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Unit - 5

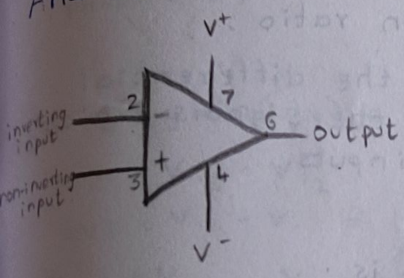
OPERATIONAL AMPLIFIERS

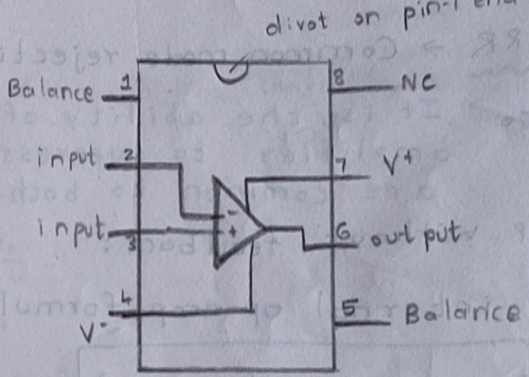
* Op-amp is a versatile building block that can be used for realising several electronic circuits
* Operational → it performs mathematical operations.

* Amplifiers → amplifies the input
(Eg: 1 V → 10^5 V)
10^5 times - amplification

* General OP-AMP => IC 741 with 8 pins,
* Out of 8, 7 pins are active)
* 8^{th} pin is for balance

There are two inputs
-Inverting & Non-inverting
And one output





* This amplifier is called differential amplifier.

*

$I_2 = 1$ V
$I_3 = 1.0001$ V

$0.0001 \times 10^5 = 100$ V ⊗
$= 15$ V

$I_2 = 1$ V
$I_3 = 1$ V

$0 \times 10^5 =$ ~~15~~ 0 V ⊗ ✓
$= 15$ V

15 → Saturation voltage

* OP - AMP is highly unstable

* Output always = +15 (or) - 15 .

Characteristics of The ideal op-amp:

Examples.

i) Infinite voltage gain:

* A voltage difference at the two inputs is magnified infinitely.
* In truth, something like 200,000

ii) Infinite input impedance: → In reality: ($10^6 \Omega$) (or) ($M\Omega$)

* No current flows into inputs.

iii) Zero output impedance:

* rock-solid independent of load.
* roughly true up to current maximum (5 - 25 mA)

iv) Infinitely fast (infinite bandwidth):

* in truth, limited to few MHz range
* slew rate, limited to 0.5 - 20 V/μs
  response rate

OP-AMP is Used both for DC & AC currents,

v) CMRR → Common mode rejection ratio.

~~Both~~ It is the ability of the differential amplifier to suppress the signals which are common to both inputs.

OP-amp without feedback:

* The internal op-amp formula is;

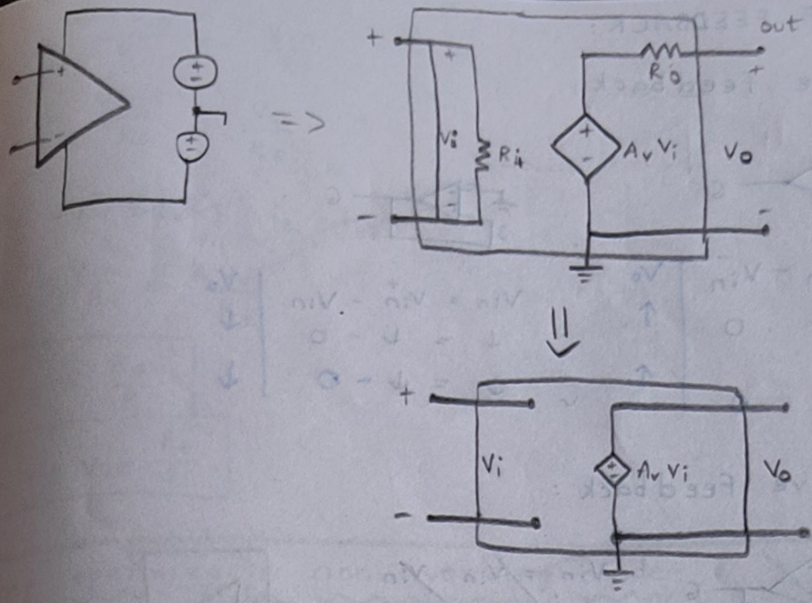
$$\boxed{V_{out} = \text{gain} \times (V_+ - V_-)}$$

