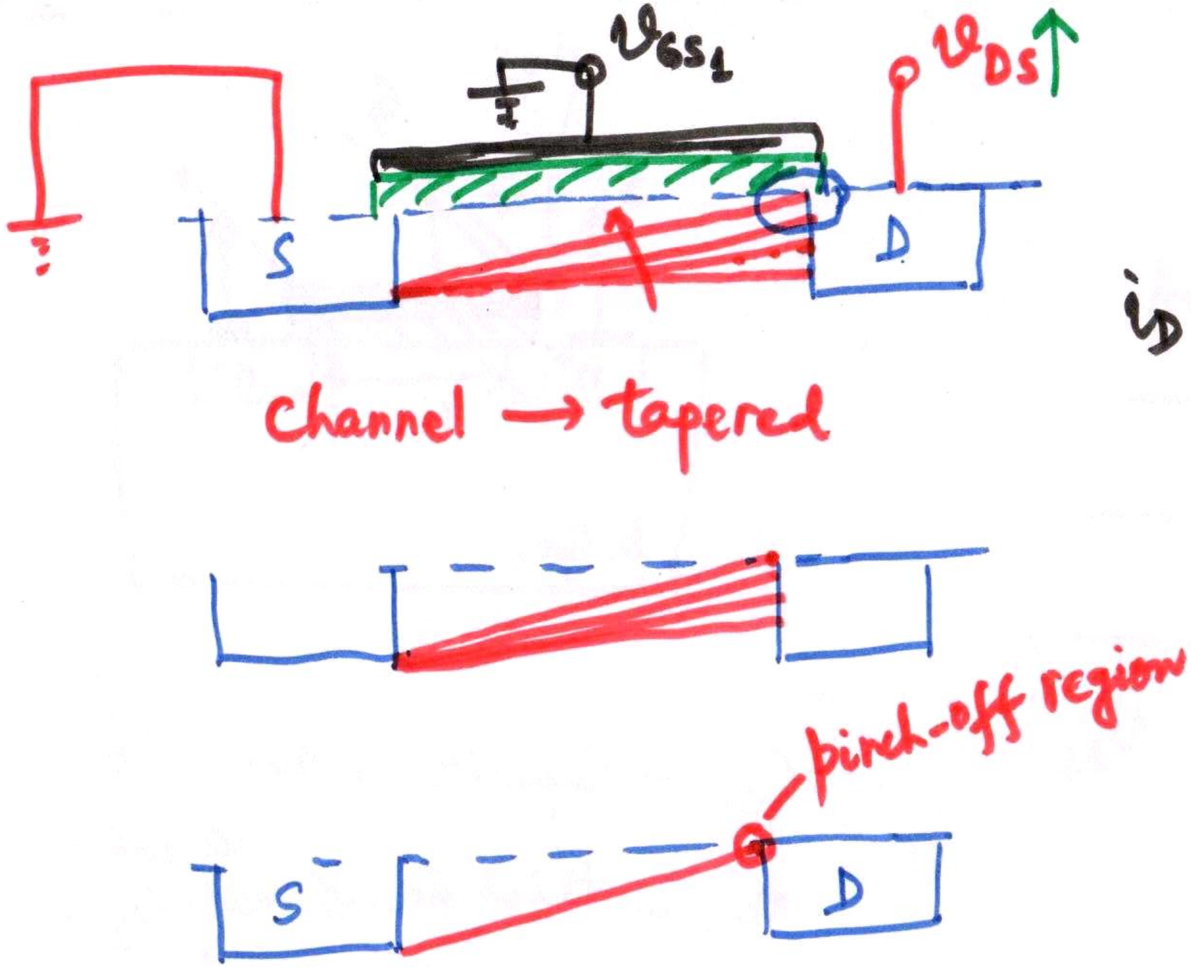
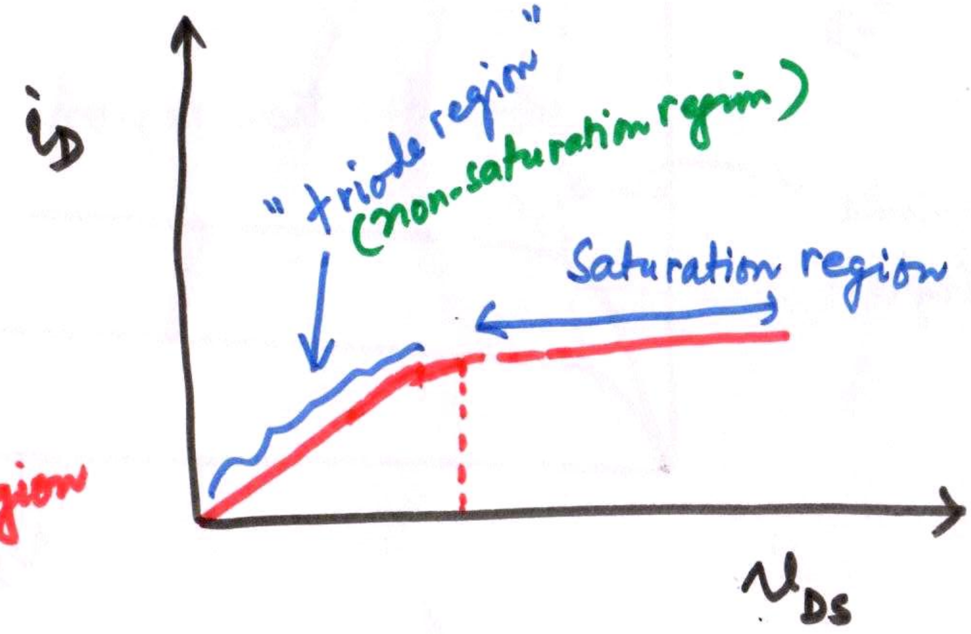
