UNIT III

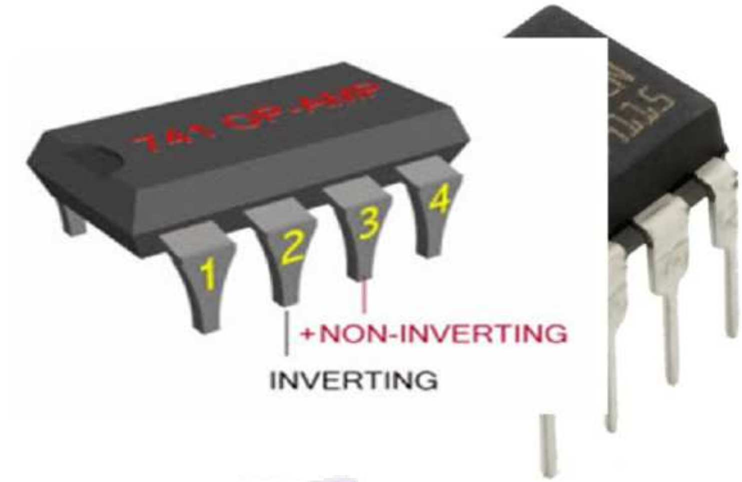
OPERATIONAL AMPLIFIERS

Introduction of Operational Amplifier (Op-Amp)

- This term is used by John R. Ragazzini in 1947.
- Op-Amp performs a variety of operations such as amplifications, addition, subtraction, differentiation and integration.
- Op-Amp is a multistage amplifier which uses a number of differential amplifier stages interconnected to each other in a complicated manner.
- These internal differential amplifiers use BJT (Bipolar Junction Transistor) or FET (Field Effect Transistor) as an amplifying device.
- Differential amplifier is the combination of two BJT in CE (common emitter) mode configuration or two FET in CS (common source) mode configuration.
- Space occupied to a pin-head.
- Op-Amp offers all the advantages of monolithic IC's such as small size, high reliability, reduced cost, less power consumption.
- Op-Amp was brought commercialize by "Fair Child" company named as µA741.

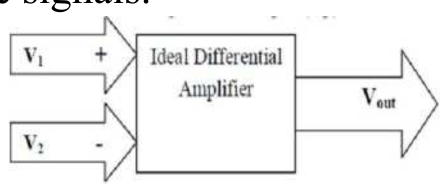
Features of IC 741

- No frequer
- Short circu
- Offset volt
- Large com voltage rar
- No latch-u short circu improperly



Differential amplifier

- A differential amplifier amplifies the difference between two input voltage signals.
- As shown in figure, V_1 & V_2 are two input (i/p) signals while V_{out} is the single ended output (o/p). Each signal is measured with respect to ground.



For an ideal differential amplifier; $\boxed{V_{out} \ \alpha \ (V_1 - V_2)}$

Differential Gain (A_d): We can write above equation as;

$$\boxed{V_{out} = A_d (V_1 - V_2) \text{ or } V_{out} = A_d V_d}$$

- Where;
  A_d = Differential Gain
  V_d = Difference in input voltage

We can write; $A_d = \frac{V_{out}}{V_d}$ **OR** $A_d = 20\log\left(\frac{V_{out}}{V_d}\right)$ dB (**dB** - decibel)

Differential amplifier (continue…

- **Common Mode Gain (A_{cm} or A_c):**
- If $V_1 = V_2$ then ideally $V_{out} = 0$.
- But practically we get some value of V_{out} because of noise and mismatch in internal circuitry.
- That means the output of practical differential amplifier not only depends on difference voltage but also depends on the average common level of two inputs. Such signals is called as common mode signal (V_{cm} or V_c) and given as;

$$V_{cm} = \frac{V_1 + V_2}{2}$$

- Therefore here; $\boxed{V_{out}\ \alpha\ V_{cm}}$ **OR**

$$\boxed{V_{out} = A_{cm} V_{cm}}$$

- Where;
  A_{cm} = Common Mode Gain
  V_{cm} = Common Mode signal

- Therefore; the total output of any differential amplifier can be expressed as;

$$\boxed{V_{out} = A_d V_d + A_{cm} V_{cm}}$$

- Here; A_d is very large and A_{cm} is very small.

