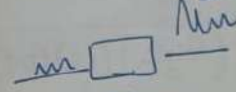
Module-4

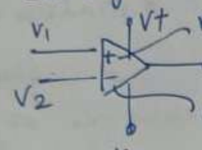
Operational Amplifiers

High gain differential Amplifier



Addition
Sub.
Multi
Division

ckt symbol



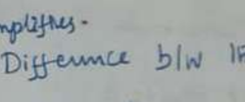
2 I/p - 1 O/p

2 power supply . Symmetric

Amplifies -
Difference b/w the 2 I/p signals

Gain A

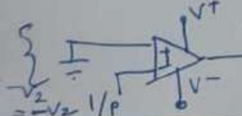
$O/p = A(V_1 - V_2)$



$V_{out} = A \times V_1$

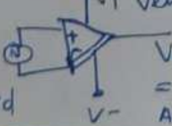
A - openloop gain
ie) no feedback

If I/p is sin O/p sine wave must be multiplied by the factor A Phase is same.



$V_{out} = -A V_2$

O/p is inverted



very high gain

$V_{ot} = A V_d$

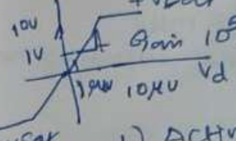
$A = 10^5$ or 10^6

1mV - O/p   A vd

$1mV \times 10^5 = 100V$

1V $1 \times 10^5 = 10^5 V$ | not possible

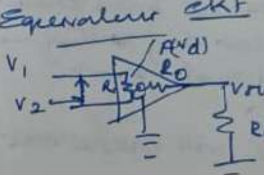
V_o O/p is limited by biasing voltages



Application
Open loop gain   Comparator

1) Active filter 2) oscillator 3) Waveform converter 4) ADC & DAC

Equivalent ckt



$R_i = \infty$

$R_o = 0$

$BW = \infty$

of Ideal. Supports all frequency

Gain of the ideal $A = \infty$

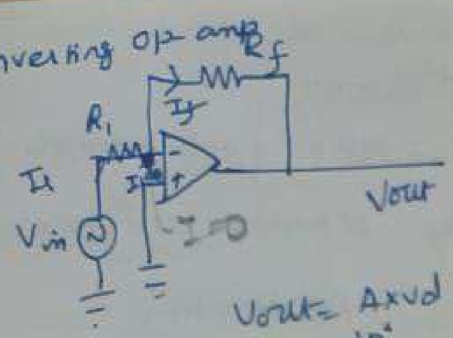
Slew rate , CMRR

Virtual Ground

O/p should be linear , In open loop linear region is very small , Fb, will control the linear region

Feedback O/p - +ve fb - Non-Inverting amplifier
O/p - −ve fb - Inverting amplifier

Inverting op-amp



$A_{OL} = 10^6$

o/p voltage $V_{out} = A \times V_d$

$V_{out} = 10V$

$10^6 \times V_d$

$V_{out} = \frac{A \times V_d}{10^6}$

$V_d = 10\mu V$

$V_d = V_1 - V_2$

difference b/w Inverting & non-inverting

$V^+ - V^- = 10\mu V$

$V^+ - V^- \simeq 0V$

$\simeq V^+ = V^-$ Inverting & noninverting are at same potential or we can say they are virtual short

V^+ is grounded

$V^+ = 0$ then $V^- = 0$

Negative feedback resistor will ensure that

$V_d = 0$ or negligible

I_1 is current flowing through R_1

I_f is " " " R_f

Ideal op-amp $R_{in} = \infty$ at this point when no current is entering into op-amp so $I = 0$

$I_1 = I_f$

$$\frac{V_1 - V_x}{R_1} = \frac{V_x - V_{out}}{R_f}$$

Applying virtual ground, $V_x = 0$

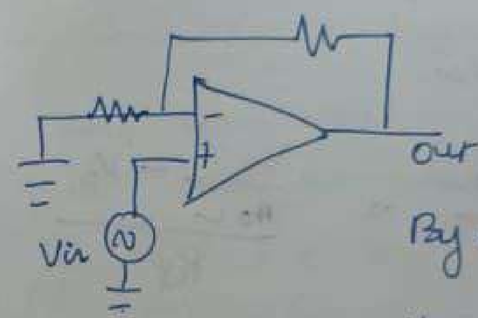
$$\frac{V_{in}}{R_1} = -\frac{V_{out}}{R_f} \Rightarrow \frac{V_{out}}{V_{in}} = -R_f / R_1$$

