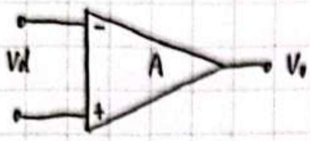
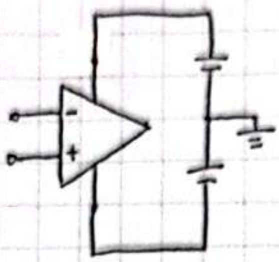
运算放大器

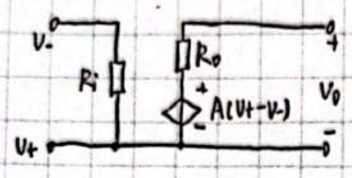


双电源直流供电



[理想运算放大器]

电路模型：



(1) $R_i\to\infty$，输入阻抗无穷大，$i_+\to0$，$i_-\to0$。输入端看进去，元件相当于开路——虚断

(2) [仅限负反馈接法!] $A\to\infty$，$(V_+-V_-)\to0$

V_o为有限值，$V_+\to V_-$，两个输入端相当于短路（虚短）

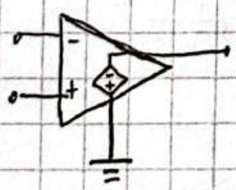
(3) $R_o\to0$，输出阻抗$\to0$。

输出电压与负载无关，$R_o=A(V_+-V_-)$

(4) 共模抑制比（$CMRR\to\infty$）(?)

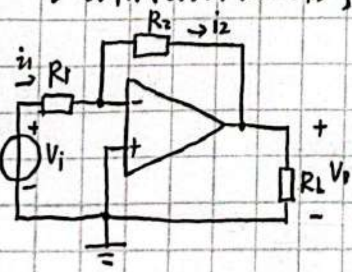
$$CMRR=\left|\frac{A_{vd}}{A_{cm}}\right|=\left|\frac{\frac{V_o}{V_+-V_-}}{\frac{V_o}{(V_+-V_-)/2}}\right|\to\infty$$

∴理想运放：



[应用电路]

[反相接法放大器]

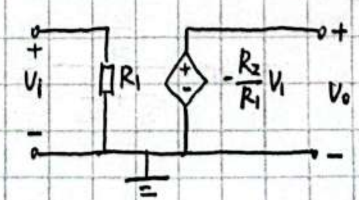


· 虚短：$V_-=V_+=0$

· 虚断：$i_-=0$，$i_1=i_2$

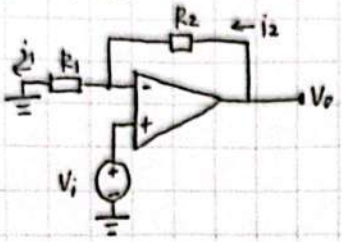
$$\therefore A_v=\frac{V_o}{V_i}=\frac{-i_2R_2}{i_1R_1}=-\frac{R_2}{R_1}$$

电路模型：



此时输入电阻：$R_i=R_1$，输出电阻：$R_o=0$

[同相接法放大器]



虚短：$V_+ = V_- = V_i$

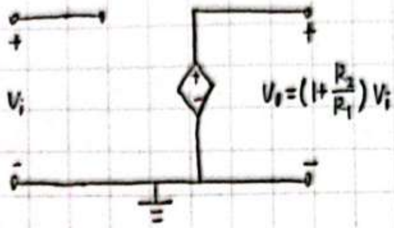
虚断：$i_1 = i_2 \Rightarrow \frac{V_i}{R_1} = \frac{V_o - V_i}{R_2}$

$\therefore \frac{V_o}{R_2} = (\frac{1}{R_1} + \frac{1}{R_2}) V_i \Rightarrow V_o = (1 + \frac{R_2}{R_1}) V_i$

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

(没有I_i. $R_i \to \infty$.)

电路模型：

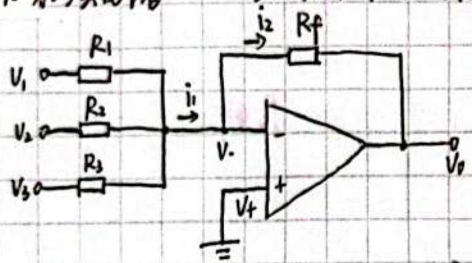


[常用运放应用电路]

[运放线性电路]

1. 加法电路

[反相加权加法器]



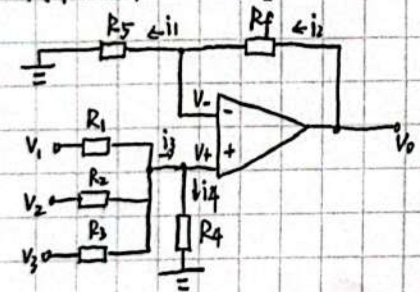
虚短：$V_- = V_+ = 0$

虚断：$i_1 = i_2$

$\therefore \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_o}{R_f}$

$\Rightarrow V_o = -(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3)$

[同相加权加法器]



