第5章

含运算放大器的电路

5.1 集成运算放大器 Operational amplifier

5.2 理想运算放大器 Ideal op amp

5.3 运算放大电路 Op amp circuits

第5章

含运算放大器的电路

目标： 1.了解实际运算放大器特性和电路模型。

2.理解理想运放特性。

3.熟练分析含理想运放的电路。

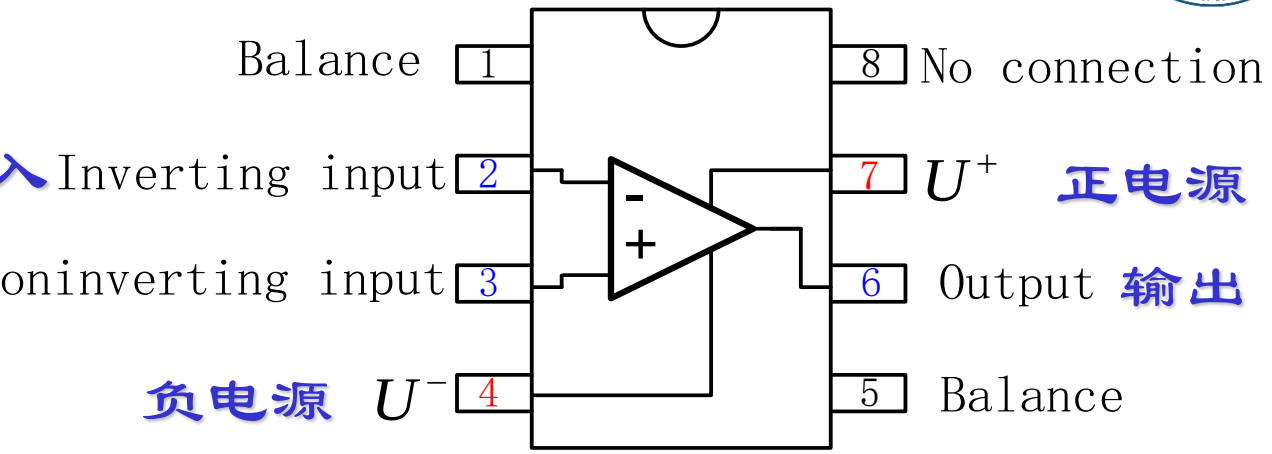
4.掌握基本运算电路的设计。

难点： 运算电路设计。

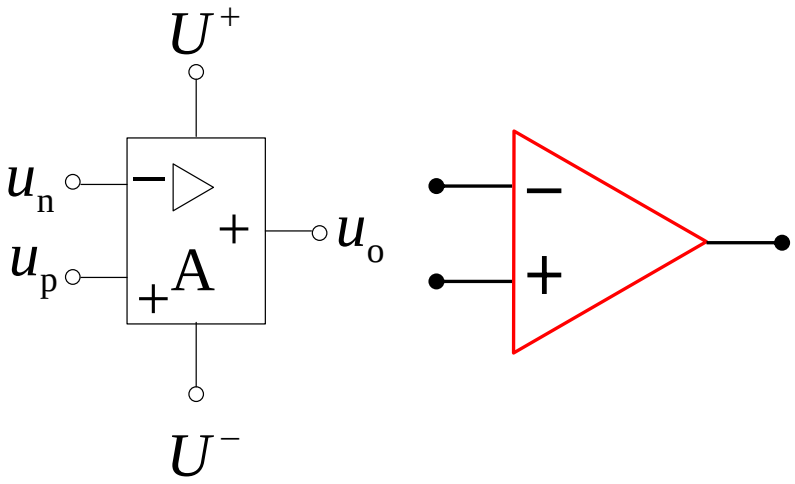
讲授学时： 1.5　　**讨论学时：** 0.5

5.1集成运算放大器 operational amplifiers

1. Terminals

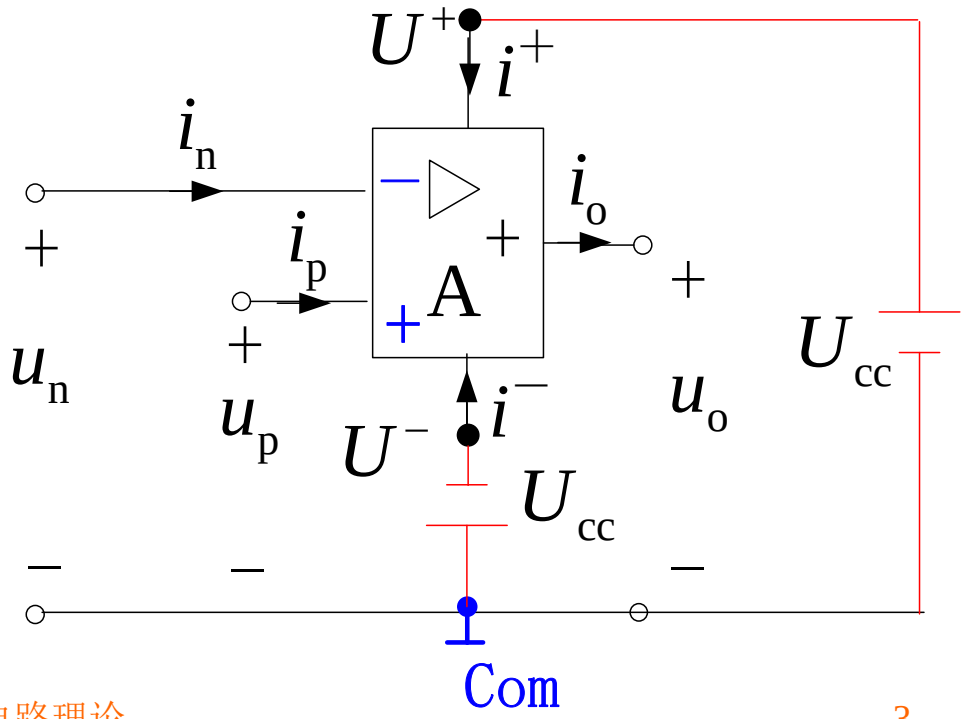


2.Circuit symbol

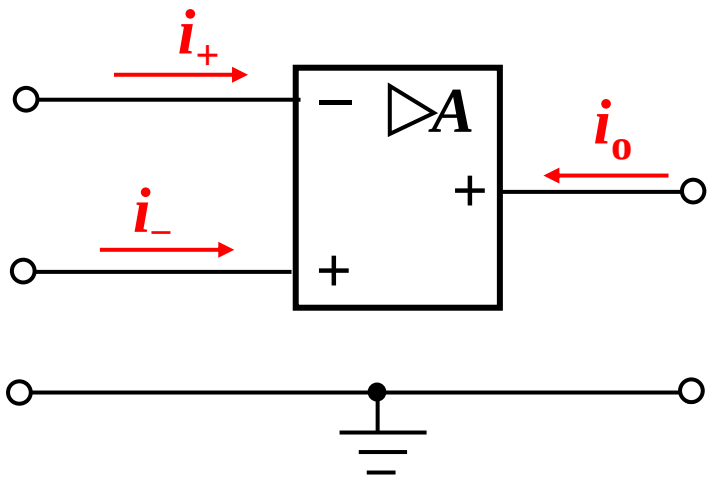


3.Voltage and current

