TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
THAPATHALI CAMPUS

Instrumentation I

BEX, BCT, BEL

Chapter 4: Electrical Signal Processing and Transmission

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Chapter 4. Electrical Signal Processing and Transmission (6 hours/10 Marks)

4.1 Basic Op-amp characteristics

4.2 Instrumentation amplifier

4.3 Signal amplification, attenuation, integration, differentiation, network isolation, wave shaping

4.4 Effect of noise, analog filtering, digital filtering

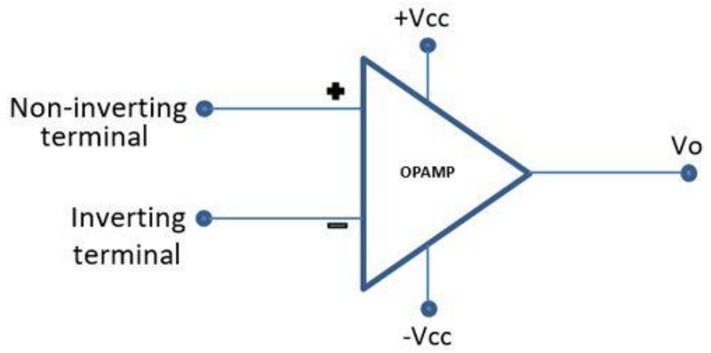
4.5 Optical communication, fiber optics, electro-optic conversion devices

Operational Amplifier

- The operational amplifier commonly referred to as Op-Amp was introduced in 1940s
- In those days it was used in analog computer to perform a variety of mathematical operations such as addition, subtraction, multiplication, differentiation, integration etc
- Now a days Op-Amp can be used for sign changing, scale changing , phase shifting, voltage regulation , oscillator circuit, active filters, active rectification (called precision rectification) wave generators, converters, & to construct the sample and hold circuits etc
- Due to the use of vacuum tubes, the early Op-Amp's were bulky, power consuming and expensive
- The Op-Amp manufactured with integrated circuit technology contains transistors, diodes, resistors and capacitors, is an extremely versatile device that does countless jobs in many electronic circuits

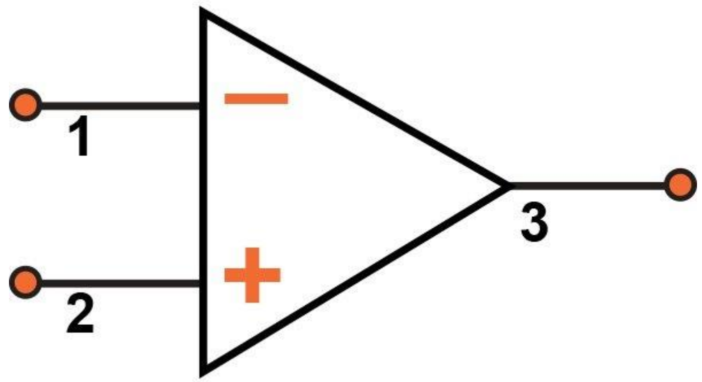
Introduction

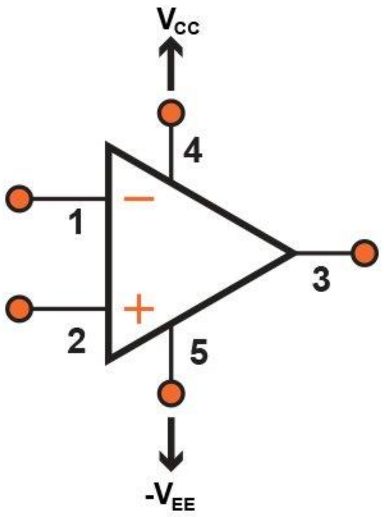
- An Op-Amp is basically a multi-stage, very high gain, direct-coupled, negative feedback amplifier that uses voltage-shunt feedback to provide a stabilized voltage gain
- An op-amp is a direct coupled amplifier which is often powered by both positive and negative supply voltage which allows output to swing above and below ground.
- An Op-Amp is a high gain differential amplifier having very high input impedance (typically a few mega ohms) and low output impedance (less than 100 Ω)
- The symbol of Op-Amp is shown below

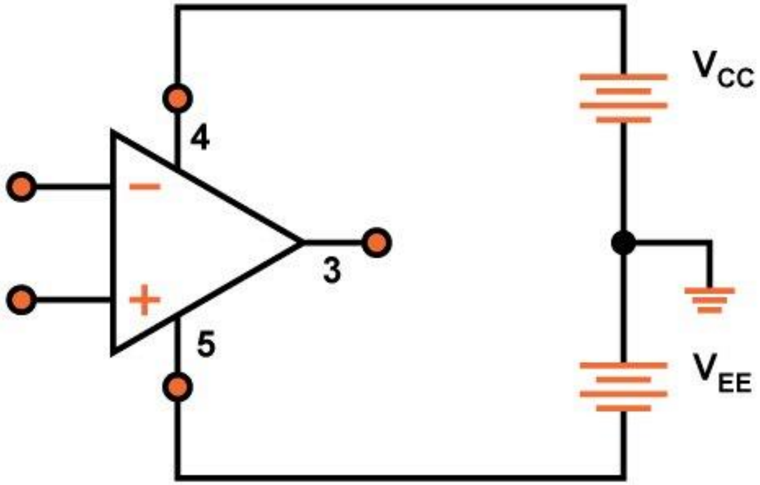


Op-amp symbol

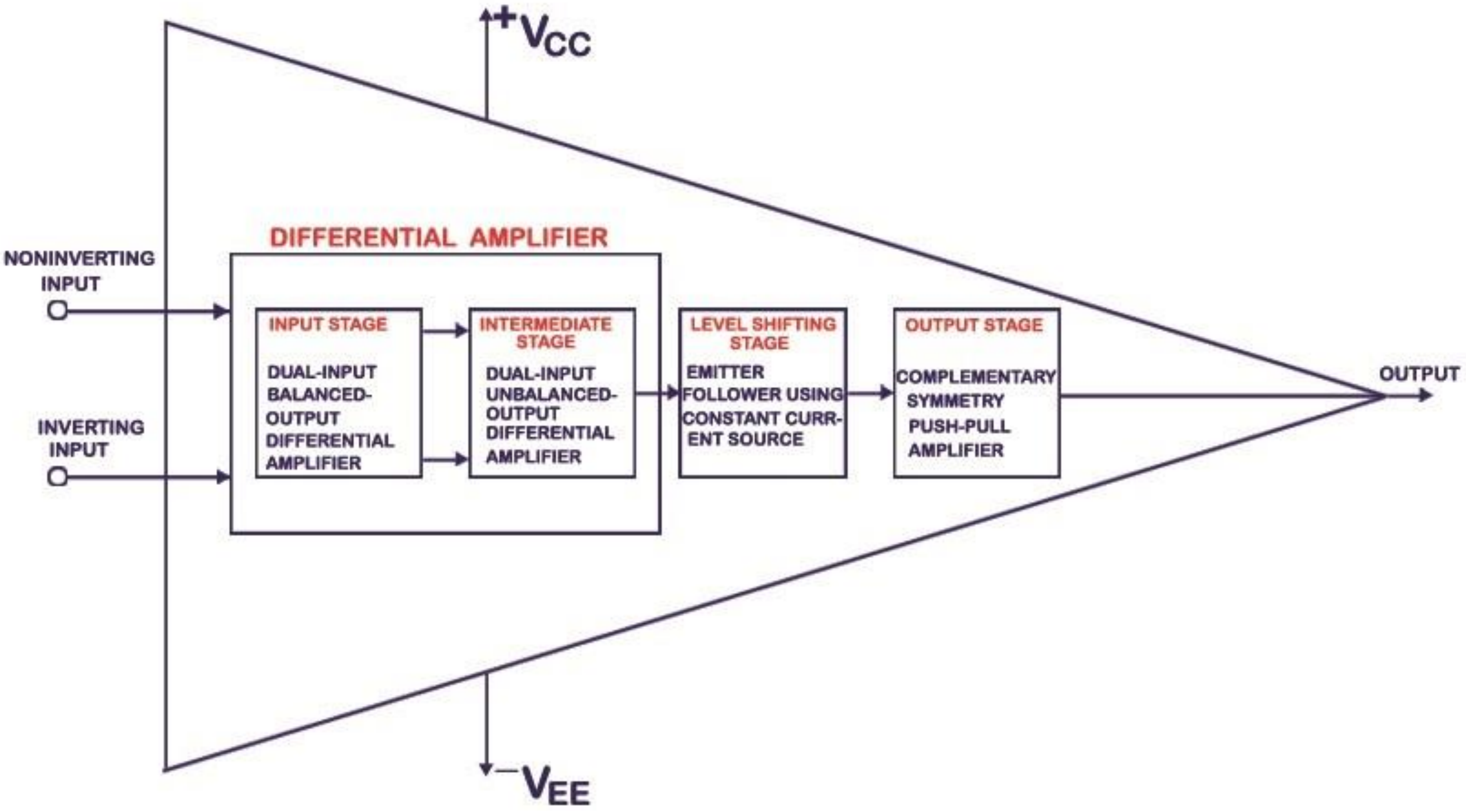
- There are mainly five terminals in an Op-Amp
  1. Inverting input terminal
  2. Non inverting input terminal
  3. Output terminal
  4. Positive supply terminal
  5. Negative supply terminal
- The op-amp does not work without the supply voltage
- Figure shows the dc power supplies as batteries, having a common ground source. The ground source that the two dc power supplies are connected to is actually just the common terminal of the two power supplies. It is interesting that this is so because not one terminal on the op-amp package is physically connected to the ground.







Block diagram of typical Op-Amp



Block diagram of typical Op-Amp

- The inverting and non-inverting inputs are provided to the input stage which is a dual input, balanced output differential amplifier.
- The voltage gain required for the amplifier is provided in this stage along with the input resistance for the op-amp.
- The output of the initial stage is given to the intermediate stage, which is driven by the output of the input stage.
- In this stage direct coupling is used, which makes the dc voltage at the output of the intermediate stage above ground potential. Therefore, the dc level at its output must be shifted down to 0 Volts with respect to the ground.
- For this, the level shifting stage is used where usually an emitter follower with the constant current source is applied.
- The level shifted signal is then given to the output stage where a push-pull amplifier increases the output voltage swing of the signal and also increases the current supplying capability of the op-amp.

Summary

Input Stage:

- Increases the CMRR.
- High gain requirement is adjusted.
- Most of the gain is adjusted.
- Provides the input impedance very high.

Intermediate Stage:

- Driven by output of 1st
- Adjust the half gain of 1st
- Error voltage is cancelled in this stage.

Level Shifting:

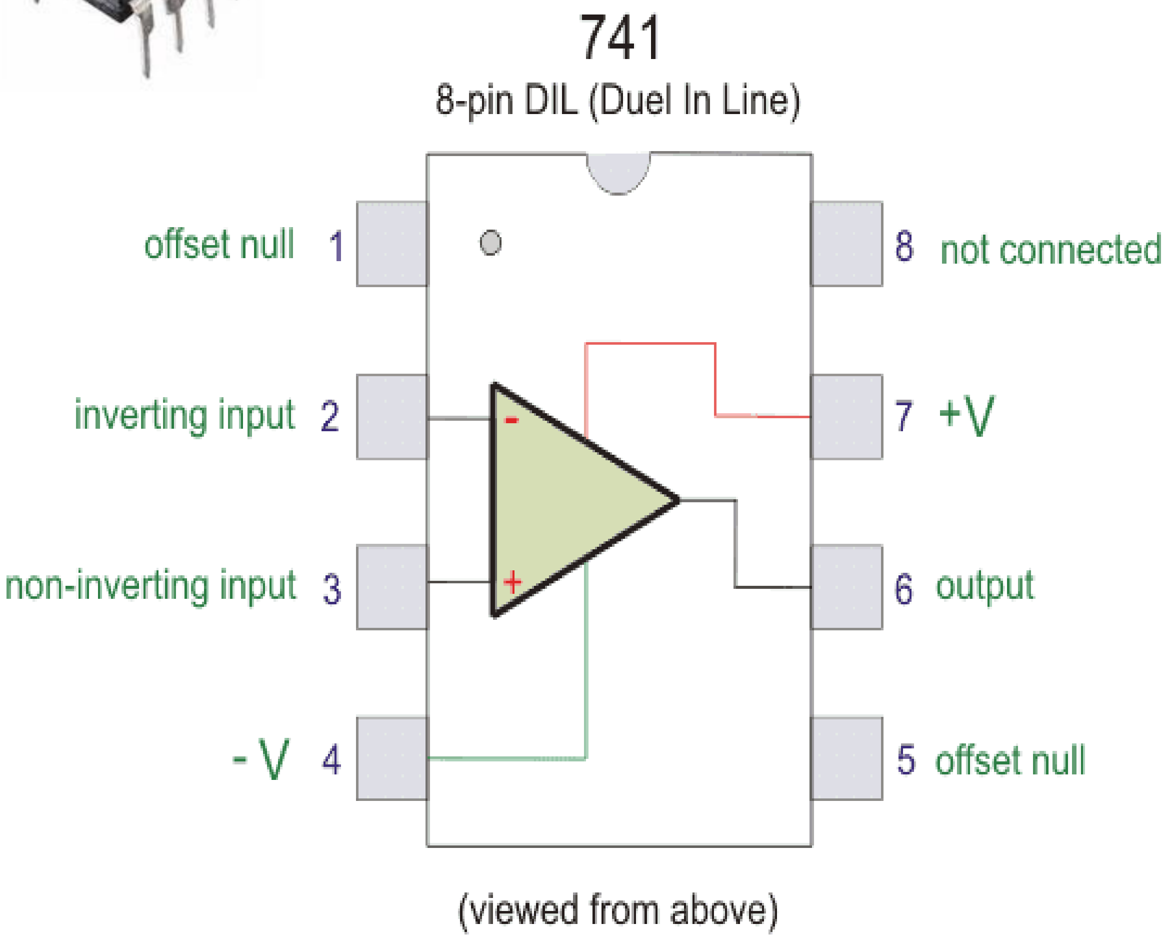
- Suppress the dc level downward to zero volt with respect to ground
- Consisting of current amplifiers as emitter followers.
- Also minimizes the error by suppressing dc level to ground.

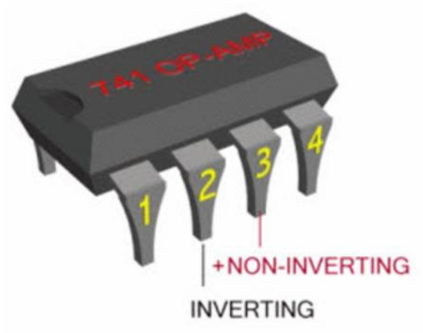
Output Stage:

- This stage increases the output voltage swing and the current in supplying capability of the amplifiers.
- Provides low output impedance.