If V_+ is greater than V_-, output goes +

$V_- > V_+$, output => -

* What other electronic circuits we give to op-amp is

Current will flow outside the amplifier & not ats



* $R_i \to \infty$; $R_o \to 0$

= V_{cc} & $-V_{EE}$ ($\sim \pm 5V$ to $\pm 15V$)

parameter

Gain

10^4

$V_o = \text{gain}(A_v) \times V_i$

$V_i = V_{i_3} - V_{i_2}$

$V_i = V_+ - V_- = \frac{V_o}{A_V}$

$\frac{V_o}{V_i} = AV$; $V_o = AV_1$

If : $V_i = 0.1\,mV$

Broadly op-amp circuits can be divided in two;

i) op-amp operating in linear region

ii) op-amp operating in saturation region

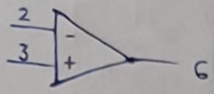
whether an op-amp in a given circuit will operate in linear (or) saturation region depends on;

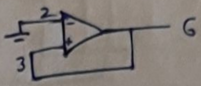
i) input voltage magnitude

ii) type of feedback (positive or negative)

TYPES OF FEEDBACK:

i) Positive feedback:





$V_{in} = V_{in}^{+} - V_{in}^{-}$ | V_o

$\uparrow \quad \uparrow \quad 0$ | $\uparrow$

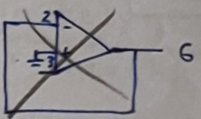
$\uparrow \quad \uparrow \quad 0$ | $\uparrow$

$V_{in} = V_{in}^{+} - V_{in}$ | V_o

$\downarrow = \downarrow - 0$ | $\downarrow$

$\downarrow = \downarrow - 0$ | $\downarrow$

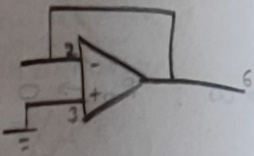
ii) Negative feedback:



~~$V_{in} = V_{in} - V_{in}$~~

~~$\downarrow = \downarrow \quad 0$~~

~~$\downarrow = \downarrow$~~



$V_{in} = V_{in}^{+} - V_{in}$ | V_o

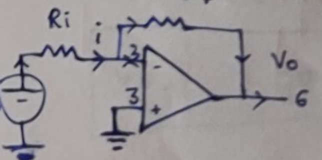
$= 0 - \downarrow$ | $\uparrow$

V_o $\uparrow$ $= 0 - \downarrow$

$\downarrow$ $= 0 - \uparrow$ | $\downarrow$

* All op-amp negative feedback only will be used.

Op-amp operated in inverting mode:



$i_{R_i} = \frac{0 - V_{in}}{R_i} = -\frac{V_{in}}{R_i}$

$i_{Rf} = \frac{V_o - 0}{R_f} = \frac{V_o}{R_f}$

$i = i_{R_i} = i_{R_f}$

$-\frac{V_{in}}{R_i} = \frac{V_o}{R_f}$

$$\boxed{V_o = -V_{in} \frac{R_f}{R_i}}$$

Golden Rules:

i) No current flows through op-amp.