$$i_n + i_p + i^+ + i^- - i_o = 0$$



当放大器工作在线性区时，端电压关系式中不出现直流电源电压。在电路符号中去掉电源端，以简化符号。



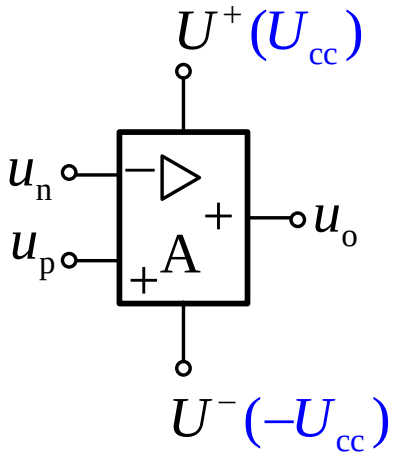
注意： 端电流仍是 $i_+ + i_- + i_o + i_{us+} + i_{us-} = 0$

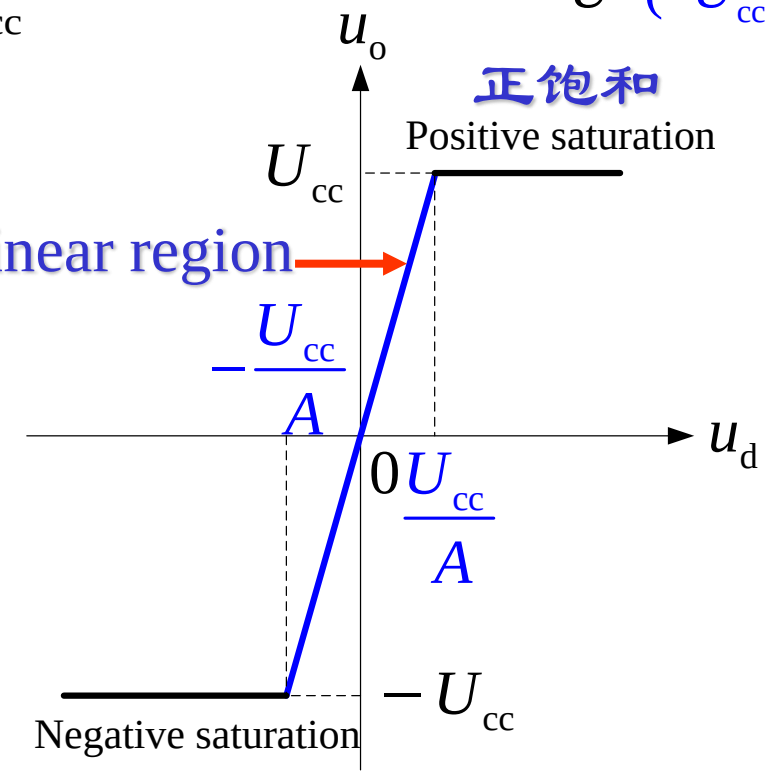
$$i_+ + i_- + i_o \neq 0$$

5.1集成运算放大器 operational amplifiers

4. Characteristic (输出端开路时的特性)

$$u_o = \begin{cases} -U_{cc} & A(u_p - u_n) < -U_{cc} \\ A(u_p - u_n) & -U_{cc} < A(u_p - u_n) < U_{cc} \\ U_{cc} & A(u_p - u_n) > U_{cc} \end{cases}$$