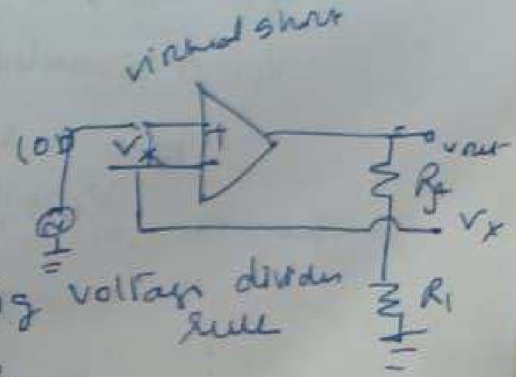
Closed loop gain of inverting amplifier

— Indicates o/p is 180° out of phase.

$R_1 = 1k\Omega$ $R_2 = 2k\Omega$

Non-inverting amplifier





By using voltage divider rule

$$V_x = \frac{R_1}{R_1 + R_f} \times V_{out}$$

$V^+ = V^-$ ($\because$ virtual short)

$V^+ = V_{in}$

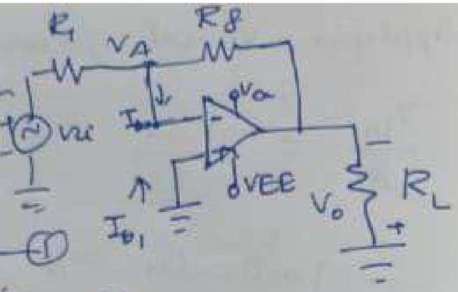
$V^- = V_{in} = V_x$

$$V_{in} = \frac{R_1}{R_1 + R_f} \times V_{out}$$

$$V_{out}/V_{in} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}$$

Closed loop gain of non-inverting amplifier

Practical Inverting amplifier



$R_{in} \neq \infty$ $\quad I_{in} = I_f + I_{b2}$

I_{b2} = negligible $I_{in} = I_f$ — (1)

$$\frac{V_{in} - V_A}{R_1} = \frac{V_A - V_O}{R_f} \quad \text{— (3)}$$

$V_0 = A_{OL} V_d = A_{OL}(V_1 - V_2)$

$V_1 = 0$ grounded $\quad V_2 = V_A$

$V_0 = -A_{OL} V_A$

Sub. in

$$\frac{V_{in} + \frac{V_0}{A_{OL}}}{R_1} = \frac{-\frac{V_0}{A_{OL}} - V_0}{R_f}$$

$$\therefore V_{in} R_f + V_0 \frac{R_f}{A_{OL}} = -\frac{R_1}{A_{OL}} V_0 - R_1 V_0$$

$$V_{in} R_f = -V_0 \left[\frac{R_1}{A_{OL}} + R_1 + \frac{R_f}{A_{OL}}\right]$$

$$A_{CL} = V_0 / V_{in}$$

$$\therefore A_{CL} = \frac{A_{OL} R_f}{R_1 + R_f + R_1 A_{OL}}$$

Now ideally A_{OL} is very large tending to ∞

A_{CL} $\quad R_1 >> R_1 + R_f \quad A_{CL} = -\frac{R_f}{R_1}$ (ideal)

DC Characteristics

An ideal op-amp draws no current from source & its response is also independent of temp.

→ Real op-amp - Current taken from source to op-amp I/ps

→ 2 I/p respond differently to current & voltage due to mismatch in transistors.

