# Operational Amplifiers (op-amp)

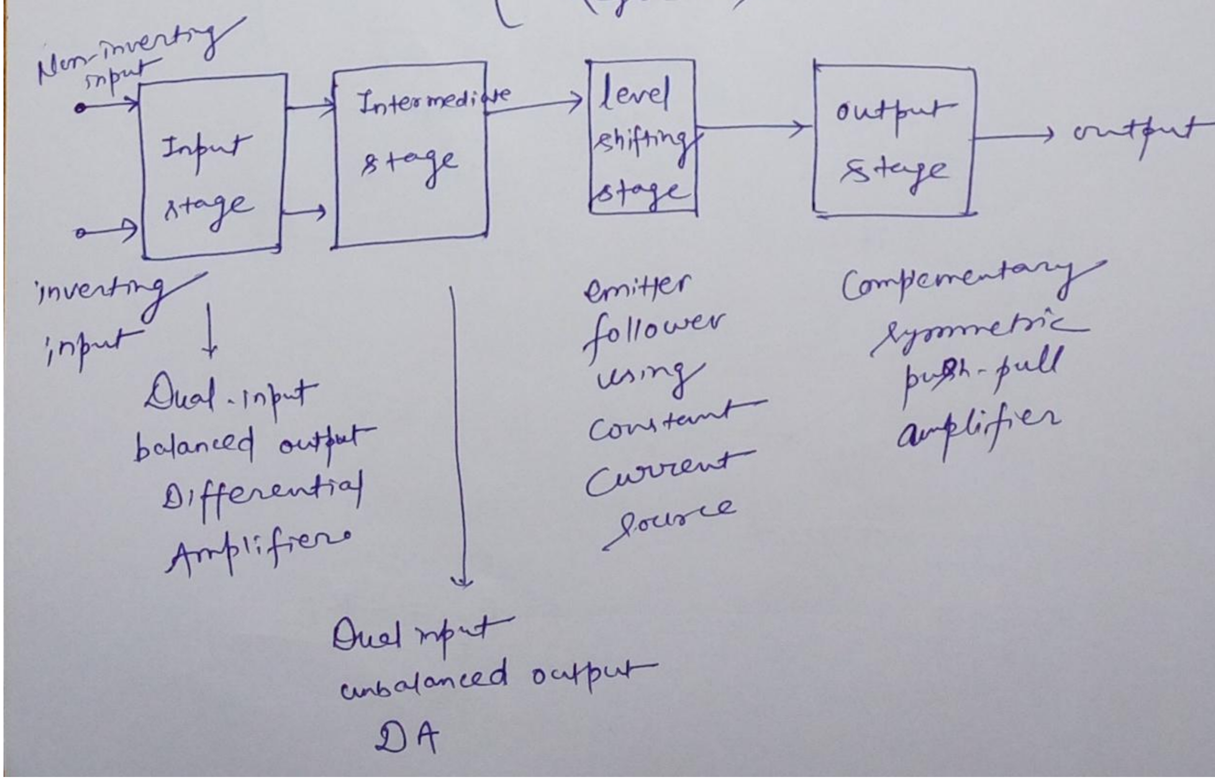
An operational amplifier is a direct coupled high gain amplifier usually consisting of one or more differential amplifiers & usually followed by a level translators and an output stage of push-pull or push-pull complementary symmetry pair.

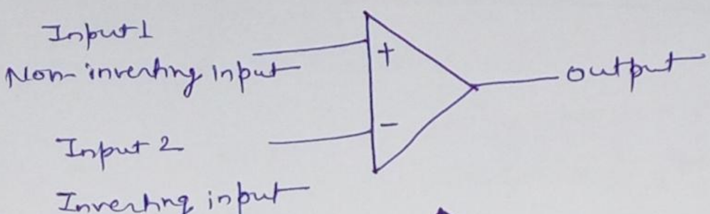
* It is available as a single Integrated circuit package.

* It is a versatile device used to amplify dc as well as ac input signals.

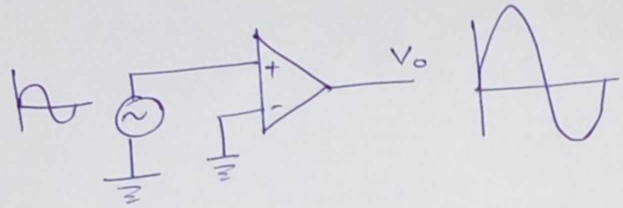
* It was originally designed for performing mathematical operations such as addition, Substraction, multiplication, differentiation & integration.