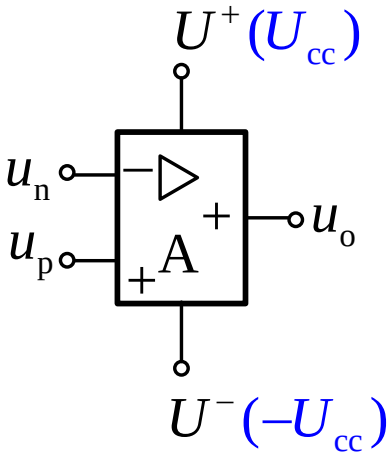


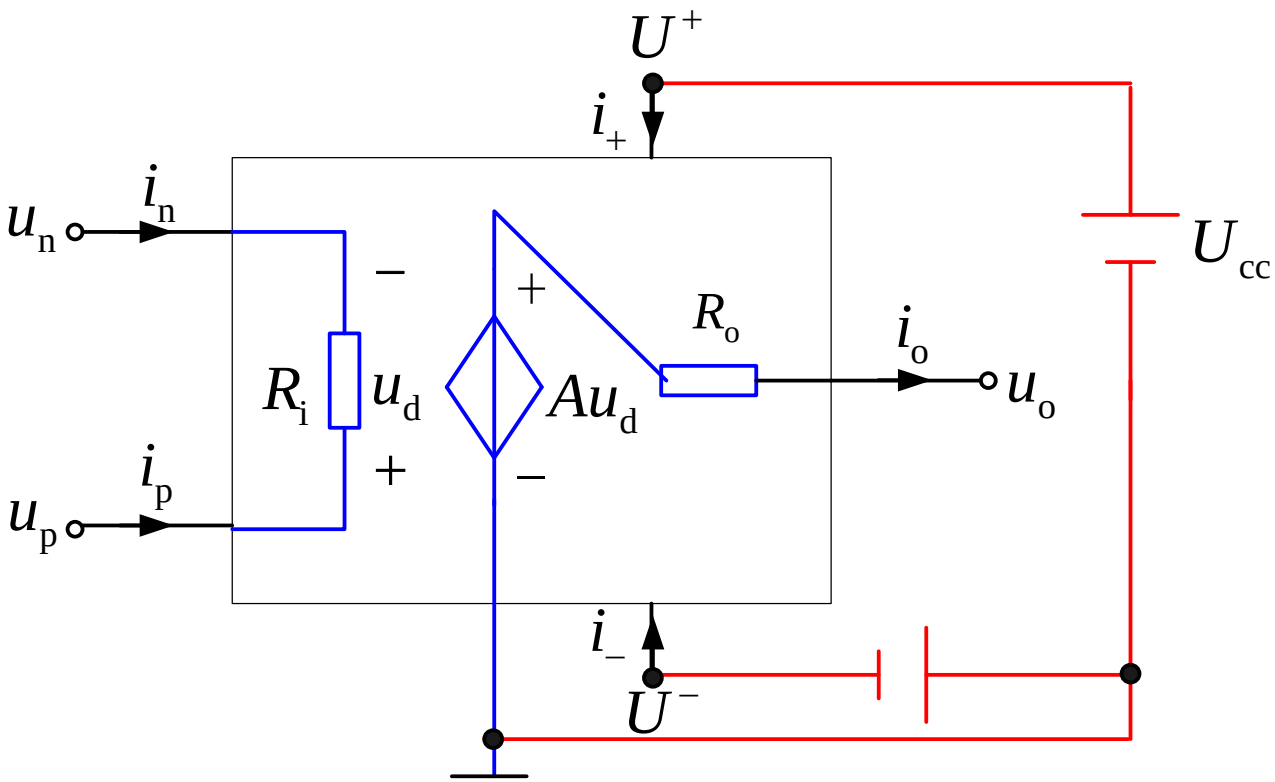
- A——开环增益
- $u_d = u_p - u_n$ ——差分输入电压

5.1集成运算放大器 operational amplifiers

5. Circuit model (linear region)

$$u_o = A(u_p - u_n) \qquad -U_{cc} < A(u_p - u_n) < U_{cc}$$



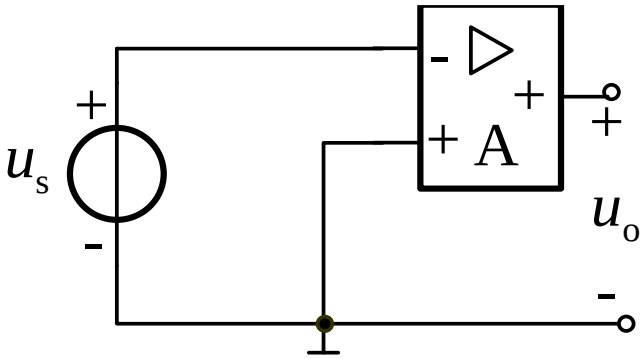


R_i：运算放大器两输入端间的输入电阻，通常为$10^6\Omega$-$10^{13}\ \Omega$。

R_o：运算放大器的输出电阻，通常为10Ω-$100\ \Omega$。

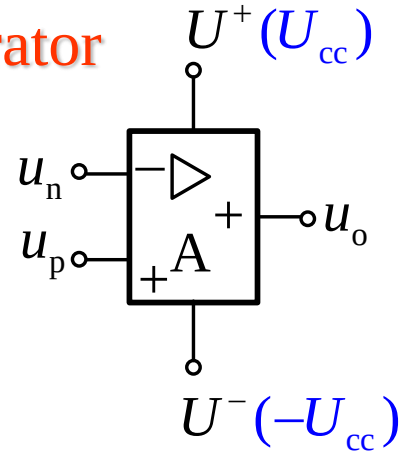
5.1集成运算放大器 operational amplifiers

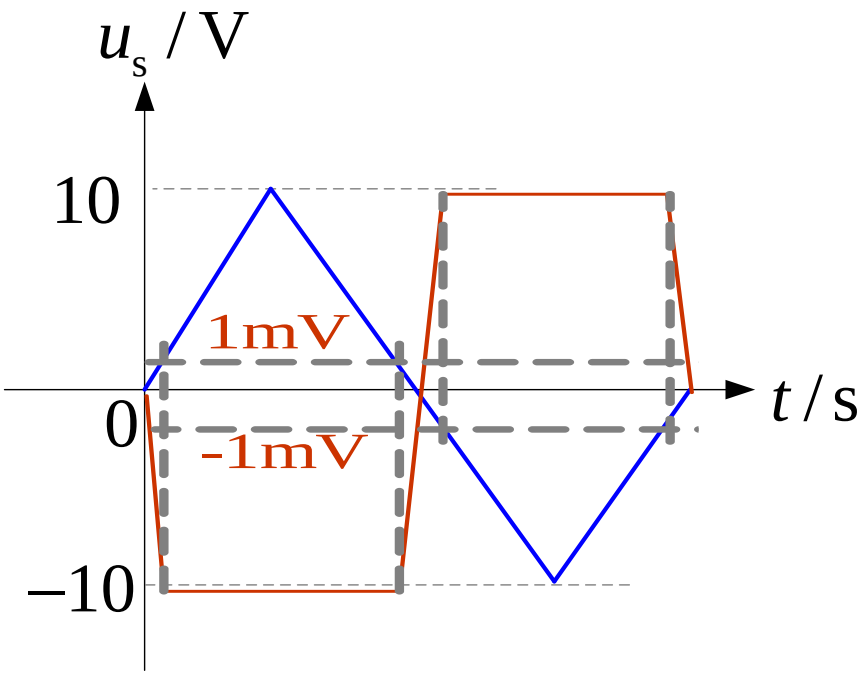
6.开环工作——工作于饱和区——比较器 Comparator

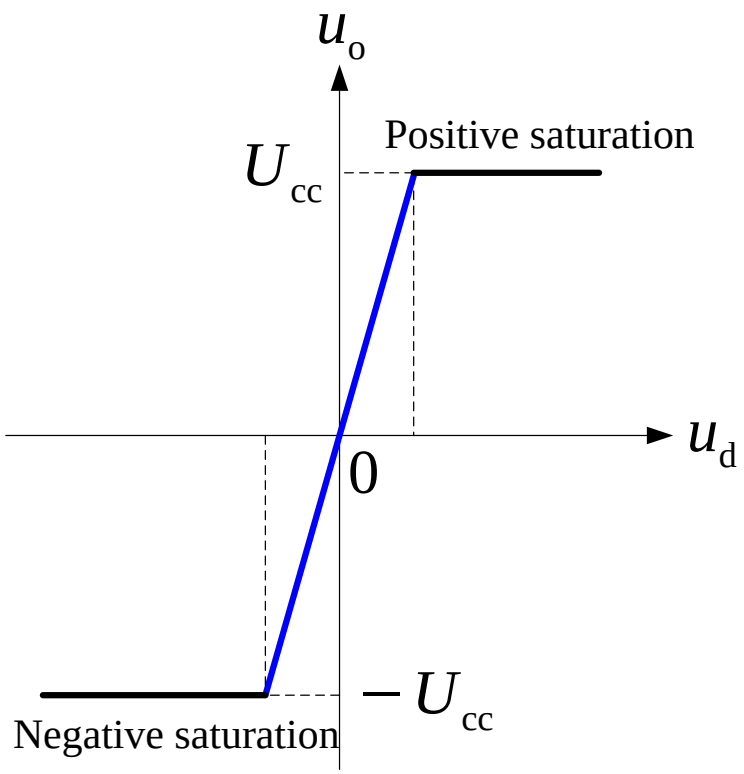


