V_d(f)|$
幅度解调就是将载频位置的已调波信号
平移到零频和**2**倍频，之后滤除**2**倍频

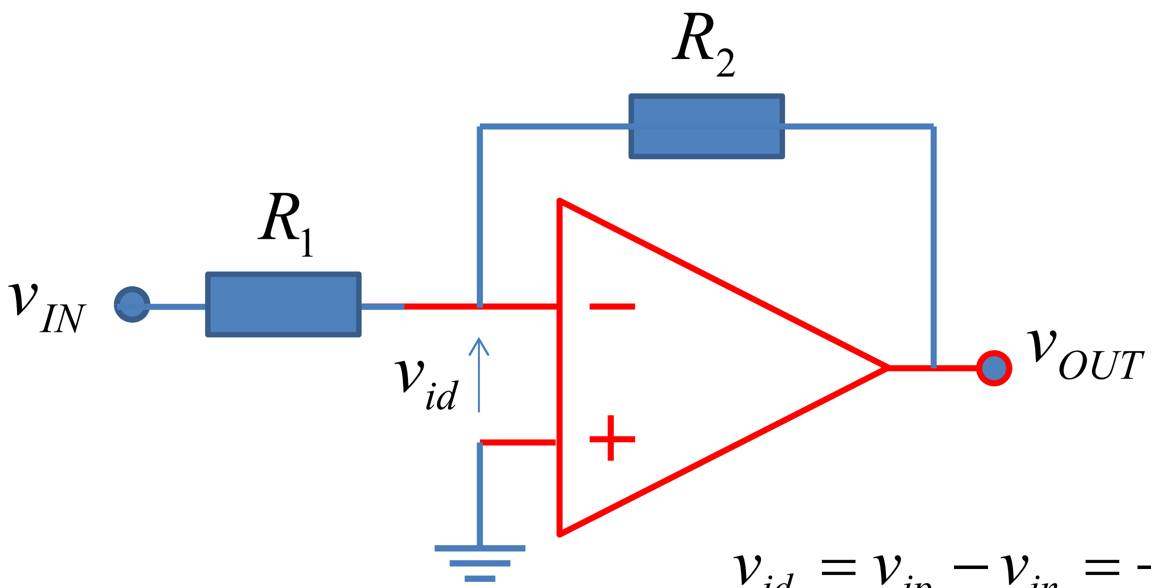
作业7　同相施密特触发器

- 分析并画出如下滞回比较器的输入输出转移特性曲线（滞回曲线分析）
  - 和课堂上讲述的反相施密特触发器的滞回曲线比较，两者差别在哪里？
  - 用图解法分析其转移特性曲线和反相电压放大器的区别
    - 课堂上讨论了反相施密特触发器与同相电压放大器的图解法





反相电压放大器外围电路分析



$$v_{id} = v_{ip} - v_{in} = -\frac{R_2}{R_1 + R_2} v_{IN} - \frac{R_1}{R_1 + R_2} v_{OUT}$$

$$v_{ip} = 0$$

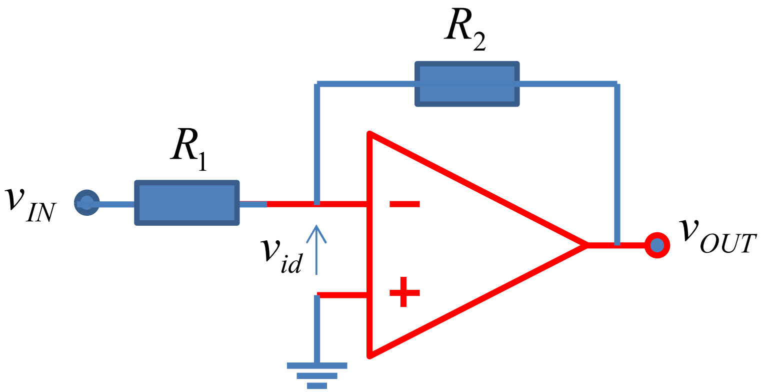
$$v_{in} = \frac{R_2}{R_1 + R_2} v_{IN} + \frac{R_1}{R_1 + R_2} v_{OUT}$$

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

外加激励源形成一系列关系

对运放电路而言，这是负反馈关系

反相放大器输入输出转移特性曲线

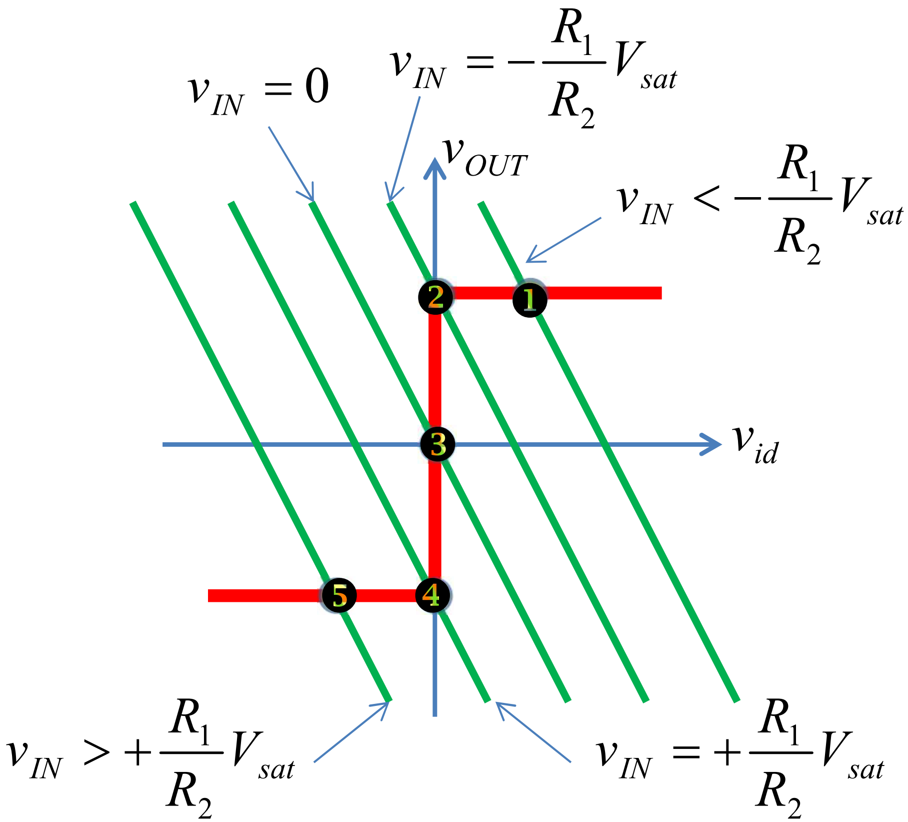


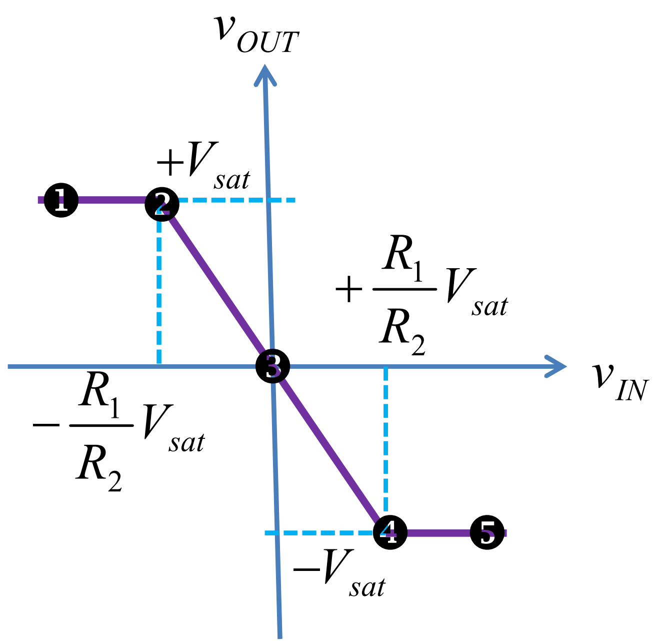
$$v_{OUT}=-\frac{R_2}{R_1}v_{IN}-\frac{R_1+R_2}{R_1}v_{id}$$