→ Real op amp shifts operation temperature

These non-ideal dc characteristics that add error components to dc O/p voltage

(i) I/p bias current

(ii) I/p off set current

(iii) I/p off set Voltage

(iv) Thermal drift

I/p Bias current

* I/p to op-amp → Differential amplifier

FET (or) BJT

Both must be biased in linear region by supplying current into bases by the external cir

Ideal op-amp - no current drawn to I/p

Practical I/p terminals conduct small value of dc current to bias the I/p transistors

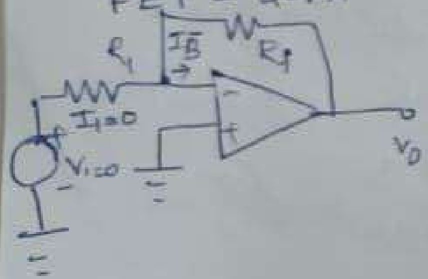
→ Base currents entering +, - terminals are

$I_B^+ \times I_B^-$

They are not exactly equal

$I_B = \frac{I_B^+ + I_B^-}{2}$ (Manufacturer specify the average of I_B)

FET - 50PA



If V_i is set at 0V then $V_0 = 0V$

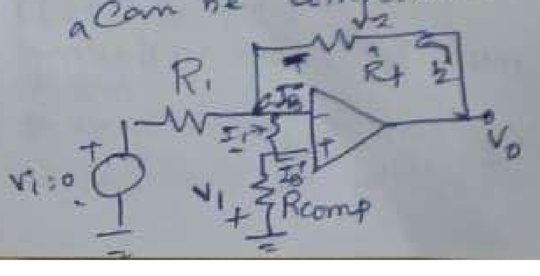
Instead we find O/p voltage is off set by

$V_0 = (I_B^-) R_f$

For 741 $V_0 = (500nA) \times 1M\Omega$
$= 500mV$

→ Not acceptable.

This effect can be compensated by Rcomp



current I_B^+ flowing through Rcomp develops V_1 across

By KVL,

$-V_1 + 0 + V_2 - V_0 = 0$; $V_0 = V_2 - V_1$

By selecting proper value of Rcomp V_2 can be cancelled with V_1 & V_0 will be zero.

$V_1 = I_B^+ R_{comp}$

$I_B^+ = \frac{V_1}{R_{comp}}$

The node 'a' is at voltage $(-V_1)$ since voltage at non-inverting I/p terminal is $(-V_1)$

So with $V_i = 0$

$I_1 = \frac{V_1}{R_1}$ $\quad I_2 = \frac{V_2}{R_f}$

For compensation V_0 should be zero for $V_i = 0$

$\because V_0 = V_2 - V_1 \quad \therefore V_2 = V_1$

$I_2 = V_1 / R_f$

KCL at 'a' gives

$I_B^- = I_2 + I_1 = \frac{V_1}{R_1} + \frac{V_1}{R_f}$

$= V_1 (R_1 + R_f) / R_1 R_f$

Assuming $I_B^- = I_B^+$ for bias current compensation

$$V_1 \times \frac{(R_1+R_f)}{R_1 R_f} = \frac{V_1}{R_{comp}}$$

$$R_{comp} = \frac{R_1 R_f}{R_1 + R_f} = R_1 \parallel R_f$$

I/p offset current

Bias current compensation will work if both bias currents I_B^+ & I_B^- are equal

∴ I/p transistors are not identical, there will be small difference b/w I_B^+ & I_B^-

This difference is called offset current I_{os}

$$|I_{os}| = I_B^+ - I_B^-$$

No way to predict which I_B's will be larger

I_{os} for BJT - 200nA

FET - 10 pA

Offset current will produce an o/p voltage when I/p voltage $V_i = 0$

$$V_1 = I_B^+ R_{comp}$$

$$I_1 = V_1 / R_1$$

KCL at node 'a'

$$I_2 = (I_B^- - I_1) = I_B^- - \left(I_B^+ \frac{R_{comp}}{R_1}\right)$$

$$V_o = I_2 R_f - V_1 = I_2 R_f - I_B^+ R_{comp}$$

$$= \left(I_B^- - \left(I_B^+ \frac{R_{comp}}{R_1}\right)\right) R_f - I_B^+ R_{comp}$$