* Applications : {
  - ac & dc signal amplification
  - active filters
  - Oscillators
  - Comparators
  - Regulators

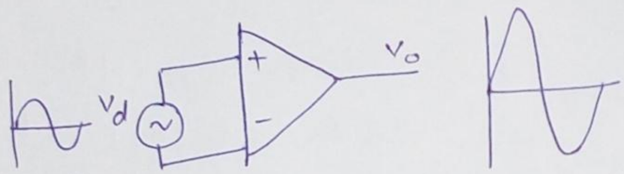





Basic Op-amp

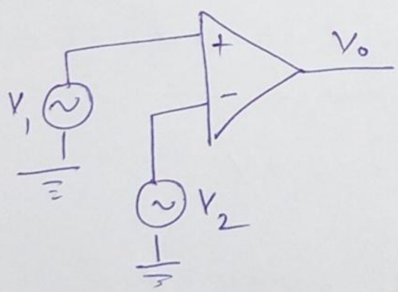



⇐ Single-ended operations

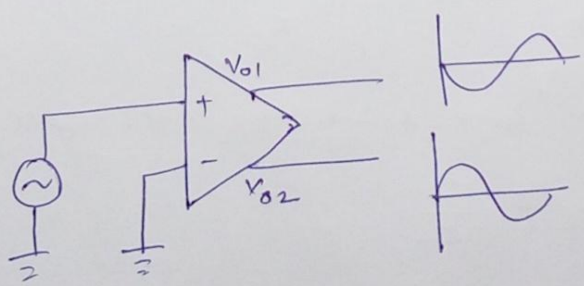



⇐ Double-ended (differential) operation

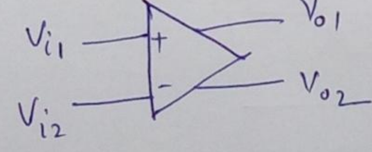
or



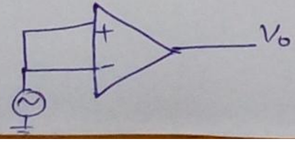

⇐ " "




⇐ Double-ended output with single-ended input

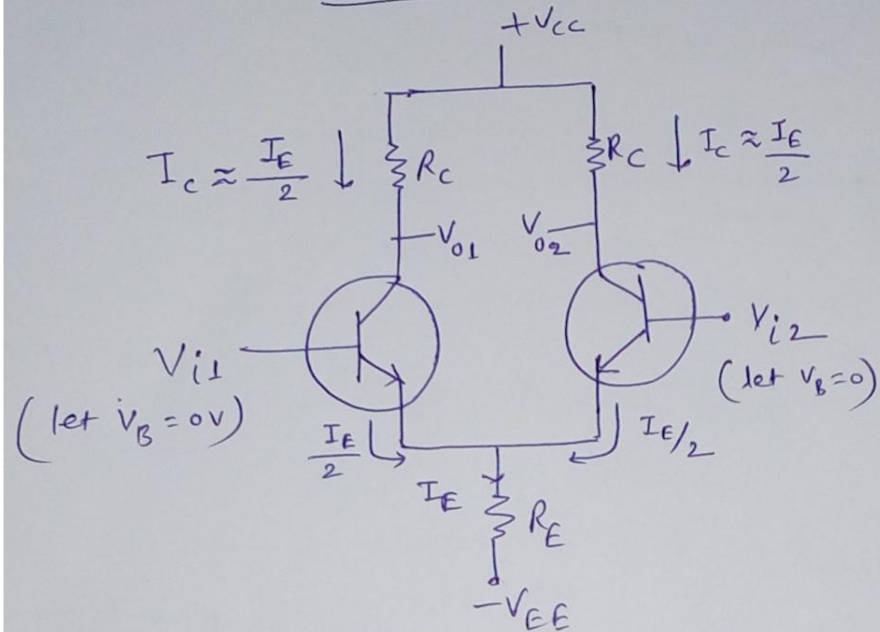


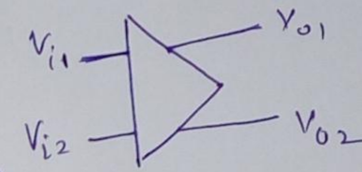

Double ended input & outputs.




Common-mode operation

# Differential Amplifier circuit.




* The main feature is very large gain when opposite signals are applied to the inputs as compared to very small gain resulting from common inputs.