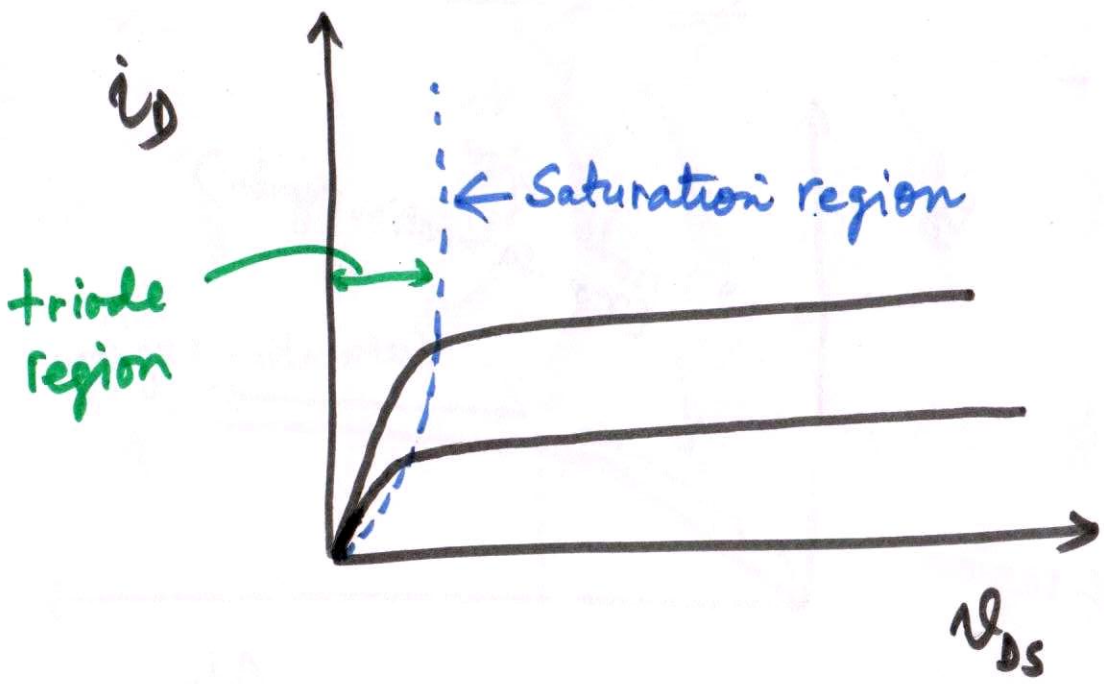
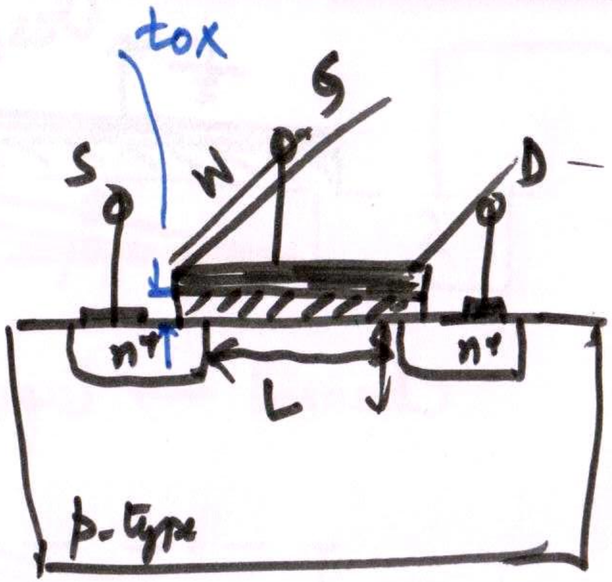