虚短：$V_+ = V_-$

虚断：$i_1 = i_2$，$i_3 = i_4$

$\therefore V_- = \frac{R_5}{R_5 + R_f} \cdot V_o$

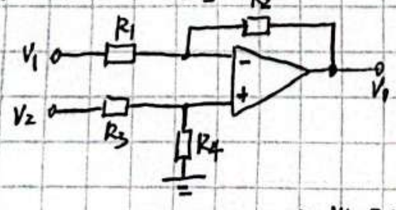
$\frac{V_+}{R_4} = \frac{V_1 - V_+}{R_1} + \frac{V_2 - V_+}{R_2} + \frac{V_3 - V_+}{R_3}$

$\Rightarrow V_+ = \frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}$，令 $\frac{1}{R^+} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}$

化简：$V_+ = \frac{R_+}{R_1} \cdot V_1 + \frac{R_+}{R_2} \cdot V_2 + \frac{R_+}{R_3} \cdot V_3$

$\therefore V_o = (1 + \frac{R_f}{R_5}) V_- = (1 + \frac{R_f}{R_5}) V_+ = (1 + \frac{R_f}{R_5}) \cdot (\underbrace{\frac{R_+}{R_1}}_{<1} V_1 + \underbrace{\frac{R_+}{R_2}}_{<1} V_2 + \underbrace{\frac{R_+}{R_3}}_{<1} V_3)$

[差分放大电路]



虚短：$V_+ = V_-$ 虚断：$\frac{V_1 - V_-}{R_1} = \frac{V_- - V_o}{R_2}$

$\frac{V_2 - V_+}{R_3} = \frac{V_+}{R_4}$

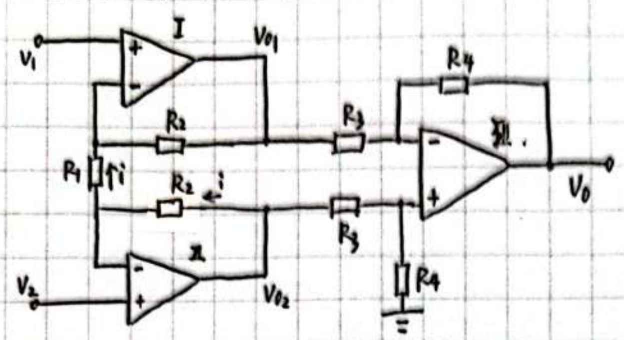
$\Rightarrow V_+ = \frac{\frac{V_2}{R_3}}{\frac{1}{R_3} + \frac{1}{R_4}} = \frac{R_4}{R_3 + R_4} \cdot V_2$，$V_o = R_2 \cdot [\frac{V_1}{R_1} - (\frac{1}{R_1} + \frac{1}{R_2}) V_-]$

$= \frac{R_2}{R_1} V_1 - (1 + \frac{R_2}{R_1}) \cdot \frac{R_4}{R_3 + R_4} \cdot V_2$

若 $\frac{R_2}{R_1} = \frac{R_4}{R_3} = k$，$V_o = kV_1 - (1+k) \cdot \frac{kR_3}{R_3 + kR_3} V_2 = k(V_1 - V_2)$

$\Rightarrow \boxed{V_o = \frac{R_2}{R_1}(V_2 - V_1)}$

[典型的仪表放大电路]



I: 虚短: $V_1 = V_+ = V_-$

虚断: $\underline{V_{o1} = V_1 - iR_2}$

II: $\underline{V_{o2} = V_2 + iR_2}$

又: $V_1 + iR_1 = V_2 \Rightarrow i = \frac{V_2 - V_1}{R_1}$.

后面即差分放大:

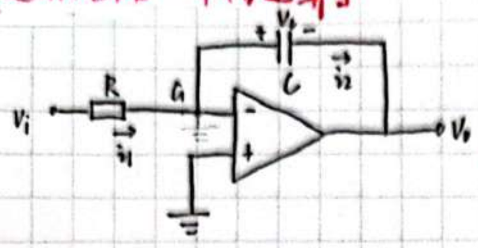
$V_o = \frac{R_4}{R_3}(V_{o2} - V_{o1}) = \frac{R_4}{R_3}(V_2 - V_1 + 2iR_2)$

代入. $V_o = \frac{R_4}{R_3} \cdot \left(1 + \frac{2R_2}{R_1}\right)(V_2 - V_1)$

三运放仪表放大器:

① 输入R_i无穷大 ②可以使A_1.A_2一致, CMRR特性好.

[运放电路 一积分运算]



虚断: $i_1 = i_2$

虚短: $V_- = V_+ = 0$

$i_1 = i_2 \qquad i_2 = C\cdot\frac{dV_c}{dt} = C\cdot\frac{d(-V_o)}{dt}$

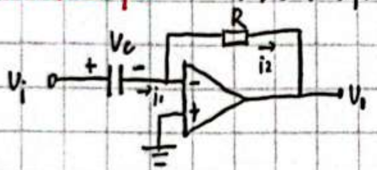
$i_1 = \frac{V_i}{R}$

$\therefore\ C\cdot\frac{d(-V_o)}{dt} = \frac{V_i}{R}$

$V_o(t) = -\frac{1}{RC}\int V_i(t)\,dt$

[微分运算]

