第二章 运算放大器及其线性应用

——2.3 运放运算电路

李泳佳
东南大学电子系国家ASIC工程中心
yongjia.li@outlook.com

本节内容

2.3.1 比例运算电路

2.3.2 加减运算电路

2.3.3 微分与积分运算电路

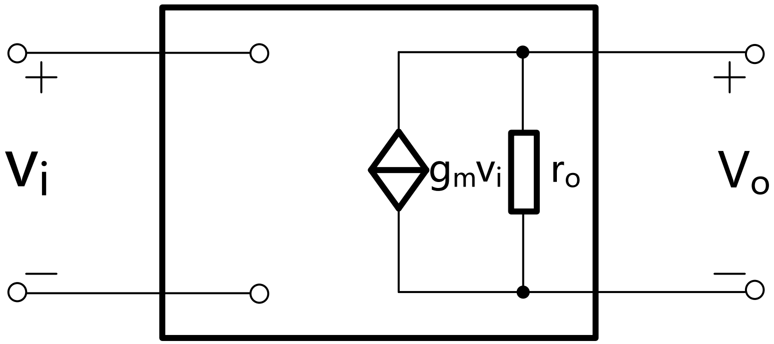
2.3.4 对数和指数运算电路

2.3.5 运放分析举例

2.3 运放运算电路

✓ **运放回顾：**

- **虚断：**无穷大输入阻抗，输入“断路”
- **虚短：**无穷高增益的前提下，正负输入“短路”
- 为什么运放需要高增益？应该怎么使用运放？

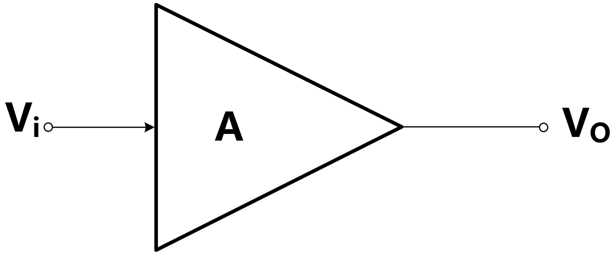


$$\boxed{\mathbf{A} = \frac{\mathbf{v_o}}{\mathbf{v_i}} = \mathbf{g_m} \times \mathbf{r_o}}$$

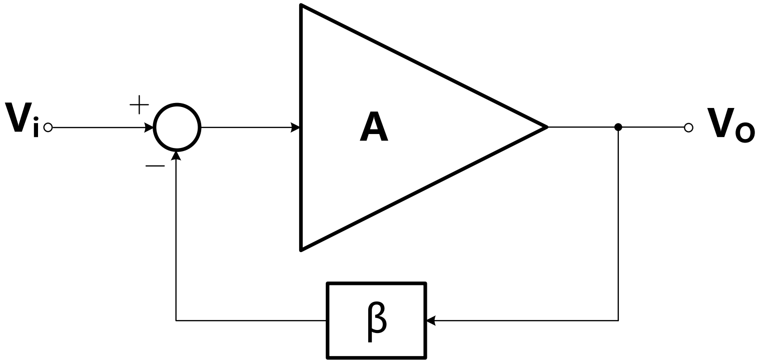
- 数学角度理解跨导gm和电阻ro
- 工艺角度理解变化趋势
- 开环使用的工艺误差>10%!

2.3 运放运算电路

✓ **开环和闭环放大对比：**



$$\frac{v_o}{v_i} = g_m \times r_o$$



$$v_o = (v_i - \beta \times v_o) \times A$$

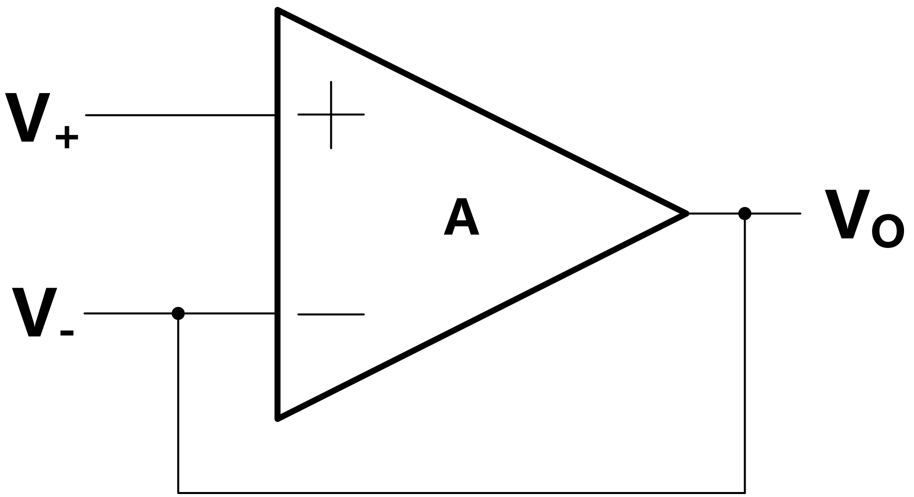
$$\frac{v_o}{v_i} = \frac{A}{1 + A \times \beta} = \frac{1}{\frac{1}{A} + \beta} \approx \frac{1}{\beta}$$

- A无穷大时，增益由1/β决定
- β由同类型的器件决定，如电阻比例

2.3 运放运算电路

✓ **最基本的电压缓冲电路：**

- V_+输入，V_O输出，负反馈在V_-
- 运放的输出接回**反相输入**，形成**负反馈**
- 运放输入输出关系：$v_o=(v_+-v_-)\times A$
- 两个输入相等程度由**开环放大倍数A**决定



$$\begin{cases} v_o = v_- \\ v_o = (v_+ - v_-)\times A \end{cases}$$

$$v_o = (v_+ - v_o)\times A$$

$$\boxed{v_o = v_+ \times \frac{A}{A+1}}$$

✓ **运用“虚断”和“虚短”分析：**

- **虚断**：$v_o = v_-$
- **虚短**：$v_+ = v_-$

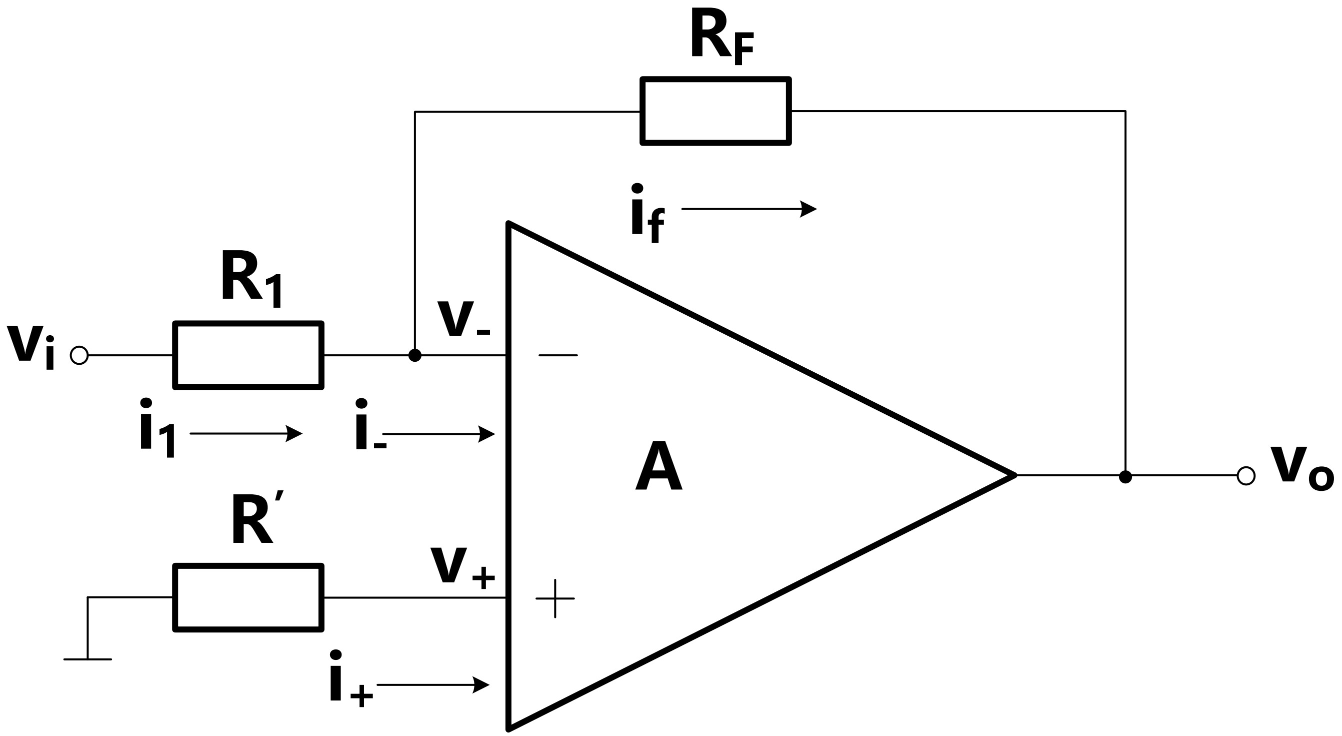
2.3.1 比例运算电路

- ✓ **反相比例运算电路：**
- ✓ **运用“虚断”和“虚短”分析：**
  - **- 虚断：** $i_+ = i_- = 0$
  - **- 虚短：** $v_+ = v_- = 0$