$v_{GS} - v_{DS} \uparrow$



Drain current becomes independent of Drain voltage





C_{ox} - Capacitance per unit area

t_{ox} - thickness of oxide layer

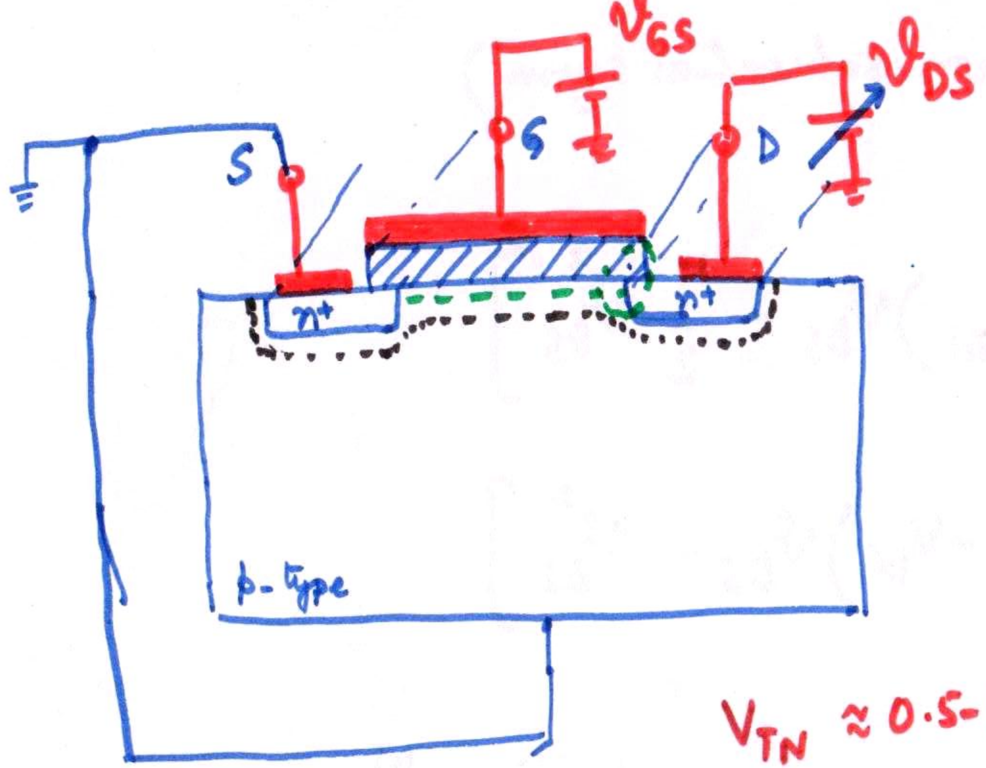
~ 50nm

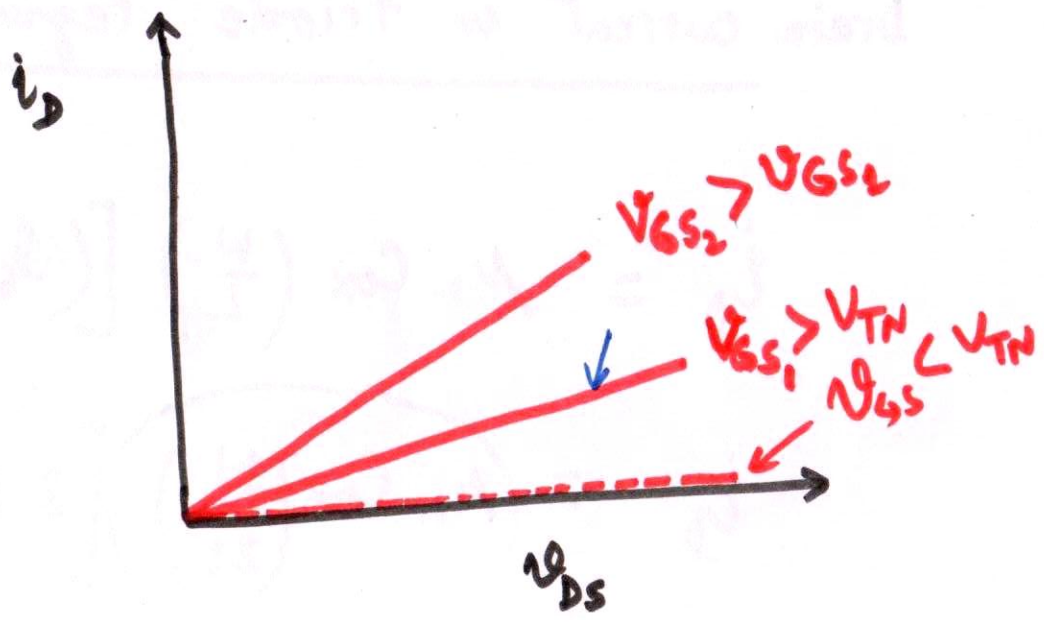
(SiO_2 layer)

$$\epsilon_{ox} = \epsilon \cdot \epsilon_0 = 3.9\epsilon_0$$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$

$$C_{ox} = \frac{3.9\epsilon_0}{t_{ox}} \approx 6.9 \times 10^{-4}\ F/m^2$$



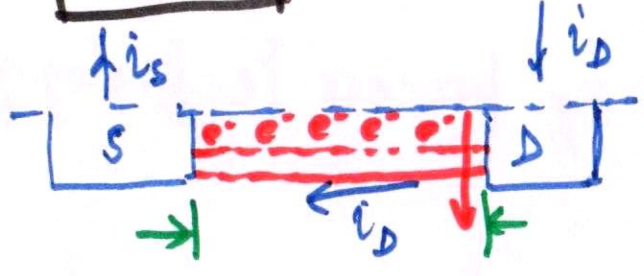


$V_{TN} \approx 0.5 - 1V$

$v_{GS} = V_{TN}$ (Inversion layer is introduced)

$v_{DS} \sim mV$

NMOS



$i_S = i_D$

Conductance of Channel $\propto$ excess voltage $(v_{GS} - V_{TN})$

$\boxed{\text{overdrive voltage}}$

or effective voltage

$i_D \propto (v_{GS} - V_{TN})$, also depend on v_{DS}

Drain current in triode region (non-saturation region)

$$i_D = \mu_n C_{ox} \left(\frac{W}{L}\right) \left[(v_{GS} - v_{TN}) v_{DS} - \frac{1}{2} v_{DS}^2 \right]$$

$$i_D = \mu_n C_{ox} \left(\frac{W}{2L}\right) \left[2 (v_{GS} - V_{TN}) v_{DS} - v_{DS}^2 \right]$$

Conduction parameter $K_n = \mu_n C_{ox} \frac{W}{2L}$

$\mu_n C_{ox}$: Constant $\Rightarrow$ determined by process technology

process transconductance parameter

$k_n' = \mu_n C_{ox}$; $K_n = k_n' \left(\frac{W}{2L}\right)$

In Saturation region

$$v_{DS} = v_{GS} - V_{TN}$$

$$i_D = K_n\left[2(v_{GS} - V_{TN})^2 - (v_{GS} - V_{TN})^2\right]$$

$$\boxed{i_D = K_n(v_{GS} - V_{TN})^2}$$

$\boxed{\underline{\text{Saturation}}}$

1

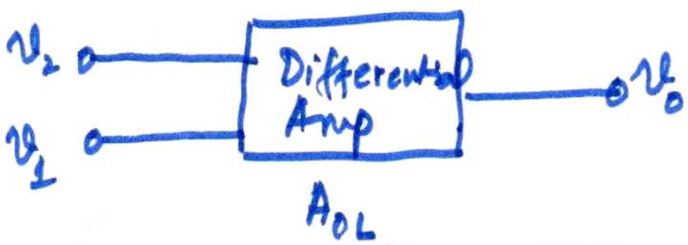
27/3/19

BJT, FET → Integrated ckt

Operational Amplifier (OP-AMP) – uses more than one transistor

IC 741

- First building block – Differential Amplifier (most widely used block)



open-loop gain

v_o depends on the difference between input signals.

Ideal Output voltage, $v_o = A_{OL}(v_1 - v_2)$

Case 1 : If $v_1 = v_2$, $v_o = 0$

Case 2 : $v_1 = -v_2$, ______ .

differential mode input voltage

$$v_d = v_1 - v_2 \; ;$$

common-mode input voltage

$$v_{cm} = \frac{v_1 + v_2}{2}$$

$v_1 = v_2$

$v_d = 0$, $v_{cm} = v_1 = v_2$

$v_1 = -v_2$

$v_d = 2v_1$, $v_{cm} = 0$

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$$\boxed{v_o = A_d v_d + A_{cm} v_{cm}}$$