运放外围器件关系

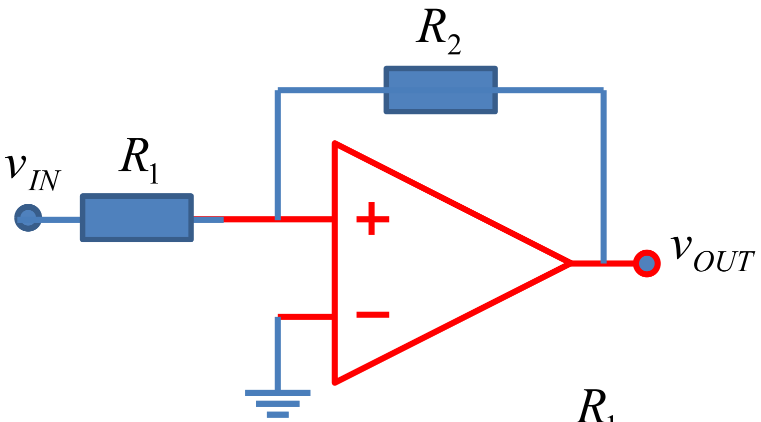
$$v_{OUT}=f\left(v_{id}\right)$$

运放自身关系





同相施密特触发器转移特性曲线



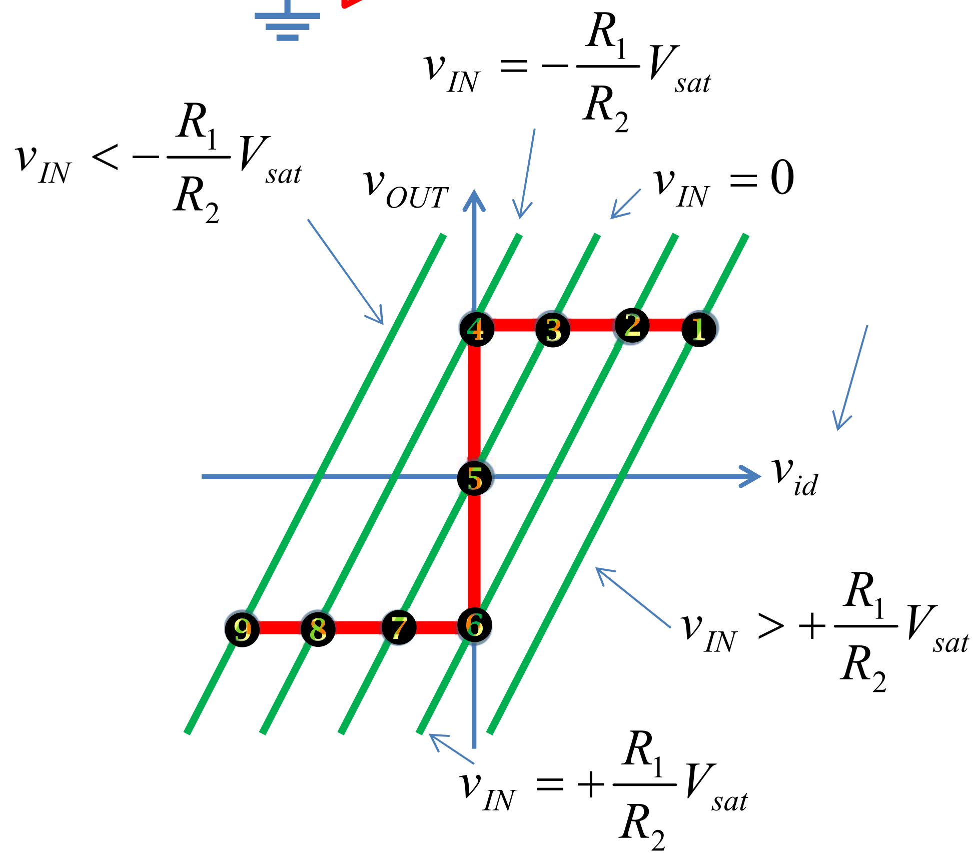
$$\boxed{v_{OUT}=-\frac{R_2}{R_1}v_{IN}+\frac{R_1+R_2}{R_1}v_{id}}$$