$$\frac{v_i - v_-}{R_1} = \frac{v_- - v_o}{R_F}$$

$$\boxed{v_o = -\frac{R_F}{R_1} v_i}$$

- ✓ **当$R_F = R_1$时，$v_o = -v_i$**
  - 倒相器



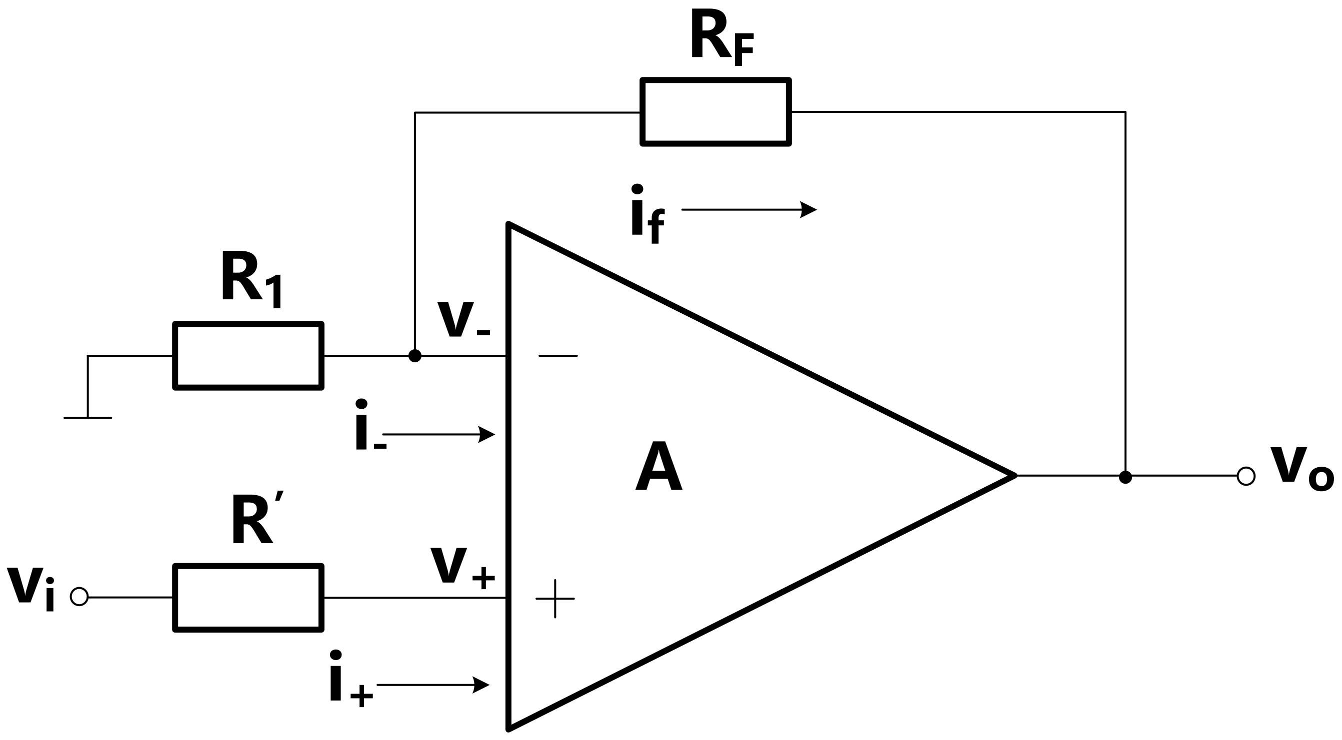
- ✓ **R′ 的作用?**
  - “虚断”不完全成立时，匹配输入两端阻抗
  - $R' = R_1 // R_F$

2.3.1 比例运算电路

- ✓ **同相比例运算电路：**
- ✓ **运用“虚断”和“虚短”分析：**
  - **虚断：** $i_+ = i_- = 0$， $v_+ = v_i$
  - **虚短：** $v_+ = v_- = v_i$

$$v_i\left(\frac{R_1 + R_F}{R_1}\right) = v_o$$

$$\boxed{v_o = \left(1 + \frac{R_F}{R_1}\right)v_i}$$

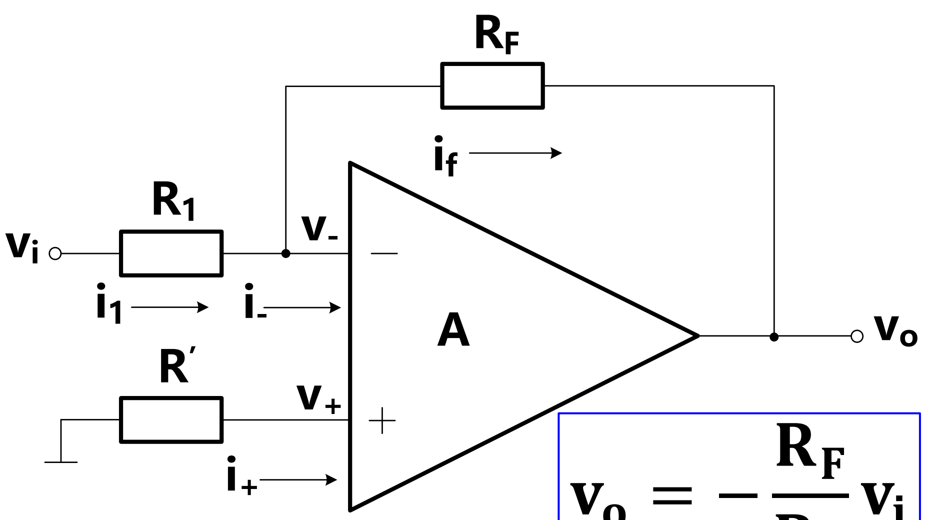


- ✓ **当$R_F = 0, R_1 = \infty$时，** $v_o = v_i$
  - 电压跟随器（缓冲器）
- ✓ **R′ 的作用?**
  - “虚断”不完全成立时，匹配输入两端阻抗
  - R′ $=R_1//R_F$