Pin Configuration

- One of the most popular Op-Amps is the 741 type, which has been produced by several manufacturers for many years
- The 741 is a plastic encapsulated device with dual in line (DIL) rows of pin
- It is an 8 pin IC.
- Two pins (1 and 5) are provided on 741 and are labelled offset null. The offset effects are one of the several types of non-ideal behavior of Op-Amps





Function and types of Op-Amp

- Op-Amp has high input impedance and low output impedance and capable to amplify the ac o dc signal having the frequency of 0 Hz dc to 1MHz ac
- It is a differential input and single ended output amplifier. In other words, it senses the difference between two input terminals and output is equal to amplification factor times the difference in input voltage.

$$\boxed{V_{out} = A_V(V_2 - V_1)}$$

A_V = Gain of Op-Amp

V_2 & V_1 are two inputs of the Op-Amp

- Basically there are two types of Op-Amp
  1. Ideal Op-Amp: is the theoretical abstraction and cant be practically realizable in the circuit
  2. Practical Op-Amp: is out of the order of theoretical abstraction and can be realized in the circuit

Characteristics of Ideal Operational Amplifiers

1) The open loop Voltage Gain A_0 is infinity. $[\therefore A_0 = \infty]$
2) The input impedance Z_i is infinite, so that almost any signal source can be drive it and there is no loading of the preceding stage. $[\therefore Z_i = \infty]$
3) The output impedance Z_o is zero, so that the output can be drive an infinity number of other devices. $[\therefore Z_O = 0]$
4) Perfect Balance, i.e. the differential voltage in inverting and non-inverting terminals be zero. [i.e. two inputs are virtually grounded]
5) Zero output voltage when input is zero.
6) Infinity bandwidth so that any frequency signal from 0 to ∞ Hz can be amplified without attenuation. [BW = ∞]
7) The CMRR [common-mode rejection ratio] is infinite so that the output common-mode noise voltage is zero. [CMRR→ ∞]
8) Infinity slew rate [SR] so that output voltage changes occur simultaneously with input voltage changes. [SR→ ∞]
9) Zero drift of characteristics with temperature.

Characteristics of Practical Op-amp

There are practical op-amps that can be made to approximate some of these characteristics using a negative feedback arrangement. In practical, the input resistance, output resistance, and bandwidth can be brought close to ideal values by this method.

The practical op-amp has the following characteristics:

1) The open loop voltage gain A_0 is maximum and finite, typical value for practical op-amp is considered to be 200,000.
2) The input impedance Z_i is maximum and is finite i.e. in the order of 100 KΩ or more.
3) The output impedance Z_O is minimum not zero, in the order of 100 Ω or less.
4) The CMRR is maximum and finite.
5) Bandwidth is maximum and finite i.e. it can amplify dc to 1 MHz signal.
6) Slight drift of characteristics due to the change in temperature not null.
7) Two terminal may be virtually ground not $V_d = 0$ exactly, for all conditions.
8) Maximum slew-rate and has the finite value.
9) Output is negligible due to dc-bias, when the input is zero.

Virtual ground concept

- As the name indicates it is virtual, not real ground, for some purposes we can consider it as equivalent to ground.
- In Op-Amps the term virtual ground means that the voltage at that particular node is almost equal to ground voltage (0V).
- It is not physically connected to ground and this concept is very useful in analysis of Op-Amps circuits and it will make a lot of calculations very simple.

Lets see how the virtual ground concept is employed in inverting amplifier.

- We already know that an ideal Op-Amps will provide infinite voltage gain. For real Op-Amps also the gain will be very high such that we can consider it as infinite for calculation purposes.

$$\text{Gain} = \frac{V_{out}}{V_{in}}$$

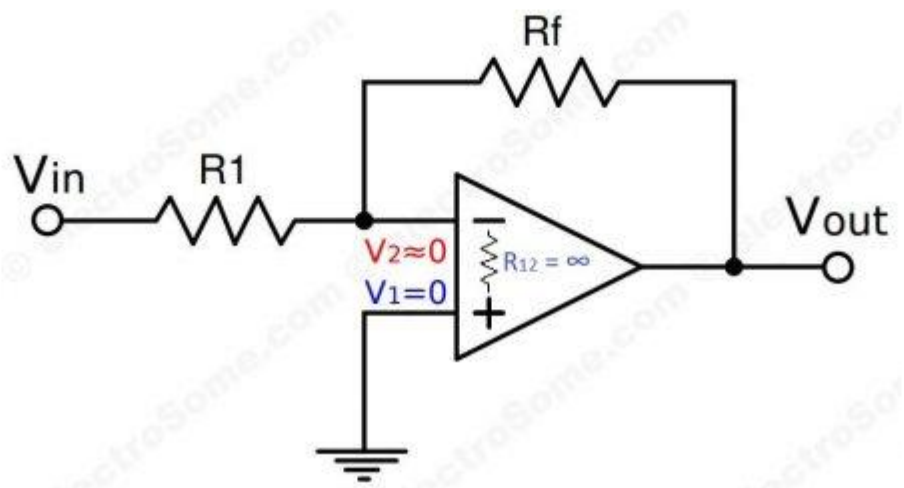
As gain is infinite, $V_{in} = \mathbf{0}$

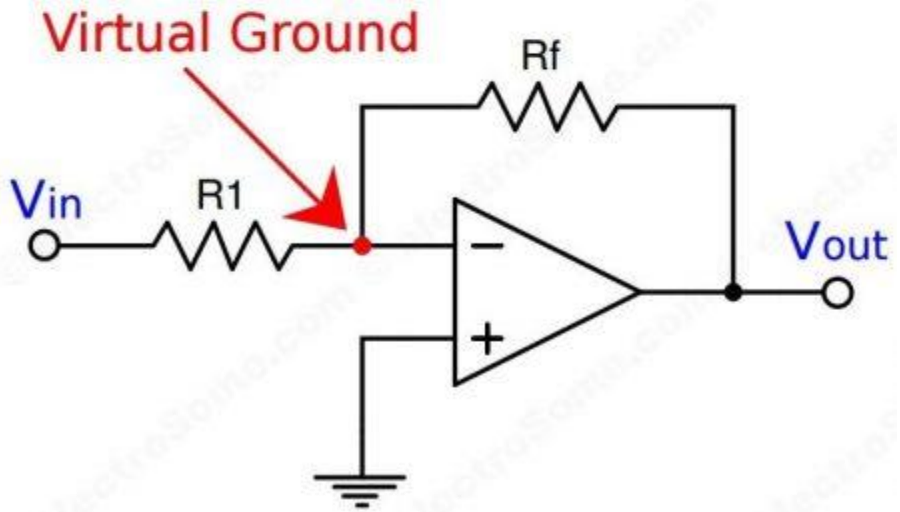
$$V_{in} = V_2 - V_1$$

In the above circuit V_1 is connected to ground, so $V_1 = 0$. Thus V_2 also will be at ground potential.

i.e. $V_2 = 0$

Virtual ground concept





Though for an ideal Op-Amp, Gain $A_0 = \infty$, for actual one , it is extremely high i.e. about 10^6. However it doesn't mean that 1V is amplified to 10^6 V at output. The maximum value of output voltage V_0 is limited by the bias supply voltage , typically $\pm 15V$. With gain $A_0 = 10^6$ and $V_0 = 15V$, the maximum value of input voltage is limited to $\frac{15}{10^6} = 15\mu V$. Though 1V can not become 1 Million volt in Op-Amp, 1μV can certainly become 1Volt

Signal Amplification

Normally the output of Transducer in electrical form is very weak and low level. To drive the other stages of the instrumentation system , the direct output of transducer is not able. So the strength of the weak signal to be increased. This boosting function is done by the signal amplifier. In instrumentation system Op-Amp based amplifiers are used. Some of the important amplifiers constructed using Op-Amps are listed below:

1. Inverting Amplifier
2. Non-Inverting Amplifier
3. Differential Amplifier
4. Summer/ Adder Amplifier
5. Buffer Amplifier
6. Logarithmic Amplifier
7. Antilog Amplifier
8. Instrumentation Amplifier
9. Integrating Amplifier (Integrator Circuit)
10. Differentiating Amplifier (Differentiator Circuit)

Inverting Amplifier

The inverting amplifier circuit is shown. From figure,

$$I_1 = \frac{V_{in} - V_1}{R_{in}}$$

But $V_2 = V_1 = 0V$ [virtual ground concept]

$$I_1 = \frac{V_{in}}{R_{in}}$$

and again

$$V_{out} - V_1 = I_f R_f$$

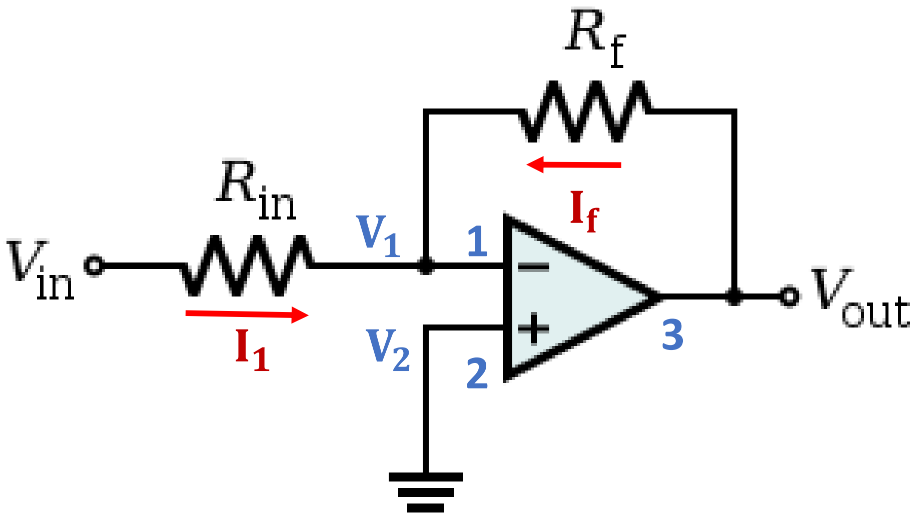
$$I_f = \frac{V_{out} - V_1}{R_f} = \frac{V_{out}}{R_f}$$

Applying Kirchhoff's current law

$$I_1 + I_f = 0$$

$$\frac{V_{in}}{R_{in}} + \frac{V_{out}}{R_f} = 0$$

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



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

$$\boxed{V_{out} = -\frac{R_f}{R_{in}} V_{in}}$$

$$\therefore V_{out} = -A_C V_{in}$$

Where $A_C = \frac{R_f}{R_{in}}$ is closed loop gain of the inverting amplifier

- ❖ If $R_f > R_{in}$, the circuit acts as a Multiplier
- ❖ If $R_f < R_{in}$, the circuit acts as a Divider

Non-Inverting Amplifier

The non-inverting amplifier circuit is shown. From figure,

$$I_1 = \frac{V_1 - 0}{R_1}$$

But $V_2 = V_{in} = V_1$ [virtual ground concept]

$$I_1 = \frac{V_1}{R_1} = \frac{V_{in}}{R_1}$$

and again

$$V_{out} - V_1 = I_f R_f$$

$$I_f = \frac{V_{out} - V_1}{R_f} = \frac{V_{out} - V_{in}}{R_f}$$

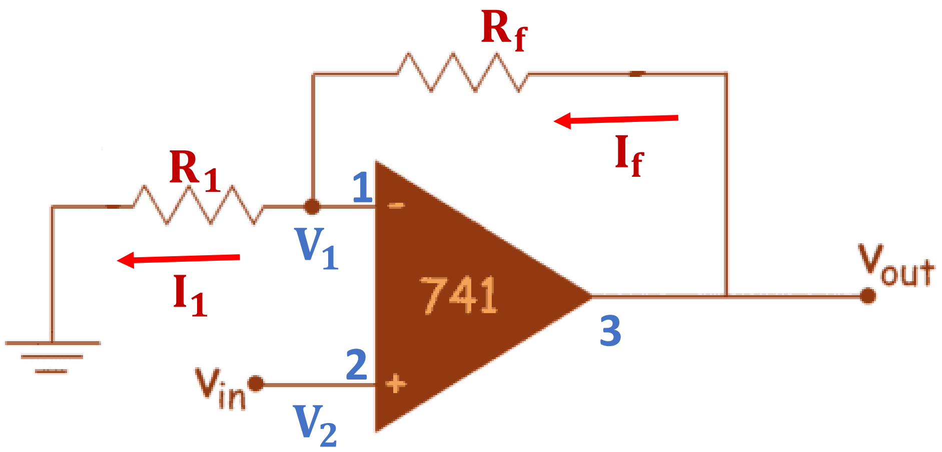
Applying Kirchhoff's current law

$$I_1 = I_f$$

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

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

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



$$V_{in}\left[\frac{1}{R_1} + \frac{1}{R_f}\right] = \frac{V_{out}}{R_f}$$

$$\frac{V_{out}}{V_{in}} = \left[\frac{R_f}{R_1} + 1\right]$$

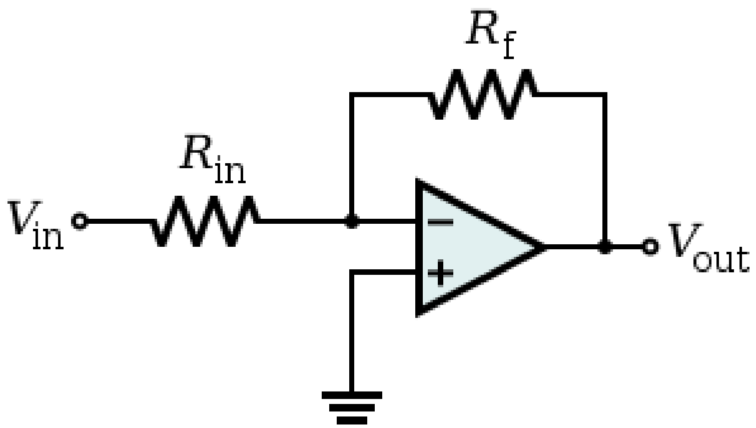
$$\boxed{V_{out} = \left[1 + \frac{R_f}{R_1}\right] V_{in}}$$

$$\therefore V_{out} = A_C V_{in}$$

Where $A_C = \left[1 + \frac{R_f}{R_{in}}\right]$ is closed loop gain of the non-inverting amplifier

It is to be noted that for higher gain achievement we prefer non-inverting rather than inverting Op-Amp amplifier

Sign Changer or Inverter



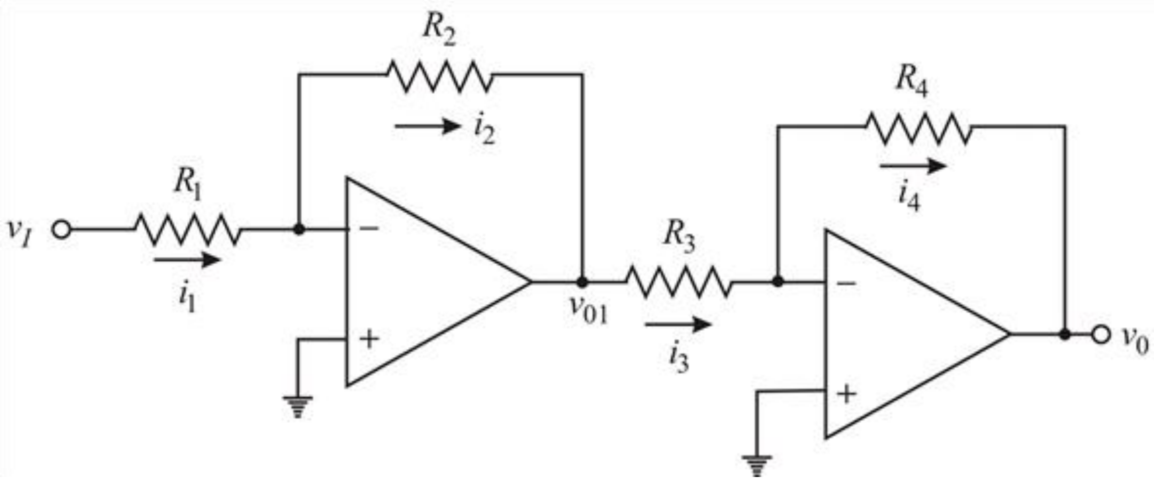
For inverting amplifier, when $R_1 = R_f = R$ (say) then the output of the circuit can be expressed as

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

$$V_{out} = -\frac{R}{R} V_{in}$$

$$\boxed{V_{out} = -V_{in}}$$

This performance of the amplifier changes or inverts the sign of the input when available at the output.