电容C与电阻R调换



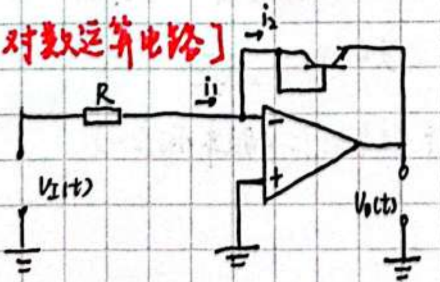
虚断: $i_1 = i_2 = C\cdot\frac{dV_c}{dt}$

虚短: $V_- = V_+ = 0 \quad \Rightarrow \quad V_o = -CR\frac{dV_c}{dt}$

P.S. 虚积

多个端口 → 卷积

[对数运算电路]



$V_{BE} = V_T \ln\frac{i_c}{I_s} \approx V_T \ln\frac{i_2}{I_s} \qquad i_2 = i_1 = \frac{V_I}{R}$

$\therefore V_O = -V_{BE} = -V_T \ln\frac{i_2}{I_s} = -V_T \ln\frac{V_I}{RI_s} = -V_T\left[\ln V_I - \ln(RI_s)\right]$

$= -V_T \ln V_I + K$

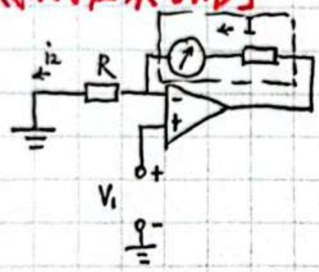
实际运用中: 需保证bjt正偏

[指数运算电路]

$$i_2 = i_1 = I_s e^{\frac{V_I(t)}{V_T}}$$

$$V_o = -i_2 R = -I_s R e^{\frac{V_I(t)}{V_T}}$$

[模拟电压表电路]



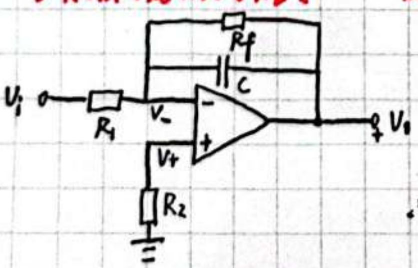
虚短: $I = i_2$

虚断: $V_- = V_+ = V_1$ $\therefore i_2 = \frac{V_-}{R} = \frac{V_1}{R}$

$\Rightarrow I = \frac{V_1}{R}$

同时可满足电压表内阻无穷大 ($R_i \to \infty$)

[有源滤波电路]



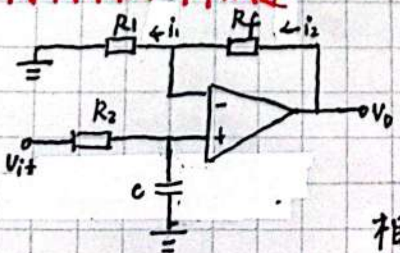
反相输入一阶低通

· 小频率 ⇒ 开路 ⇒ 反相放大器 $A(s) = -\frac{R_f/R_1}{1+s/w_H} = \frac{A_m}{1+s/w_H}$

· 大频率 ⇒ 短路 ⇒ 增益无. 其中 $w_H = \frac{1}{2\pi R_f C}$

∴ 低通滤波 (具体推导见后《频率响应》)

同相输入一阶低通



· 小频率: c开路, 同相放大器.

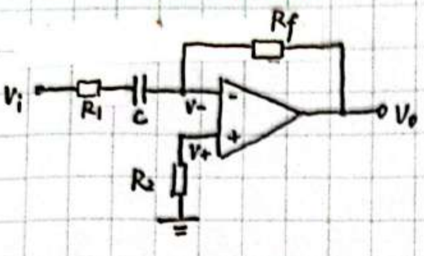
· 大频率: $V_+ = V_- = 0 \Rightarrow i_1 = i_2 = 0 \Rightarrow V_0 = 0$

无增益.

相关公式:

$$A(s) = \frac{1+\frac{R_f}{R_1}}{1+\frac{s}{w_H}} = \frac{A_m}{1+\frac{s}{w_H}} \qquad w_H = \frac{1}{2\pi R_2 C}$$

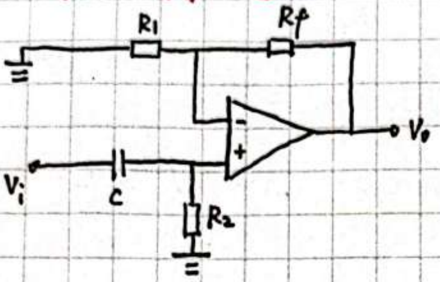
反相输入一阶高通



$$A_s = \frac{-\frac{R_f}{R_1}}{1+\omega_L/s} = \frac{A_M}{1+\frac{\omega_L}{s}}$$

$$\omega_L = \frac{1}{2\pi R_1 C}$$

同相输入一阶高通

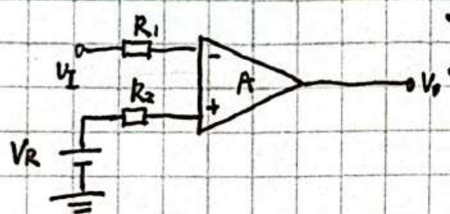


$$A_s = \frac{1+\frac{R_f}{R_1}}{1+\frac{\omega_L}{s}} = \frac{A_M}{1+\frac{\omega_L}{s}}$$