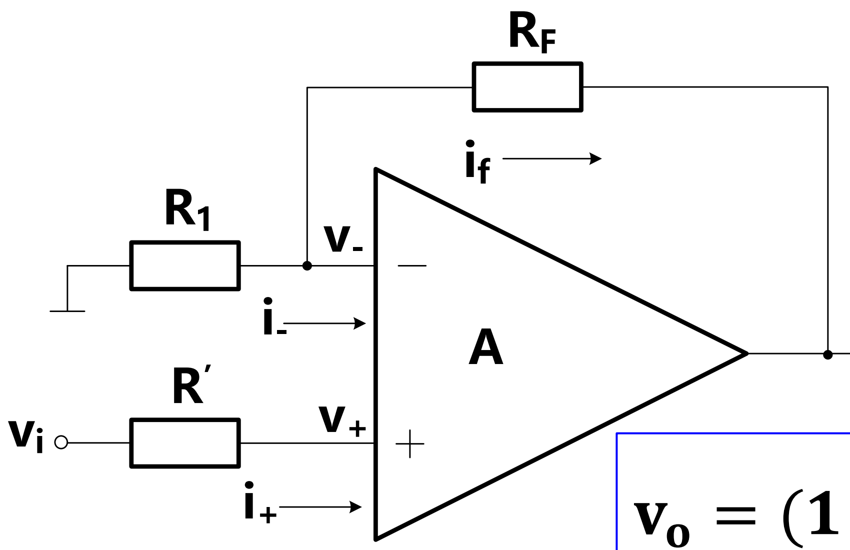
2.3.1 比例运算电路

✓ **同相和反相有什么区别?**

- 传递函数极性
- 输入共模
- 输出摆幅



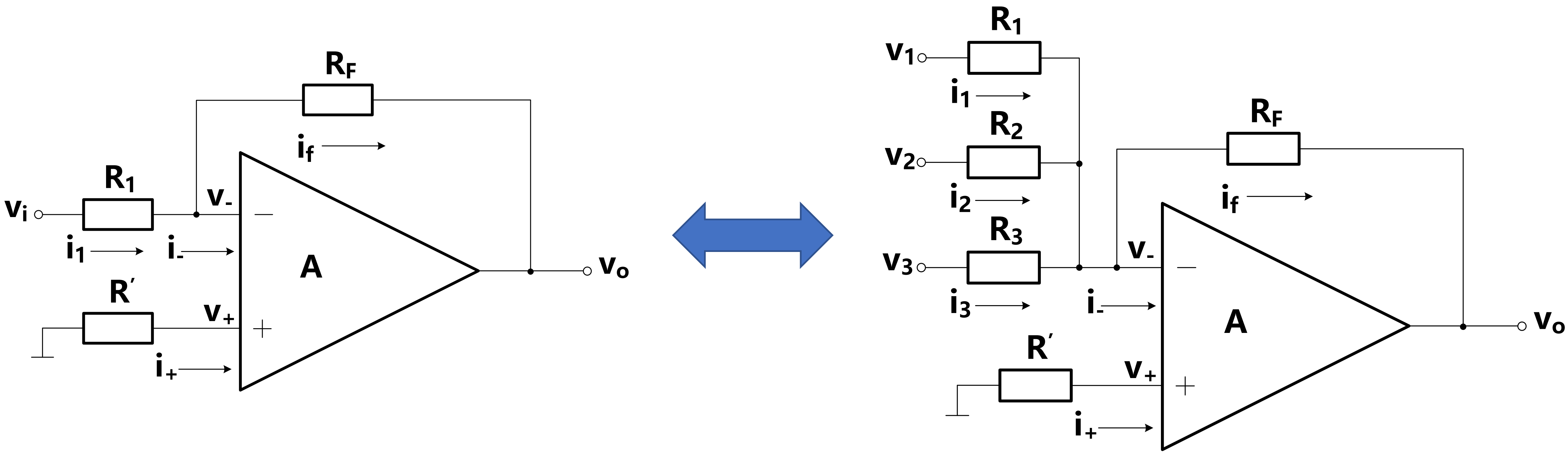
$$v_o = -\frac{R_F}{R_1}v_i$$



$$v_o = (1+\frac{R_F}{R_1})v_i$$

2.3.2 加减运算电路

✓ **反相加法器：**



2.3.2 加减运算电路

- ✓ **反相加法器：**
- ✓ **方法一：“虚断”和“虚短”**

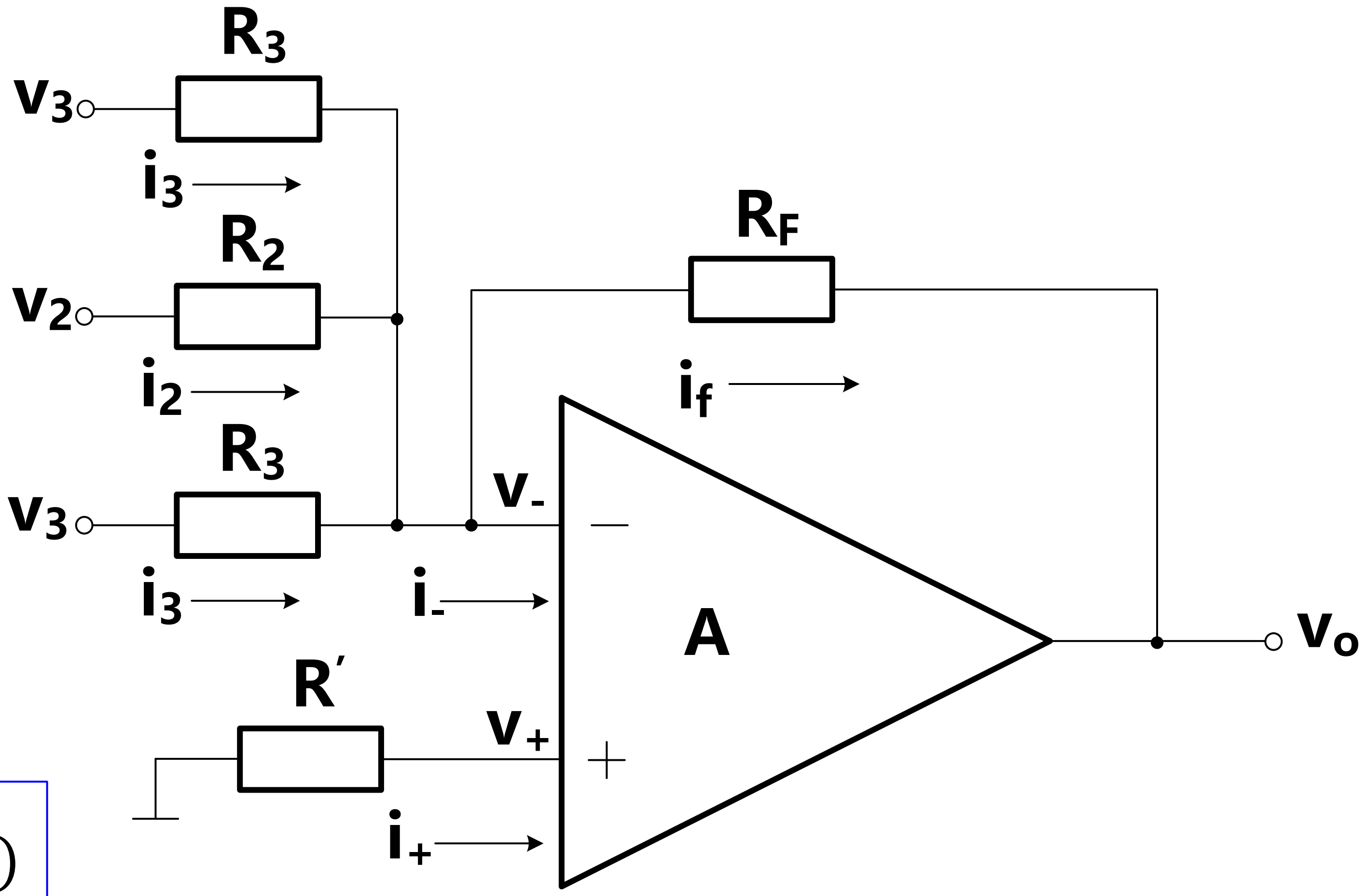
  - 虚断：$i_+ = i_- = 0$

  - 虚短：$v_+ = v_- = 0$

$$i_1 + i_2 + i_3 = i_f$$

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} = -\frac{v_o}{R_F}$$

$$\boxed{v_o = -\left(\frac{R_F}{R_1}v_1 + \frac{R_F}{R_2}v_2 + \frac{R_F}{R_3}v_3\right)}$$