If we cascade two stages of such sign changer then, let $R_1 = R_2 = R_3 = R_4 = R$ (say)

$$V_{01} = -\frac{R_2}{R_1} V_{in} = -\frac{R}{R} V_{in} = -V_{in}$$

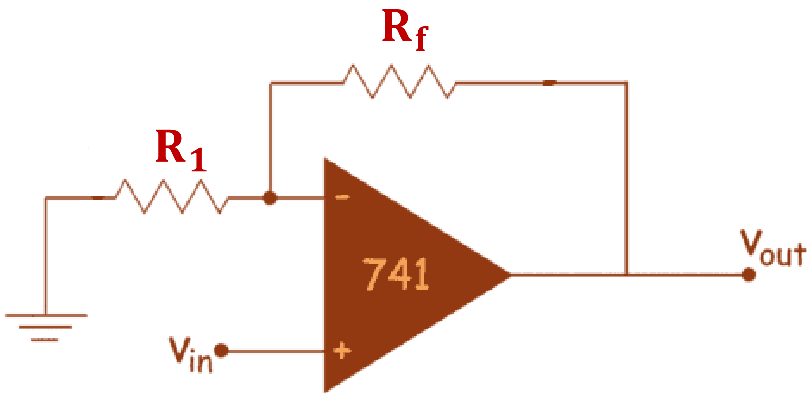
And

$$V_O = -\frac{R_4}{R_3} V_{01} = -\frac{R}{R}(-V_{in}) = V_{in}$$

$$\boxed{V_{out} = V_{in}}$$

This circuit is suitable for avoiding attenuation in the wire connection in the circuit

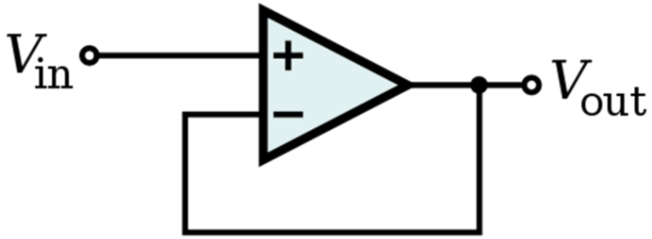
Buffer Amplifier/Unity follower/Voltage follower/Isolation Amplifier



- In non inverting Op-Amp circuit, We calculate gain for a non-inverting amplifier with the following formula

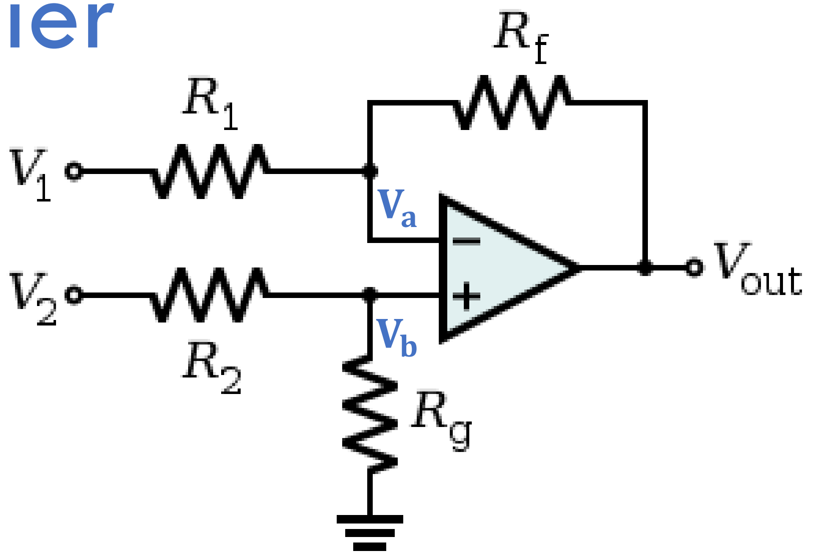
$$V_{out} = [1 + \frac{R_f}{R_1}]\ V_{in}$$

- If we make $R_f = 0$, and $R_1 = \infty$, we'll have an amplification with a gain of exactly 1.
- The buffer has an output that exactly mirrors the input ,so it looks kind of useless at first.



- Here, R_f is a plain wire, which has effectively zero resistance. We can think of R_1 as an infinite resistor. We don't have any connection to ground at all
- However, the buffer is an extremely useful circuit, since it helps to solve many impedance issues. A buffer amplifier is one that provides electrical impedance transformation from one circuit to another, with the aim of preventing the signal source from being affected by whatever currents that the load may be produced with. The signal is 'buffered from' load currents.

Subtracting or Differential Amplifier



The two inputs V_1 and V_2 are fed in to inverting and non inverting terminal respectively

Using the Superposition theorem,

Taking the input source V_1 only, the output becomes

$$V_{01} = -\frac{R_f}{R_1} V_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (i)$$

The voltage across R_g is V_b

$$V_b = \left[\frac{R_g}{R_2+R_g}\right] V_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (ii)$$

We know that from the concept of virtual ground,

$$V_b = V_a = \left[\frac{R_g}{R_2+R_g}\right] V_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (iii)$$

Taking the input source V_2 only, the output becomes

$$V_{02} = \left[1 + \frac{R_f}{R_1}\right] V_b$$

Differential Amplifier….

$$V_{02} = \left[1 + \frac{R_f}{R_1}\right]\left[\frac{R_g}{R_2+R_g}\right] V_2 \ldots\ldots\ldots (iv)$$

Therefore the total output can be expressed as,

$$V_{out} = V_{01} + V_{02}$$

$$= -\frac{R_f}{R_1} V_1 + \left[1 + \frac{R_f}{R_1}\right]\left[\frac{R_g}{R_2+R_g}\right] V_2 \ldots . (v)$$

If $R_1 = R_2$ and $R_f = R_g$ then equation (iv) becomes,

$$V_{02} = \left[1 + \frac{R_f}{R_1}\right]\left[\frac{R_f}{R_1+R_f}\right] V_2$$

$$= \left[\frac{R_1+R_f}{R_1}\right]\left[\frac{R_f}{R_1+R_f}\right] V_2$$

$$= \left[\frac{R_f}{R_1}\right] V_2$$

Hence equation (v) becomes,

$$V_{out} = -\frac{R_f}{R_1} V_1 + [1 + \frac{R_f}{R_1}][\frac{R_g}{R_2+R_g}] V_2$$

$$V_{out} = -\frac{R_f}{R_1} V_1 + \frac{R_f}{R_1} V_2$$

$$\boxed{V_{out} = \frac{R_f}{R_1}[V_2 - V_1]}$$

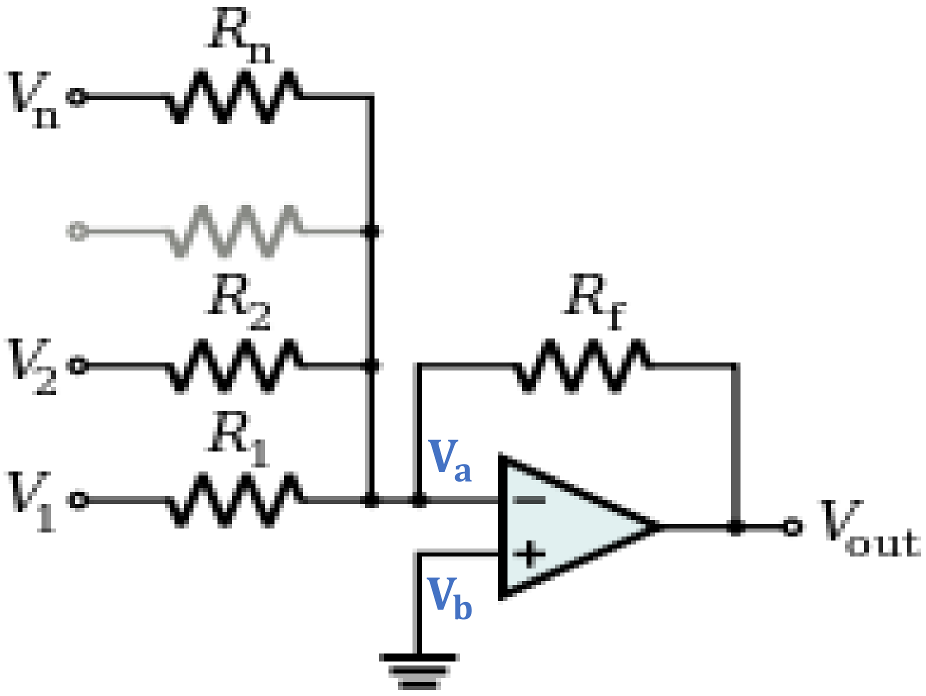
If $R_f = R_1$ then

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

This is the final expression of differential or difference or subtracting amplifier

Summing Amplifier/Adding Amplifier

The circuit diagram for inverting type summing amplifier is as shown



From figure

$$V_b = 0$$

From virtual ground concept,

$$V_a = V_b = 0$$

So the current at different branch becomes,

$$I_1 = \frac{V_1 - V_a}{R_1} = \frac{V_1}{R_1}$$

$$I_2 = \frac{V_2 - V_a}{R_2} = \frac{V_2}{R_2}$$

$$I_3 = \frac{V_3 - V_a}{R_3} = \frac{V_3}{R_3}$$

……………………

$$I_n = \frac{V_n - V_a}{R_n} = \frac{V_n}{R_n}$$

Summing Amplifier….

Applying KCL, Total current

$$I = I_1 + I_2 + I_3 + \cdots + I_n$$

$$I = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \cdots + \frac{V_n}{R_n}$$

Again current through feedback resistor,

$$I_f = \frac{V_{out} - V_a}{R_f} = \frac{V_{out}}{R_f}$$

Applying KCL,

$$I + I_f = 0$$

$$I = -I_f$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \cdots + \frac{V_n}{R_n} = -\frac{V_{out}}{R_f}$$

$$V_{out} = -R_f[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \cdots + \frac{V_n}{R_n}]$$

If $R_1 = R_2 = R_3 = R_n = R$

$$\boxed{V_{out} = -\frac{R_f}{R}[V_1 + V_2 + V_3 + \cdots + V_n]}$$

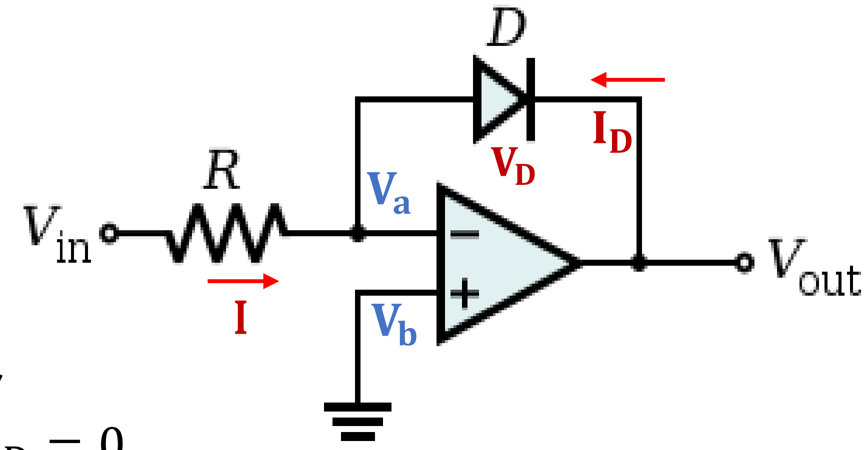
So V_{out} is the scale sum of $V_1, V_2, V_3,$ and V_n by a factor of $\frac{R_f}{R}$. Here the sign is negative, so this is the scaled negated summing output

If $R_f = R$

$$\boxed{V_{out} = -[V_1 + V_2 + V_3 + \cdots + V_n]}$$

Hence this circuit is known as Negation or Inverting summing amplifier

Logarithmic Amplifier



From figure

$$V_b = 0$$

From virtual ground concept,

$$V_a = V_b = 0$$

The output of the circuit is evaluated by,

$$I = \frac{V_{in} - V_a}{R} = \frac{V_{in}}{R}$$

Again, current across the diode

$$I_D = I_S(e^{\frac{V_D}{nV_T}} - 1)$$

$$I_D \approx I_S . e^{\frac{V_D}{nV_T}}$$

Again diode voltage V_D

$$V_D = V_{out} - V_a = V_{out}$$

$$I_D \approx I_S . e^{\frac{V_{out}}{nV_T}}$$

$I_D = I_S . e^{\beta V_{out}}$ Where $\beta = \frac{1}{nV_T} = \frac{1}{V_T}$

Applying KCL,

$$I + I_D = 0$$

$$I = -I_D$$

$$\frac{V_{in}}{R} = -I_S . e^{\beta V_{out}}$$

$$\frac{V_{in}}{I_S R} = -e^{\beta V_{out}}$$

Taking natural log,

$$-\beta V_{out} = \ln[\frac{V_{in}}{I_S R}]$$

$$-V_{out} = \frac{1}{\beta} \ln[\frac{V_{in}}{I_S R}]$$

$$\boxed{V_{out} = -V_T \ln[\frac{V_{in}}{I_S R}]}$$

Anti-Logarithmic Amplifier

The positions of diode and resistance are exchanged as compared to log amplifier circuit.