Features of Differential Amplifier

- Two input terminals [Non-inverting **(+)** and Inverting **(-)**].
- One output terminal.
- High differential voltage gain.
- Low common mode gain.
- High CMRR (Common Mode Rejection Ratio), where; .
- High input impedance.
- Low output impedance.
- Large bandwidth (BW).
- Low input Offset voltage [V_{in}(off)].
- Low input Offset current [I_{in}(off)].

Numerical On Differential Amplifier

- **Q.** An operational amplifier has a differential gain of 5000 and CMRR of 100, input voltages are 300µV and 240µV, determine output voltage.

Solution: Given;
A_d = 5000, CMRR = 100,
V_1(non-inverting i/p) = 300µV, and V_2(inverting i/p) = 240µV;
We know that the output voltage; $\mathbf{V_{out} = A_d\, V_d + A_{cm}\, V_{cm}}$

$$\text{OR;}\quad V_{out} = A_d\,(V_1 - V_2) + \frac{A_d}{CMRR}\left(\frac{V_1+V_2}{2}\right)$$

$$V_{out} = 5000\,(300 - 240) + \frac{5000}{100}\left(\frac{300+240}{2}\right)$$

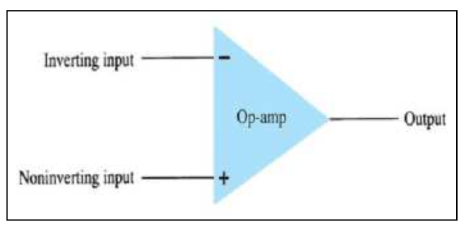
$$V_{out} = 5000 \times 60 + 50 \times 270$$

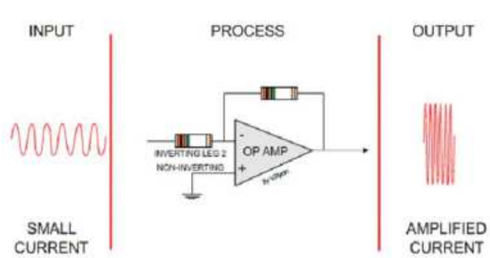
$$V_{out} = 313500\,\mu V$$

$$\boxed{V_{out} = 313.5\,mV}$$

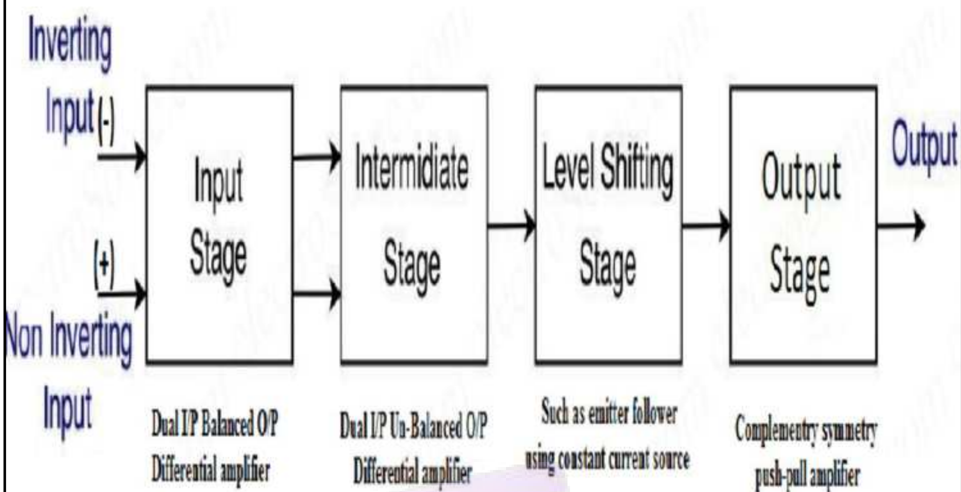
Operational Amplifier

- An Op-Amp is an active circuit element designed to perform mathematical operations of addition, subtraction, multiplication and integration.
- A high gain differential amplifier with a high input impedance (typically in MΩ) and low output impedance (less than 100Ω)
- Op-Amp can amplify signals having frequency range from 0Hz to 1MHz.





