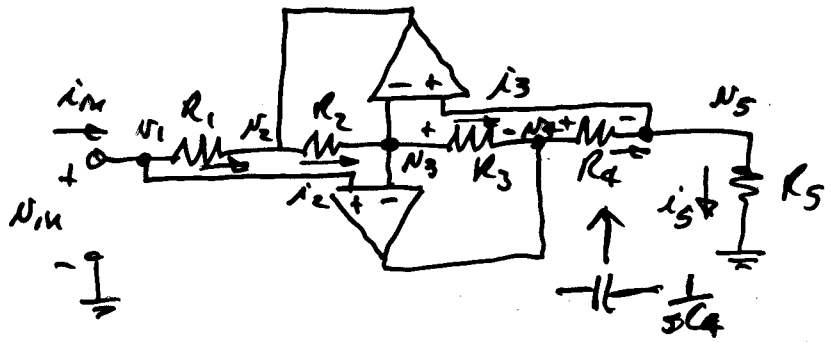
Find R_{in} of the op amp ckt. (Op amps are ideal)



Ideal op amp: $v_1 = v_3 = v_5$, $i_2 = i_3$, $i_{in} = i_1$, $i_4 = i_5$

$$\frac{v_{in}}{i_{in}} = \frac{v_1}{i_1} = ? = \frac{v_3}{i_1} = \frac{v_5}{i_1}$$

$$i_4 = i_5$$

$$i_3 R_3 + i_4 R_4 = 0 \rightarrow i_3 = -\frac{R_4}{R_3} i_4 = -\frac{R_4}{R_3} i_5$$

$$i_2 = i_3 = -\frac{R_4}{R_3} i_5$$

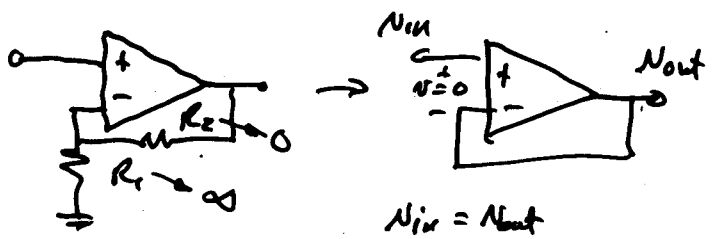
$$i_1 R_1 + i_2 R_2 = 0 \rightarrow i_1 = -\frac{R_2}{R_1} i_2 = \left(-\frac{R_2}{R_1}\right)\left(-\frac{R_4}{R_3}\right) i_5$$

$$\therefore \quad \frac{v_{in}}{i_{in}} = \frac{v_5}{i_1} = \frac{v_5}{\frac{R_2 R_4}{R_1 R_3} i_5} = \frac{R_1 R_3}{R_2 R_4} \frac{v_5}{i_5} = \frac{R_1 R_3 R_5}{R_2 R_4}$$

$$Z_{in} = \frac{R_1 R_3 R_5}{R_2} sC_4 = sL_{eq.}$$

Some Op Amp Ckts.

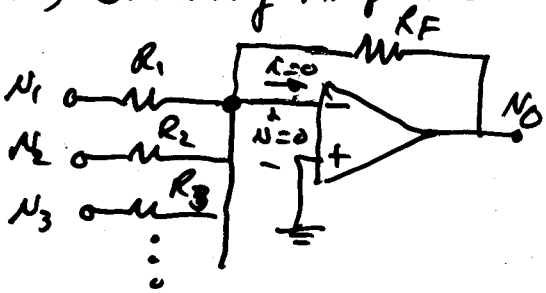
1.) Voltage buffer



$v_{in} = v_{out}$

$$\frac{v_{out}}{v_{in}} = 1$$

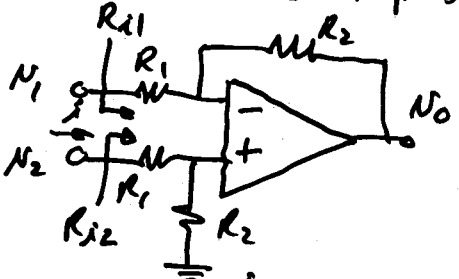
2.) Summing Amplifier



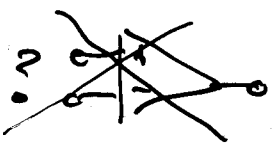
$$v_o = -\frac{R_F}{R_1}v_1 - \frac{R_F}{R_2}v_2 - \frac{R_F}{R_3}v_3 - \cdots$$