$$\omega_L = \frac{1}{2\pi R_2 C}$$

【运算放大器的非线性应用】

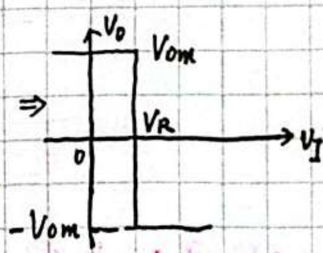
1. 单限电压比较器



· $V_I = V_- > V_+ = V_R$，$V_I = -V_{om}$

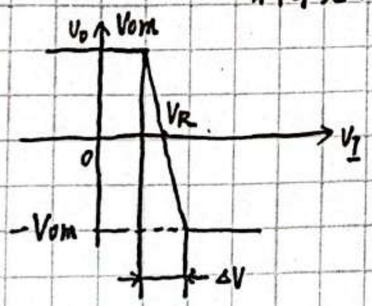
· $V_I = V_- < V_+ = V_R$，$V_I = +V_{om}$

⇒



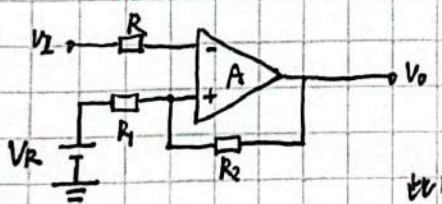
△实际工作中，放大器的增益并非无穷大（接近V_R时，会在(0, Vom)中）.

→斜率是A的增益：$\left|\frac{V_O}{V_I}\right|$.



2. 迟滞（双限）电压比较器

<比较器：无法放大信号>



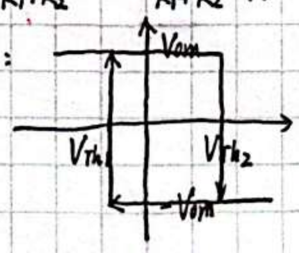
一开始，$V_O = V_{om}$.

$$\therefore V_+ = \frac{R_1}{R_1+R_2}(V_{om}-V_R)+V_R = \frac{R_1}{R_1+R_2}V_{om} + \frac{R_2}{R_1+R_2}V_R$$

此时V_I与V_+比较，阈值较高

·反向：$V_O = -V_{om}$　此时 $V_- = \frac{R_1}{R_1+R_2}\cdot(-V_{om}-V_R)+V_R = -\frac{R_1}{R_1+R_2}V_{om} + \frac{R_2}{R_1+R_2}V_R$

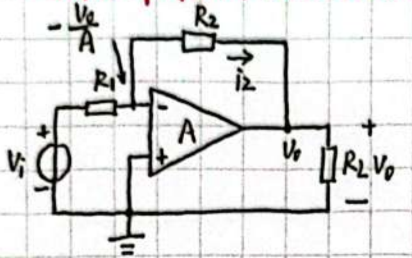
∴ 门限电压 $V_{Th} = \pm\frac{R_1}{R_1+R_2}V_{om} + \frac{R_2}{R_1+R_2}V_R$，$V_O$-$V_I$图：



[运算放大器性能参数对电路的影响]

[有限开环增益对带宽影响]

一、有限开环增益A对反相接法放大电路增益的影响



$V_0, A \Rightarrow$ 放大器幅值 $\frac{V_0}{A}$

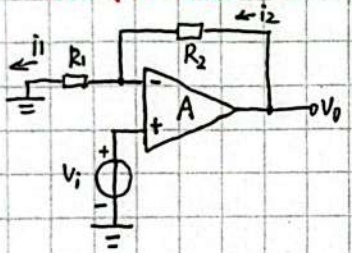
又∵ $V_+ = 0$ ∴ $V_- = -\frac{V_0}{A}$

虚断仍满足：$i_1 = i_2 \Rightarrow \frac{V_i + \frac{V_0}{A}}{R_1} = \frac{-\frac{V_0}{A} - V_0}{R_2}$

$\Rightarrow V_0 = \frac{R_2 \cdot V_i}{-R_1 - \frac{1}{A}(R_1+R_2)}$，$A_v = -\frac{\frac{R_2}{R_1}}{1+\frac{1}{A}\left(1+\frac{R_2}{R_1}\right)}$

△当$A \to \infty$时，$A_v = -\frac{R_2}{R_1}$，与先前理想运放结论统一. $\frac{1}{A}\left(1+\frac{R_2}{R_1}\right)$：增益误差项

二、有限开环增益A对同相接法放大电路增益的影响



$V_i - V_- = \frac{V_0}{A} \Rightarrow V_- = V_i - \frac{V_0}{A}$

∴ 由 $i_1 = i_2 \Rightarrow \frac{V_i - \frac{V_0}{A}}{R_1} = \frac{V_0 - V_i + \frac{V_0}{A}}{R_2} \Rightarrow \left(R_1 + \frac{R_1}{A} + \frac{R_2}{A}\right)V_0 = (R_1+R_2)V_i$

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

三、有限带宽对放大电路增益的影响 (现在好像看不懂，略)

[直流误差]

一、失调电压 (略)

二、偏置电流

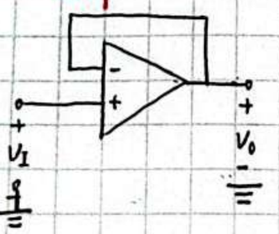
三、输入偏置电阻

[运放大信号分析]