Block Diagram of Op-Amp

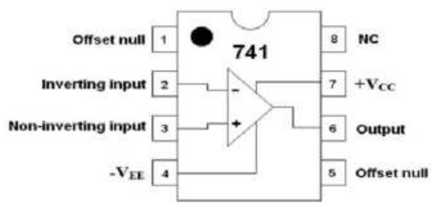


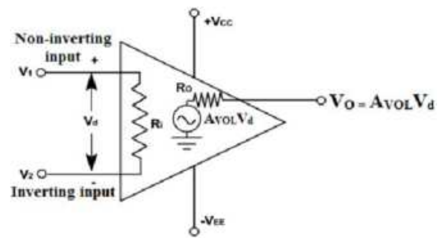
Description of Block Diagram of Op-Amp

- An Operational-Amplifier (Op-Amp) is a basically multistage amplifier.
- The input (i/p) stage is **dual i/p balanced o/p differential amplifier.**
- This stage provides most of the voltage gain of the Op-Amp and decides the i/p resistance value (R_{in}).
- This stage provides high i/p resistance (R_{in}) (typically in **MΩ).**
- The second block is a **dual i/p un-balanced o/p differential amplifier.**
- It consists of many stages of direct coupled differential amplifiers which provides additional gain.
- The last block consist of two stages, one constant currents source (Is) for dc level shifting (usually emitter follower) and second class B push-pull amplifier.
- Due to direct coupling b/w the first two stages, the o/p of more stages of amplifier is an amplified signal (s/g) with some non zero dc level.
- Level shifting stage is used to bring this dc level to zero volts with respect to ground.
- The second one is increases the magnitude of voltage and raises the current capability of the Op-Amp.
- It also provides low o/p resistance (R_{out}) (typically less than **100Ω)**.

Pin Diagram and Equivalent Circuit of Op-Amp

Pin Diagram **Equivalent Circuit**





** For Offset null we use 10kΩ resistance (as a potentiometer) between pin no. 1 & 5.

Ideal Op-Amp

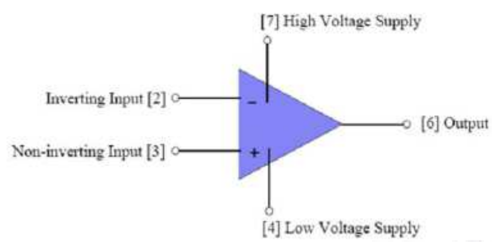
- An ideal Op-Amp is an amplifier with infinite open loop gain, infinite input resistance and zero output resistance.

Characteristics (parameters) of Ideal Vs practical Op-Amp

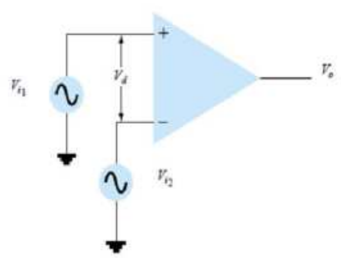
Category (AC/DC)	Parameters	Ideal values	Practical values (741)
AC	Open Loop Voltage Gain	∞	10,0000 (10^5)
	Unity Gain Bandwidth	∞	1 MHz
	CMRR	∞	90dB
	Slew Rate	∞	0.5 V/μ-sec
AC/DC	Input Impedance	∞	2 MΩ
	Output Impedance	0	75 Ω
DC	Input offset voltage	0	2 mV
	Input offset current	0	20 nA
	Input bias current	0	80 nA

Summary

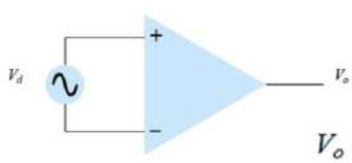
- Op-Amp is a high gain differential amplifier with a high input impedance (typically in MΩ) and low output impedance (less than 100Ω).



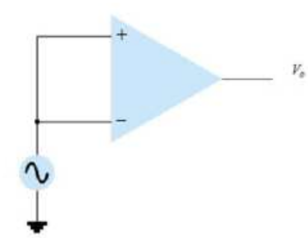
Modes of Operation



Differential Mode



Common Mode



$$V_o = A_d V_d + A_c V_c$$

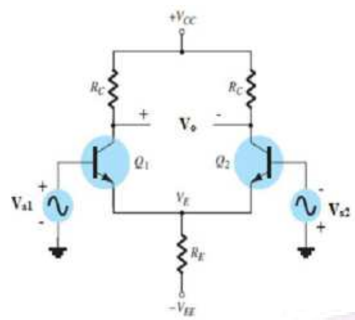
V_d = difference voltage
V_c = common voltage
A_d = differential gain
A_c = common-mode gain