$A = 10000$

$U_{cc} = 10\text{V}$

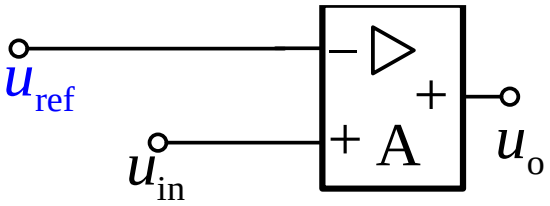






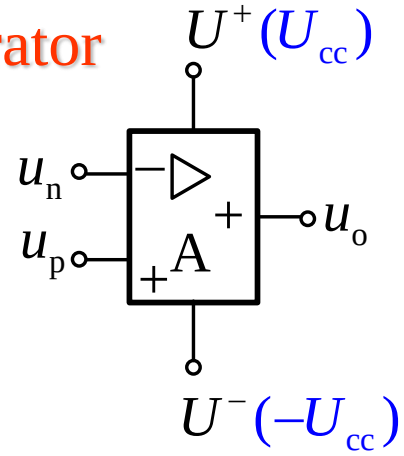
5.1集成运算放大器 operational amplifiers

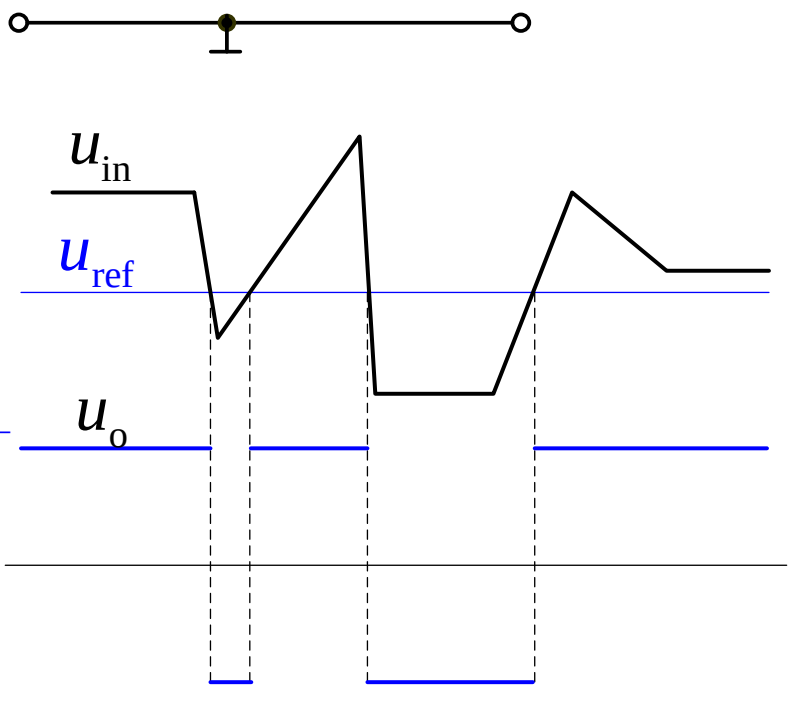
6.开环工作——工作于饱和区——比较器 Comparator

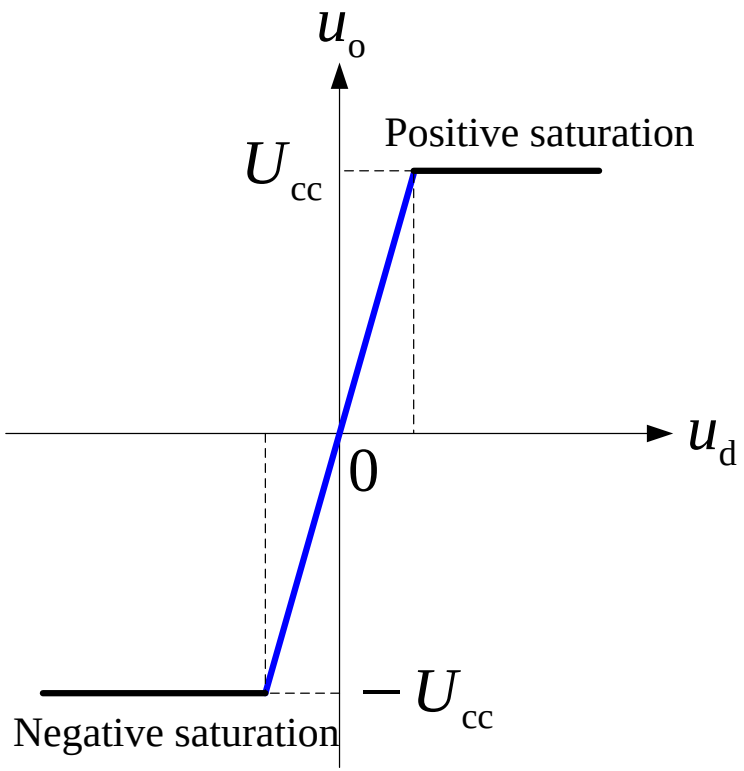


$A = 10000$

$U_{cc} = 10\text{V}$

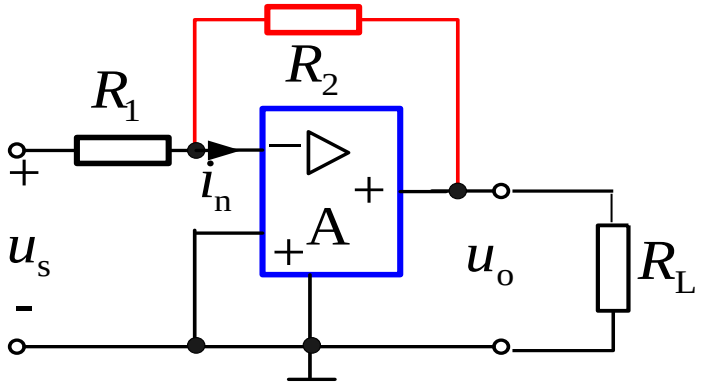




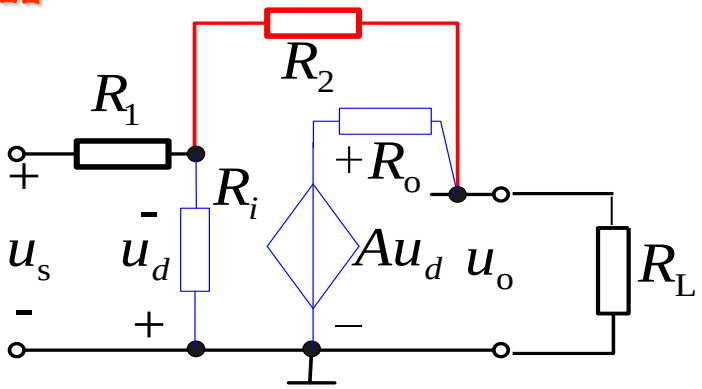


5.1 集成运算放大器 operational amplifiers

6. 闭环工作——工作于线性区——放大器



A=50000
R_i=2MΩ
R_o=100Ω
u_s=5V
R_1=100Ω
R_2=200Ω
R_L=200Ω