一、输出饱和

· 输出电压受 V_{om}, $-V_{om}$ 限制，无法无限制增大，造成输出饱和

二、摆率

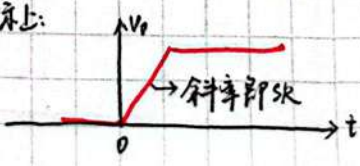


如图为电压跟随器

理论上：

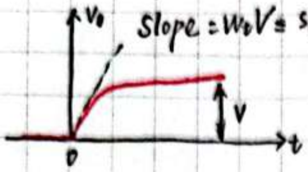
输入阶跃.
输出阶跃

实际上：



$SR = \left.\frac{dV_0}{dt}\right|_{max}$，即摆率

小信号情况:



斜率 ≤ 摆率，不失真（否则就是阶梯信号）

频率 × 幅度 → 摆率. 频率↗, 幅度↘; 频率↘, 幅度↗

三. 满功率带宽

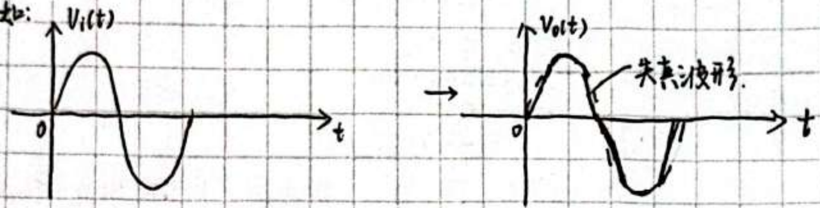
- 定义: 运放输出最大峰值电压时允许的最大频率

若 $V_o(t) = V_{omax} \sin wt$

则 $\left.\dfrac{dV_o}{dt}\right|_{max} = \left.\dfrac{d(V_{omax}\sin wt)}{dt}\right|_{max} = \left. w V_{omax} \cos wt\right|_{t=0,\pi} = \pm w V_{omax}$

∴ 当 $|w \cdot V_{omax}| \le SR$ 时, 输出波形不失真, 否则失真

例如:



∴ 由输出不失真条件 $|w \cdot V_{omax}| \le SR$ 可得该放大器的满功率带宽

$$W = \frac{SR}{V_{omax}} \qquad f_M = \frac{W}{2\pi} = \frac{SR}{2\pi V_{omax}} \qquad \Rightarrow V_{omax} \cdot f_M = V_o \cdot f$$

∴ 减小放大信号幅度可增加放大器不失真带宽

[运放习题网站]

[知识点1]

Ex.1. $R_i \to \infty$ $R_o \to 0$ A.B ✓

C ✓. $V_i \to \infty$. $V_o = V_{om}$

D. $A_v = \frac{V_o}{V_i}$ 闭环一般可计算(?) X

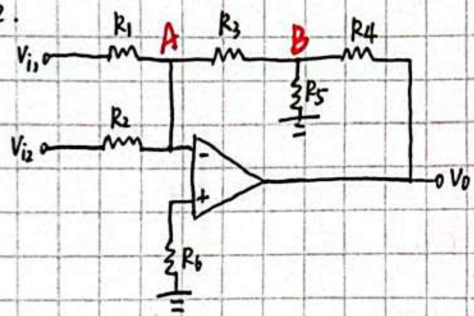
Ex.2. 虚短: $V_+ = V_-$ A ✓

虚断: $i_1 = i_2$ B ✓

[知识点2]

Ex.1. D

Ex.2.



$\boxed{R_f = (R_3 // R_5) + R_4}$ X

反相加法:

$$V_0 = -\left(\frac{R_f}{R_1} V_{i1} + \frac{R_f}{R_2} V_{i2}\right)$$

$$= -\boxed{(R_3 // R_5 + R_4)} \cdot \left(\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2}\right) \text{ X}$$

根据虚短虚断求:

对节点A、B列基尔霍夫:

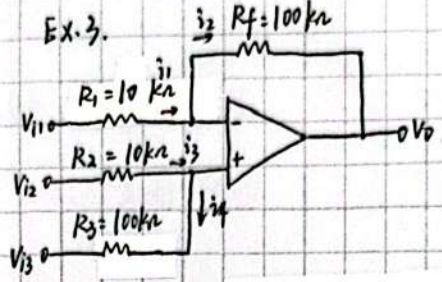
$$\begin{cases} \frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2} = -\frac{V_B}{R_3} \\ \frac{V_B}{R_3} + \frac{V_B}{R_5} = \frac{V_0 - V_B}{R_4} \end{cases}$$

$$\therefore V_0 = \left(\frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5}\right) \cdot (-R_3) \cdot \left(\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2}\right) \cdot R_4.$$

$$= -\left(R_3 + R_4 + \frac{R_3 R_4}{R_5}\right) \cdot \left(\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2}\right)$$

△为什么不能并联? 关键在 $\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2} = -\frac{V_B}{R_3}$. 未包含 $\frac{V_B}{R_5}$, 本质上不通!

Ex.3.