differential gain

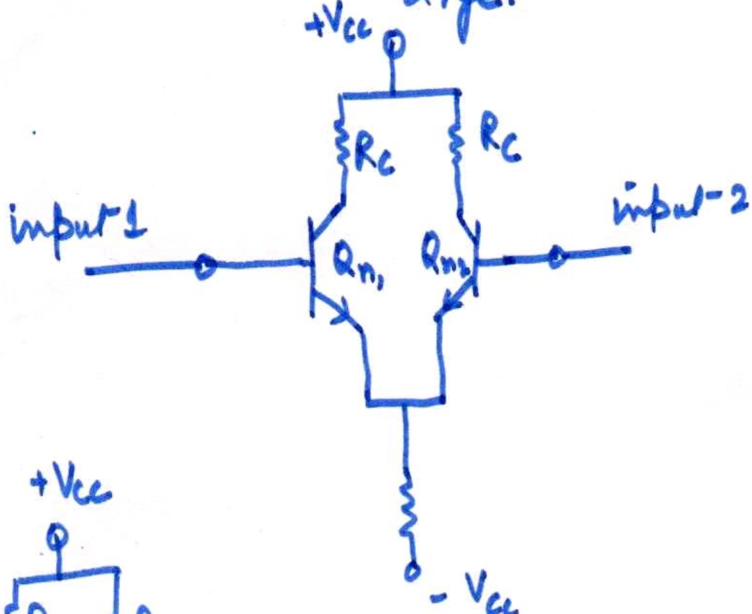
common-mode gain

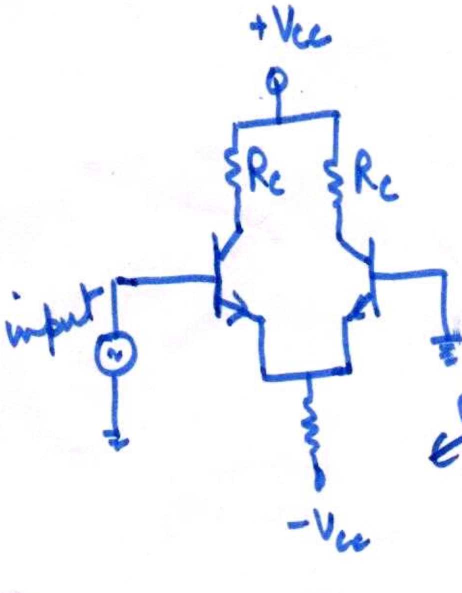
CMRR (Common Mode Rejection Ratio)

$$\text{CMRR} = \frac{A_d}{A_{cm}}$$

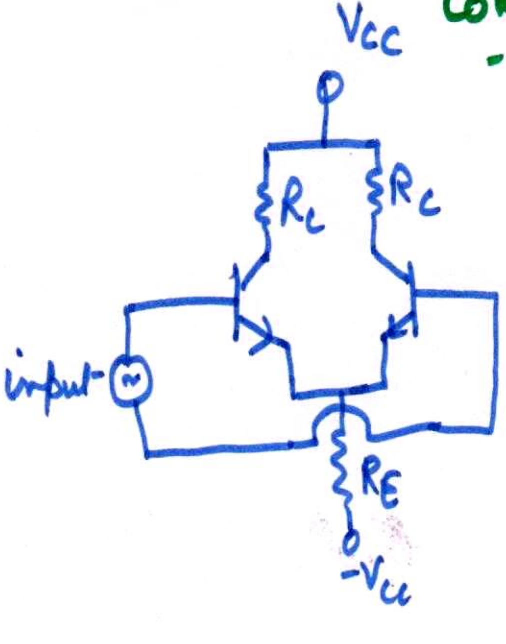
$$\text{CMRR (dB)} = 20 \log_{10} \left(\frac{A_d}{A_{cm}} \right)$$

$A_d >> A_{cm}$, CMRR of the device (OP-AMP) is very large.





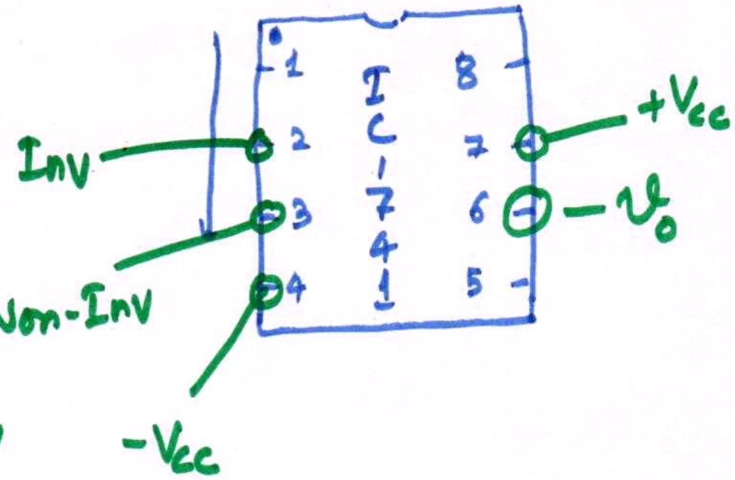
differential



common -mode

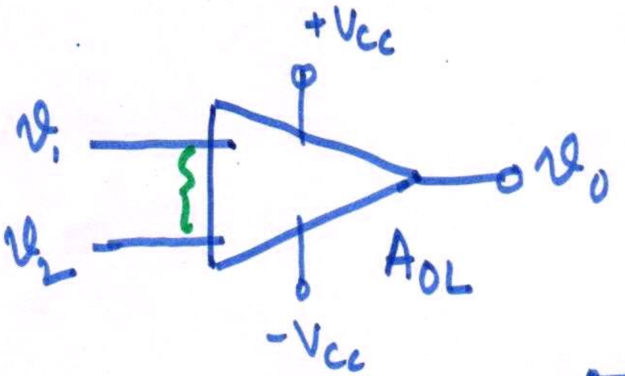
3 Op-amp (IC 741)

- Uses differential amplifier
- Very high gain amplifier
- High Input Impedance (~ MΩ)
- low Output Impedance
- large gain bandwidth

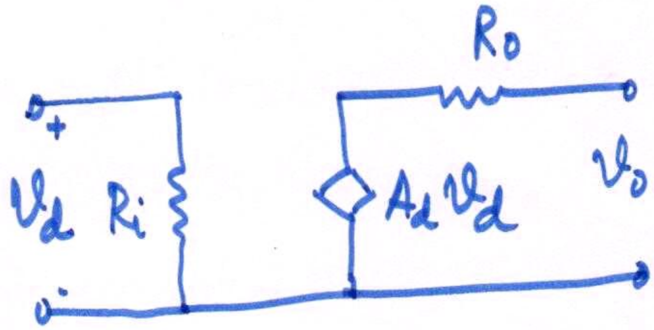


Inverting

Non-inv.