Substituting $R_{comp} = R_1 \parallel R_f$ & simplification

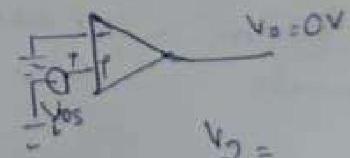
$$V_o = R_f (I_B^- - I_B^+)$$

$$V_o = R_f I_{os}$$

T-feedback network is a good solution

I/p offset Voltage

V_{os} can be applied to make o/p zero



$V_2 =$

If $V_i = 0$

$$V_2 = \left(\frac{R_1}{R_1+R_f}\right) V_o$$

$$V_o = \left(\frac{R_1 + R_f}{R_1}\right) V_2$$

$$= (1 + R_f/R_1) V_2$$

$V_{ios} = |V_i - V_2|$ & $V_i = 0$

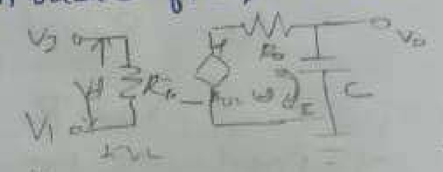
$V_{ios} = |V_i - V_2|$ $V_i = 0 \Rightarrow V_{ios} = V_2$

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_{ios}$$

AC Characteristics

→ Ideally an op-amp should have infinite BW

→ If its open loop gain is 90dB, with dc signal its gain should remain 90dB through audio and on to high radio frequencies.



Op-amp applications:-

Scale changer / inverter

Summing amplifier:-

→ op-amp may be used to design a ckt whose o/p is sum of several I/p signals

→ Such ckt is summer

Inverting Summing amplifier

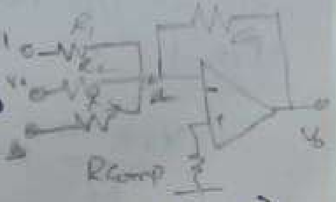
3 I/p Voltages V_1, V_2, V_3 with R_1, R_2, R_3

× feedback resistors R_f

Assume ideal op-amp

$A_{OL} = \infty$ $R_i = \infty$ I/p bias current zero, no Voltage drop across R_{comp}, non-inverting I/p terminal is ground

Voltage at node 'a' is zero, as non-inverting terminal is grounded



$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \frac{V_o}{R_f} = 0$$

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

o/p is an inverted, Weighted sum of I/ps

If $R_1 = R_2 = R_3 = R_f$

$V_o = -(V_1 + V_2 + V_3)$

V_o - inverted sum of the I/p signals

we may also set $R_1 = R_2 = R_3 = 3R_f$

in which case

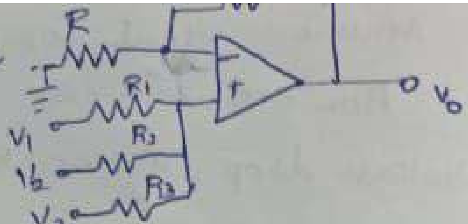
$$V_o = -\left(\frac{V_1 + V_2 + V_3}{3}\right)$$

In practical ckt

$R_{comp} = R_i \parallel R_f$

$= R_1 \parallel R_2 \parallel R_3 \parallel R_f$

Non-Inverting Summer



A summer that gives non-inverting summing amplifier,

'−' I/p terminal − V_a

also + ' ' V_a

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

from which we have

$$V_a = \frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{1/R_1 + 1/R_2 + 1/R_3}$$

Op-amp and 2 resistors R_f and R constitute a non-inverting amplifier

$$V_0 = \left(1 + \frac{R_f}{R}\right) V_a$$

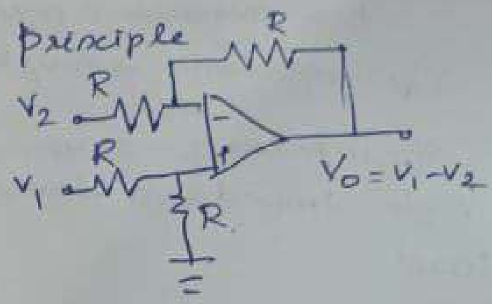
Therefore the O/p voltage

$$V_0 = \left(1 + \frac{R_f}{R}\right)\left(\frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{1/R_1 + 1/R_2 + 1/R_3}\right)$$