## DC Bias

with each base voltage at 0 V. The common-emitter dc bias voltage is

$$V_E = 0 - V_{BE} = -0.7\,V$$

$$I_E = \frac{V_E - (-V_{BE})}{R_E} \approx \frac{V_{EE} - 0.7\,V}{R_E}$$

Assuming that both transistors are well matched

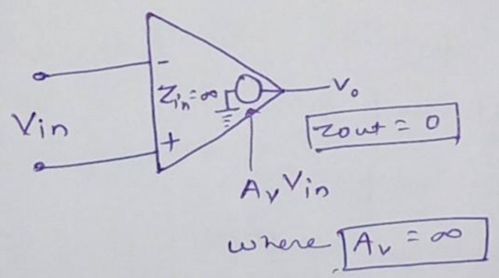
$$I_{e_1} = I_{e_2} = \frac{I_E}{2}$$

& $V_{C_1} = V_{C_2} = V_{CC} - I_C R_C$

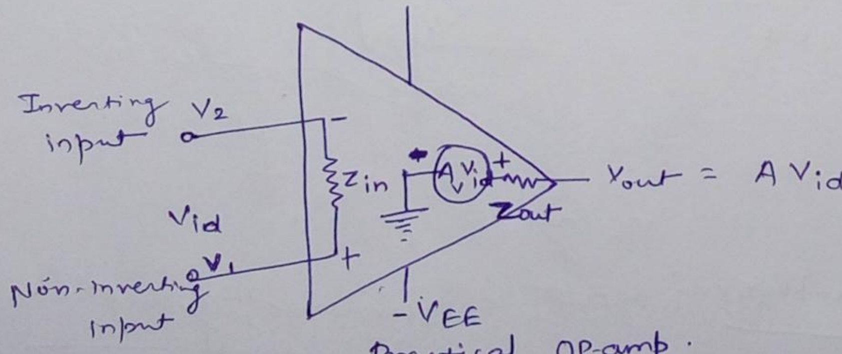
$$\boxed{V_{C_1} = V_{C2} = V_{CC} - \frac{I_E}{2} R_C}$$

# Ideal OP-AMP

1. Infinite voltage gain A.
2. Infinite input resistance $R_i$ so that almost any signal source can drive it and there is no loading of the preceding stage.
3. Zero output resistance $R_o$ so that it can drive an infinite no. of other devices.
4. Zero output voltage when input voltage is zero.
5. Infinite bandwidth (any signal (0 to ∞Hz) can be amplified without attenuation.
6. Infinite common-mode rejection ratio so that the output common-mode noise voltage is zero.
7. Infinite slew rate so that the output voltage changes occur simultaneously with input voltage changes.