From figure

$$V_b = 0$$

From virtual ground concept,

$$V_a = V_b = 0$$

Now the current flowing through the diode is I_D and the voltage across diode is V_D

Hence from the diode current equations we can write,

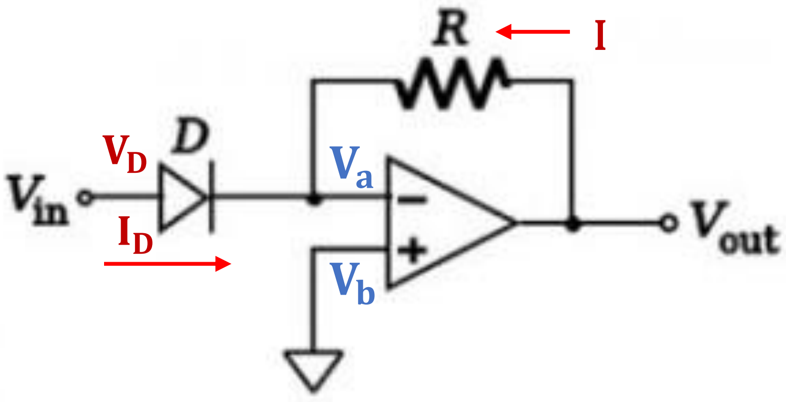
$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$

$$I_D \approx I_S.e^{\frac{V_D}{nV_T}}$$

And diode voltage $V_D = (V_{in} - V_a) = V_{in}$

Now the current across the resistor is,

$$I = \frac{V_{out}-V_a}{R} = \frac{V_{out}}{R}$$



Applying KCL,

$$I + I_D = 0$$

$$I = -I_D$$

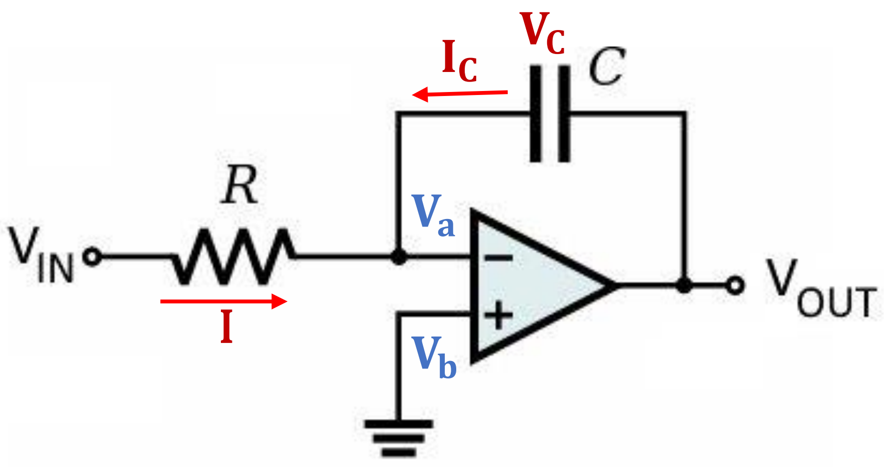
$$\frac{V_{out}}{R} = -I_S.e^{\frac{V_{in}}{nV_T}}$$

$$\frac{V_{out}}{I_S R} = -e^{\frac{V_{in}}{nV_T}}$$

$$\boxed{V_{out} = -I_S R.e^{\frac{V_{in}}{nV_T}}}$$

The output voltage is proportional to the anti-natural logarithm (exponential) of the input voltage V_{in}. The exponential function is nothing but the antilog and thus circuit works as an antilog amplifiers.

Integrating Amplifier



From figure,

$$V_b = 0$$

From virtual ground concept,

$$V_a = V_b = 0$$

Current across the resistor R,

$$I = \frac{V_{in} - V_a}{R} = \frac{V_{in}}{R}$$

Current across capacitor C,

$$I_C = C.\frac{d(V_C)}{dt}$$

$$I_C = C.\frac{d(V_{out} - V_a)}{dt} = C.\frac{d(V_{out})}{dt}$$

Applying KCL

$$I + I_C = 0$$

$$I = -I_C$$

$$\frac{V_{in}}{R} = -C.\frac{d(V_{out})}{dt}$$

$$\frac{d(V_{out})}{dt} = -\frac{V_{in}}{RC}$$

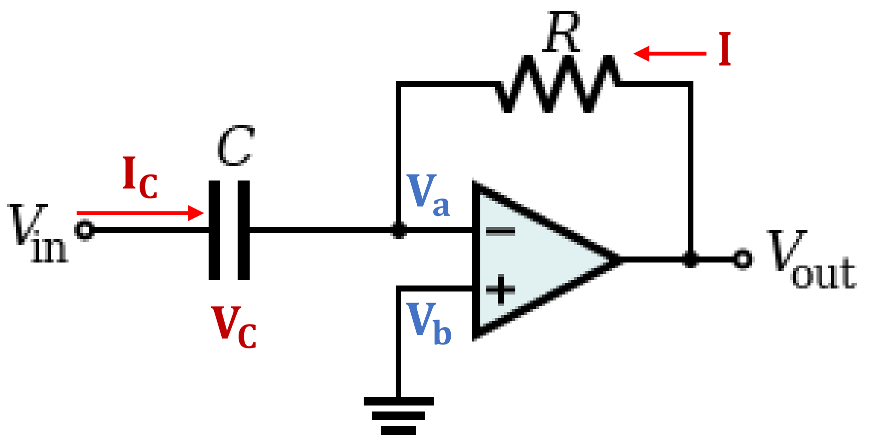
Integrating on both sides,

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

This is the final expression of integrator circuit. This circuit is called integrator or integrating amplifier because the output V_{out} is proportional to the integration of input voltage V_{in}

The term $-\frac{1}{RC}$ is known as scale factor.

Differentiating Amplifier



From figure,

$$V_b = 0$$

From virtual ground concept,

$$V_a = V_b = 0$$

Current across the resistor R,

$$I = \frac{V_{out} - V_a}{R} = \frac{V_{out}}{R}$$

Current across capacitor C,

$$I_C = C.\frac{d(V_C)}{dt}$$

$$I_C = C.\frac{d(V_{in} - V_a)}{dt} = C.\frac{d(V_{in})}{dt}$$

Applying KCL

$$I + I_C = 0$$

$$I = -I_C$$

$$\frac{V_{out}}{R} = -C.\frac{d(V_{in})}{dt}$$

$$\frac{V_{out}}{RC} = -\frac{d(V_{in})}{dt}$$

Integrating on both sides,

$$\boxed{V_{out} = -RC\frac{d(V_{in})}{dt}}$$

This is the final expression of differentiating circuit. This circuit is called differentiator or differentiating amplifier because the output V_{out} is proportional to the derivative of input voltage V_{in}

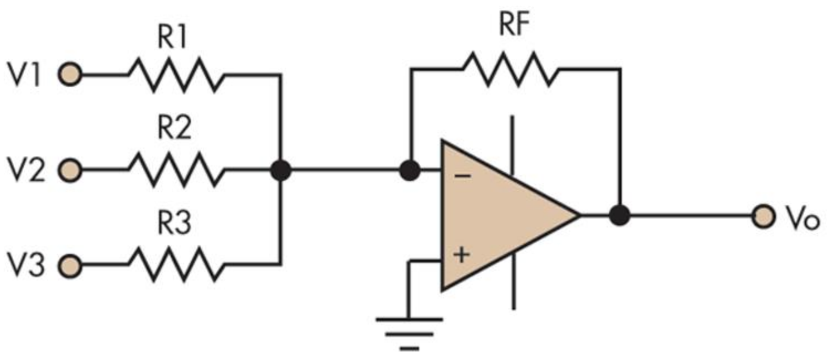
The term $-RC$ is known as scale factor.

Class Work

1. Realize a circuit to obtain $V_{out} = -2V_1 + 3V_2 + 4V_3$ using an operational amplifier. Use minimum value of resistance as 10KΩ.

2. Find the output voltage of the following circuit.

$V_1 = 0.2V, R_1 = 33K\Omega$
$V_2 = -0.5V, R_2 = 22K\Omega$
$V_3 = 0.8V, R_3 = 12K\Omega$
$R_f = 68K\Omega$



3. A 10mV, 2 kHz sinusoidal signal is applied to the inverting input terminal of an op-amp integrator for which R = 50KΩ and capacitance C = 2μF. Determine the output voltage.

Instrumentation Amplifier(IA)

- The output signal provided by the transducer is in very weak form i.e. low-level so need to be amplified before further processing and this is normally done with instrumentation amplifiers.
- The important features of the instrumentation amplifiers are given below:

1) Selectable gain with high gain accuracy and gain linearity.
2) Differential input capability with high common mode rejection ratio (CMRR), even with sources having unbalanced high output impedances.
3) High stability of gain with low temperature coefficient.
4) Low dc offset and drift errors referred to low output impedance.

Instrumentation Amplifier(IA)….

- The instrumentation amplifier is superior than other amplifiers while amplifying the low level signals because it differs to the other Op-amp based amplifier in the following respects :

1) It is the complete package provided with wired up with accurate and stable resistive feedback network to provide desired gain
2) The gain is often selectable to a precise value by a single external resistance
3) Can amplify signal with a fixed amplification factor
4) The gain accuracy, gain stability and drift performance are normally specified by the manufacturer.
5) Provides high CMRR for any source impedances exceeding up to 1MΩ and with the source unbalance of a large value (1 to 10 KΩ)

Instrumentation Amplifier(IA)….

- Generally, in practice, an instrumentation amplifier is a specific combination of a dc Op-amp wired up with feedback and needs very little design effort from the user
- On the basis of Op-amps used to construct the instrumentation amplifiers, it has two sections

1) Input stage amplifier with double Op-amps. (Adjusting input stage)
2) Differential amplifier with third of Op-amps. (Input + differential stage)

Instrumentation Amplifier (IA) with double Op-Amp

- The instrumentation amplifier is a dedicated differential amplifier with extremely high input impedance.
- Its gain can be precisely set by a single internal or external resistor.
- The high common mode rejection ratio makes this amplifier very useful in recovering small signals buried in large common mode offsets and noise.
- The circuit diagram of the double Op-Amp based instrumentation amplifier input stage is shown below. The amplifier consists of two stages:
- The first stage offers very high input impedance to both input signals and allows to set the gain with a single resistor.
- The second stage is a differential amplifier with the output, negative feedback, and ground connections all brought out.

IA with double Op-Amp….

According to the circuit, it consists of two carefully matched Op-Amps. Each input $V_1 \& V_2$ is applied to the non-inverting terminal of respective Op-Amps

The output of Op-Amps are connected together through a string of resistors. The two resistors 'R' are internal to integrated circuit while R_g is the gain setting resistor. It may be internal or connected externally.

Now the voltage across the resistor R_g may be expressed as:

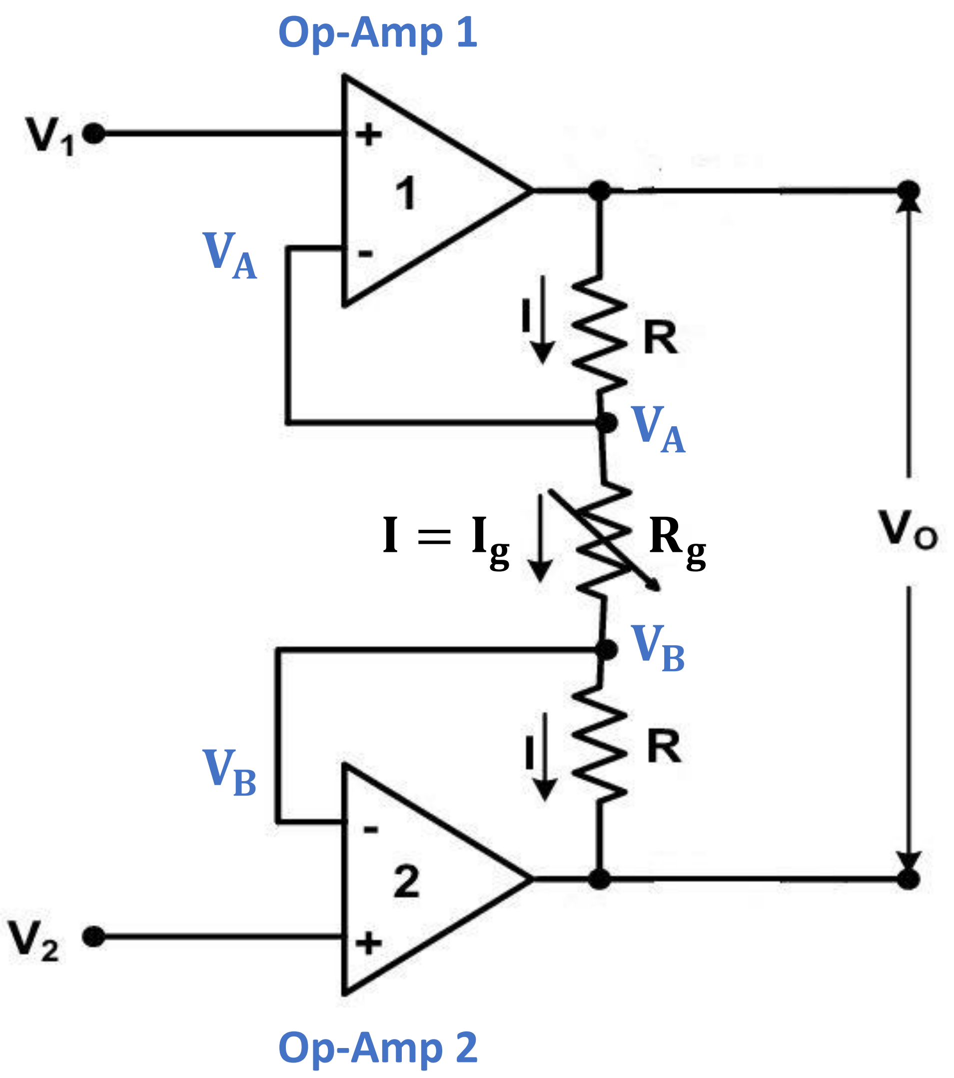
$$V_{R_g} = I_g R_g \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . \dots . (i)$$

The differential voltage input of 1st Op-Amp is given by,

$$V_d = V_1 - V_A$$

Now the voltage at the node V_A is given by,

$$-V_A = V_d - V_1$$



IA with double Op-Amp….