利用 $V_+ = V_-$:

$$V_- = V_0 + \frac{10}{11}(V_{i1} - V_0) = \frac{10}{11} V_{i1} + \frac{1}{11} V_0$$

$$V_+ = \frac{10}{11} V_{i2} + \frac{1}{11} V_{i3}$$

$$\Rightarrow 10V_{i1} + V_0 = 10V_{i2} + V_{i3}$$

$$\therefore V_0 = -10V_{i1} + 10V_{i2} + V_{i3}$$

Ex.4. A

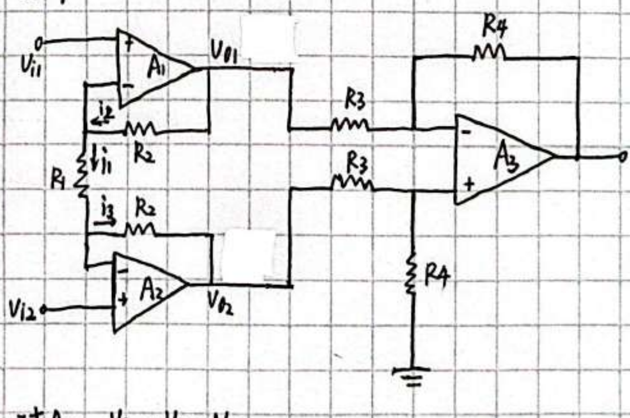
Ex.5. C

Ex.6. $V_0 = V_+$ 由虚断, 在+处用基尔霍夫:

$$\frac{V_1 - V_+}{R_1} + \frac{V_2 - V_+}{R_2} + \frac{V_3 - V_+}{R_3} = 0$$

$$\therefore V_0 = V_+ = \frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Ex.7.



对 A_1: $V_{i1} = V_+ = V_-$

$V_{i2} = V_+ = V_-$

$$\therefore \frac{V_{01} - V_{i1}}{R_2} = \frac{V_{i1} - V_{i2}}{R_1} = \frac{V_{i2} - V_{02}}{R_2}$$

$$\therefore V_{01} = R_2 \cdot \left[\left(\frac{1}{R_1} + \frac{1}{R_2}\right) V_{i1} - \frac{1}{R_1} \cdot V_{i2}\right]$$

$$= \left(1 + \frac{R_2}{R_1}\right) V_{i1} - \frac{R_2}{R_1} V_{i2}$$

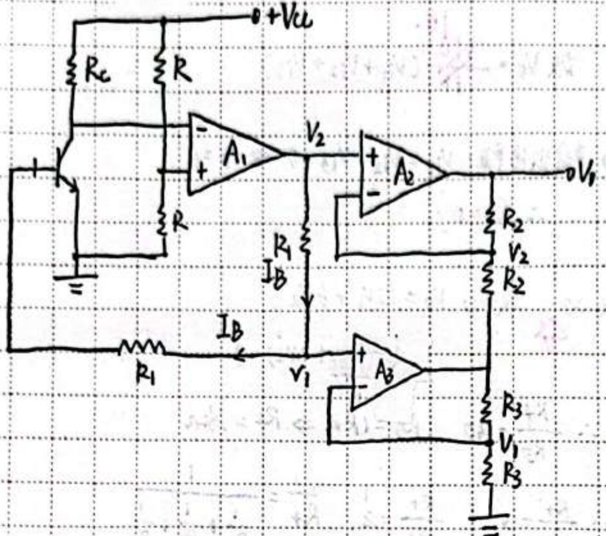
$$V_{02} = R_2 \left[\left(\frac{1}{R_2} + \frac{1}{R_1}\right) V_{i2} - \frac{1}{R_1} \cdot V_{i1}\right]$$

$$= \left(1 + \frac{R_2}{R_1}\right) V_{i2} - \frac{R_2}{R_1} V_{i1}$$

又∵第二级差分放大

$\therefore V_0 = \frac{R_4}{R_3}(V_{02}-V_{01}) = \frac{R_4}{R_3}\cdot(1+2\cdot\frac{R_2}{R_1})(V_{i2}-V_{i1})$

Ex.8. ☆ bjt+运放!!!



解. $V_+ = V_- = \frac{1}{2}V_{cc}$

$\therefore I_c = \frac{V_{cc}}{2R_c}$

$V_1 = I_B R_1 + V_B$ $V_2 = 2I_B R_1 + V_B$

对于A_2:

$V_2 + IR_2 = V_0$

$V_1 = IR_3$

$V_1 + I(R_2+R_3) = V_2 \Rightarrow V_2 = 2IR_3 + IR_2$

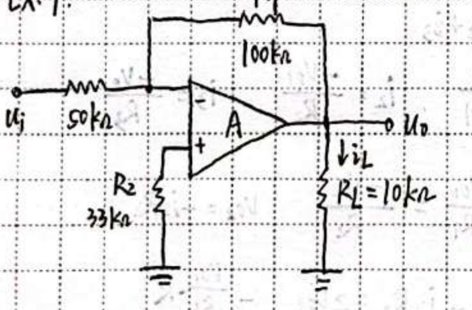
$V_0 = 2IR_3 + 2IR_2$

$\Rightarrow V_0 = 2(V_2 - 2V_1) + 2V_1$

$= 2(V_2 - V_1)$

$= 2I_B R_1 = \frac{V_{cc}R_1}{\beta R_c}$

Ex.9.