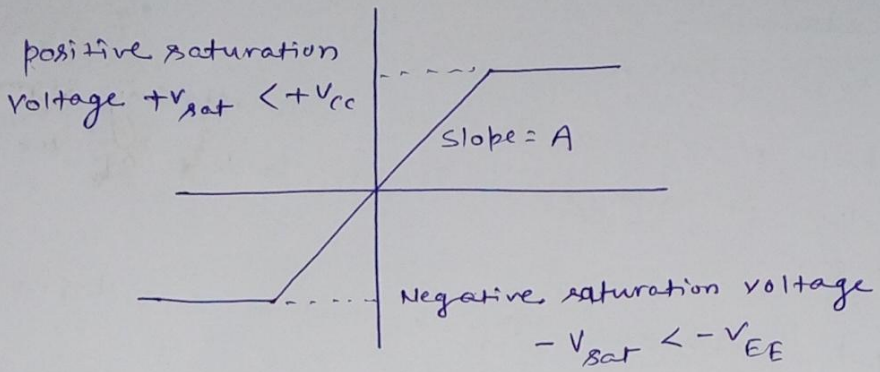



Ideal OP-Amp



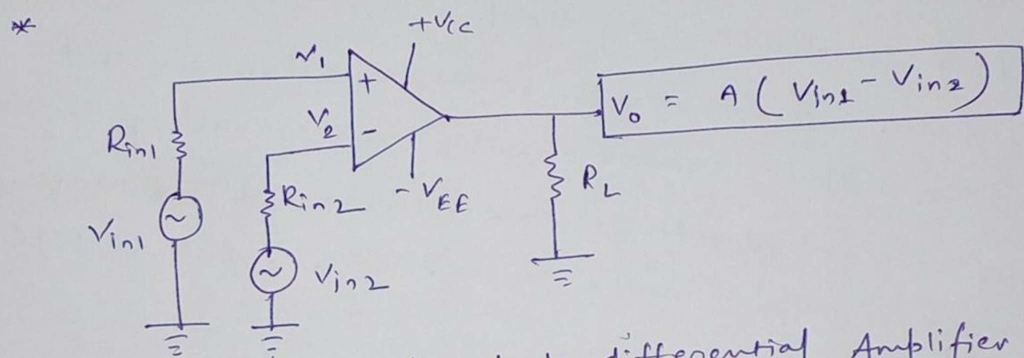

Practical OP-amp.

* Slew rate (SR) = $\frac{\Delta V_o}{\Delta t}$ V/μs



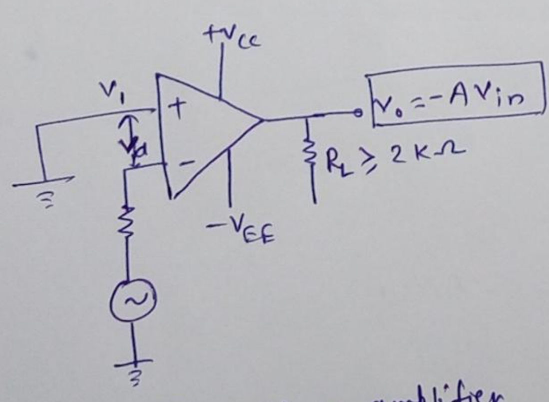

Ideal voltage transfer curve.

*

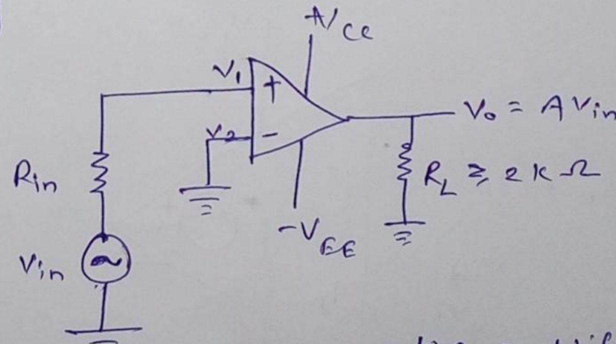



Open-loop differential Amplifier

* There are three open-loop op-amp configurations.
  1. Differential amplifier
  2. Inverting amplifier
  3. Non-inverting amplifier




Inverting amplifier




Non-inverting amplifier.

* Input Offset Voltage: The voltage that must be applie between the two input terminals of an op-amp to null the output.

* Input offset current: The algebraic difference between the currents into inverting and non-inverting terminals is referred to as input offset current.

* Input Bias current: The average of the currents that flows into the inverting and non-inverting input terminals of the op-amp.

$$I_B = \frac{I_{B1} + I_{B2}}{2}$$

* Differential Input Resistance: The equivalent resistance that can be measured at either inverting or non-invertin input terminals with other terminal connected to ground.

* Input Capacitance: The equivalent Capacitance that can be measured at either inverting or non-inverting terminal with other terminal connected to ground.

* Common-Mode Rejection ratio: (CMRR)

$$\boxed{CMRR = \frac{A_d}{A_{cm}}} \quad \& \quad \boxed{CMRR(\log) = 20\log_{10}\frac{A_d}{A_{cm}}}$$

* Output voltage swing: The output voltage never exceeds the limit of given supply voltages, $+V_{CC}$ & $-V_{EE}$.

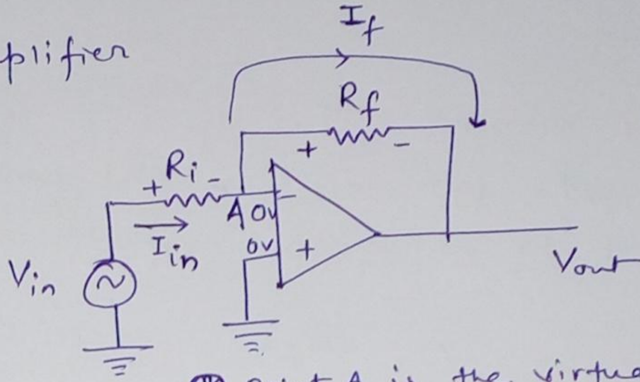
* Output Resistance: The equivalent resistance that can be measured betn the output terminals of op-am and ground. eg: 75Ω for the 741 IC op-amp.