ii) If operating in negative feedback, the output will make sure that difference between two input voltage is zero

$$V^{+} - V^{-} = 0$$

Virtual ground: When the terminal 3 is grounded, then 2 is also grounded

$$i_{R_1} = \frac{0 - V_{in}}{R_i} = -\frac{V_{in}}{R_i}$$

$$i_{R_f} = \frac{V_o - 0}{R_f} = \frac{V_o}{R_f}$$

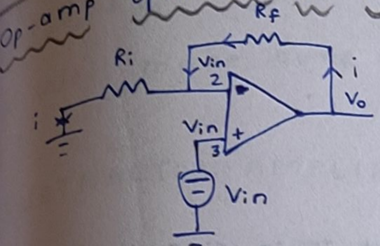
$$i = i_{R_1} = i_{R_f} \qquad i_{R_1} = i_{R_f}$$

$$-\frac{V_{in}}{R_i} = \frac{V_o}{R_f}$$

$$\boxed{A_v = -\frac{R_f}{R_i}}$$

$$\boxed{V_o = -V_{in}\frac{R_f}{R_i}}$$

Op-amp operated in non-inverting mode:



$$i_{R_i} = \frac{V_{in} - 0}{R_i}$$

$$i_{R_f} = \frac{V_o - V_{in}}{R_f}$$

$$i_{R_i} = i_{R_f}$$

$$\frac{V_{in}}{R_i} = \frac{V_o - V_{in}}{R_f}$$

$$\frac{V_o}{R_f} = V_{in}\left(\frac{1}{R_i} + \frac{1}{R_f}\right)$$

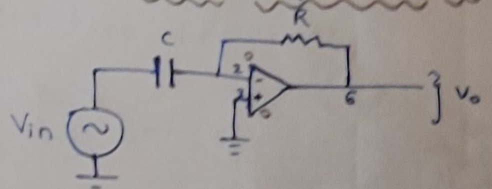
$$\frac{V_o}{R_f} = V_{in}\left[\frac{R_f + R_i}{R_i R_f}\right]$$

$$V_o = V_{in} R_f \left[\frac{R_f + R_i}{R_i R_f}\right] = V_{in} R_f \left[\frac{1}{R_i} + \frac{1}{R_f}\right] = V_{in}\left[1 + \frac{R_f}{R_i}\right]$$

$$\boxed{V_o = V_{in}\left(1 + \frac{R_f}{R_i}\right)} \qquad A_v = 1 + \frac{R_f}{R_i}$$

Op-amp with capacitor in inverting mode :

(Differentiator).



WKT :

$$q = C\,V_{in}$$

$$\frac{dq}{dt} = C\frac{dV_{in}}{dt}$$

$$i_c = C\frac{dV_{in}}{dt}$$

$$i_R = \frac{V_o}{R}$$

$$i = i_c = i_R$$

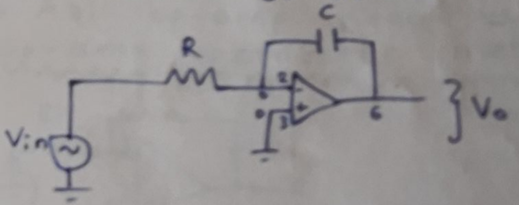
$$C\frac{dV_{in}}{dt} = \frac{V_o}{R} \rightarrow ①$$

$$\boxed{V_o = RC\frac{dV_{in}}{dt}} \rightarrow ②$$

If input is in sine wave, output will be cos wave.

This is form differential.

RC → time constant.



$$i_R = \frac{0 - V_{in}}{R} = -\frac{V_{in}}{R} \; ; \; \boxed{i_R = -\frac{V_{in}}{R}}$$

$$\boxed{i_c = C\frac{dV_o}{dt}}$$

$$i_c = i_R$$

$$C\frac{dV_o}{dt} = -\frac{V_{in}}{R}$$

$$dV_o = -\frac{1}{RC} V_{in}\,dt$$

$$\boxed{V_o = -\frac{1}{RC}\int V_{in}\,dt}$$

If input is sin, output = cos,

This in integral

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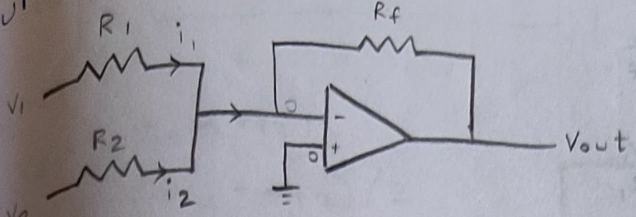
SUMMING AMPLIFIER :