$u_i = 0.5V$

$u_0 = ?$

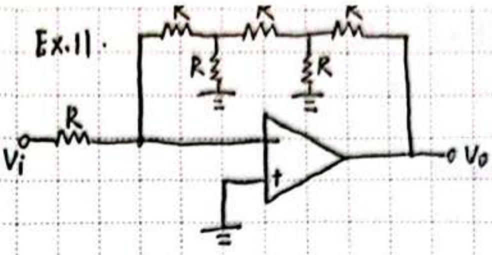
$i_L = ?$

$\frac{u_0}{100} = \frac{0-u_i}{50} \Rightarrow u_0 = -2u_i$

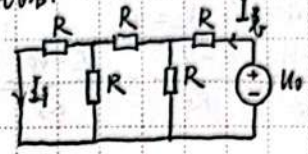
$\therefore u_0 = -1.0V$ $i_L = -0.1mA$

Ex.10. 10倍. 20dB

Ex.11.



解: 反馈电路



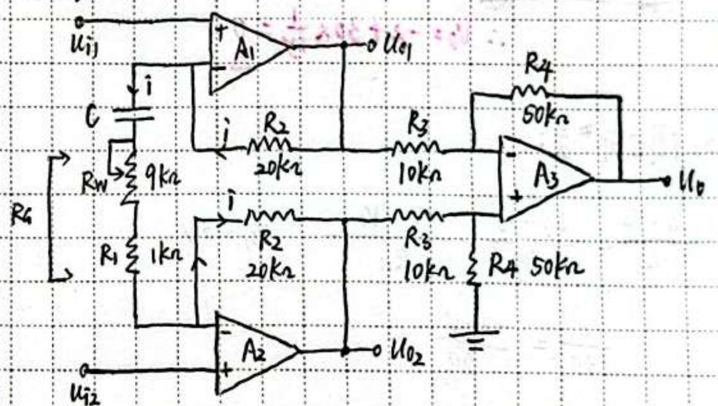
$I_f = \frac{u_0}{(\frac{3}{2}R//R)+R} = \frac{5u_0}{8R}$

$I_i = \frac{1}{8}\cdot\frac{u_0}{R}$

$\therefore -V_i = \frac{1}{8}V_0$ $\frac{V_0}{V_i} = -8$

Ex.12. 20kΩ 80kΩ

Ex.13 ☆



(1) $A_u = \frac{u_0}{u_{i2}-u_{i1}}$ 的表达式

$A_u = \frac{u_0}{u_{02}-u_{01}}\cdot\frac{u_{02}-u_{01}}{u_{i2}-u_{i1}}$

仪表放大+差分放大

虚短: $V_1 = V_{1+} = V_{1-}$ $V_2 = V_{2+} = V_{2-}$

虚断: $V_{01} - iR_2 = V_1$

$V_{02} + iR_2 = V_2$

$i = \frac{V_1 - V_2}{R_G}$

后差分放大, $u_0 = \frac{R_4}{R_3}(u_{02}-u_{01})$

$= \frac{R_4}{R_3}(V_2 - V_1 - 2iR_2)$

$= \frac{R_4}{R_3}\cdot(1+2\frac{R_2}{R_G})\cdot(V_2-V_1)$

$\therefore A_u = \frac{R_4}{R_3}\cdot(1+\frac{R_2}{R_G})$. 其中$R_G = R_1 + R_W$

(2) $1k\Omega \le R_a \le 10k\Omega$ $R_2 = 20k\Omega$

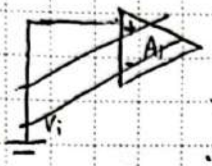
$A_u = 5(1+\frac{2R_2}{R_a})$

$\therefore 25\ \cancel{15} \le A_u \le \cancel{105}\ 205$

Ex.14. A

Ex.15. (1) $V_1 = V_i = 1V$, $V_2 = 0$

$\frac{V_{o1}-V_1}{R_3} = \frac{V_1-V_2}{R_4} = \frac{V_2-V_{o2}}{R_5}$



$\because R_3 = R_4 = R_5 = 10k\Omega$

$\therefore V_{o2} = -1V$, $V_{o1} = 2V$

$\frac{V_{o1}-V_4}{R_8} = \frac{V_4-V_{o4}}{R_{12}}$ 可简化为仅含上半部分的运放

$\cancel{\frac{V_4}{R_6} = \frac{0-V_3}{R_7}}$ $V_{o4} = -1.5V_{o1} = -3V$

$\cancel{\therefore V_o = 6V}$ 看清. $V_5 = -2V$

$\cancel{\frac{V_3-V_{o2}}{R_1} = \frac{V_{o3}-V_3}{R_2}}$ $\therefore i_9 = \frac{-1}{15}$

$\therefore V_o = -2 + 30\times\frac{1}{15} = 0.$

(2) 闭合开关:

$\frac{V_{o1}-V_4}{R_8} = \frac{V_4-V_5}{R_9} = \frac{V_5-V_o}{R_{11}}$ $V_{o1} = 2V$

$\therefore \frac{4}{35} = \frac{-2-V_o}{30}$

Ex.17. 差分放大, $V_o = 8(V_{i2}-V_{i1})$ C.