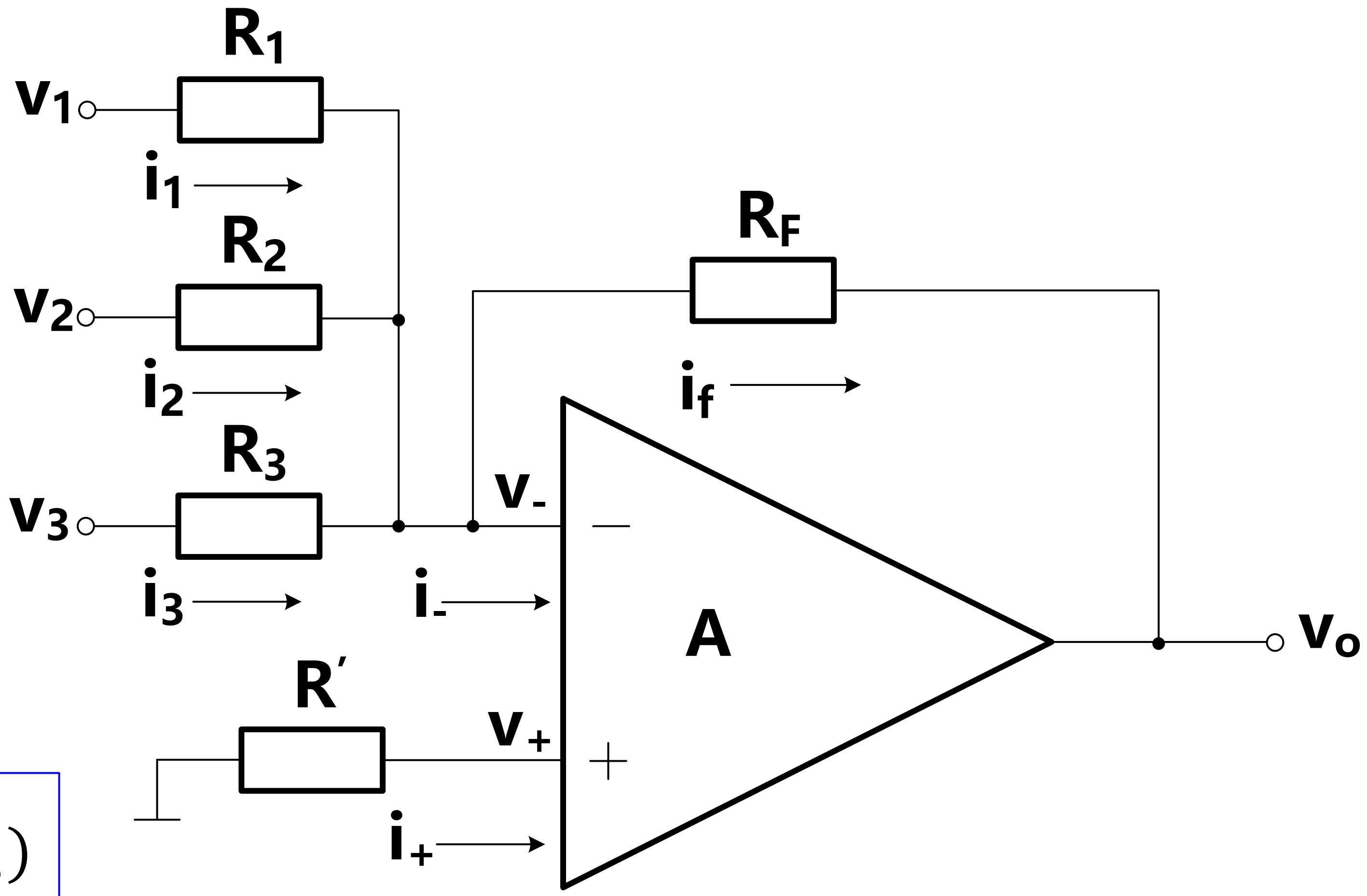


2.3.2 加减运算电路

- ✓ 反相加法器：
- ✓ 方法二：叠加定理

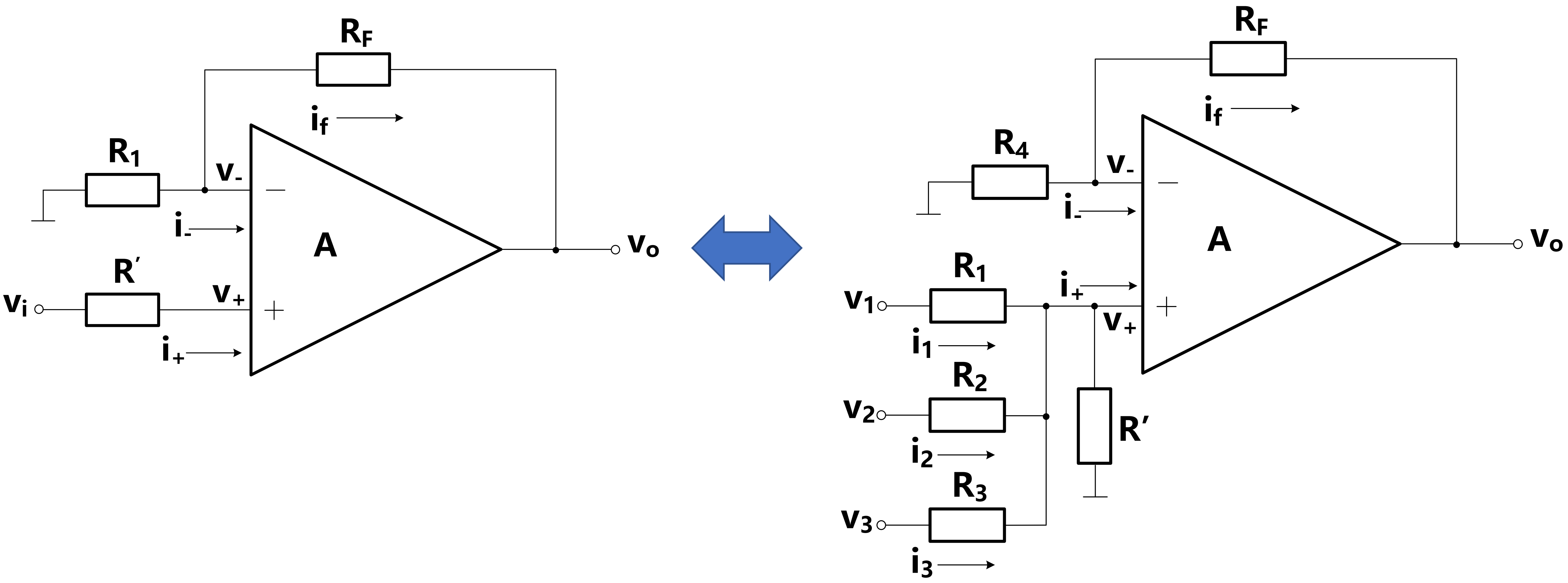
- v_1： $\frac{v_1}{R_1} = -\frac{v_o}{R_F}$
- v_2： $\frac{v_2}{R_2} = -\frac{v_o}{R_F}$
- v_3： $\frac{v_3}{R_3} = -\frac{v_o}{R_F}$

$$\boxed{v_o = -\left(\frac{R_F}{R_1}v_1 + \frac{R_F}{R_2}v_2 + \frac{R_F}{R_3}v_3\right)}$$



2.3.2 加减运算电路

✓ **同相加法器：**



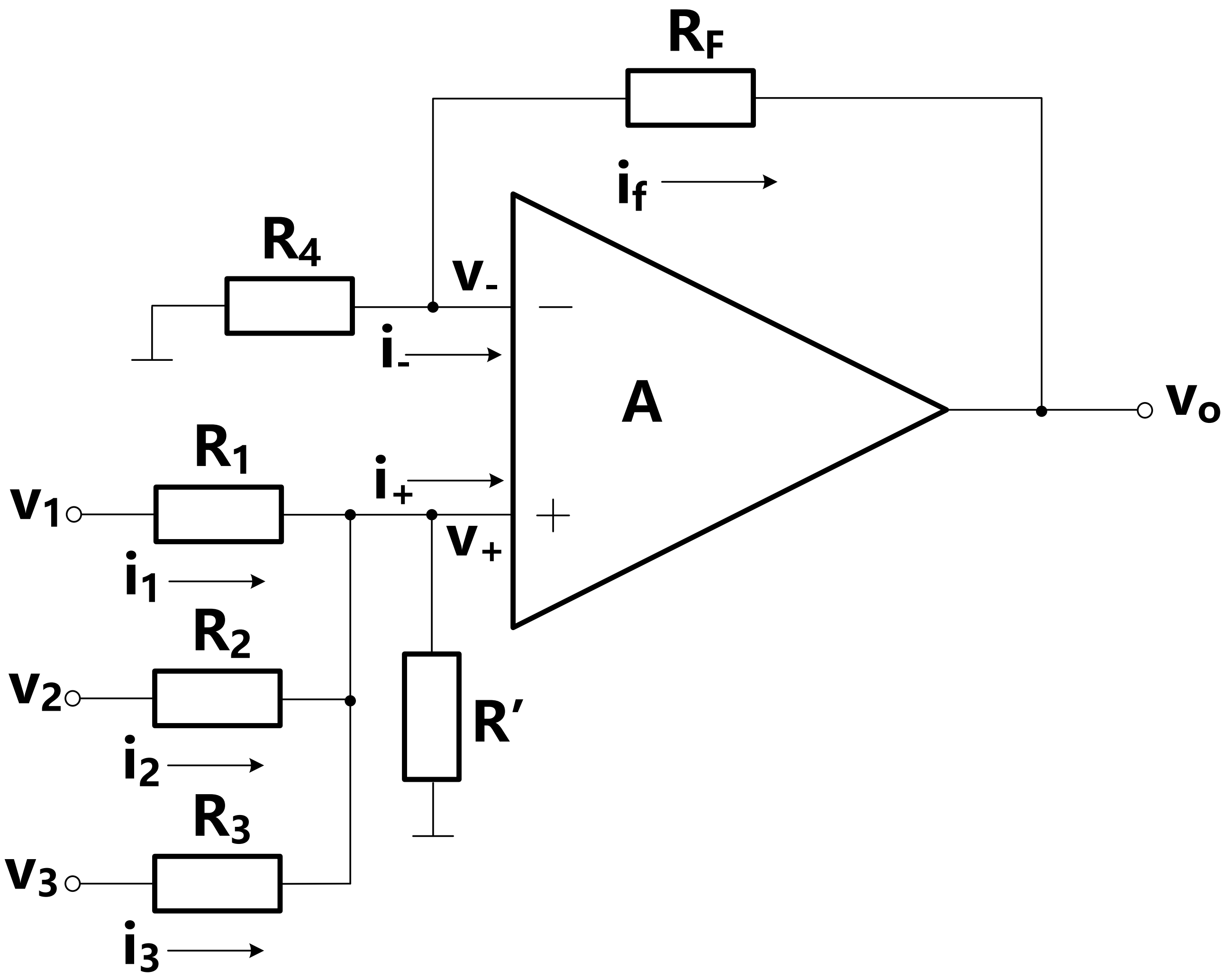
2.3.2 加减运算电路

- ✓ **同相加法器：**
- ✓ **“虚断”和“虚短”**
  - **- 虚断：** $i_+ = i_- = 0$
  - **- 虚短：** $v_+ = v_-$