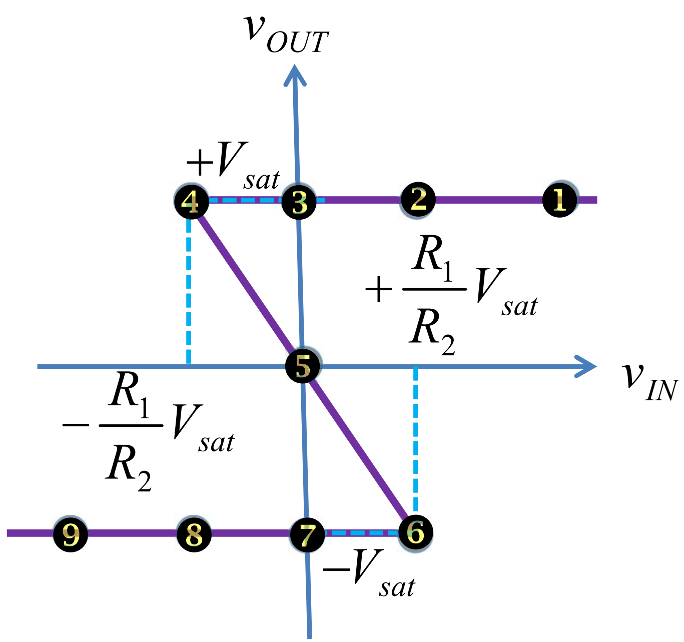
运放外围器件关系

正反馈的表现

$$\boxed{v_{OUT}=f\left(v_{id}\right)}$$

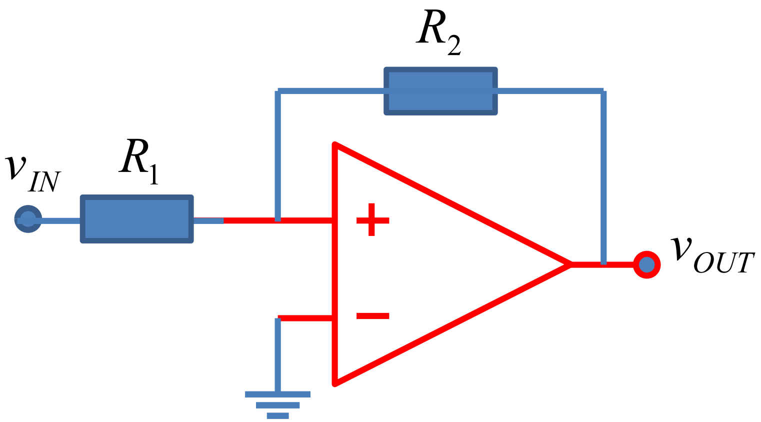
运放自身关系

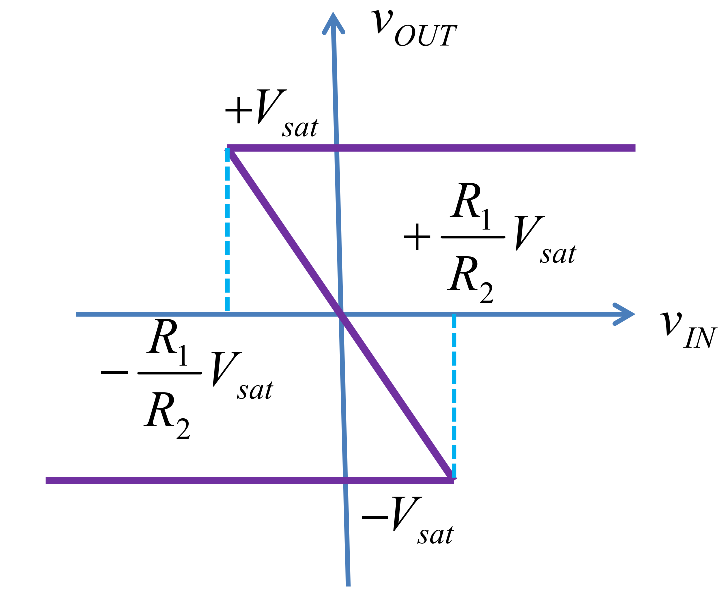




同相滞回曲线

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

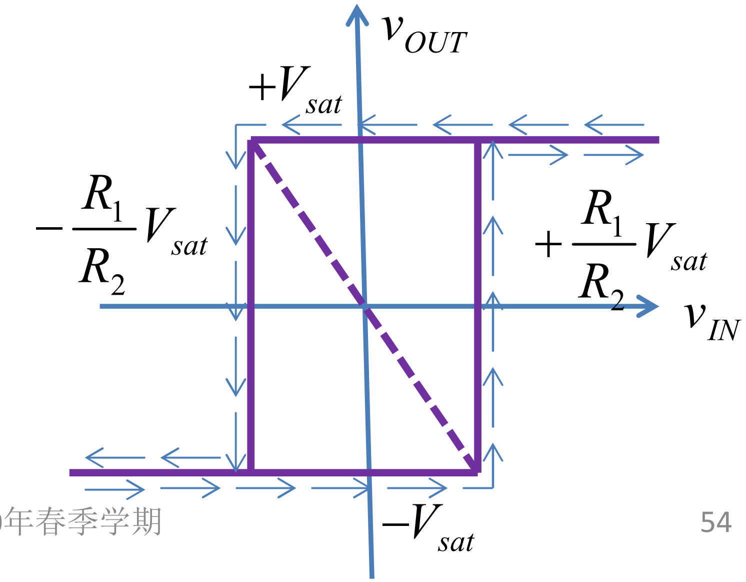




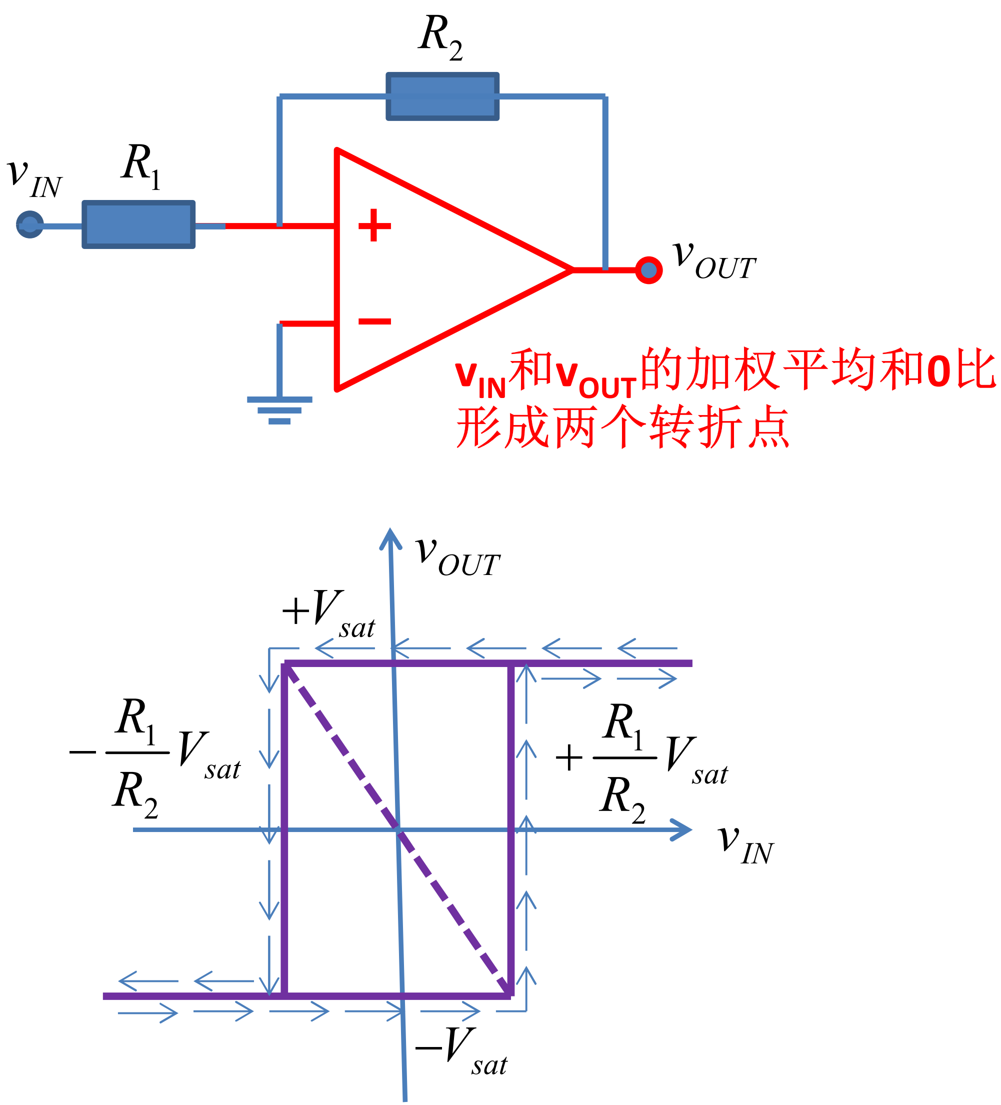
数学上的理论转移特性曲线
中间为不稳定区，实际工作点无法稳定平衡
实测为正相滞回转移特性曲线

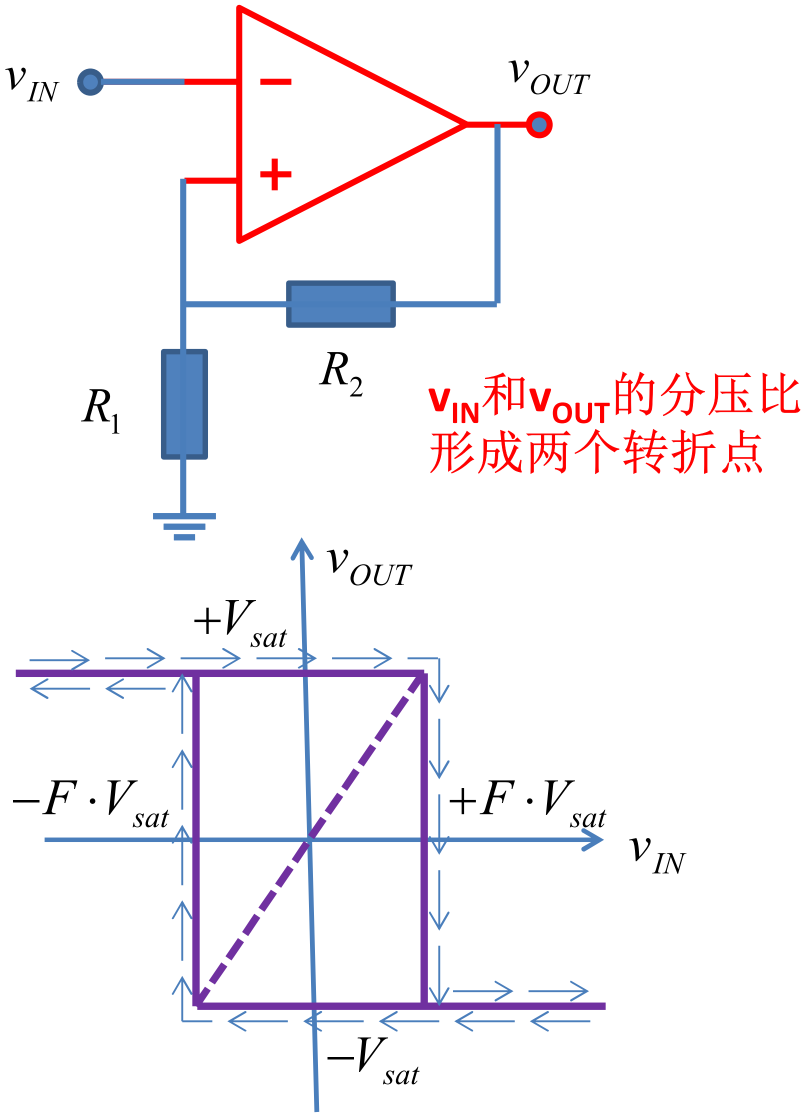
正反馈导致多个工作点
一个不稳定工作点，待不住
两个稳定工作点，具有记忆能力
到底在哪个稳定工作点，由之前的经历决定