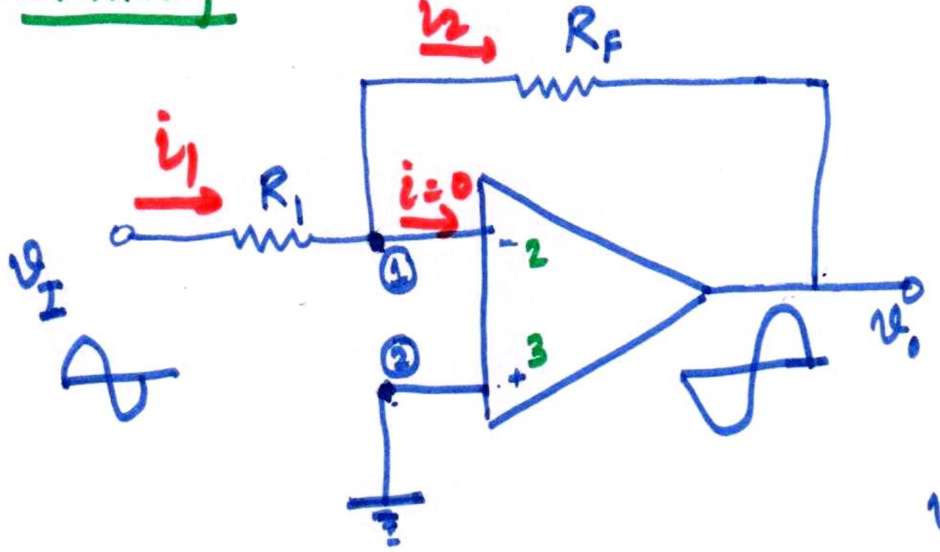


$$v_0 = A_{OL}(v_1 - v_2)$$



Inverting

① 1/4/19



Op-amp : ideal
(open loop gain is infinite

$$v_o = A_{OL}(v_2 - v_1)$$

$$v_1 \rightarrow v_2$$

potential at ① $\xrightarrow[\text{as}]{\text{same}}$ ②
(voltage)

"virtual ground concept"

② → at ground, $v_2 = 0$, $v_1 = 0$

$$i_1 = \frac{v_I - v_1}{R_1} = \frac{v_I}{R_1}$$

$\cancel{i_1}$ $i_2 = i_1$,

$$v_o = v_1 - i_2 R_F ,$$

$$v_o = -\frac{v_I}{R_1} R_F \Rightarrow \boxed{\frac{v_o}{v_I} = -\frac{R_F}{R_1}}$$

$$\text{Gain, } \frac{v_o}{v_I} = -\frac{R_F}{R_1}$$

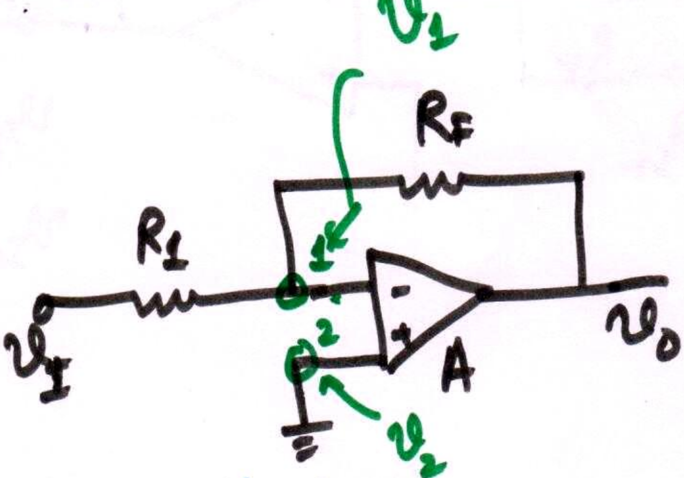
Closed loop gain

Assume that op-amp has finite gain A

$$v_o = A(v_2 - v_1)$$

$$v_o = A(-v_1)$$

$$\Rightarrow v_1 = -v_o/A$$



$$i_1 = \frac{v_I - v_1}{R_1} = \frac{v_I - (-v_o/A)}{R_1}$$

$$i_2 = i_1, \quad v_o = v_1 - i_2 R_F$$

$$v_o = \left(\frac{-v_o}{A}\right) - \left(\frac{v_I + v_o/A}{R_1}\right) \cdot R_F$$

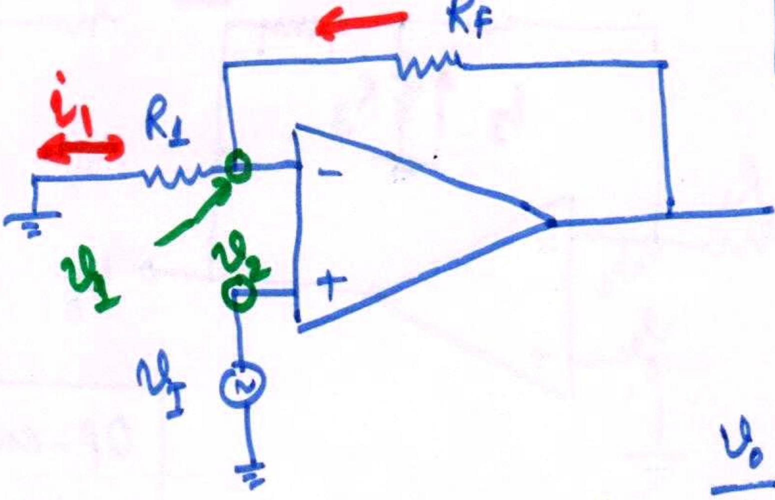
$\vdots$

$$\Rightarrow \boxed{\frac{v_o}{v_I} = \frac{-(R_F/R_1)}{\left[1 + \frac{1}{A}\left(1 + \frac{R_F}{R_1}\right)\right]}}$$

Effect of finite gain!