* Supply current: The current drawn by the op-amp from the power supply.

For 741 IC: $I_S = 2.8\,mA$

# Applications of OP-Amps

## 1. Inverting Amplifier




* Point A is the virtual ground.

$$I_{in} = \frac{V_{in} - V_A}{R_i} = \frac{V_{in} - 0}{R_i} = \frac{V_{in}}{R_i}$$

$$I_f = \frac{V_A - V_{out}}{R_f} = \frac{0 - V_{out}}{R_f} = \frac{-V_{out}}{R_f}$$

Since $I_f = I_{in}$ (for ideal op-amp)

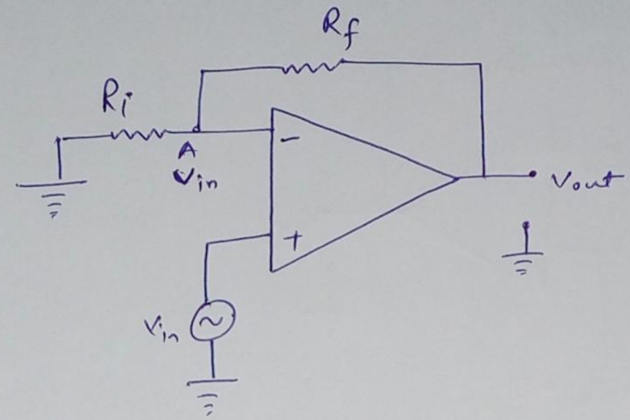
$$\frac{-V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

Voltage gain $\boxed{A_{CL} = \frac{V_{out}}{V_{in}} = \frac{-R_f}{R_i}}$

* The closed-loop voltage gain is independent of the op-amp's internal open-loop voltage gain.

*

## 2. Noninverting Amplifier




Current through $R_i$ = current through $R_f$

$$\frac{V_{in} - 0}{R_i} = \frac{V_{out} - V_{in}}{R_f}$$

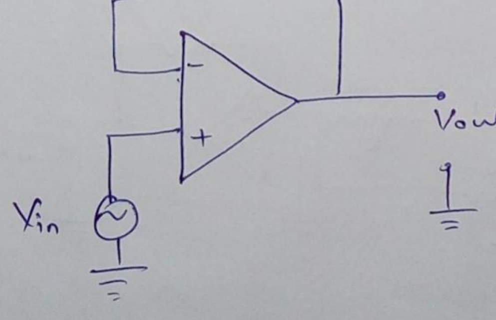
$$V_{in} R_f = V_{out} R_i - V_{in} R_i$$

$$V_{in} (R_f + R_i) = V_{out} R_i$$

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

$$\boxed{A_{CL} = 1 + \frac{R_f}{R_i}}$$

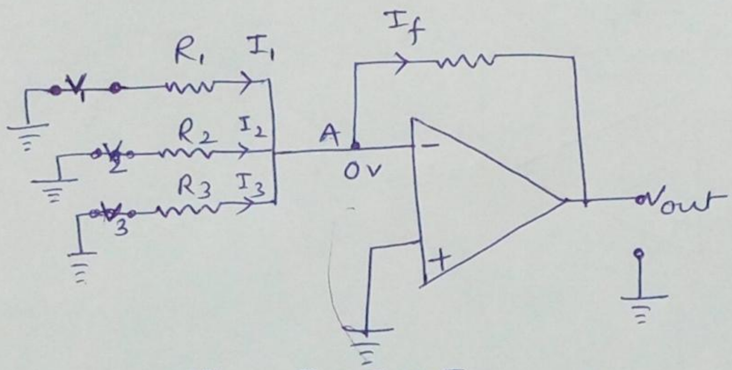
## 3. Voltage follower




$$A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{0}{R_i} = 1$$

* It have very high input impedance & very low output impedance. Hence, it is nearly ideal buffer amplifier to be connected betn high impedance source & low Z lo