负阻具有多个工作点
施密特触发器可形成负阻

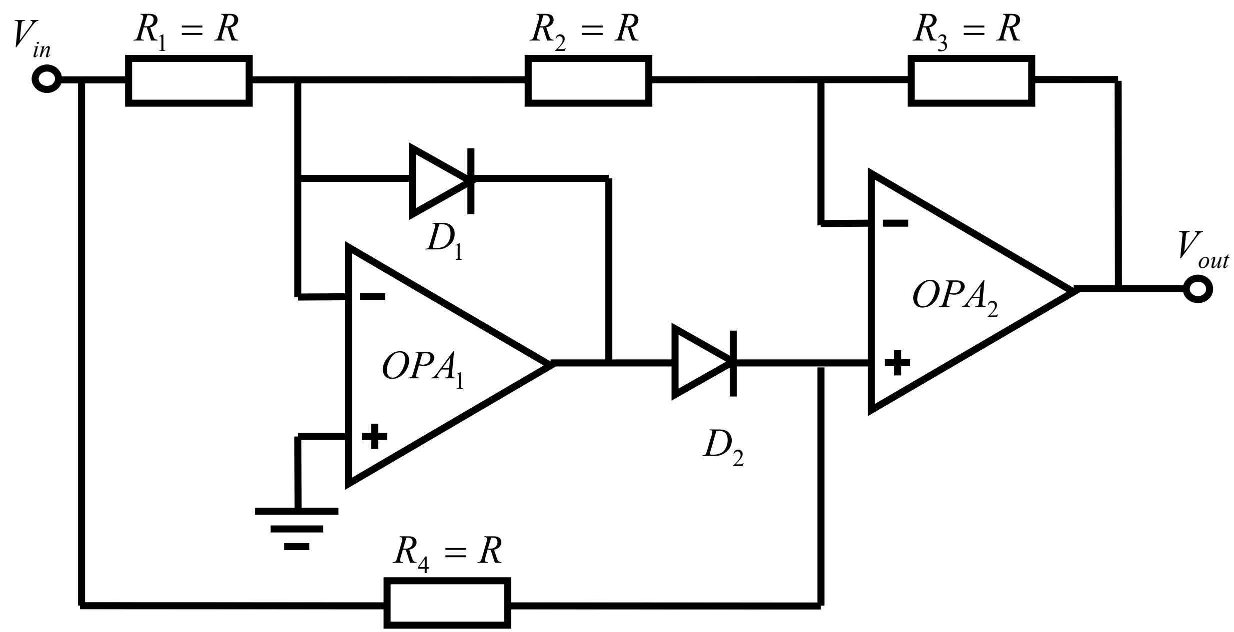


同相滞回曲线和反相滞回曲线



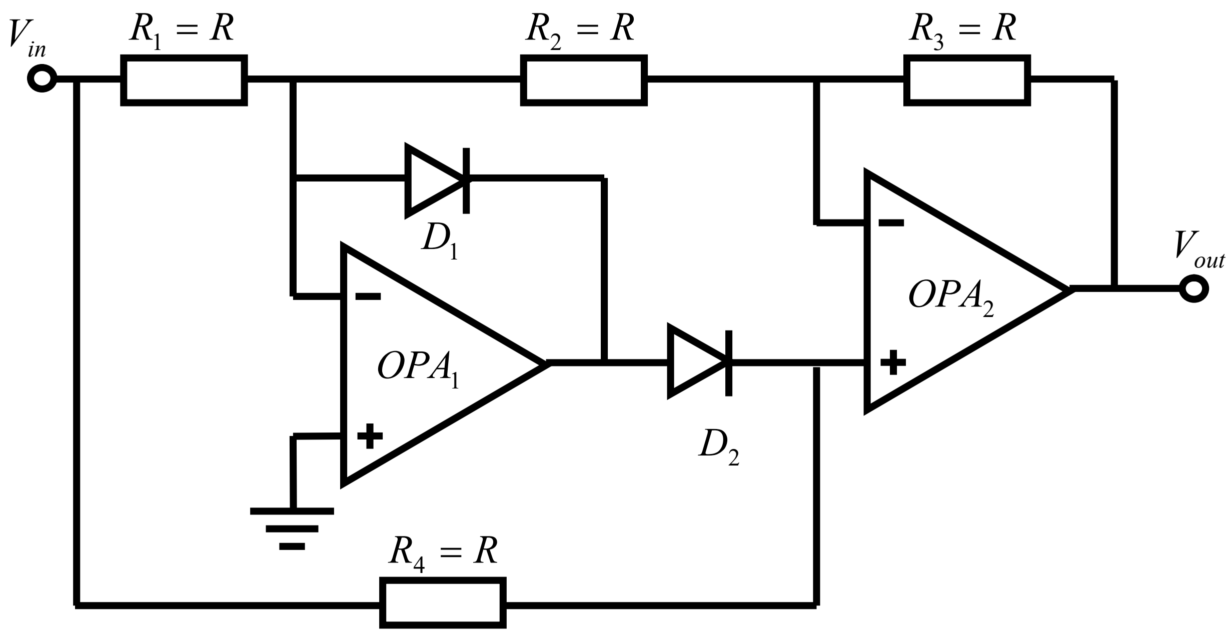


作业8 双运放非线性应用



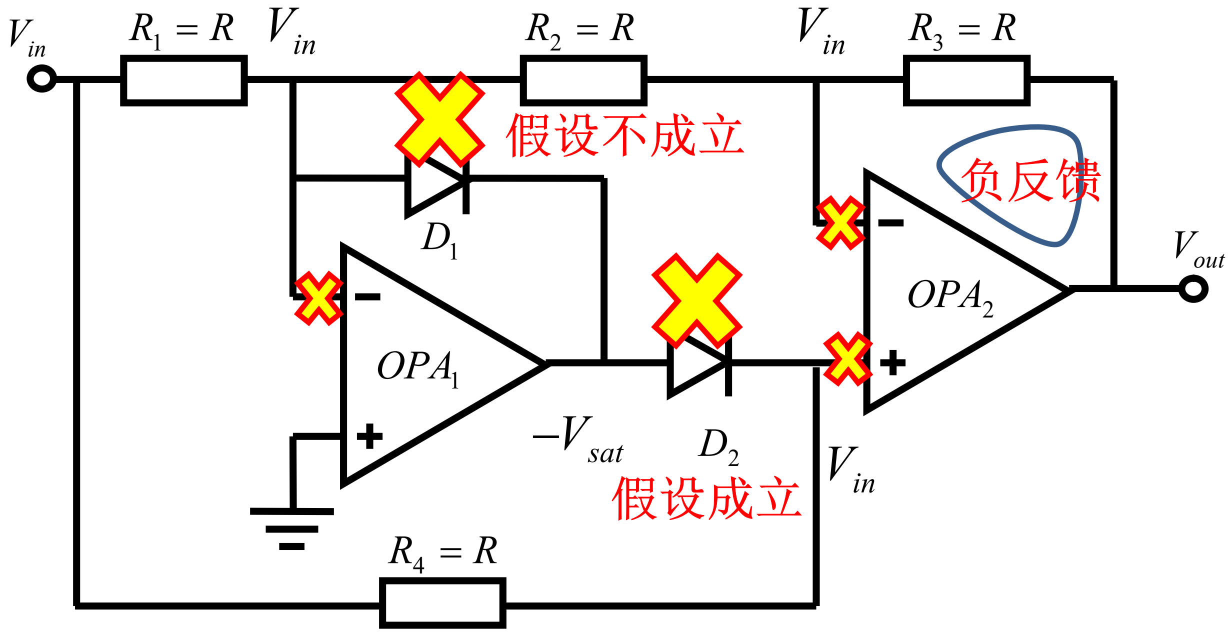
- 分析这个双运放二极管电路实现了什么电路功能？
  - 画出输入输出转移特性曲线
  - 如果输入为正弦波，输出为什么波形？