$$\frac{V_{out}}{-R_f} = \left(V_1/R_1 + V_2/R_2\right)$$

$i R_f = \frac{V_o}{R_f}$

$$i_1 = \frac{0 - V_1}{R_1} = \frac{-V_1}{R_1}$$

$$i_2 = \frac{0 - V_2}{R_2} = -\frac{V_2}{R_2}$$

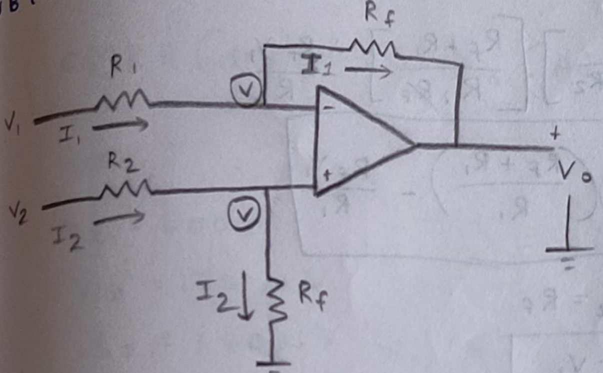
$$i_{in} = -\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right)$$

$i R_f = i_{in}$; $\boxed{V_o = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right)}$

If $R_1 = R_2$;
we get sum proportional to $V_1 + V_2$
then ; $V_1 + V_2$

* We'll make our D/A converter this way.

SUBTRACTOR AMPLIFIER :



$$I_1 = \frac{V_1 - V}{R_1} = \frac{V - V_o}{R_f}$$

$$I_2 = \left[\frac{V_2 - V}{R_2}\right] = \left[\frac{V - 0}{R_f}\right]$$

$$\frac{V_2}{R_2} - \frac{V}{R_2} = \frac{V}{R_f}$$

$$\frac{V_2 - V}{R_2} = \frac{V}{R_f}$$

$$V = \frac{R_f}{R_2}(V_2 - V)$$

$$\frac{V_2}{R_2} = \frac{V}{R_2} + \frac{V}{R_f}$$

$$V = \frac{R_f V_2}{R_2} - \frac{R_f V}{R_2}$$

$$\frac{V_2}{R_2} = V\left[\frac{1}{R_2} + \frac{1}{R_f}\right]$$

$$V + \frac{R_f V}{R_2}$$

$$V\left[1 + \frac{R_f}{R_2}\right] = \frac{R_f V_2}{R_2}$$

$$V = \frac{V_2}{R_2} / \left(\frac{R_2 + R_f}{R_2 R_f}\right)$$

$$V = \frac{V_2}{\cancel{R_2}}\left(\frac{\cancel{R_2} R_f}{R_2 + R_f}\right)$$

$$\boxed{V = V_2\left(\frac{R_f}{R_2 + R_f}\right)} \rightarrow 1$$

$$I_1 = \frac{V_1 - V}{R_1} = \frac{V - V_o}{R_f}$$

$$\frac{V_1}{R_1} - \frac{V}{R_1} = \frac{V}{R_f} - \frac{V_o}{R_f}$$

$$\frac{V_o}{R_f} = \frac{V}{R_f} + \frac{V}{R_1} - \frac{V_1}{R_1}$$

$$\frac{V_o}{R_f} = V\left[\frac{1}{R_f} + \frac{1}{R_1}\right] - \frac{V_1}{R_1}$$

$$\frac{V_o}{R_f} = V\left[\frac{R_1 + R_f}{R_1 R_f}\right] - \frac{V_1}{R_1}$$

From (1); $V = V_2\left[\frac{R_f}{R_2 + R_f}\right] \rightarrow$

$$\frac{V_o}{R_f} = V_2\left[\frac{R_f}{R_2 + R_f}\right]\left[\frac{R_1 + R_f}{R_1 R_f}\right] - \frac{V_1}{R_1}$$

$$V_o = V_2 \cancel{R_f}\left[\frac{R_f}{R_f + R_2}\right]\left[\frac{R_f + R_1}{R_1 \cancel{R_f}}\right] - \frac{R_f V_1}{R_1}$$