## 4. Summing Amplifiers




$$I_f = I_1 + I_2 + I_3$$

$$V_{out} = -I_f R_f$$

$$= -R_f\,(I_1 + I_2 + I_3)$$

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

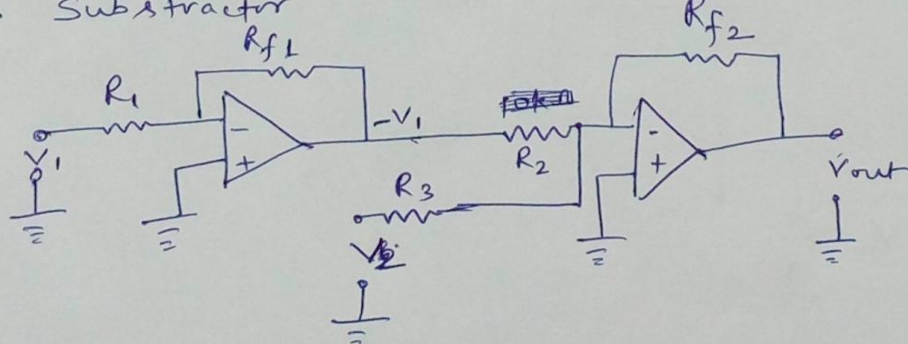
If $R_1 = R_2 = R_3 = R$, we have

$$\boxed{V_{out} = -\frac{R_f}{R}\left(V_1 + V_2 + V_3\right)}$$

again, if gain is unity

$$\boxed{V_{out} = -\left(V_1 + V_2 + V_3\right)}$$

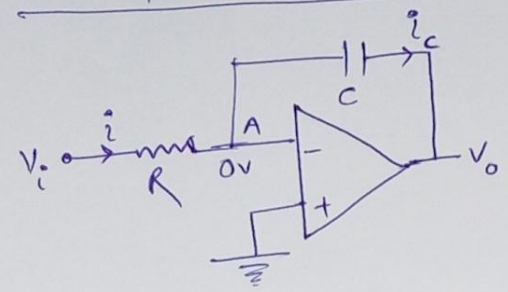
## 5. Substractor




$$\boxed{V_{out} = V_1 - V_2}$$

(If both op-amp have
$R_3 = R_1 = R_{f1} = R_{f2} = R_2$

## 6. OP-Amp Integrator




Since $i = i_c$ for ideal op-amp.

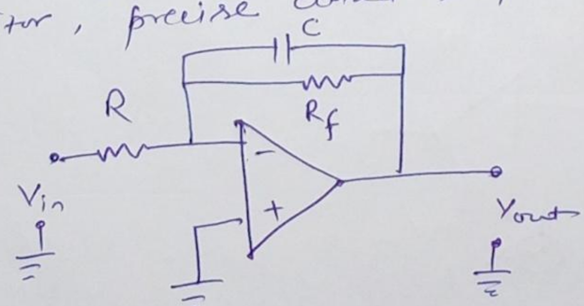
$$\frac{V_i}{R} = \frac{C\,dV_c}{dt} \qquad \left(\because \text{Voltage across capacitor } V_c = 0 - V_o = -V_o\right)$$

$$\frac{V_i}{R} = -C\frac{dV_o}{dt}$$

$$\frac{dV_o}{dt} = -\frac{1}{RC}V_i$$

$$\therefore \boxed{V_o = \frac{-1}{RC}\int_0^t V_i\,dt}$$

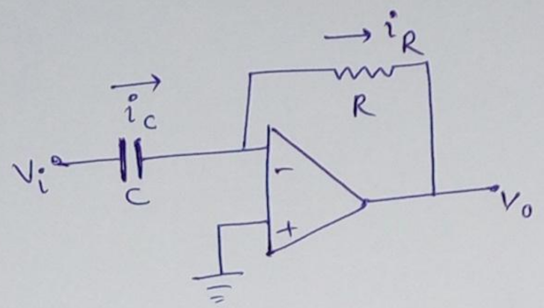
* It has serious disadvantage in low frequency applications. By connecting a feedback resistor $R_f$ in parallel with capacitor, precise closed-loop voltage gain is possible.




$$\boxed{f_c = \frac{1}{2\pi R_f C}}$$

$f_c$ is the critical frequency below which the above circuit cannot perform proper integration. It will behave as inverting amplifier.

## 7. OP-Amp differentiator




$$i_c = i_R$$

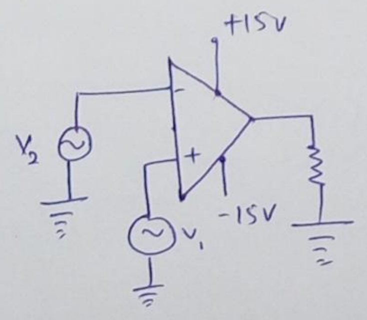
$$C\frac{dV_c}{dt} = \frac{-V_o}{R}$$

$$C\frac{dV_i}{dt} = \frac{-V_o}{R} \qquad (\because V_c = V_i - 0 = V_i)$$

$$\boxed{V_o = -RC\frac{dV_i}{dt}}$$

## 8. Comparators

A comparator is an op-amp circuit without negative feedback and takes advantage of very high open voltage gain of op-amp.