二极管抽象为两个状态：导通或截止

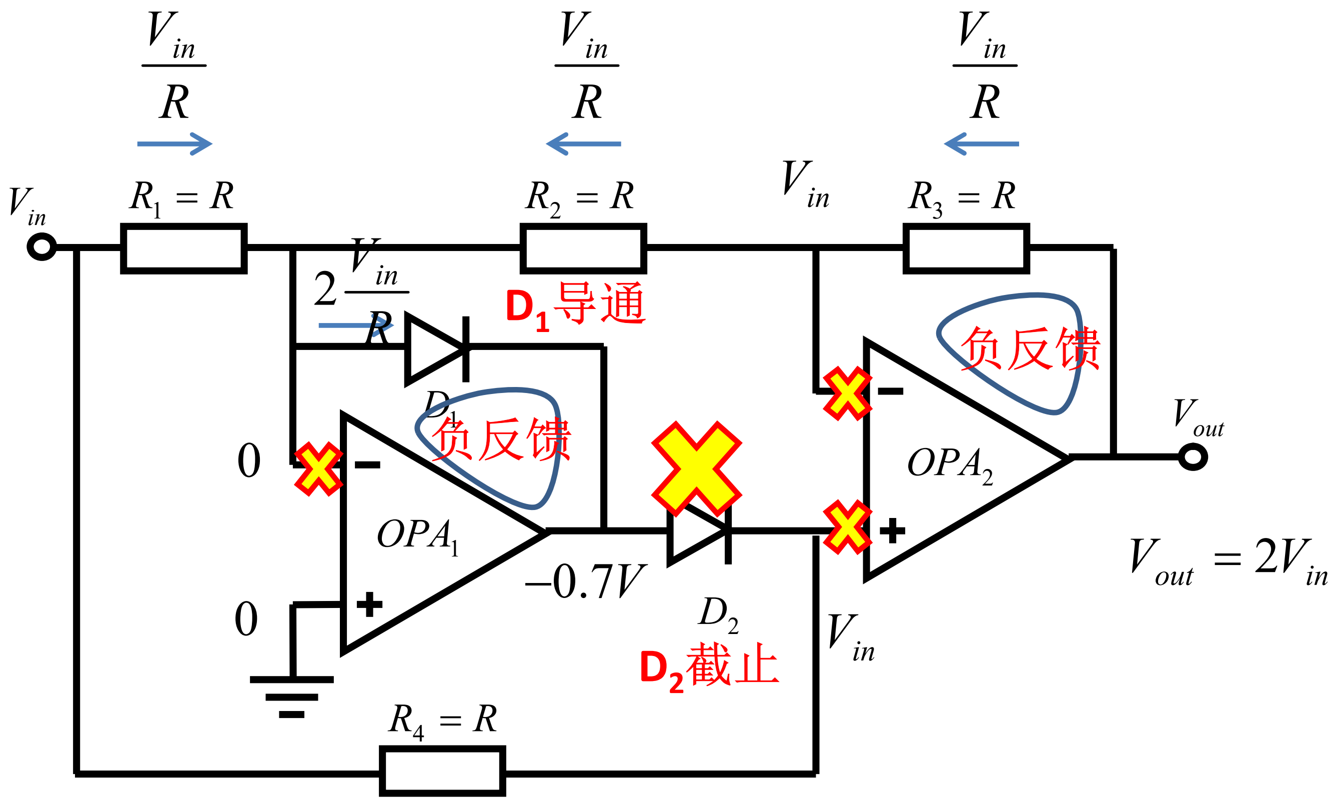


假设二极管工作在截止区，分析电路工作状态，如果二极管外围电路确实满足二极管截止条件（v_D<0.7V,i_D=0），则假设成立，如果二极管外围电路不满足二极管截止条件（v_D>0.7V），假设则不成立，需要重新假定二极管工作在导通区（v_D=0.7V,i_D>0），分析结果符合则分析结束