$$\begin{cases}\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_i}\right)(-u_d)-\frac{1}{R_2}u_o=\frac{u_s}{R_1}\\ -\frac{1}{R_2}(-u_d)+\left(\frac{1}{R_2}+\frac{1}{R_o}+\frac{1}{R_L}\right)u_o=\frac{Au_d}{R_o}\end{cases}$$

$$u_o=-1.9998u_s$$
$$u_d=-0.320\text{mV}$$
$$i_n=1.60\times10^{-10}\text{mA}$$

$A\to\infty$ $\quad u_o\approx-\frac{R_2}{R_1}u_s=-2u_s$

闭环增益 G

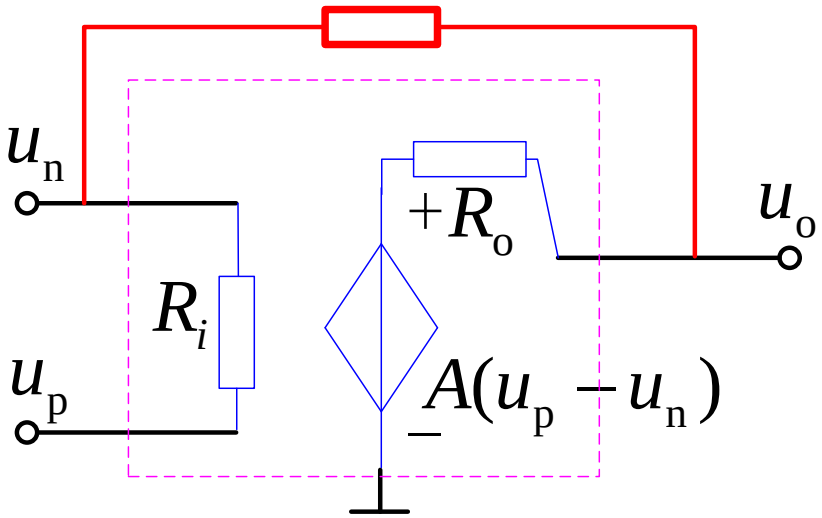
$$u_o=\frac{\frac{1}{R_1}\left(\frac{1}{R_2}-\frac{A}{R_o}\right)}{\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_i}\right)\left(\frac{1}{R_2}+\frac{1}{R_o}+\frac{1}{R_L}\right)+\frac{1}{R_2}\left(-\frac{1}{R_2}+\frac{A}{R_o}\right)}u_s$$