Non-inverting weighted sum of I/ps

Subtractor

If all resistors are equal in value then O/p voltage can be derived by superposition principle



Difference amplifier
Instrument
Differentiator
Integrator
I/V, V/I

To find V_{01} due to V_1 alone make $V_2 = 0$

Then the ckt becomes non-inverting amplifier having I/p voltage $V_1/2$ at the non-inverting I/p terminal & the O/p becomes

$$V_{01} = \frac{V_1}{2}\left(1 + \frac{R}{R}\right) = V_1 \Rightarrow$$

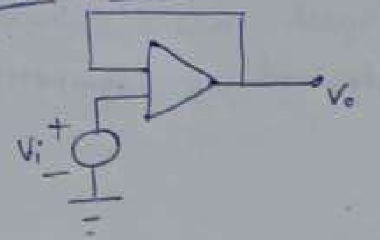
$$V_{02} = -V_2$$

O/p voltage V_0 due to both I/ps

$$V_0 = V_{01} + V_{02} = V_1 - V_2$$

Voltage follower

$R_f = 0 \quad R_1 = \infty$



$V_o = V_1$

o/p voltage = I/p voltage both magnitude & phase

- I/p impedance is very high MΩ

o/p impedance - zero

used to connect high impedance source to low impedance load.

Instrumentation amplifier

Measurement & control of temperature, humidity, light intensity, waterflow etc. → Measured using transducers

o/p of transducer is amplified so that it can drive the indicator/ display system

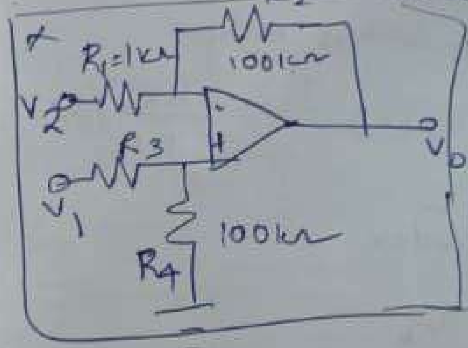
This is done by an instrumentation amplifier

& Features

1) High gain accuracy
2) High CMRR
3) High gain stability with low temp. coefficient
4) Low dc offset
5) Low o/p impedance

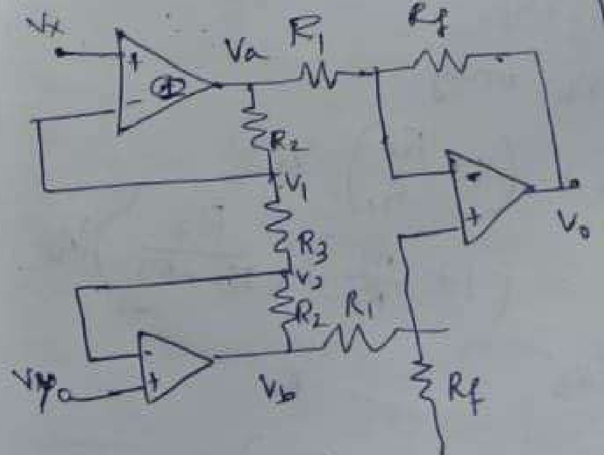
MA 725 - Special op-amp to meet stated requirements

Single chip Ic available - AD521, AD524, AD620, AD625, LM363 xx



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

$$\left(V^+ = \frac{R_4}{R_3+R_4} V_1\right)$$



$V_1 = V_x$

$V_2 = V_y$

$$\frac{V_a - V_1}{R_2} = \frac{V_1 - V_2}{R_3} \quad (1)$$

$$\frac{V_1 - V_2}{R_3} = \frac{V_2 - V_b}{R_2} \quad -(2)$$

$V_1 = V_x ; V_2 = V_y$

$$\frac{V_a - V_x}{R_2} = \frac{V_x - V_y}{R_3} \Rightarrow V_a = \frac{R_2}{R_3}(V_x - V_y) + V_x$$