For idealized concept,

$$V_d = 0, \text{ so}$$
$$-V_A = -V_1$$
$$\therefore V_A = V_1 \dots\dots\dots\dots\dots\dots\dots\dots.\dots\dots.(ii)$$

Similarly for 2nd loop

$$V_B = V_2 \dots\dots\dots\dots\dots\dots\dots\dots.\dots\dots..(iii)$$

but

$$V_{R_g} = V_B - V_A = V_{AB} \dots\dots\dots\dots\dots.(iv)$$

From equation (i) and (iv) we have

$$V_{R_g} = V_2 - V_1 = I_g R_g$$
$$\therefore I_g = \frac{V_2 - V_1}{R_g} \dots\dots\dots\dots\dots\dots\dots\dots\dots..(v)$$

But the output voltage V_O be the summation of all the voltage drop across series network of R-R_g-R resistors arrangement

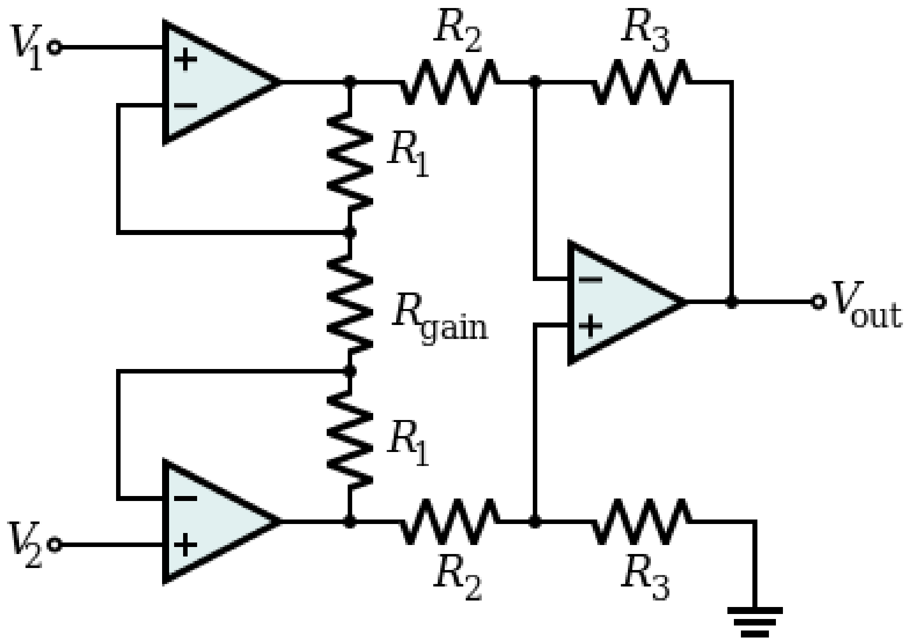
$$V_O = I_g(R + R_g + R)$$
$$\therefore V_O = I_g(2R + R_g) \dots\dots\dots\dots\dots.(vi)$$

Putting the value of I_g from equation (v) in equation (vi)

$$V_O = I_g(2R + R_g)$$
$$V_O = \frac{V_2 - V_1}{R_g}(2R + R_g)$$
$$\therefore \boxed{V_O = (V_2 - V_1)\left(1 + \frac{2R}{R_g}\right)}$$

This is the output provided by the input stage of the instrumentation amplifier

Differential Amplifier with third Op-Amp



The complete circuit diagram of the instrumentation amplifier with both stages is shown

Let V_3 be the output of 1st Op-Amp

V_4 be the output of 2nd Op-Amp,then

$$V_3 = \left(1 + \frac{R_1}{R_g}\right)V_1 - \frac{R_1}{R_g}(V_2 + V_{CM})$$

$$V_4 = \left(1 + \frac{R_1}{R_g}\right)V_2 - \frac{R_1}{R_g}(V_1 + V_{CM})$$

When $R_2 = R_3$ then

$$V_O = V_4 - V_3$$

Putting the values of V_4&V_3

$$V_O = V_4 - V_3$$

$$= \left(1 + \frac{R_1}{R_g}\right)V_2 - \frac{R_1}{R_g}(V_1 + V_{CM}) - \left(1 + \frac{R_1}{R_g}\right)V_1 + \frac{R_1}{R_g}(V_2 + V_{CM})$$

$$= \left(1 + \frac{R_1}{R_g}\right)V_2 - \frac{R_1}{R_g}(V_1) - \left(1 + \frac{R_1}{R_g}\right)V_1 + \frac{R_1}{R_g}(V_2)$$

$$= \left(1 + \frac{R_1}{R_g}\right)(V_2 - V_1) + \frac{R_1}{R_g}(V_2 - V_1)$$

$$= (V_2 - V_1)[1 + \frac{R_1}{R_g} + \frac{R_1}{R_g}]$$

$$\therefore \boxed{V_O = (V_2 - V_1)[1 + 2\frac{R_1}{R_g}]}$$

Attenuation

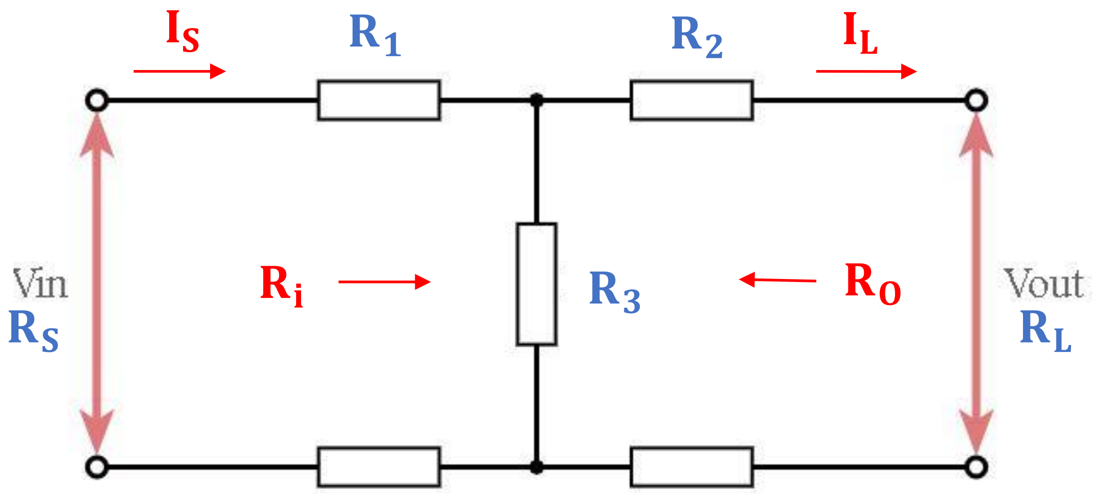
- Attenuation is the reverse process of the amplification.
- The circuit which performs the reverse process of the amplification is known as the attenuator circuit.
- All kinds of amplifier circuit can be utilized as the attenuator circuit.
- If the input signal provided to the instrumentation system is higher then the strength of the input signal be degraded or reduced by the attenuator circuit before providing to the next stage of the instrumentation system.
- Examples of attenuator circuits are listed below:
    1. Passive resistive Attenuator circuit
    2. Active Op-Amp based attenuator

Passive resistive attenuator circuit

- Normally an interpretation of the term attenuator may be applied to the potential dividers, shunts, current and voltage transformers etc.
- But resistive attenuators are also called the resistance attenuation pad which capable of dividing the potential or which may reduce the voltage and/or power of the input to provide to the load.
- The general circuit diagram of the resistance/resistive attenuator is shown below.
- Here for maximum power delivery,

$$R_S = R_i \text{ and } R_L = R_O$$

And V_i & V_O are the input and output voltages of the attenuator network



It should be noted that attenuation is reciprocal of amplification and is given in dB as

$$A_t = 10\log_{10}\frac{P_S}{P_L}$$

i.e. $A_t = 20\log_{10}\frac{V_S}{V_L}$ assuming $R_S = R_L$

For the above given circuit, let the attenuation may be $20\log_{10} K$ then

$$20\log_{10} K = 10\log_{10}\frac{P_S}{P_L}$$

$$\log_{10} K = \frac{10}{20}\log_{10}\frac{P_S}{P_L}$$

$$\log_{10} K = \frac{1}{2}\log_{10}\frac{P_S}{P_L}$$

$$\log_{10} K = \log_{10}\left(\frac{P_S}{P_L}\right)^{\frac{1}{2}}$$

$$K = \left(\frac{P_S}{P_L}\right)^{\frac{1}{2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (i)$$

Where

P_S = Power delivered by source or input circuit

& P_L = Power delivered and seen to the load

In terms of input and output currents

$$K = \left(\frac{P_S}{P_L}\right)^{\frac{1}{2}} = \left(\frac{I_S{}^2 R_S}{I_L{}^2 R_L}\right)^{\frac{1}{2}} \ldots\ldots\ldots\ldots\ldots (ii)$$

From circuit

$$R_i = R_S = R_1 + R_3 || (R_2 + R_L)$$

$$R_S = R_1 + \frac{R_3\,(R_2+R_L)}{R_3+(R_2+R_L)} \ldots\ldots\ldots. (iii)$$

Similarly,

$$R_O = R_L = R_2 + R_3 || (R_1 + R_S)$$

$$R_L = R_2 + \frac{R_3(R_1+R_S)}{R_3+(R_1+R_S)} \ldots\ldots\ldots.. (iv)$$

Similarly,

$$I_L = I_S \times \frac{R_3}{R_3+(R_2+R_L)}$$

$$\frac{I_S}{I_L} = \frac{R_3+(R_2+R_L)}{R_3} = \frac{R_2+R_3+R_L}{R_3}$$

From equation (ii)

$$\frac{I_S}{I_L} = \frac{K}{\sqrt{\frac{R_S}{R_L}}} = \frac{K}{(\frac{R_S}{R_L})^{\frac{1}{2}}} \ldots\ldots\ldots\ldots\ldots (v)$$

From equation (iii)

$$R_S = R_1 + \frac{R_3\,(R_2+R_L)}{R_3+(R_2+R_L)}$$

$$R_1 = R_S - \frac{R_3\,(R_2+R_L)}{R_3+(R_2+R_L)}$$

Solving the above equations (ii), (iii) and (iv)

$$\therefore R_1 = R_S\left(\frac{K^2+1}{K^2-1}\right) - 2(R_SR_L)^{\frac{1}{2}}\left[\frac{K}{K^2-1}\right]$$

$$\therefore R_2 = R_L\left(\frac{K^2+1}{K^2-1}\right) - 2(R_SR_L)^{\frac{1}{2}}\left[\frac{K}{K^2-1}\right]$$

$$\therefore R_3 = 2(R_SR_L)^{\frac{1}{2}}\left[\frac{K}{K^2-1}\right]$$

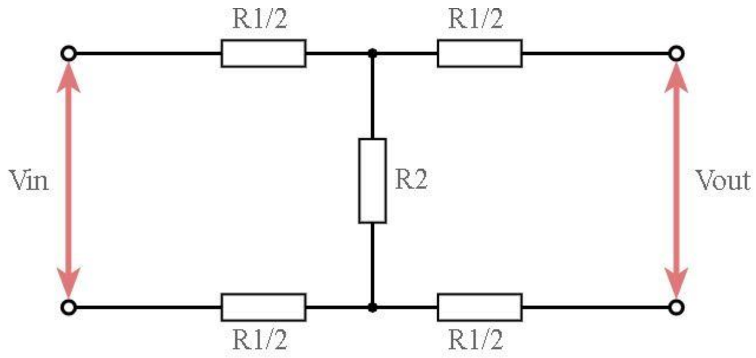
Resistive attenuator are of 2 types

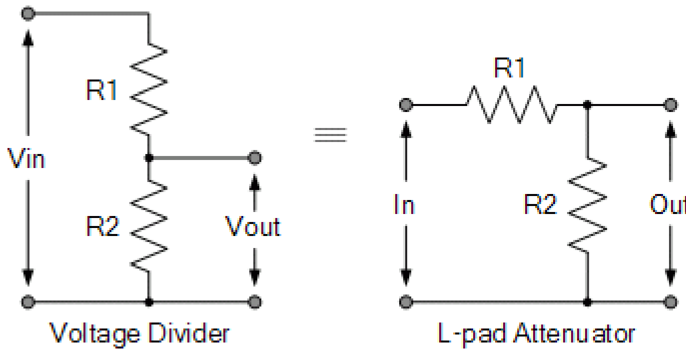
1. Symmetrical attenuator
2. Asymmetrical attenuator

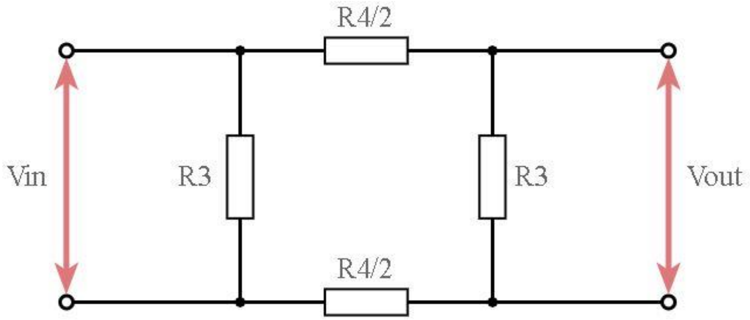
Symmetrical attenuator

- These are also called the balanced attenuators
- Symmetrical attenuator may be of following types
  1. T-type balanced attenuator
  2. L-section balanced attenuator
  3. π-type balanced attenuator

The circuit arrangement of these all are shown below.

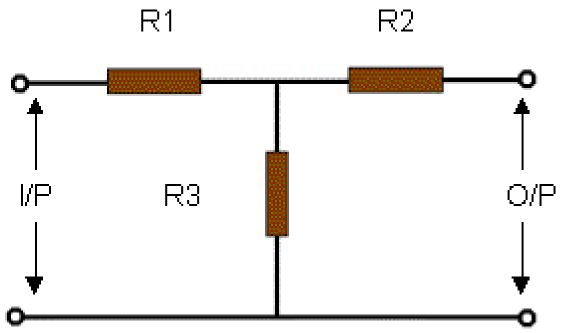


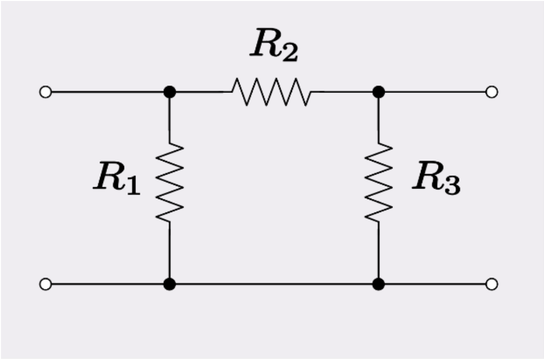




Asymmetrical (resistive) attenuator

- These are also known as the unbalanced attenuator
- These may be of following types according to the resistor used and their arrangement
    1. T-type unbalanced attenuator
    2. L-section unbalanced attenuator
    3. π-type unbalanced attenuator

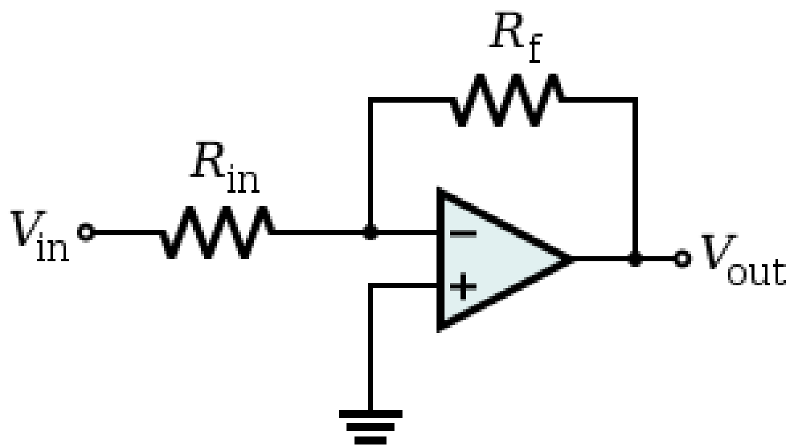




Active Op-amp based attenuator

- Here the value of the gain of the Op-Amp in closed loop is set below '1' for attenuating the input signal
- As gain is reduced ultimately the output provided by the any op-amp configuration is less than the input signal, so behaving as the de-amplifier or the attenuator circuit