$V_{o1} = A_d V_d$
Where; $V_d = V_1 - V_2$

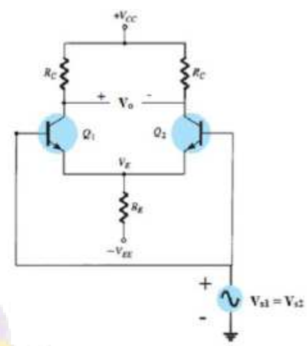
$V_{o2} = A_c V_c$
Where; $V_c = (V_1 + V_2) / 2$

DIFFERENTIAL AMPLIFIRE CIRCUITS USING BJT

DIFFERENTIAL MODE OF OPERATION



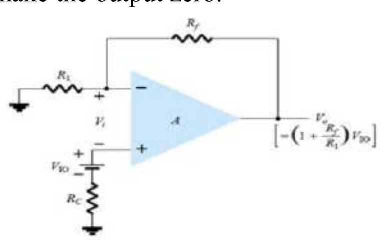
COMMON MODE OF OPERATION



DC- offset Parameters

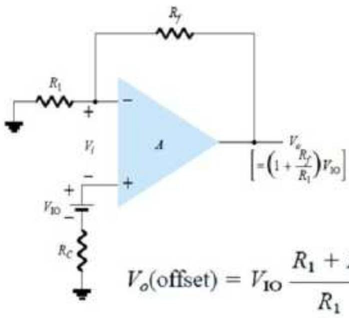
• Even when the input voltage is zero, an Op-Amp can have non zero output voltage called as **output offset voltage**. The following parameters can cause this offset

- **Input offset voltage (V_{IO})**: It is the differential DC voltage required between the inputs of an Op-Amp to make the output zero.



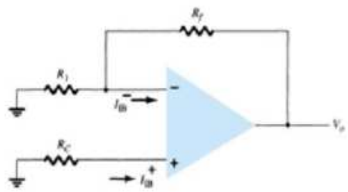
- **Input offset current (I_{IO})**: It is the difference of the currents flowing in the input terminals of the op-amp. $I_{IO} = I_{IB}^{+} - I_{IB}^{-}$
- **Input bias current :** It is the difference of the currents flowing in the input terminals of the Op-Amp. $I_{IB} = \dfrac{I_{IB}^{+} + I_{IB}^{-}}{2}$

Output offset Voltage due to Input offset voltage



$$V_o(\text{offset}) = V_{IO}\frac{R_1 + R_f}{R_1}$$

Output offset Voltage due to Input offset current



$$V_o(\text{offset due to } I_{IO}) = I_{IO}\, R_f$$

TOTAL OFFSET DUE TO V_{IO} AND I_{IO}

$$|V_o(\text{offset})| = |V_o(\text{offset due to } V_{IO})| + |V_o(\text{offset due to } I_{IO})|$$

AC Parameters

An Op-Amp is a wide-bandwidth amplifier. The following factors affect the bandwidth of the Op-Amp:

- CMRR
- Slew rate
- Open loop Gain
- BW

Common Mode Rejection Ratio (CMRR)

- It is the ability of a Differential Amplifier (Op-Amp) to reject the common mode signals successfully and defined as the ratio of Differential mode gain and Common mode gain.

$$\text{CMRR} = \left|\frac{A_d}{A_c}\right| \quad \textbf{OR} \quad \text{CMRR(dB)} = 20\log\left|\frac{A_d}{A_c}\right|$$

- For ideal op-amp, CMRR is infinite.
- For practical op-amp, CMRR is 90dB.

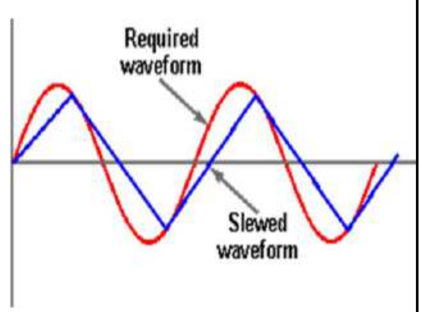
Slew Rate (SR)

Definition:

- The slew rate is defined as the maximum rate of change of output voltage with respect to time.
- For ideal op-amp, SR is infinite.
- For practical op-amp, SR is 0.5 V/μs.

$$\boxed{SR = \left.\frac{\Delta V_o}{\Delta t}\right|_{max} \quad \text{(in V/μs)}}$$

- It is also defined as the maximum rate at which an Op-Amp can change output without distortion and expressed in Volt per microsecond.