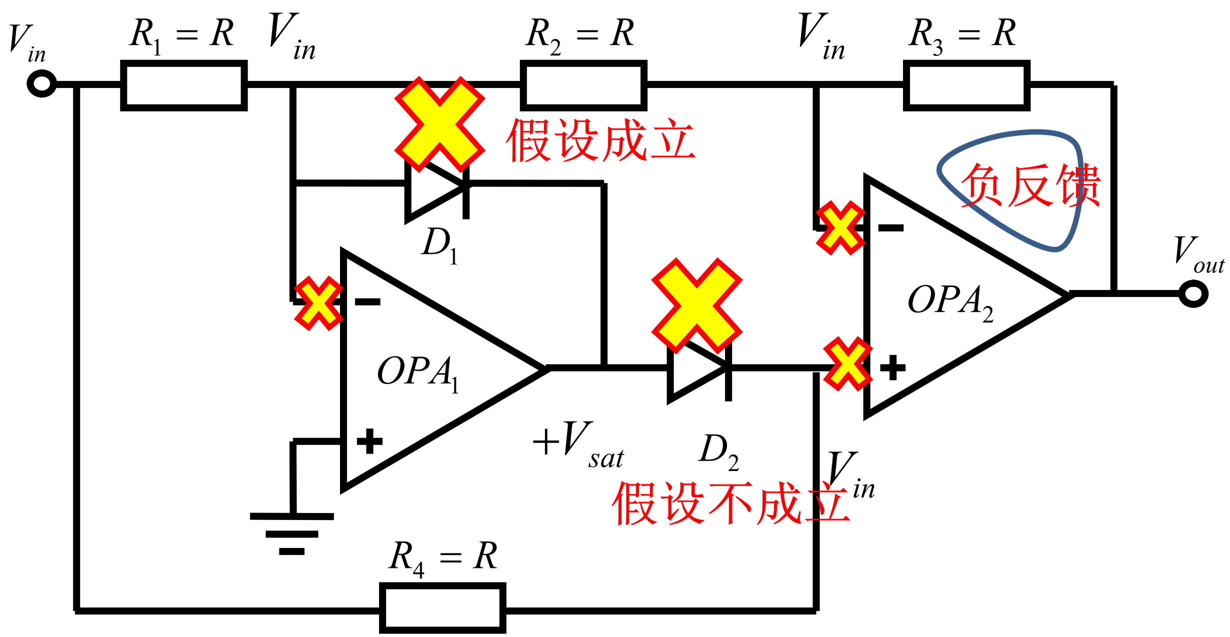
V_{in}>0:假设二极管截止



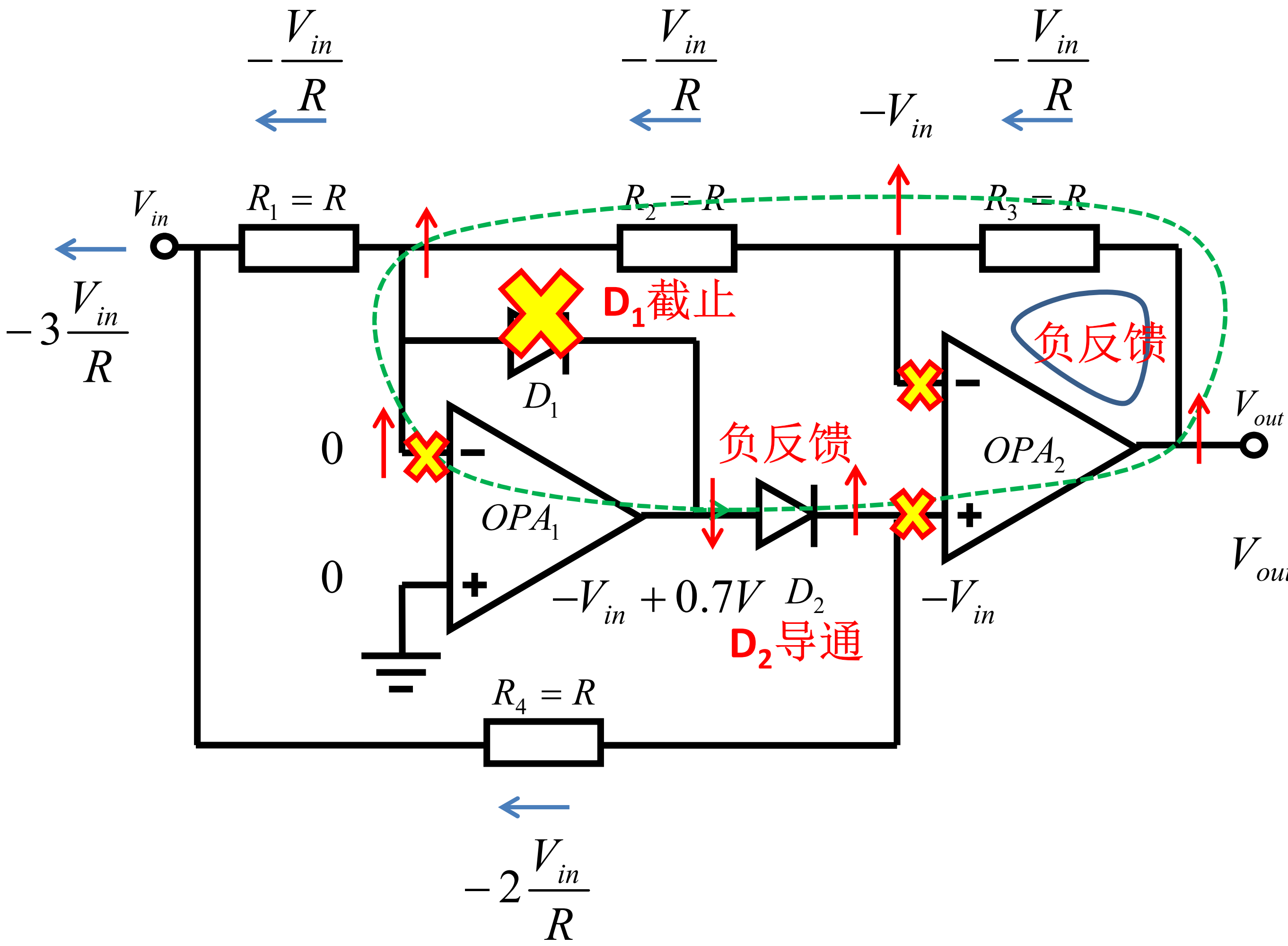
V_{in}>0:D_1导通，D_2截止



V_{in}<0:假设二极管截止

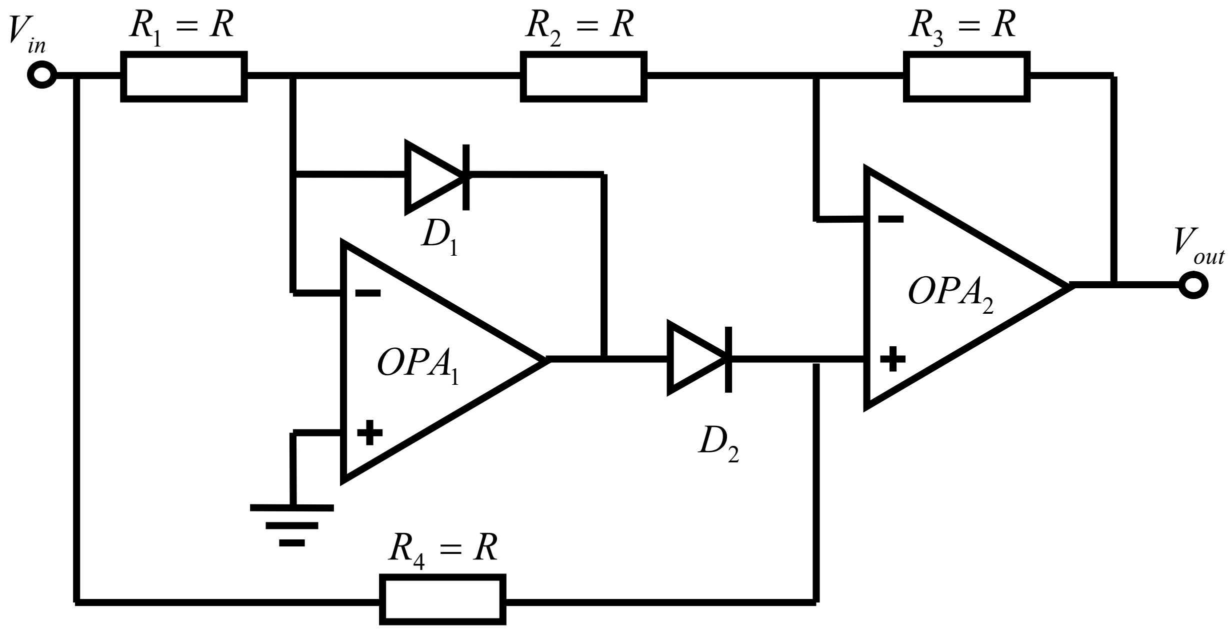


V_{in}<0:D_1截止，D_2导通



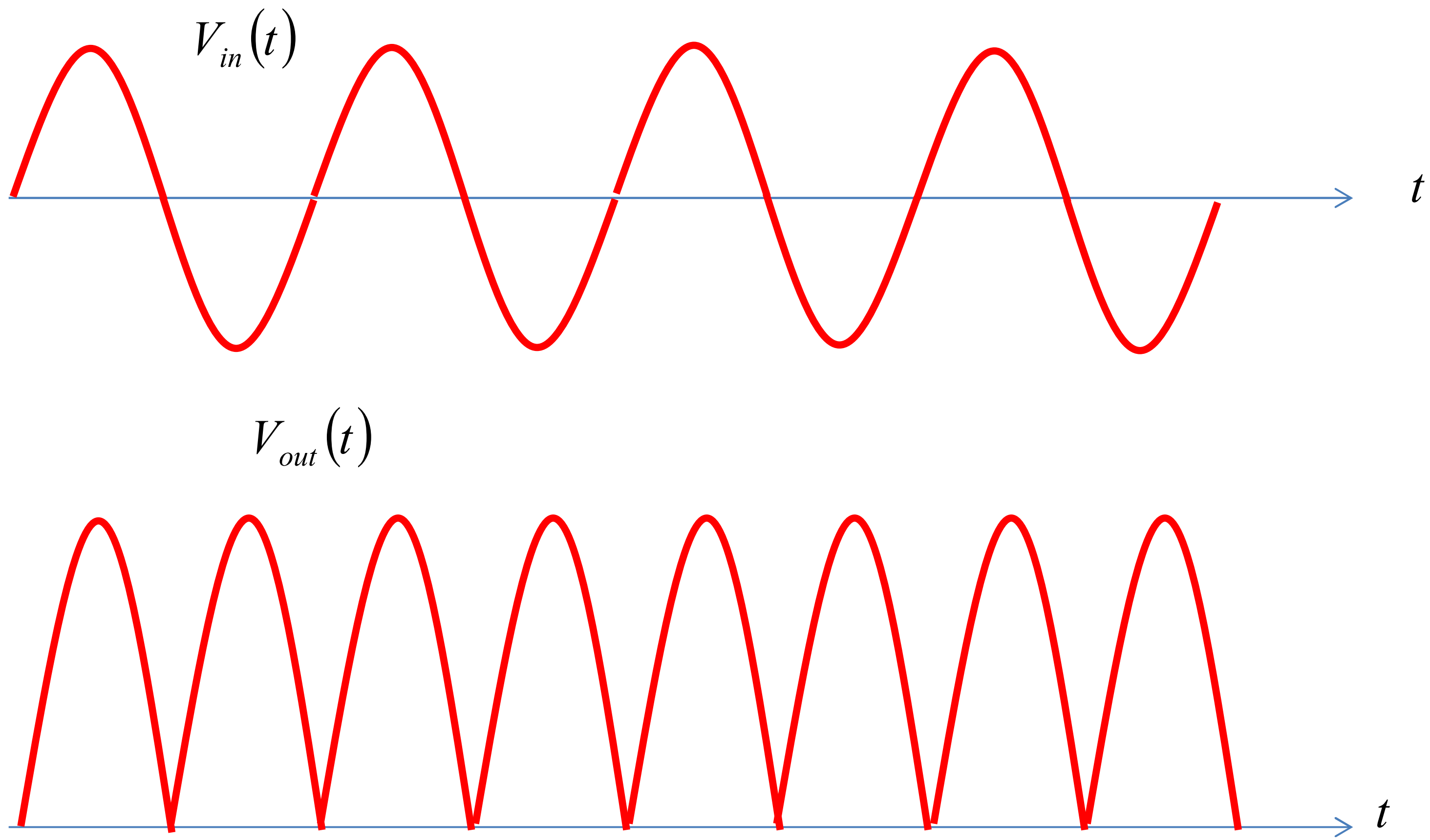