Non-Inverting ~~termin~~ OP-AMP

Op-amp is ideal

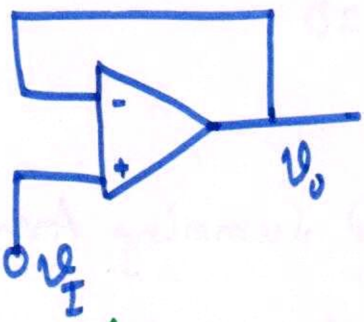


- virtual ground concept

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

From the "virtual ground concept"

$$v_1 = v_2 = v_I$$

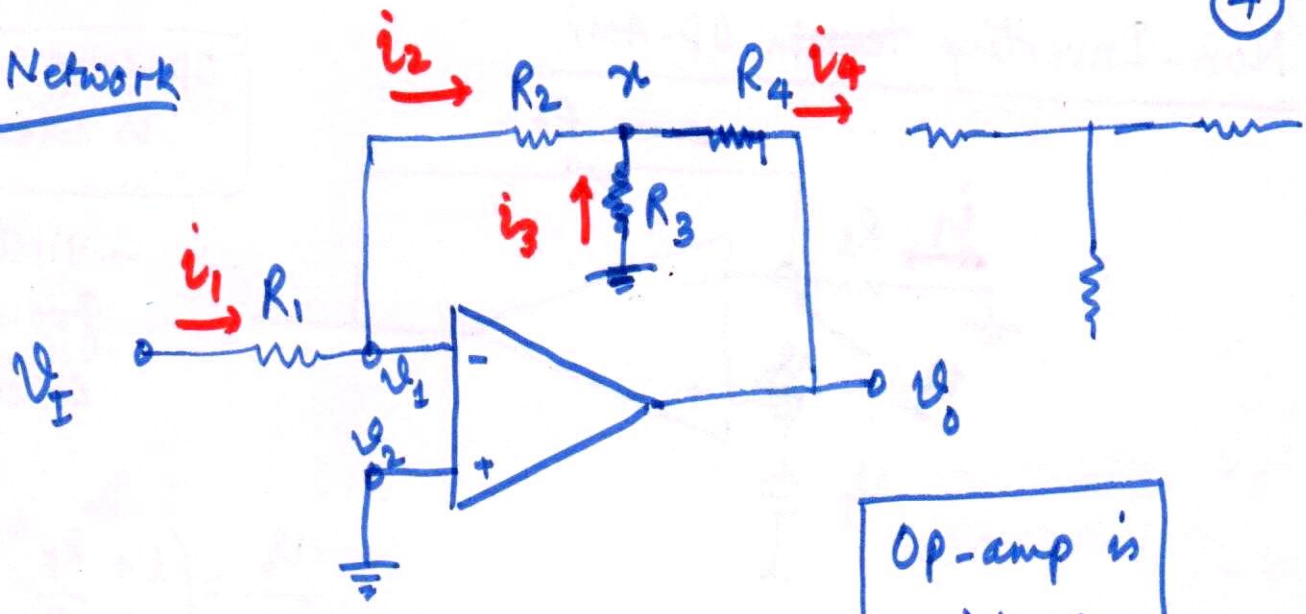


Voltage follower / Unity 'buffer' $\frac{v_o}{v_I} = 1$

$$\boxed{v_o = v_I}$$

HW/Tutorial : Op-amp has finite gain ?

T-Network

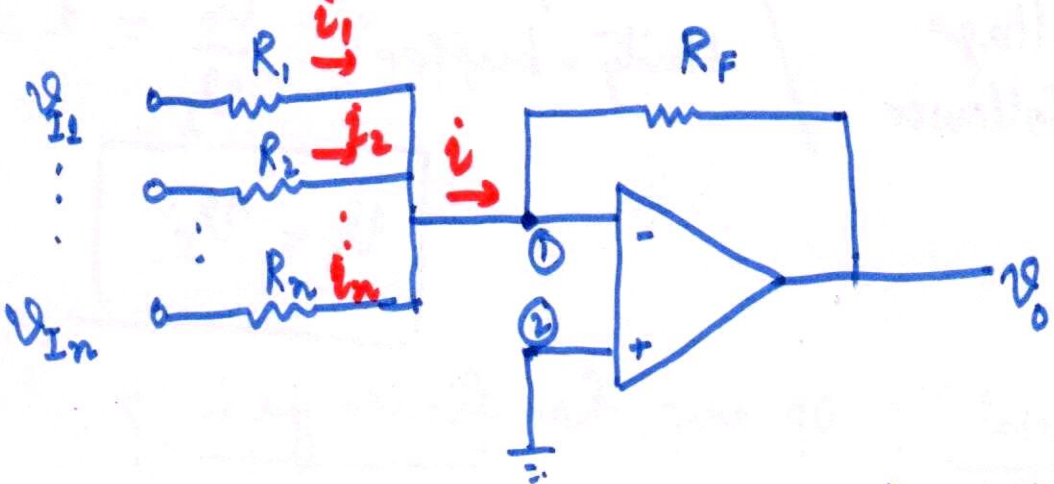


Op-amp is ideal

$v_0 = ?$, $\frac{v_0}{v_I} = ?$

$v_1 = 0, \; v_2 = 0$

Adder (Weighted Summing Amplifier)



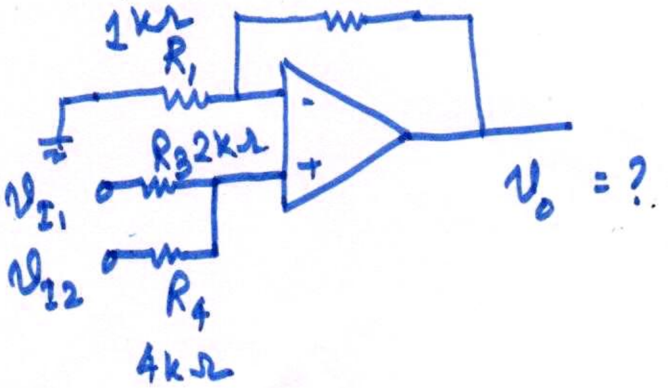
$$i = i_1 + i_2 + \dots + i_n = \frac{v_{I1}}{R_1} + \frac{v_{I2}}{R_2} + \dots \frac{v_{In}}{R_n}$$