Maximum Signal Frequency

• The slew rate determines the highest frequency of the op-amp without distortion. It is given as:

$$\boxed{f \leq \frac{SR}{2\pi V_p}}$$

• where V_P is the peak output voltage or in numerical it is output voltage Vo.

OR

$$\omega_{max} = \frac{SR}{V_o}$$

• For inverting op-amp $V_o = -\frac{R_f}{R_1} V_{in}$

• For non-inverting op-amp $V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}$

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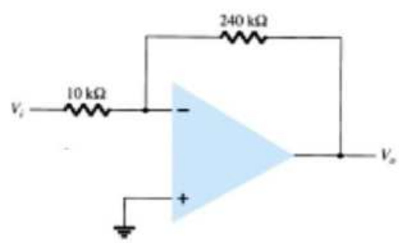
NUMERICAL

- For an input of 50 mV, determine the maximum frequency that may be used for the Op-Amp in non-inverting configuration if its slew rate is 0.4 μV/s.



Soln: $\omega_{max} = \frac{SR}{V_o}$; as we see in this numerical maximum frequency has been asked for non-inverting case, and the o/p of **non-inverting** op-amp is $V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}$

Therefore, $V_o = \left(1 + \frac{240 \times 10^3}{10 \times 10^3}\right) 50 \times 10^{-3} = 1250\text{ mV}$

Now; $\omega_{max} = \frac{0.4 \times 10^{-6}}{1250 \times 10^{-3}} = \mathbf{0.00032 \times 10^{-3}}$ **(rad/sec)**

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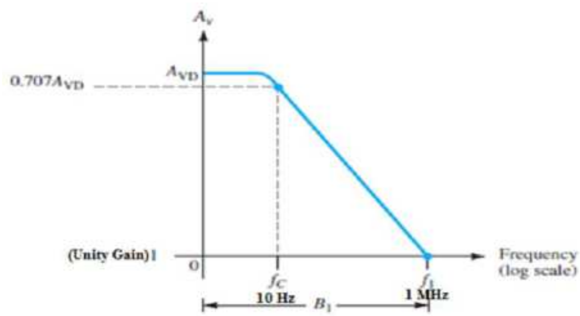
Gain and Bandwidth (Frequency Response)

- The Op-Amp's high frequency response is limited by its internal circuitry. The plot shown is for an open loop voltage gain (A_{VOL}) or voltage differential gain (A_{VD}). Open loop gain is ideally infinite or as high as possible but BW (10 Hz) for the same is small as shown in fig.

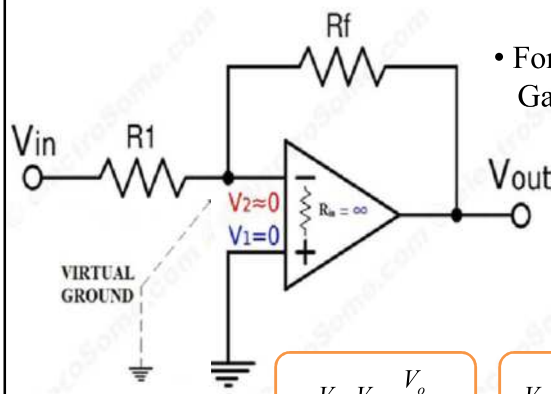


- The Gain Bandwidth product is defined as: $\boxed{f_1 = A_{VD} f_C \ \textbf{OR}\ f_1 = A_{VOL} f_C}$
- As gain decrease, frequency will increase. As shown in fig. if gain is unity (1) then BW is 1MHz.