$$v_+ = (i_1 + i_2 + i_3) \times R'$$

$$i_k = \frac{v_k - v_+}{R_k},\quad k = 1,\ 2,\ 3$$

$$\boxed{v_o = \left(1 + \frac{R_F}{R_4}\right)\left(\frac{R_P}{R_1}v_1 + \frac{R_P}{R_2}v_2 + \frac{R_P}{R_3}v_3\right)}$$



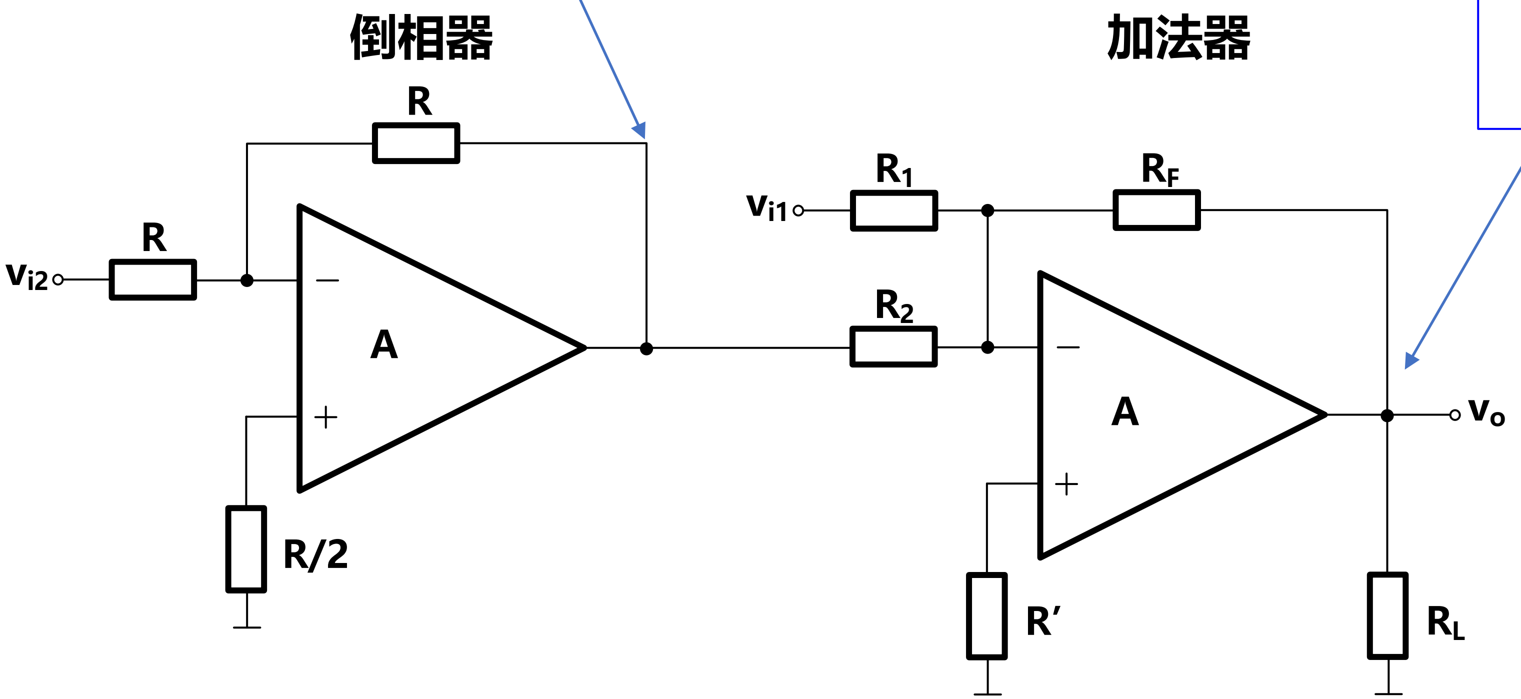
2.3.2 加减运算电路

✓ **如何实现减法电路?**

- 同相/反相的加法器/比例运算电路

$$\boxed{v_{o2} = -v_{i2}}$$

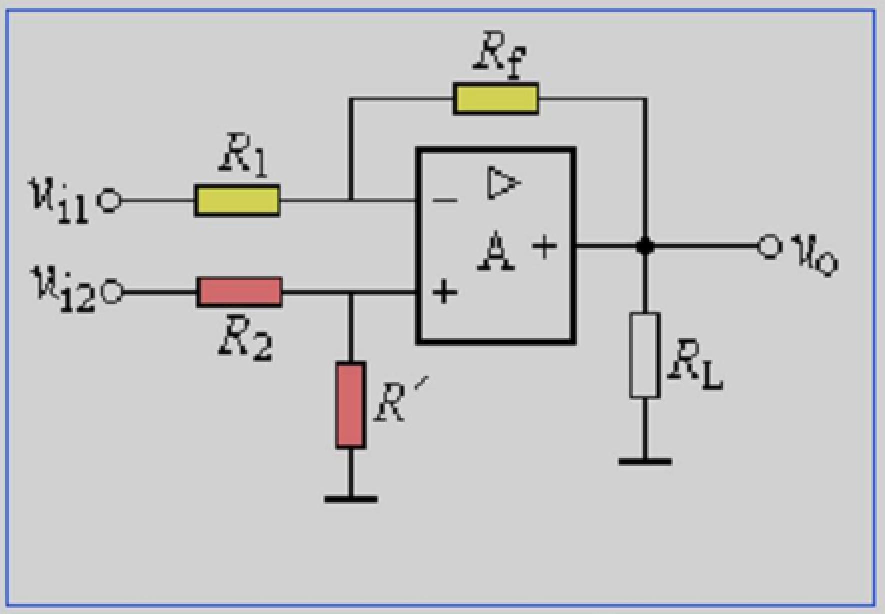
$$\boxed{\begin{aligned} v_o &= -\left(\frac{R_F}{R_1}v_{i1} + \frac{R_F}{R_2}v_{o2}\right) \\ &= -\left(\frac{R_F}{R_1}v_{i1} - \frac{R_F}{R_2}v_{i2}\right) \\ &= \frac{R_F}{R_1}v_{i2} - \frac{R_F}{R_2}v_{i1} \end{aligned}}$$



2.3.2 加减运算电路

✓ **如何实现减法电路?**

- **同相/反相的加法器/比例运算电路**
- **差动减法器**
  - 运用**叠加定理**
  - **v_{i1}作用：** $v_{o1} = -\frac{R_F}{R_1} v_{i1}$
  - **v_{i2}作用：** $v_{o2} = \left(1 + \frac{R_F}{R_1}\right) \frac{R'}{R' + R_2} v_{i2}$



➡ - **叠加：** $v_o = v_{o1} + v_{o2} = -\frac{R_F}{R_1} v_{i1} + \left(1 + \frac{R_F}{R_1}\right) \frac{R'}{R' + R_2} v_{i2}$

➡ - 如果 $\frac{R_F}{R_1} = \frac{R'}{R_2}$， $v_o = \frac{R_F}{R_1}(v_{i2} - v_{i1})$