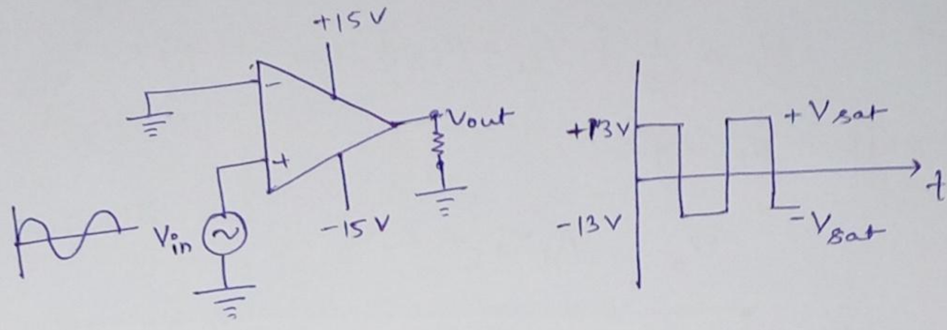



If differential input is +ve, the circuit is driven to saturation and output goes to max$^m$ +ve value.

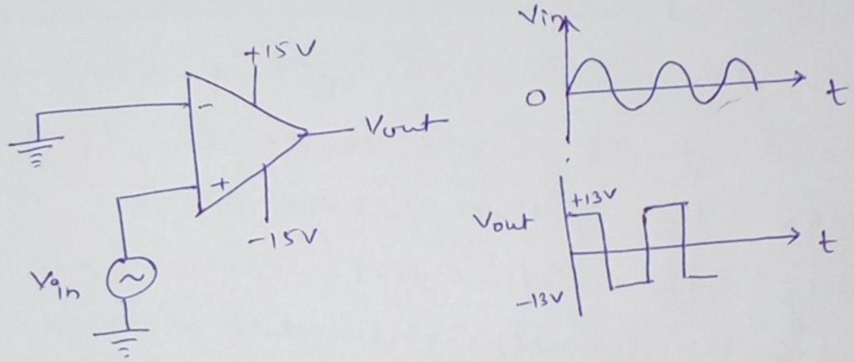
* It uses no feedback so that the voltage gain is equal to the open-loop voltage gain of op-amp.

* It is operated in a non-linear mode.

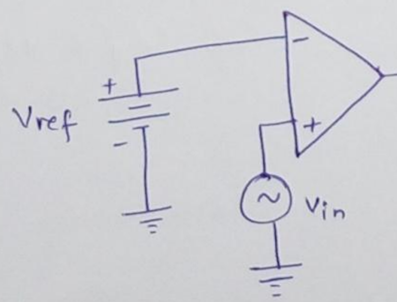
1. As a square wave generator.

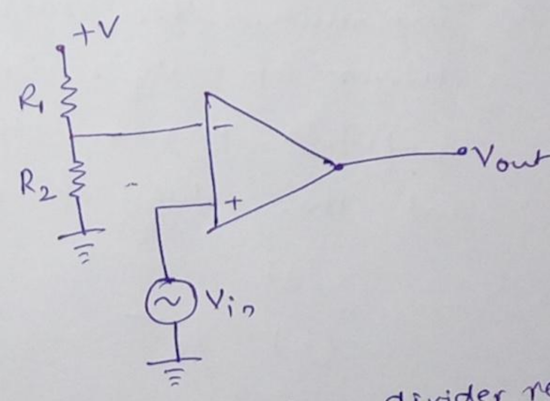



2. As a zero-crossing detector



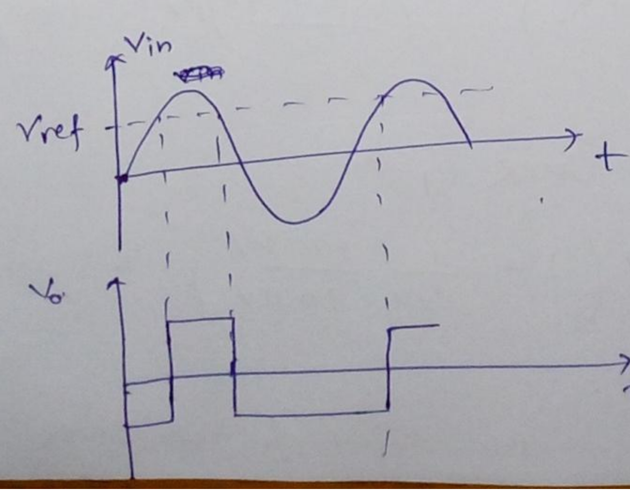

3. As a level detector




Battery ref.