Summary

Input offset current	$I_{IO} = I_{IB}^{+} - I_{IB}^{-}$
Input bias current	$I_{IB} = \dfrac{I_{IB}^{+} + I_{IB}^{-}}{2}$
Common Mode Rejection Ratio	$CMRR = \left\lvert \dfrac{A_d}{A_c} \right\rvert$
Slew Rate	$SR = \dfrac{\Delta V_o}{\Delta t}\Big\rvert_{max}$ (in V/μs)

CONCEPT OF VIRTUAL GROUND



- For the Op-Amp, we know that; Gain, $A = \frac{V_o}{V_d}$

$V_d = V_1 - V_2$

$$A = \frac{V_o}{V_1 - V_2}$$

$$V_1 - V_2 = \frac{V_o}{A}$$

$$V_1 - V_2 = \frac{V_o}{\infty} = 0$$

$$V_1 = V_2$$

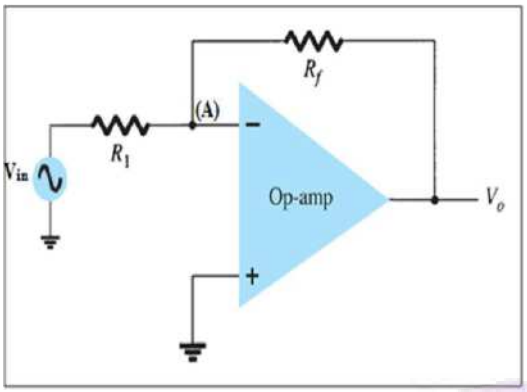
- Since $V_1 = 0$ (actual ground), then $V_2 = 0$ (but it is not actually grounded, which means it is virtual ground).
- Also, if V_1 = any value e.g. K, then $V_2 = K$.

CONCEPT OF VIRTUAL SHORT

- We know that; $I_{in} = \frac{V}{R_{in}}$
- Input resistance $R_{in} = \infty$.
- Therefore; $I_{in} = \frac{V}{\infty} = 0$
- Hence, current in-to Op-Amp is always zero.
- This is the concept of virtual short (because actually we are not shorting it).

Inverting Amplifier

Definition: An op-amp circuit that produces an amplified output signal that is 180° out of phase with input signal.



$$V_o = -\frac{R_f}{R_1} V_{in}$$

The closed loop Gain

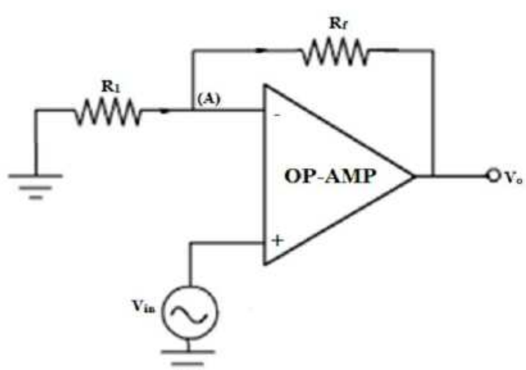
$$\boxed{A_v = \frac{V_o}{V_{in}} = -\frac{R_f}{R_1}}$$

Gain can be set to any value by manipulating the values of R_f and R_1.

The negative sign denotes a 180° phase shift between input and output.

Non-inverting Amplifier

Definition: A non-inverting amplifier is an op-amp circuit designed to provide positive voltage gain. The input is applied directly to the non-inverting terminal.



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

The closed loop Gain

$$\boxed{A_v = \frac{V_o}{V_i} = 1 + \frac{R_f}{R_1}}$$

Gain can be set to any value by manipulating the values of R_f and R_1.

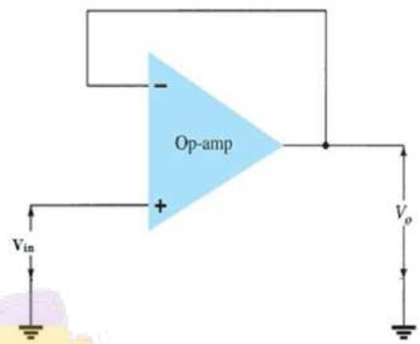
The positive sign denotes that input and output are in same phase.

Unity Follower/Buffer Amplifier

- In non-inverting amplifier if we put $R_f = 0\ \Omega$ and $R_1 = \infty\ \Omega$, then;

$$V_o = \left(1 + \frac{0}{\infty}\right) V_{in} \qquad V_o = V_{in}$$

- **Features of Buffer amplifier:**
- The Voltage Gain is unity
- Highest Bandwidth
- High input impedance
- Low output impedance
- Impedance Matching

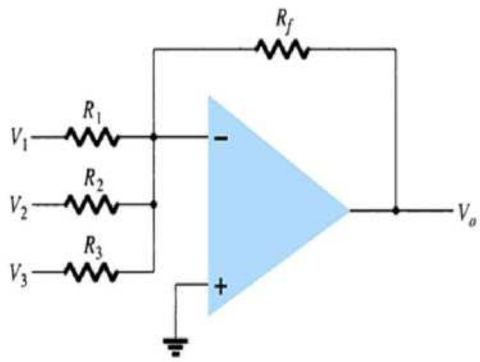


Op-Amp Applications

- Summing Amplifier or Adder
- Averager
- Sub-tractor
- Integrator
- Differentiator

Voltage Summing Amplifier

- Adder is an op-amp circuit, which can accept two or more inputs and produces output as the sum of these inputs.