$$v_0 = -i R_F$$

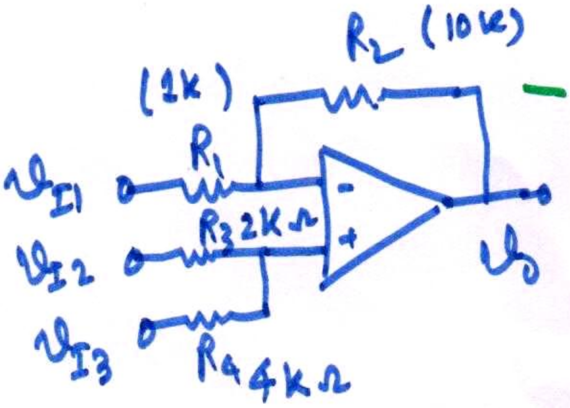
$$v_0 = -R_F \left(\quad \right)$$

Tut/HW ①

3/4/19

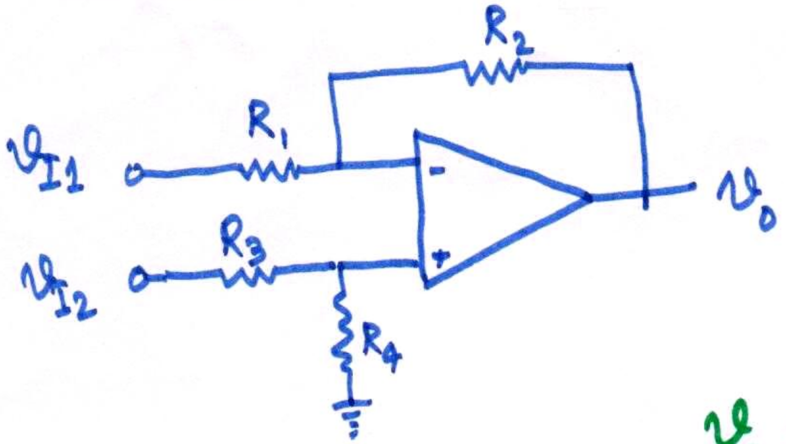


$v_o = ?$



$v_o =$ ______

Difference Amplifier (Substraction)



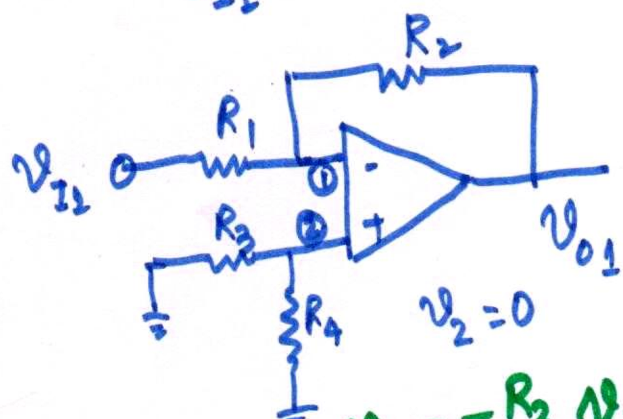
Ideal op.amp
- virtual ground concept
- Superposition principle

$$v_o = v_{01} + v_{02}$$

v_{01} (v_{I2} is grounded) v_{I1}

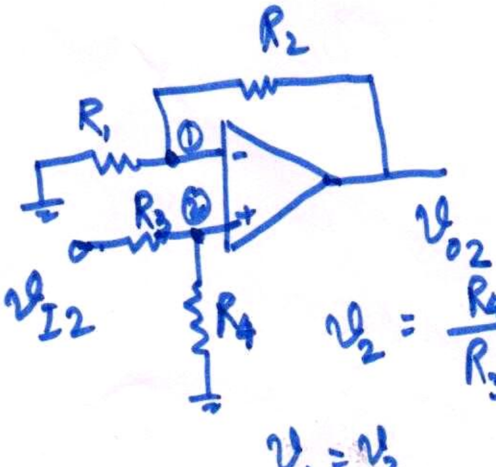
v_{02} (v_{I1} is grounded) v_{I2}

$$v_{02} = \left(1+\frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3+R_4}\right) v_{I2}$$



$v_2 = 0$

$$v_{01} = -\frac{R_2}{R_1} v_{I1}$$



$$v_2 = \frac{R_4}{R_3+R_4} \cdot v_{I2}$$

$v_1 = v_2$

$$v_o = v_{O1} + v_{O2}$$

$$v_o = -\left(\frac{R_2}{R_1}\right) v_{I1} + \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) v_{I2}$$

$\vdots$

$$v_o = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4/R_3}{1 + R_4/R_3}\right) v_{I2} - \left(\frac{R_2}{R_1}\right) v_{I1}$$

If $\underbrace{v_{I1} = v_{I2}}_{\text{common-mode}}$, Output voltage zero } ideal-opamp difference amplifier

$$\Rightarrow \boxed{\frac{R_4}{R_3} = \frac{R_2}{R_1}}$$

$v_o =$

$$v_o = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_2/R_1}{1 + R_2/R_1}\right) v_{I2} - \left(\frac{R_2}{R_1}\right) v_{I1}$$

$\downarrow$

$$v_o = \left(\frac{R_2}{R_1}\right)(v_{I2} - v_{I1})$$

$$v_o = A_d \cdot v_d$$

If $\underbrace{v_{I1} \neq v_{I2}}_{\text{differential-mode}}$, $\frac{R_4}{R_3} \neq \frac{R_2}{R_1}$

$v_{cm} = ?$

$v_d = ?$

$$v_{cm} = \left(\frac{v_{I1} + v_{I2}}{2}\right) \longleftrightarrow v_d = v_{I2} - v_{I1}$$

v_{I1}, v_{I2} ?