$$V_{out} = -2V_{in}$$

求绝对值电路

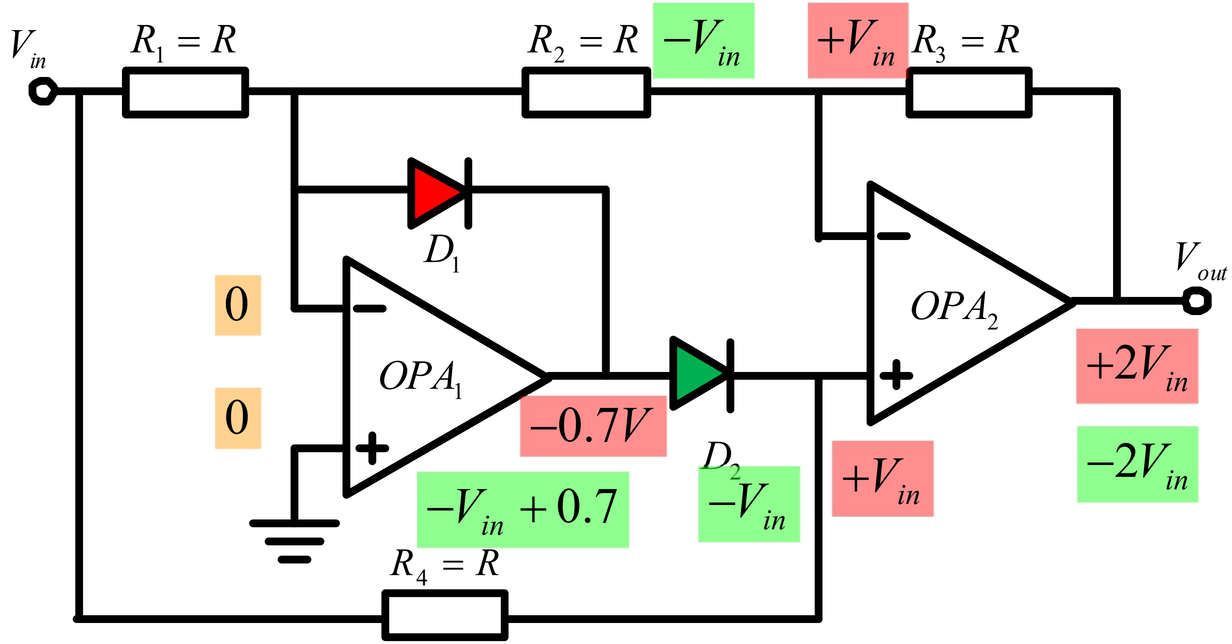


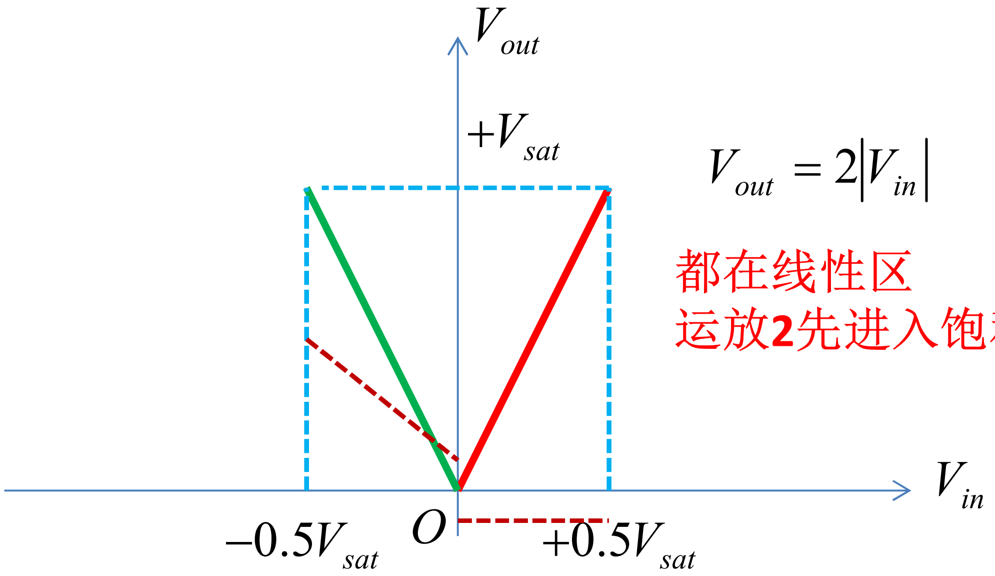
$$V_{out} = \begin{cases} +2V_{in} & V_{in} > 0 \\ -2V_{in} & V_{in} < 0 \end{cases} = 2|V_{in}|$$