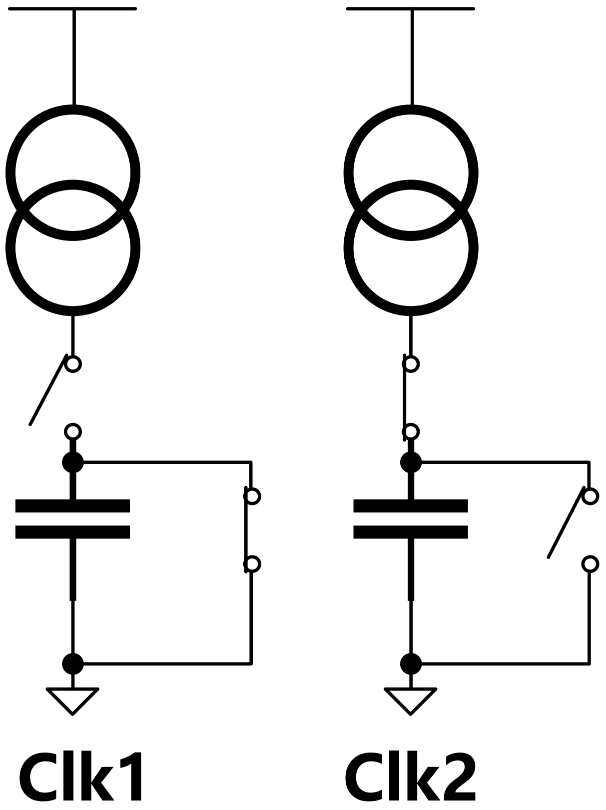
2.3.3 微分与积分电路

✓ **积分运算电路**

- 与加减法/比例运算电路类似
- **电流源+电容**
  - **瞬态波形?**

$$C = \frac{Q}{V}$$

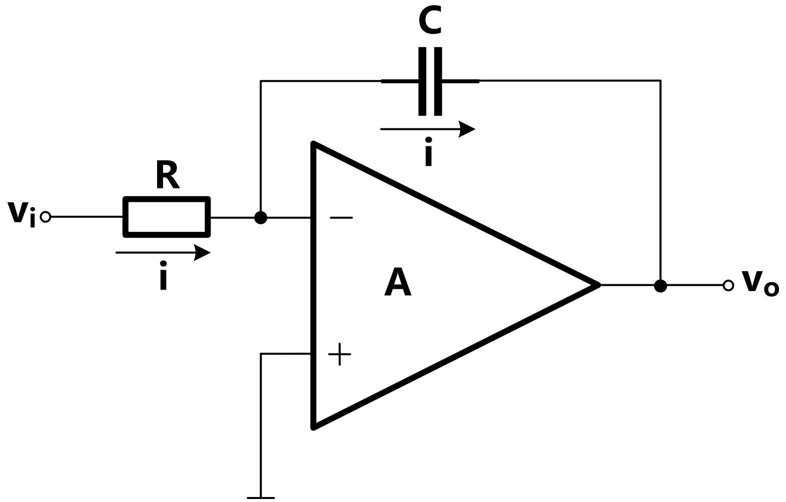
$$V = \frac{Q}{C} = \frac{I * t}{C}$$



2.3.3 微分与积分电路

✓ **积分运算电路**

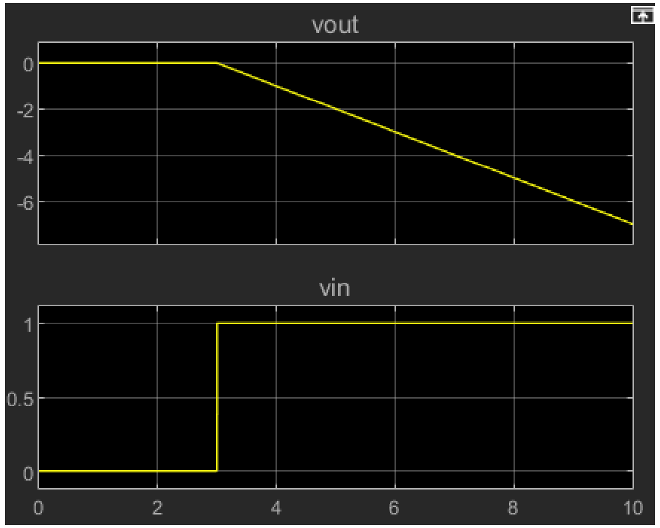
- 与加减法/比例运算电路类似
- 虚短：$i = v_i / R$

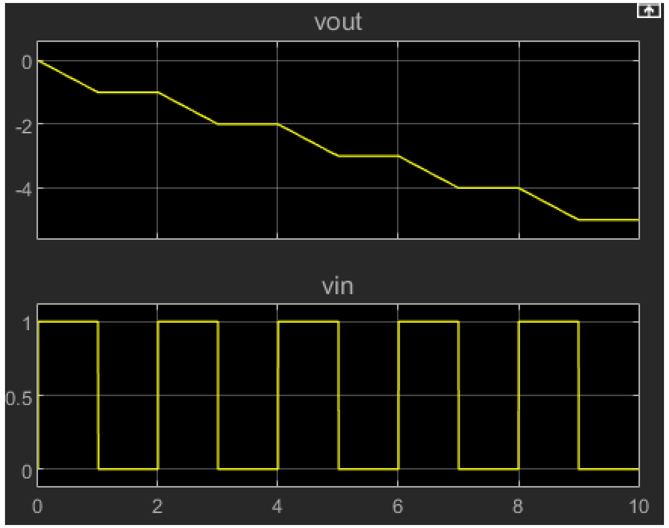


$$\Rightarrow \quad v_o = -v_c = -\frac{1}{C}\int i_c dt = -\frac{1}{RC}\int v_i dt$$