- $u_d\to0$
- $i_n\to0$

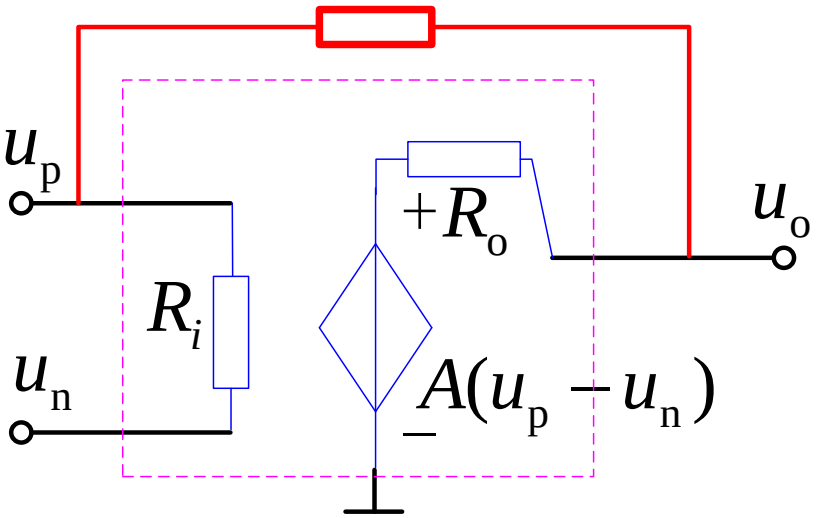
5.1 集成运算放大器 operational amplifiers

7. 正反馈与负反馈

负反馈：



正反馈：



负反馈：

扰动 $\rightarrow u_p \uparrow \rightarrow u_o = A(u_p-u_n) \uparrow \rightarrow u_n \uparrow \rightarrow (u_p-u_n) \downarrow \rightarrow u_o \downarrow$

正反馈：

扰动 $\rightarrow u_p \uparrow \rightarrow u_o = A(u_p-u_n) \uparrow \rightarrow u_p \uparrow\uparrow \rightarrow (u_p-u_n) \uparrow\uparrow \rightarrow u_o \uparrow\uparrow$

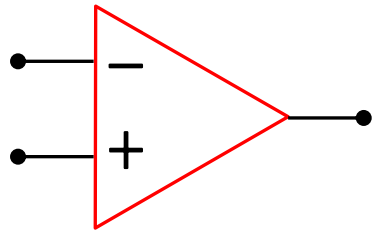
5.2 理想运放 ideal operational amplifiers

在线性放大区，将运放电路作如下的理想化处理：

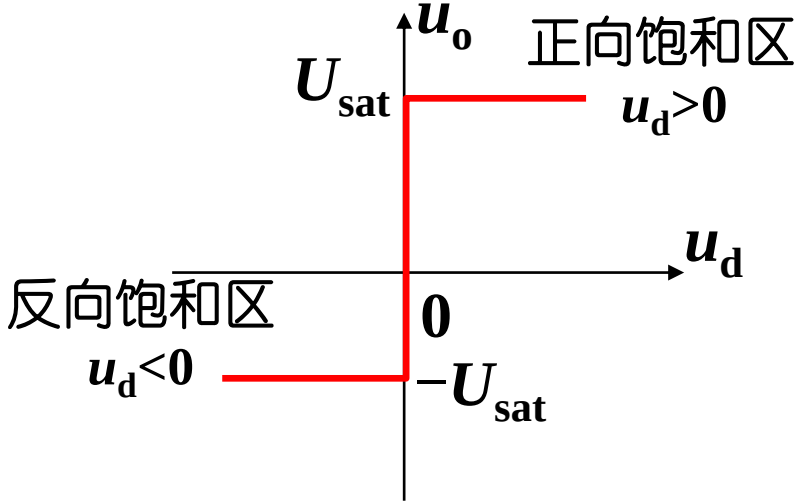
(1) $A\to\infty$ u_o为有限值，则$u_d=0$,即$u_+=u_-$，两个输入端之间相当于短路(虚短)；