The figure shown below depicts the inverting attenuator



$$\boxed{V_{out} = -\frac{R_f}{R_{in}} V_{in}}$$

$$\therefore V_{out} = -A_C V_{in}$$

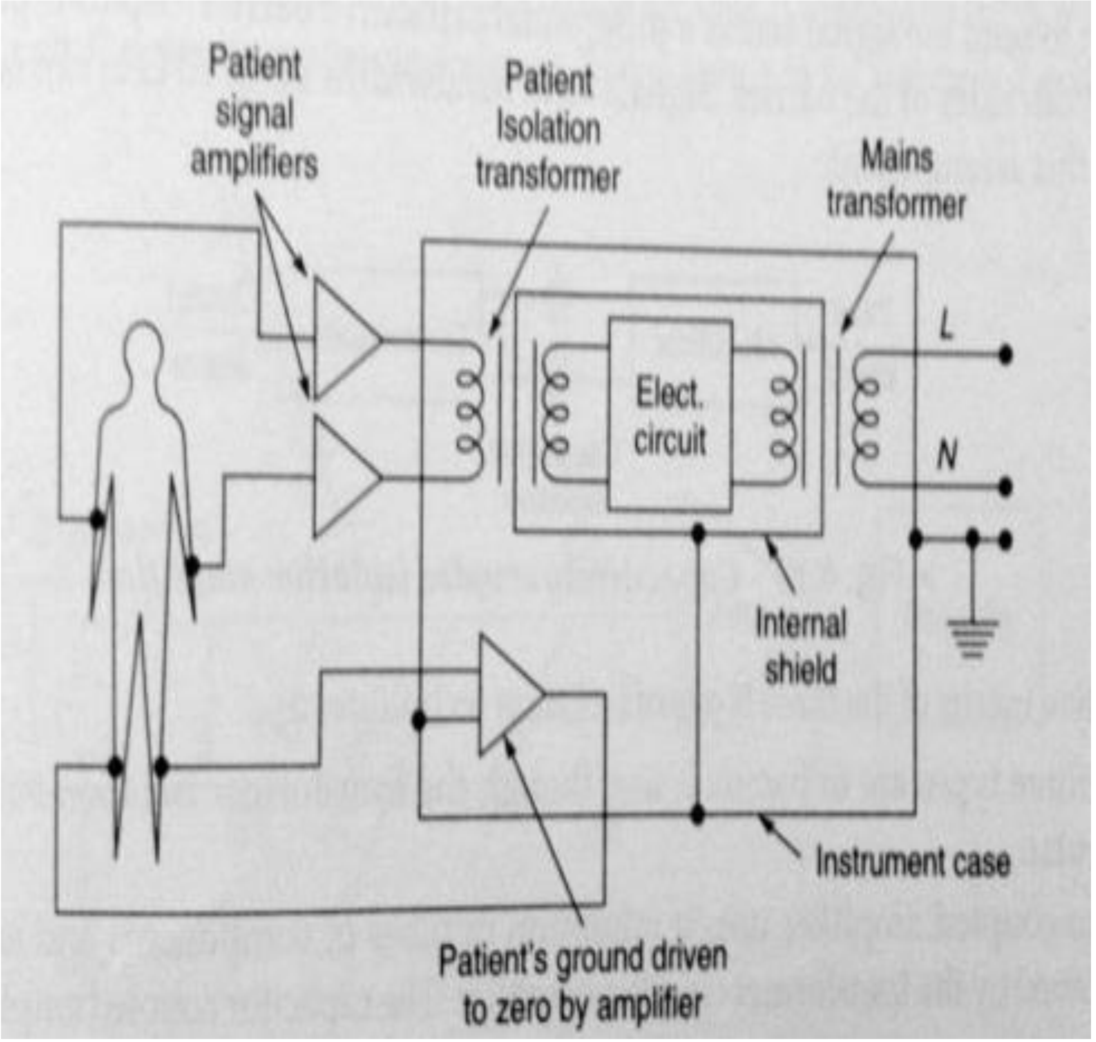
Where $A_C = \frac{R_f}{R_{in}}$ is closed loop gain of the inverting amplifier

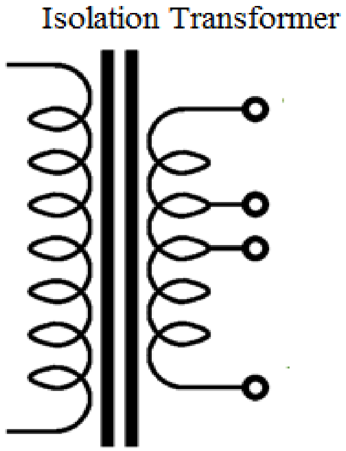
- If $R_f \ll R_{in}$, then the closed loop gain is less than 1.This leads to output voltage V_{out} always less than V_{in}
- Hence this circuit performs the task of attenuator or de-amplifier while placed in closed loop arrangement

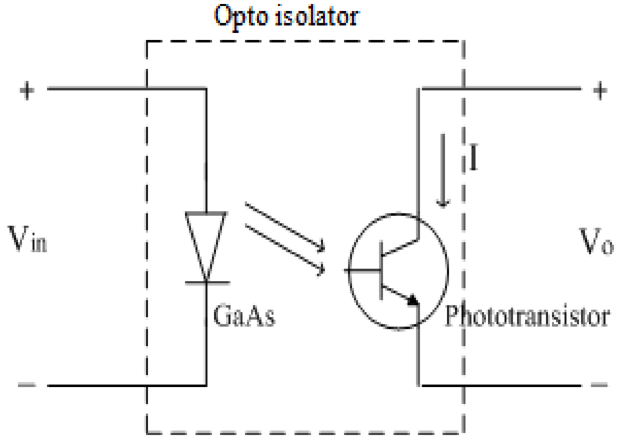
Network Isolation/Isolation amplifier

- Isolation indicates the electrical isolation and is provided by the transformer or by the isolation amplifier
- The isolation amplifier may be constructed using Op-Amps or by using Transistors.
- An isolation amplifier is designed to provide an electrical barrier between the input and output in order to provide protection in applications where hazardous conditions exist.
- These are subclass of instrumentation amplifier that allows measurement of small signals in presence of high common mode voltage by providing electrical isolation and an electrical safety barrier.
- Electrical isolation and electrical safety barrier are required to protect the processing circuitry from faults and power transits, interference from motors, power lines etc. Also, patient protection is important in biomedical applications.
- Isolation can be achieved by the use of transformers and photo resistors.

- A transformer-isolated amplifier relies on transformer coupling of a high-frequency carrier signal between input and output. The isolation between input and output is provided by insulation on the transformer windings.
- An optically-isolated amplifier modulates current through a LED coupler. The isolation is provided by LED and Photo-transistor pair.







Wave Shaping

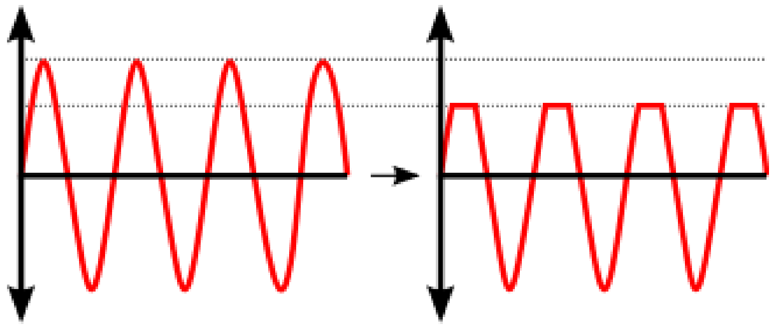
- Wave shaping task is related to the signal conditioning section of the instrumentation system.
- Normally the clipper and the clamper circuits are used for the wave shaping purposes in the electrical field.
- Wave shaping may be
  a) linear and
  b) non-linear.

Clipper circuit

- Clipper circuit performs the non-linear wave shaping.
- A wave shaping circuit which controls the shape of the output waveform by removing a or cutting away a portion of the applied wave is known as clipping circuit.
- Clipping circuit consists of non-linear and linear device . The non-linear devices generally used for clipping are diodes and transistors.
- According to non-linear devices used, clippers may be classified as diode clippers & transistor clippers

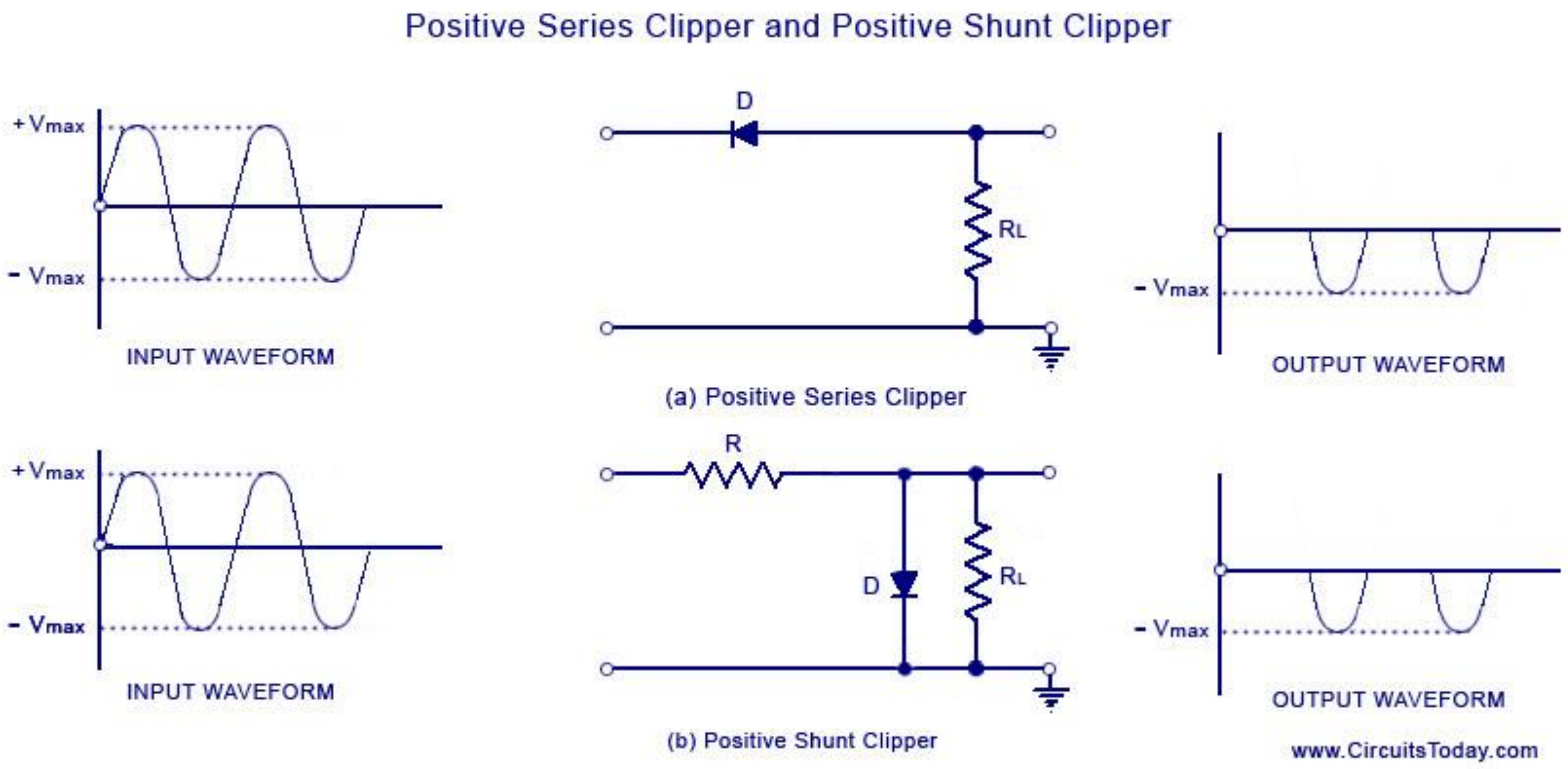
Diode Clipper circuit

- A clipping circuit or a clipper is a device used to 'clip' the input voltage to prevent it from attaining a value larger than a predefined one. As you can see in the picture below this device cuts off the positive or negative peak value of a cycle.
- The basic components required for a clipping circuit are – an ideal diode and a resistor. In order to fix the clipping level to the desired amount, a dc battery must also be included. When the diode is forward biased, it acts as a closed switch, and when it is reverse biased, it acts as an open switch. Different levels of clipping can be obtained by varying the amount of voltage of the battery and also interchanging the positions of the diode and resistor.
- Depending on the features of the diode, the positive or negative region of the input signal is "clipped" off and accordingly the diode clippers may be positive or negative clippers.
- There are two general categories of clippers: series and parallel (or shunt). The series configuration is defined as one where a diode is in series with the load, while the shunt clipper has the diode in a branch parallel to the load.



❑ Unbiased Positive Diode Clipper

- In a positive clipper, the positive half cycles of the input voltage will be removed. The circuit arrangements for a positive clipper are illustrated in the figure given below.