$\Rightarrow$ **- 阶跃/方波输入：**

$$v_o = -v_c = -\frac{1}{RC}\int v_i dt$$

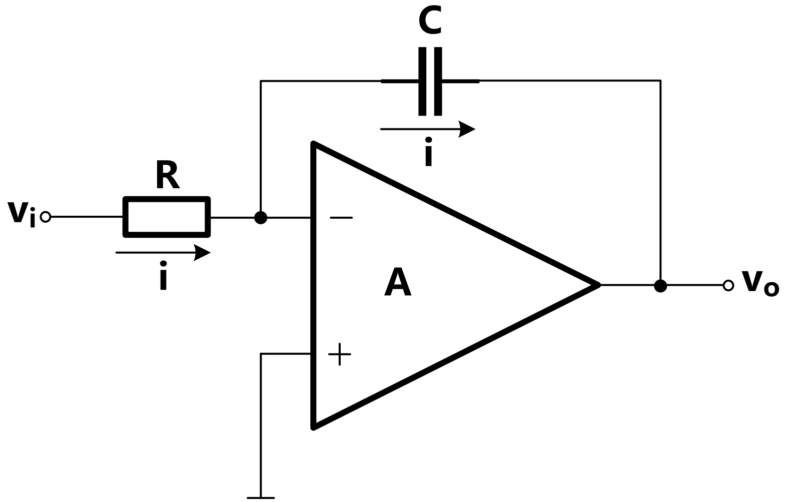


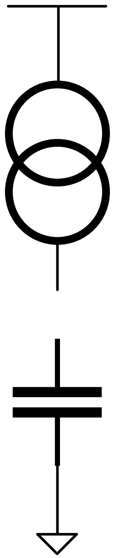


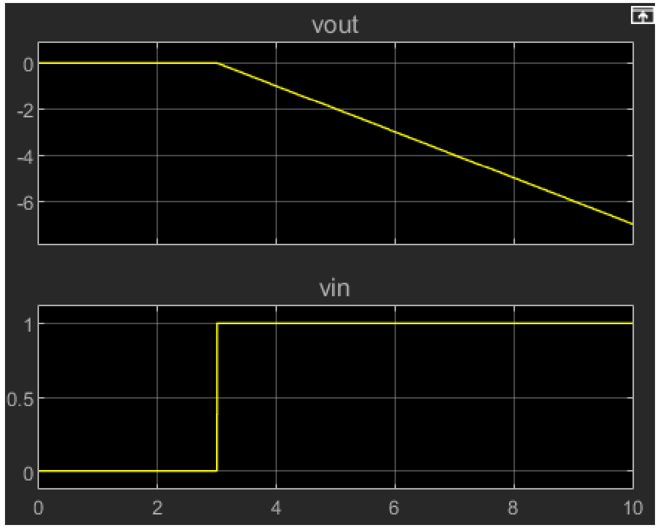
2.3.3 微分与积分电路

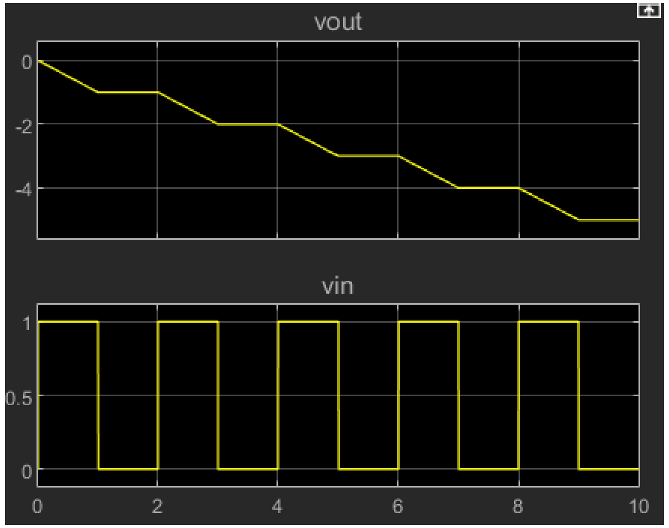
✓ **积分运算电路**

- **与加减法/比例运算电路**类似
- 运放输入相等时，积分器输出不变?
- 积分电阻R两端无电位差，无积分电流









2.3.3 微分与积分电路

✓ **微分运算电路**

- **与加减法/比例运算电路类似**

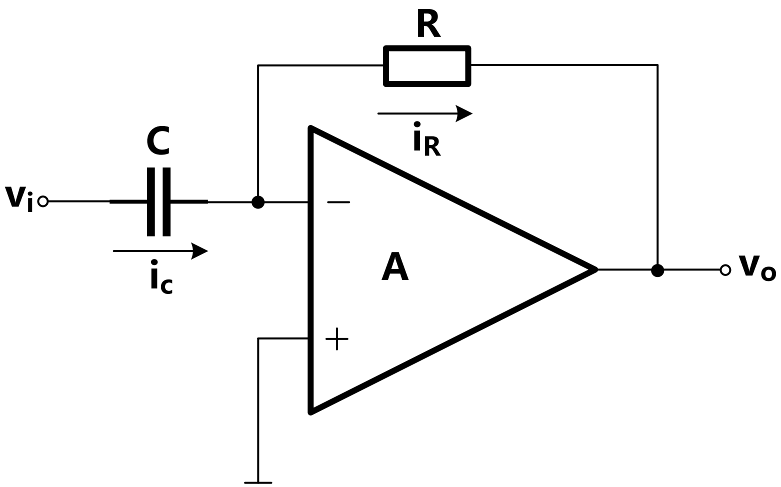
- **虚短：** $i = C\dfrac{dv_c}{dt}$

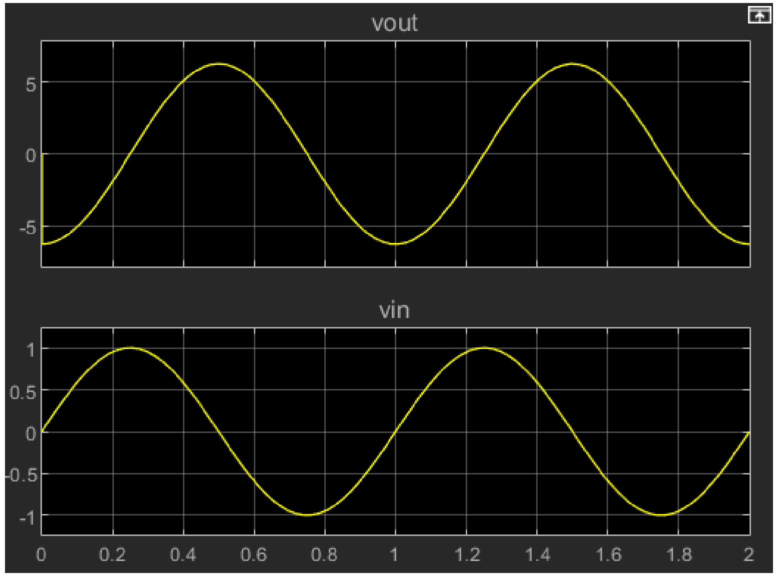
$$v_o = -i_R R = -i_c R = -RC\frac{dv_c}{dt} = -RC\frac{dv_i}{dt}$$

- **正弦波输入：**

- $v_i = v_m \sin \omega t$

- $v_o = -RC\dfrac{dv_i}{dt} = -RCv_m\omega \cos \omega t$

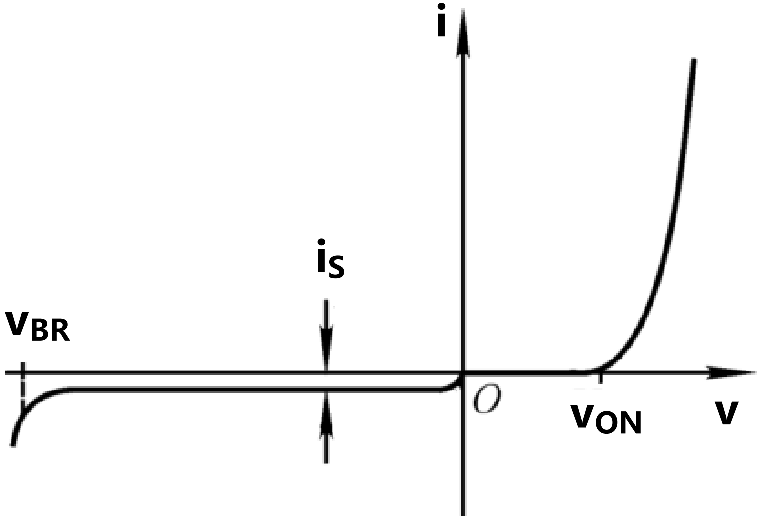


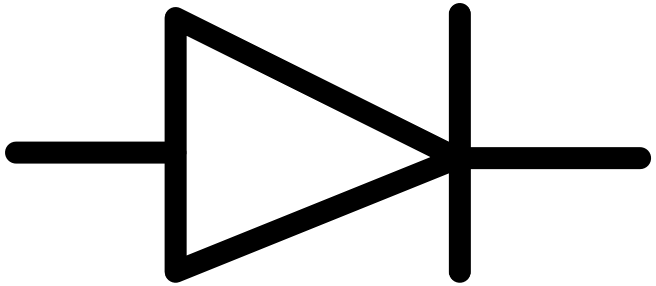


2.3.4 对数和指数运算电路

✓ 二极管I-V特性：$i_D = i_S(e^{\frac{v_D}{v_T}} - 1) \approx i_S e^{\frac{v_D}{v_T}}$

- 二极管反相饱和电流：i_S
- 热电压：$v_T = kT/q$

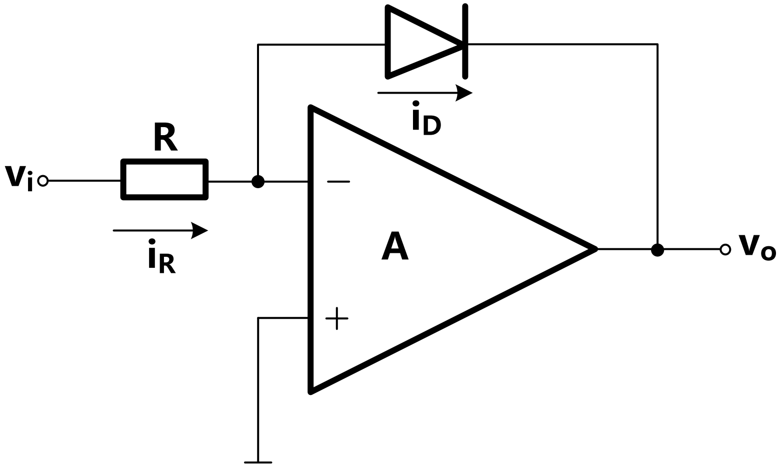




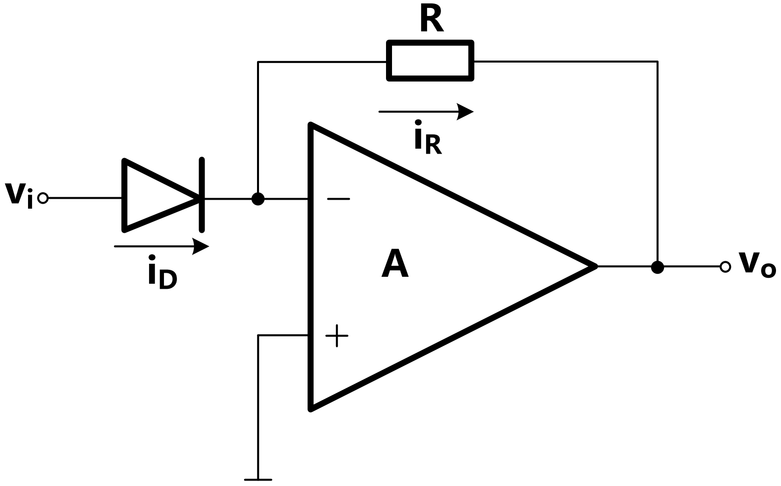
2.3.4 对数和指数运算电路

✓ **对数运算电路**

- 虚短：$v_+ = v_-$
- 虚断：$i_R = i_D$
- $i_D = i_S(e^{\frac{v_D}{v_T}} - 1) \approx i_S e^{\frac{v_D}{v_T}}$