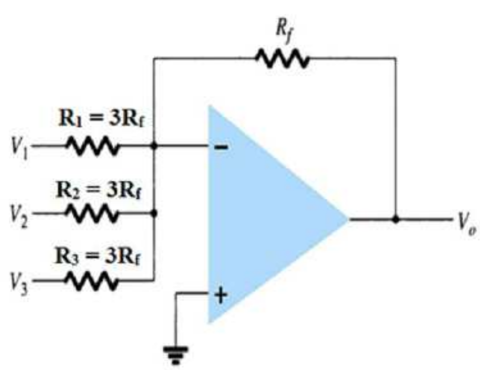
$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

The Averager

- Averaging amplifier gives an output voltage proportional to the average of all the input voltages.
- If there are three input voltages, the average should be the sum of input voltages divided by three.

Conditions:

- All i/p resistors are equal in values.
- The ratio of any i/p resistor to the feedback resistor is equal to the number of inputs. $\frac{R_{in}}{R_f} = n$



- Where;

  R_{in} = i/p resistor
  R_f = feedback resistor
  n = number of inputs

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

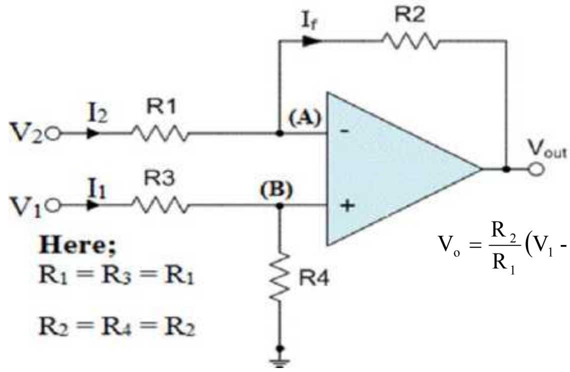
Subtractor

• A circuit that amplifies the difference between two signals is called difference amplifier or subtractor.

Conditions:

$R_1 = R_3 = R_1$

$R_2 = R_4 = R_2$



$$V_o = \frac{R_2}{R_1}(V_1 - V_2)$$

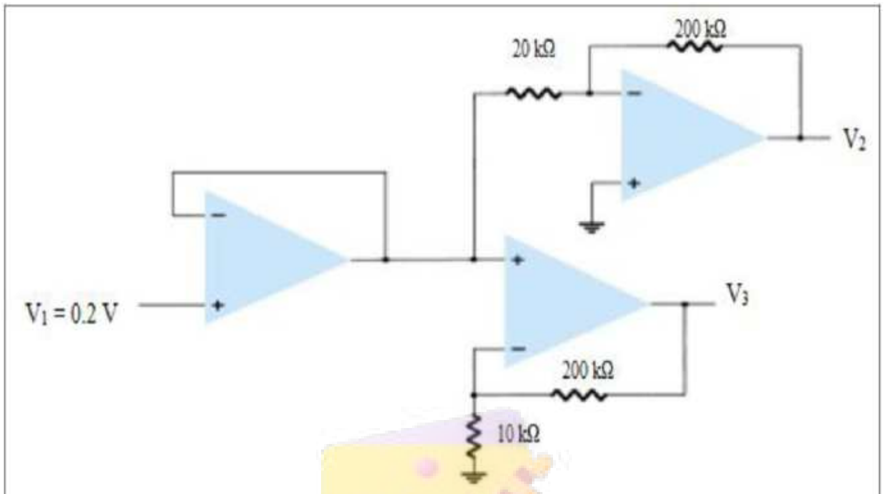
$$\text{If, } R_1 = R_2\text{; then, } V_o = (V_1 - V_2)$$