voltage divider ref



Common inputs in Op-amp

$$V_c = \frac{1}{2}(V_{i_1} + V_{i_2}) \longrightarrow (i)$$

output voltage

$$V_o = A_d V_d + A_c V_c \longrightarrow (ii)$$

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

Even when both $V_c$ & $V_d$ components of signals are present, the eqn shows that for large value of CMRR, the output voltage will be due to mostly differential signal & common-mode component greatly reduced or rejected.

Q Determine the output voltages of op-amp for input voltages of $V_{i_1} = 150\,\mu V$ and $V_{i_2} = 140\,\mu V$. The amplifier has a differential gain of $A_d = 4000$ and the value of CMRR is

(a) 100

(b) $10^5$

Soln

$$V_d = V_{i_1} - V_{i_2} = (150 - 140)\,\mu V = 10\,\mu V$$

$$V_c = \frac{1}{2}(V_{i_1} + V_{i_2}) = \left(\frac{150 + 140}{2}\right)\mu V = 145\,\mu V$$

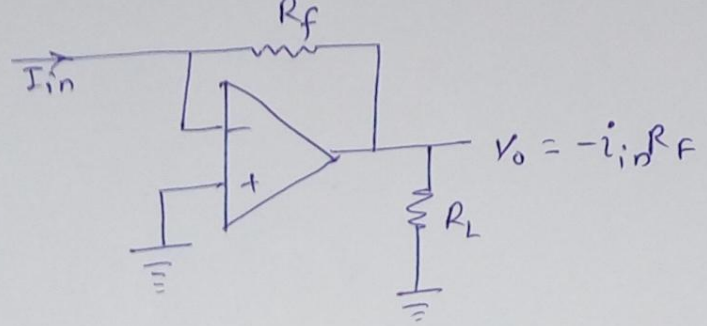
$$V_o = A_d V_d \left(1 + \frac{1}{CMRR}\frac{V_c}{V_d}\right)$$

(a) $V_o = 4000 \times 10\,\mu V \left(1 + \frac{1}{100}\frac{145\,\mu V}{10\,\mu V}\right) = 45.8\,mV$

(b) $V_o = 40.006\,mV$.

* This Question shows the effect of high CMRR.

# Current to Voltage converter




As $\frac{V_o}{V_{in}} = -\frac{R_f}{R_{in}}$ (for inverting amplifier)

$$V_o = -\frac{R_f V_{in}}{R_{in}} = -\left(\frac{V_{in}}{R_{in}}\right) R_f$$

As $\frac{V_{in}}{R_{in}} = i_{in}$

hence, $\boxed{V_o = -i_{in} R_f}$

It indicates that the $V_{in}$ & $R_{in}$ combination is replaced by current source $i_{in}$. The output voltage $V_o$ becomes proportional to the input current $I_{in}$. Hence, the above circuit converts the input current into a proportional output voltage.

* It is used in sensing the current from photodetectors and digital to Analog converter applications.

open loop gain $(\infty)$ very high $\geq 10^4$

open loop Bandwidth $(\infty)$ very high

common mode rejection ratio $(\infty)$ High $(\geq 70\,dB)$

Input resistance $(\infty)$ High $(\geq 10\,M\Omega)$

output resistance $(0)$ low $(< 500\,\Omega)$

off-set voltage and current $(0)$ low $(< 10\,mV;\ < 0.2\,nA)$

* Slew rate

$$\boxed{S_R = 2\pi f_{max} V_p}$$

$V_p$ = peak of the output sin wave.

$f_{max}$ = highest undistorted frequency

## References:


1. Op-Amps and Linear Integrated Circuits by R. A. Gayakwad
2. Linear Integrated Circuits by D. R. Choudhury and S. B. Jain
3. Electronics Fundamentals and Applications by D. Chattopadhyay and P.C. Rakshit
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