express v_{I1} & v_{I2} $\rightarrow$ in form of v_d, v_{cm}

$$A_{cm} = \frac{v_o}{v_{cm}}$$

$$v_{cm} = \frac{v_{I_1} + v_{I_2}}{2}$$

$$v_d = v_{I_2} - v_{I_1}$$

$$v_{I_1} = ?\ v_{cm} - v_d/2$$

$$v_{I_2} = v_{cm} + v_d/2$$

If $\frac{R_2}{R_1} = 10$, $\frac{R_4}{R_3} = 11$

Obtain the CMRR of the difference amplifier

v_d, v_{cm},

A_d, A_{cm}

$$CMRR = \frac{A_d}{A_{cm}}$$

$$(dB) = 20 \log_{10}\left(\frac{A_d}{A_{cm}}\right)$$

$$v_o = A_d \cdot v_d + A_{cm} v_{cm}$$

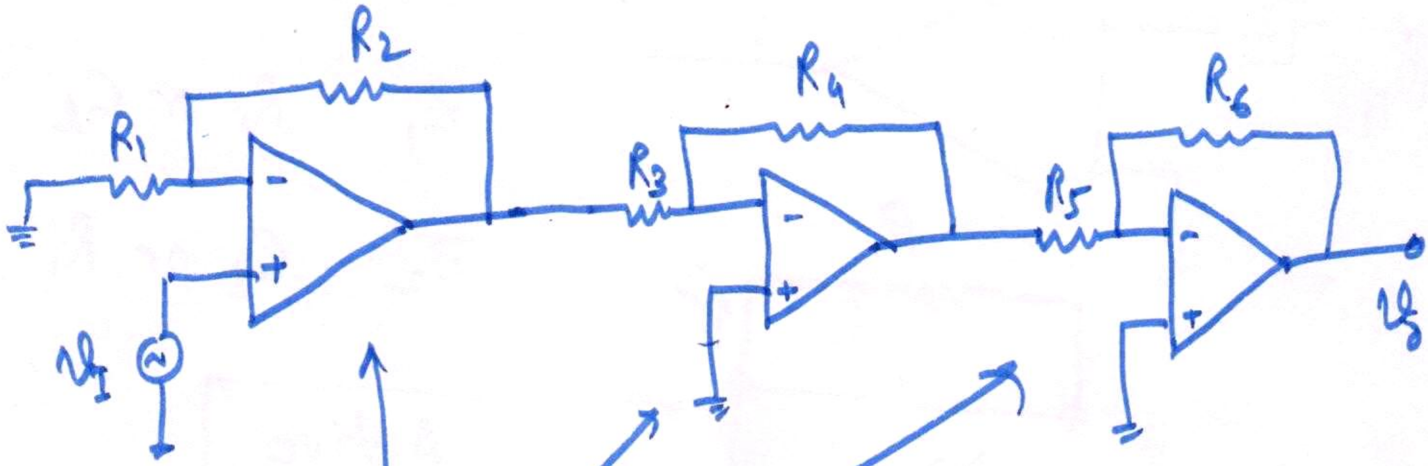
$$v_o = \left(\frac{121}{12}\right) v_{I_2} - 10 v_{I_1}$$

$A_d = ?$

$A_{cm} = ?$

CMRR = 2

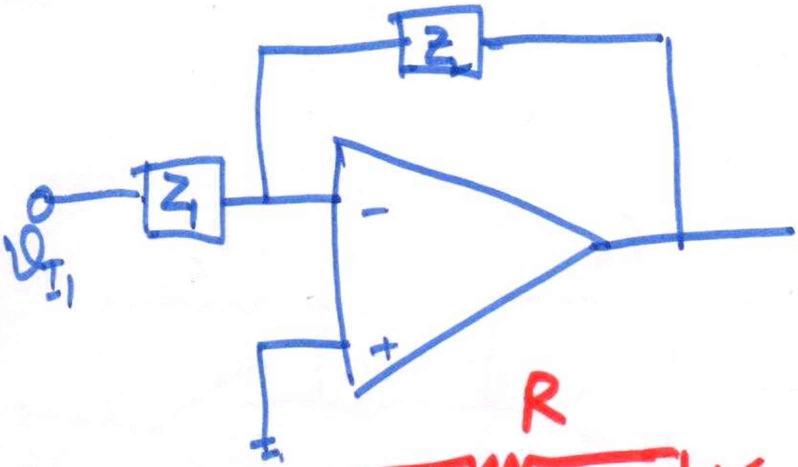
Multi-stage Op-amps.



$$A = A_1 A_2 A_3$$

$A_1 \rightarrow$ gain of individual Op-amps

$$\left.\begin{aligned} A_1 &= \left(1 + \frac{R_2}{R_1}\right) \\ A_2 &= -\frac{R_4}{R_3} \\ A_3 &= -\frac{R_6}{R_5} \end{aligned}\right\} \quad A = (\quad)(\quad)(\quad)$$

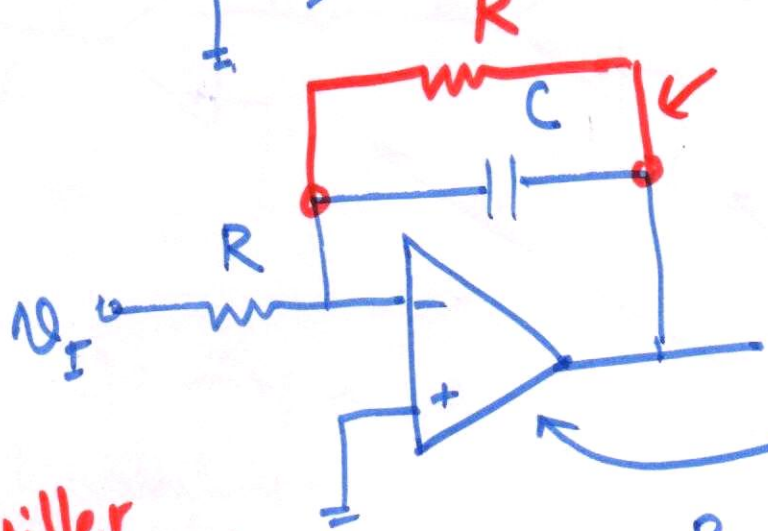


Z_1, Z_2

impedances

Z_1 R_1 or C_1

Z_2 C_1 or R_1

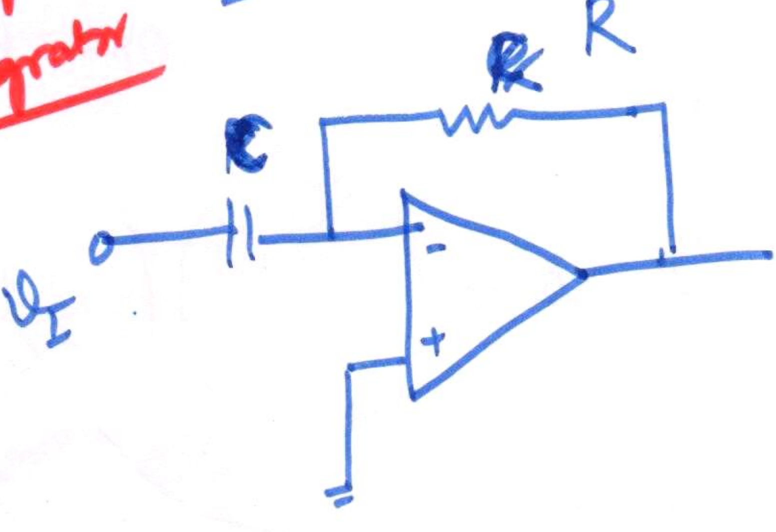


Active

low-pass filter

Integrator

Miller Integrator



high-pass filter

Differentiator