Summary

Inverting Amplifier	$A_v = \frac{V_o}{V_i} = -\frac{R_f}{R_1}$
Non-inverting Amplifier	$V_o = (1 + \frac{R_f}{R_1})V_1$
Unity Follower	$V_o = V_1$
Voltage Summing amplifier	$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$
Averager	$V_o = -\left(\frac{R_f}{3R_f}V_1 + \frac{R_f}{3R_f}V_2 + \frac{R_f}{3R_f}V_3\right) = -\left(\frac{V_1 + V_2 + V_3}{3}\right)$
Subtractor	$V_o = \frac{R_2}{R_1}(V_1 - V_2)$

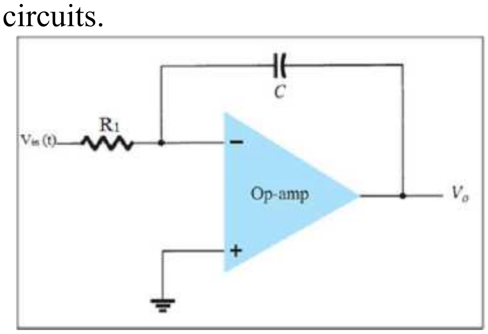
Practice question

- Find out the voltage V2 and V3 of the network of the figure.

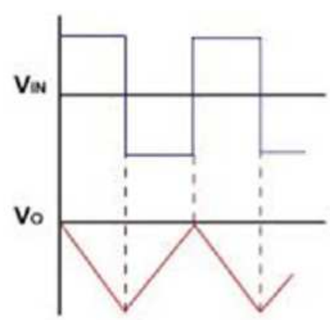


Integrator

- A circuit that performs integration of i/p signals is called integrator.
- The output of an integrator is proportional to the area of the input waveform over a period of time.
- This circuit is useful in low-pass filter circuits and sensor conditioning circuits.



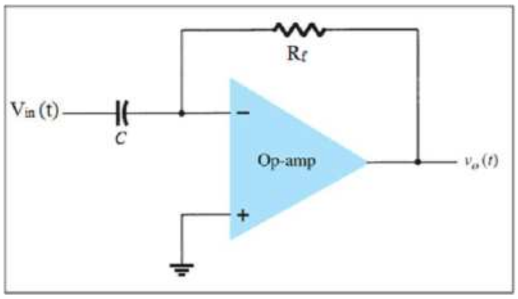
Waveform:



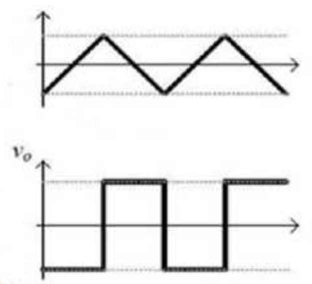
$$v_o(t) = -\frac{1}{R_1 C}\int v_{in}(t)dt$$

Differentiator

- A circuit that performs mathematical differentiation of input signal is called differentiator.
- The o/p of a differentiator is proportional to the rate of change of its input signal.
- This circuit is useful in high-pass filter circuits.



Waveform:



$$v_o(t) = -R_f C \frac{dv_{in}(t)}{dt}$$

Summary

- **Op-amp outp** $V_o = A_d V_d + A_c V_c$
- **Input offset current**
  $I_{IO} = I_{IB}^{+} - I_{IB}^{-}$
- **Input bias current**
  $I_{IB} = \frac{I_{IB}^{+} + I_{IB}^{-}}{2}$
- **Slew Rate** $SR = \frac{\Delta V_o}{\Delta t}\Big|_{max}$ (in V/µs)
- **CMRR** $CMRR = \left|\frac{A_d}{A_c}\right|$
- **Inverting amp** $A_v = \frac{V_o}{V_i} = -\frac{R_f}{R_1}$
- **Non-Inverting amp** $V_o = (1 + \frac{R_f}{R_1})V_1$
- **Summing amp**
  $V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$
- **Subtractor** $V_o = \frac{R_2}{R_1}(V_1 - V_2)$
- **Integrator**
  $v_o(t) = -\frac{1}{R_1 C}\int v_{in}(t)dt$
- **Differentiator**
  $v_o(t) = -R_f C \frac{dv_{in}(t)}{dt}$
- **Gain Bandwidth product**
  $f_1 = A_{VD} f_C$