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

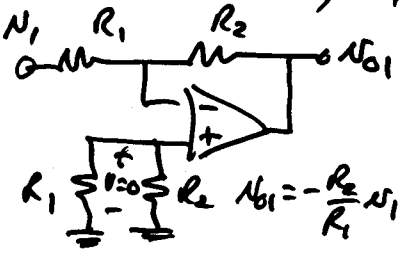
3.) Difference Amplifier



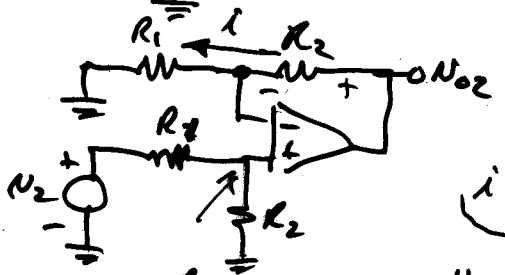
?



$v_o = f(v_1, v_2) = ?$



$$v_{o1} = -\frac{R_2}{R_1}v_1$$



$$\frac{v_2 R_2}{R_1+R_2}$$

$$i = \left(\frac{v_2 R_2}{R_1+R_2}\right)\frac{1}{R_1}$$

$$v_{o2} = \frac{v_2 R_2}{R_1+R_2} + iR_2 = \frac{v_2 R_2}{R_1+R_2} + \frac{R_2}{R_1}\left(\frac{R_2}{R_1+R_2}v_2\right)$$

$$v_{o2} = \frac{v_2 R_2}{R_1+R_2}\left[1 + \frac{R_2}{R_1}\right] = \left(\frac{R_2}{\cancel{R_1+R_2}}\right)\left(\frac{\cancel{R_1+R_2}}{R_1}\right)v_2$$

$$v_{o2} = \frac{R_2}{R_1}v_2$$

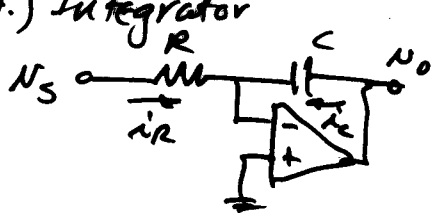
$\therefore v_o = v_{o1} + v_{o2}$

$$\boxed{v_o = \frac{R_2}{R_1}(v_2 - v_1)}$$

$$R_{i1} = \left.\frac{v_1}{i_1}\right|_{v_2=0} = ? \qquad i_1 = \frac{v_1 - 0}{R_1} \rightarrow \underline{\underline{R_{i1} = R_1}}$$

$$R_{i2} = \left.\frac{v_2}{i}\right|_{v_1=0} = \underline{\underline{R_1+R_2}}$$

4.) Integrator



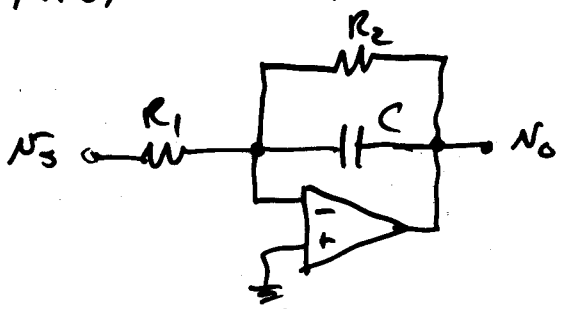
$$\left.\begin{aligned} i_R &= \frac{v_s}{R} \\ i_c &= C\frac{dv_o}{dt} \end{aligned}\right\} i_R + i_c = 0$$