Ex.18. ① 设 $V_i = 1V$

$i_1 = 1mA \Rightarrow R_{in} = 1k\Omega$

② $\frac{V_o-V_i}{R_2} = \frac{V_i}{R_1}$ $R_2 = 5R_1 \Rightarrow 5V_i = V_o - V_i$

$\therefore V_o = 6V$ $\therefore \frac{5V}{5k\Omega} = 1mA \Rightarrow R_{in} = \cancel{1}k\Omega$

电源侧虚断无电流就是无穷大

Ex.19.

$V_+ = V_{i1} - i_1R_1 = V_{i2} - i_2R_1 = V_{i3} - i_3R_1$

$i = i_1 + i_2 + i_3$

$V_+ = iR_2$

$\Rightarrow V_+ = (V_{i1}+V_{i2}+V_{i3})\cdot\frac{R_2}{R_1+3R_2} = \frac{10}{\cancel{11}\ 31}(V_{i1}+V_{i2}+V_{i3})$

又: $\frac{V_o-V_+}{R_2} = \frac{V_+}{R_3}$

$R_2 = 330k\Omega$, $R_3 = 11k\Omega$ $\therefore \frac{R_2}{R_3} = 30$

$\therefore \frac{V_o-V_+}{V_+} = 30$ $V_o = 31V_+$

故 $V_o = \frac{\cancel{310}\ 10}{\cancel{11}}(V_{i1}+V_{i2}+V_{i3})$

(2) 输出电阻: $V_{i1} = V_{i2} = V_{i3} = 0 \Rightarrow V_o = 0$

$\therefore R_o = 0$.

Ex.20. 实现 $V_o = 15V_1 + 6V_2$

$= 30(\frac{1}{2}V_1 + \frac{1}{5}V_2)$

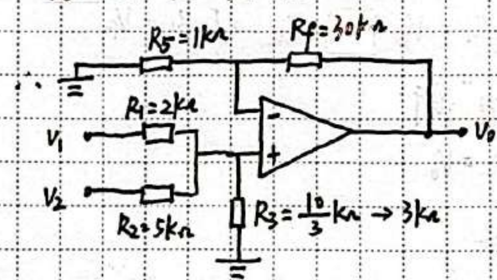
$\therefore \frac{R_f}{R_5} = 30$ $R_5 = 1k\Omega \Rightarrow R_f = 30k\Omega$

$\therefore \frac{R_+}{R_1} = \frac{1}{2}$ $\frac{R_+}{R_2} = \frac{1}{5}$ $R_+ = \frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}}$

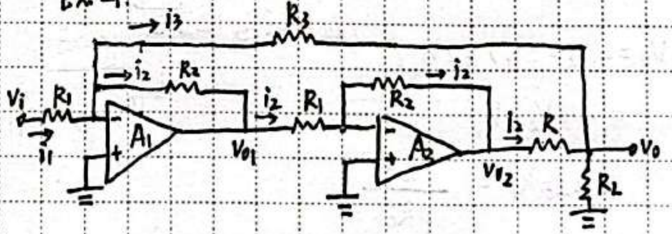
令 $R_1 = 2k\Omega$ $R_2 = 5k\Omega \Rightarrow R_+ = 1k\Omega$

$\Rightarrow \frac{1}{R_3} = \frac{1}{R_+} - \frac{1}{R_1} - \frac{1}{R_2} = \frac{3}{10} \Rightarrow R_3 = \frac{10}{3}k\Omega$

∴



Ex.21.



A_1: $V_+ = V_- = 0$

$i_1 = i_2 + i_3$

$i_1 = \frac{V_i}{R_1}$ $i_2 = \frac{-V_{o1}}{R_2}$ $i_3 = \frac{-V_o}{R_3}$

A_2: $i_2 = \frac{V_{o1}}{R_1} = \frac{-V_{o2}}{R_2}$ $V_{o2} = -i_2R_2$

$V_o = V_{o2} - i_2R = -\frac{R_1}{R_2}V_{o1} - \frac{V_{o1}}{R_1}\cdot R$

$\frac{V_i}{R_1} = \frac{-V_{o1}}{R_2} + \frac{V_{o1} + \frac{V_{o1}}{R_1}\cdot R}{R_3}$

$V_{o1} = \frac{V_i}{R_1} \Big/ (\frac{1+\frac{R}{R_1}}{R_3} - \frac{1}{R_2}) = \frac{V_i}{(\frac{R_1+R}{R_3}-1)}$

$\therefore V_o = (1+\frac{R}{R_1})\frac{V_i}{(1-\frac{R_1+R}{R_3})}$

$$i_L = \left(1+\frac{R}{R_1}\right)\cdot\frac{V_i}{\left(1-\frac{R_1+R}{R_3}\right)R_L}$$

要使 $i_L = \frac{V_i}{R}$

$$\therefore \left(1+\frac{R}{R_1}\right)\cdot\frac{1}{\left(1-\frac{R_1+R}{R_3}\right)R_L} = \frac{1}{R}$$

$$\frac{R_1+R}{R_1}\cdot\frac{R_3}{R_3-R_1-R}\cdot\frac{1}{R_L} = \frac{1}{R}$$

[感觉纯算术sos，解不出，放弃]