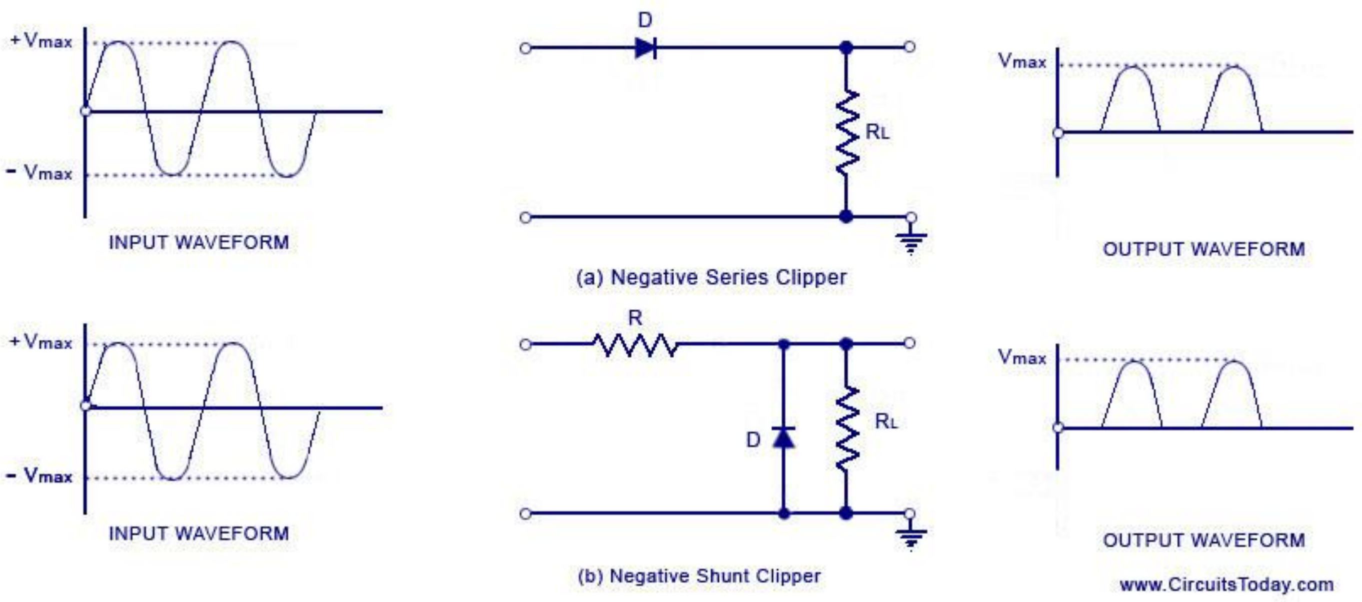


- As shown in the figure, the diode is kept in series with the load.
- During the positive half cycle of the input waveform, the diode 'D' is reverse biased, which maintains the output voltage at 0 Volts. This causes the positive half cycle to be clipped off.
- During the negative half cycle of the input, the diode is forward biased and so the negative half cycle appears across the output.
- In Figure (b), the diode is kept in parallel with the load. This is the diagram of a positive shunt clipper circuit.
- During the positive half cycle, the diode 'D' is forward biased and the diode acts as a closed switch. This causes the diode to conduct heavily. This causes the voltage drop across the diode or across the load resistance R_L to be zero. Thus output voltage during the positive half cycles is zero, as shown in the output waveform.
- During the negative half cycles of the input signal voltage, the diode D is reverse biased and behaves as an open switch. Consequently, the entire input voltage appears across the diode or across the load resistance R_L if R is much smaller than R_L
- Actually the circuit behaves as a voltage divider with an output voltage of $\left[\frac{R_L}{R+R_L}\right]V_{max} = -V_{max}$ when $R_L \gg R$

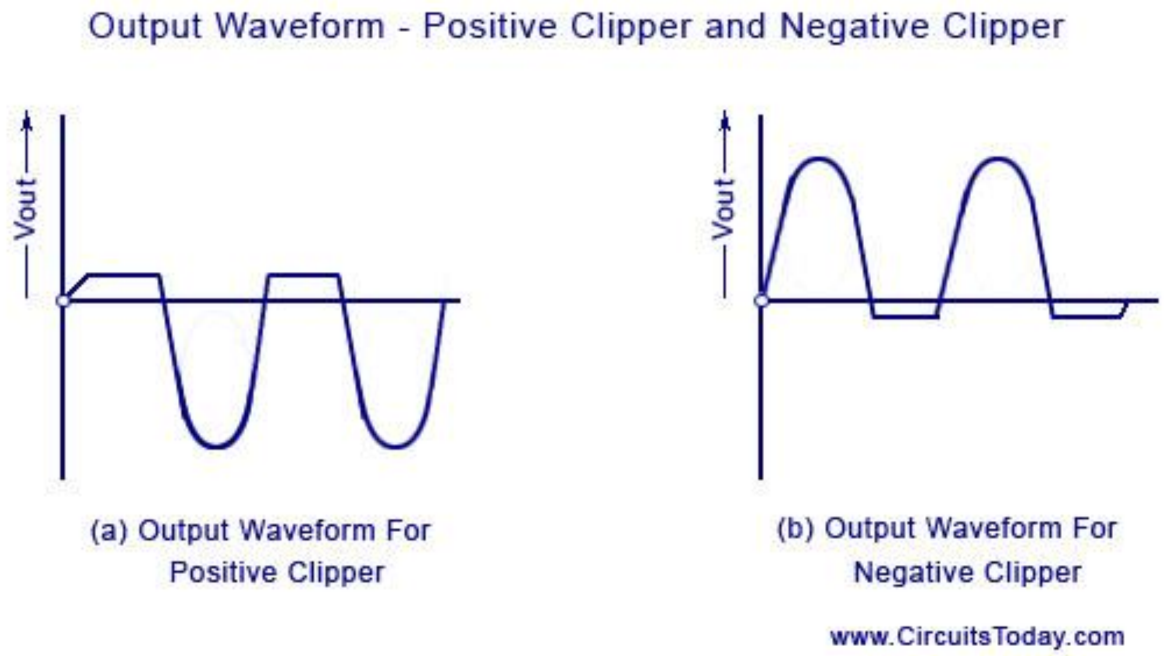
❑ Unbiased Negative Diode Clipper

- The negative clipping circuit is almost the same as the positive clipping circuit, with only one difference.
- If the diode in figures (a) and (b) is reconnected with reversed polarity, the circuits will become for a negative series clipper and negative shunt clipper respectively.
- The negative series and negative shunt clippers are shown in figures (a) and (b) as given below.

Negative Series Clipper and Negative Shunt Clipper

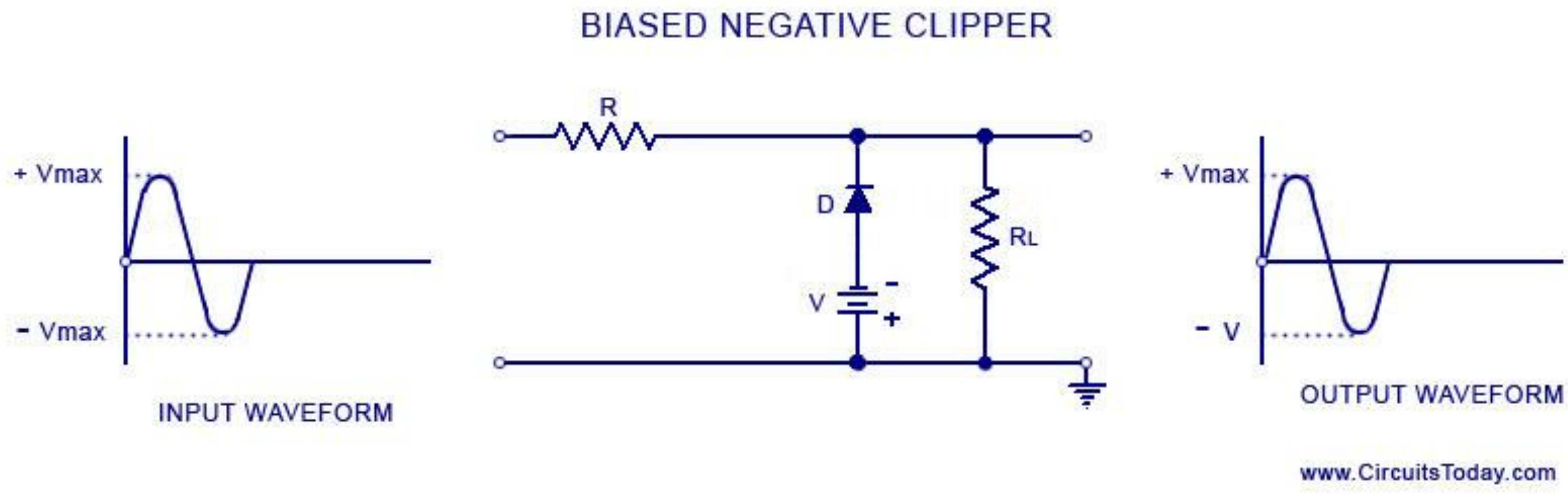


- In all the above discussions, the diode is considered to be the ideal one.
- In a practical diode, the breakdown voltage will exist (0.7 V for silicon and 0.3 V for Germanium).
- When this is taken into account, the output waveforms for positive and negative clippers will be of the shape shown in the figure below.



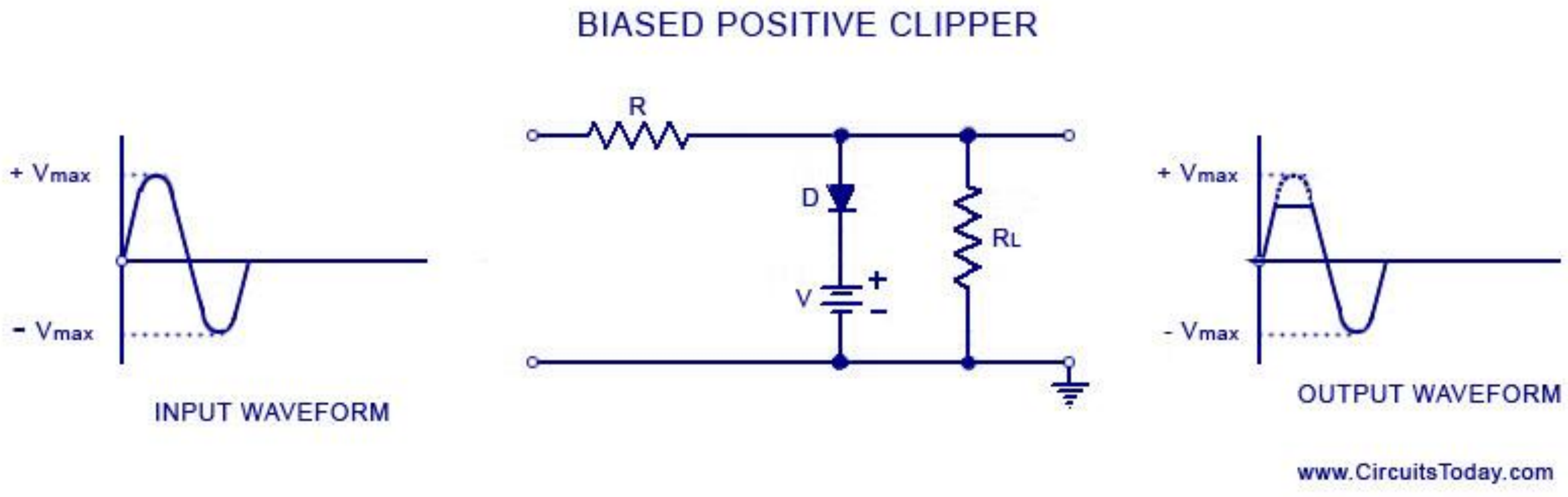
Biased negative clipper

- A biased clipper comes in handy when a small portion of positive or negative half cycles of the signal voltage is to be removed.
- When a small portion of the negative half cycle is to be removed, it is called a biased negative clipper.
- The circuit diagram and waveform is shown in the figure below.

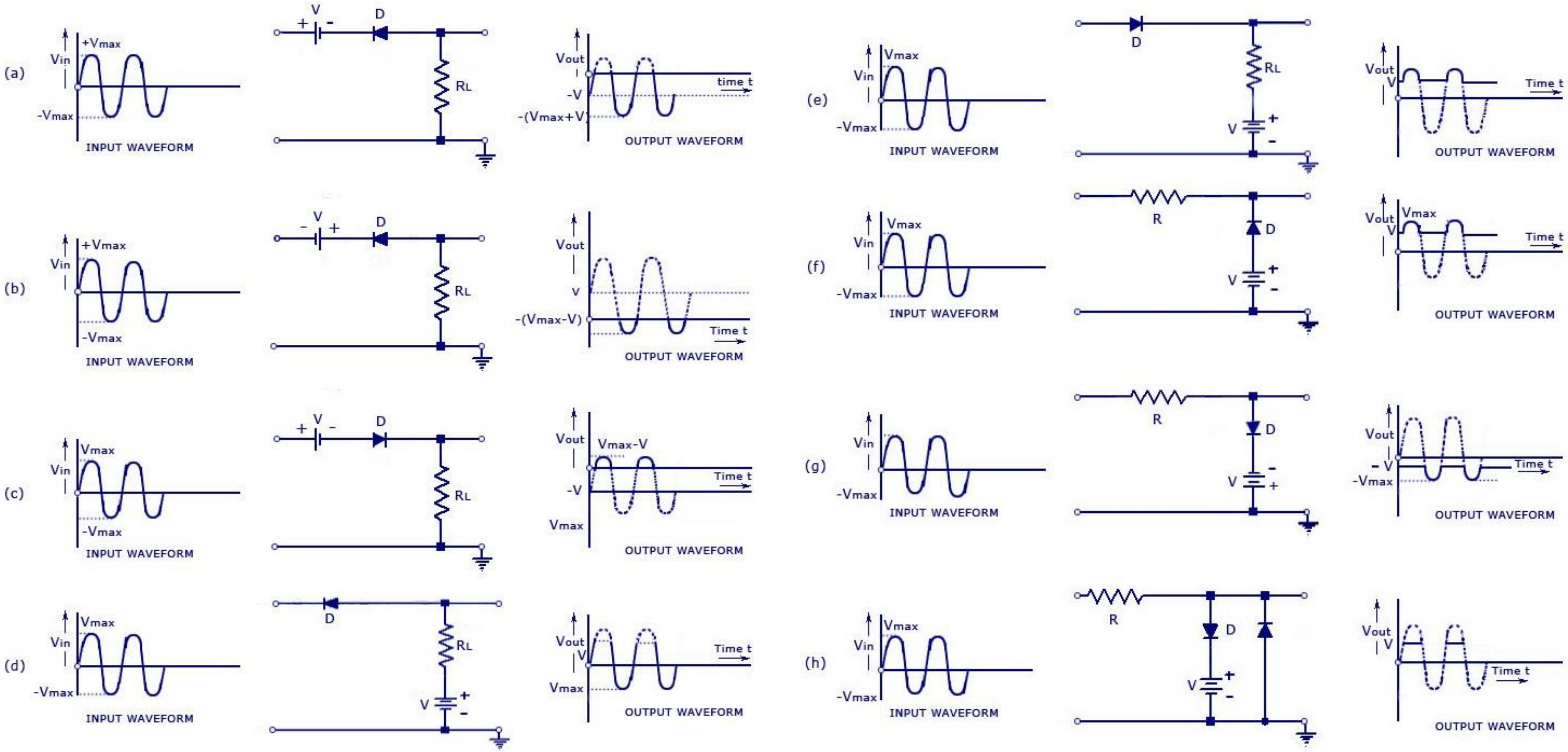


- In a biased clipper, when the input signal voltage is positive, the diode ‘D’ is reverse-biased.
- This causes it to act as an open-switch. Thus the entire positive half cycle appears across the load, as illustrated by output waveform [figure (a)].
- When the input signal voltage is negative but does not exceed battery the voltage ‘V’, the diode ‘D’ remains reverse-biased and most of the input voltage appears across the output.
- When during the negative half cycle of input signal, the signal voltage becomes more than the battery voltage V, the diode D is forward biased and so conducts heavily.
- The output voltage is equal to ‘- V’ and stays at ‘- V’ as long as the magnitude of the input signal voltage is greater than the magnitude of the battery voltage, ‘V’.
- Thus a biased negative clipper removes input voltage when the input signal voltage becomes greater than the battery voltage.
- Clipping can be changed by reversing the battery and diode connections, as illustrated in figure (b).