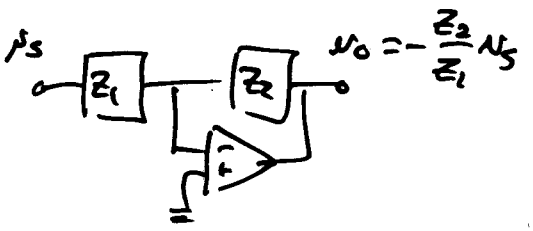
$$\frac{v_s}{R} = -C\frac{dv_o}{dt}$$

$$\frac{dv_o}{dt} = -\frac{1}{RC}v_s$$

$$v_o = -\frac{1}{RC}\int v_s\,dt$$

5.) First-order lowpass circuit





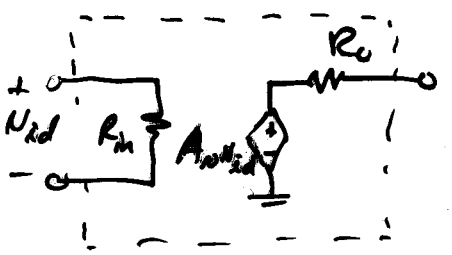
$$Z_2 = \frac{R_2 \frac{1}{sC}}{R_2 + \frac{1}{sC}} = \frac{R_2}{sR_2C+1} \longrightarrow \frac{v_o}{v_s} = -\frac{R_2}{R_1}\left(\frac{1}{sR_2C+1}\right)$$

Let $\omega_H = \frac{1}{R_2C}$ & $A_o = \frac{R_2}{R_1}$

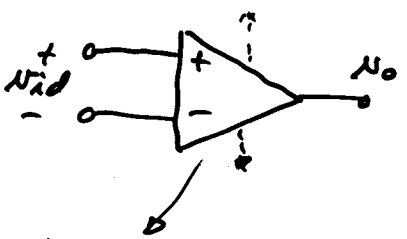
$$\frac{V_o(s)}{V_s(s)} = A_v(s) = \frac{-A_o}{\left(\frac{s}{\omega_H}+1\right)}$$

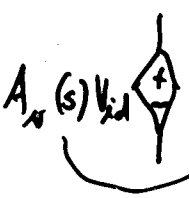
Non-ideal op amp

1.) $A_v \neq \infty$
2.) $BW \neq \infty$
3.) $R_{in} \neq \infty$ and $R_o \neq 0$



<u>Single-pole model of an op amp</u>

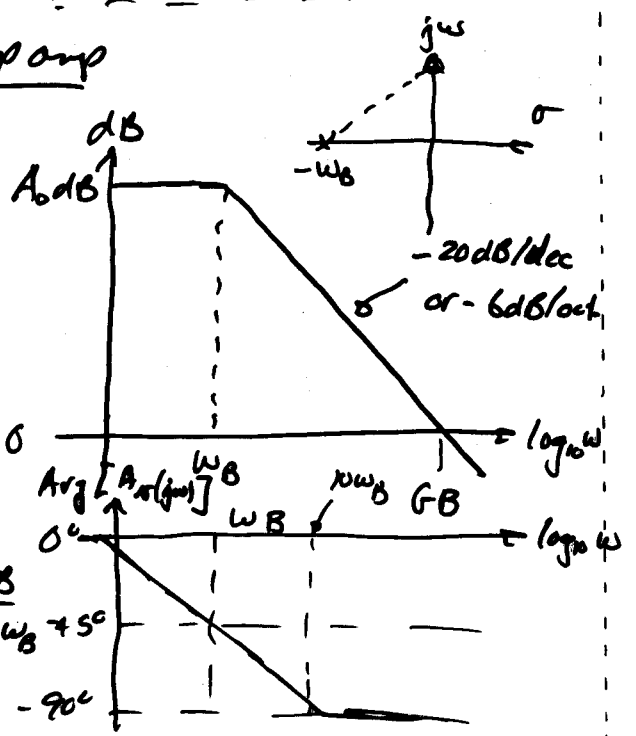




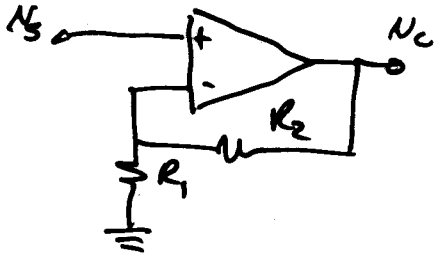
$$A_v(s) = \frac{A_o \omega_B}{s+\omega_B}$$

$$= \frac{A_o}{\frac{s}{\omega_B}+1} = \frac{\omega_T}{s+\omega_B} = \frac{GB}{s+\omega_B}$$

$\omega_T = GB$ = unity-gain frequency



Frequency Response of the Noninverting Amplifier



If $A_v(s) = \frac{GB}{s + \omega_B}$, what is $\frac{V_o(j\omega)}{V_s(j\omega)}$?