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

If $R_1 = R_2 = R_f$

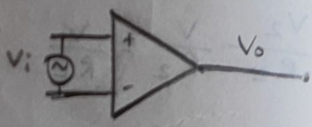
$$\boxed{V_o = V_2 - V_1}$$

P-AMP CHARACTERISTICS :

Differential mode operation : (Difference should be amplified

$V_o = A_d V_i$

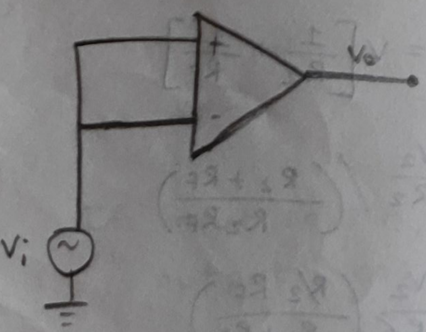
A_d is typically very large



Common mode operation: (Common should be eliminat (Nois

$V_o = A_c V_i$

$A_c << A_d$



Output voltage :

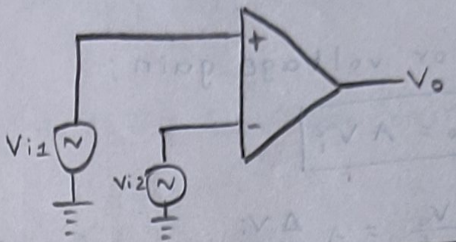
Total = $\boxed{V_o = A_d V_d + A_c V_c}$

where ;

$V_d = (V_{i1} - V_{i2})$

$V_c = (V_{i1} + V_{i2})/2$

$A_d >> A_c$



COMMON MODE REJECTION RATIO :

(Removes noice and amplifies the signal)

* The ratio of the differential gain to the common mode gain yields the common mode rejection ratio.

$$CMRR = A_d / A_c$$

$$CMRR(dB) = 20 \log_{10} (A_d / A_c)$$

Ex :

$A_d = 4000$

$V_{i1} = 150 \mu V$

$V_{i2} = 140 \mu V$

CMRR = a) 100 b) 10^5

A) WKT :

$$V_d = (V_{i1} - V_2) = (150 - 140) \mu V = 10 \mu V$$

$$V_c = \frac{V_{i1} + V_{i2}}{2} = \frac{150 + 140}{2} = \frac{\overset{145}{\cancel{290}}}{\cancel{2}} = 145 \mu V$$

WKT :

$$V_o = A_d V_d + A_c V_c = A_d V_d \left[1 + \frac{A_c V_c}{A_d V_d}\right]$$

$$\boxed{V_o = A_d V_d \left[1 + \frac{1}{CMRR}\left(\frac{V_c}{V_d}\right)\right]}$$

For CMRR = 1000

$$= 4000 * 10\mu \left[1 + \frac{145\mu}{100 * 10\mu}\right] = 45.8 \text{ mV}$$

For CMRR = 10^5

$$= 4000 * 10\mu \left[1 + \frac{145\mu}{10^5 * 10\mu}\right] = 40.006 \text{ mV}$$

To increase accuracy, we have increase CMRR value.

Ex : Slew rate $= 2\ V/s$,
$\left(\frac{dV_o}{dt}\right)$
what is the maximum closed-loop voltage gain that can be used when the input signal varies by 0.5 V in 10 s ?

A) For voltage gain ;

$$\boxed{V_o = A V_i}$$

$$\frac{\Delta V_o}{\Delta t} = A \frac{\Delta V_i}{\Delta t} \qquad \text{Given: } \frac{\Delta V_i}{\Delta t} = \frac{0.5}{10}$$

$$A = \frac{\frac{\Delta V_o}{\Delta t}}{\frac{\Delta V_i}{\Delta t}} = \frac{SR}{\frac{0.5}{10}} = \frac{2}{\frac{0.5}{10}} = \frac{20}{0.5} = \frac{\cancel{200}}{\cancel{5}} = 40$$