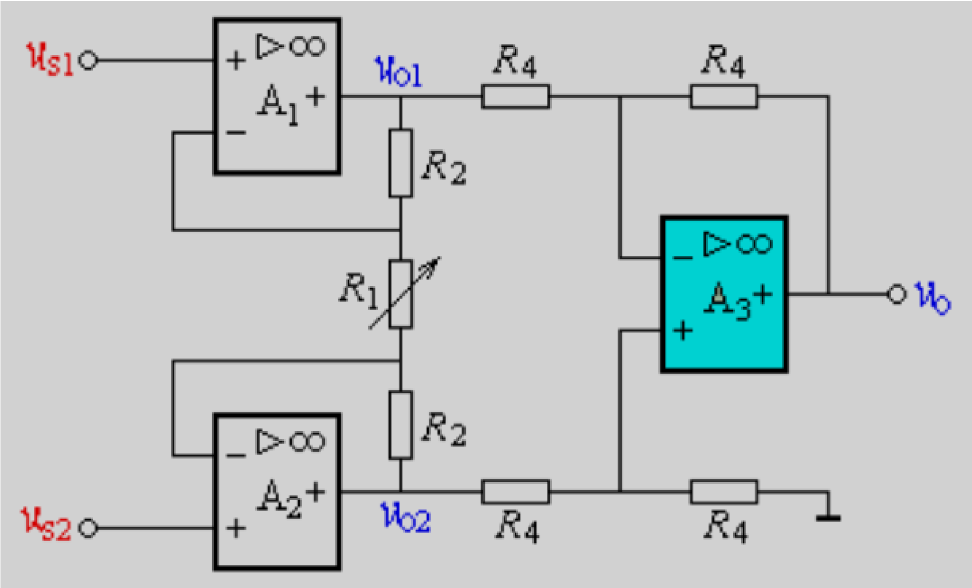
$$v_o = -v_T \ln\frac{i_D}{i_s} = -v_T \ln\frac{v_i}{Ri_s}$$



$$v_o = -i_R R = -i_D R = -Ri_s e^{\frac{v_i}{v_T}}$$

2.3.5 运放分析举例

- ✓ **仪表放大器**
  - **高共模抑制比：**对称结构
  - **高输入阻抗：**前端同相放大器
  - **高放大倍数：**放大倍数由R_1调节



- ✓ **求放大倍数：**
  - **A1和A2虚断：** $\frac{v_{R1}}{R_1} = \frac{V_{o1}-V_{o2}}{R_1+2R_2}$

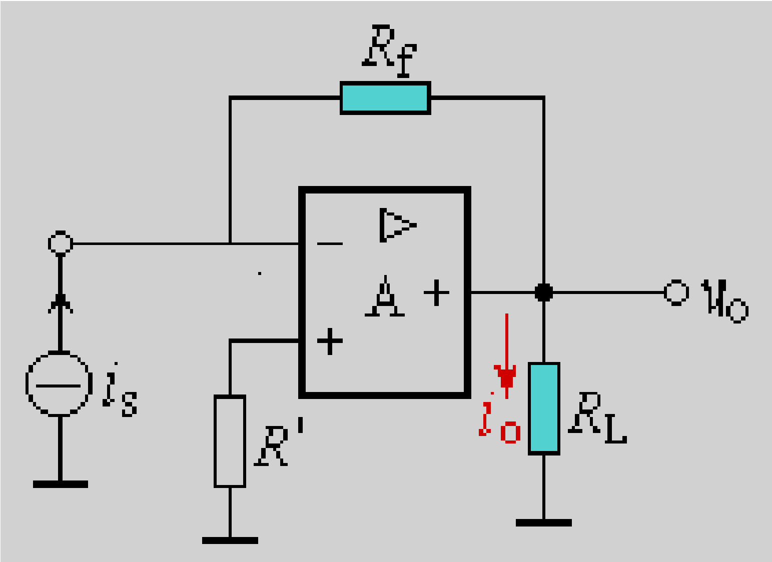
$$\Rightarrow v_{o1} - v_{o2} = \frac{R_1 + 2R_2}{R_1} v_{R1} = \frac{R_1 + 2R_2}{R_1}(v_{s1} - v_{s2})$$

  - **A3虚短：** $v_+ = v_- = v_{o2}/2$
  - **A3虚断：** $\frac{v_{o1} - v_-}{R_4} = \frac{v_- - v_o}{R_4} \Rightarrow v_o = v_{o1} - v_{o2} \Rightarrow \boxed{v_o = -\frac{R_1 + 2R_2}{R_1}(v_{s1} - v_{s2})}$

2.3.5 运放分析举例

✓ **电流-电压变换器（I/V）**

- **传感器接口电路和模数转换器**
- **A虚断：** $v_o = -i_s R_f$
- **输出负载电流：** $\boxed{i_o = \dfrac{v_o}{R_L} = -\dfrac{R_f}{R_L} i_s}$

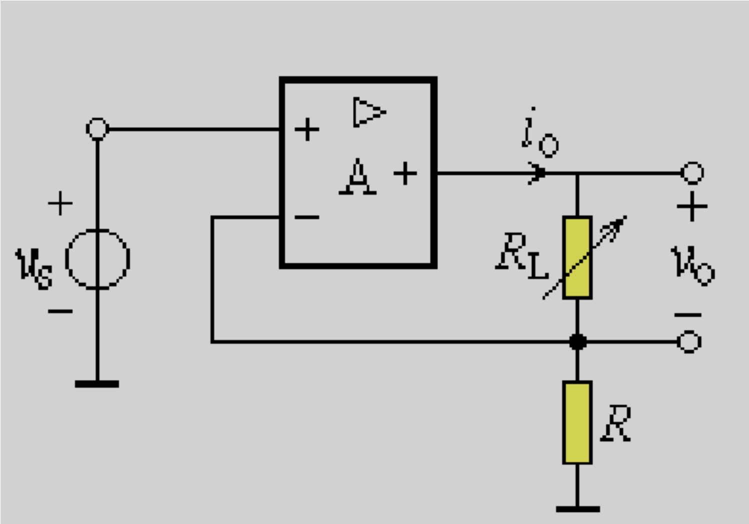


✓ **R_L固定时，输出电流与输入电流成比例，此时该电路也可视为电流放大电路**

2.3.5 运放分析举例

✓ **电压-电流变换器（V/I）**

- **负载R_L跨接在输出和R之间**
- **A虚断：** $i_o = \frac{v_s}{R}$



✓ **本质上是个同相比例运算电路**

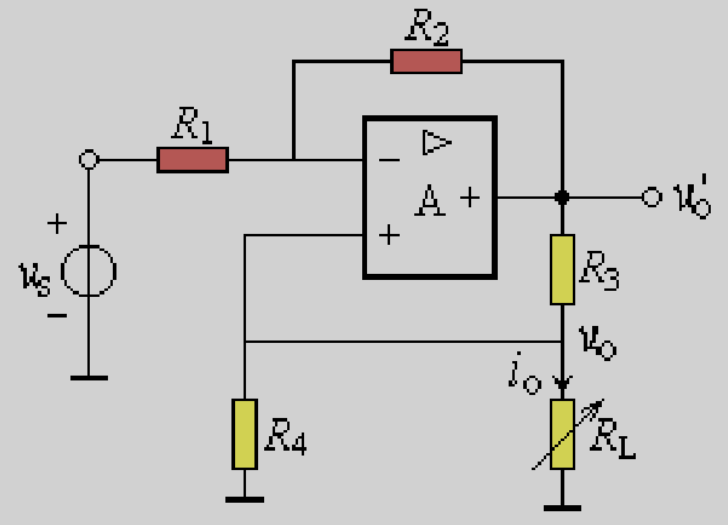
✓ **线性稳压电路**（Linear Regulator, **LDO**）

2.3.5 运放分析举例

✓ **电压-电流变换器（V/I）**

- **负载R_L接地**

$$\Rightarrow \quad \boxed{i_o = -\frac{R_2}{R_1}\frac{v_s}{(R_3 + \frac{R_3}{R_4}R_L - \frac{R_2}{R_1}R_L)}}$$



✓ **讨论：**

- **当分母为零时，i_o无穷大，电路自激**

- **当**$\frac{R_3}{R_4} = \frac{R_2}{R_1}$**时，** $i_o = -\frac{1}{R_4}v_s$

2.3.5 运放分析举例

✓ **运放相关问题**

- **输出信号与输入信号间的相位关系**
- **判断运放的反馈极性**
- **判断运放的运算类型，推导表达式**
- **给定表达式设计运算电路**