(2) $R_i\to\infty$ ， $i_+=0$, $i_-=0$。 即从输入端看进去，元件相当于开路（虚断）。

(3) $R_o\to 0$，输出端电压与负载无关，理想电压源。



理想运放的电路符号



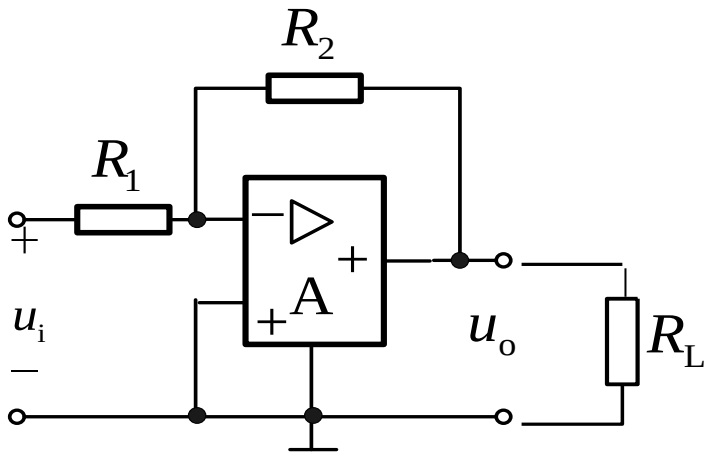
理想运放特性

5.2 理想运放 ideal operational amplifiers

再求 u_o ，视为理想运放。

$$\frac{u_i - 0}{R_1} + \frac{u_o - 0}{R_2} = 0$$

$$u_o = -\frac{R_2}{R_1} u_i$$



Closed-loop gain G

反相放大器 Inverting amplifier——VCVS

注意：

当 R_1 和 R_f 确定后，为使 u_0 不超过饱和电压（即保证工作在线性区），对u_i有一定限制。

5.3运算放大电路

1. 反向放大器 Inverting amplifier

2. 同向放大器 Noninverting amplifier

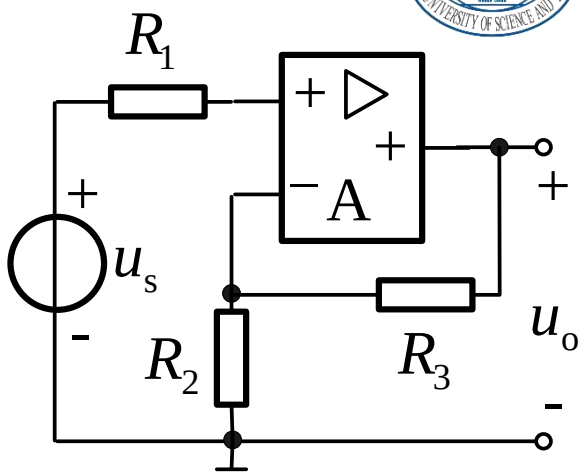
3. 电压跟随器 Voltage follower

4. 加法器 Summing amplifier

5. 差分放大器 Difference amplifier——减法器 subtractor

5.3运算放大电路

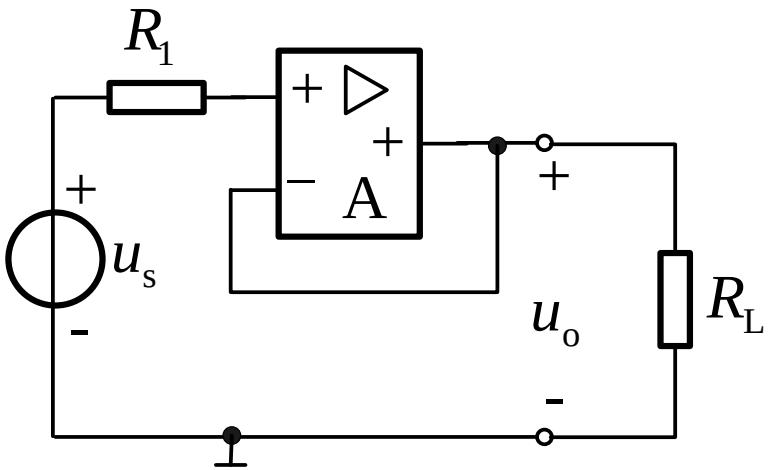
1. 反相比例放大器Inverting amplifier



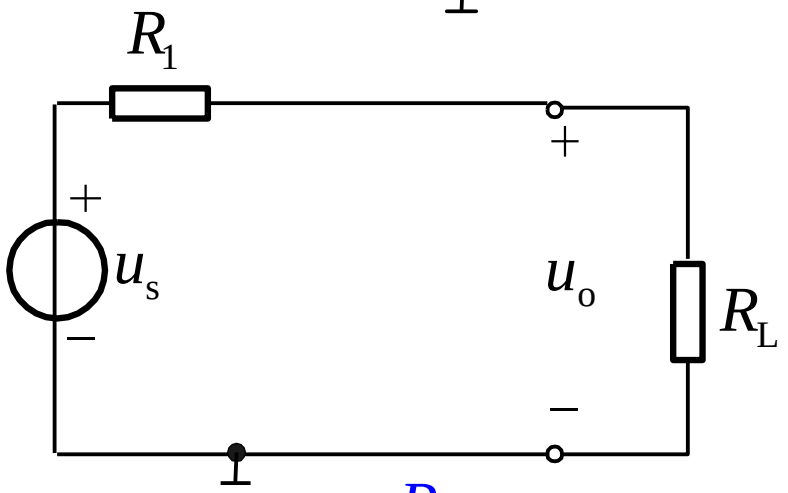
$$\frac{u_s-0}{R_2}+\frac{u_s-u_o}{R_3}=0 \qquad u_o=(1+\frac{R_3}{R_2})u_s$$