From (2)

$$\frac{V_x - V_y}{R_3} = \frac{V_y - V_b}{R_2}$$

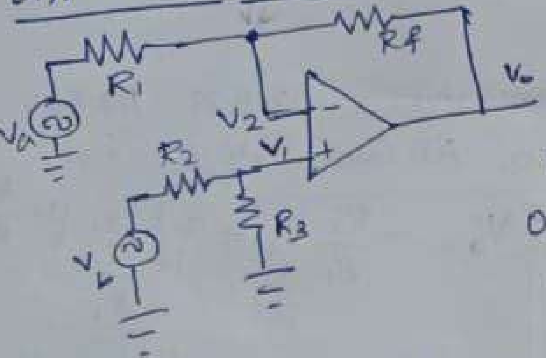
$$V_b = V_y - \frac{R_2}{R_3}(V_x - V_y)$$

$$V_o = \frac{R_f}{R_1}(V_b - V_a)$$

$$= \frac{R_f}{R_1}\left\{V_y - V_x - 2\frac{R_2}{R_3}(V_x - V_y)\right\}$$

$$V_o = -\left\{1 + \frac{2R_2}{R_3}\right\}\frac{R_f}{R_1}(V_x - V_y)$$

Differential amplifier



2 I/p's superposition theorem can be used to find O/P voltage

When $V_b = 0$; inverting
O/p due to V_a only

$$V_o(a) = -\left(\frac{R_f}{R_1}\right) V_a$$

Similarly when $V_a = 0$ –
voltage divider

$$V_1 = \frac{R_3}{R_2 + R_3} V_b$$

O/p due to V_b only

$$V_o(b) = \left(1 + \frac{R_f}{R_1}\right) V_1$$

$$= \left(1 + \frac{R_f}{R_1}\right)\left(\frac{R_3}{R_2 + R_3}\right) V_b$$

If $R_1 = R_2$ & $R_f = R_3$

$$V_o(b) = \left(\frac{R_1 + R_f}{R_1}\right)\left(\frac{R_3}{R_2 + R_3}\right) V_b$$

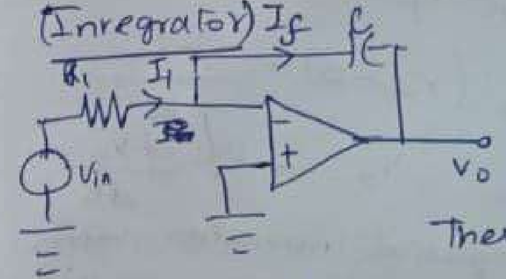
$$= \left(\frac{\cancel{R_2 + R_f}}{R_1}\right)\left(\frac{R_f}{\cancel{R_2 + R_f}}\right) V_b = \left(\frac{R_f}{R_1}\right) V_b$$

∴ Total voltage

$$V_o = V_o(a) + V_o(b)$$

$$= \frac{R_f}{R_1}\left(-V_a + V_b\right)$$

(Integrator)



Here the feedback element is capacitor.
current is zero
V_2 is virtually ground

Therefore $i_1 = i_f$ & $V_2 = V_1 = 0$

$i = \frac{dQ}{dt} = C\frac{dv_o}{dt}$

KCL

$$\frac{v_i}{R_1} + C_f \frac{dv_o}{dt} = 0$$

$$\int_0^t \frac{V_i}{R_1} = -\int_0^t C_f \frac{dv_o}{dt}$$

$$\int_0^t \frac{V_{in}}{R_1} dt = -C_f \int_0^t d\frac{V_{out}}{dt} dt$$

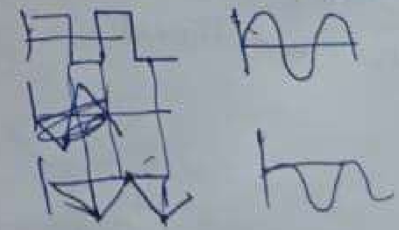
$$= -C_f V_{out}$$

$$V_{out} = -\frac{1}{R_1 C_f}\int_0^t V_{in}\, dt$$

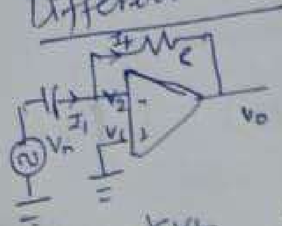
Integrating both sides with respect to time from 0 to t