获得全波信号



转移特性曲线？

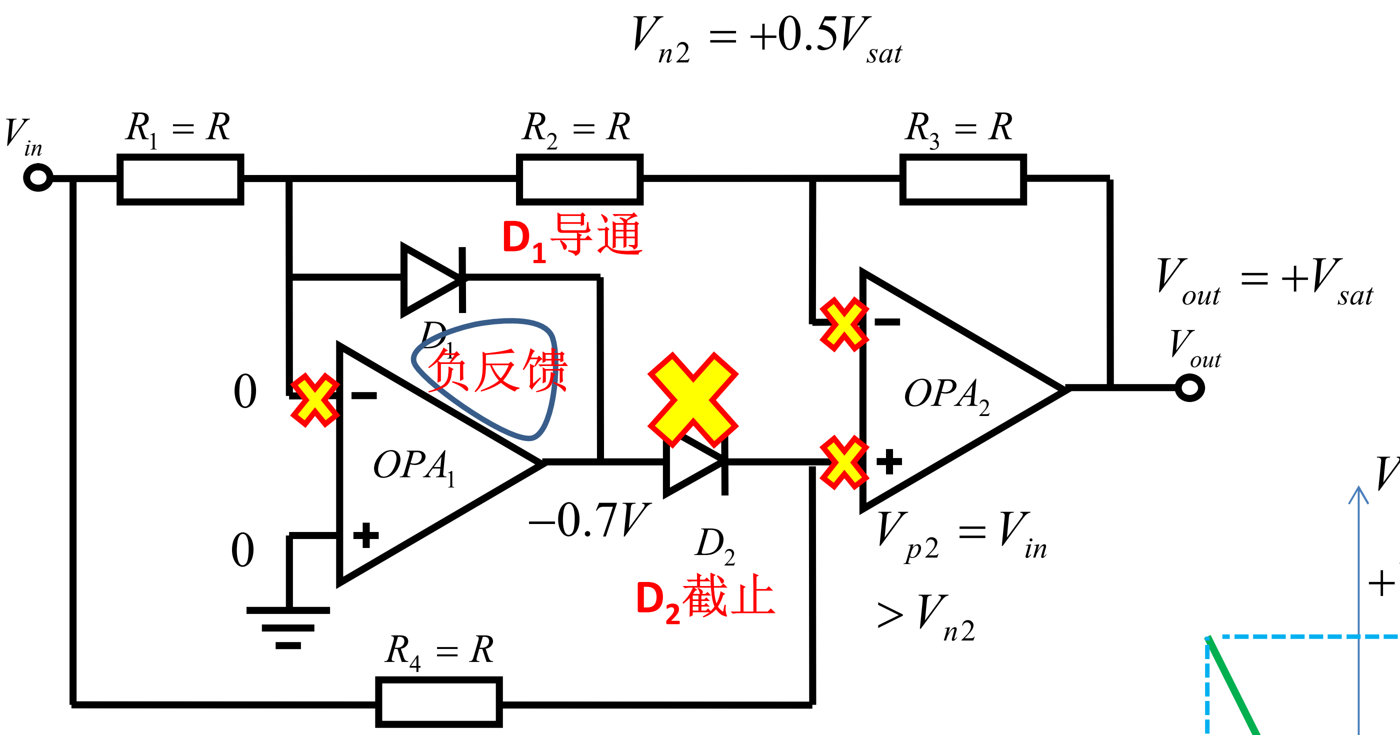




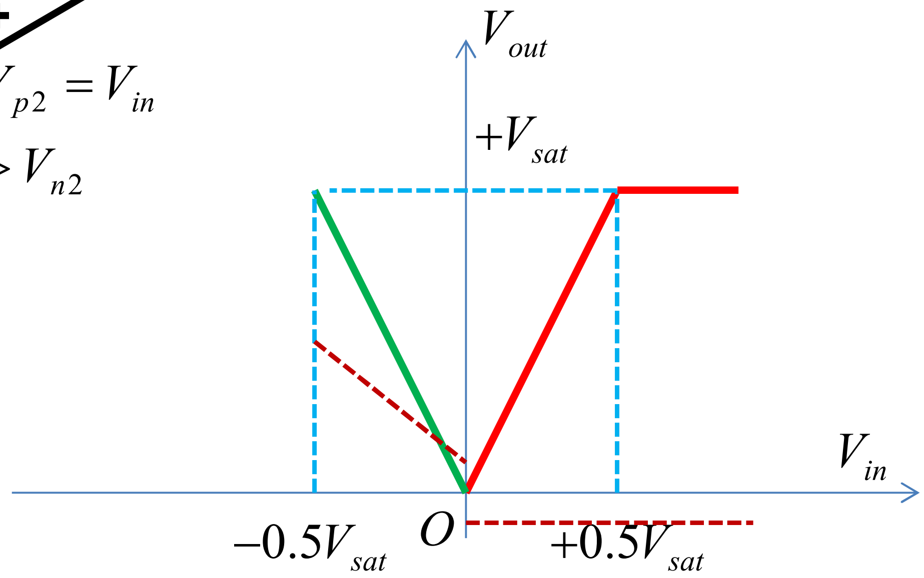
$$V_{out} = 2|V_{in}|$$

都在线性区
运放2先进入饱和区

V_{in}>$0.5V_{sat}$:运放2进入正饱和区

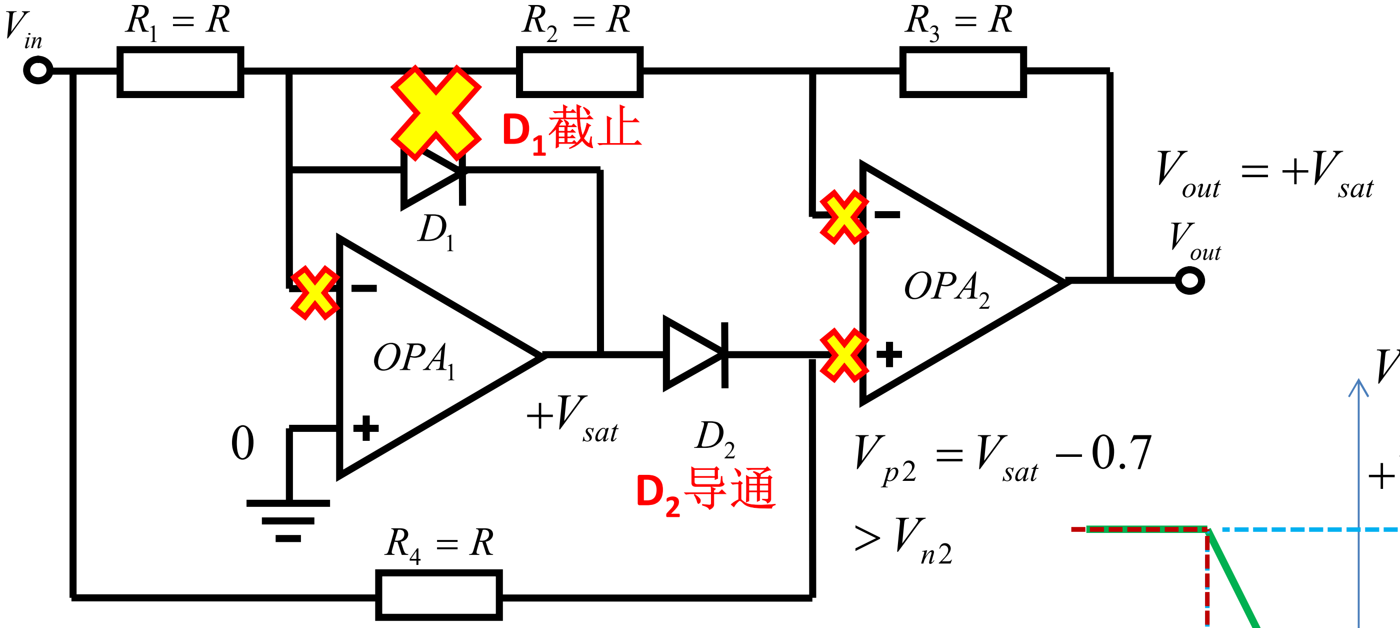


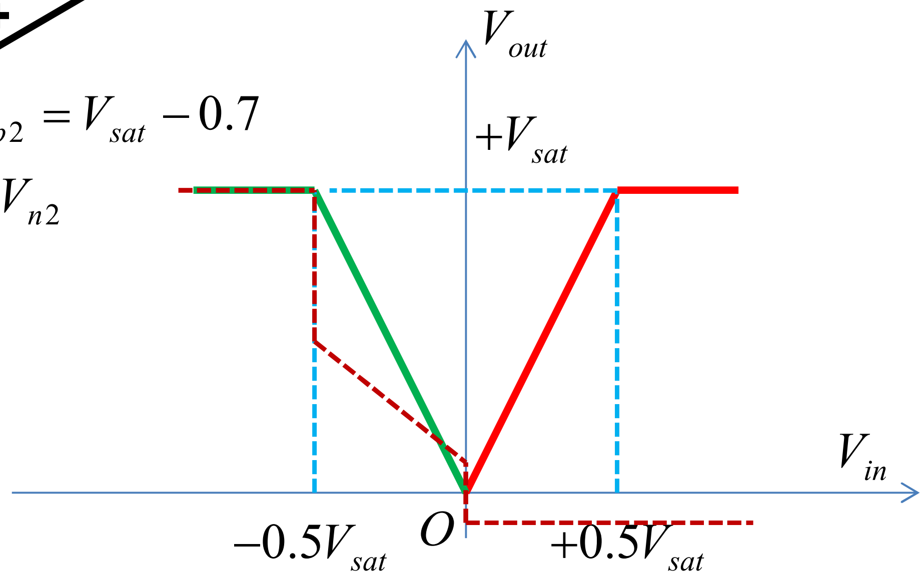
运放1仍然工作在线性区



V_{in}<-0.5V_{sat}:运放2进入正饱和区

$$V_{n1}=\frac{2}{3}V_{in}+\frac{1}{3}V_{out}<0 \qquad V_{n2}=\frac{1}{3}V_{in}+\frac{2}{3}V_{out}<-\frac{1}{6}V_{sat}+\frac{2}{3}V_{sat}=\frac{1}{2}V_{sat}$$





运放1工作正饱和区

考前答疑与考试地点

- 考前安排到时通知
  - 时间
  - 考场分配
  - 答疑

考场要求

- 自带计算器
- 隔行隔列坐，严格考场纪律，不允许自带草稿纸，不允许多拿卷子
- 手机关机装到书包中，书包放前台
- 监考老师收卷、数卷无误后，方可离场

- 祝同学获得好成绩