❑ Biased positive clipper

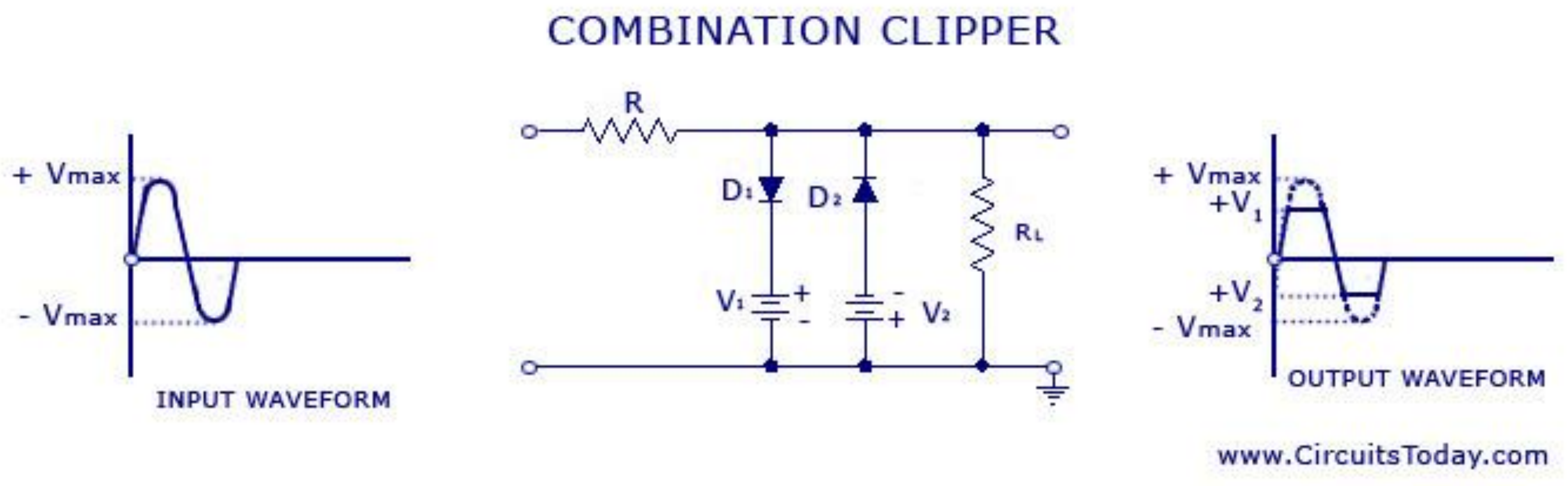


- Some of the other biased clipper circuits are given below in the figure.
- While drawing the wave-shape of the output basic principle discussed above are followed.
- The diode has been considered as an ideal one


(a)
Vin
+Vmax
-Vmax
INPUT WAVEFORM
V
+
-
D
RL
Vout
-V
-(Vmax+V)
time t
OUTPUT WAVEFORM
(b)
Vin
+Vmax
-Vmax
INPUT WAVEFORM
V
-
+
D
RL
Vout
V
-(Vmax-V)
Time t
OUTPUT WAVEFORM
(c)
Vin
Vmax
-Vmax
INPUT WAVEFORM
V
+
-
D
RL
Vout
Vmax-V
-V
Vmax
Time t
OUTPUT WAVEFORM
(d)
Vin
Vmax
-Vmax
INPUT WAVEFORM
D
RL
V
+
-
Vout
V
Vmax
Time t
OUTPUT WAVEFORM
(e)
Vin
Vmax
-Vmax
INPUT WAVEFORM
D
RL
V
+
-
Vout
V
Time t
OUTPUT WAVEFORM
(f)
Vin
Vmax
-Vmax
INPUT WAVEFORM
R
D
V
+
-
Vout
Vmax
V
Time t
OUTPUT WAVEFORM
(g)
Vin
-Vmax
INPUT WAVEFORM
R
D
V
-
+
Vout
- V
-Vmax
Time t
OUTPUT WAVEFORM
(h)
Vin
Vmax
-Vmax
INPUT WAVEFORM
R
D
V
+
-
Vout
V
Time t
OUTPUT WAVEFORM

❑ Combination Clipper

- When a portion of both positive and negative of each half cycle of the input voltage is to be clipped (or removed), combination clipper is employed.
- The circuit for such a clipper is given in the figure below.



- The action of the circuit is summarized below.
- For positive input voltage signal when input voltage exceeds battery voltage '+ V_1' diode D_1 conducts heavily while diode 'D_2' is reversed biased and so voltage '+ V_1' appears across the output.
- This output voltage '+ V_1' stays as long as the input signal voltage exceeds '+ V_1'.
- On the other hand for the negative input voltage signal, the diode 'D_1' remains reverse biased and diode 'D_2' conducts heavily only when input voltage exceeds battery voltage 'V_2' in magnitude.
- Thus during the negative half cycle the output stays at '- V_2' so long as the input signal voltage is greater than '-V_2'.

Drawbacks of Series and Shunt Diode Clippers

- In series clippers, when the diode is in ‘OFF’ position, there will be no transmission of the input signal to output. But in the case of high-frequency signals transmission occurs through diode capacitance which is undesirable. This is the drawback of using the diode as a series element in such clippers.
- In shunt clippers, when the diode is in the ‘off condition, transmission of input signal should take place to output. But in the case of high-frequency input signals, diode capacitance affects the circuit operation adversely and the signal gets attenuated (that is, it passes through diode capacitance to ground).

Applications of clipping circuits

- Used in FM transmitters to reduce noise
- To limit the voltage input to a device
- To modify an existing waveform to the desired output

Linear wave shaping

- Linear wave shaping involves passage of signal through linear systems such as R-C, R-L, and R-L-C circuits.
- The operations involved are linear such as integration, differentiation, summation, filtering etc.

High - pass RC circuit as a differentiator:

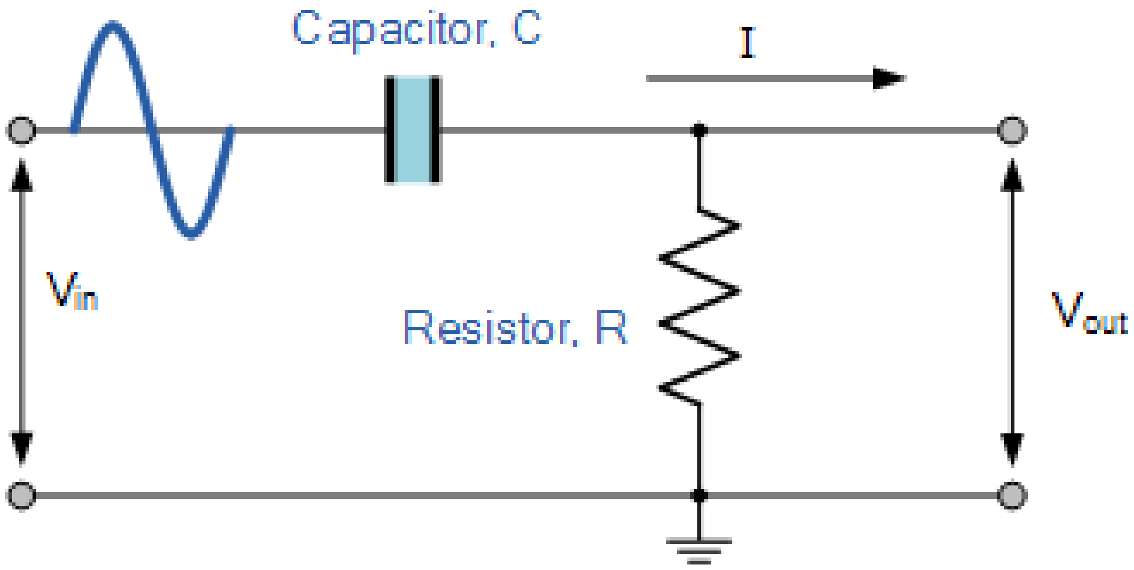
- In high pass RC circuit, if the time constant is very small in comparison with the time required for the input signal to make an appreciable change, the circuit is called a "Differentiator".
- Under these circumstances the voltage drop across R will be very small in comparison with the drop across C.
- Hence we may consider that the total input V_i appears across C.
- So that the current is determined entirely by the capacitor.

$$i = C\frac{dV_i}{dt}$$

- The output voltage across R is,

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

- i.e., The output voltage is proportional to the differential of the input.
- Hence the high pass RC circuit acts as a differentiator when **RC << T**.
- Time constant τ=RC<<T
- When we input the ramp signal it provides the dc signal at the output
- Converts
  - ➢ Sinusoidal waveform to cosinusoidal
  - ➢ Triangular to square wave
  - ➢ Ramp to dc or step signal
  - ➢ Unit step to spikes



$$X_C = \frac{1}{\omega_C} = \frac{1}{2\pi fC}$$

- ➢ Shows lower impedance to ac or signal with frequency (higher frequency)
- ➢ But offers ∞ impedance to pure dc(f=0 Hz)

Low - Pass RC circuit as an integrator

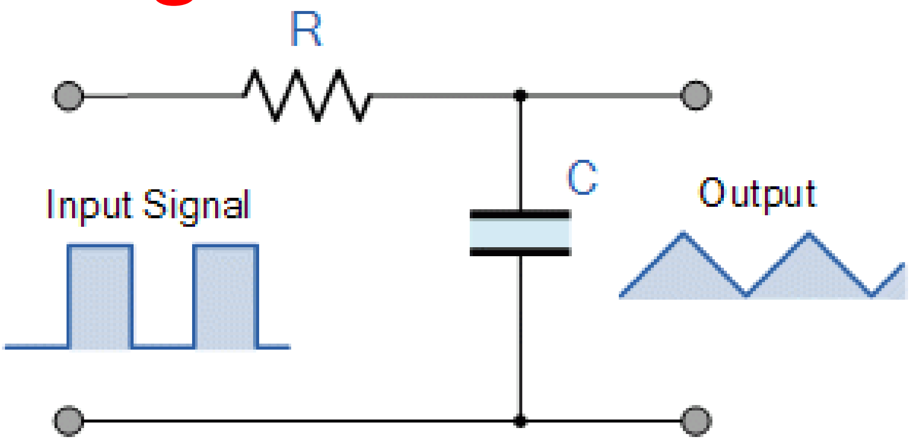
- In low pass circuit, if the time constant is very large in comparison with the time required for the input signal to make an appreciable change, the circuit is called an "integrator".
- Under these circumstances the voltage drop across C will be very small in comparison to the drop across R and almost the total input V_i appears across R

$$\text{i.e., } i = \frac{V_i}{R}$$

The output signal across C is

$$V_o = \frac{1}{C}\int i.\,dt = \frac{1}{RC}\int V_i.\,dt$$

- i.e., The output is proportional to the integral of the input.
- Hence the low pass RC circuit acts as a integrator for **RC >> T**.



Converts:

- ➢ Sinewave to negative cosine
- ➢ Dc to ramp
- ➢ Rectangular pulse to triangular waveform or saw tooth waveform
- ➢ Performs the summation operation

❖ For integrator, time constant τ=RC is to be very large to the time period of input pulse T

i.e. $\tau = RC >> T$

Effect of noise

- The unwanted signals introduced upon the desired signals
- Noise is any kind of signal that is superimposed on the desired signals
- Generally the device used in the circuit and its environment interacting the communication path existing in the circuit introduces the noise
- It may also be defined as any disturbances which generate unwanted signals at primary sensing device, communication channel and any intermediate link.
- Noise degrades the desired signal and causes attenuation and distortion in the desired signal.
- The figure of merits describing the noise behavior is known as the signal to noise ratio (SNR)

$$\text{SNR} = 10\log_{10}\left[\frac{\text{Signal power}}{\text{Noise power}}\right]$$

Types of noise

- There are various type of noises which are listed below
    1) Shot noise
    2) Partition noise
    3) Thermal noise or Johnson noise
    4) Carrier generation and recombination noise
    5) White noise

Thermal noise or Johnson noise

- When charge carriers are thermally generated then a potential drop may arise at the two terminals of the devices causing the thermal noise.
- The thermally generated noise voltage is given by
- $V_{noise} = 2\sqrt{KTBR}$

  Where K= Boltzmann's constant = 1.374×10^{-23} Joules per Kelvin

  T = Absolute temperature in Kelvin

  B = Bandwidth of the signal
- It is minimized by providing the fewer resistance value resistor near to the output taking terminal of the circuit

Partition noise

- When the partition of net current is occurred in the partition of semiconductor device
- The noise arises due to current division

Shot noise

- fluctuations of the charge Carrier in the devices (i.e. fluctuations of electrons) causes the shot noise.
- The shot noise current $I_{noise} = \sqrt{2eI_eB}$ for diode

  Where B = Bandwidth

  e = Electronic charge

  I_e= Emission current

Carrier generation & recombination noise

- In Semiconductor, the generation of carrier and its recombination occurred when the device is biased.
- Due to recombination , neutralization of holes & elections produces a class of noise known as the carrier generation & recombination noise.

White noise

- This noise is a special class of noise which when introduced upon the system can't be eliminated due to any noise cancellation or control technique.
- The power spectral density of White noise is constant for any operating conditions

Besides these noises, source time noise produced by distortion and interference

Signal Filtering

Filters are frequency selective network which passes the wanted frequency bearing signals and block the others

Signal filtering consists of processing a signal to remove a certain band of frequency within it. In general a filter attenuates certain frequency band and passes other with constant gain.

Filter may be classified as

1) Analog and digital filter
2) Active and passive filter

Analog Filter: Analog filters are defined by linear differential equations and implemented using electrical components like resistors and capacitors.

Analog filters are designed to process analog signals using technique while digital filters process signals using digital techniques.

Digital Filter: Digital filter are defined by linear difference equation and implemented using adders, subtractors and delay. Digital filters are used in digital signal filtering.

Passive Filters: Passive filters are built with passive components like resistors, capacitors, inductors.

Active Filters: Active filters are designed by using active components like op-amp in addition to resistors and capacitors.

On the basis of frequency response filters may also be classified into

Low Pass Filter

- A filter that passes signal of frequencies from 0Hz (dc levels) to certain frequencies called critical frequencies (fc) and attenuates signals of all higher frequencies is called low pass filter.

High Pass Filter

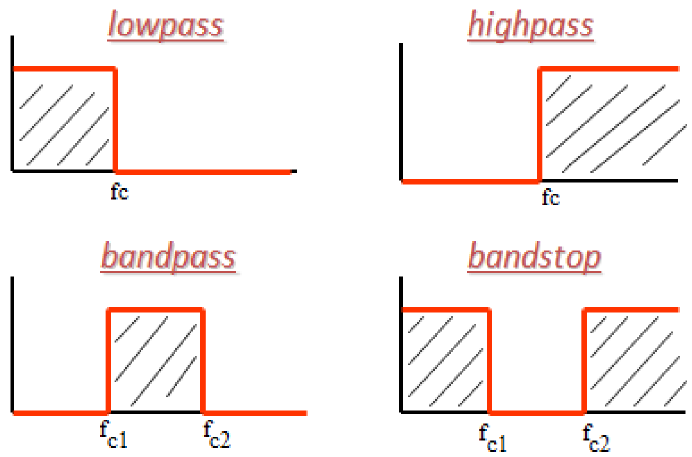
- A filter that passes signal of frequencies higher than certain frequency called critical frequency (fc) and attenuates signal of lower frequency is called high pass filter.

Band Pass Filter

- A filter that passes the frequency of only limited bandwidth ($fc_1 - fc_2$) and attenuates or stops other frequencies is called band pass filter.

Band Stop Filter

- It is a filter that stops the frequency of certain bandwidth ($fc_1 - fc_2$) and allows other frequencies is called band stop filter.



THANK YOU !

End of chapter 4