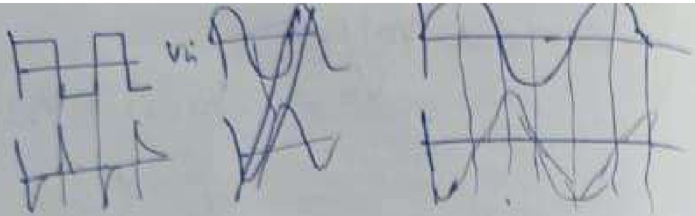
I/p is sine wave — O/p – cosine
Square wave — O/p triangular

V_{in}



Differentiator





KVL at V_2 $\quad i_{in} = I_f$

$i = C\frac{dv}{dt}$ $\quad I_f = \frac{V_o}{R_f}$ $\quad \therefore C\frac{d}{dt}(v_{in} - 0) = \frac{0 - V_o}{R}$

$\frac{C d(V_i - V_2)}{dt}$ $\quad C\frac{d(V_i) - V_2}{dt} + \frac{V_2 - V_o}{R_f} = 0$ $\qquad V_o = -RC\frac{dV_{in}}{dt}$

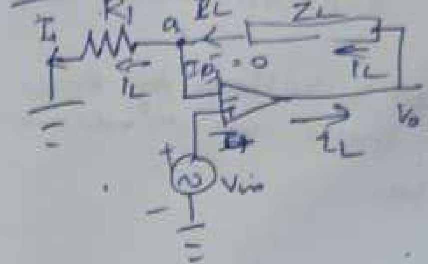
V_o – RC times negative instantaneous ~~value~~ rate of change of I/p voltage V_{in} with time.

Cosine wave I/p produces sine o/p

I/p signal will be differentiated properly if the time period 'T' of the I/p signal is larger than or equal to $R_f C$ $\quad T \geq R_f C$

As freq. changes gain changes. Also at higher freq ckt is susceptible at high freq. noise & noise gets amplified

Voltage to current converter (Transconductance)

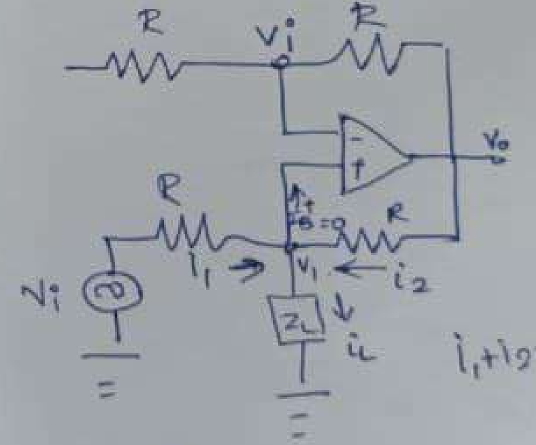


$V_i = i_L R_1$ (as $I_B = 0$)

$i_L = \frac{V_i}{R_1}$

I/p voltage V_i is converted to V_i/R_1 o/p current

$i_1 + i_2 = i_L$



$i_1 + i_2 = i_L$

$\frac{V_i - V_1}{R} + \frac{V_o - V_1}{R} = i_L$

$V_i + V_o - 2V_1 = i_L R$

$V_1 = \frac{V_i - V_o - i_L R}{2}$

Since op-amp is in non-inverting mode

Gain $1 + R/R = 2$ $\qquad 1 + R_f/R_i = 2$

O/p voltage $V_o = 2V_1$

$V_1 = V_i + V_o - i_L R$

$V_i = i_L R_1$

$V_i \propto V_d$

$i_L = V_i/R$

$V_1 = \frac{V_i - V_o - i_L R}{2}$

$2V_1 = V_i - V_o - i_L R$

$2V_1 - 2V_1 = V_i - i_L R$

$V_i - i_L R = 0$

$V_i = i_L R$

$i_L = V_i/R$