2. 同相比例放大器Noninverting amplifier

3. 电压跟随器Voltage follower



$$u_o=u_s$$



$$u_o=\frac{R_L}{R_L+R_1}u_s$$

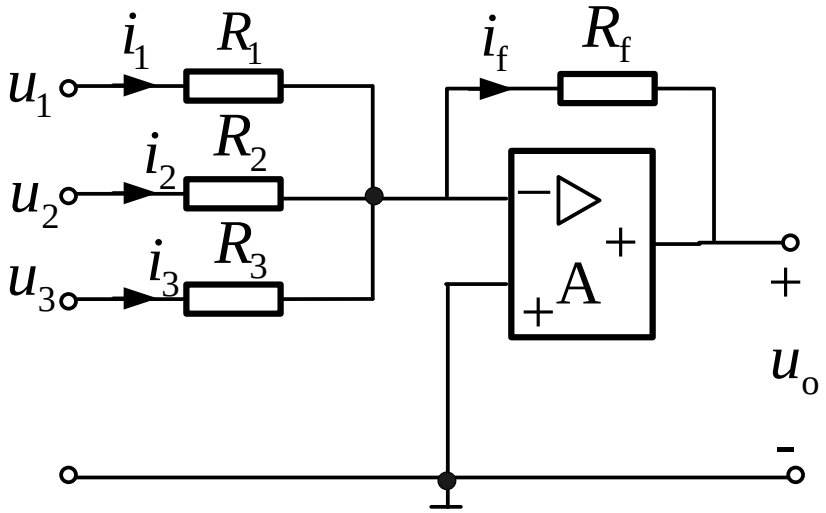
① 输入电阻无穷大（虚断）；

② 输出电阻为零；

应用：在电路中起隔离前后两级电路的作用。

5.3运算放大电路

4. 求和放大器（加法器）Summing amplifier



$$\frac{u_1-0}{R_1}+\frac{u_2-0}{R_2}+\frac{u_3-0}{R_3}+\frac{u_o-0}{R_f}=0$$

$$u_o=-(\frac{R_f}{R_1}u_1+\frac{R_f}{R_2}u_2+\frac{R_f}{R_3}u_3)$$

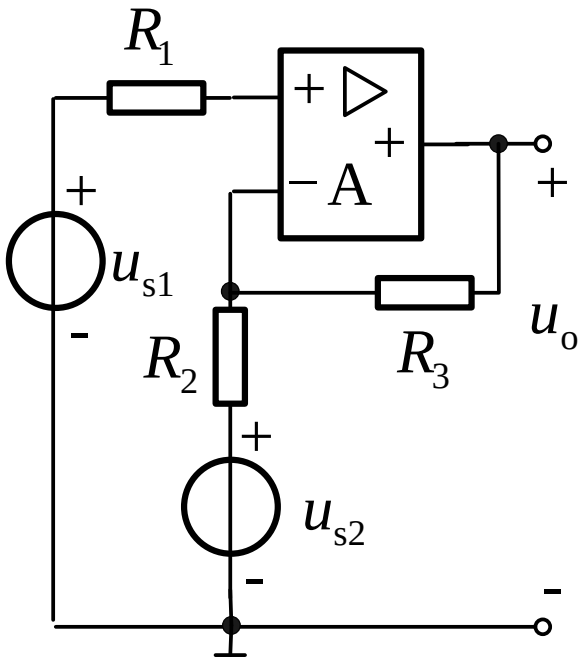
5.3运算放大电路

5. 差分放大器（减法器）

Difference amplifier（subtractor）

$$\frac{u_{s1}-u_{s2}}{R_2}+\frac{u_{s1}-u_o}{R_3}=0$$

$$u_o=(1+\frac{R_3}{R_2})u_{s1}-\frac{R_3}{R_2}u_{s2}$$

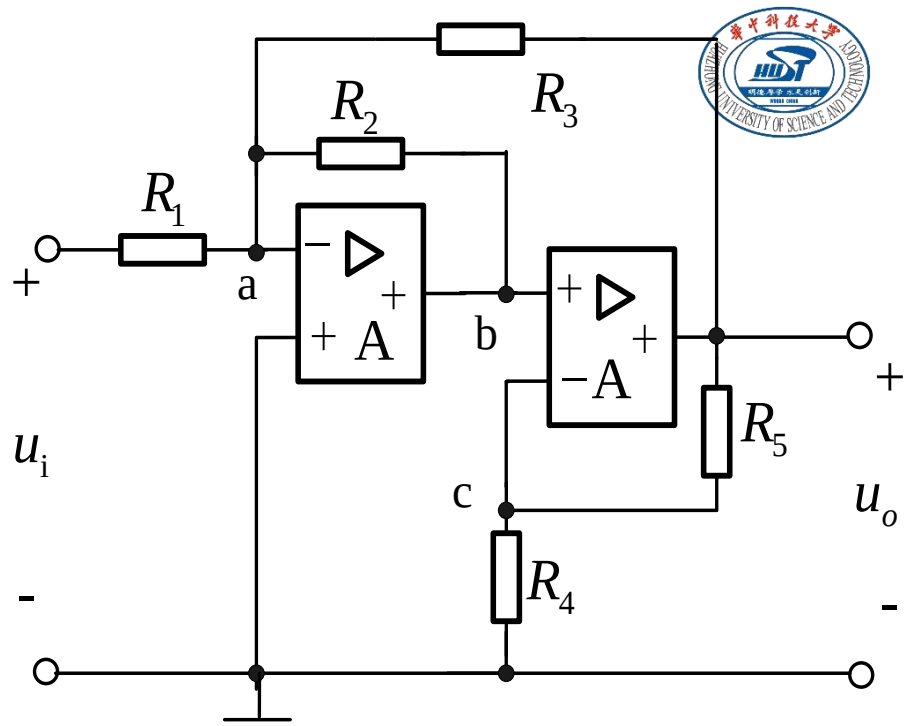


目标3： 确定输出电压。

$$\begin{cases} \dfrac{u_i-0}{R_1}+\dfrac{u_b-0}{R_2}+\dfrac{u_o-0}{R_3}=0 \\ \dfrac{u_c}{R_4}+\dfrac{u_c-u_o}{R_5}=0 \end{cases}$$

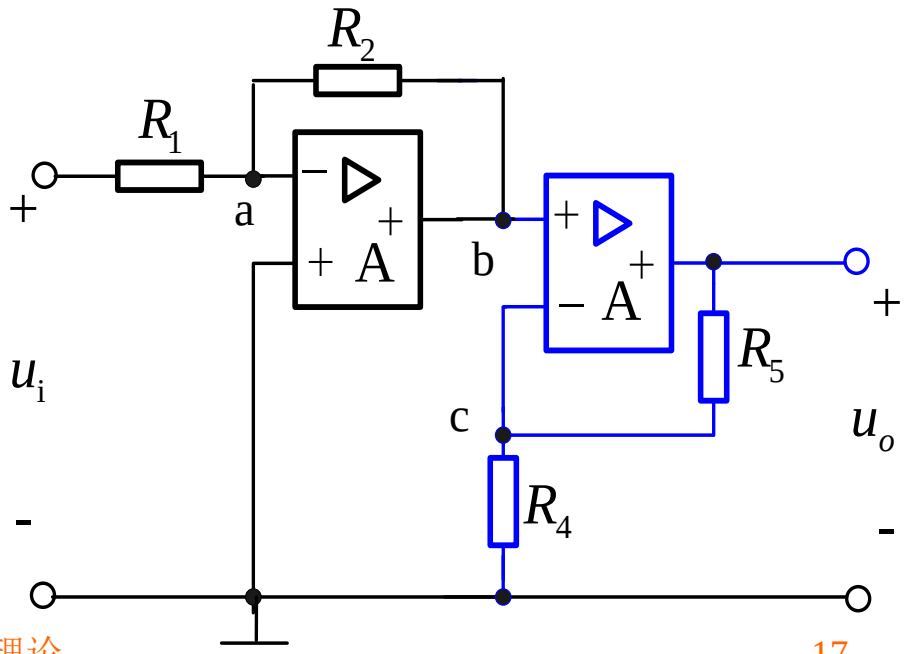
$$u_b = u_c$$

$$\frac{u_o}{u_i} = -\frac{R_2R_3(R_4+R_5)}{R_1(R_2R_4+R_2R_5+R_3R_4)}$$



$$u_b = -\frac{R_2}{R_1}u_i \qquad u_o = (1+\frac{R_5}{R_4})u_b$$

$$u_o = -\frac{R_2}{R_1}(1+\frac{R_5}{R_4})u_i$$



作业

- 5.2节：5-2
- 5.3节：5-6，5-7，5-10
- 5.4节：5-13
- 5.5节：5-22